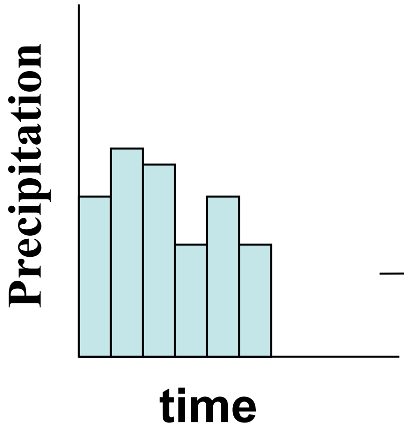
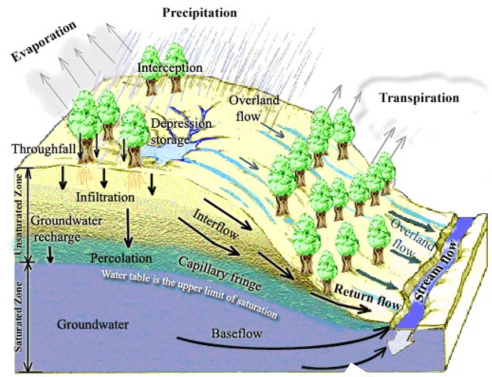
Water Cycle Physical Processes – Emerging Science: Land Surface Hydrology and **Watershed Dynamics**

Jim McNamara
Boise State University
Idaho, USA

Context: Predictive models tasked with representing processes

"need preceded science" *(Rafael Bras)*

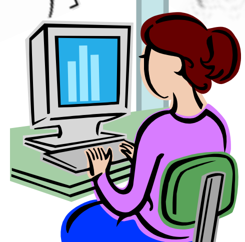


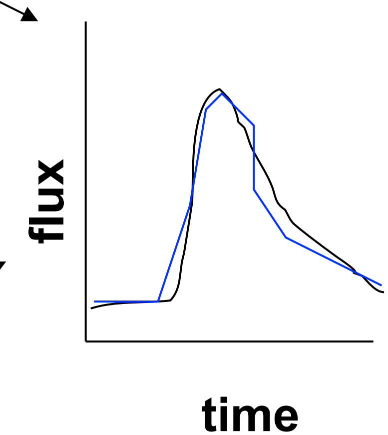


What knowledge is essential to incorporate into models?

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

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

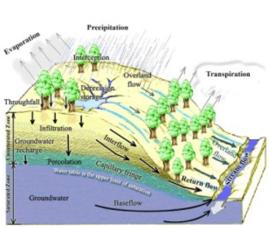


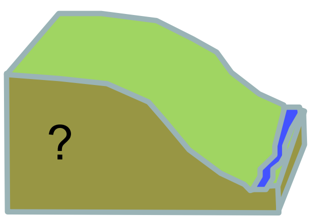


Problems

- Problem: Calibrated models criticized for not representing processes
  - Black Box can be “Right for the Wrong Reasons”
  - Flux right, internal states wrong
  - Next generation models should get fluxes AND states right

- Problem: Field experiments criticized for not asking the right questions
  - Irrelevant answers
  - Site specific

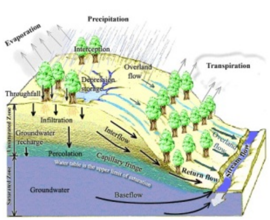


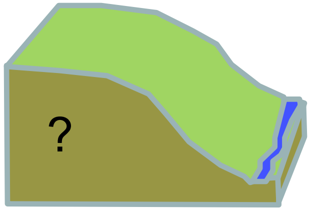


Problems

- Problem: Calibrated models criticized for not representing processes
  - Black Box can be “Right for the Wrong Reasons”
  - Flux right, internal states wrong
  - Next generation models should get fluxes AND states right

- Problem: Field experiments criticized for not asking the right questions
  - Irrelevant answers
  - Site specific

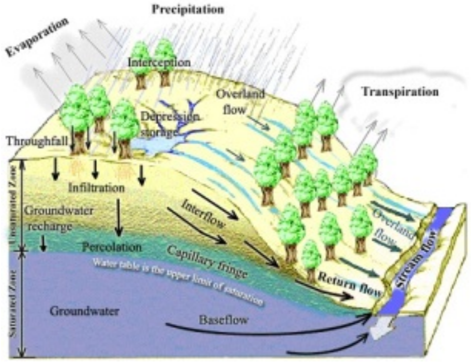


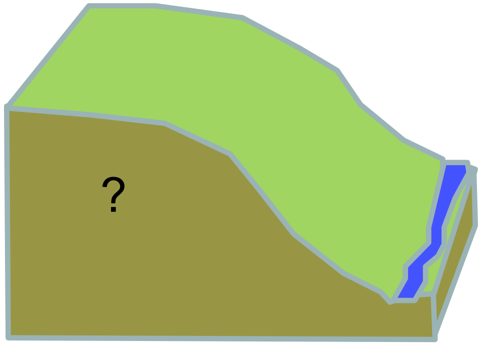


- **Solution:**
  - **Identify *significant processes and properties on the ground* at watershed scale**
  - **Develop new models informed by discovery**

Problems

- **Solution:**
  - **Processes are known**
  - **Incorporate BEHAVIOR into model evaluation strategies**
    - **More than outputs, but INTERNAL DYNAMICS**





"Emerging" Science

significant processes and properties

- "Old water" dominates storm hydrographs

1969

VOL. 5, NO. 2 WATER RESOURCES RESEARCH APRIL 19

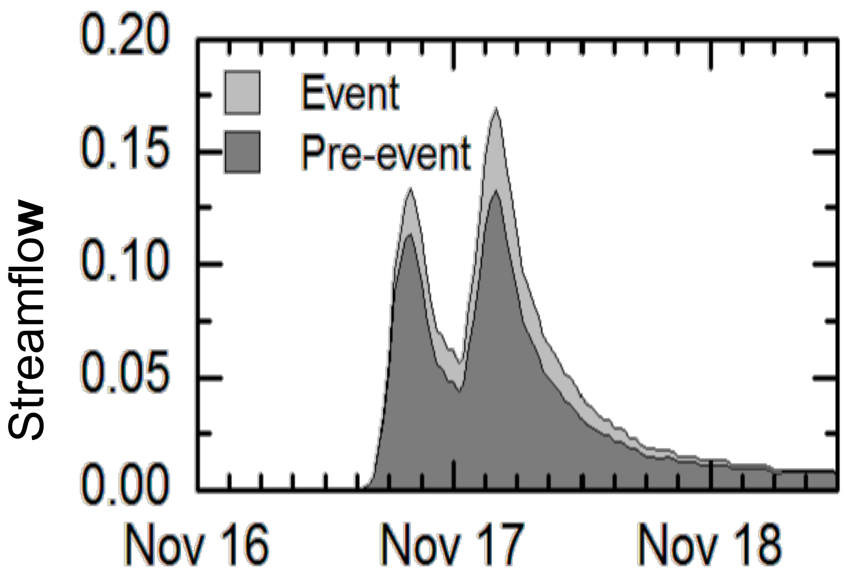
Determination of the Ground-Water Component of Peak Discharge from the Chemistry of Total Runoff

GEORGE F. PINDER AND JOHN F. JONES

Nova Scotia Department of Mines, Halifax, Nova Scotia

Abstract. The ground-water component of stream discharge may be determined from the chemical characteristics of the stream water. A chemical mass-balance is used to relate total, direct, and ground-water runoff. To solve the mass-balance equation, it is necessary to estimate the chemical composition of the ground-water and direct-runoff components. The solute concentration of ground water is determined from total runoff during baseflow; the chemical characteristics of direct-runoff are estimated from samples of total runoff collected from selected locations in a basin during peak discharge periods. In three small watersheds in Nova Scotia ground-water runoff constituted from 32 to 42% of peak discharge for the period of analysis.

The old "Old Water" problem



Hundreds of case studies since 1969

Scores of local explanations
-watershed behavior highly heterogeneous

Continued recent discoveries

-See work by Jeff McDonnell et al…and Jim Kirchner et al.

-not old vs new, but stormflow is composed of a continuum of ages

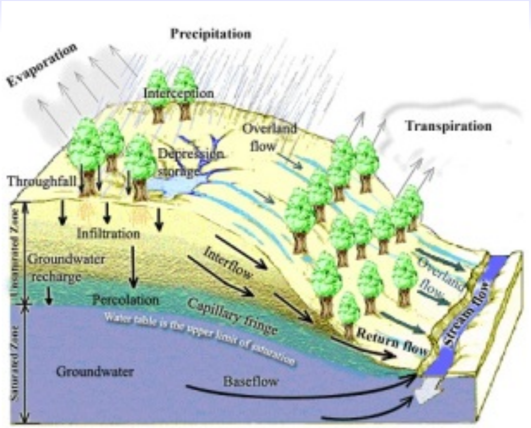
Emerging since 1969

Challenges to remain
-Still at odds with concepts embedded in many commonly used models
(Hortonian Overland Flow)

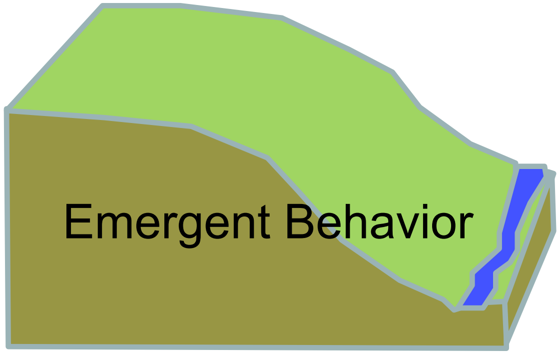
Until models get this right, they are "Right for the Wrong Reasons" and cannot handle change ***(paraphrased from Kirchner)***

The Heterogeneity Problem

- Two solutions
  - Measure everything everywhere, unknowns are simply a matter of poor characterization
    - Unrealistic (Newtonian, me, persevering science)



  - Recognize patterns and emergent properties
    - Watershed behavior is more the accumulation of arrows (Darwinian, emerging science)



-Watershed “lump” processes producing emergent properties

-A physical basis for lumped parameter modeling

The Heterogeneity Issue
Local controls vs General Concepts

Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology

J. J. McDonnell,[1,2] M. Sivapalan,[3] K. Vaché,[4] S. Dunn,[5] G. Grant,[6] R. Haggerty,[7] C. Hinz,[8] R. Hooper,[9] J. Kirchner,[10] M. L. Roderick,[11] J. Selker,[12] and M. Weiler[13]

Received 28 August 2006; revised 14 March 2007; accepted 15 March 2007; published 26 July 2007.

[1] Field studies in watershed hydrology continue to characterize and catalogue the enormous heterogeneity and complexity of rainfall runoff processes in more and more watersheds, in different hydroclimatic regimes, and at different scales. Nevertheless, the ability to generalize these findings to ungauged regions remains out of reach. In spite of their apparent physical basis and complexity, the current generation of detailed models is process weak. Their representations of the internal states and process dynamics are still at odds with many experimental findings. In order to make continued progress in watershed hydrology and to bring greater coherence to the science, we need to move beyond the status quo of having to explicitly characterize or prescribe landscape heterogeneity in our (highly calibrated) models and in this way reproduce process complexity and instead explore the set of organizing principles that might underlie the heterogeneity and complexity. This commentary addresses a number of related new avenues for research in watershed science, including the use of comparative analysis, classification, optimality principles, and network theory, all with the intent of defining, understanding, and predicting watershed function and enunciating important watershed functional traits.

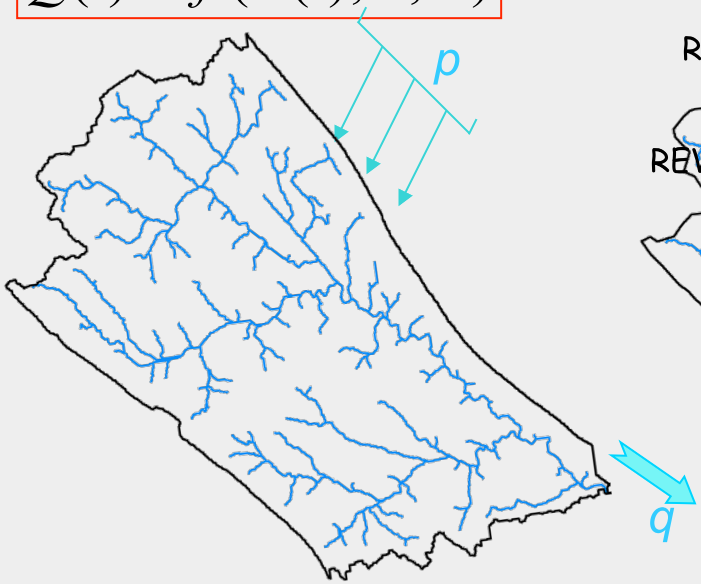
Citation: McDonnell, J. J., et al. (2007), Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology, *Water Resour. Res.*, *43*, W07301, doi:10.1029/2006WR005467.

Model Structures

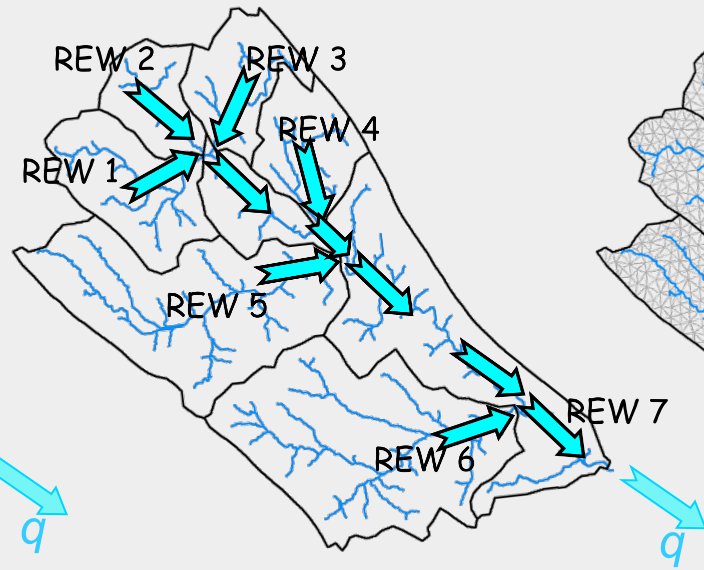
Modified from Mukesh Kumar

Lumped Model

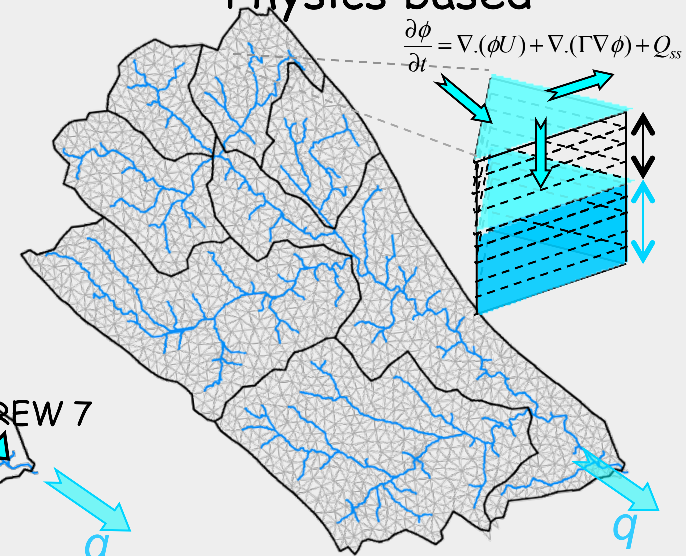
$$Q(t) = f(P(t), A, C)$$



Semi-Distributed Model, Conceptual



Distributed Model, Physics based



Process Representation: Parametric → Physics-Based

Predicted States Resolution: Coarser → Fine

Data Requirement: } Small → Large
Computational Requirement: }

Perceived Intellectual Value: Small → Large

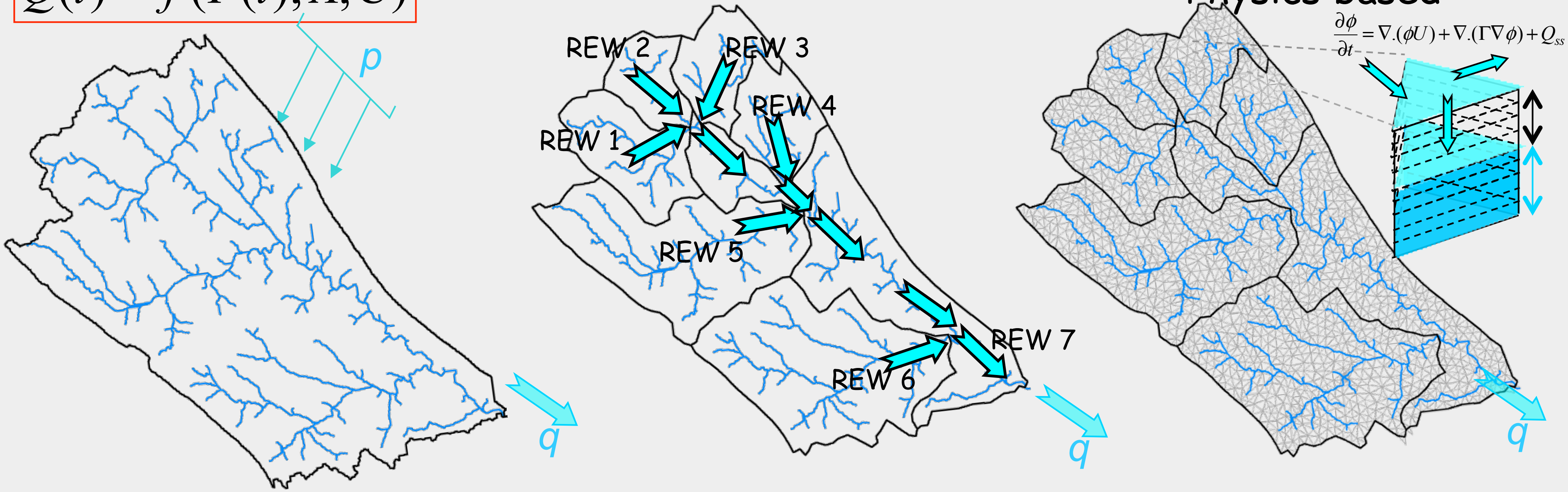
Modified from Mukesh Kumar

Lumped Model

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

Semi-Distributed Model, Conceptual

Distributed Model, Physics based



Outcome: Right for Wrong Reasons → Wrong for Right Reasons

History: Mathematical Lumping → Process Understanding

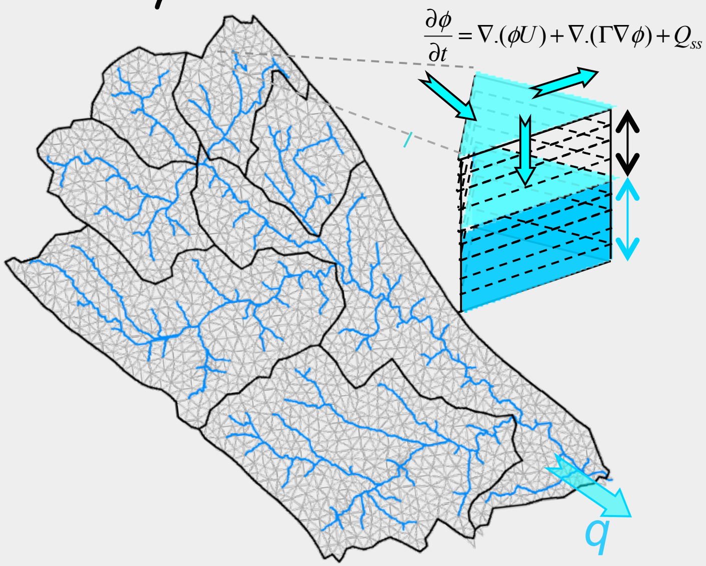
Future: ? ← Process Understanding

Modified from Mukesh Kumar

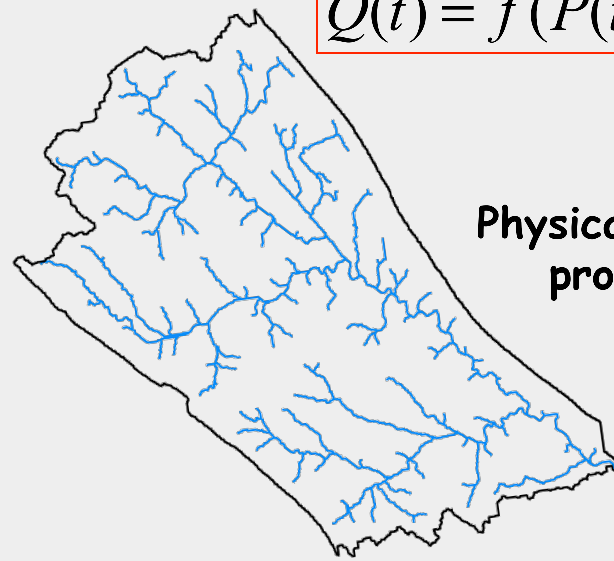
Distributed Model,

Physically Lumped Model

Physics based



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



Physically lumped properties

History: Mathematical Lumping → Process Understanding

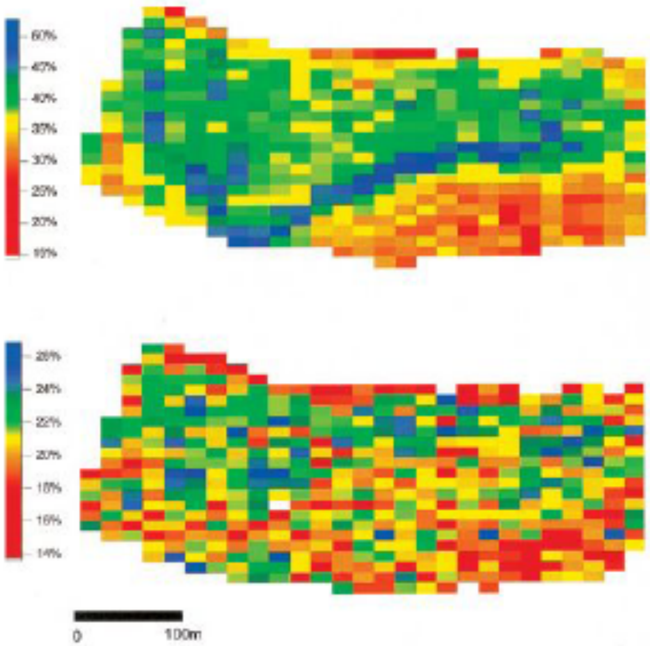
Future: Process Understanding → Emergent properties guide “lumping”

Lumped Watershed Properties (emergent behavior)

- **Hydrologic Connectivity**
  - Timing of hillslope-stream connectivity dictates response
- **Thresholds**
  - Non-linear response depending on hydrologic state
- **Water residence time**
  - Disrtribution key to watershed dynamics

Emergent Behavior: Hydrologic Connectivity

- Facilitates lateral redistribution

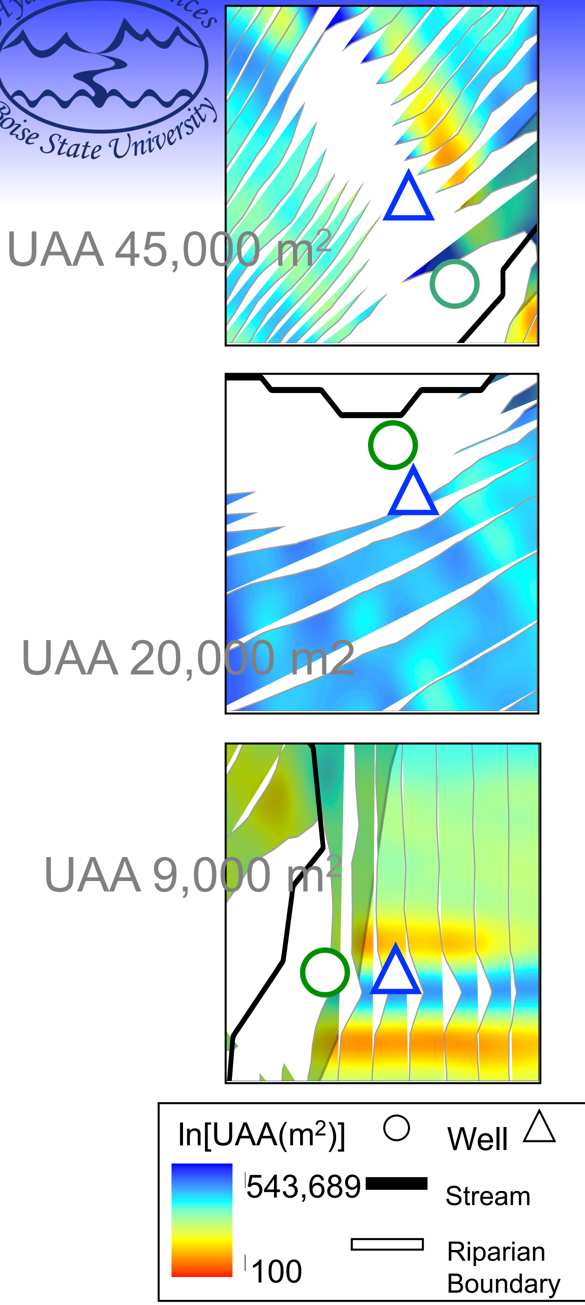


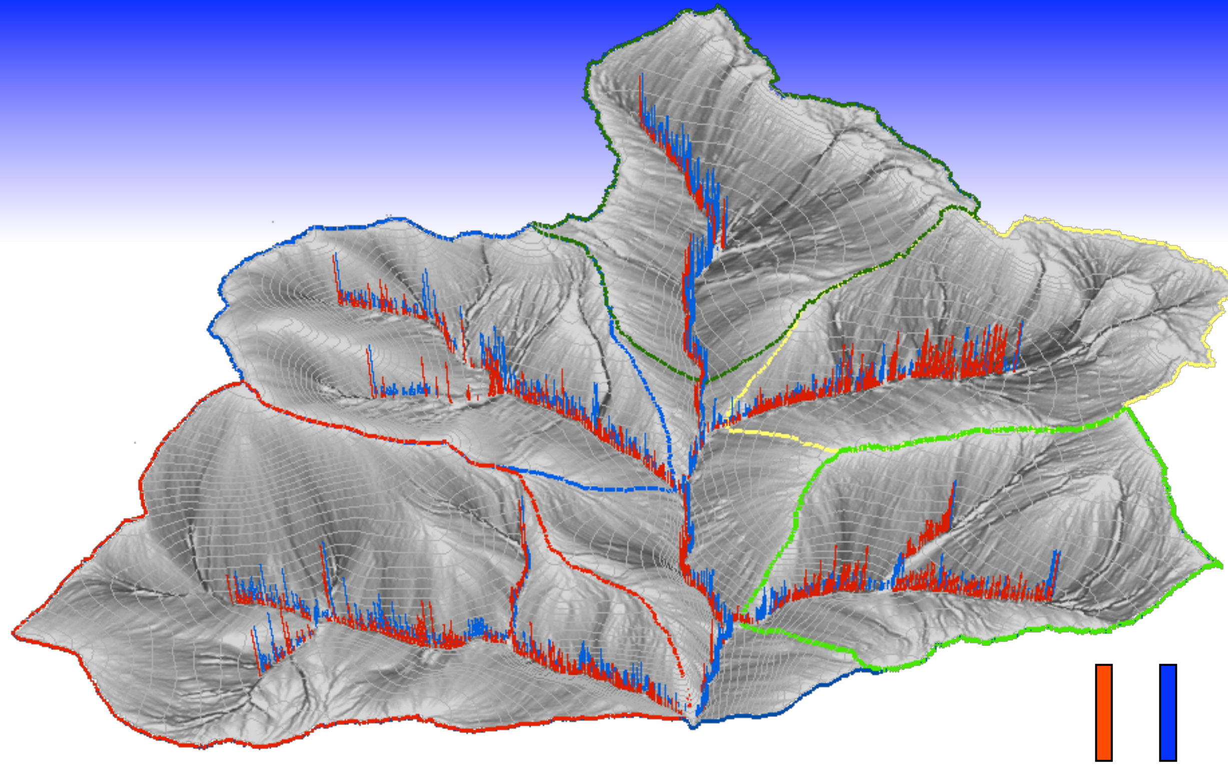
Wet conditions
Topography
controls soil moisture

Dry conditions
Soil/Vegetation
controls soil moisture

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

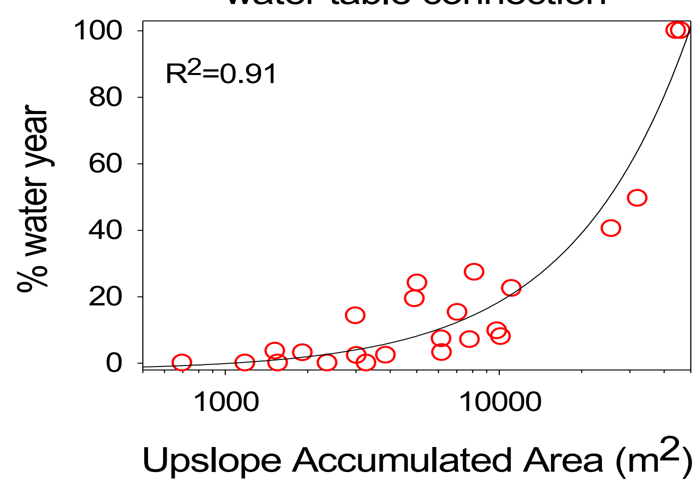
Figure courtesy of Jeff McDonnell





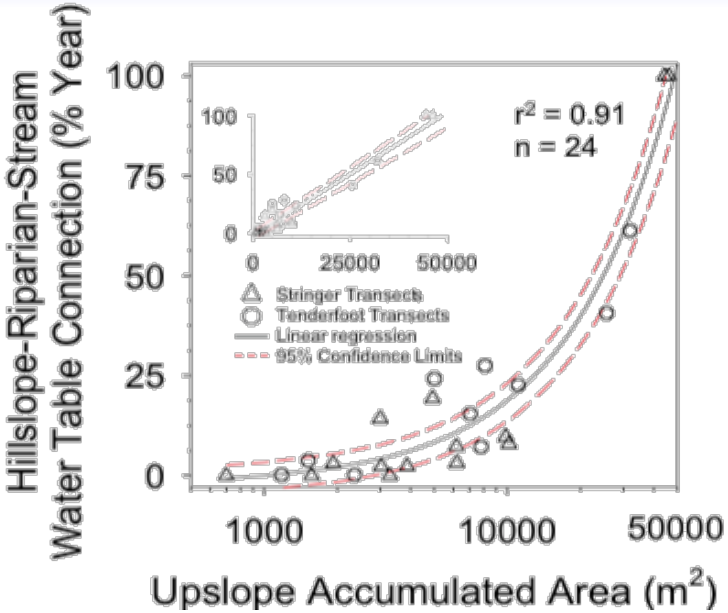
Max bar height = 100%
Of the year

Hillslope-riparian-stream water table connection

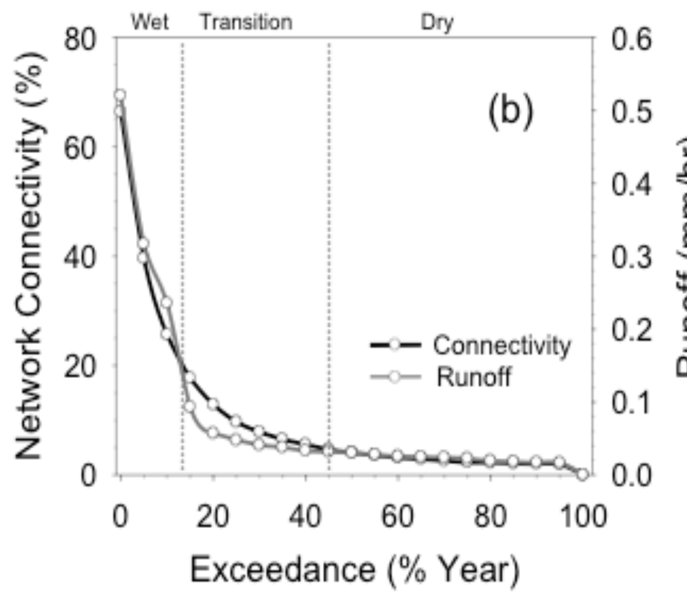


Jencso et al., 2009 *WRR*

Hydrologic connectivity may be a good predictor of watershed runoff



Strong correlations between watershed form (UAA) and function (connectivity)



Frequency of connections controls watershed discharge rather than the magnitude at the connections

Models incorporating connectivity may lead to improved prediction

Jencso et al., 2009 *WRR*

Emergent Behavior: Thresholds at storm scale

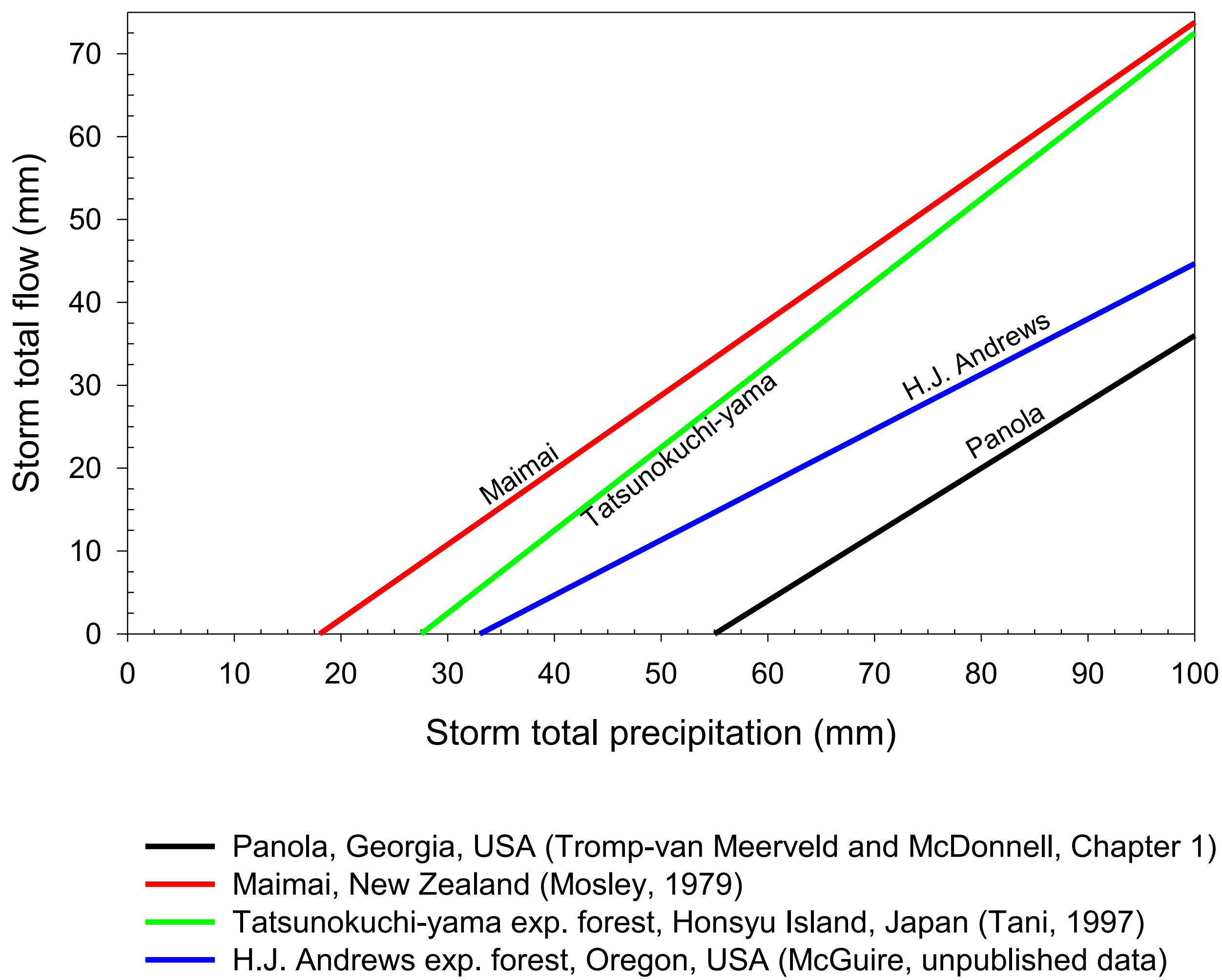
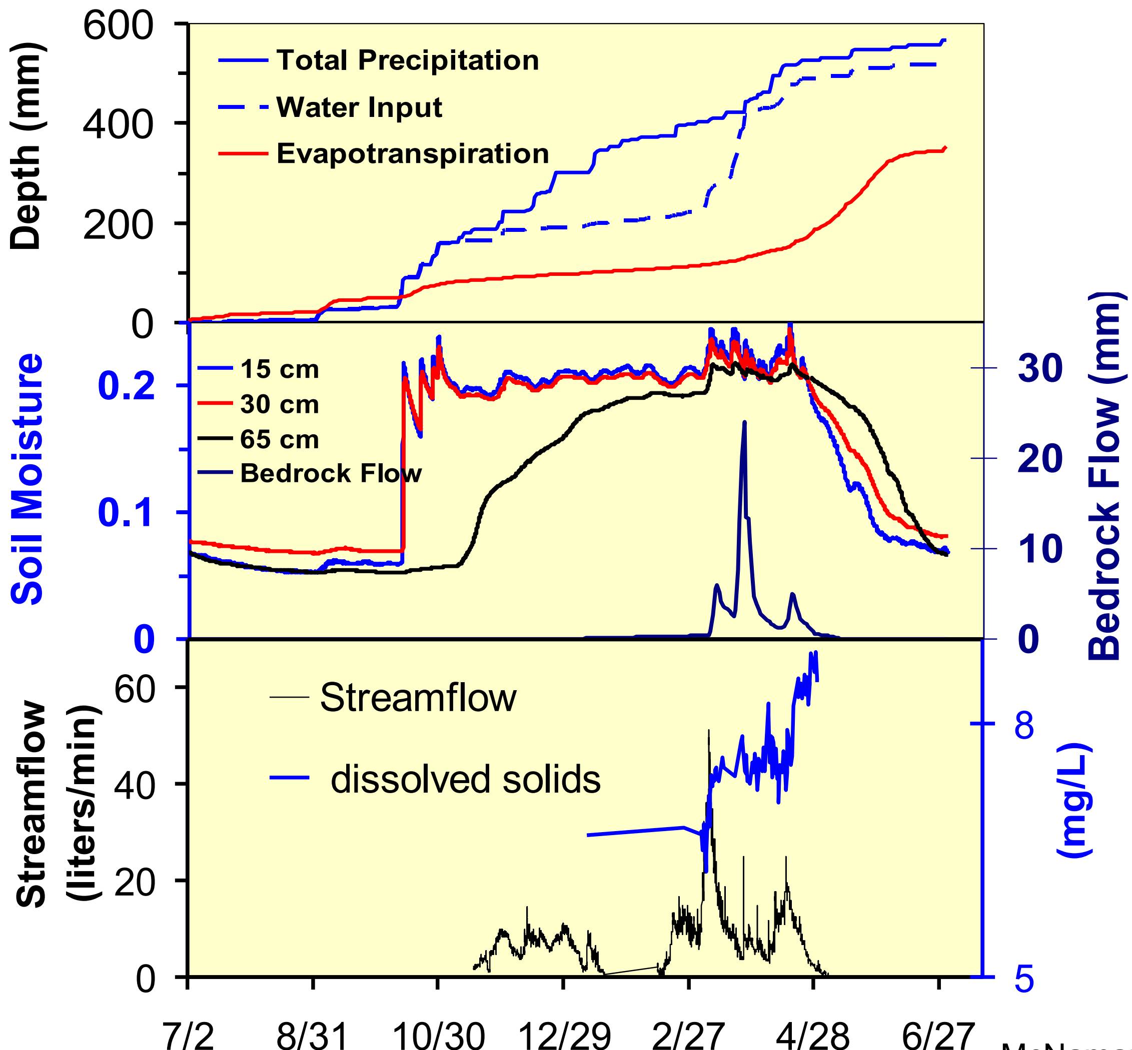


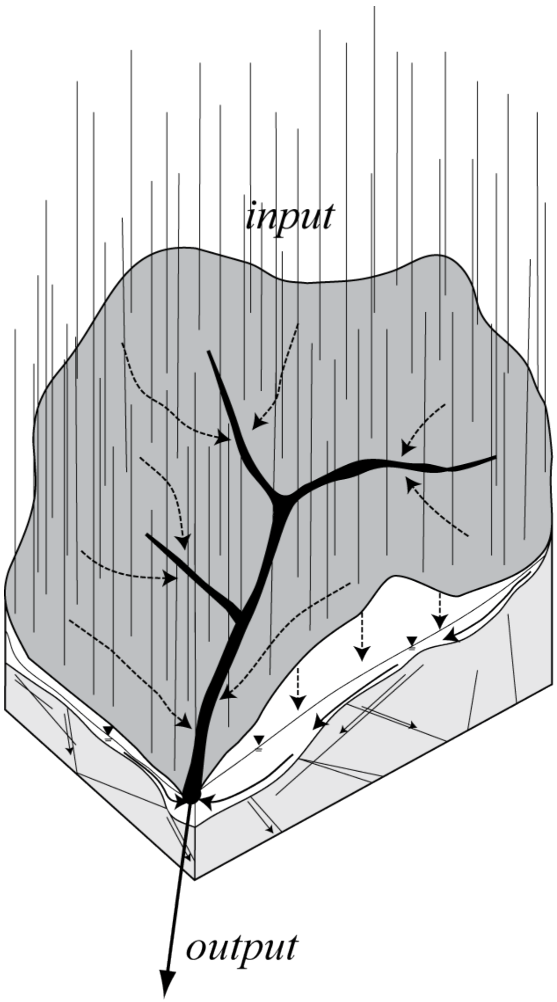
Figure courtesy of Jeff McDonnell

Emergent Behavior: Thresholds at seasonal scale



McNamara et al., 2005

Emergent Behavior: Residence time distribution



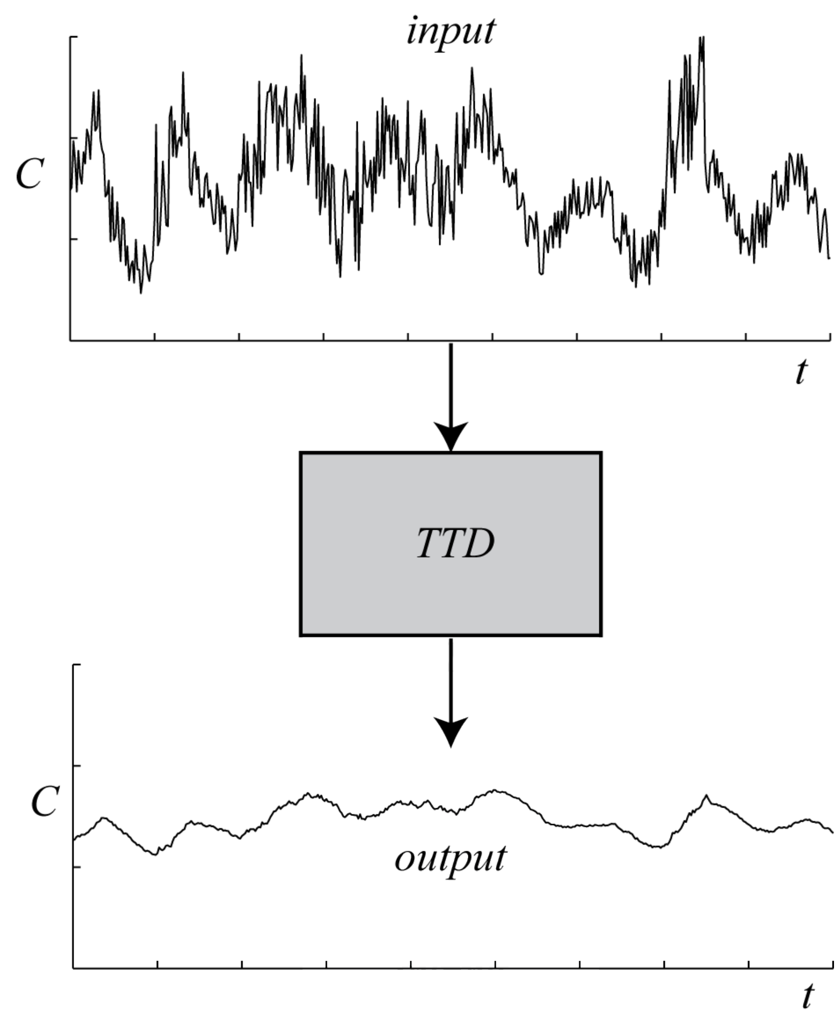
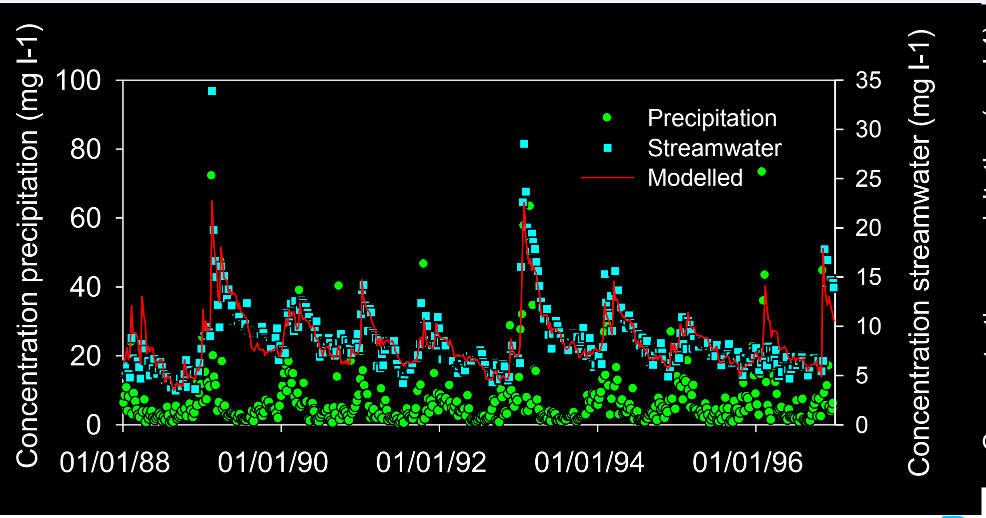
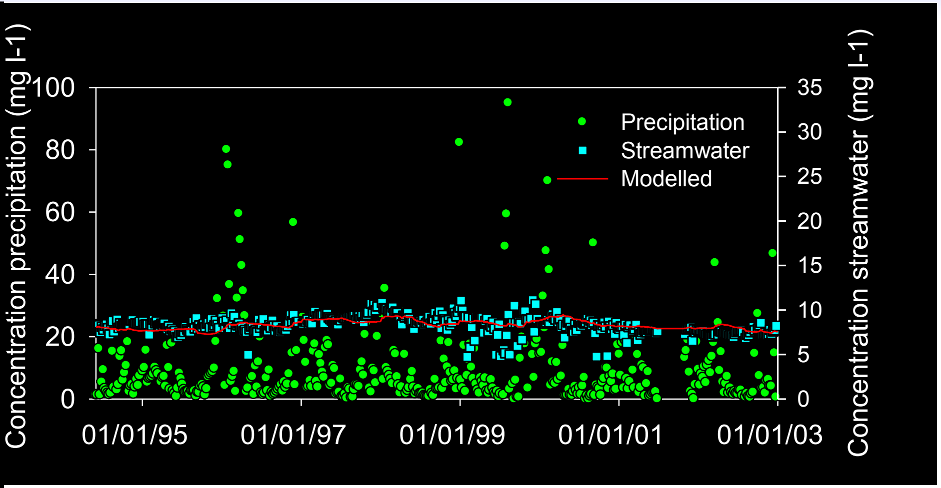


Figure courtesy Chris Soulsby

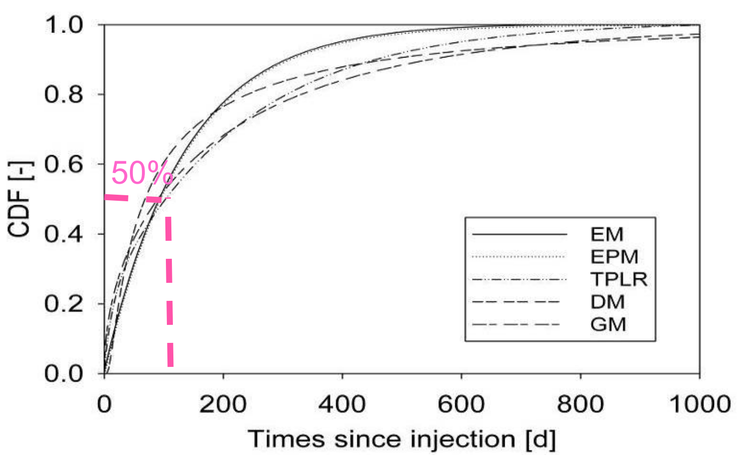
Transit times and catchment characteristics





Fast responding catchments

Deep-subsurface flow dominated catchments



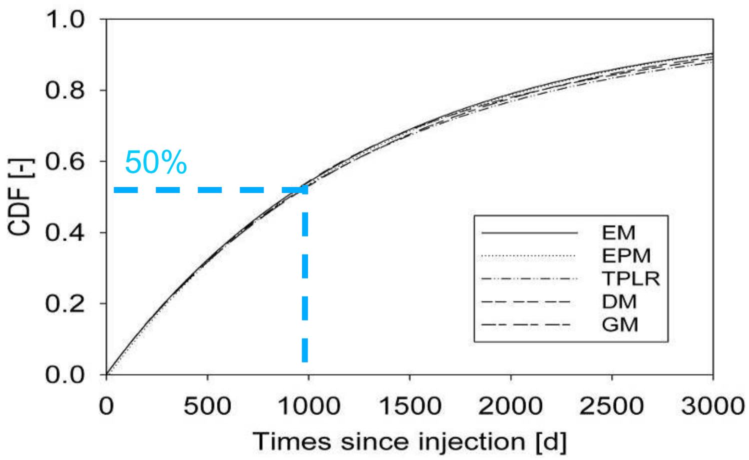


Figure courtesy Chris Soulsby

Residence Time Predicted by Watershed Properties

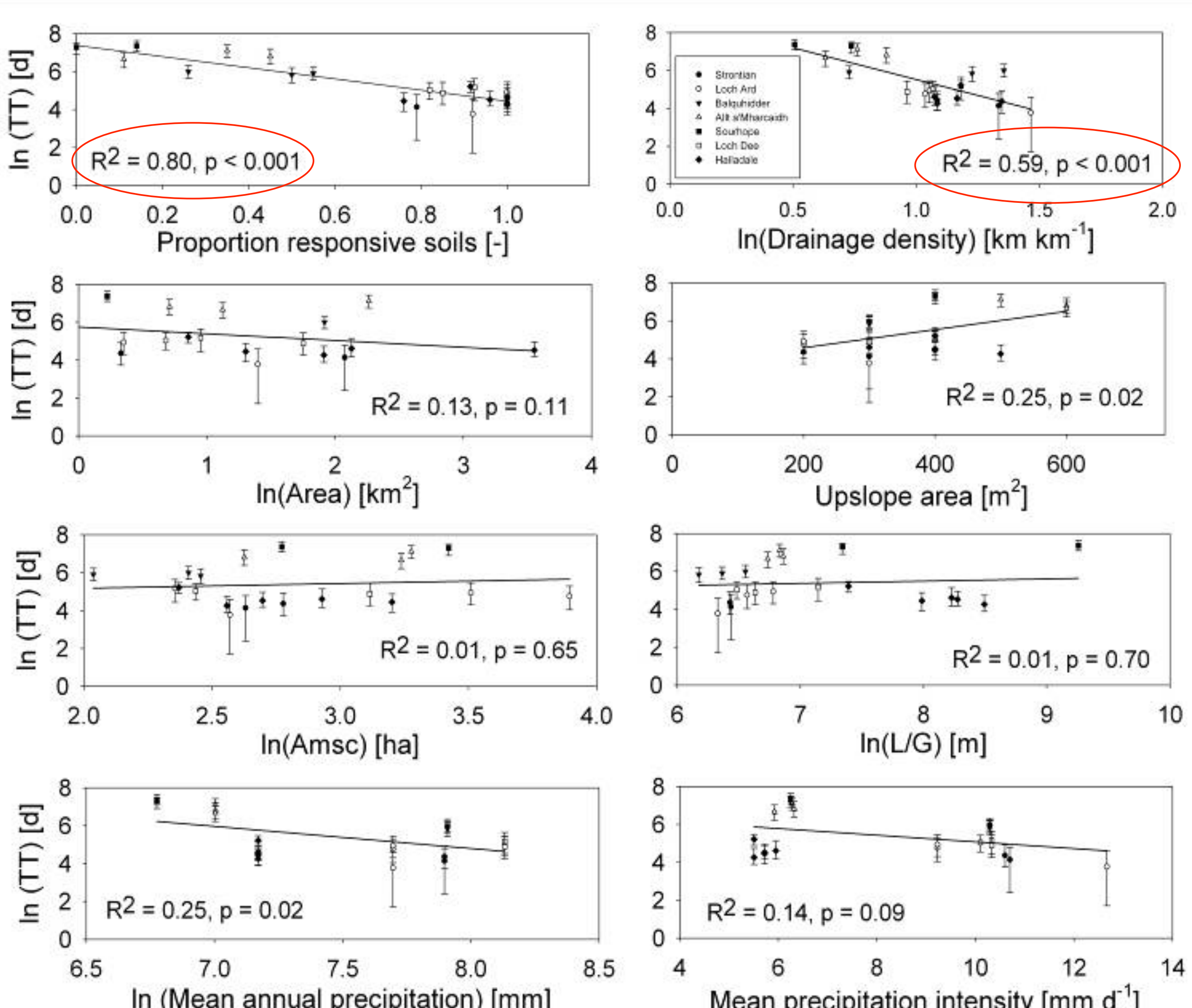


Figure courtesy Chris Soulsby

Recent Theoretical Advances

Catchment residence and travel time distributions: The master equation

Gianluca Botter,[1] Enrico Bertuzzo,[1,2] and Andrea Rinaldo[1,2]

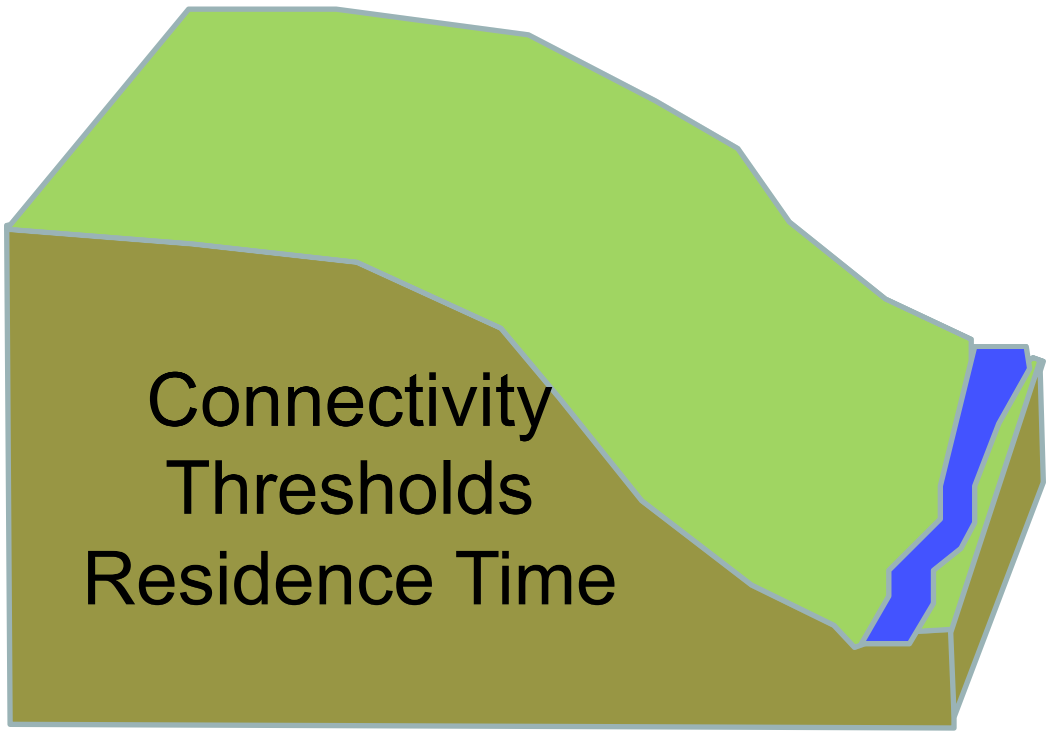
Received 4 April 2011; accepted 27 April 2011; published 7 June 2011.

[1] The probability density functions (pdf's) of travel and residence times are key descriptors of the mechanisms through which catchments retain and release old and event water, transporting solutes to receiving water bodies. In this paper we analyze theoretically such pdf's, whose proper characterization reveals important conceptual and practical differences. A general stochastic framework applicable to arbitrary catchment control volumes is adopted, where time–variable precipitation, evapotranspiration and discharge are assumed to be the major hydrological drivers. The master equation for the residence time pdf is derived and solved analytically, providing expressions for travel and residence time pdf's as a function of input/output fluxes and of the relevant mixing. Our solutions suggest intrinsically time-variant travel and residence time pdf's through a direct dependence on hydrological forcings and soil-vegetation dynamics. The proposed framework integrates age-dating and tracer hydrology techniques, and provides a coherent framework for catchment transport models based on travel times. **Citation:** Botter, G., E. Bertuzzo, and A. Rinaldo (2011), Catchment residence and travel time distributions: The master equation, *Geophys. Res. Lett.*, *38*, L11403, doi:10.1029/2011GL047666.

Travel time distributions are a product of integrated catchment processes

Can serve as a target to determine if models are right for the right reasons

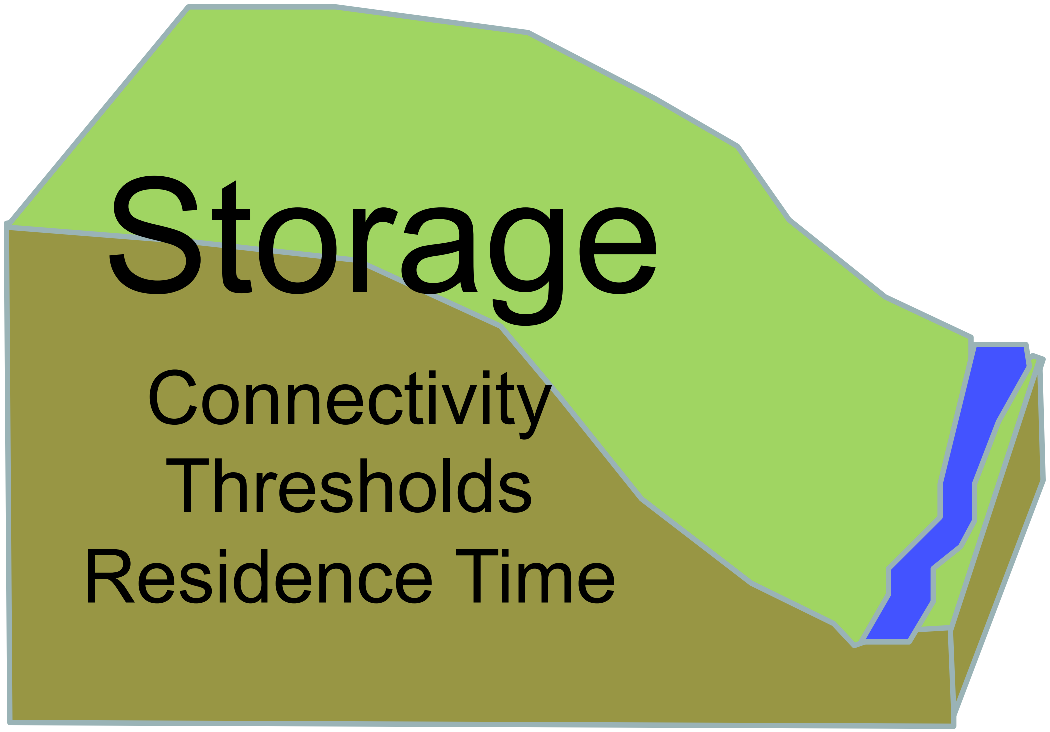
Emerging science: Emergent properties

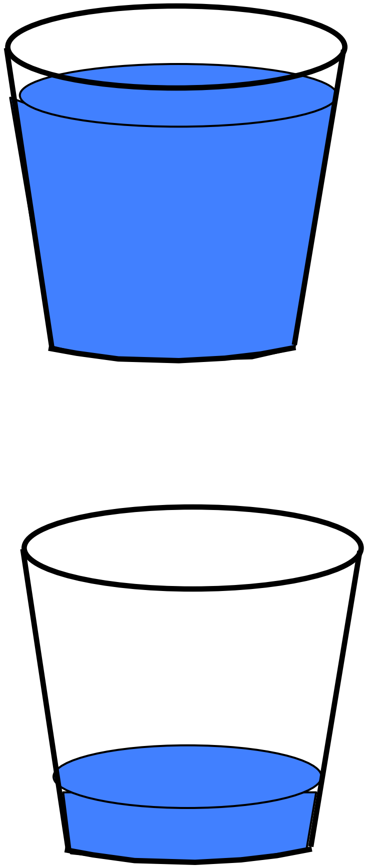


How do we quantify?
How do we incorporate in models?

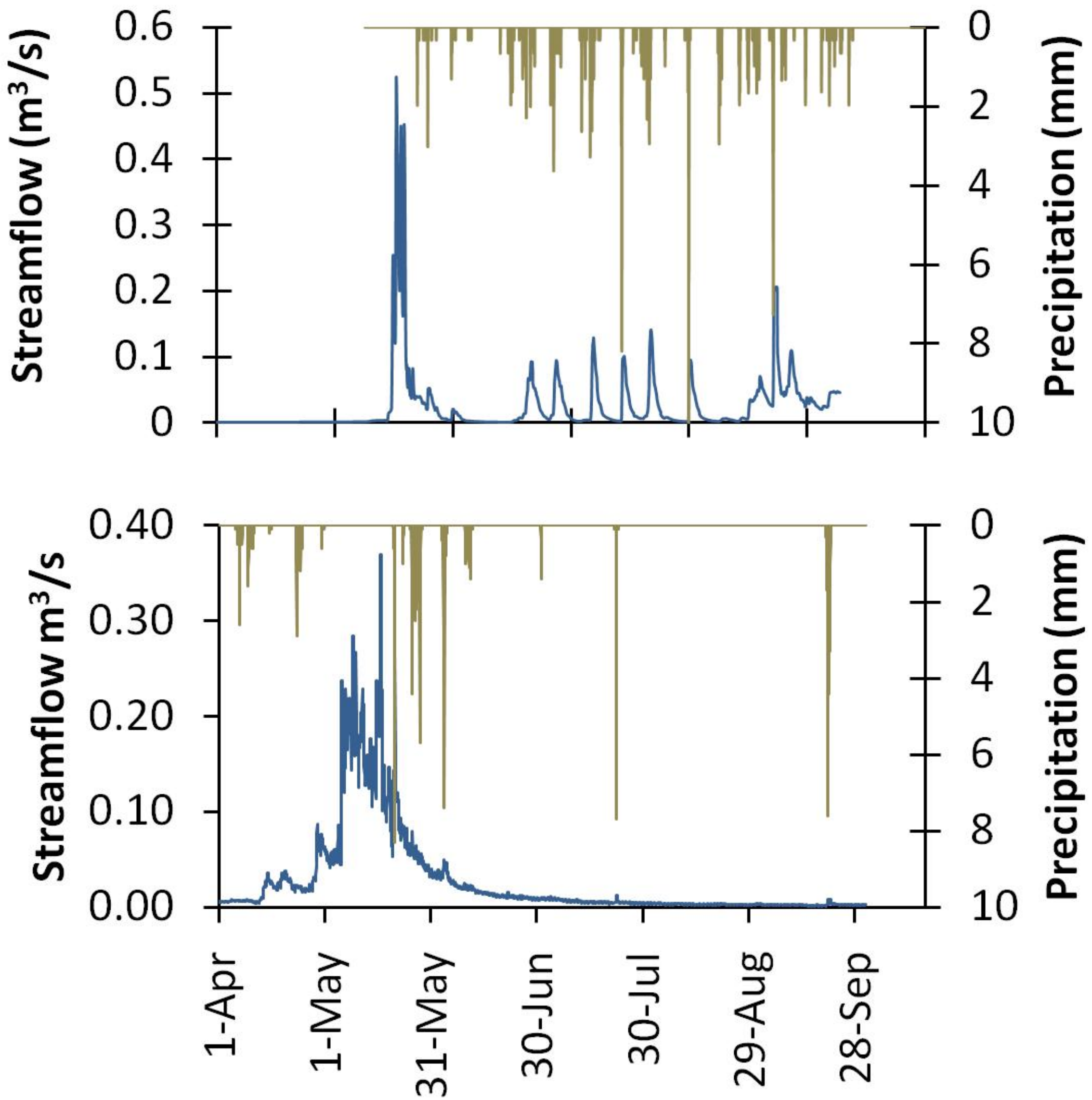
Emergent properties are a function of storage

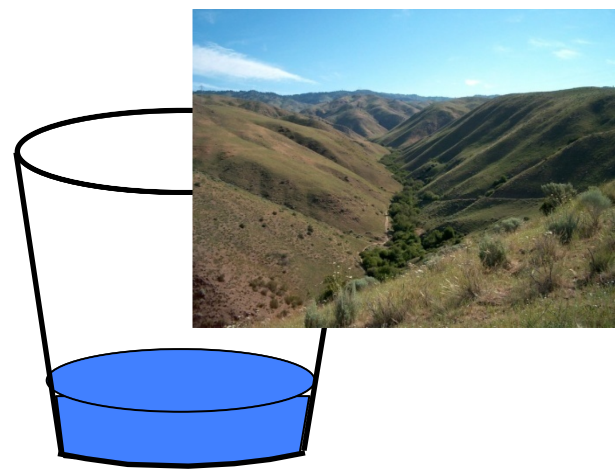
P-ET-Q =dS/dt



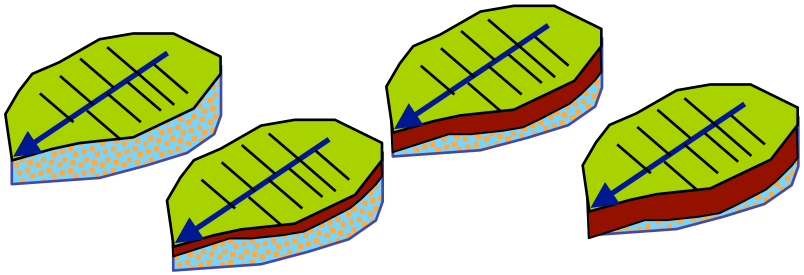


A Tale of Two Catchments

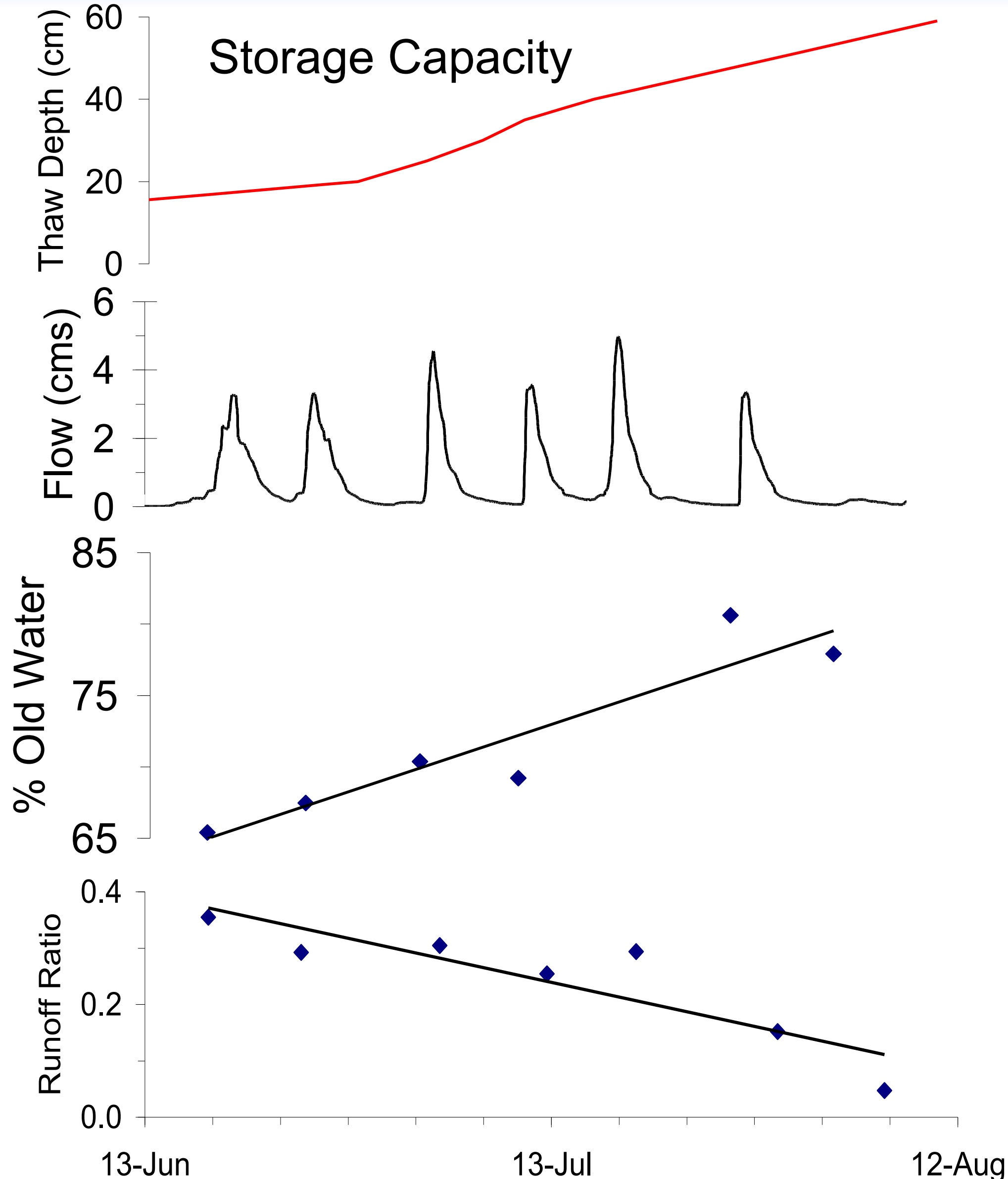




A Natural Storage Experiment

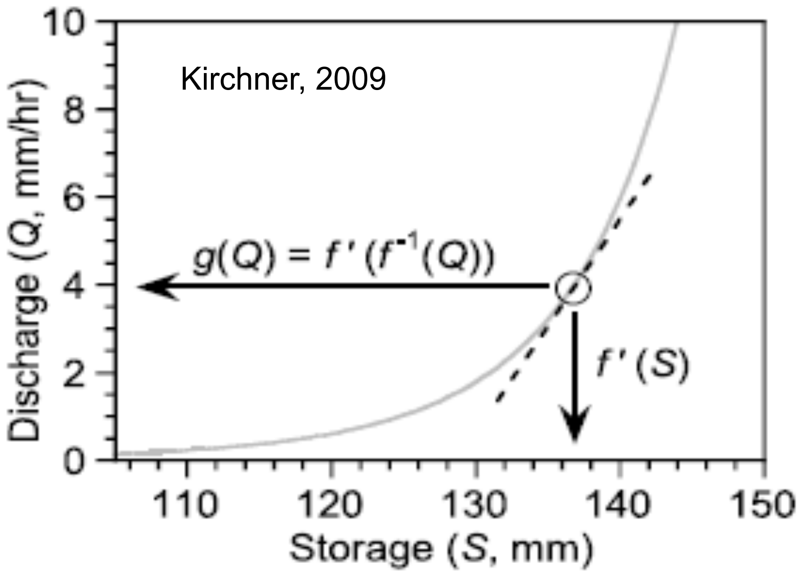


McNamara et al., 1998



Storage-Discharge

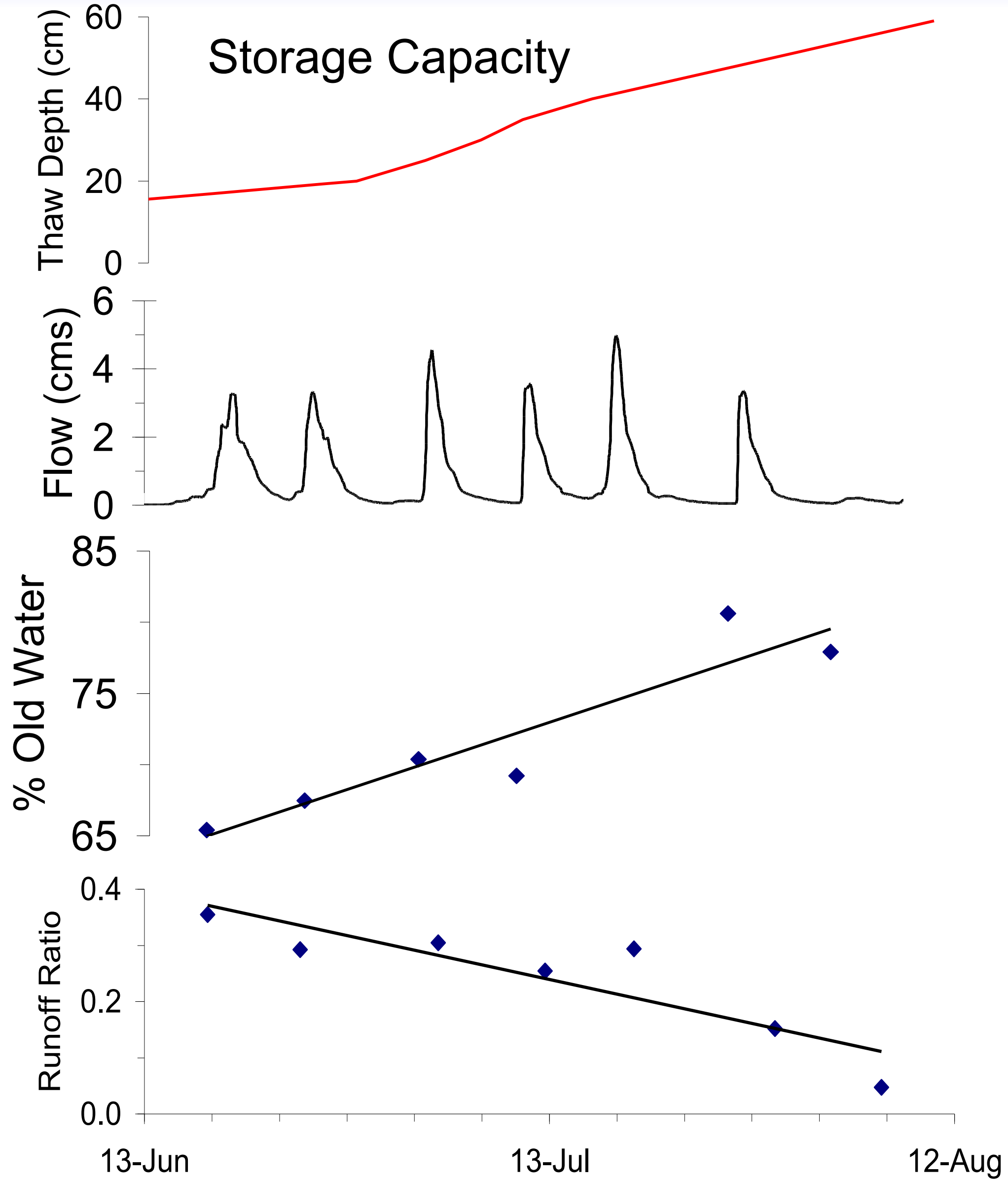
- In SOME watersheds, discharge can be modeled as a single function of storage
- The shape of the S-D curve may contain information about the watershed



Importance of Storage

P-ET-Q =dS/dt

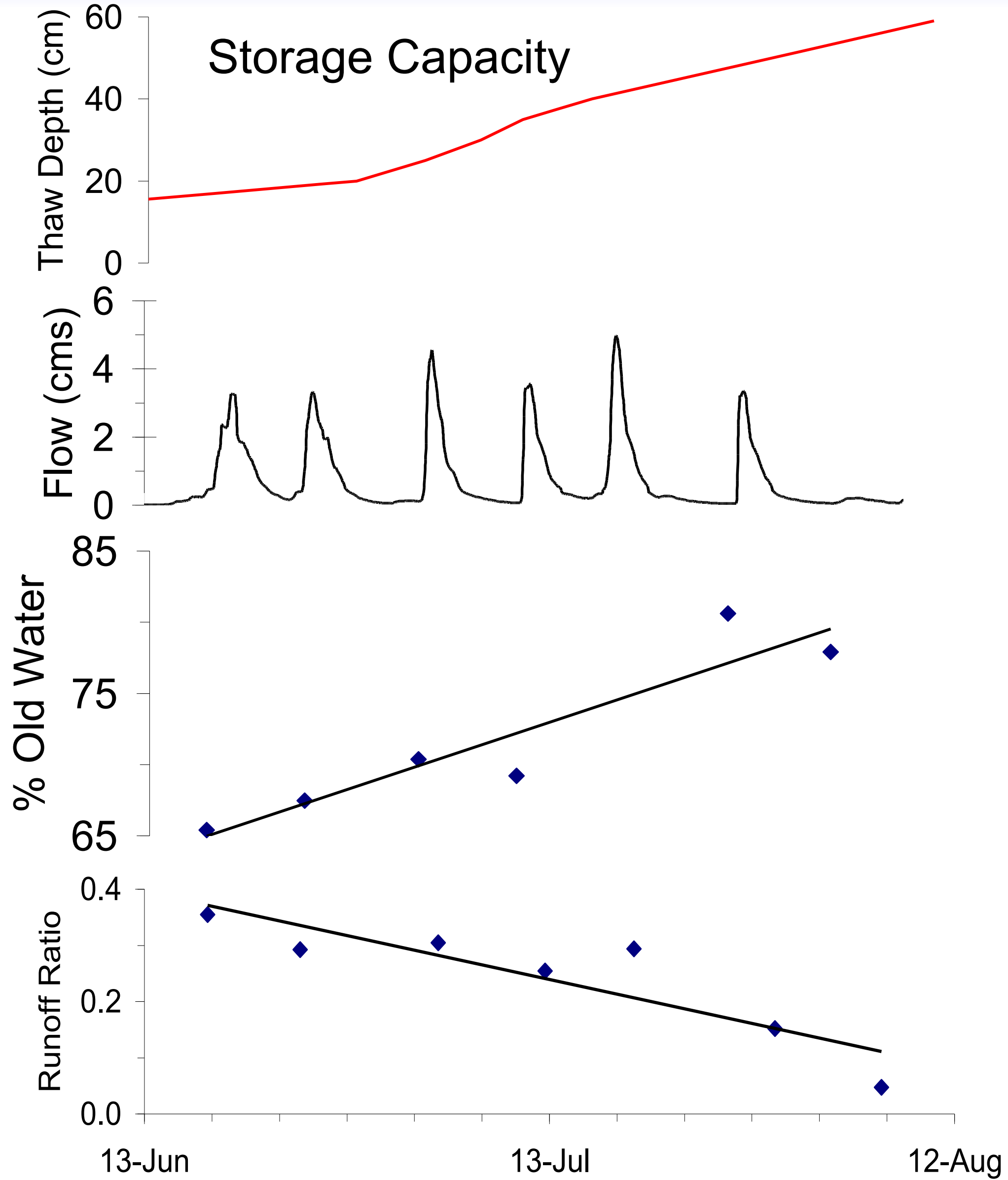
- The mechanisms by which catchments **STORE** water ultimately characterize the hydrologic **SYSTEM**
- Storage regulates fluxes (ET, Recharge, Streamflow)
- Storage is responsible for emergent behavior such as connectivity, thresholds, and residence time



Importance of Storage

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



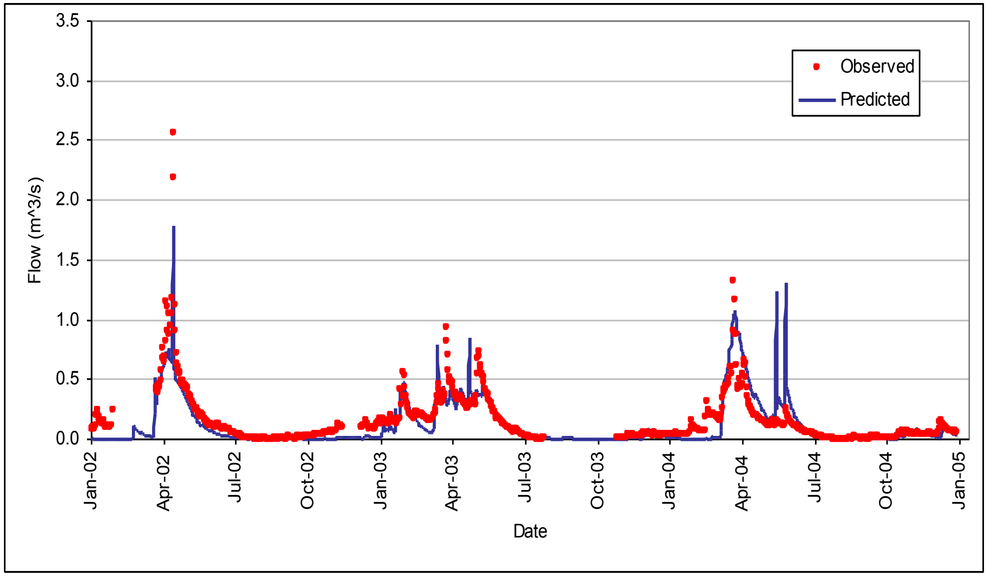
The Storage Problem

- 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

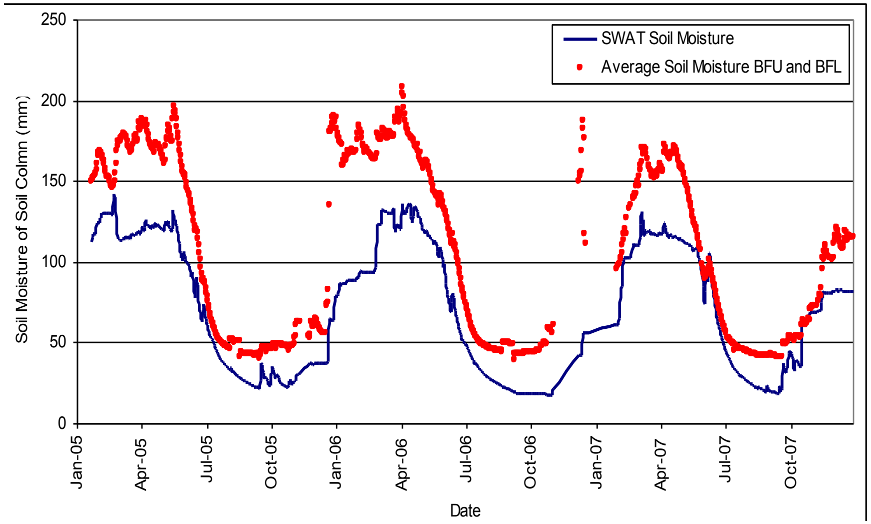
Our Modeling Experience

- Soil Water Assessment Tool (SWAT)

Hydrograph "Right"



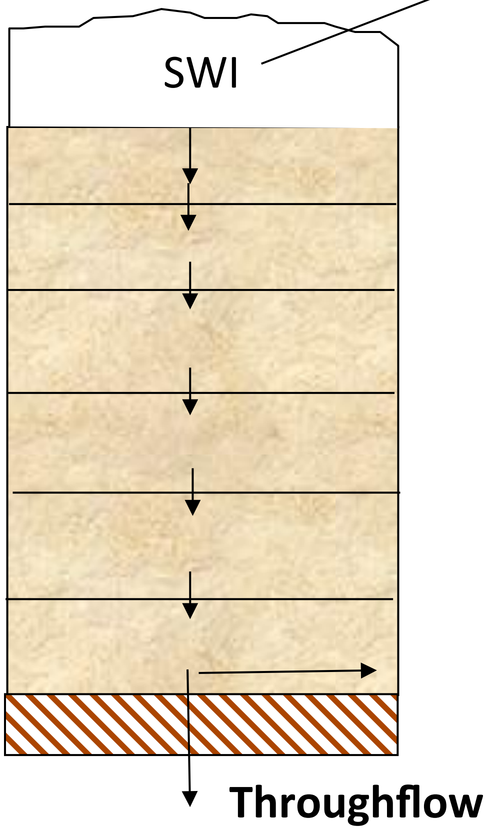
Storage Wrong



Stratton et al., 2009

Improved storage characterization will lead to improved prediction

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

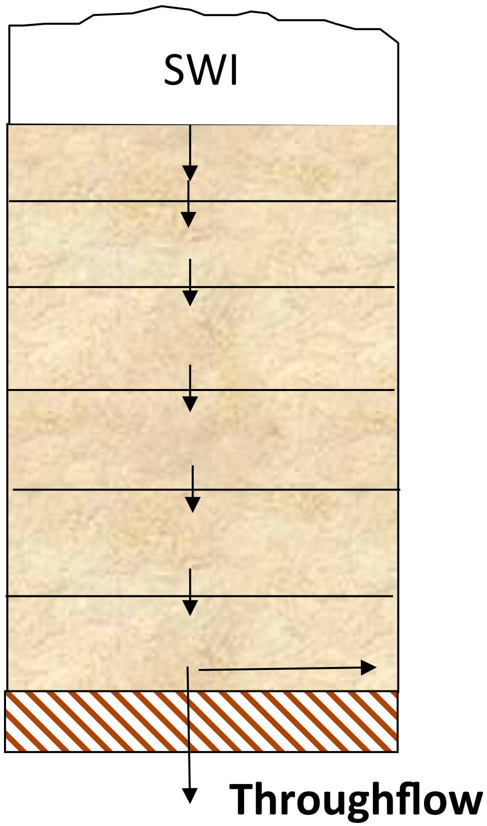
No calibration to streamflow

See what happens

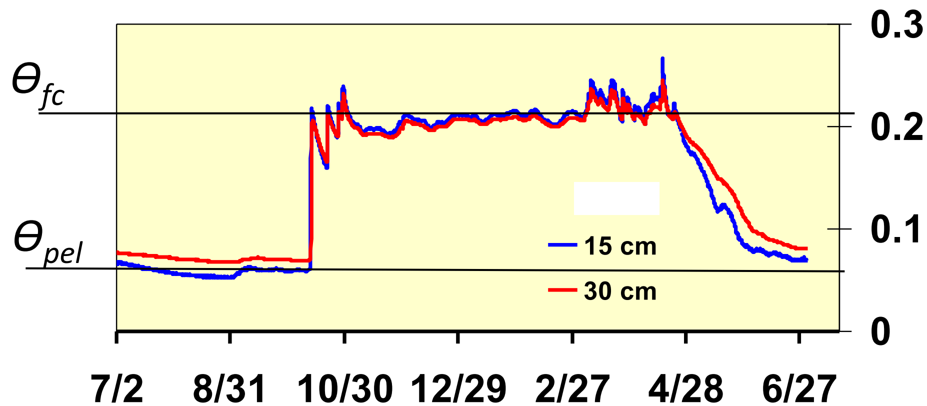
Seyfried et al., 2009, Hydrological Processes

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

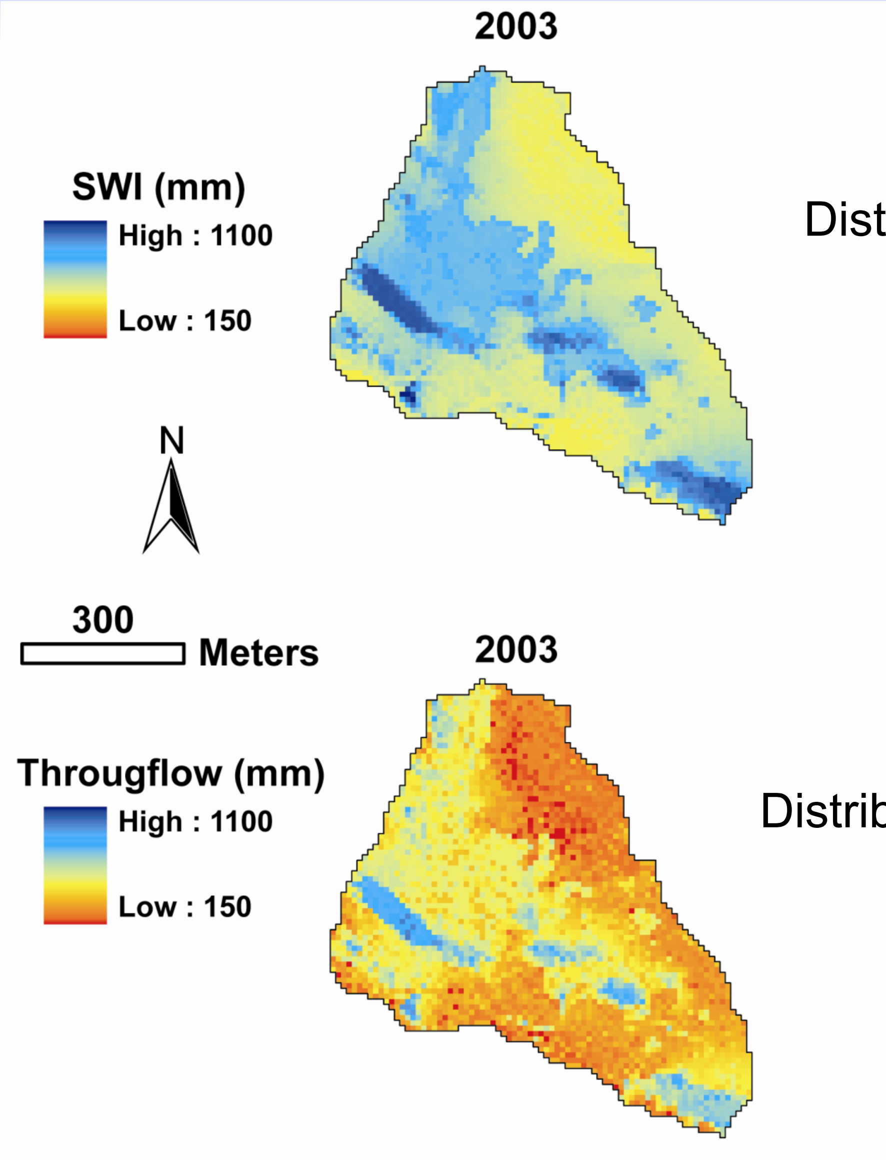


$$S = \sum_{i=1}^{i=numlayer} \theta_i T_i \qquad S_{FC} = \sum_{i=1}^{i=numlayer} \theta_{fc_i} T_i$$



Seyfried et al., 2009, Hydrological Processes

Distributed Model



Distributed energy balance forcing

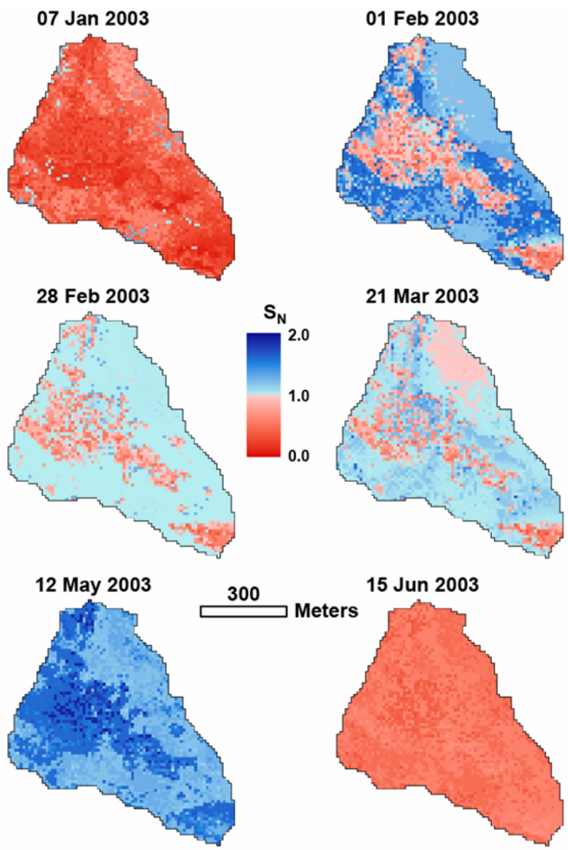
Distributed soil properties by similarity classes

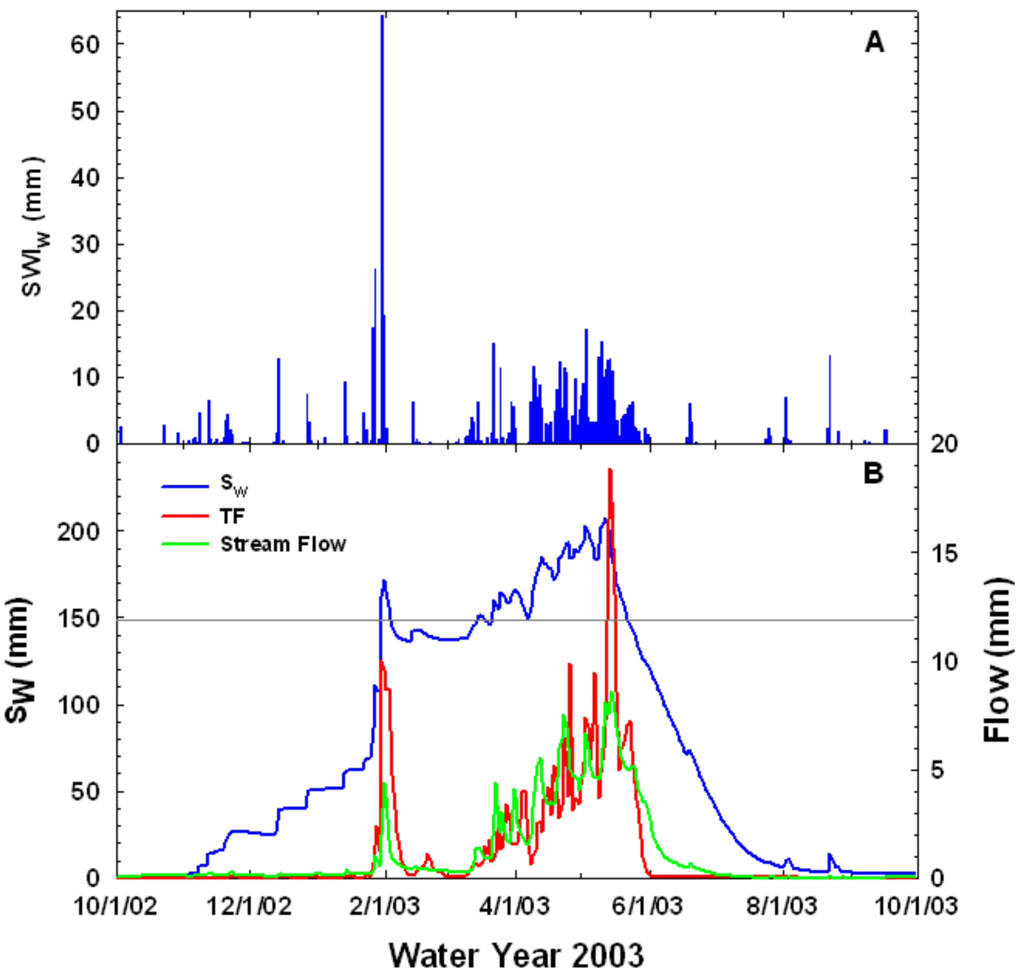
No lateral flow simulated

Simulated storage excess agrees with streamflow

Connectivity Index

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

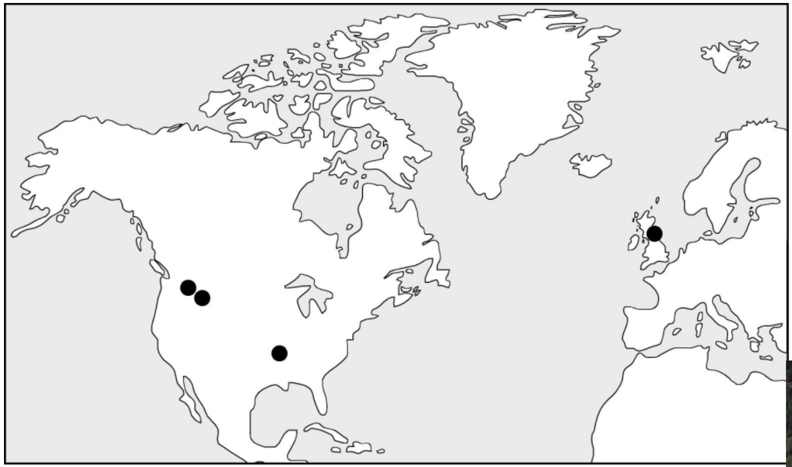




CUAHSI Catchment Comparison Exercise

Girnock, Scotland, Rain, humid

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

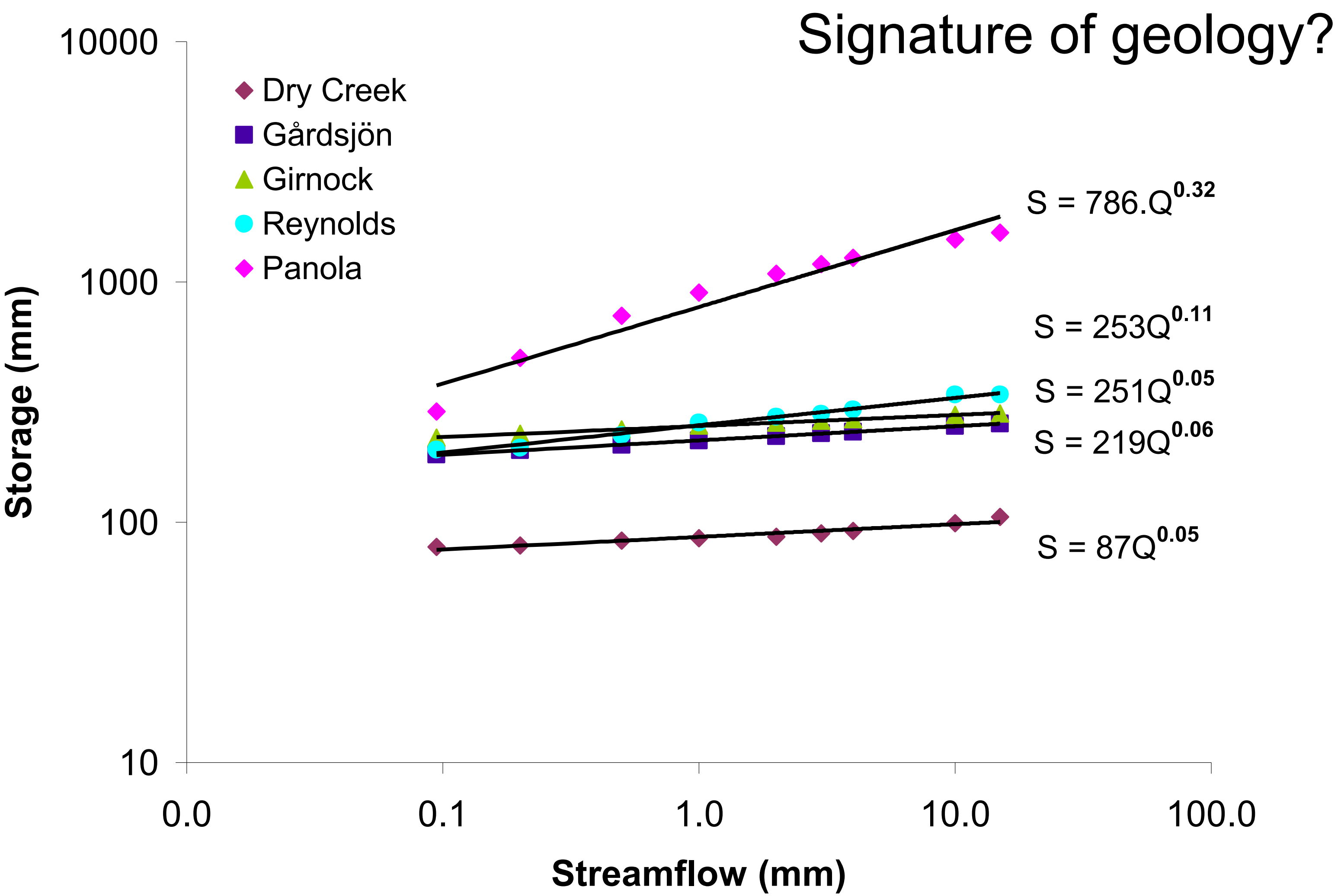


Panola, Georgia, USA
Rain, humid, perennial

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

Gårdsjön, Sweden,
Snow, ephemeral

Storage-Discharge



McNamara et al., 2011

Summary

- Use internal BEHAVIOR of watersheds, in addition to states and fluxes

- Discover metrics of internal behavior (emerging science of emergent properties)
- Requires creative coupled field and modeling experiments

Summary

- Watersheds "lump" processes producing emergent behavior manifested in
  - Connectivity, Thresholds, Residence Time Distributions (old water)
    - Incorporate into new model structures or serve as validation targets
    - Evaluate model performance on watershed behavior, or internal dynamics, in addition to traditional states and fluxes time series.
- Quantifying Storage ….quantify emergent properties
- **Get the States right, and the Fluxes will follow**