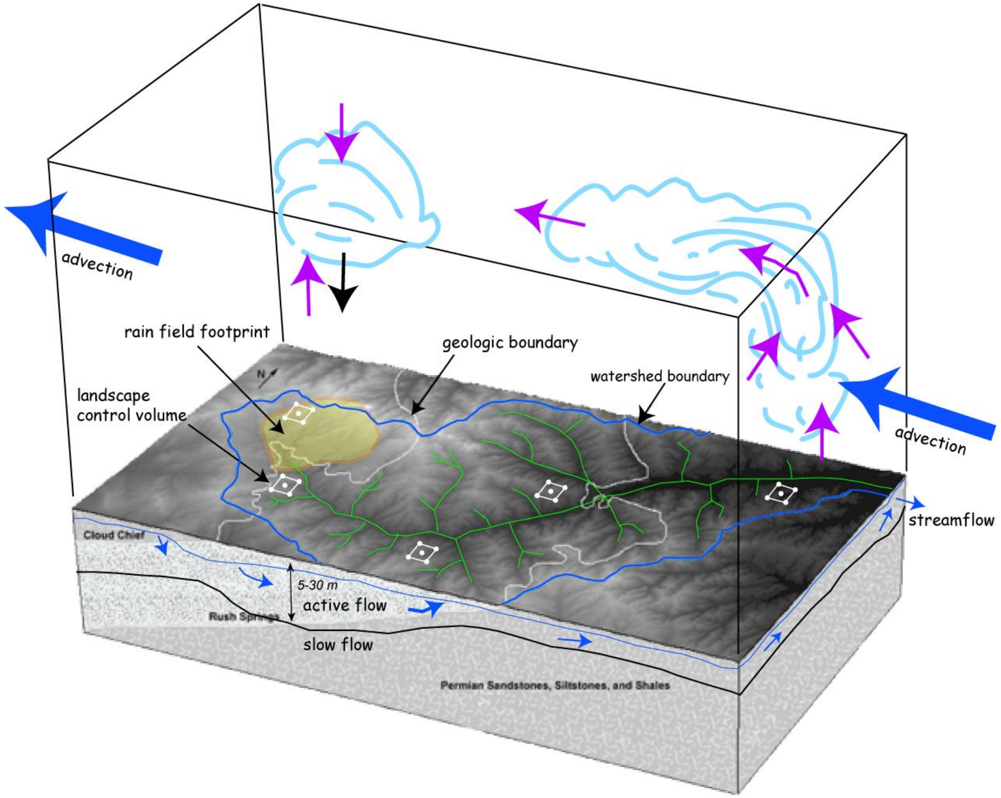
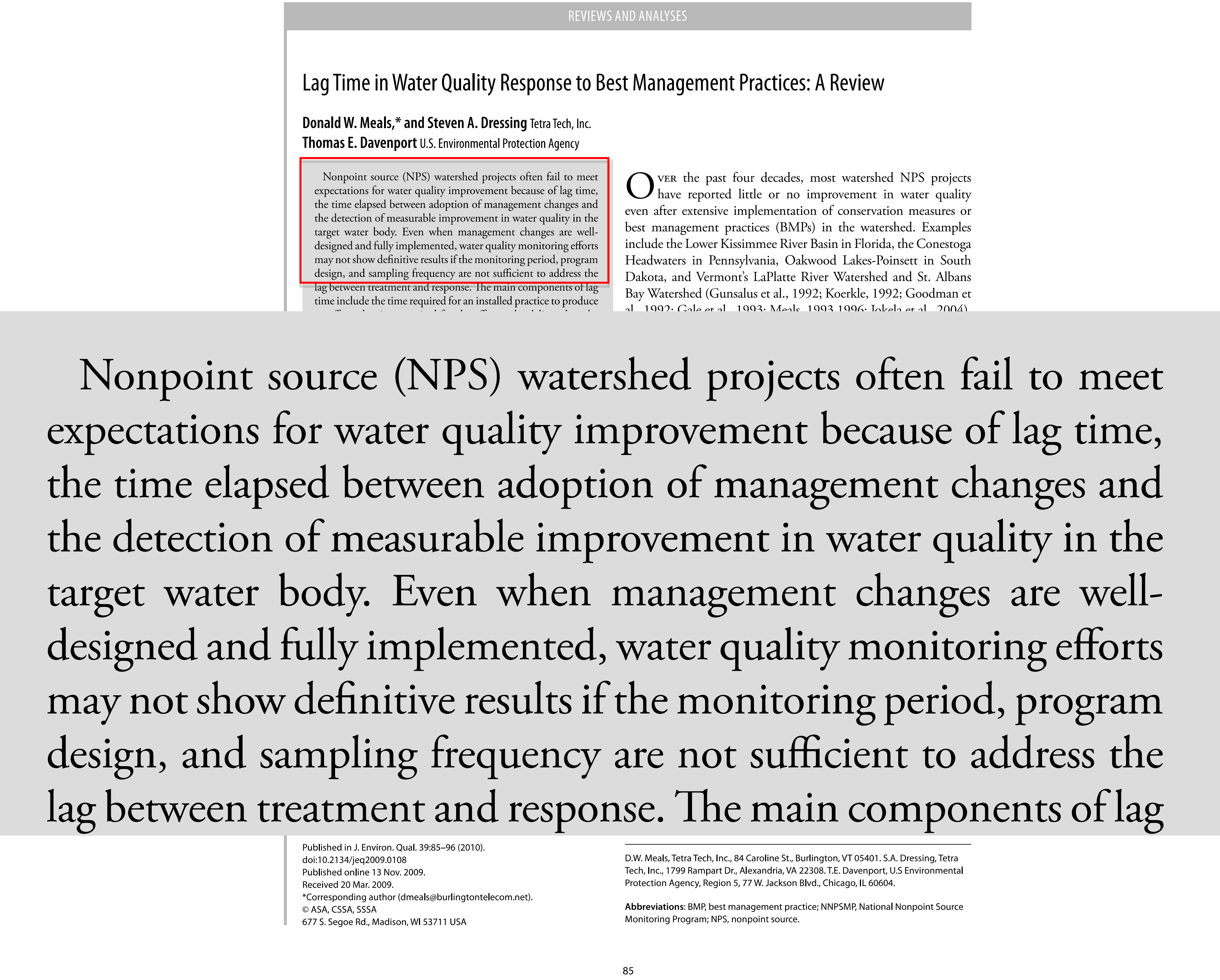
The Isotopic Age & Transit Time of Natural Flow Systems



Duffy, Bhatt, Thomas, Yu, Leonard, Penn State University



Lag Time in Water Quality Response to Best Management Practices: A Review

Donald W. Meals,* and Steven A. Dressing Tetra Tech, Inc.
Thomas E. Davenport U.S. Environmental Protection Agency

Nonpoint source (NPS) watershed projects often fail to meet expectations for water quality improvement because of lag time, the time elapsed between adoption of management changes and the detection of measurable improvement in water quality in the target water body. Even when management changes are well-designed and fully implemented, water quality monitoring efforts may not show definitive results if the monitoring period, program design, and sampling frequency are not sufficient to address the lag between treatment and response. The main components of lag time include the time required for an installed practice to produce

Over the past four decades, most watershed NPS projects have reported little or no improvement in water quality even after extensive implementation of conservation measures or best management practices (BMPs) in the watershed. Examples include the Lower Kissimmee River Basin in Florida, the Conestoga Headwaters in Pennsylvania, Oakwood Lakes-Poinsett in South Dakota, and Vermont's LaPlatte River Watershed and St. Albans Bay Watershed (Gunsalus et al., 1992; Koerkle, 1992; Goodman et al., 1992; Gale et al., 1993; Meals, 1993 1996; Jokela et al., 2004).

Nonpoint source (NPS) watershed projects often fail to meet expectations for water quality improvement because of lag time, the time elapsed between adoption of management changes and the detection of measurable improvement in water quality in the target water body. Even when management changes are well-designed and fully implemented, water quality monitoring efforts may not show definitive results if the monitoring period, program design, and sampling frequency are not sufficient to address the lag between treatment and response. The main components of lag

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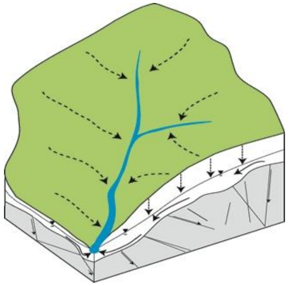
Abbreviations: BMP, best management practice; NNPSMP, National Nonpoint Source Monitoring Program; NPS, nonpoint source.

Isotopic Age/Transit Time of Watershed Storage/Runoff



Interpretation of “age” of waters is complicated since it depends on the transport, flow dynamics, chemical species, reaction kinetics

Steady flow is often assumed since the age distribution of water is difficult to evaluate from field data

This research shows how the “mean age” and “transit time” of tracers or solutes can be predicted.

An experiment conducted at the NSF-funded Shale Hills Critical Zone Observatory is testing the theory.

Scaling Up: Climate researchers have developed the capability to simulate stable isotopes in precipitation at 10 km resolution with major implications for catchment research and water management.

Theories for Age of Waters: A Sampling

The concept of “age” in mass transport research has a long history

Nauman (1965) chemical engineering

Erikson (1971) compartment models

Allison and Hughes (1973) resource assessment

Bolin and Rhode (1973) atmospheric science

Allison and Hughes (1973) resource assessment

Destouni G, Graham (1995)

Goode (1996) groundwater

Delhez et al. (1999) and Gourgue et al. (2006) in Ocean systems

Kazemi et al (2006) Groundwater age overview

IAEA publications (2001) isotope methods

Rinaldo, et al (2011)..

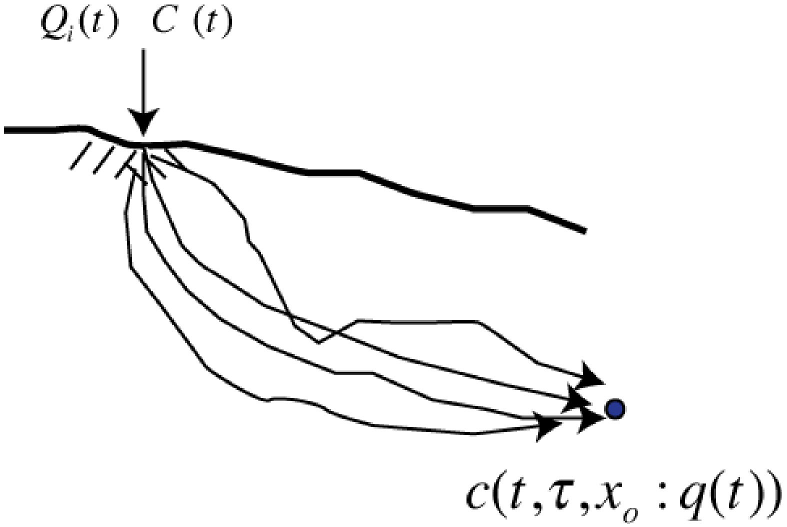
Properties of "Age" at a Point

Groundwater **Age** is an extensive property of a dissolved solutes and the flow regime

The **Age** is defined relative to the time since the solute entered the system

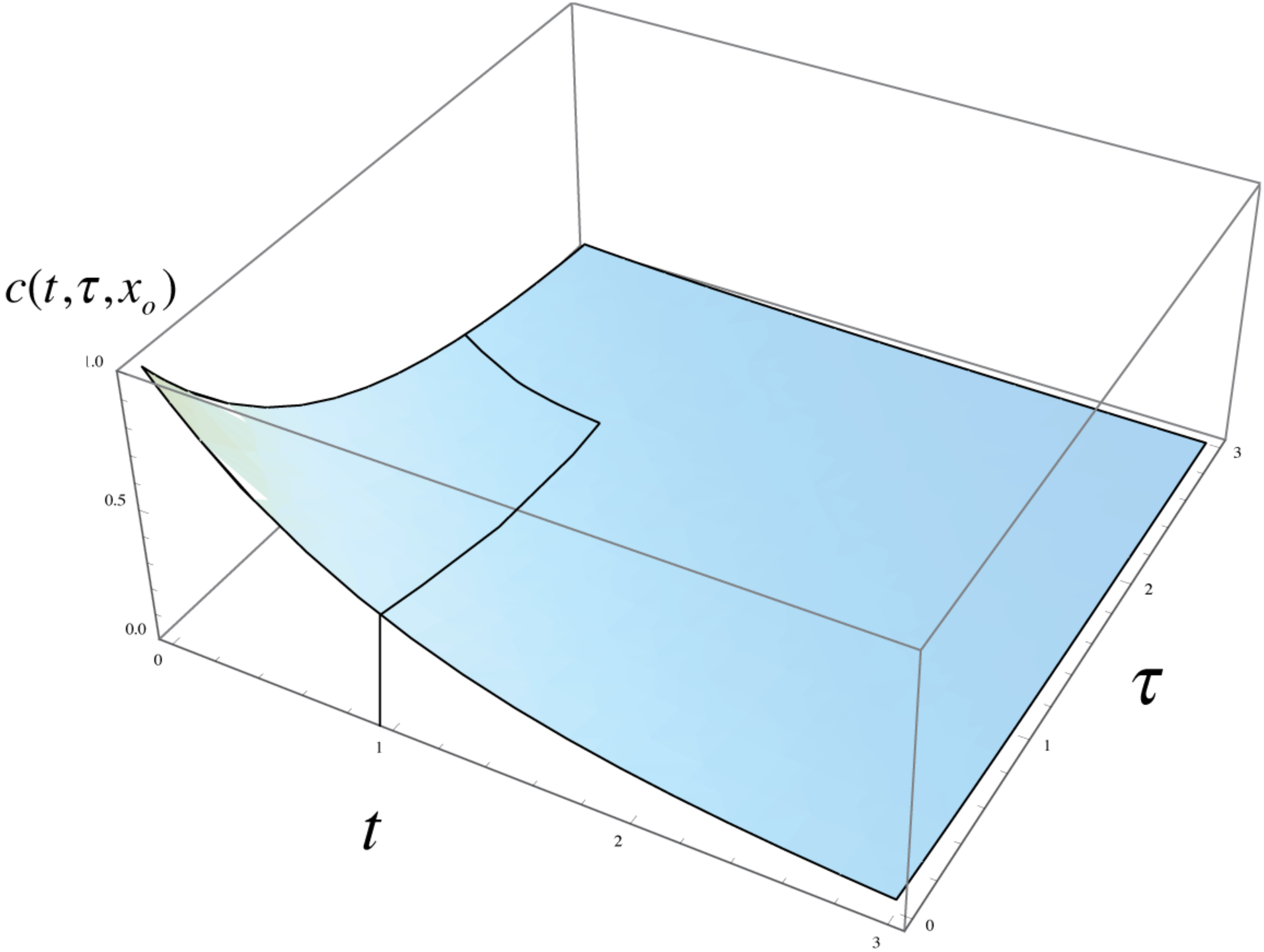
The **Age** of any solute can be calculated in an Eulerian framework

Age is subject to the usual processes of advection, dispersion, diffusion, reaction



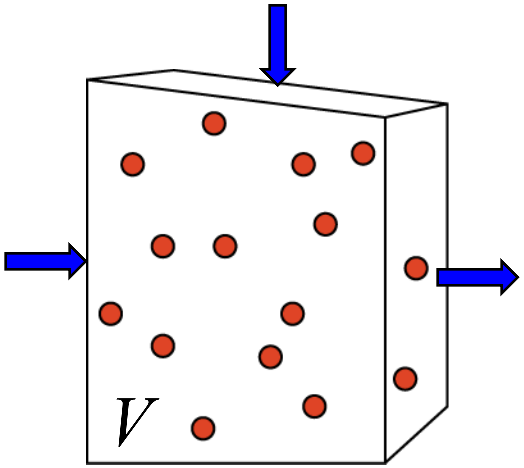
⇒ ? Age

The Age Distribution at a Point X_o



A Transport Model for Age Distribution

Rotenberg 1972, J, of Theoretical Biology, 37, 291-305



$$\boxed{\frac{\partial c}{\partial t} + \frac{\partial c}{\partial \tau}} = \Gamma_c - \boxed{L(c)}$$

$$L(c) \rightarrow D\frac{\partial^2 c}{\partial x^2} - u\frac{\partial c}{\partial x}$$

or

$$L(c)\ \text{Þ}\ \frac{Q_i}{V}(c_i - c)$$

$$\mathrm{D}M(t, \tau)\frac{1}{V} = \left(\frac{\partial M}{\partial t} + \frac{\partial M}{\partial \tau}\right)\frac{1}{V}$$

Transport Model in Terms of Moments

$$\frac{\partial c}{\partial t}+\frac{\partial c}{\partial \tau}=\Gamma_c - L(c)$$

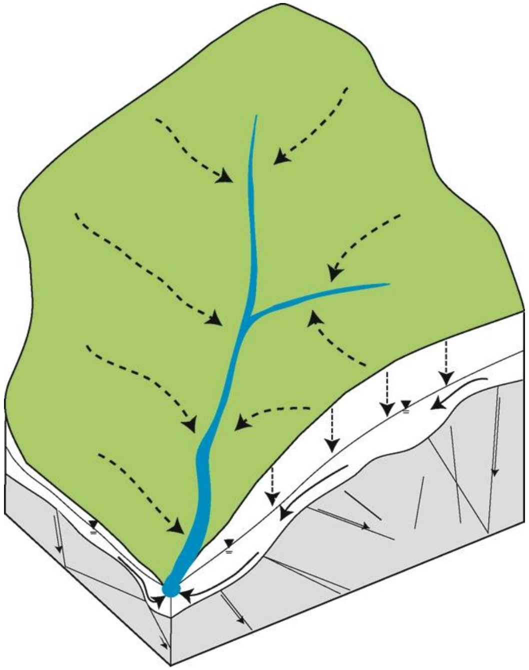
Coupling_Moment   Transport_operator

$$\frac{\partial \mu_n}{\partial t}=n\mu_{n-1}+\Gamma_{\mu_n}-L(\mu_n)$$

$$\boxed{Age=\frac{m_1}{m_0}}$$

A Concentration-Age-Flow Dynamical Model

For a volume-averaged system

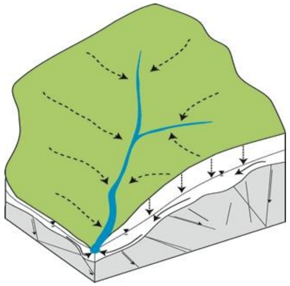


$$\mu_o \Rightarrow \boxed{\begin{aligned} \frac{dV}{dt} &= Q_i - Q \\ \frac{dC}{dt} &= \frac{Q_i}{V}(C_i - C) + \Gamma_c \end{aligned}}$$

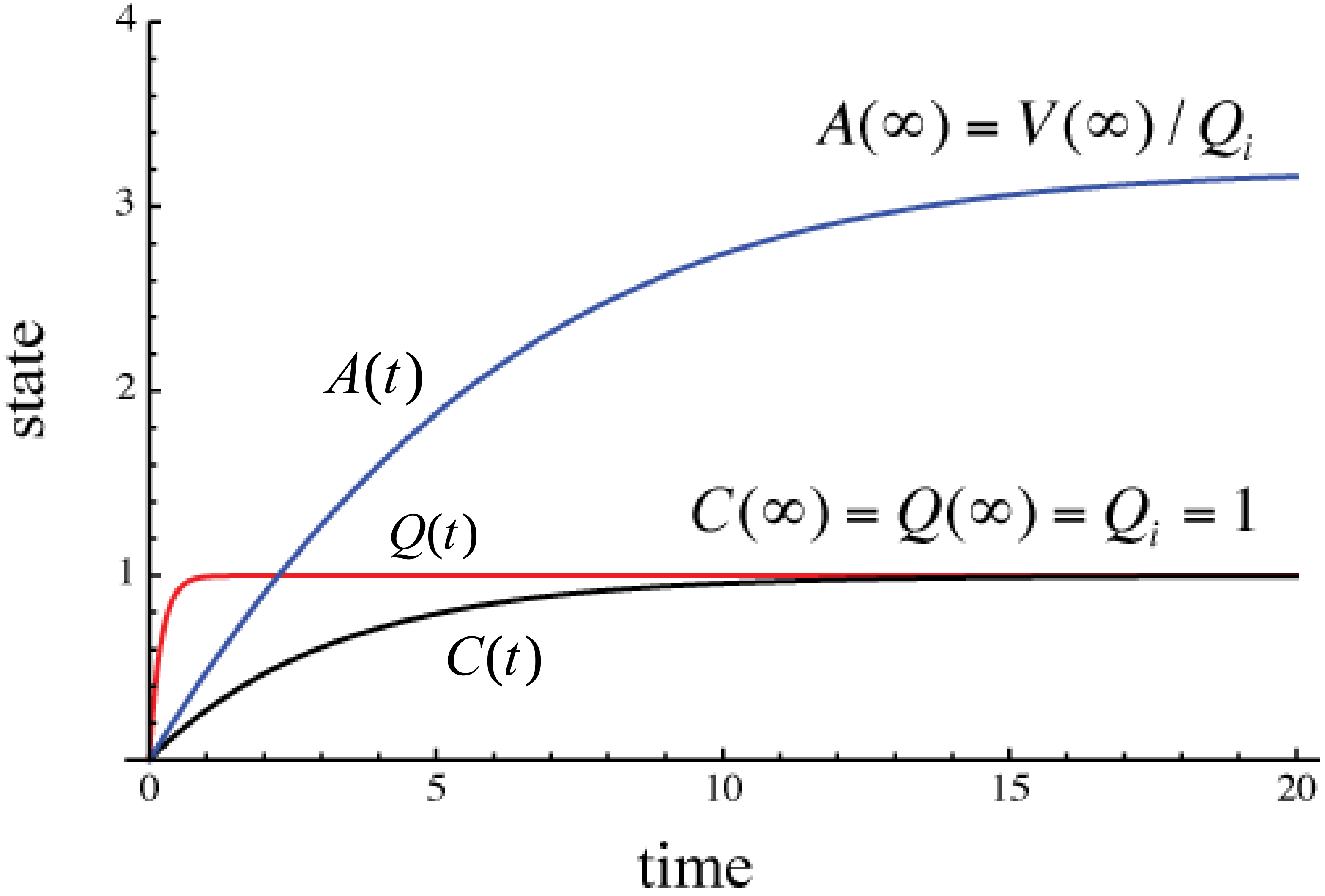
$$\begin{aligned} \mu_1 &\Rightarrow \\ \frac{\mu_1}{\mu_o} &\Rightarrow \end{aligned} \boxed{\begin{aligned} \frac{d\alpha}{dt} &= C - \frac{Q_i}{V}\alpha + \Gamma_\alpha \\ A(t) &= \alpha(t) / C(t) \end{aligned}}$$

Duffy, 2010 Hydrologic Processes

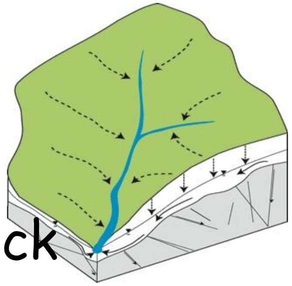
Unit Step Input C_i and Q_i



For constant inputs age reaches a constant value at large time

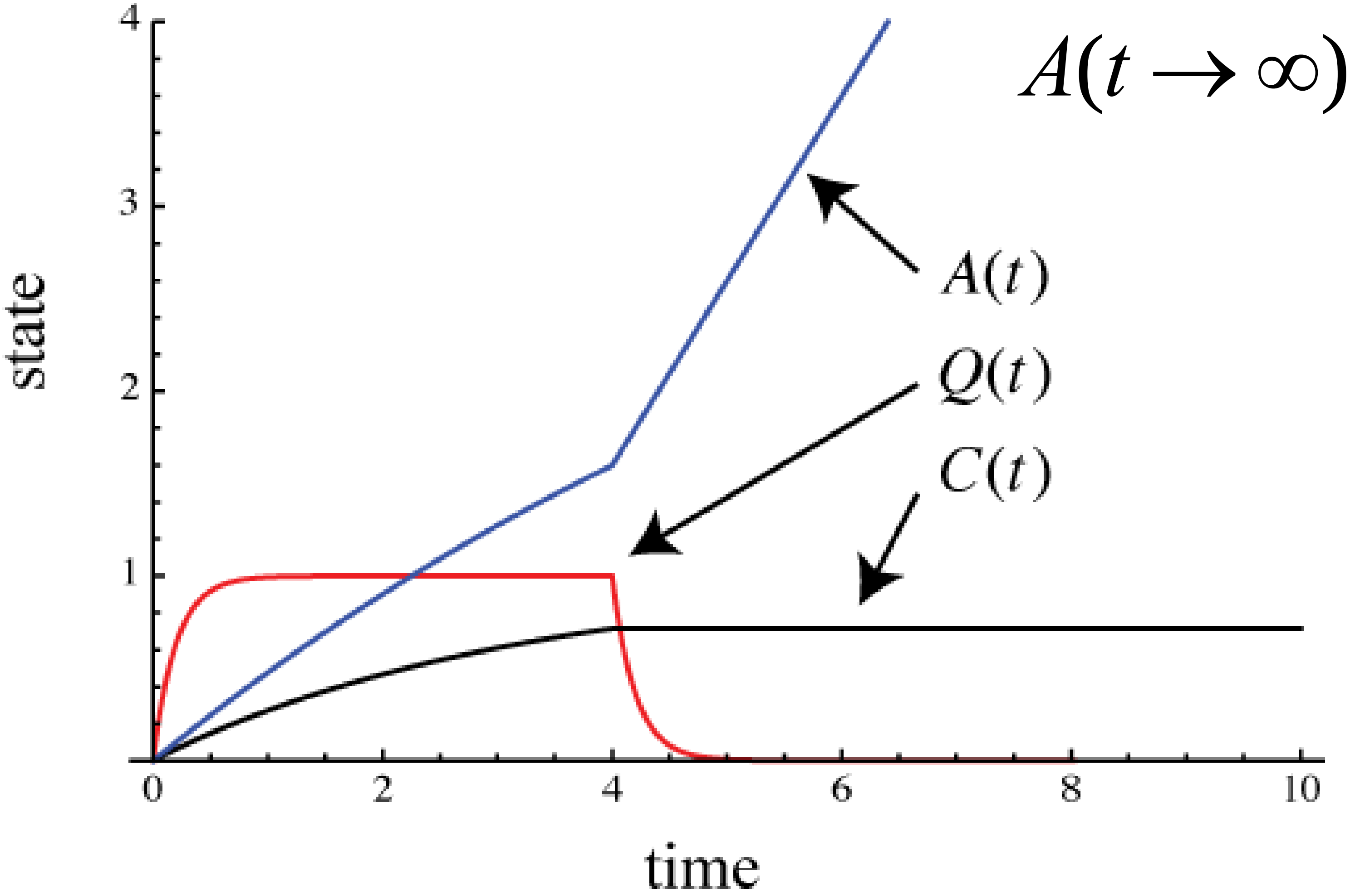


Unit Pulse Input: C_i and Q_i

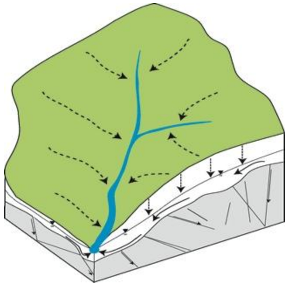


During drought periods the Age of water increases like a clock

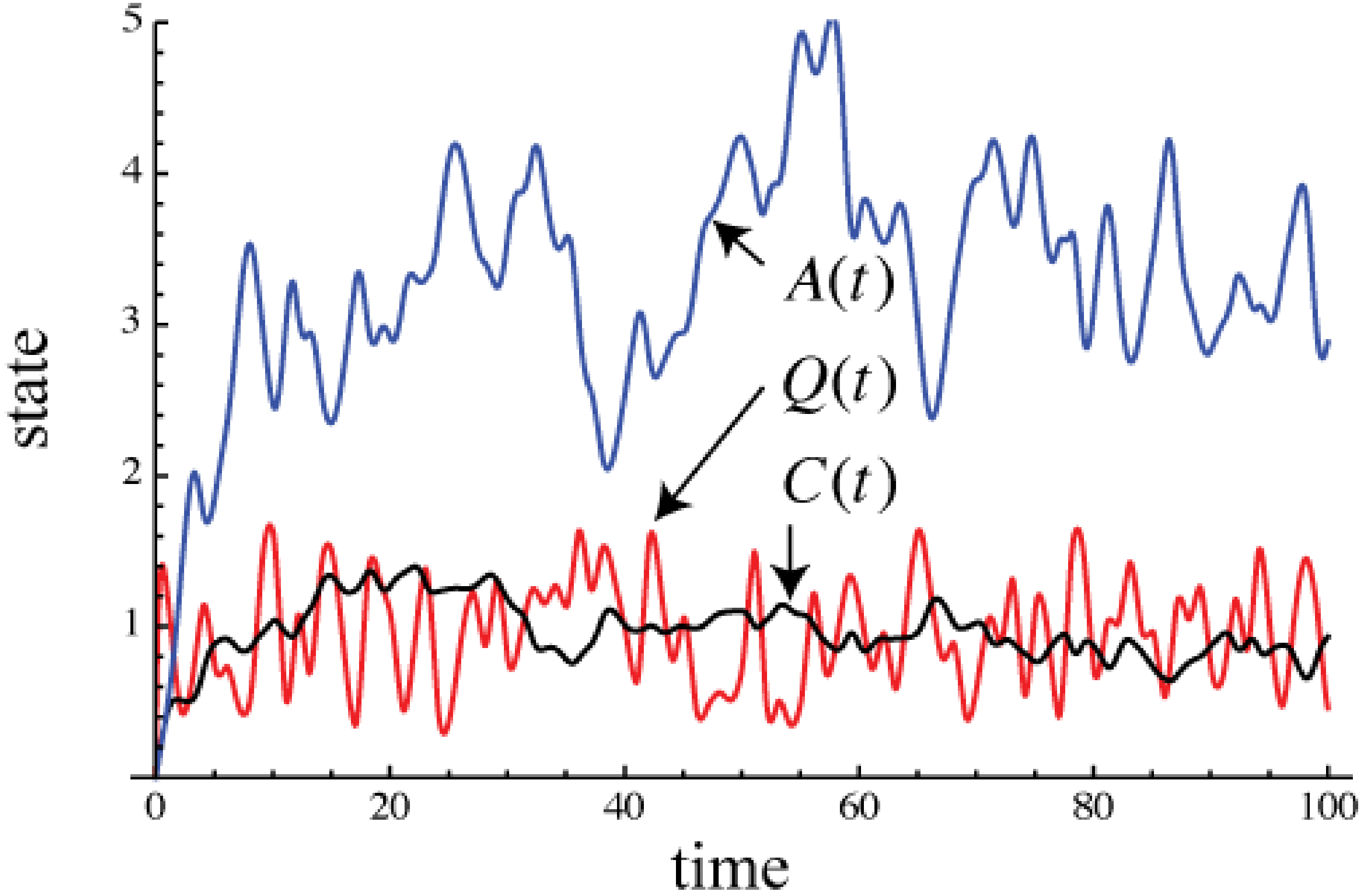
$$A(t \to \infty) \sim t$$



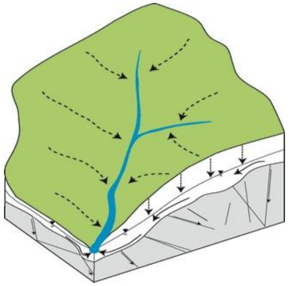
Random Watershed Inputs: C_i and Q_i



For random inputs, the of *Age* of water depends on the flow and solute inputs.



Concentration-Age-Flow Distributed Dynamical Model



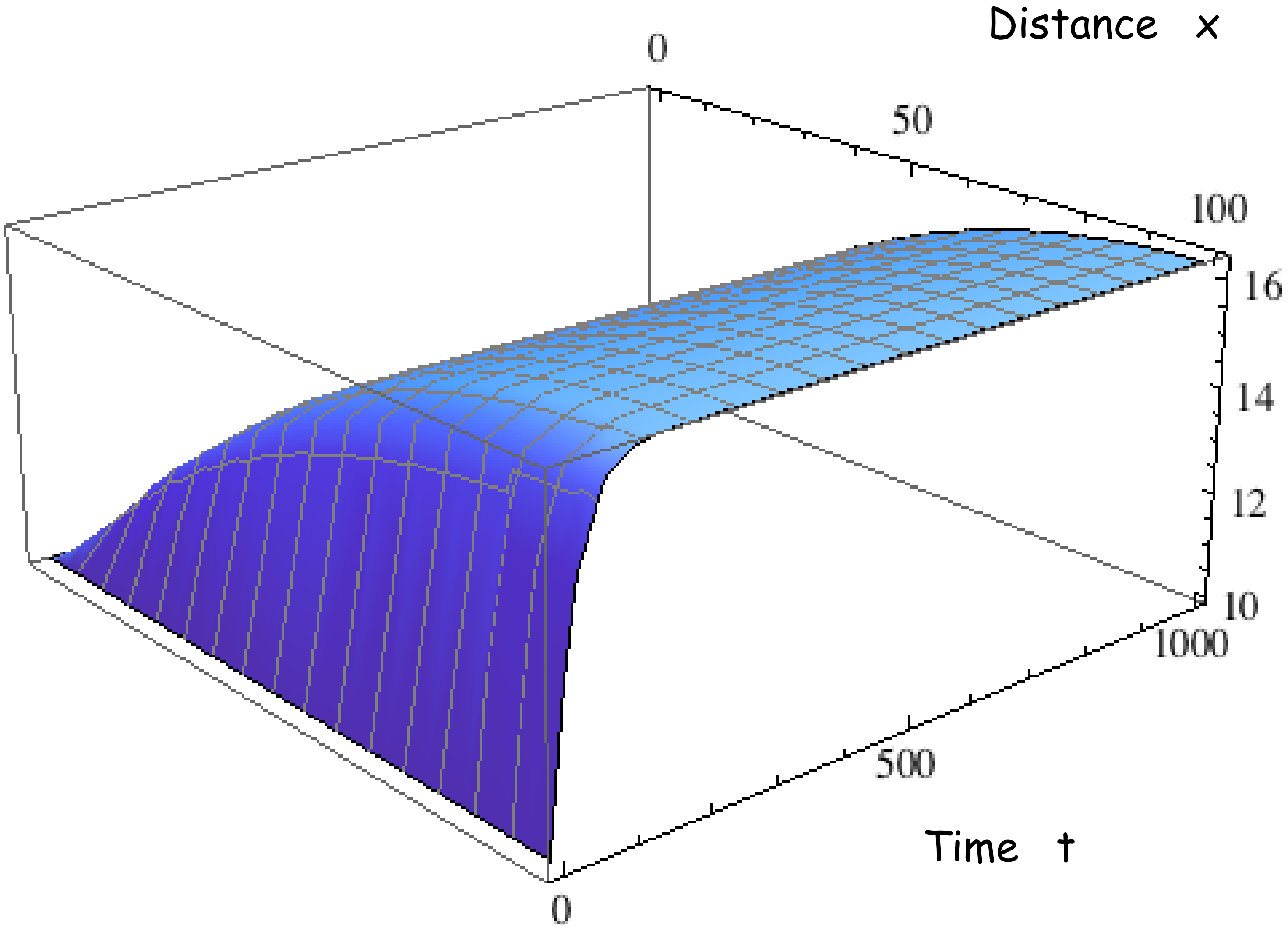
$$q_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} K h \frac{\partial h}{\partial x} + e$$

$$\mu_o \Rightarrow \quad \frac{\partial C}{\partial t} + \hat{u}(x,t)\frac{\partial c}{\partial x} = D(x,t)\frac{\partial^2 c}{\partial x^2} + k(C_i - C)$$

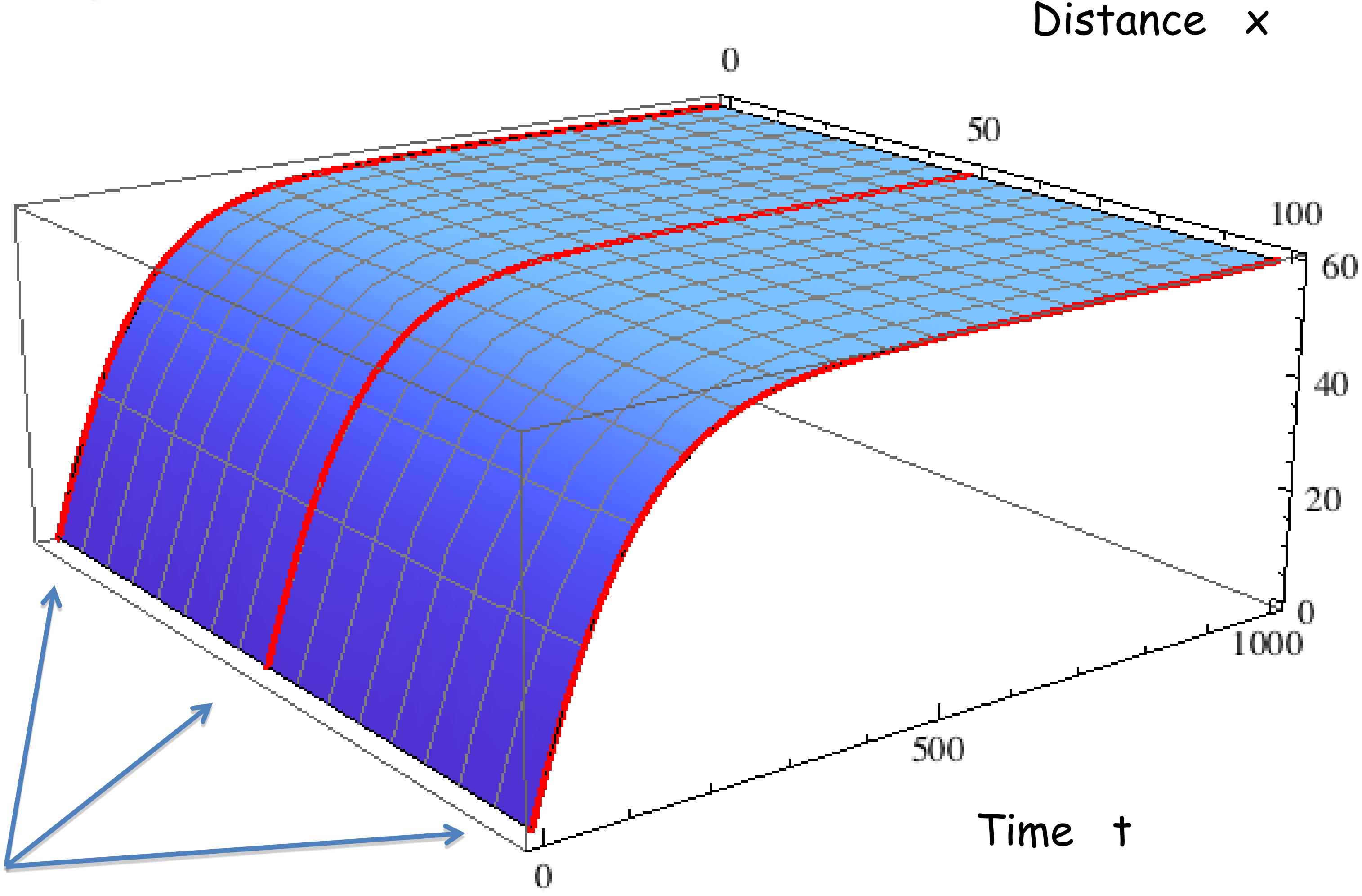
$$\mu_1 \Rightarrow \quad \frac{\partial a}{\partial t} + \hat{u}(x,t)\frac{\partial a}{\partial x} = D(x,t)\frac{\partial^2 a}{\partial x^2} + C - ka$$

$$\frac{\mu_1}{\mu_o} \Rightarrow \quad Age(x,t) = \frac{a(x,t)}{C(x,t)}$$

C(x,t)

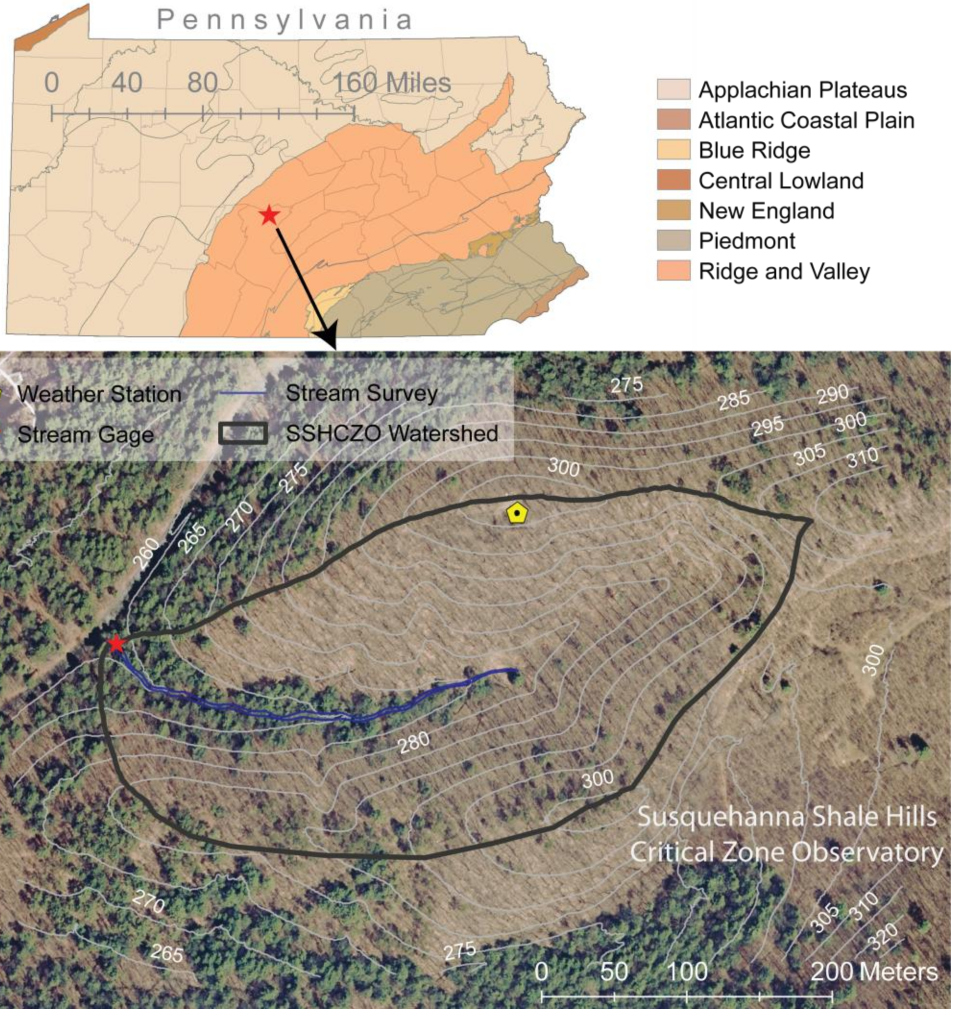


Age(x,t)

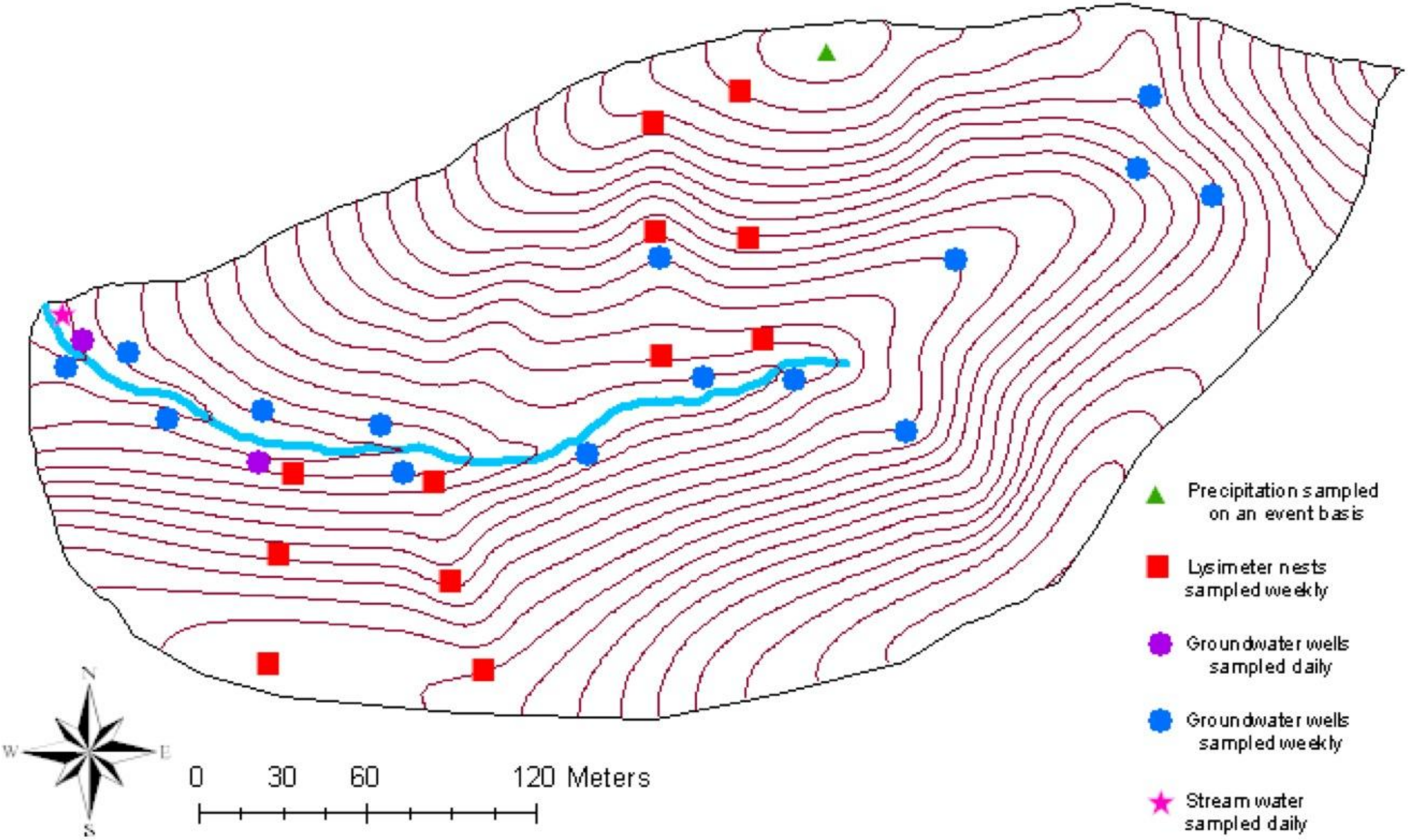


Exponential Model+ Boussinesq

Shale Hills Critical Zone Observatory
Isotope Network
Prediction of Pathways and Time Scales at the Watershed Scale



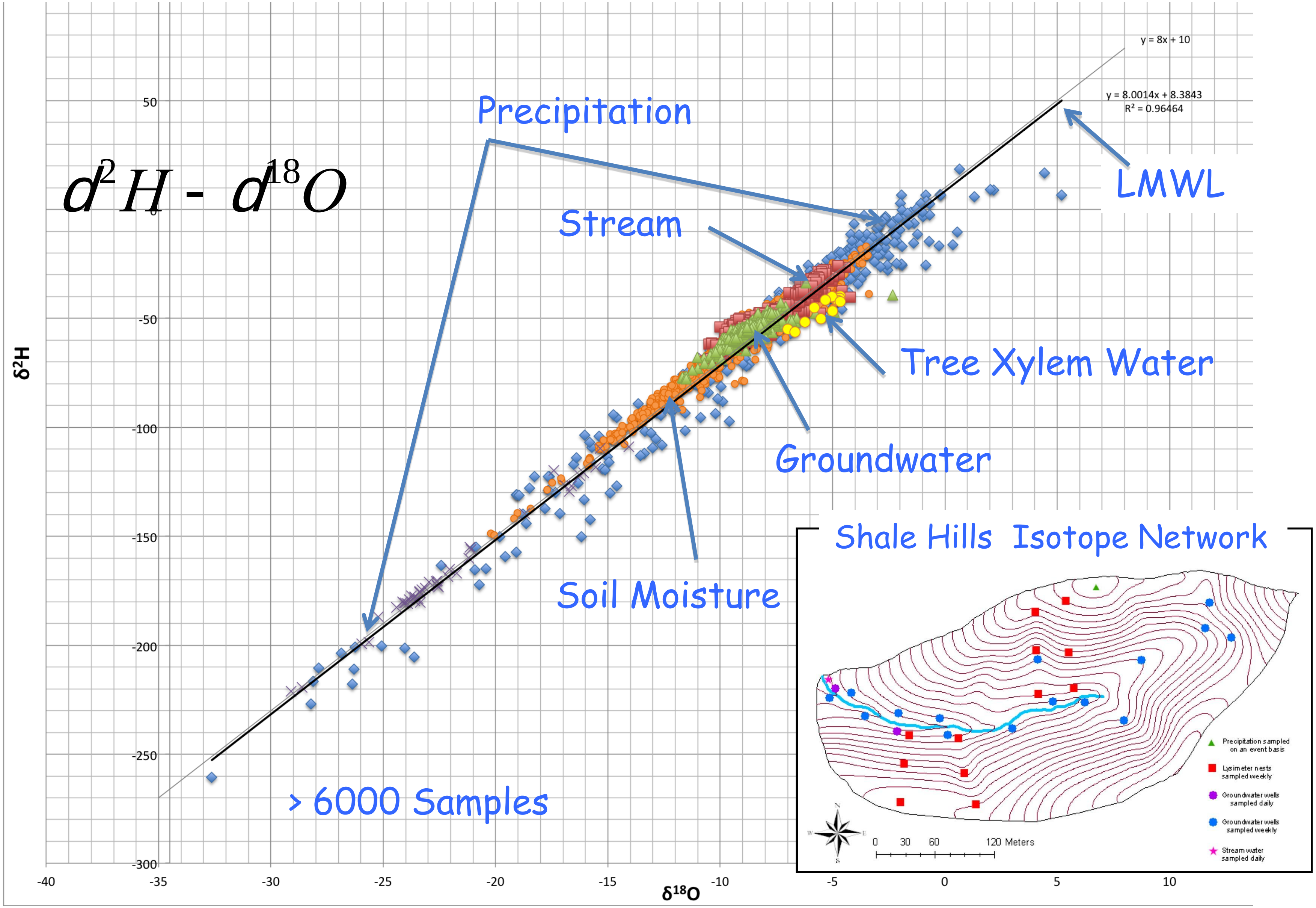
Shale Hills Stable Isotope Network



George Holmes, MS 2010

Instrumentation for Evaluating All Isotope Pools

CZO Stable Isotope Experiment 2008-20012



d^2H - $d^{18}O$

Precipitation

Stream

LMWL

Tree Xylem Water

Groundwater

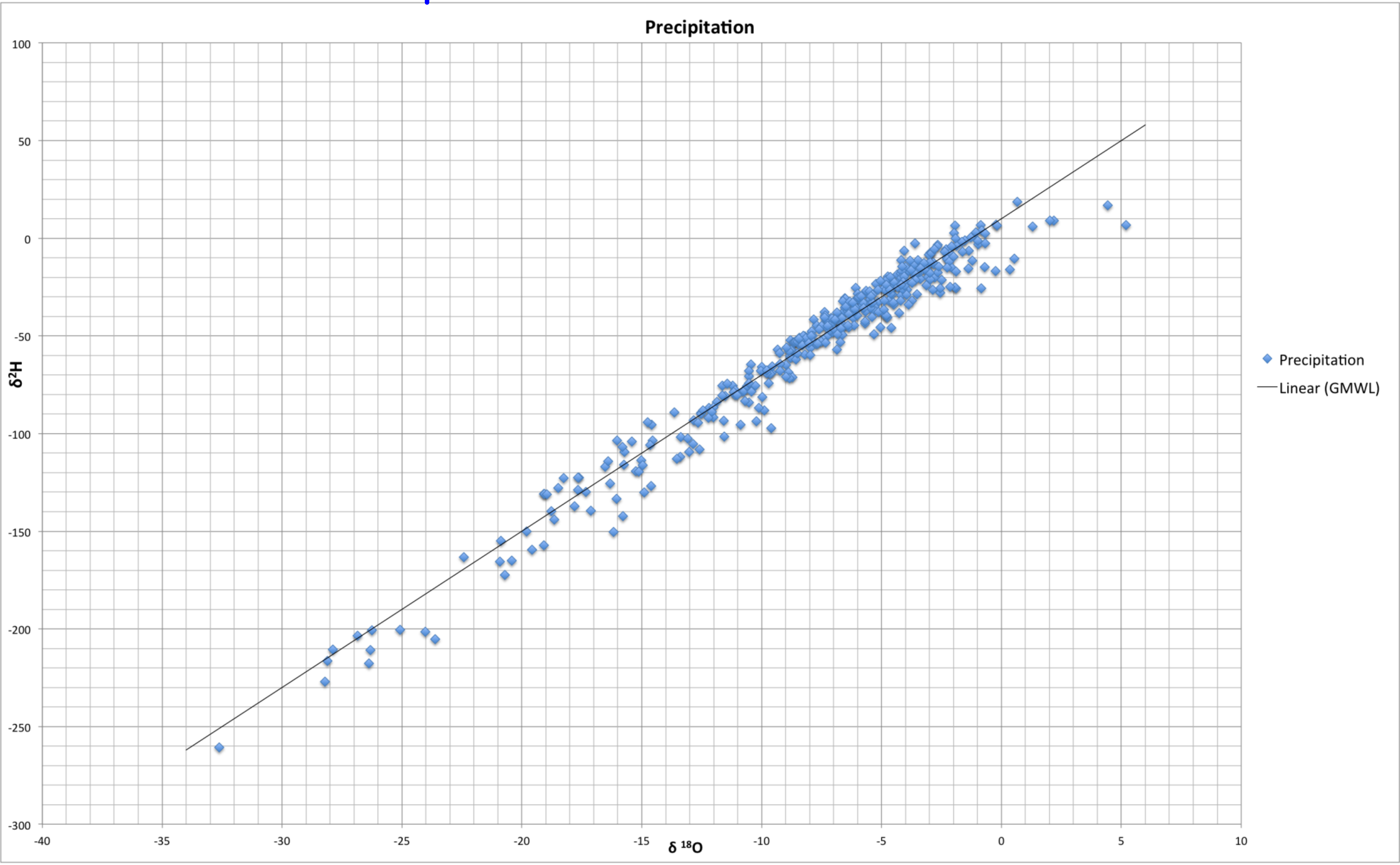
Soil Moisture

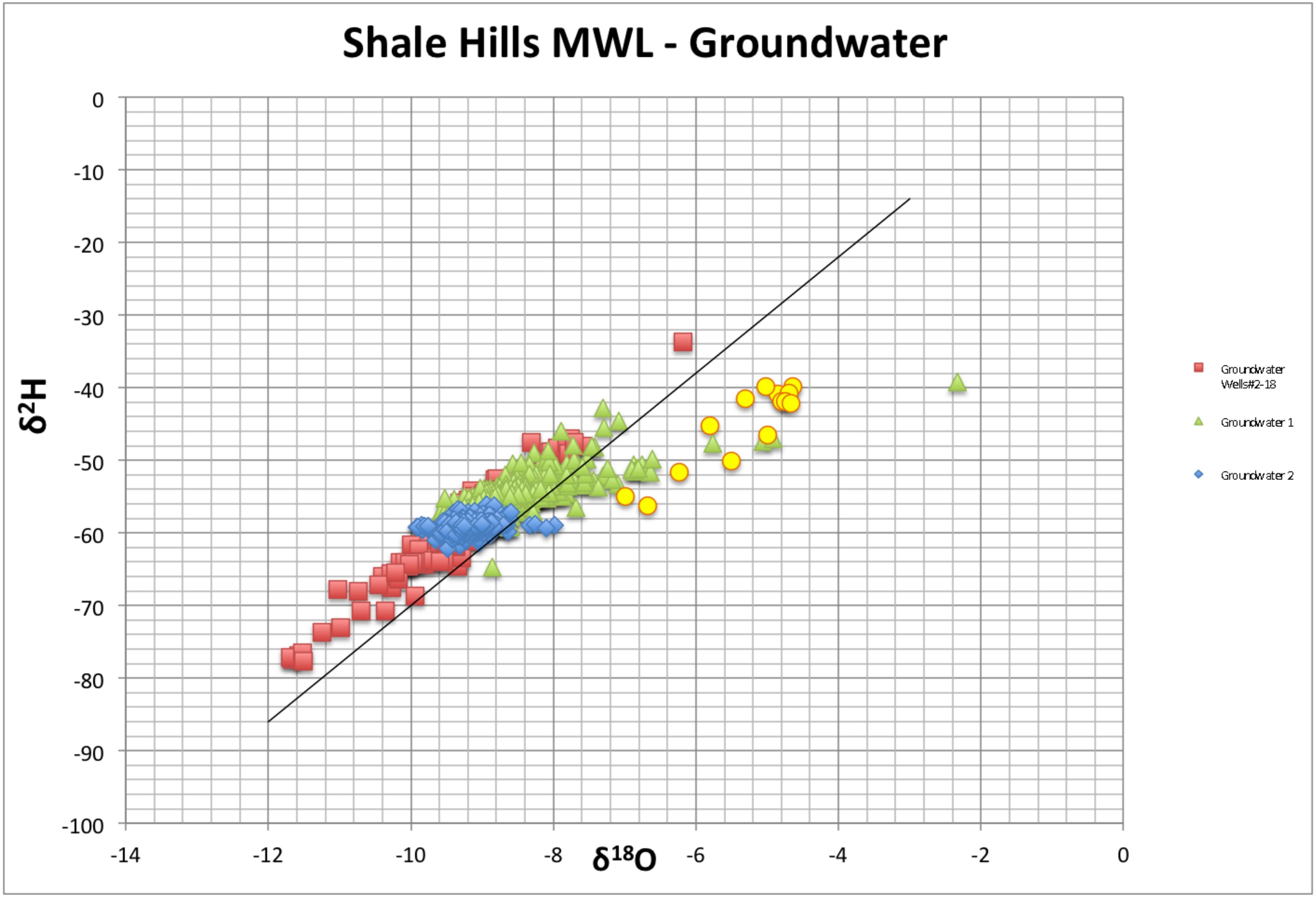
Shale Hills Isotope Network

> 6000 Samples

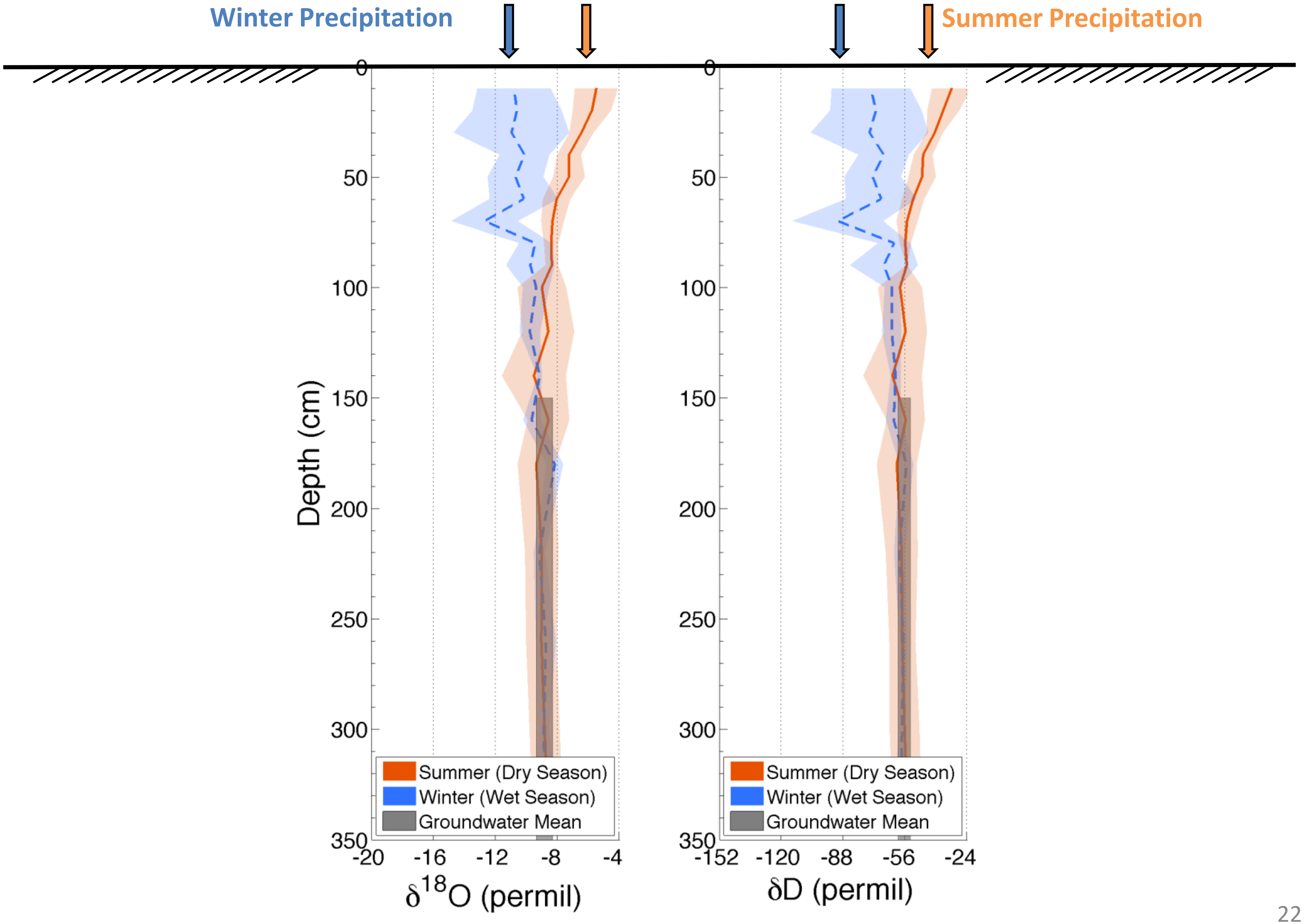
Holmes, M.S 2011, Thomas MS. 2013

Precipitation 2008-20012

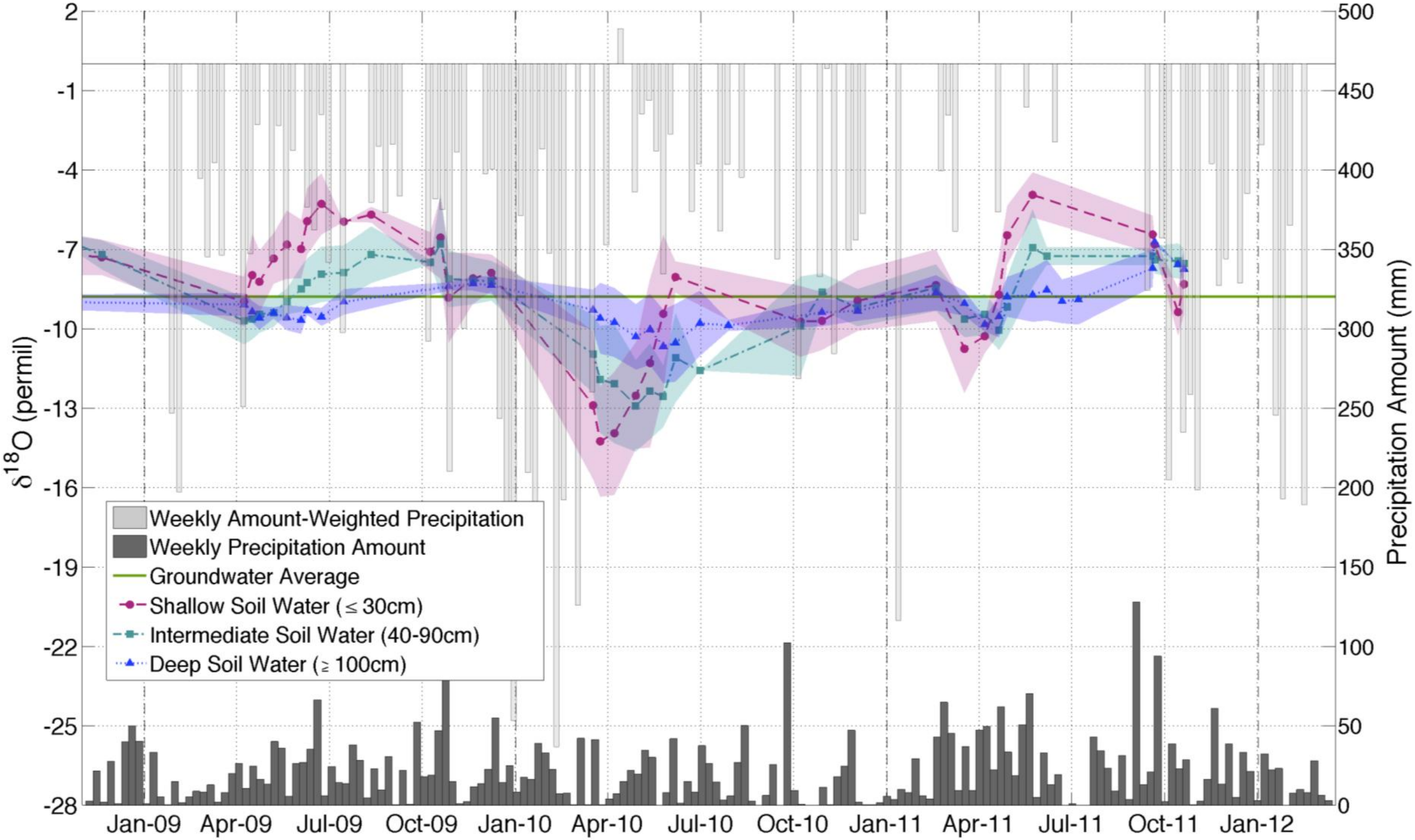



Shale Hills MWL - Groundwater
δ2H
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
δ18O
-14
-12
-10
-8
-6
-4
-2
0
Groundwater Wells#2-18
Groundwater 1
Groundwater 2

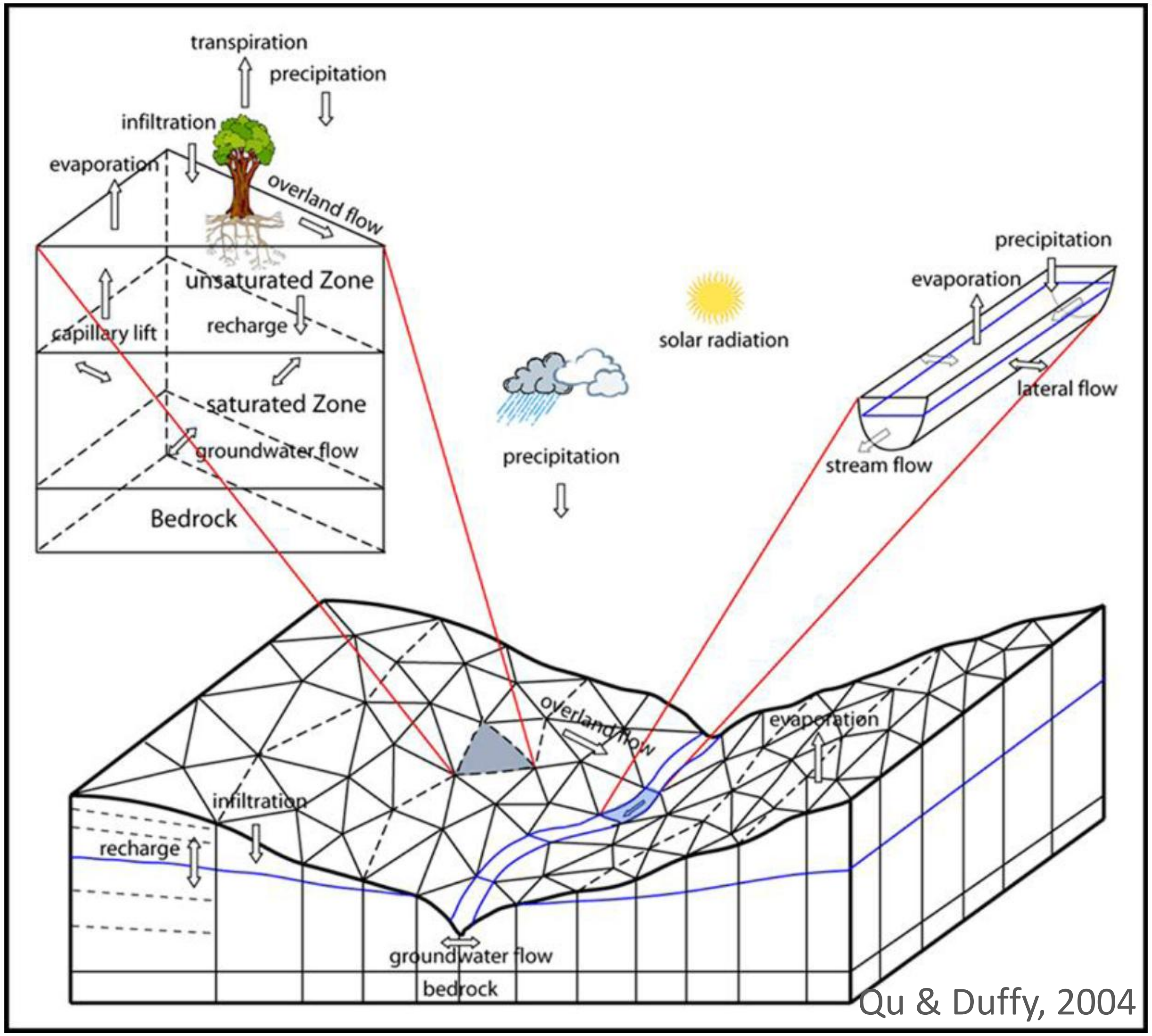
Wet-Dry Seasonal Variations for Stable Isotope Profiles



Temporal Pattern of Stable Isotopes in Soil Water



Integrated Hydrologic Modeling For Distributed Tracers
Gopal Bhatt 2012

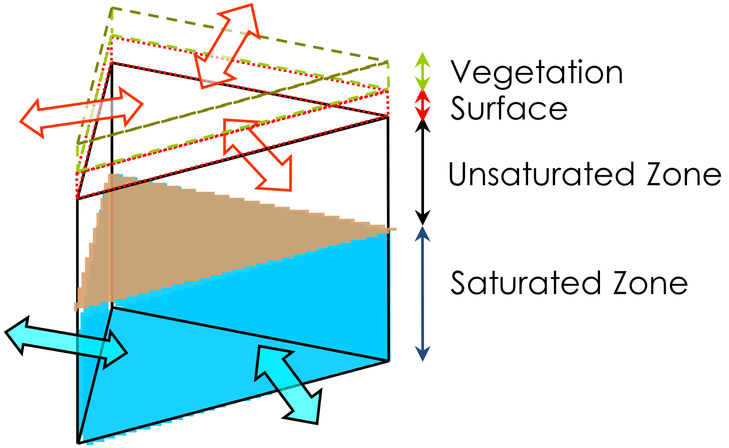


Qu & Duffy, 2004

Integrated Hydrologic Modeling System

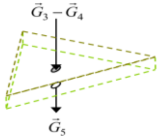
www.pihm.psu.edu

- Control Volume Kernel: Semi-Discrete Finite Volume formulation of conservation equations. Finite Volume Method ensures mass balance locally (in each control volume) and globally.



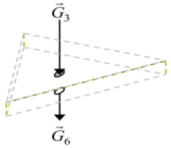
Interception

$$\frac{dy_0}{dt} = G_3 - G_4 - G_5$$

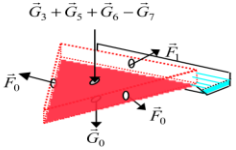


Snow Melt

$$\frac{dy_1}{dt} = G_3 - G_6$$

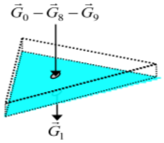


Overland Flow



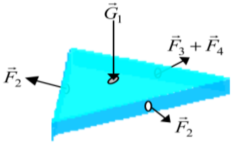
$$\frac{dy_2}{dt} = G_3 + G_5 + G_6 + G_7 - G_0 + F_0 + \|F_1\|$$

Unsaturated Zone

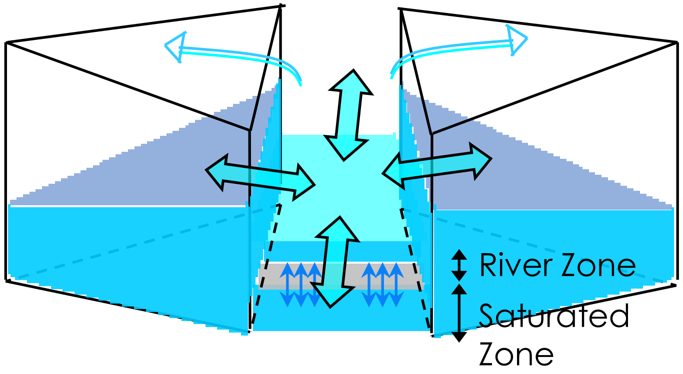


$$\frac{dy_3}{dt} = G_0 - G_1 - G_8 - G_9$$

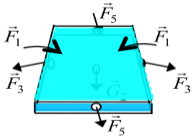
Saturated Zone



$$\frac{dy_4}{dt} = G_1 + F_2 + \|F_3\| + \|F_4\|$$

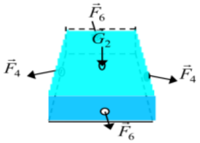


Channel



$$\frac{dy_5}{dt} = G_3 - G_2 - G_7 + F_1 + F_5 + \|F_3\|$$

Sub-Channel Aquifer

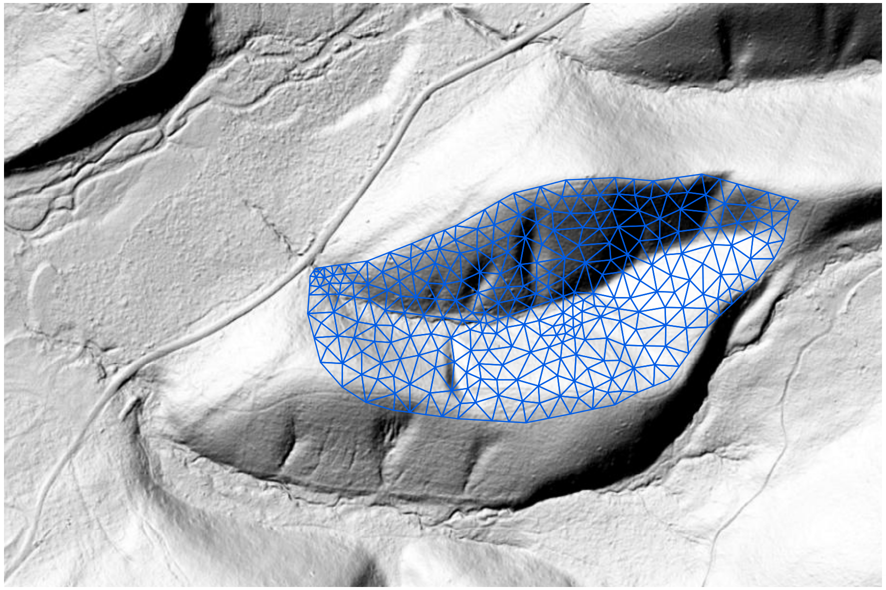


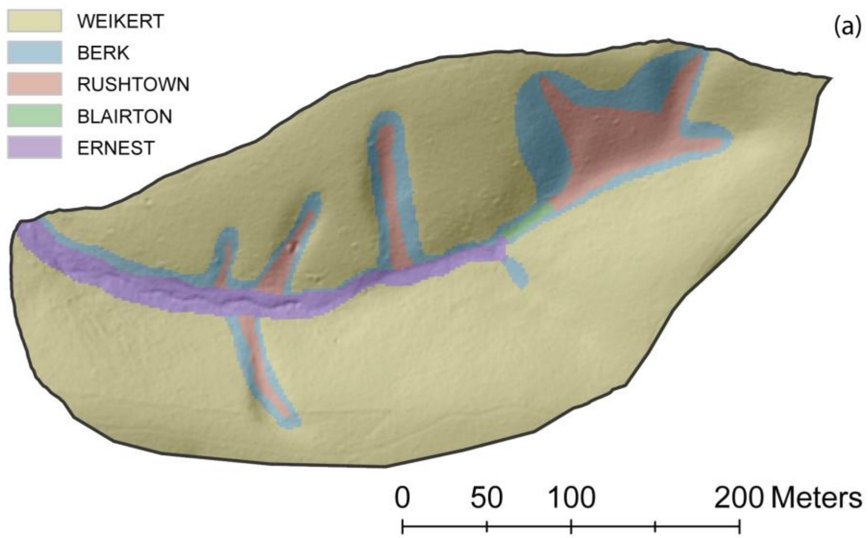
$$\frac{dy_6}{dt} = G_2 + F_4$$

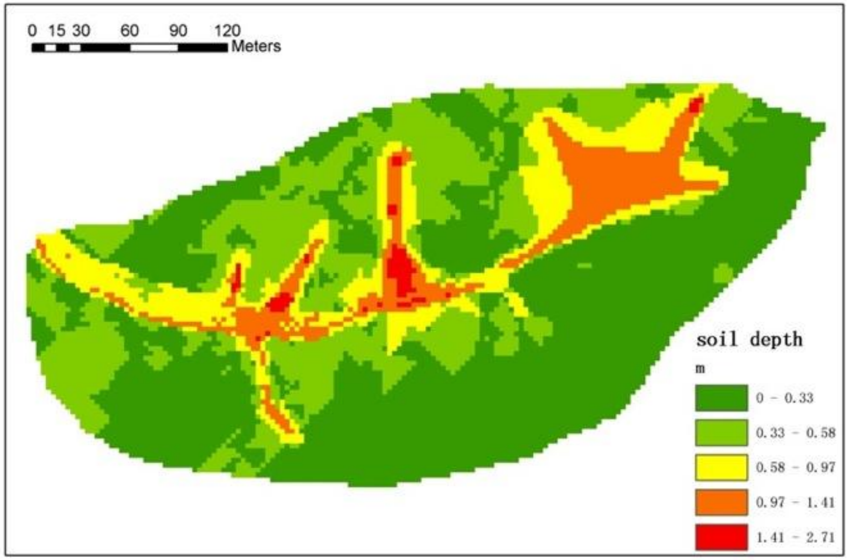
Kumar et. al., 2009

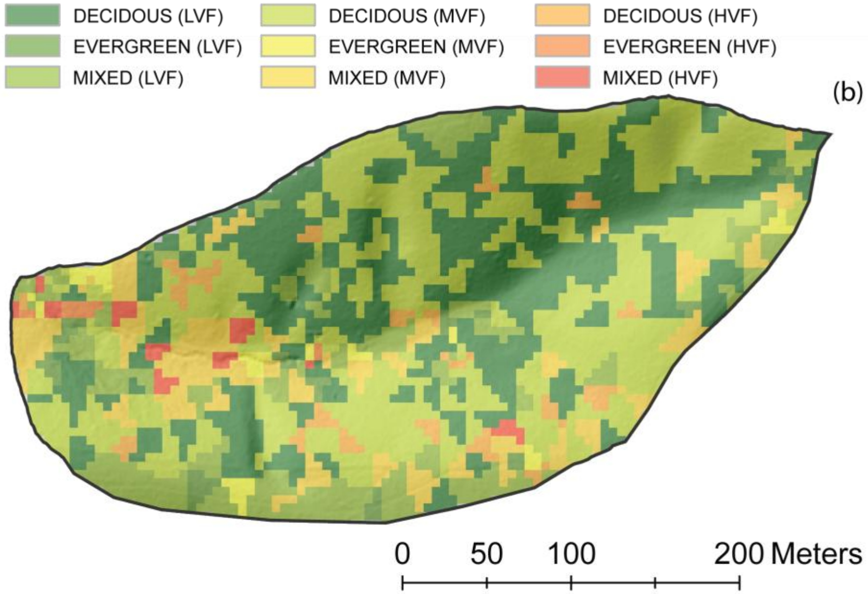
The system of ODEs is solved using state-of-the-art solver with adaptive time steps

CZO Hi-Res Data Products

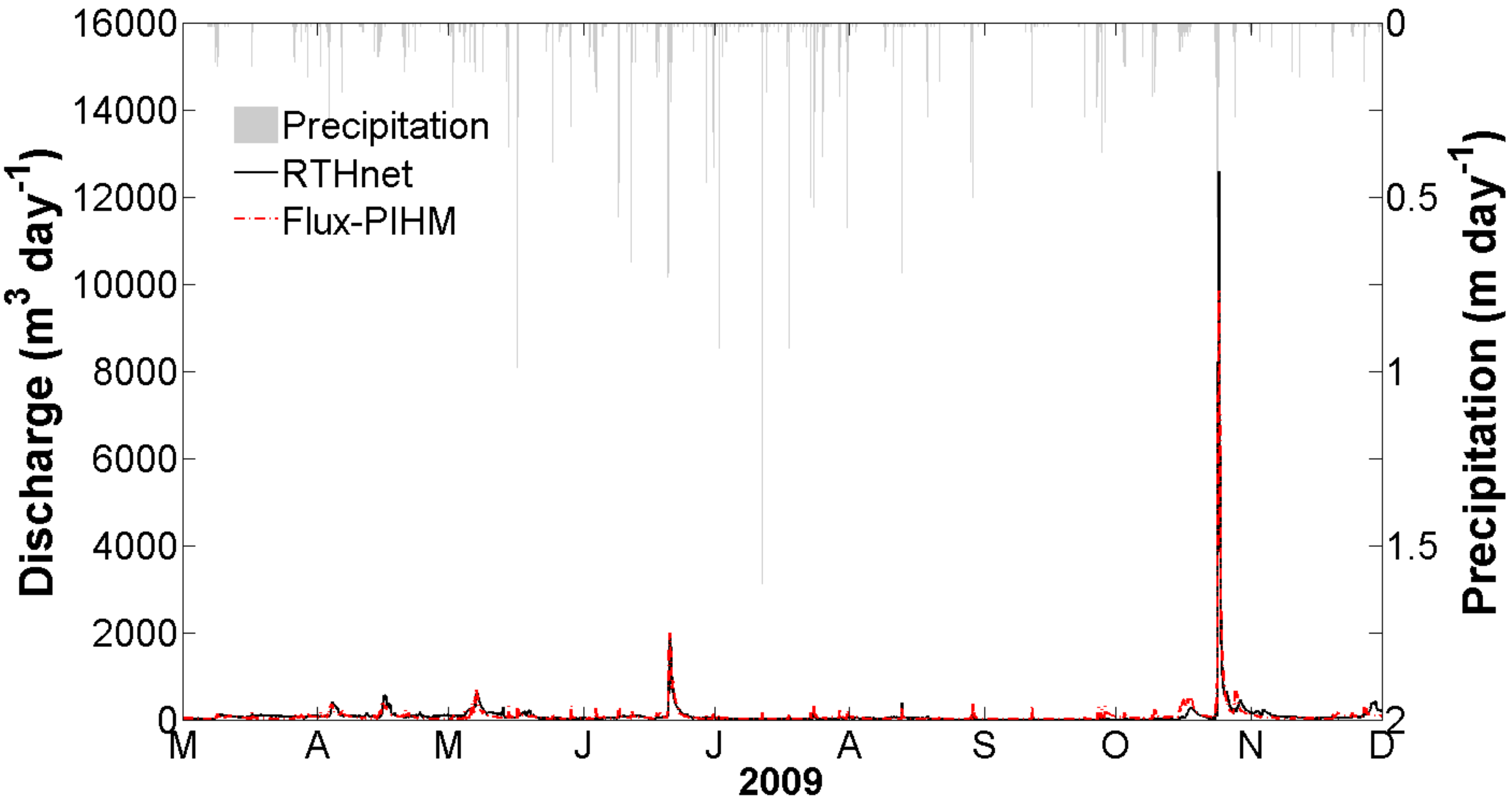




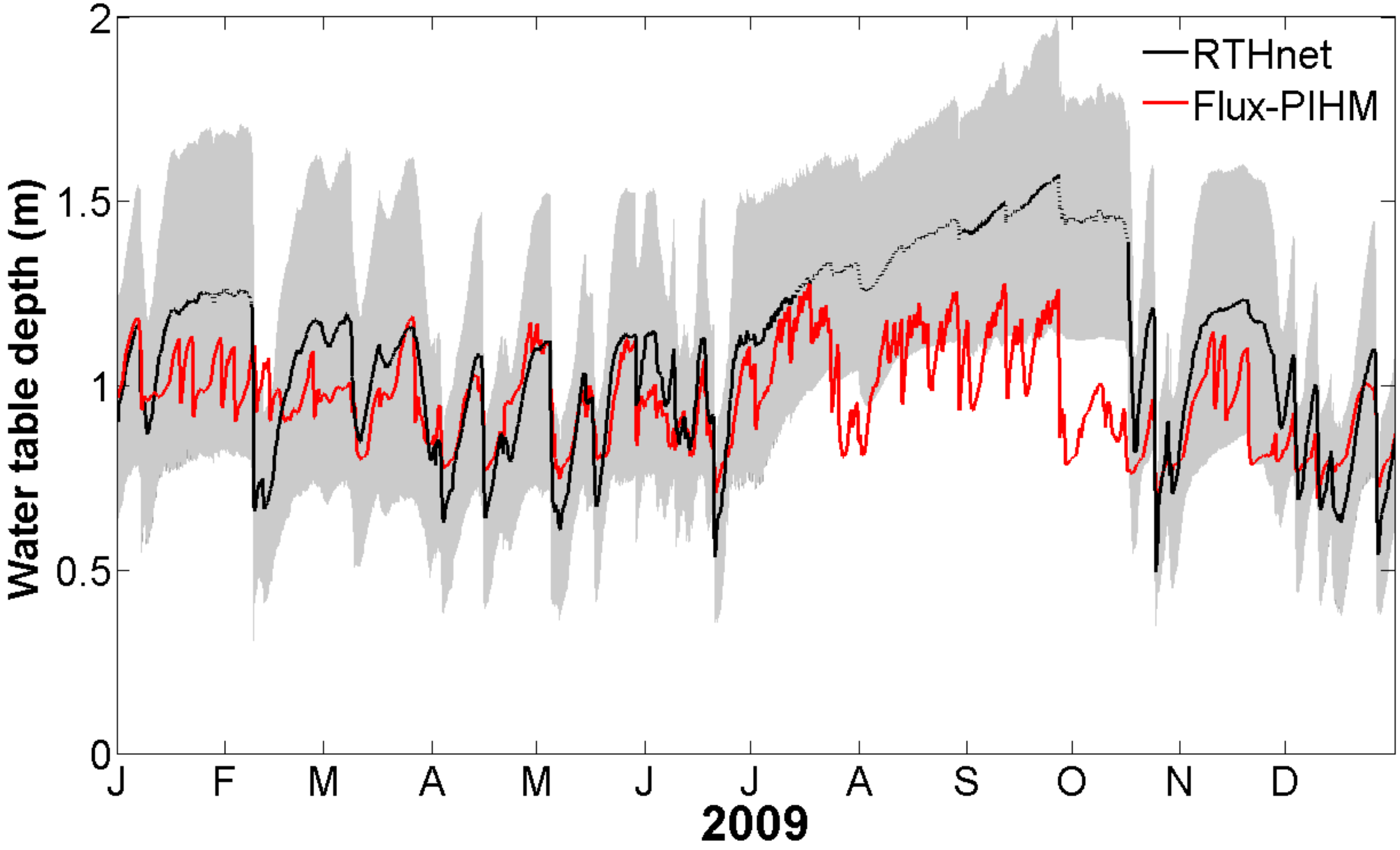




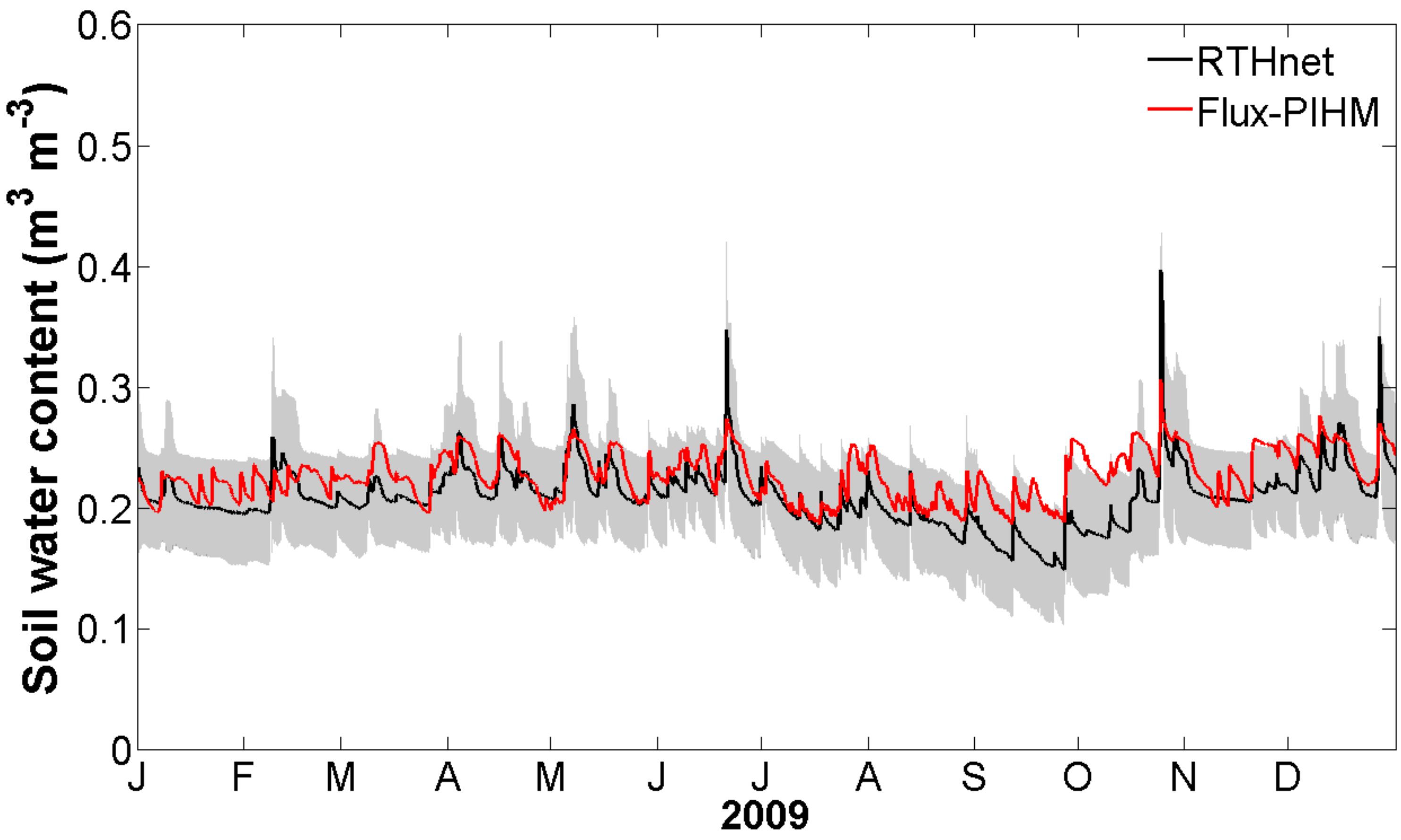
Discharge


Precipitation
RTHnet
Flux-PIHM
Discharge (m^3 day^{-1})
16000
14000
12000
10000
8000
6000
4000
2000
0
Precipitation (m day^{-1})
0
0.5
1
1.5
2
M
A
M
J
J
A
S
O
N
D
2009

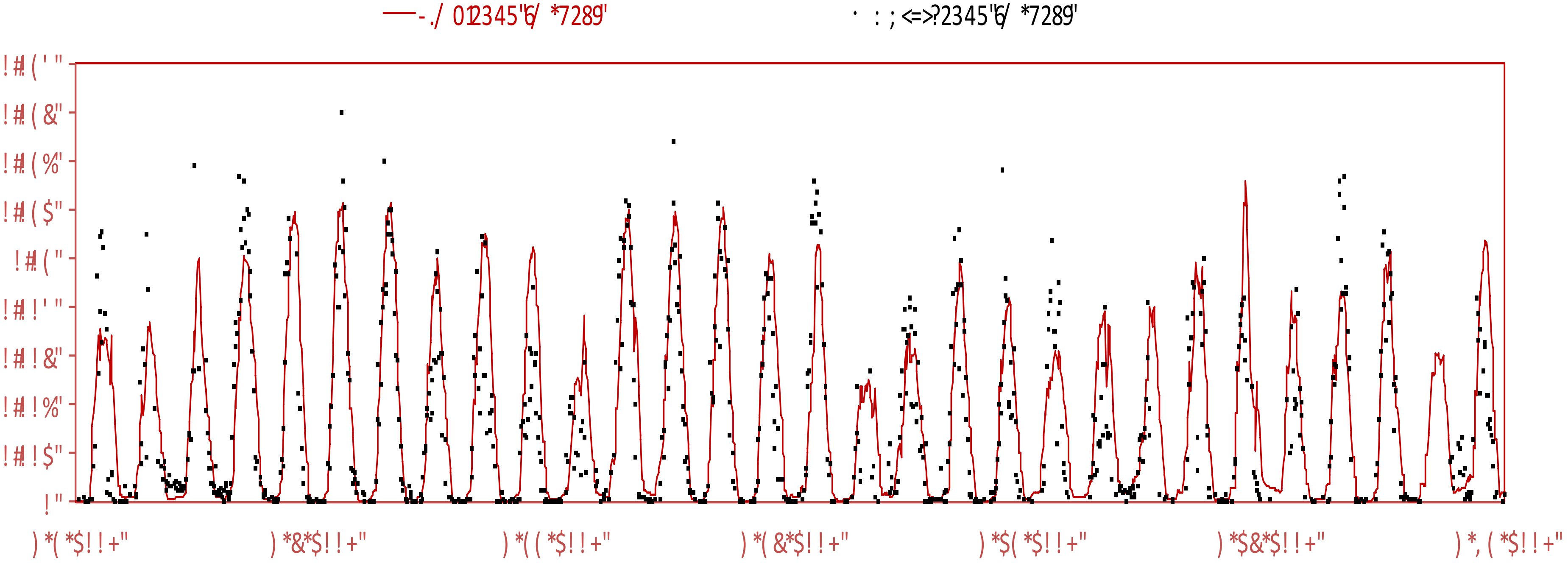
Water Table Depth



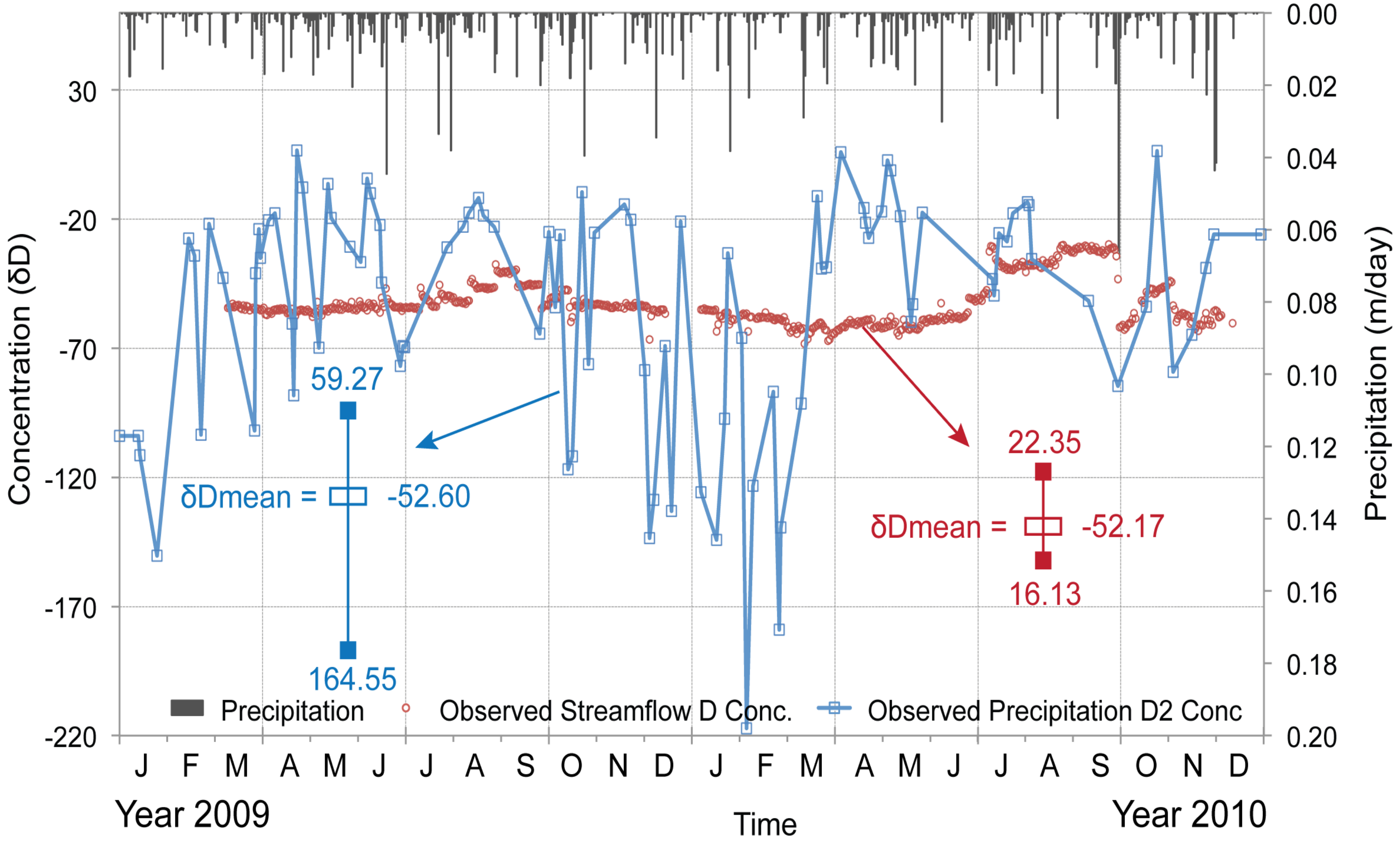
Soil moisture



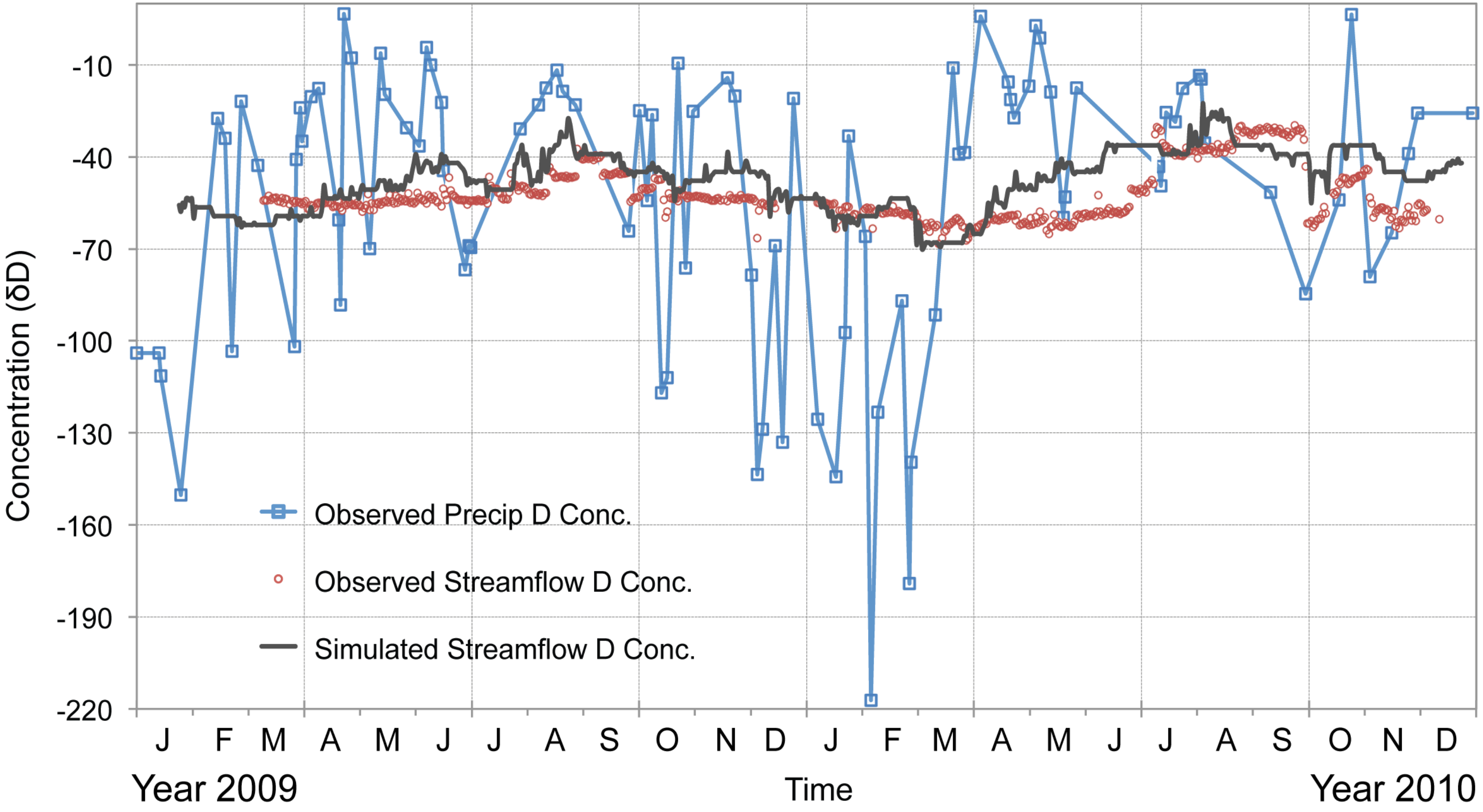
Evapotranspiration



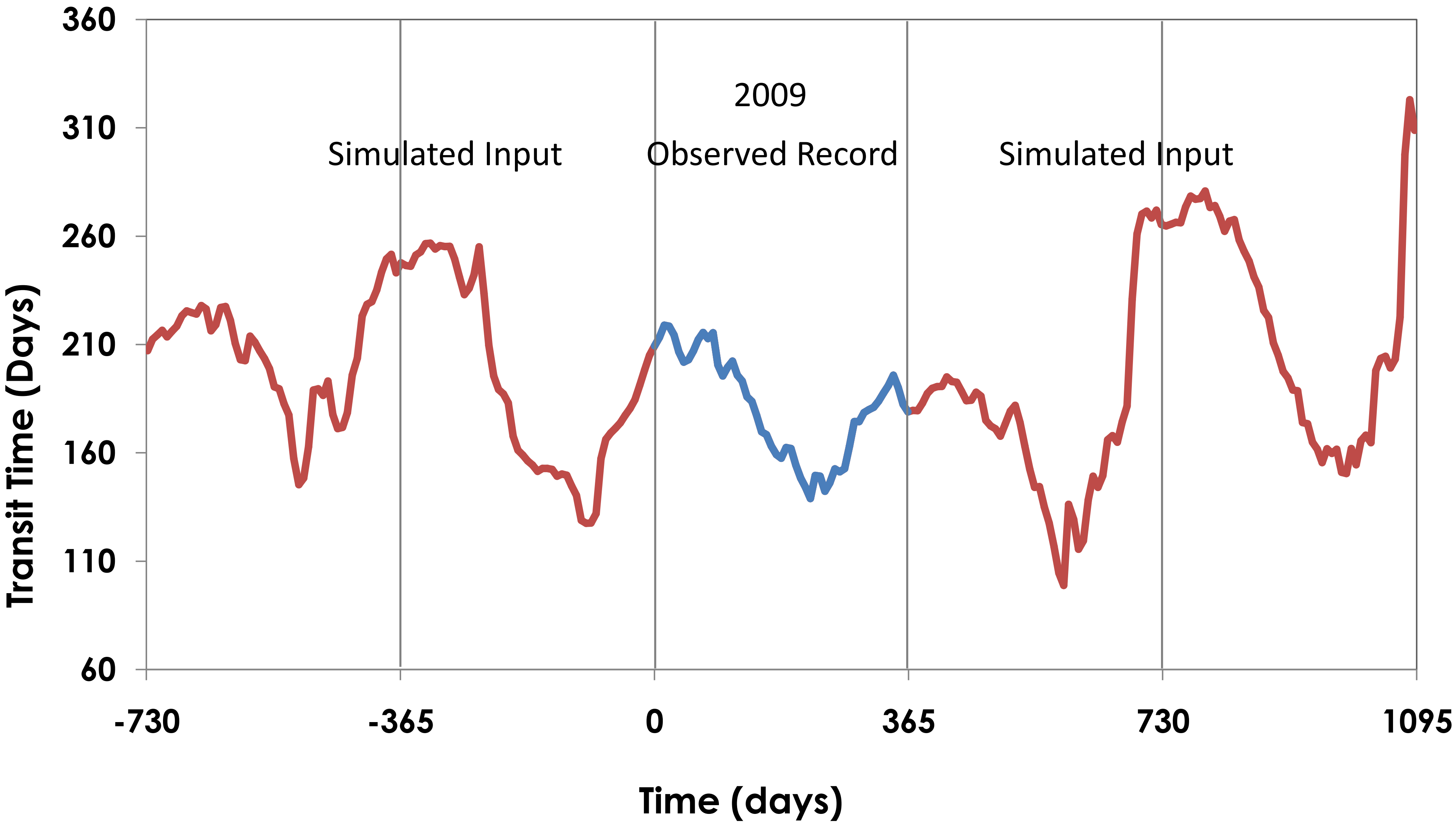
Observed D2H



Simulated-Observed Streamflow D2H.

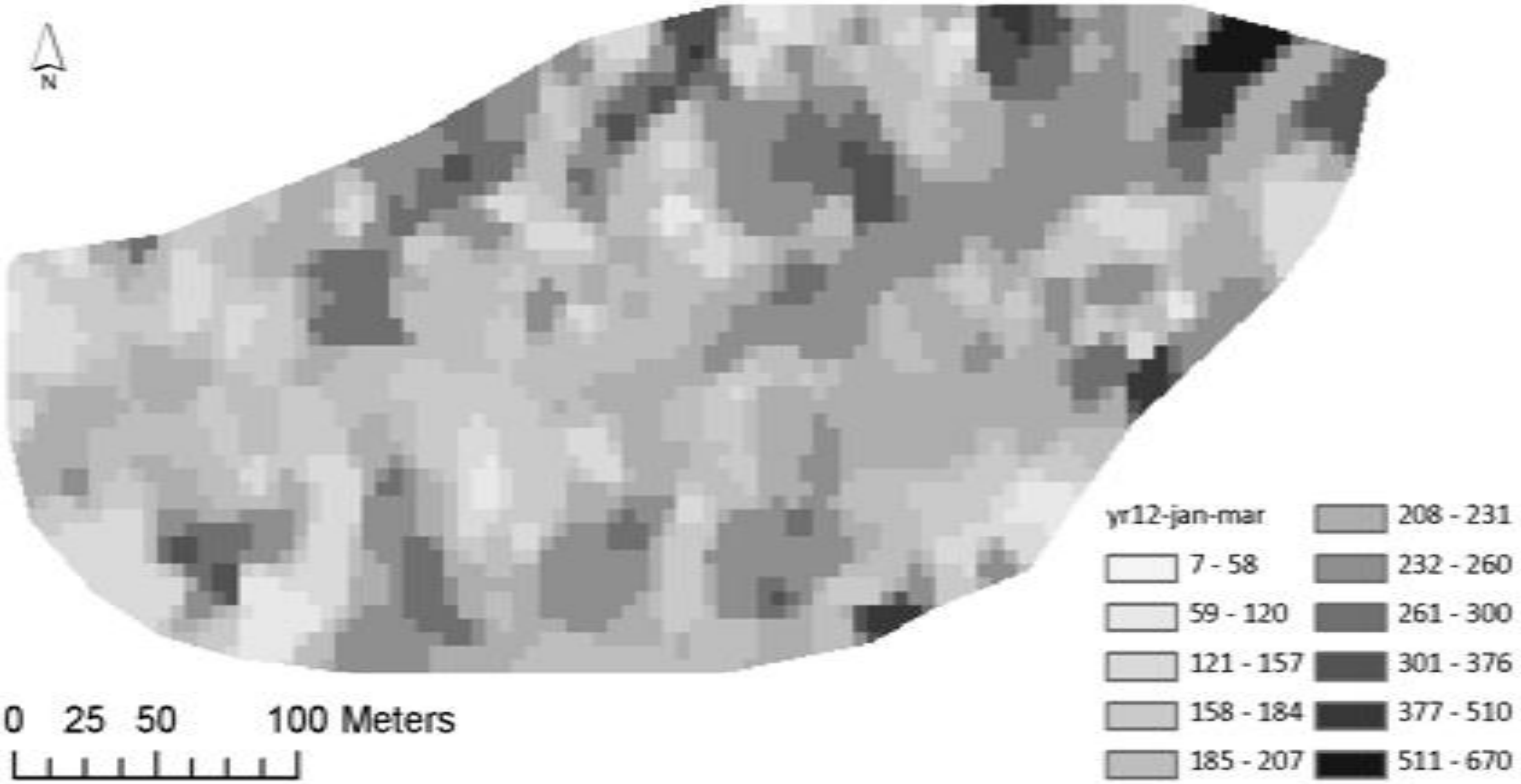


Watershed Runoff Transit Time



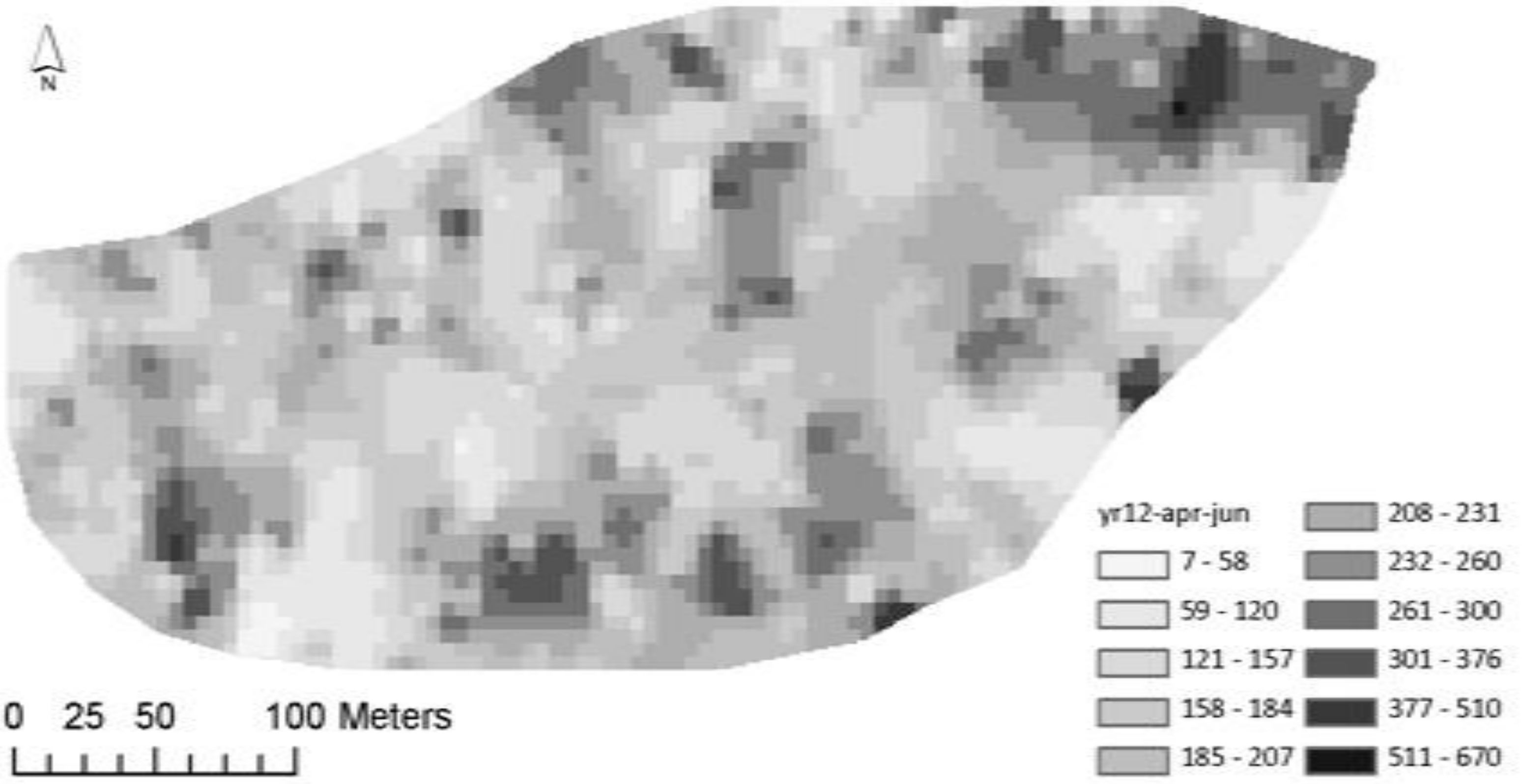
JAN – MAR

Spatial Mean Watershed Age = 210.9 days



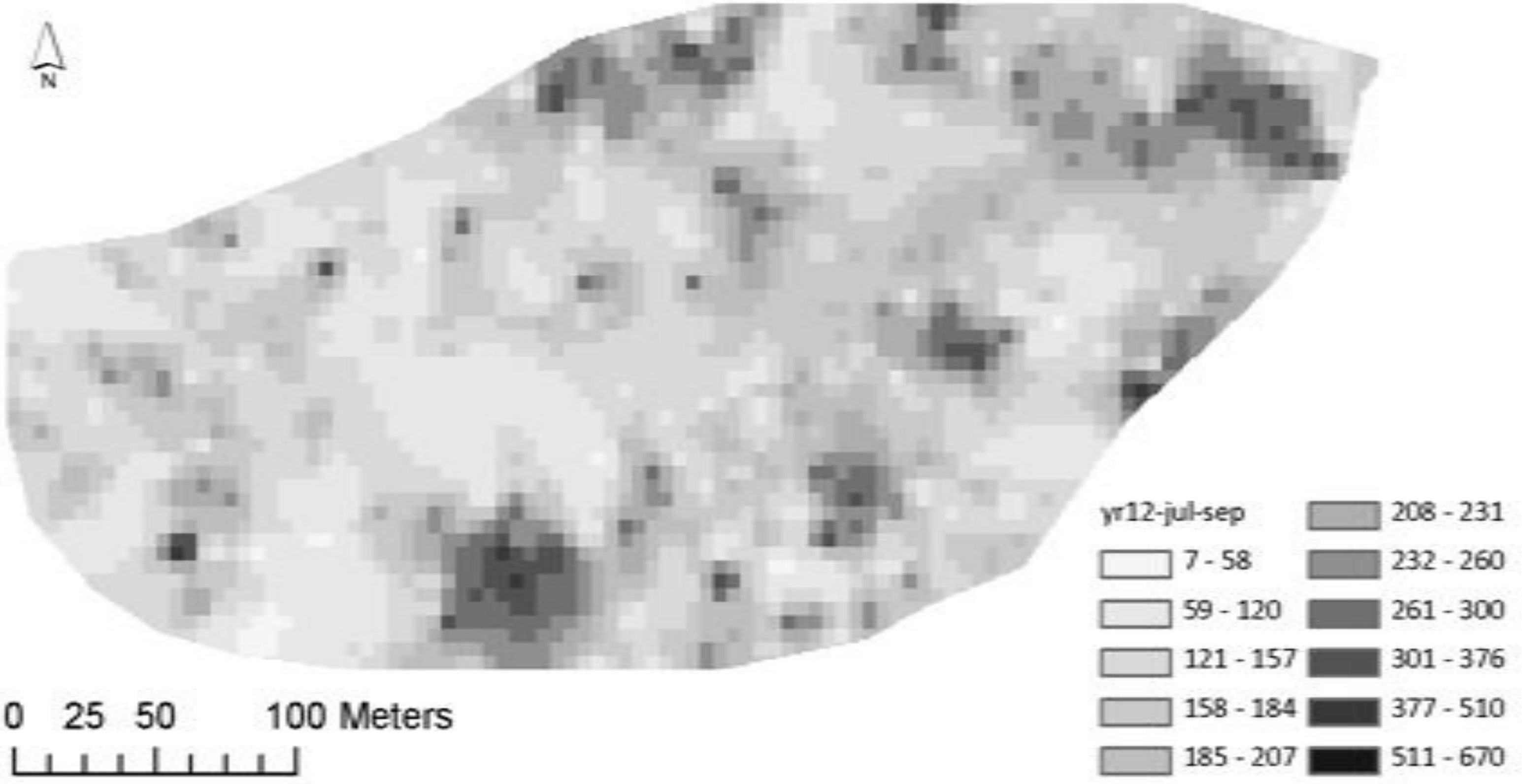
APR – JUN

Spatial Mean Watershed Age = 188.7 days



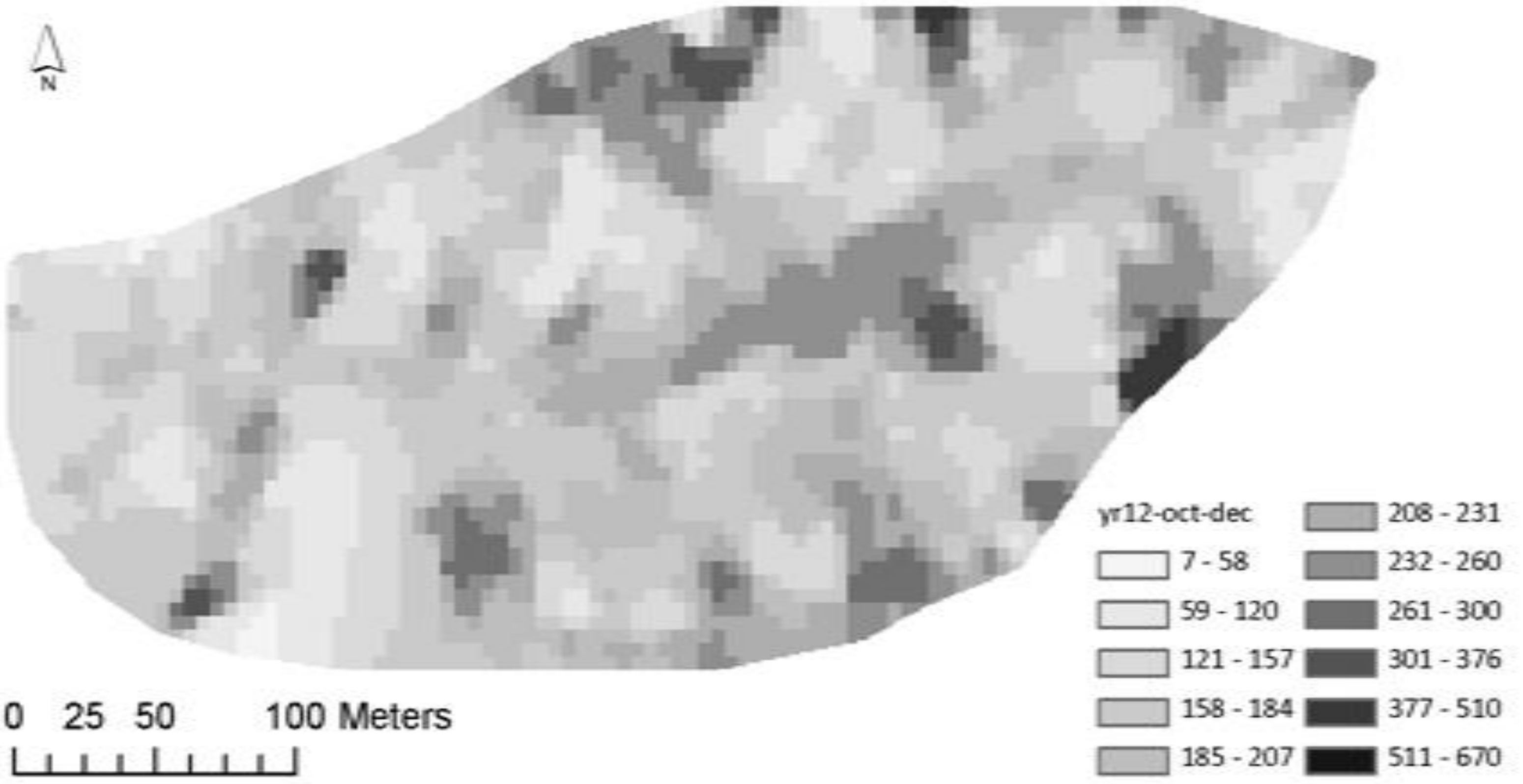
JUL – SEP

Spatial Mean Watershed Age = 161.6 days



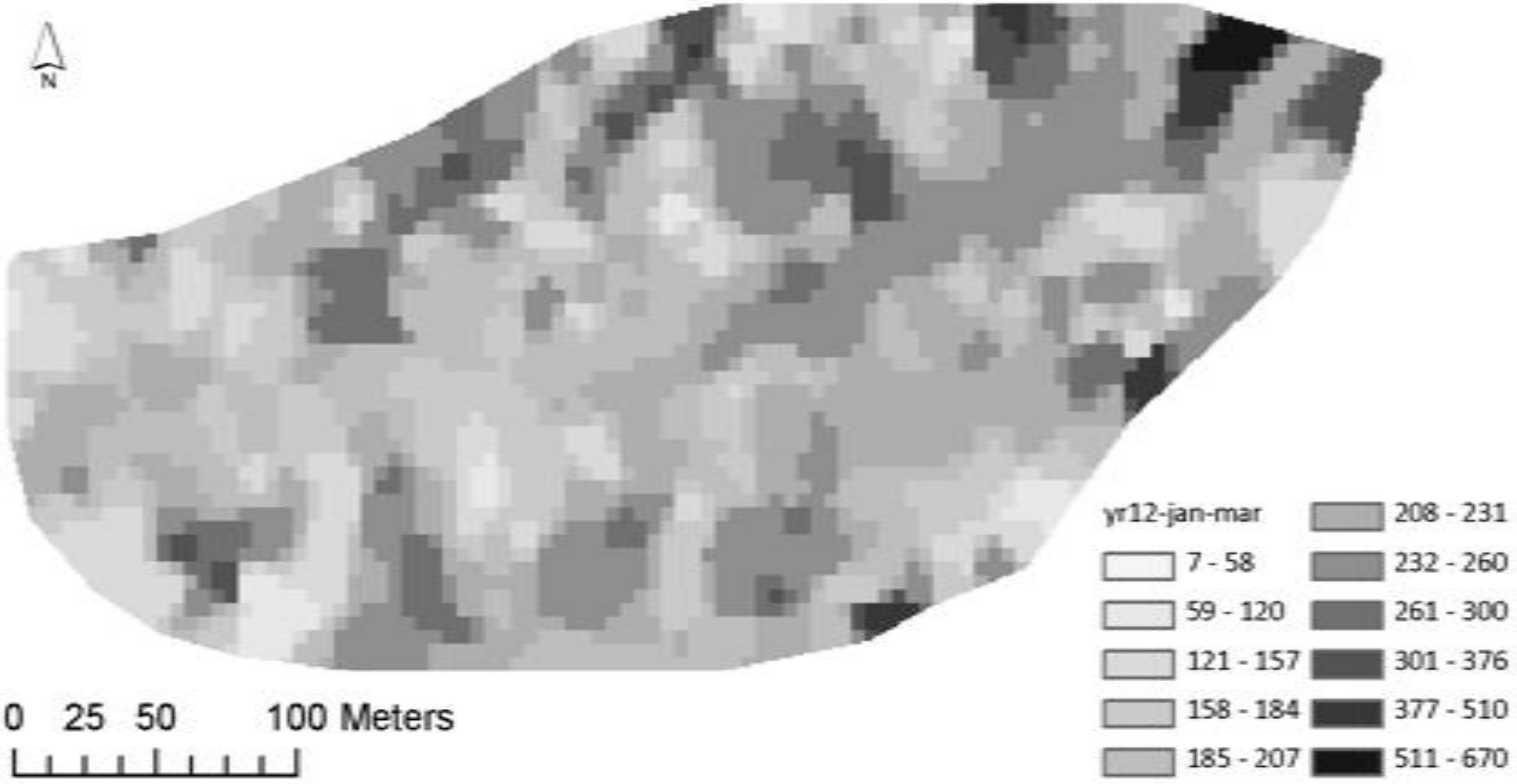
OCT – DEC

Spatial Mean Watershed Age = 180.1 days

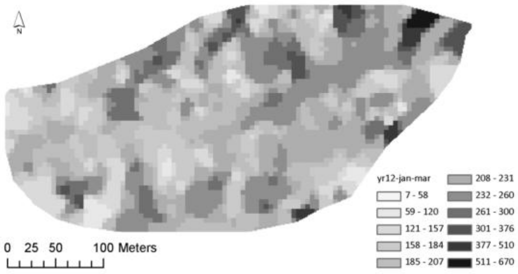


JAN – MAR

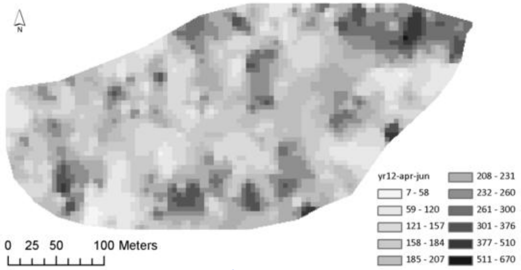
Spatial Mean Watershed Age = 210.9 days



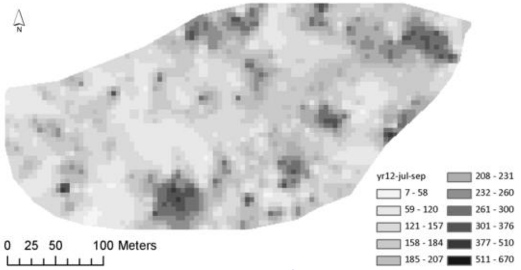
Summary:A New Transport Theory and Distributed Model for Direct Simulation of the "Age" of Water from Stable Isotopes for "all states of the watershed (PIHM)



Jan-Mar '09



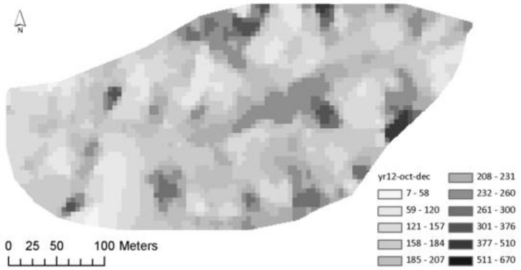
Apr-Jun '09

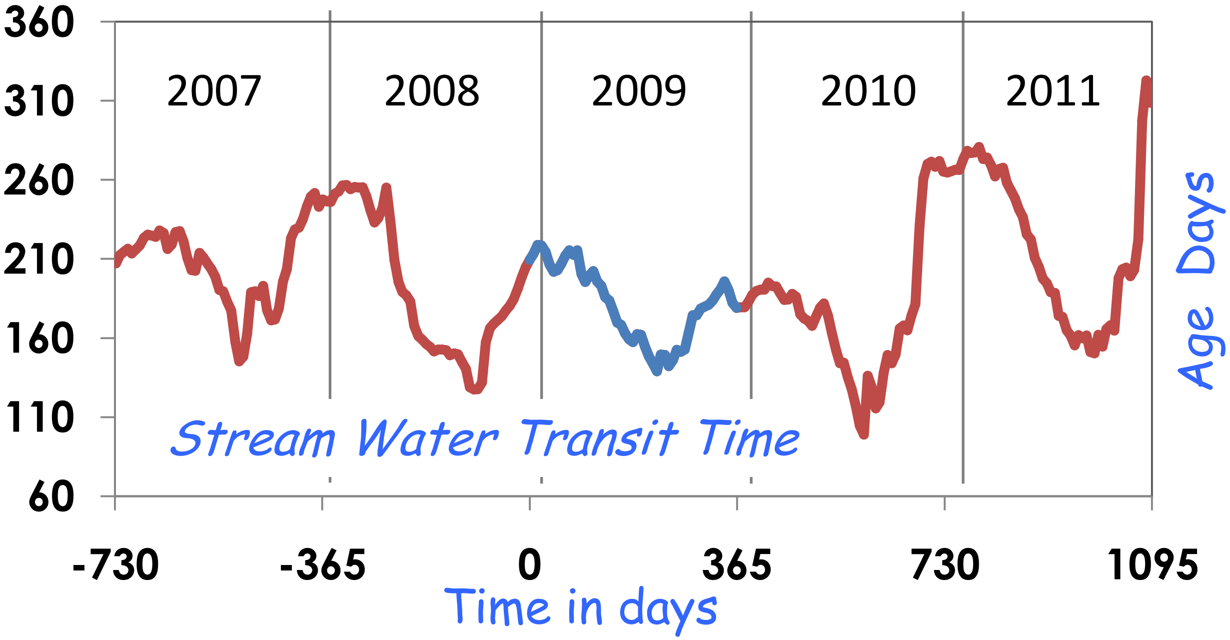


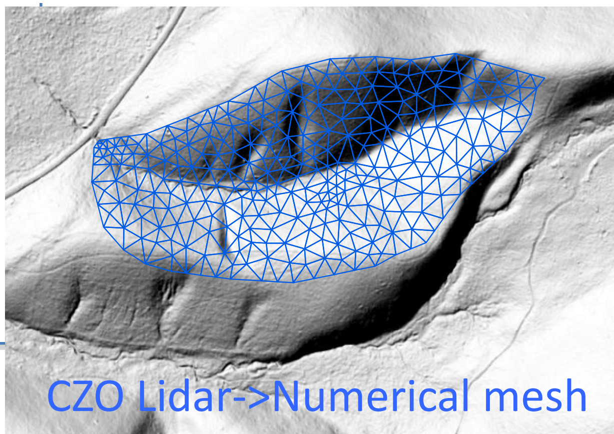
Jul-Sep '09

Seasonal Pattern of Groundwater Age---→

Oct-Dec '09







CZO Lidar->Numerical mesh

Duffy, 2010, Hydrologic Processes; G. Bhatt, PhD Oct 2012

Next Steps

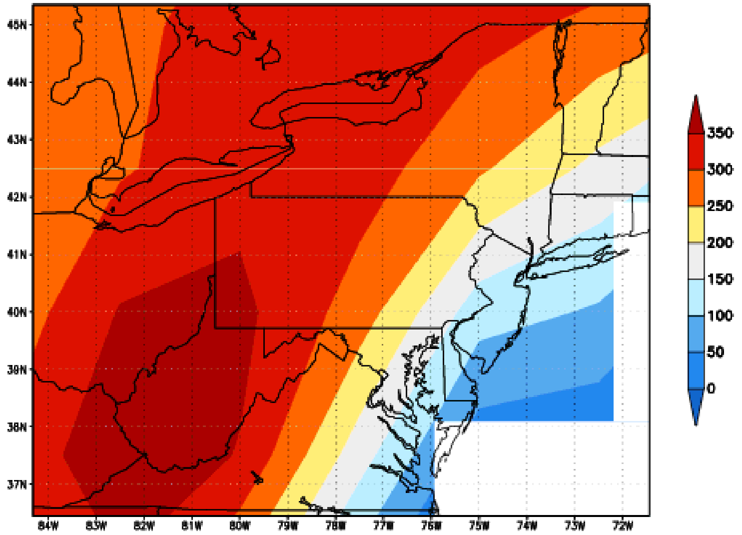
IsoRSM experiment over Chesapeake Bay Watershed

Kei Yoshimura
University of Tokyo, Japan

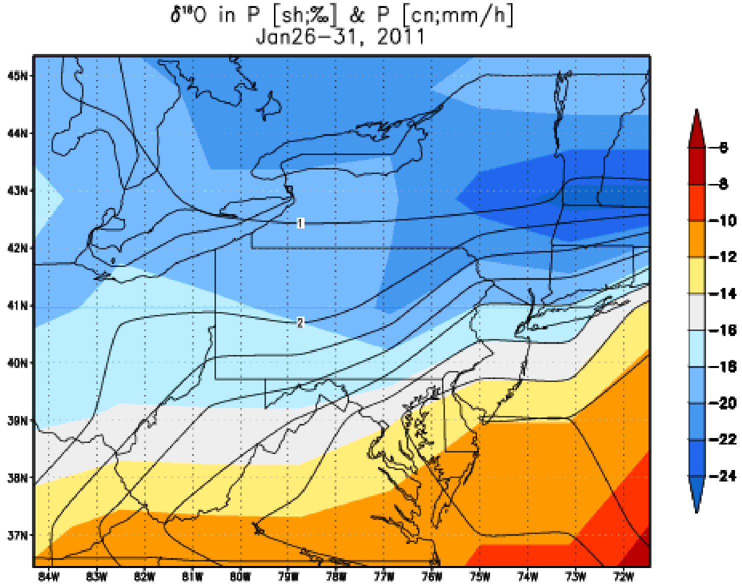
Specification

- IsoRSM (Yoshimura et al., 2010) simulation covering 85.5W-71.3W/35.5N-46.2N by 10km.
- 2007/1/1-2012/1/1
- Boundary Conditions: IsoGSM simulation based on NCEP2 Reanalysis.

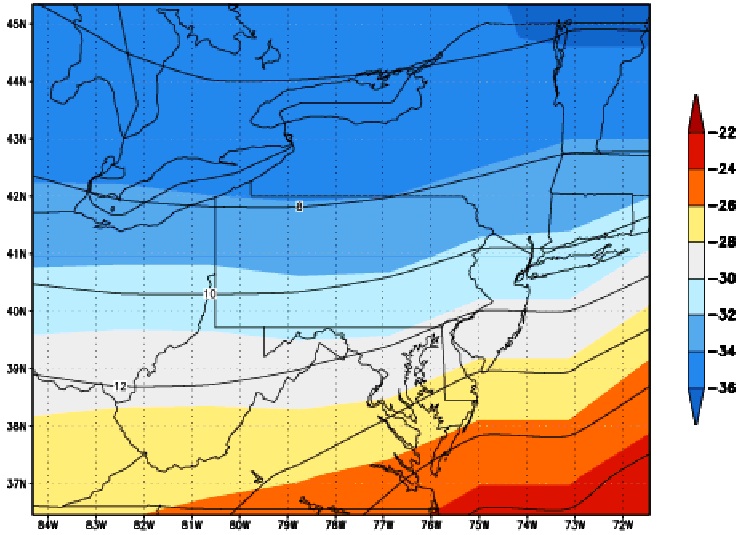
Global(100km res.)



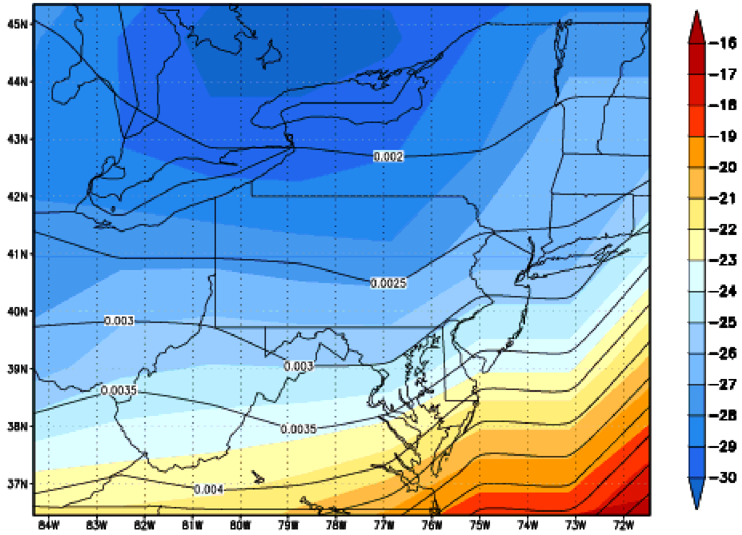
HGTSFC[m]



δ¹⁸O in P [sh;‰] & P [cn;mm/h]
Jan26–31, 2011



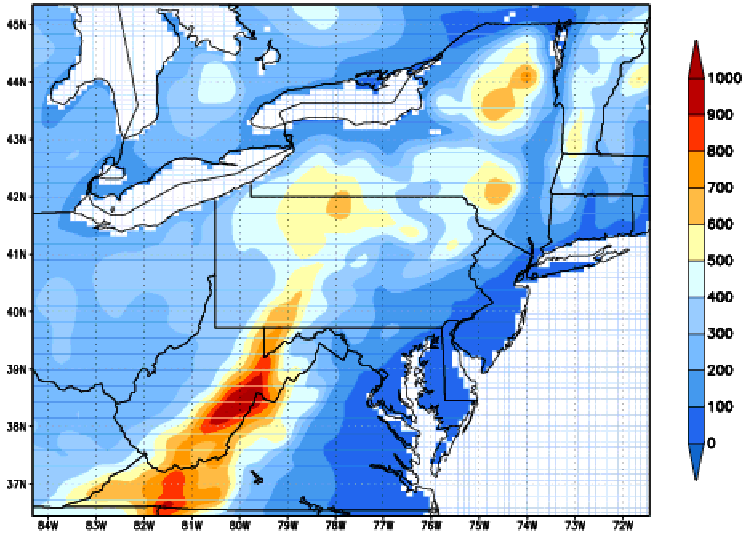
δ¹⁸O in TPW [sh;‰] & TPW [cn;mm]
Jan26–31, 2011



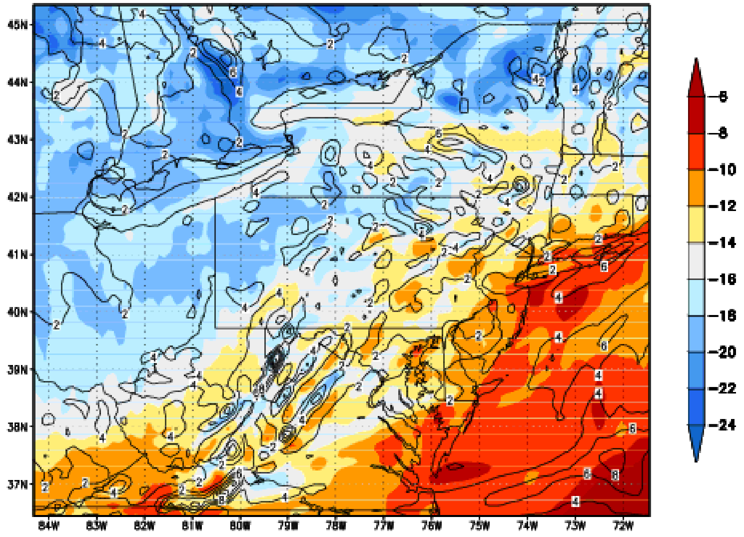
δ¹⁸O at 2m [sh;‰] & SH [cn;kg/kg]
Jan26–31, 2011

Regional 10 km res.

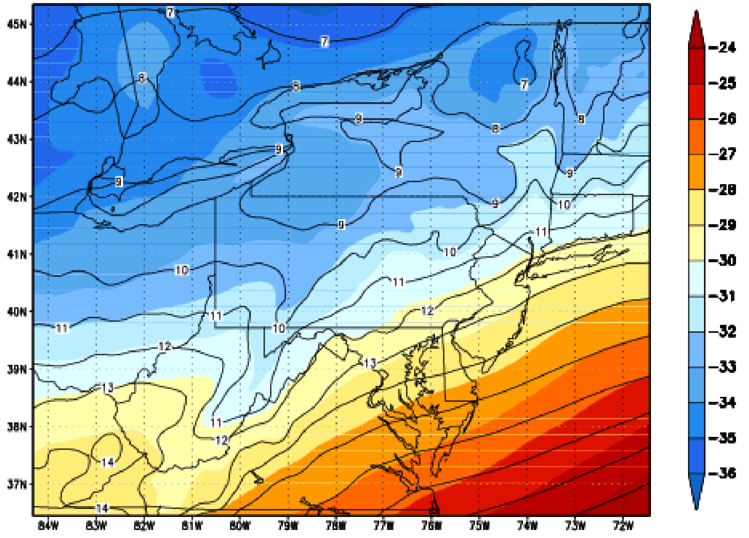
HGTSFC[m]



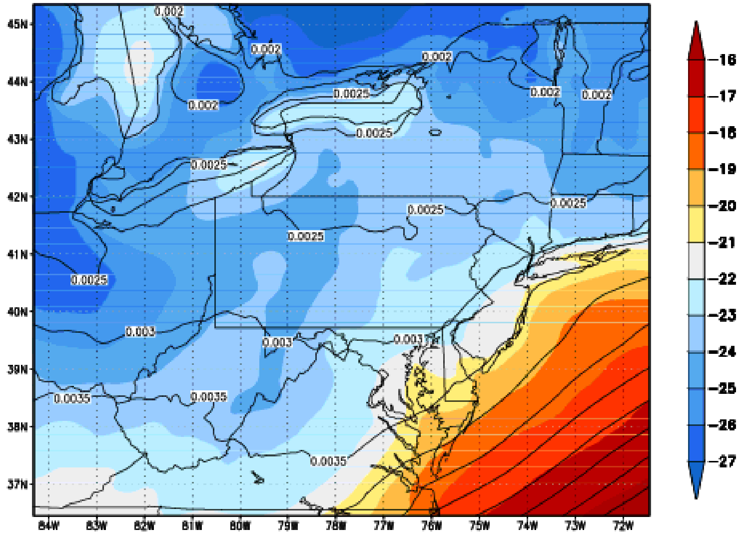
δ18O in P [sh;‰] & P [cn;mm/h]
Jan16–21, 2011



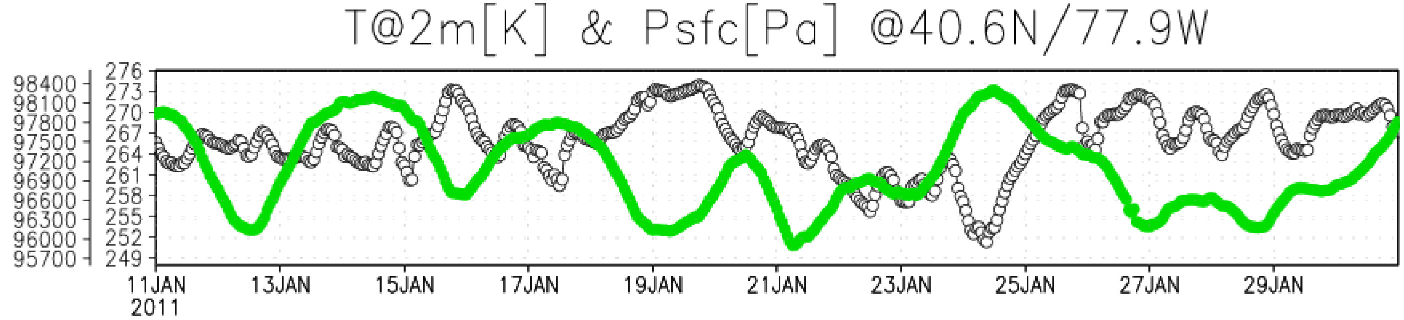
δ18O in TPW [sh;‰] & TPW [cn;mm]
Jan16–21, 2011

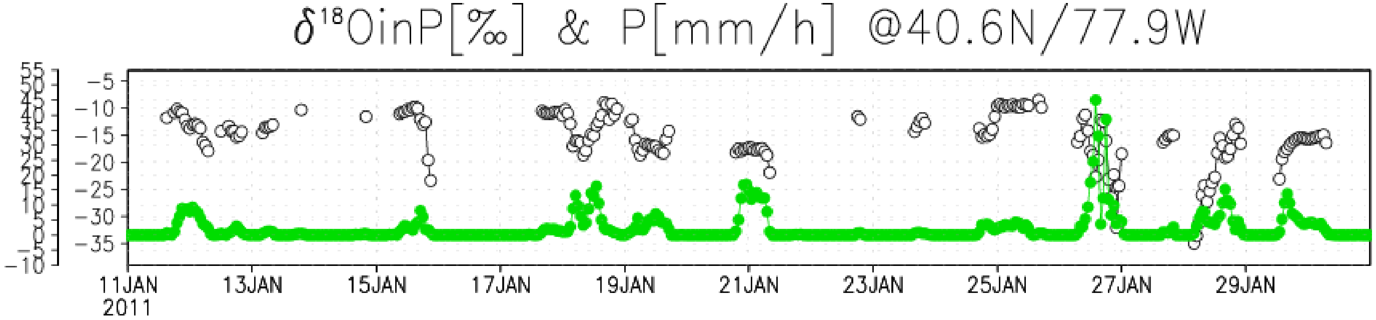


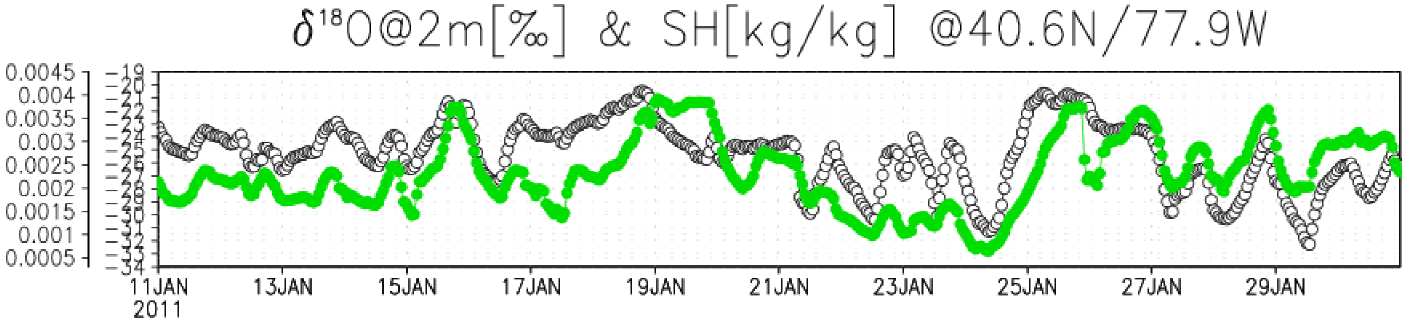
δ18O at 2m [sh;‰] & SH [cn;kg/kg]
Jan16–21, 2011



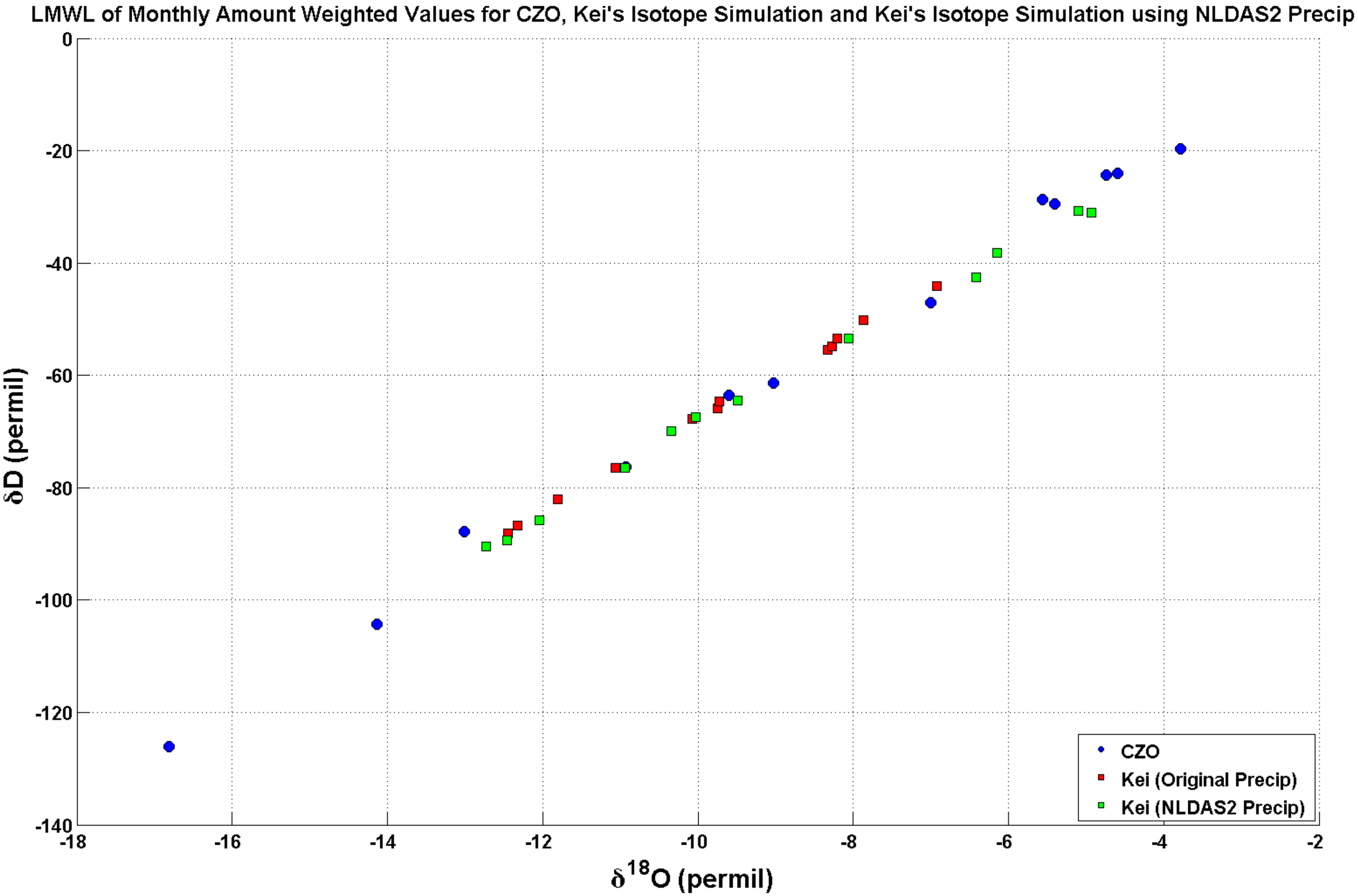
Regional


T@2m[K] & Psfc[Pa] @40.6N/77.9W

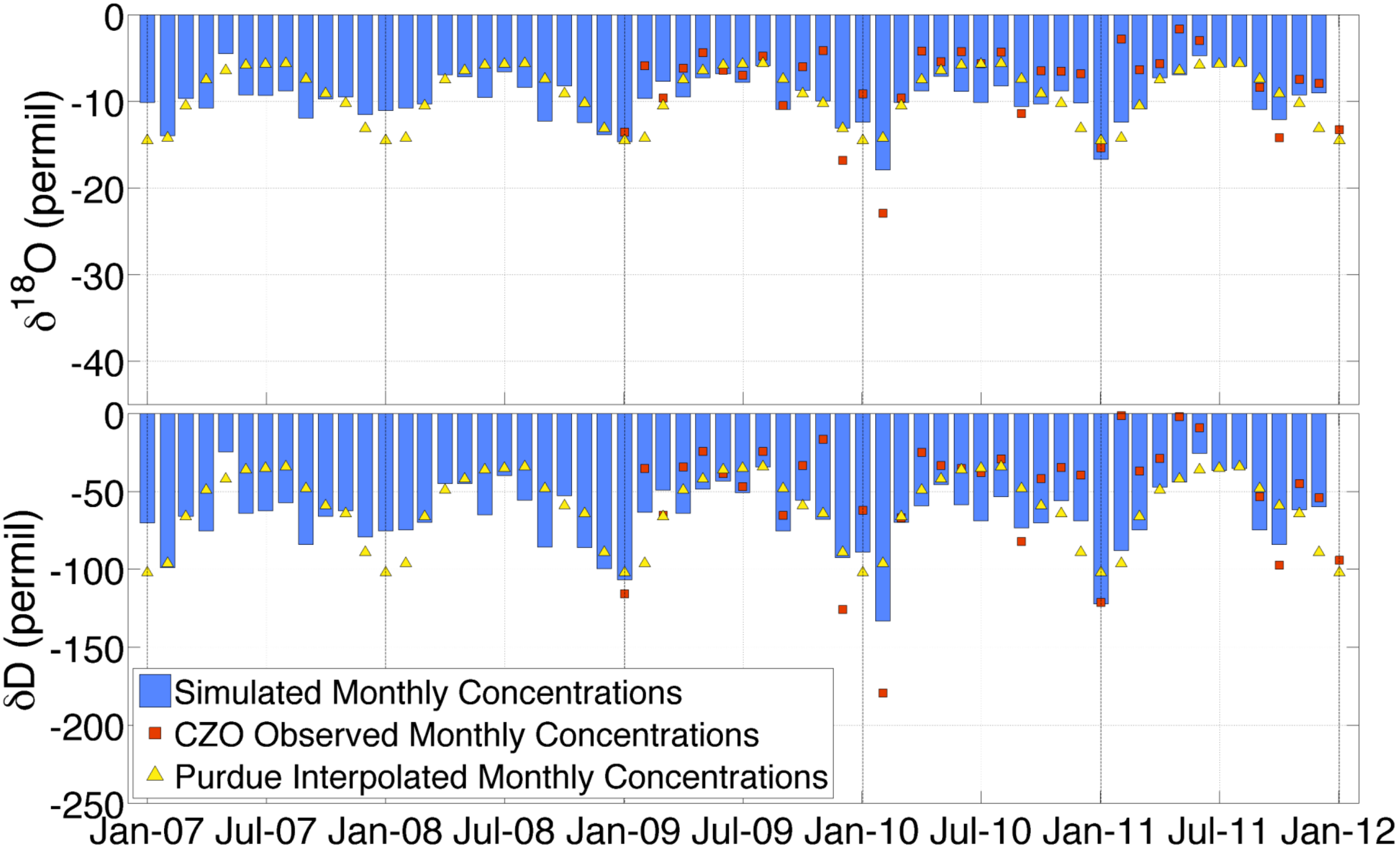

δ^{18}OinP[‰] & P[mm/h] @40.6N/77.9W


δ^{18}O@2m[‰] & SH[kg/kg] @40.6N/77.9W

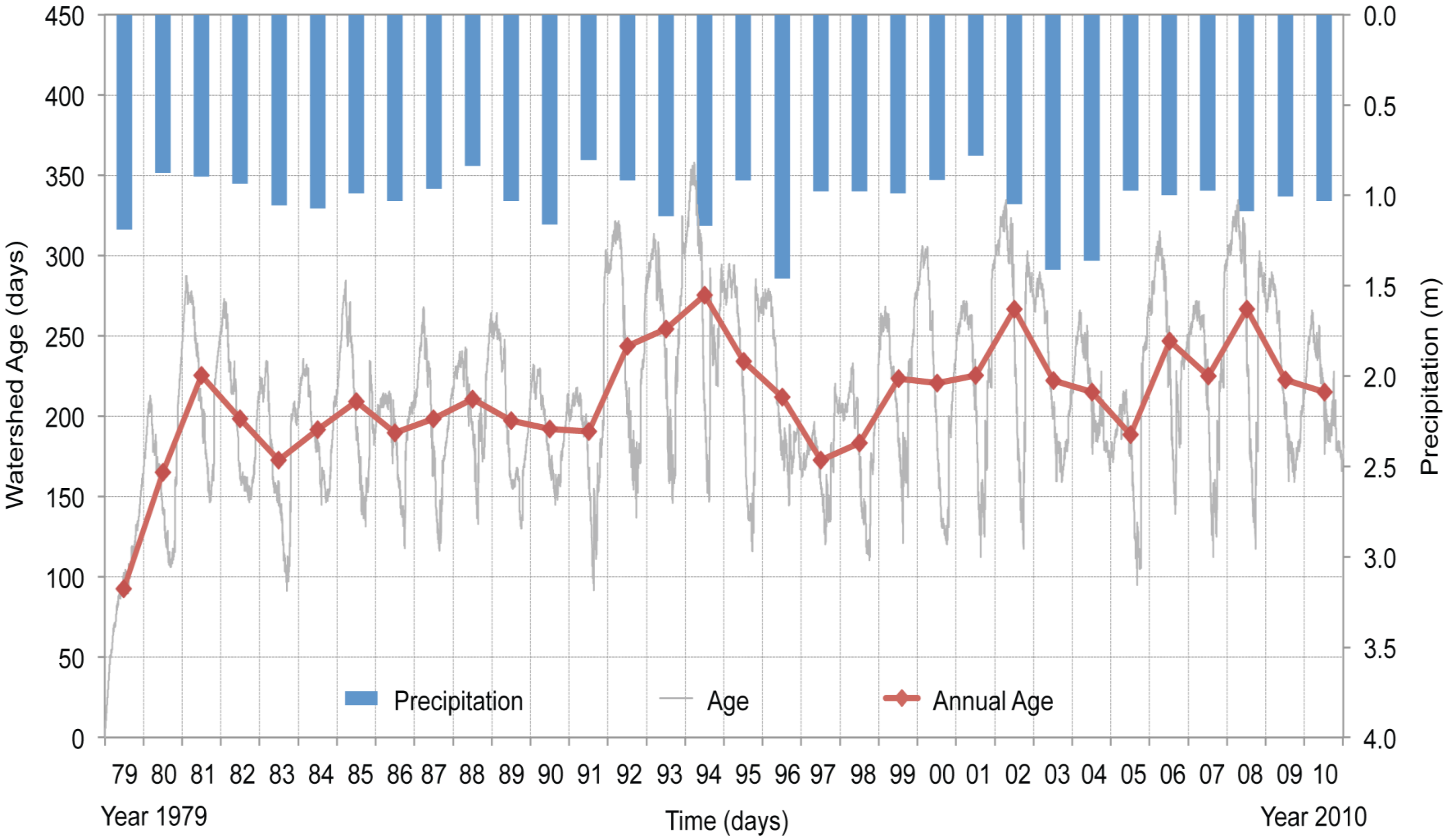
Simulated and Observed LMWL



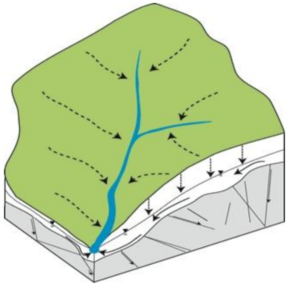
Simulated and Observed Seasonal Isotopic Response



Simulated Transit Time for 32 Year Reanalysis



Isotopic Age/Transit Time of Watershed Storage/Runoff



Interpretation of "age" of waters is complicated since it depends on the transport, flow dynamics, chemical species, reaction kinetics

Steady flow is often assumed since the age distribution of water is difficult to evaluate from field data

This research shows how the "mean age" and "transit time" of tracers or solutes can be predicted.

An experiment conducted at the NSF-funded Shale Hills Critical Zone Observatory is testing the approach.

Scaling Up: Climate researchers have developed the capability to simulate stable isotopes in precipitation at 10 km resolution with major implications for catchment research and water management.