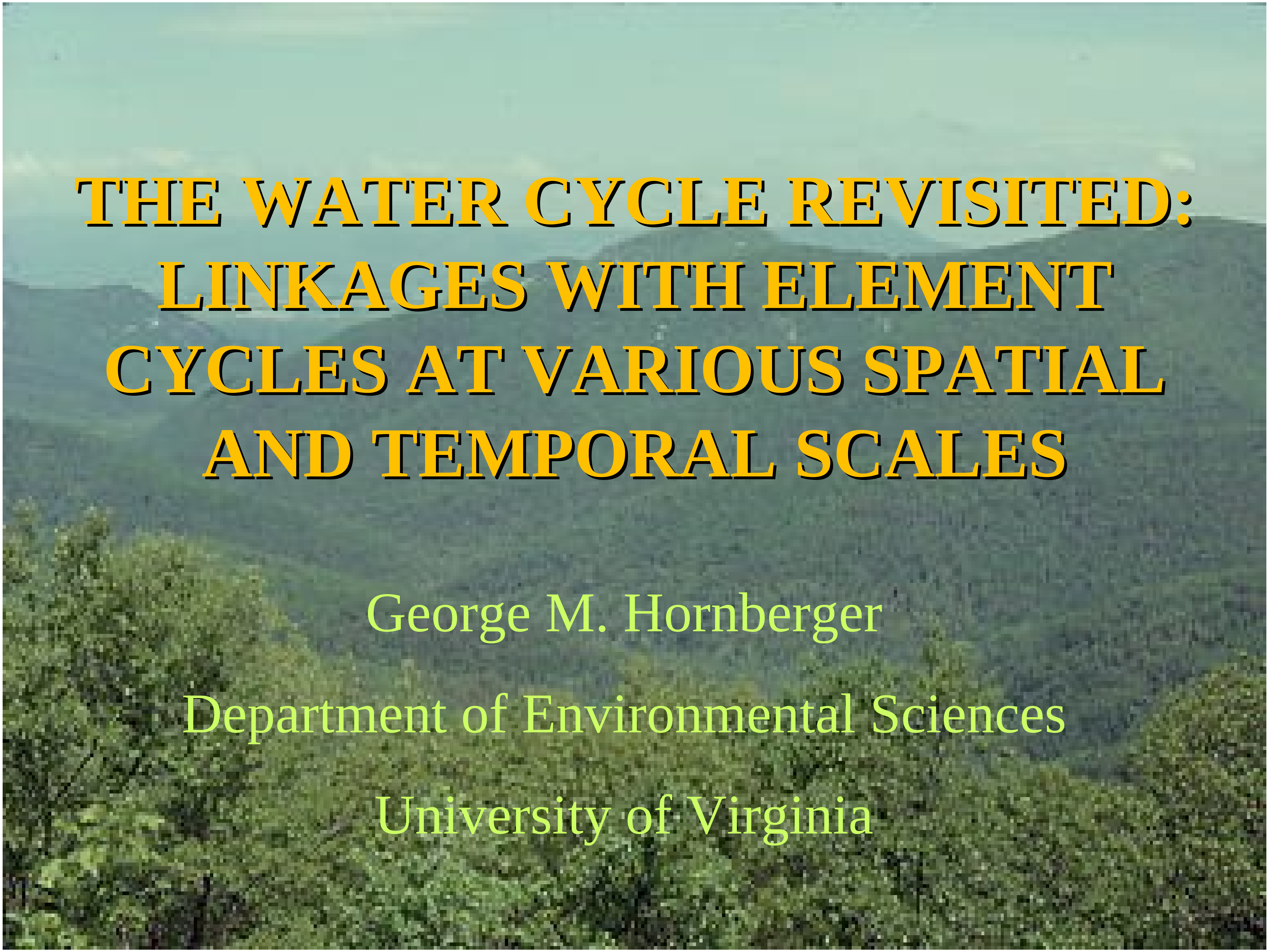


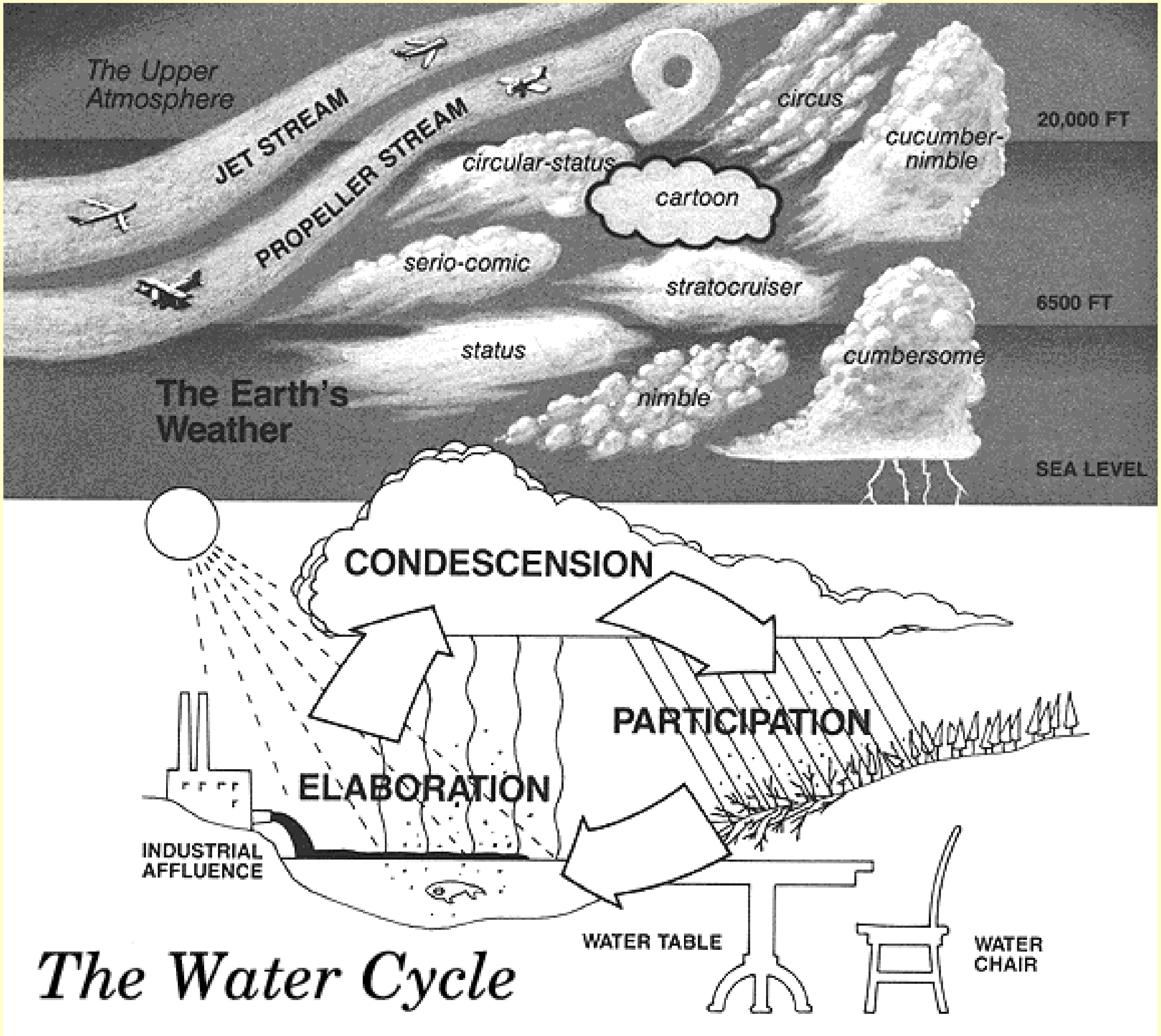
# THE WATER CYCLE REVISITED: LINKAGES WITH ELEMENT CYCLES AT VARIOUS SPATIAL AND TEMPORAL SCALES

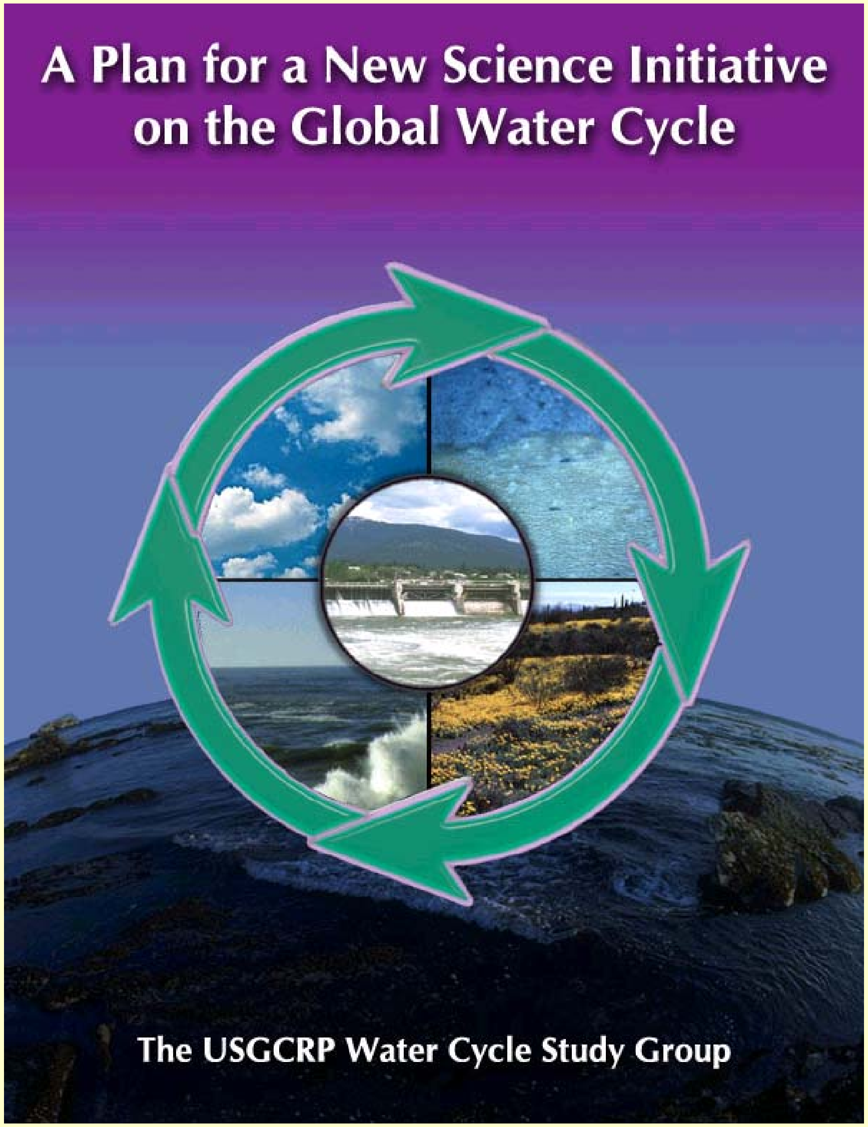
George M. Hornberger

Department of Environmental Sciences

University of Virginia

# What's to revisit?






# USGCRP Water Cycle Science Plan

Hornberger et al. 2001

(3rd Science Question)

**How will variability and changes in the cycling of water though terrestrial and freshwater ecosystems be linked to variability and changes in the cycling of carbon, nitrogen and other nutrients at regional and global scales?**

Water-cycle web site:

http://www.usgcrp.gov/usgcrp/ProgramElements/water.htm/

"One of the principal conclusions to come from the American Geophysical Union Chapman Conference on *Hydrogeochemical Responses of Forested Catchments* convened in the Fall of 1989 was that integrated watershed research, indeed, is hampered by a lack of a structured and efficient means of communication of results among studies. ……… Something that would be a great aid to watershed researchers would be the development of a taxonomic scheme for watersheds based upon not just catchment characteristics (e.g. aspect or percentage of conifer coverage), but also on catchment hydrochemical function."

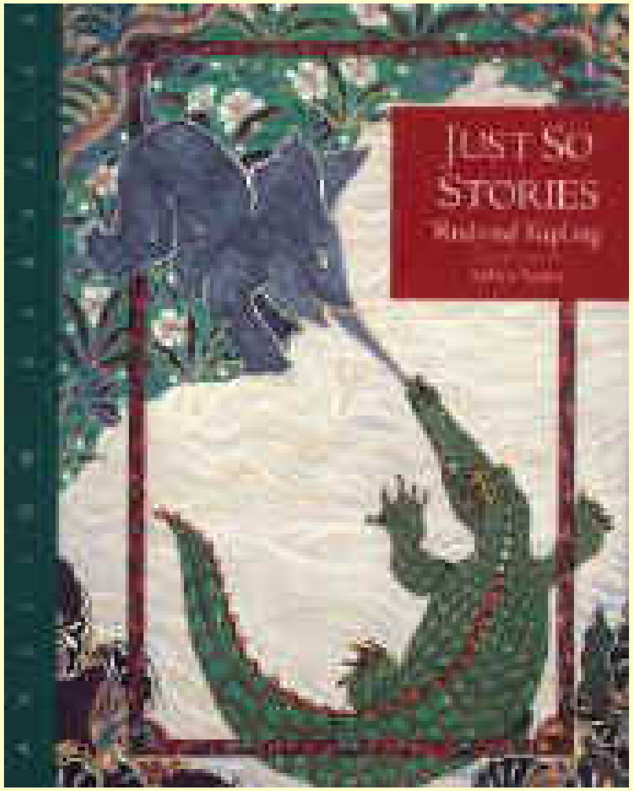
Church MR 1997. Hydrochemistry of forested catchments. ***Annual Review of Earth and Planetary Sciences 25***: 23-59.

Rudyard Kipling, “Just So Stories”

•How the leopard got its spots

•How the rhinoceros got its skin

•The elephant’s child

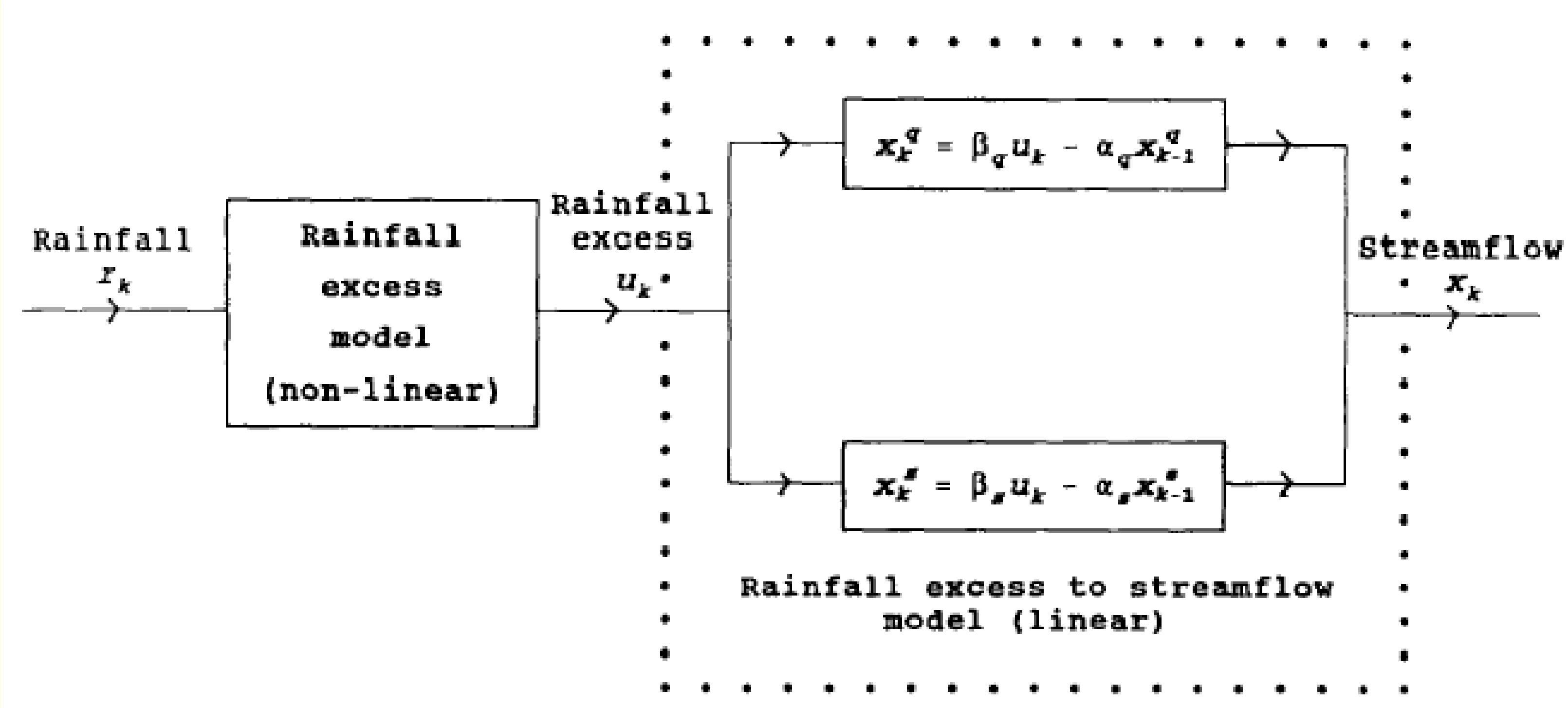


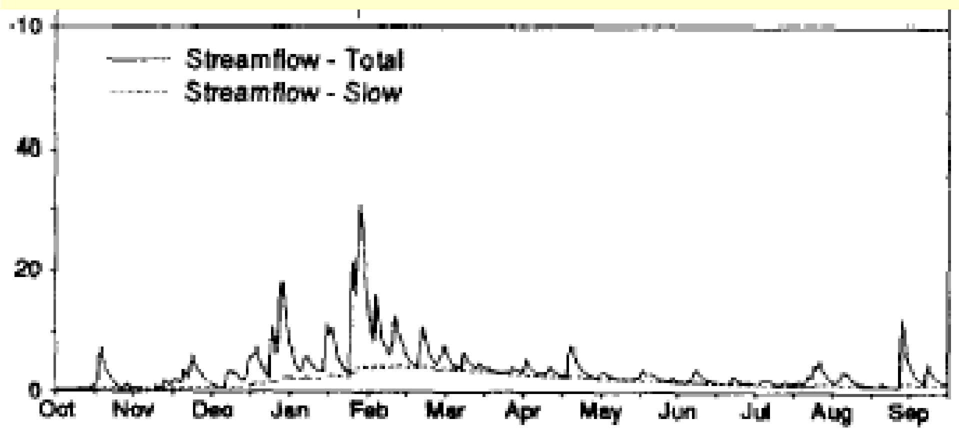

*“Then the Elephant's Child put his head down close to the Crocodile's musky, tusky mouth, and the Crocodile caught him by his little nose, which up to that very week, day, hour, and minute, had been no bigger than a boot, though much more useful. ……. and he pulled, and pulled, and pulled, and at each pull the Elephant's Child's nose grew longer and longer …..”*

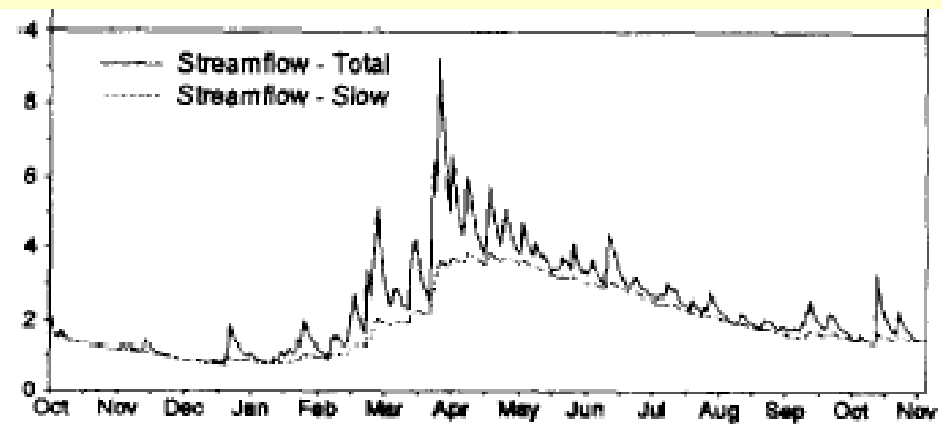
# Small Watershed Investigations in the U.S. Geological Survey

"The challenge for the coming decade will be for small watershed investigations to improve understanding of the effect of human influences on natural systems and to provide information for the restoration of damaged watersheds."

Hirsch, RM, 1998, Small Watershed Investigations in the U.S. Geological Survey, [abs] ***EOS, Transactions American Geophysical Union, vol. 79:*** S124




Jakeman, AJ and GM Hornberger 1993. How much complexity is needed in a rainfall-runoff model? ***Water Resources Research 29***:2637-2649.

Jakeman AJ, Hornberger GM, Littlewood IG, et al. 1992. A Systematic-Approach to Modeling the Dynamic Linkage of Climate, Physical Catchment Descriptors and Hydrologic Response Components. ***Mathematics and Computers in Simulation 33***: 359-366.

Post DA and Jakeman AJ 1996. Relationships between catchment attributes and hydrological response characteristics in small Australian mountain ash catchments. ***Hydrological Processes 10***: 877-892.

Sefton CEM and Howarth SM, 1998. Relationships between dynamic response characteristics and physical descriptors of catchments in England and Wales. ***Journal of Hydrology 211***: 1-16.

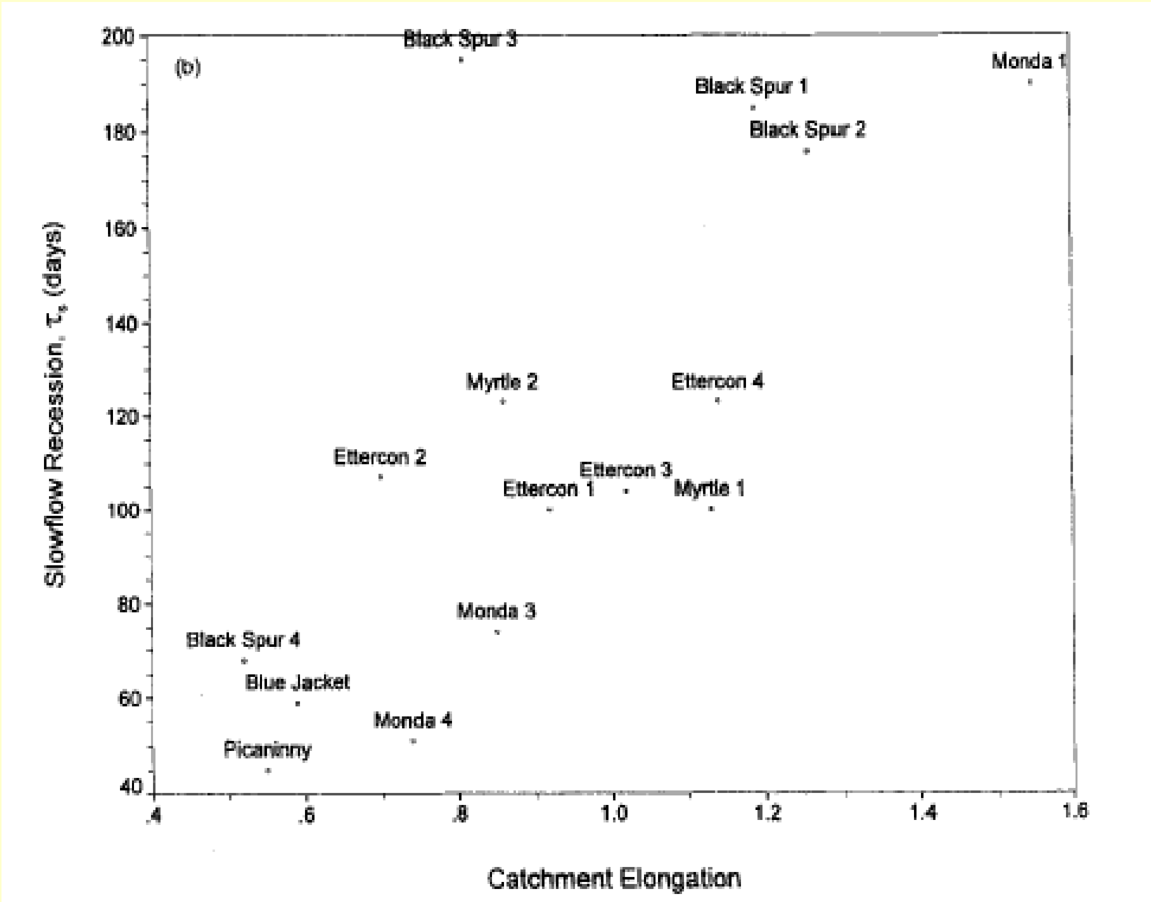
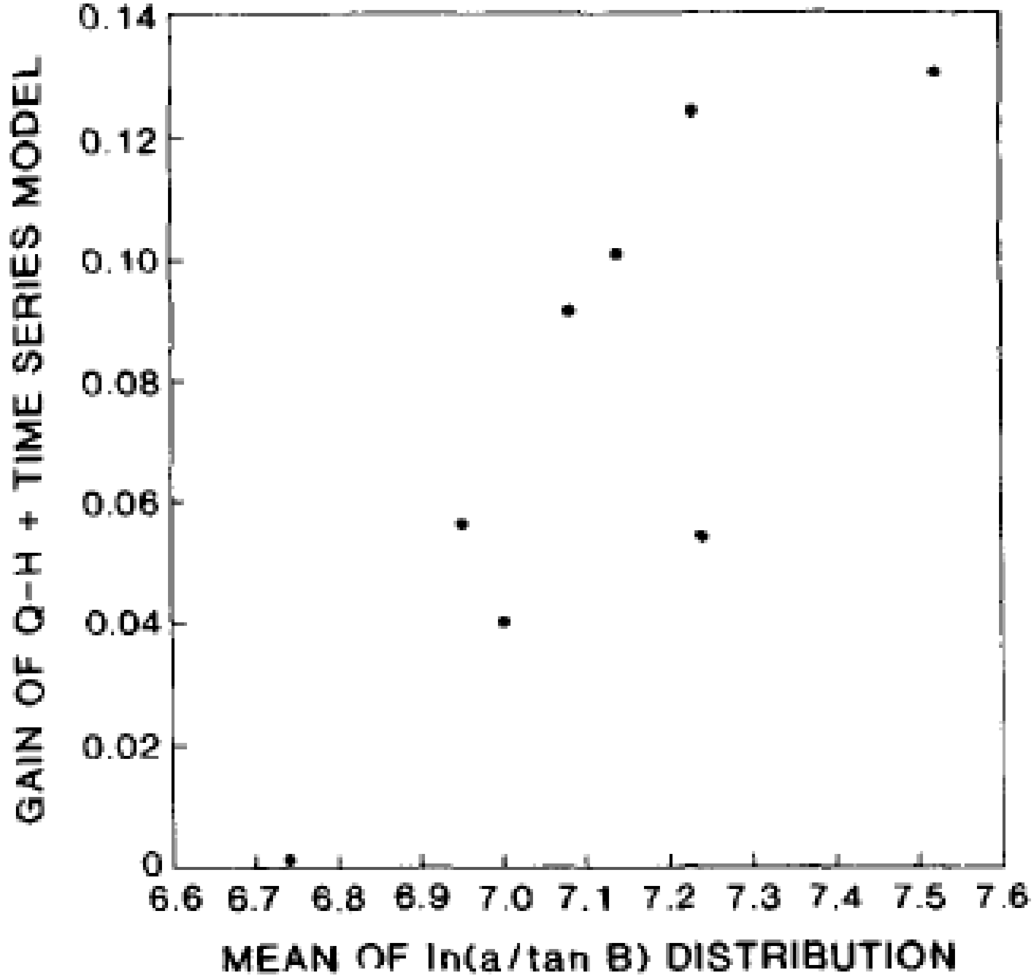


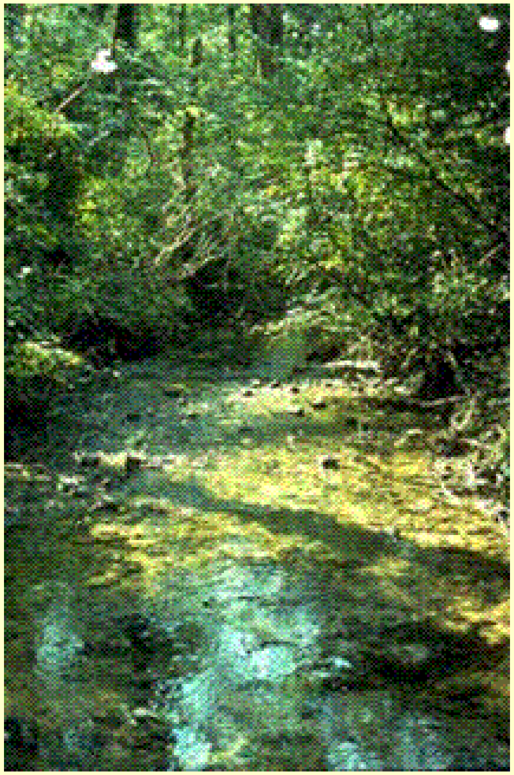

Figure from Post & Jakeman, 1996.



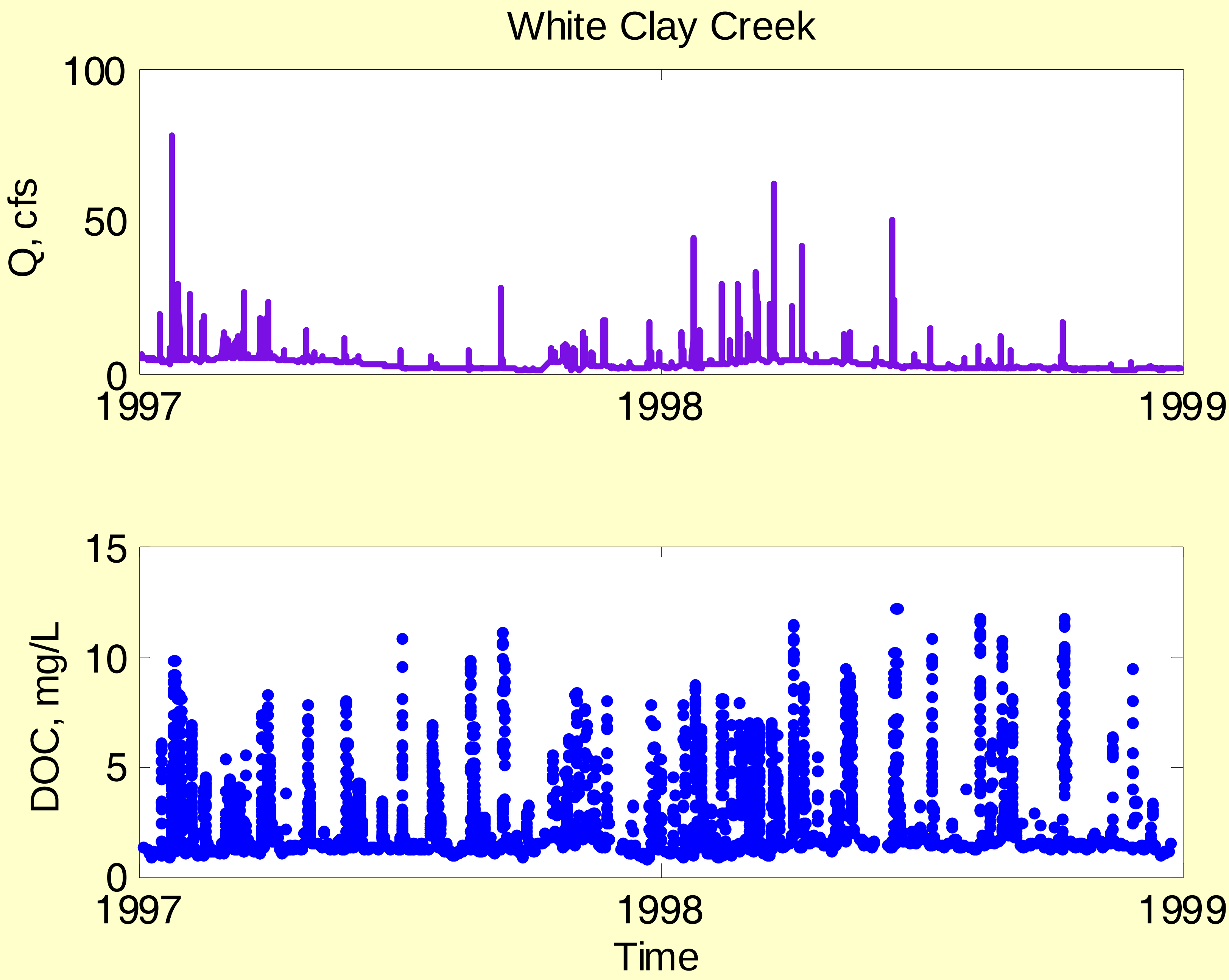

pH changes with discharge in Llyn Brianne catchments in Wales.

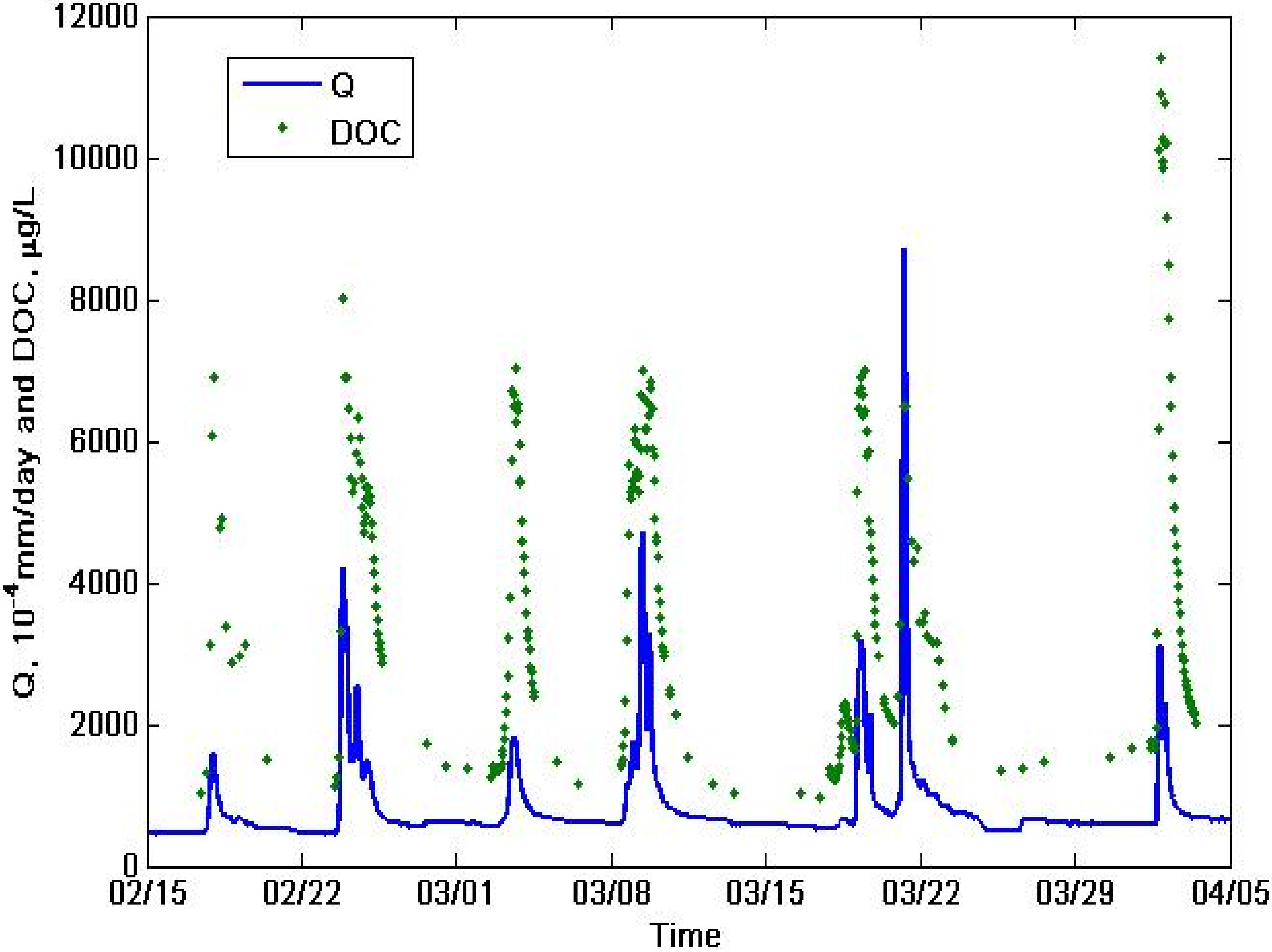
$$(1+a_1 z)H_t^+ = b_0 Q_t + e;\ \text{Gain} = b_0/(1+a_1)$$

Wolock, DM, Hornberger GM and T Musgrove 1990. Topographic controls on episodic streamwater acidification in Wales. ***J.Hydrology 115***:243-259.

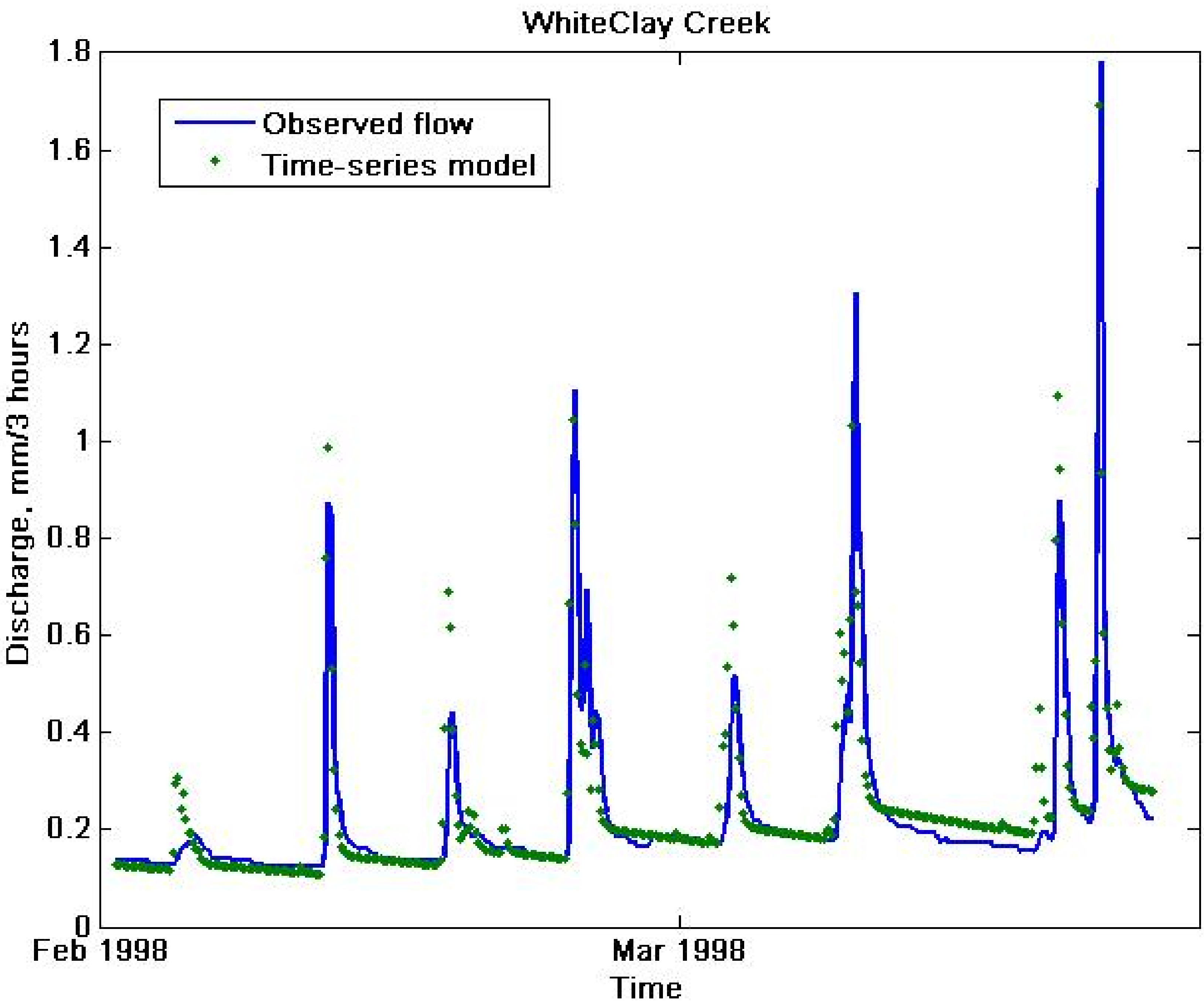



Lou Kaplan, Denis Newbold, and colleagues have been studying a 725-ha piedmont catchment in the headwaters of the East Branch White Clay Creek, SE Pennsylvania U.S.A for many years. Land use consists of deciduous woodlands, meadows, pastures and arable agriculture.

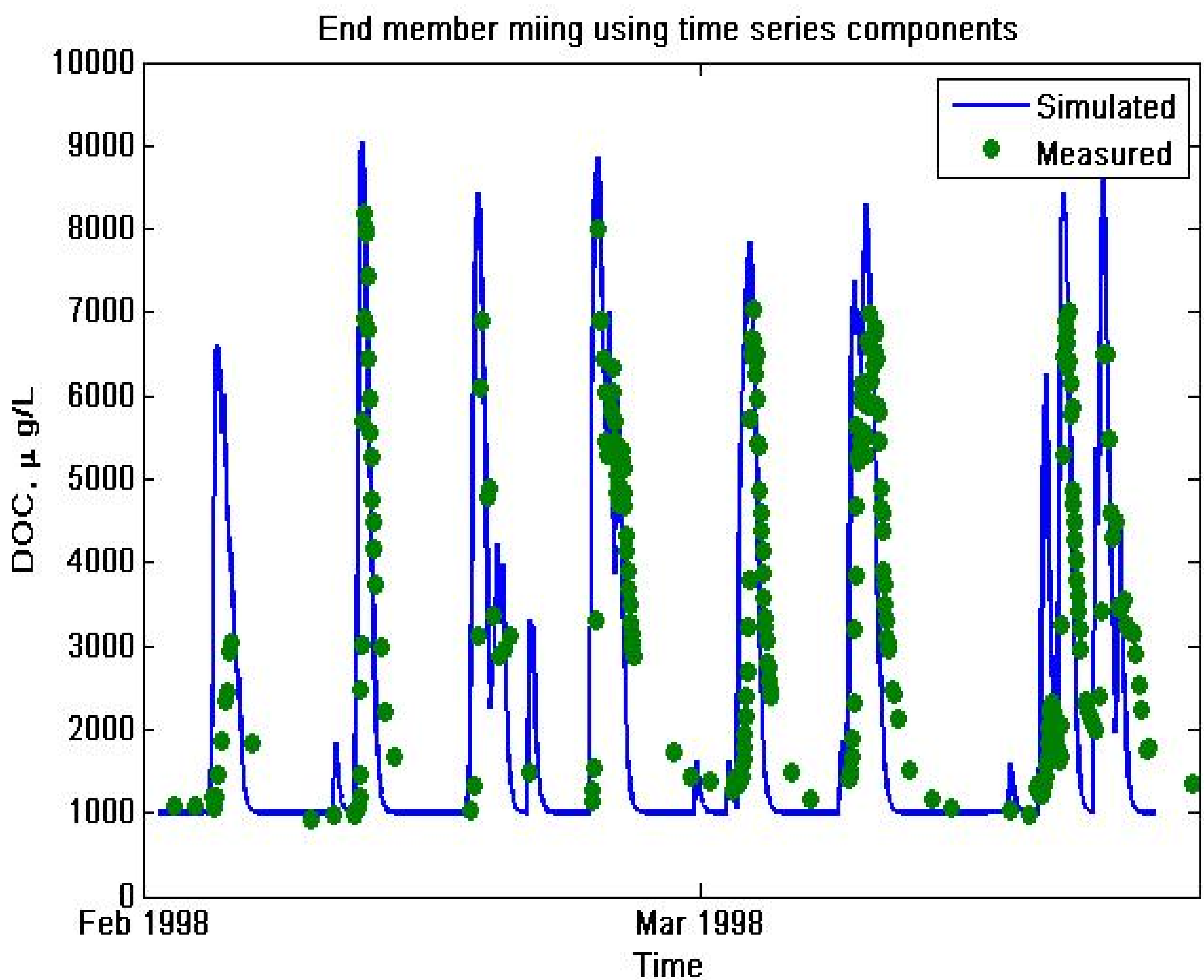

White Clay Creek
Q, cfs
100
50
0
1997
1998
1999
DOC, mg/L
15
10
5
0
1997
1998
1999
Time



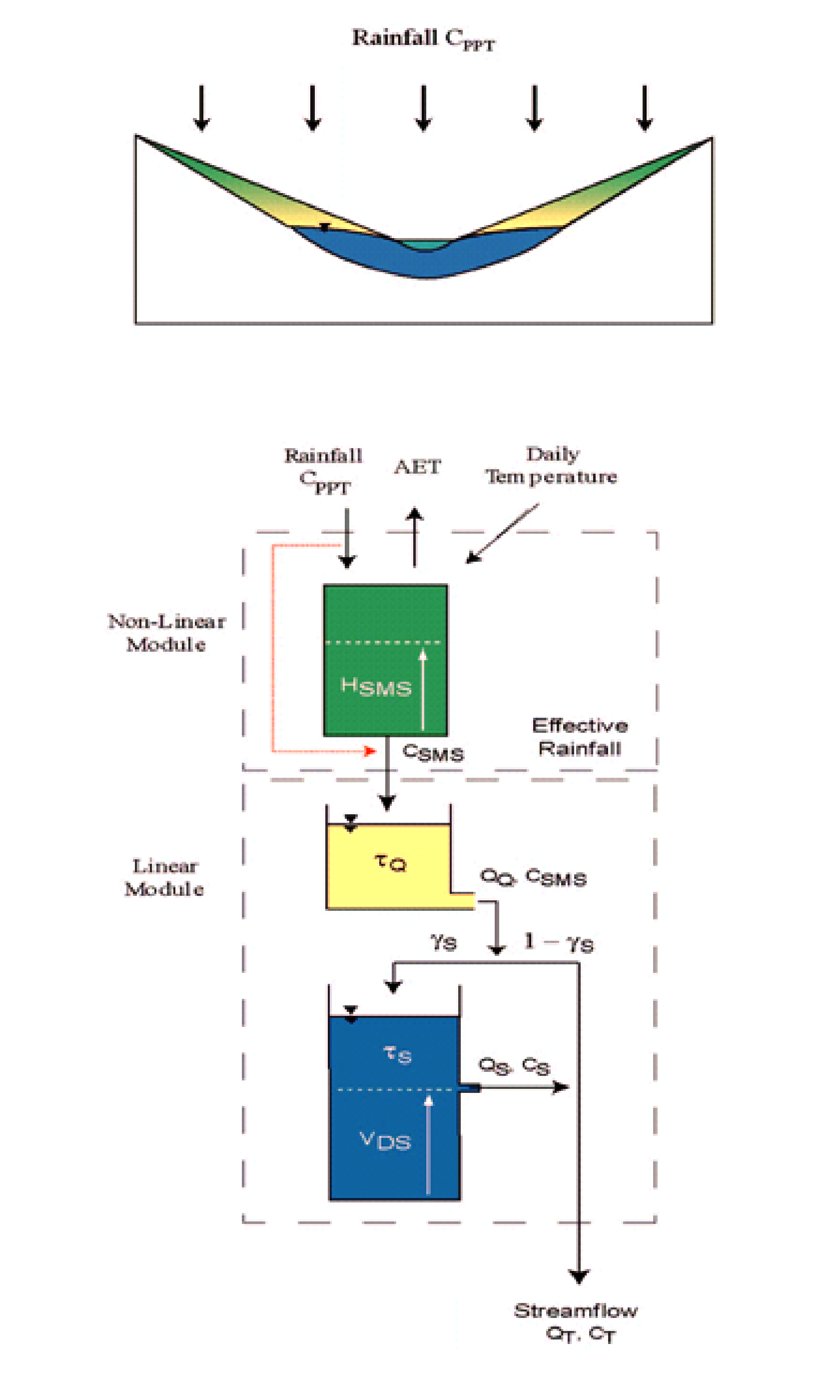
Q
DOC
Q, 10^-4 mm/day and DOC, µg/L
0
2000
4000
6000
8000
10000
12000
02/15
02/22
03/01
03/08
03/15
03/22
03/29
04/05
Time



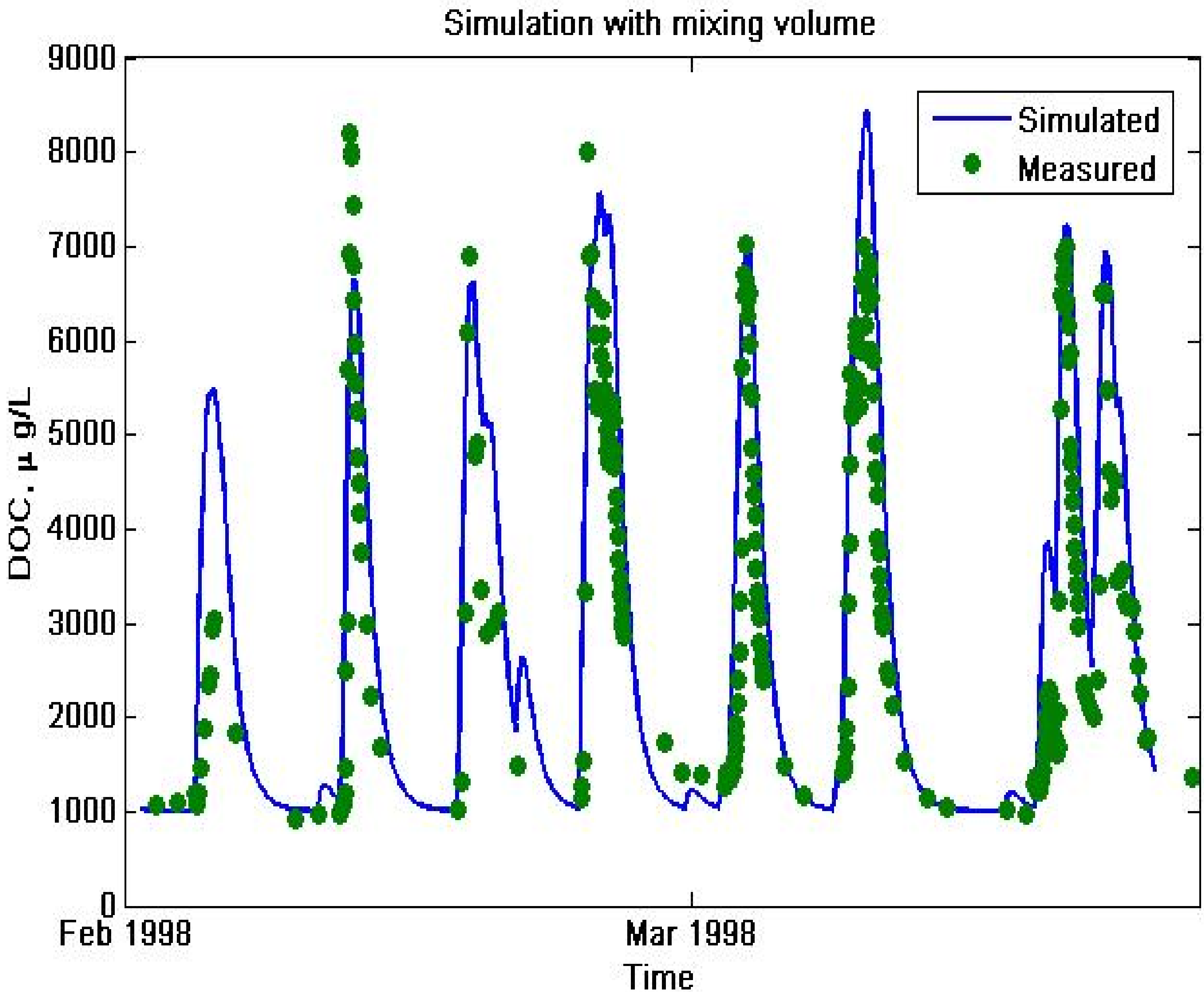
WhiteClay Creek
Observed flow
Time-series model
Discharge, mm/3 hours
Time
Feb 1998
Mar 1998
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8



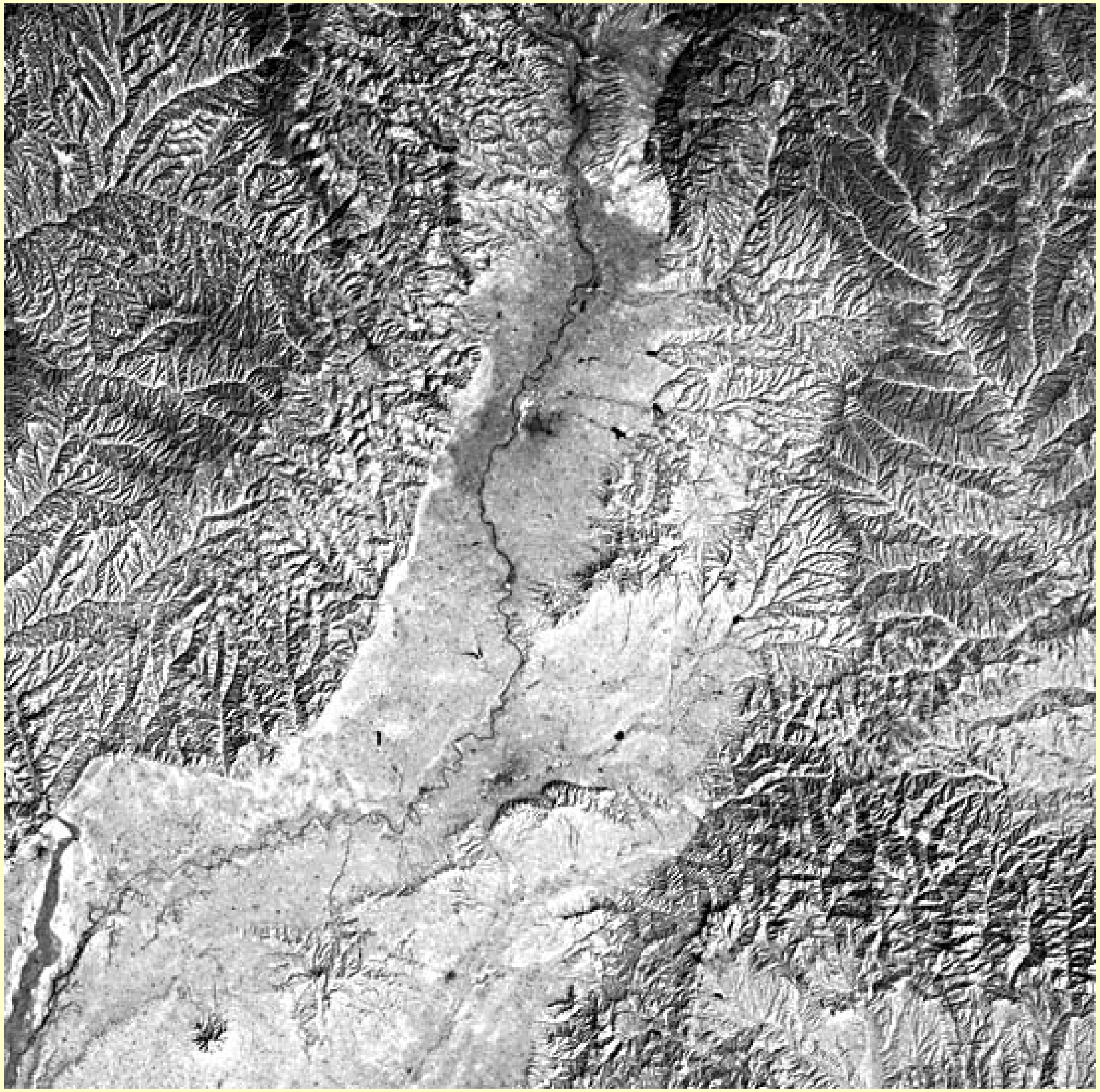
End member miing using time series components
Simulated
Measured
DOC , µ g/L
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Feb 1998
Mar 1998
Time




Conceptual model -- solute flux in terms of two cascading travel-time distributions. The first might represent sporadic downslope movement in the shallow subsurface; the second might represent continuous movement along deeper perennial flowpaths.


Simulation with mixing volume
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
DOC, µ g/L
Feb 1998
Mar 1998
Time
Simulated
Measured

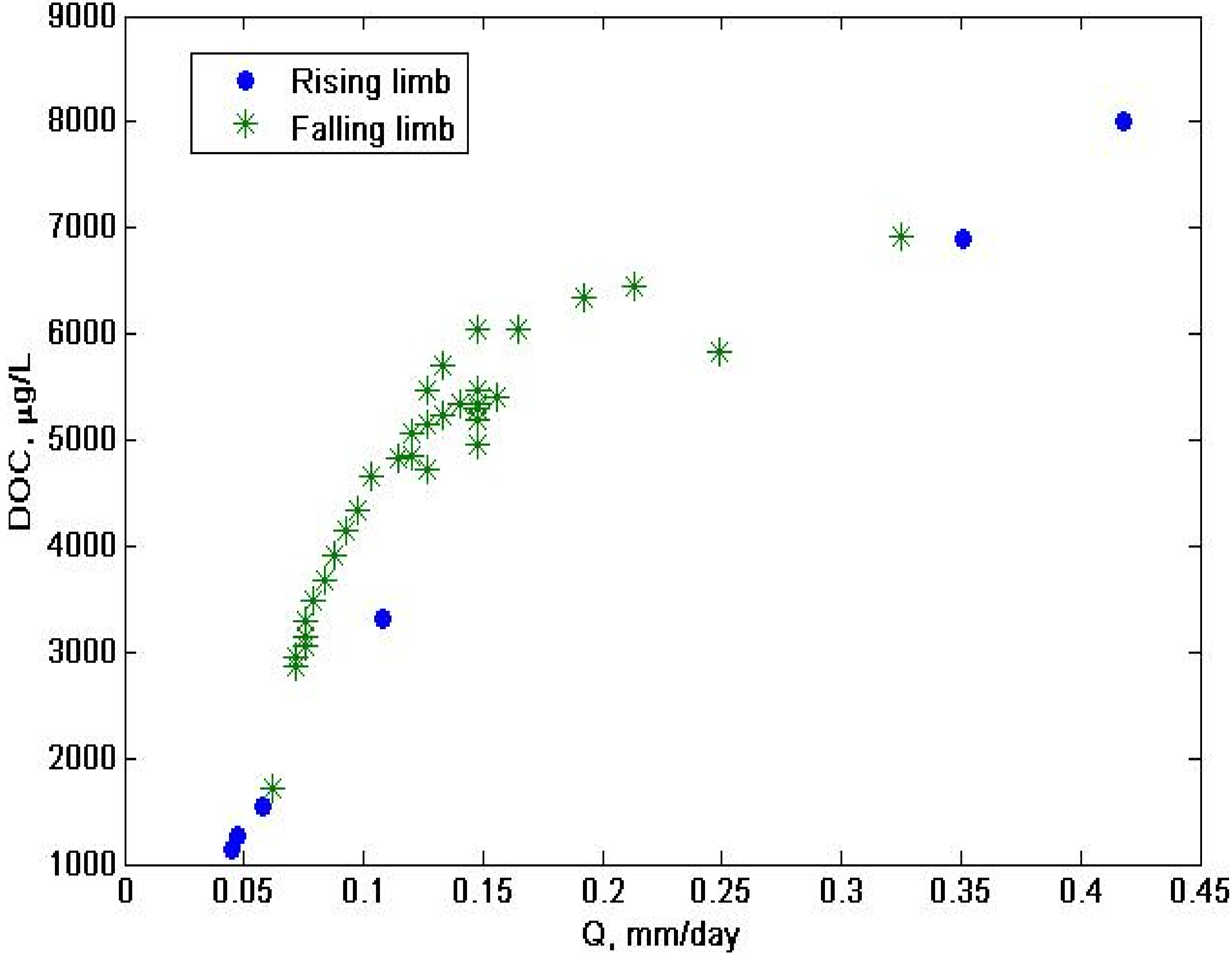
The Huang He, China.



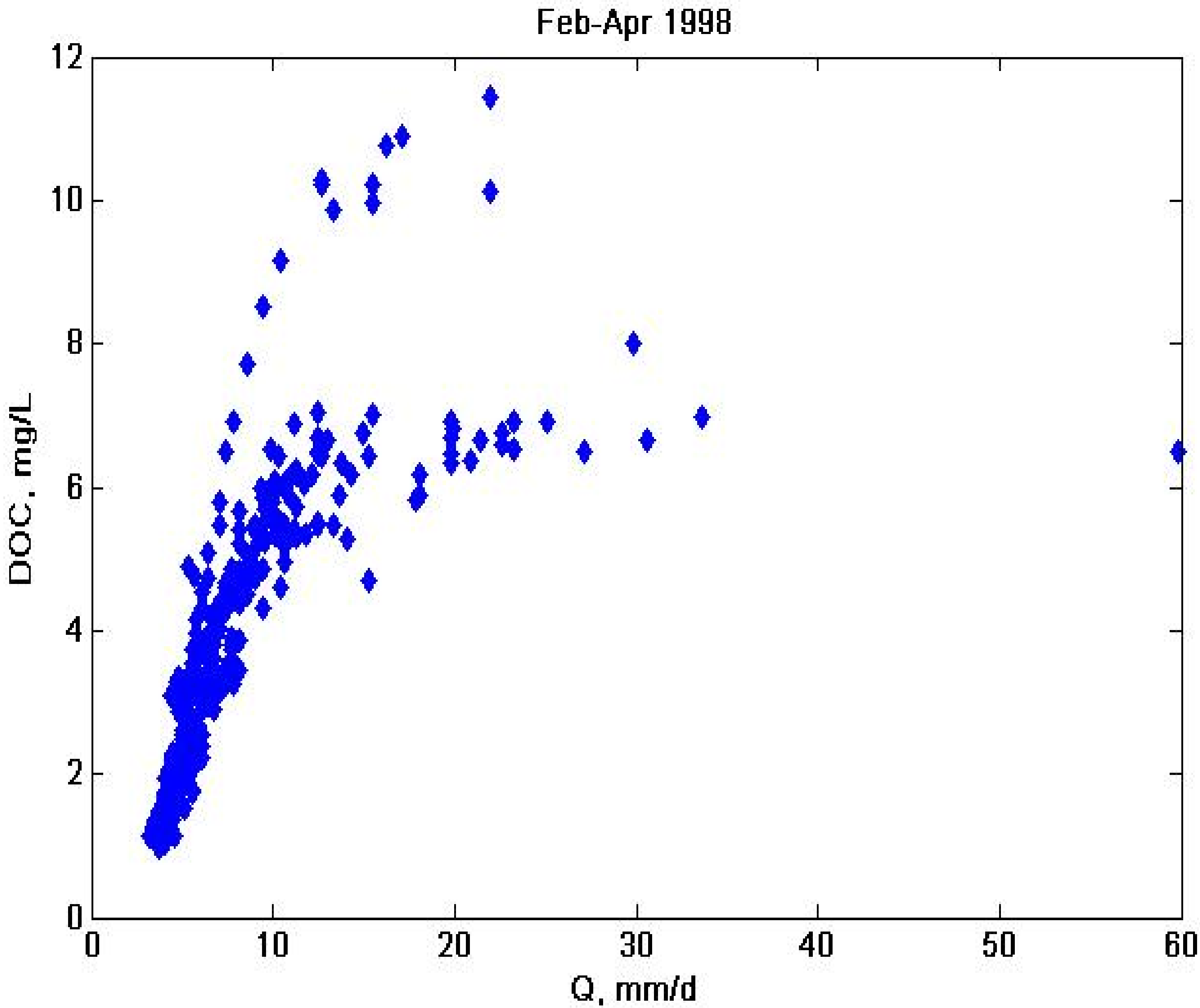
"While process-based hydrological research remains successful on a small scale, there is a critical need for synthesis studies of complex drainage basins on continental or global domains."

Int'l Hydrological Programme:

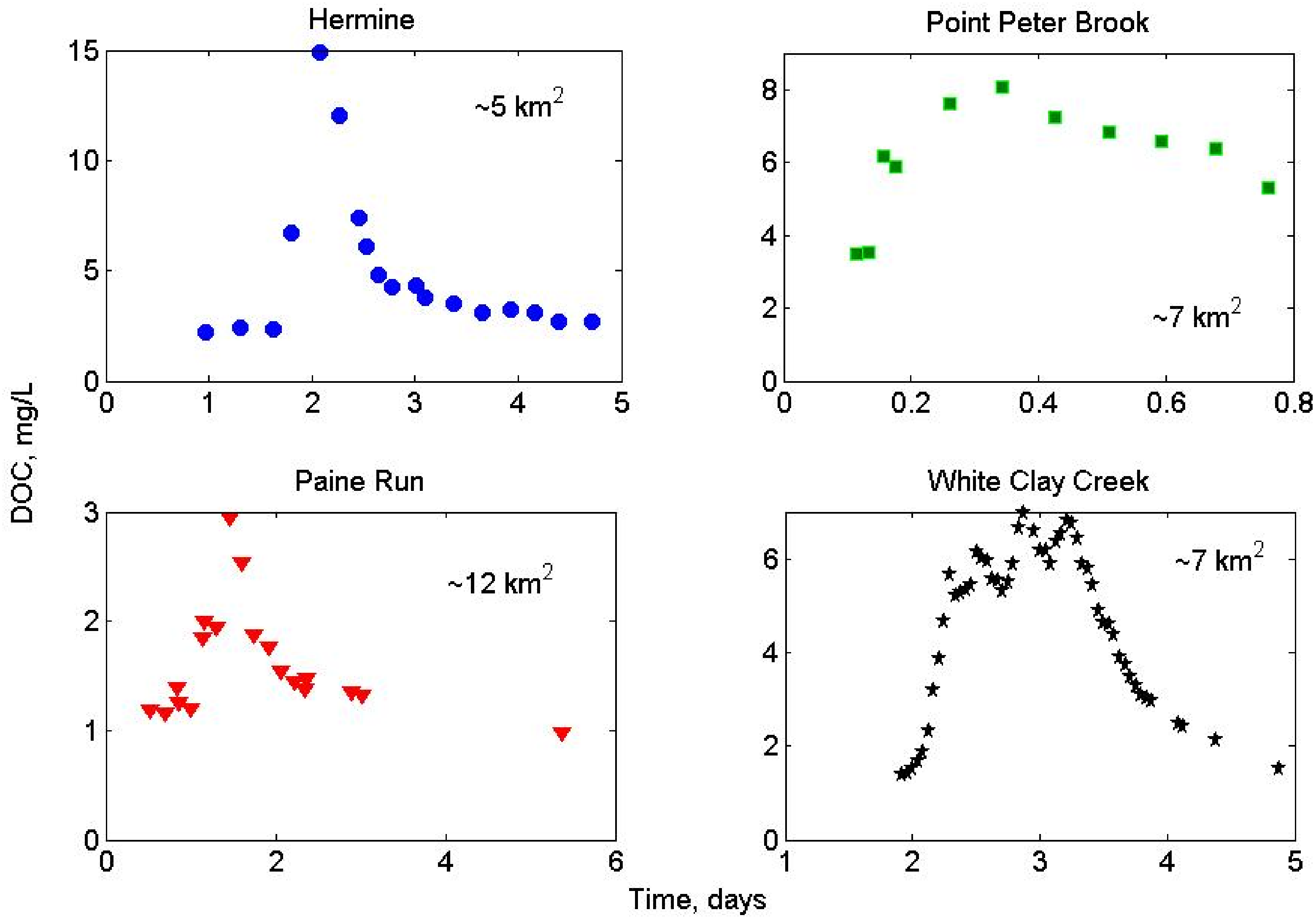
http://typo38.unesco.org/en/themes/global-changes-and-water-resources.html



Rising limb
Falling limb
DOC, µg/L
Q, mm/day
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45



Feb-Apr 1998
DOC, mg/L
Q, mm/d
0
2
4
6
8
10
12
0
10
20
30
40
50
60




Biron et al. 1999. *Hydrol. Process. 13*: 1541:1555 (Hermine)

Inamdar et al. 2006. *Hydrol. Process. 20*: 3423–3439 (Point Peter Brook)

Buffam et al. 2001. *Biogeochemistry 53***:** 269–306 (Paine Run

Simple scaling rule for catchment response time?

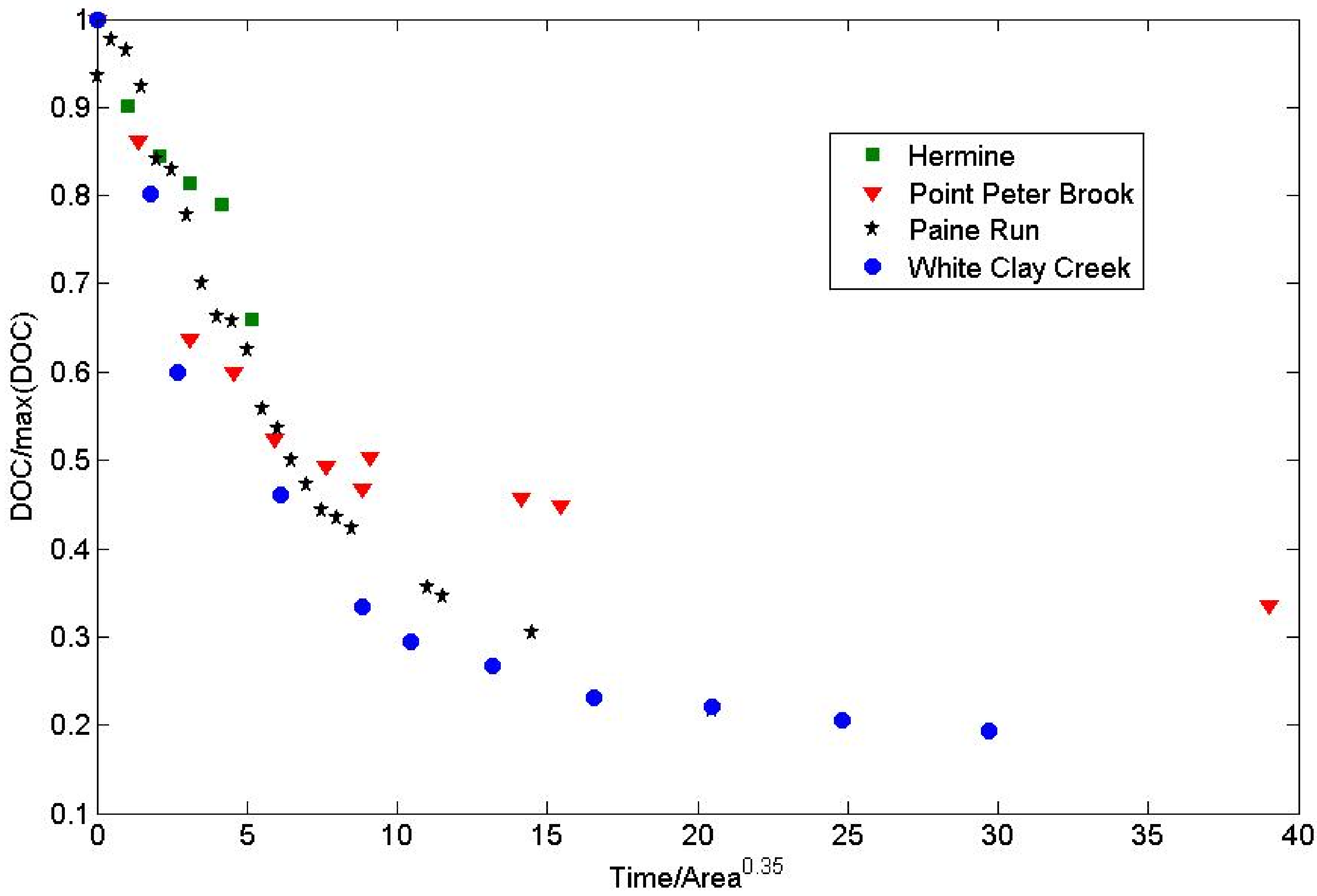
If so, might there be a relationship with solute fluxes?

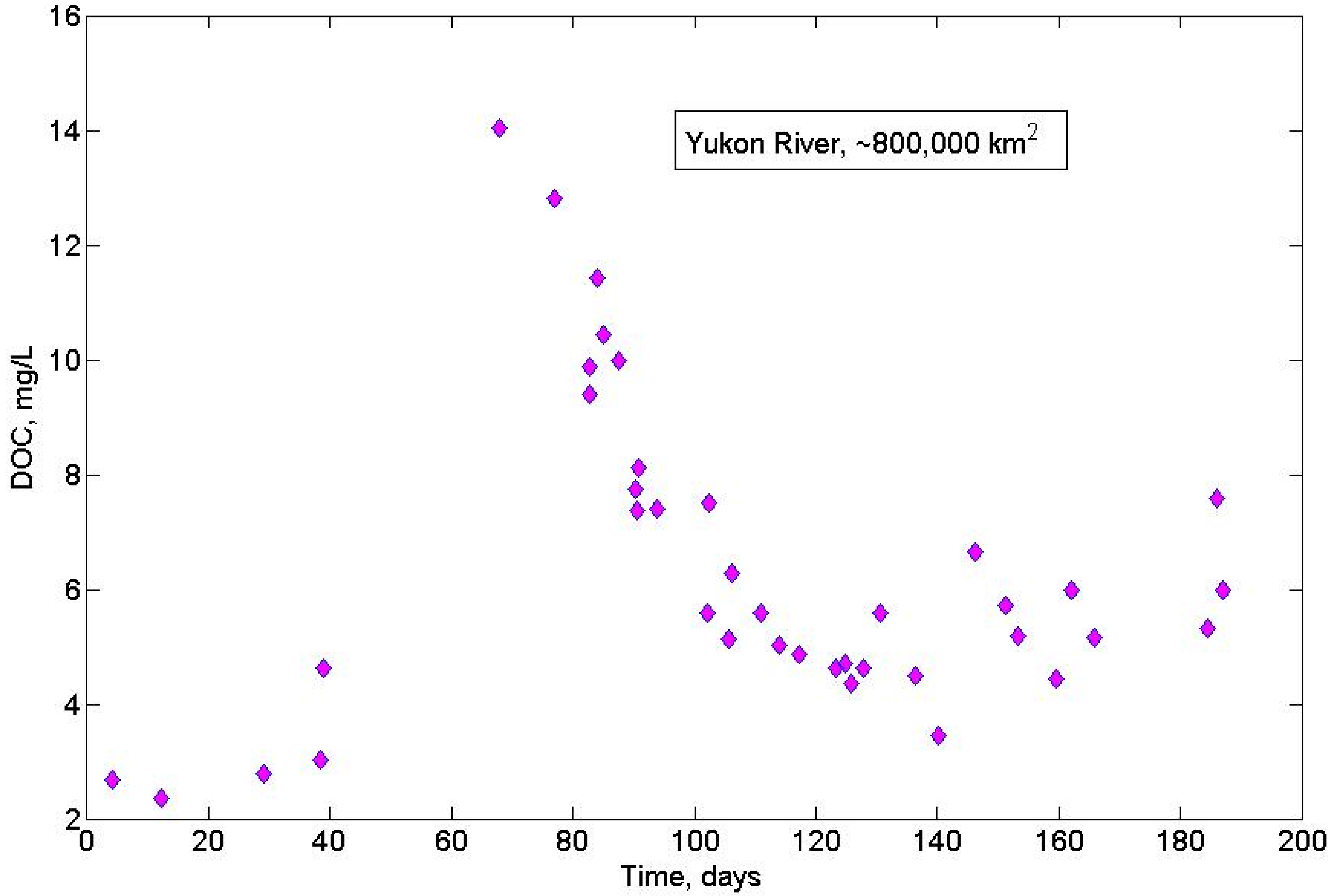
$$T \propto A^{\kappa}$$

$\kappa$ Is found to be between about 0.3 and 0.4.

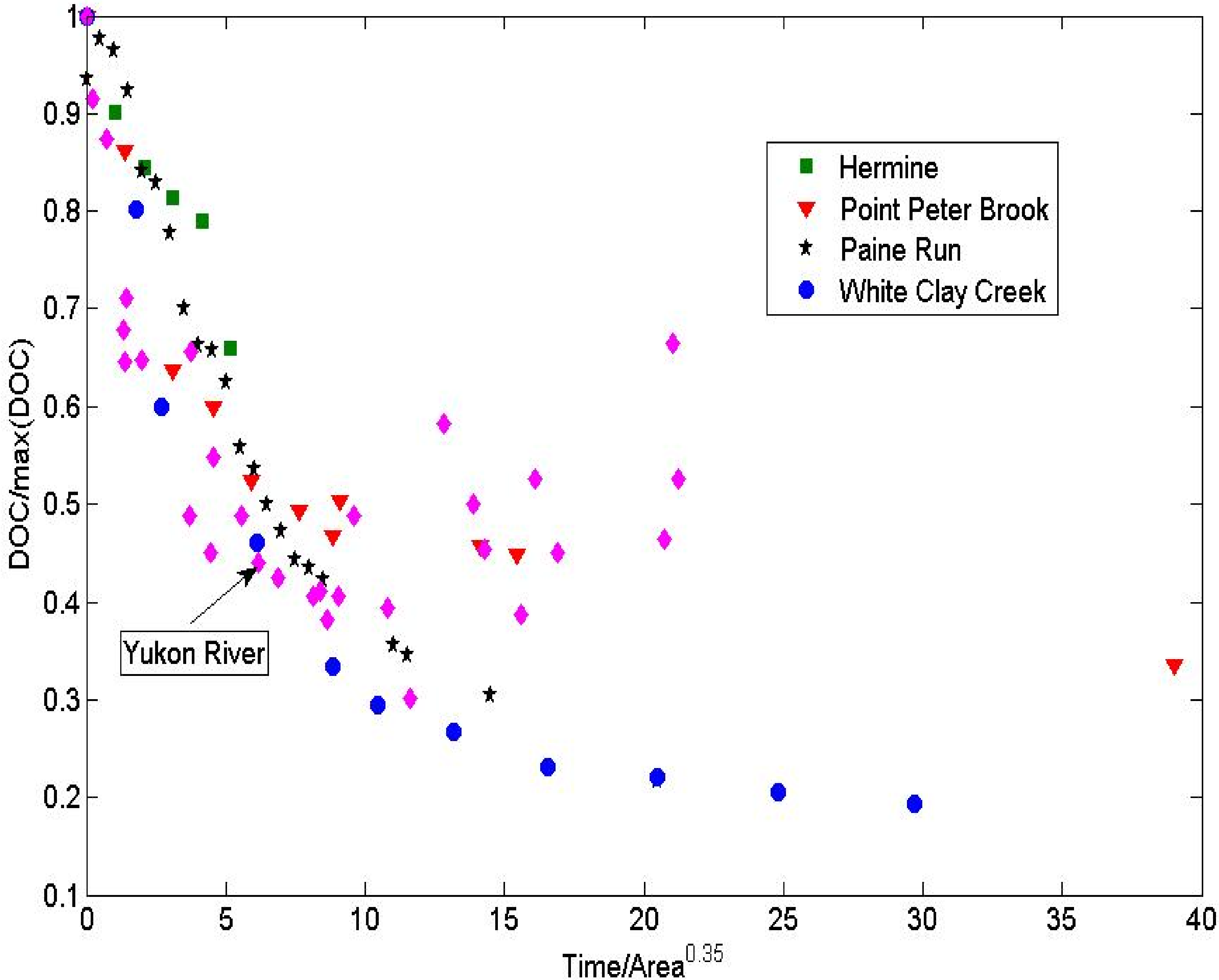
Skøien, JO and G Blöschl 2006. Catchments as space-time filters – a joint spatio-temporal geostatistical analysis of runoff and precipitation. ***Hydrol. Earth Syst. Sci. 10***: 645–662

# DOC recession curves



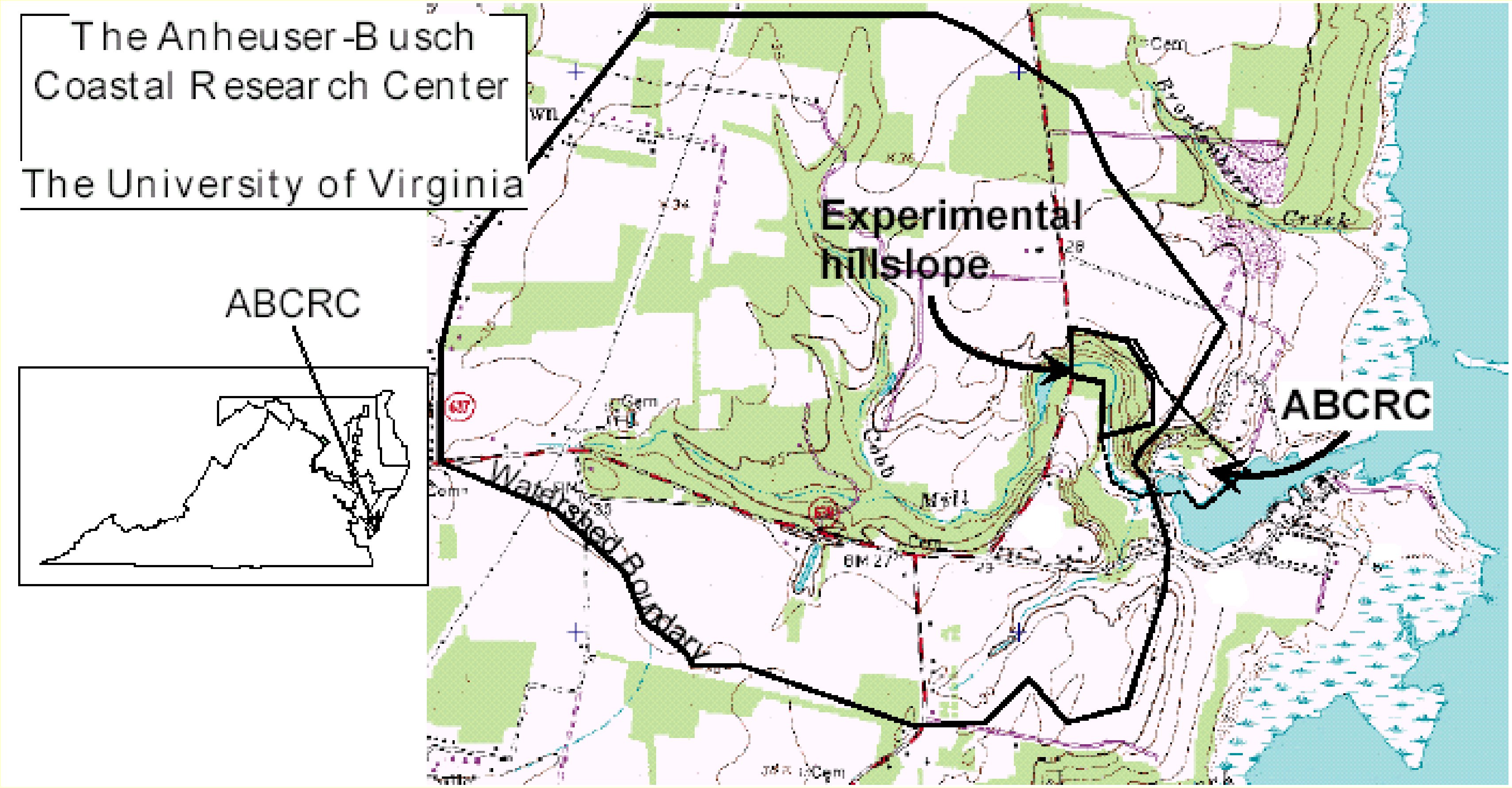



Striegl et al. 2007. *Water Resources Research 43*: W02411, doi:10.1029/2006WR005201

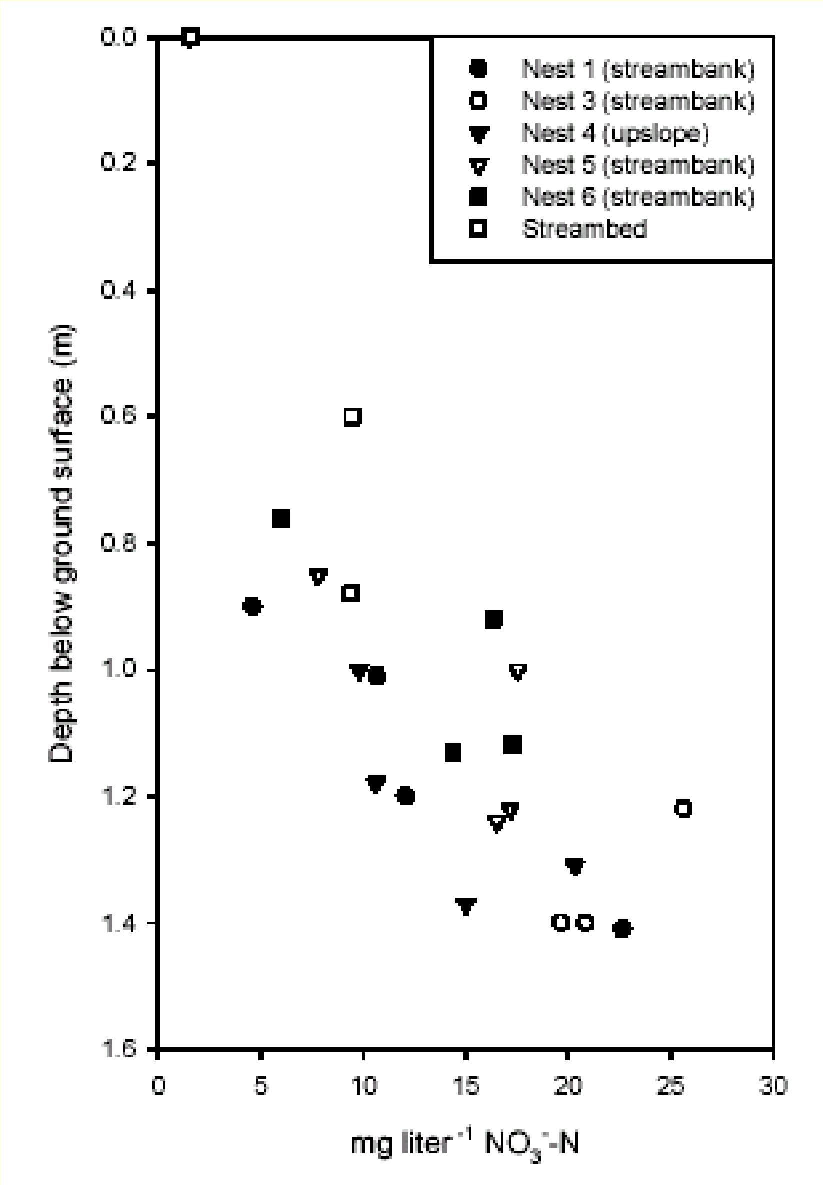


Hermine
Point Peter Brook
Paine Run
White Clay Creek
Yukon River
DOC/max(DOC)
Time/Area^0.35
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
10
15
20
25
30
35
40

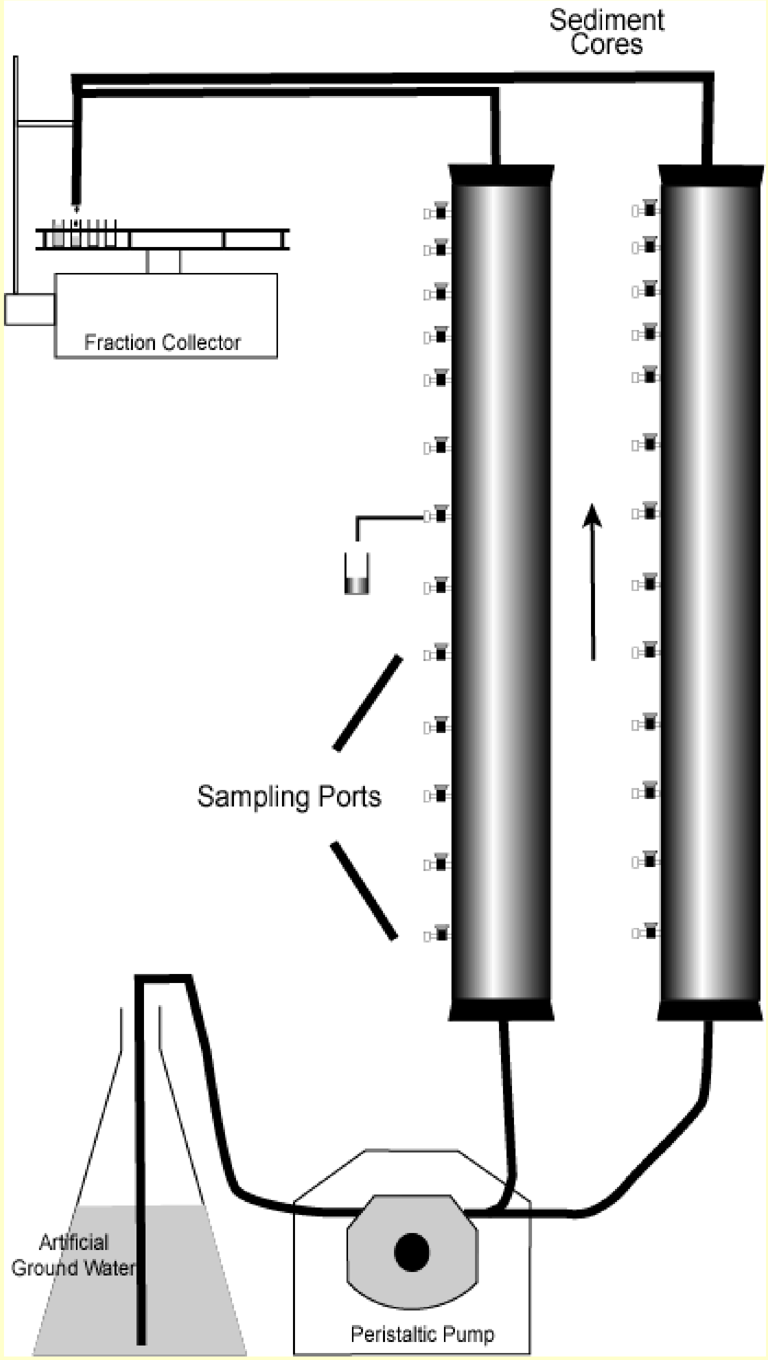
# Another example – a more physically based approach.




Cobb Mill Creek – Eastern Shore of Virginia; low relief; sandy, permeable soils; agricultural fields => high nitrate in groundwater; streams are incised, with relatively steep hillslopes.




Relatively high nitrate in groundwater grades to much lower values in the stream.



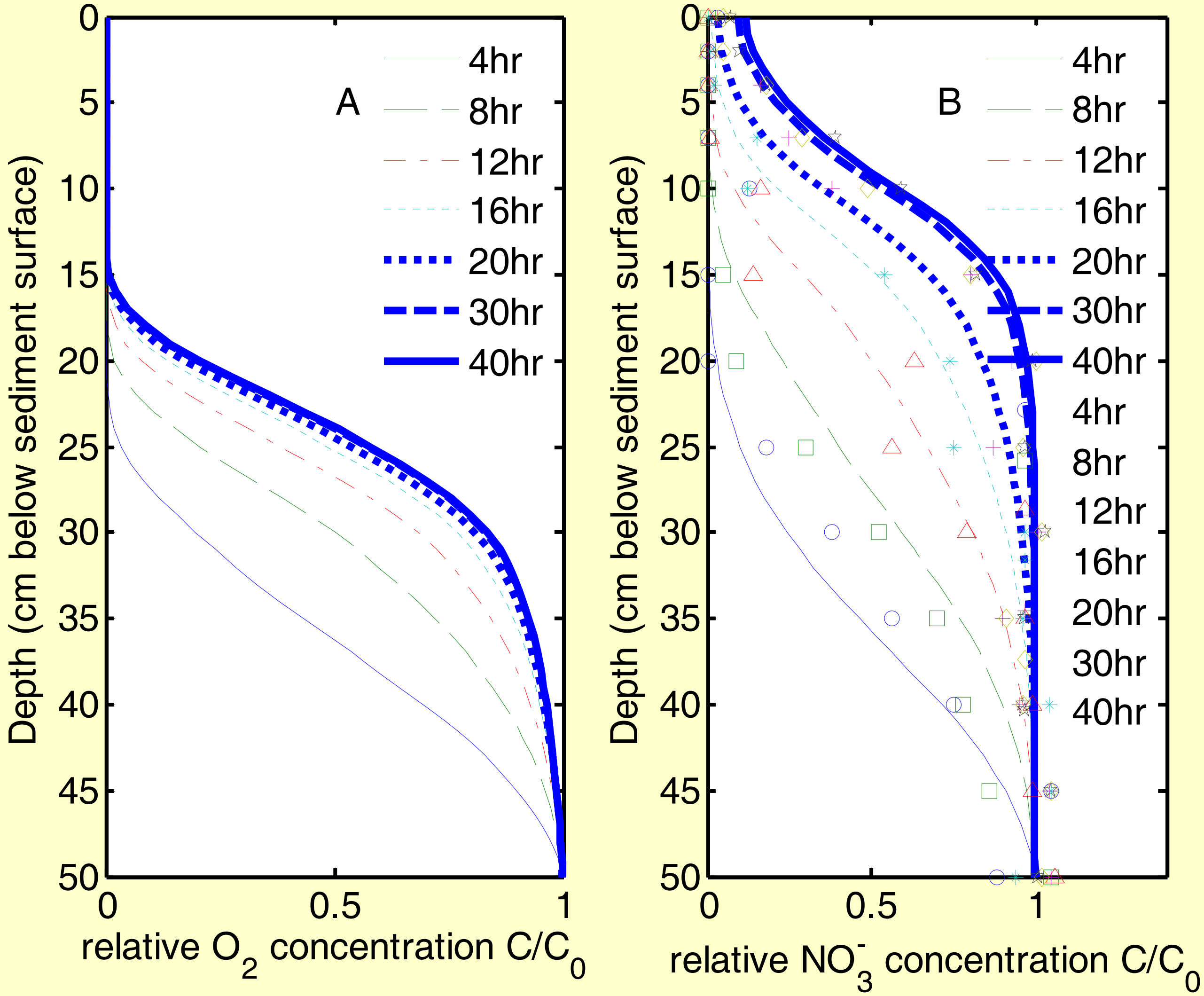

Intact cores were obtained from the stream sediments of a 20-m long reach of Cobb Mill Creek by driving sharpened 5-cm diameter PVC pipes vertically into the sediments. The averaged POC content is about 3% for the upper 30 cm of sediments and about 0.2% for the bottom sandy part. Experiments with varying solute flow rates were performed on two cores to investigate nitrate removal.

A mathematical model of reactive transport comprised 4 coupled, nonlinear partial differential equations. For example, for dissolved oxygen:

$$\frac{\partial O}{\partial t} = D\frac{\partial^2 O}{\partial x^2} - v\frac{\partial O}{\partial x} - V_O X \beta_O \left(\frac{C}{K_C + C}\right)\left(\frac{O}{K_O + O}\right)$$

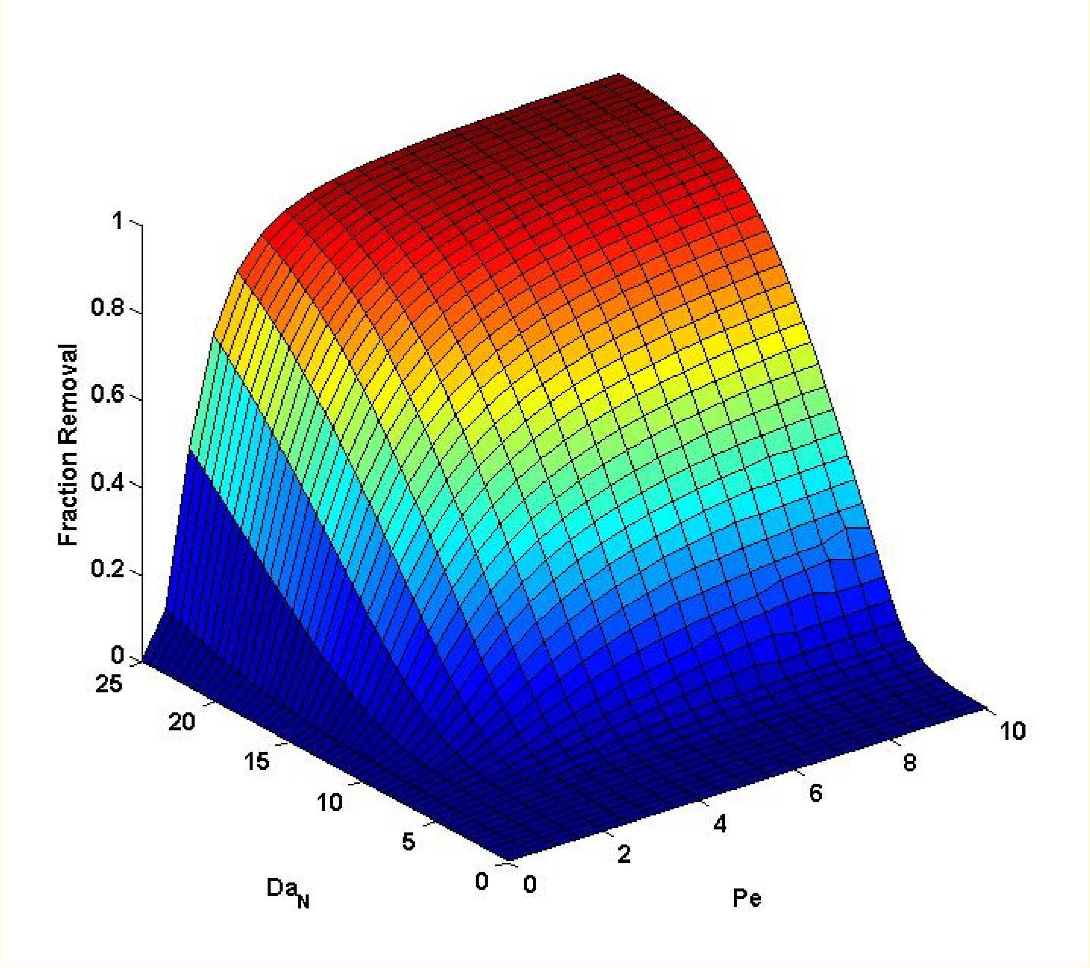
The reaction terms express the denitrification reaction using double Monod kinetics – carbon and oxygen are potentially limiting. The set of equations were solved numerically.

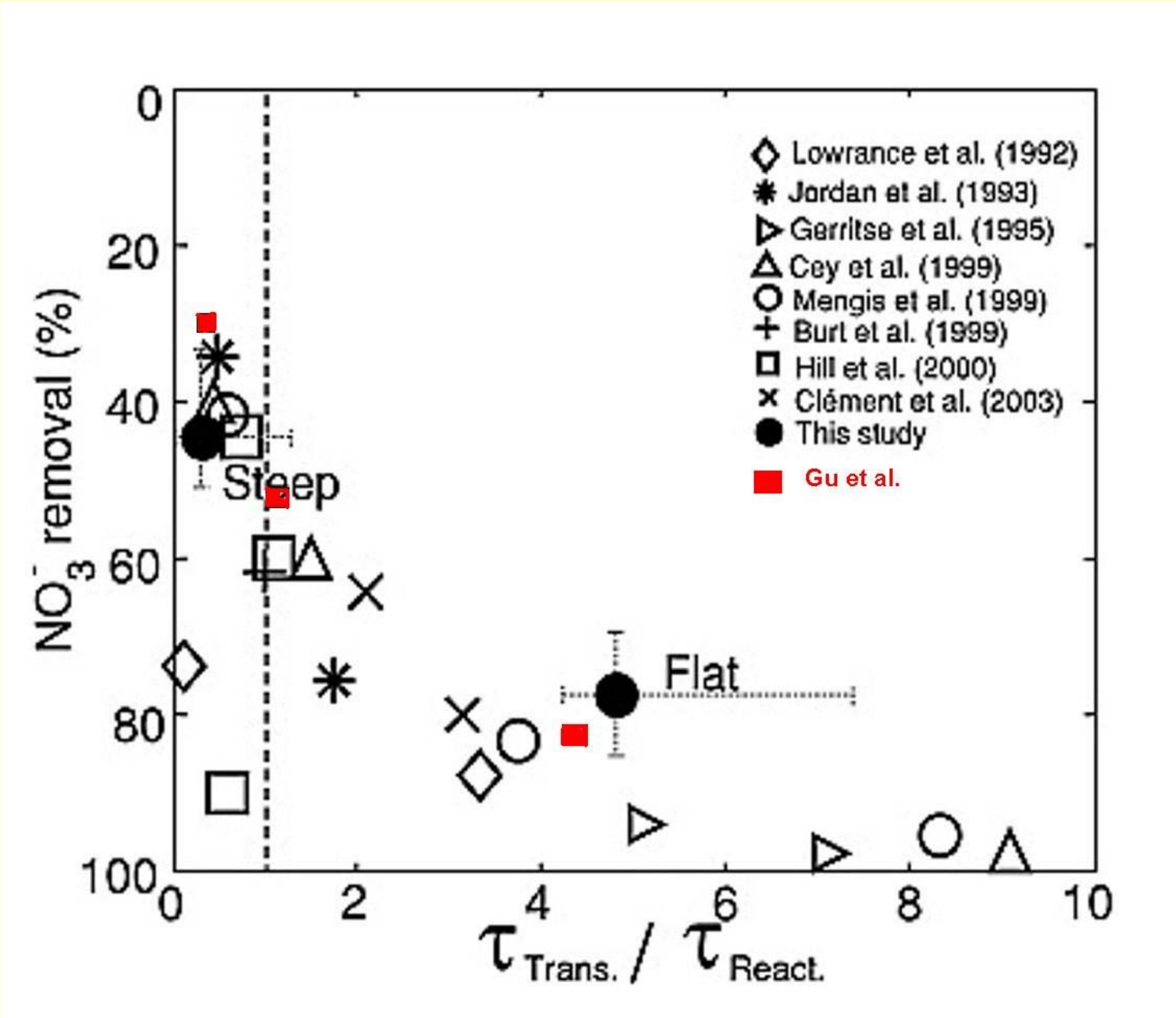
Gu, C., Hornberger, G.M., Mills, A.L., Herman, J.S., and S. A. Flewelling. 2007. Nitrate Reduction in Streambed Sediments: Effects of Flow and Biogeochemical Kinetics, ***Water Resour. Res.***, ***43***: W12413, doi:10.1029/2007WR006027 .




Our results indicate that most of the $NO_3^-$ (>80%) that is being transported through streambed sediment at the hillslope site at Cobb Mill Creek is removed by uptake in sediments near the GSI.

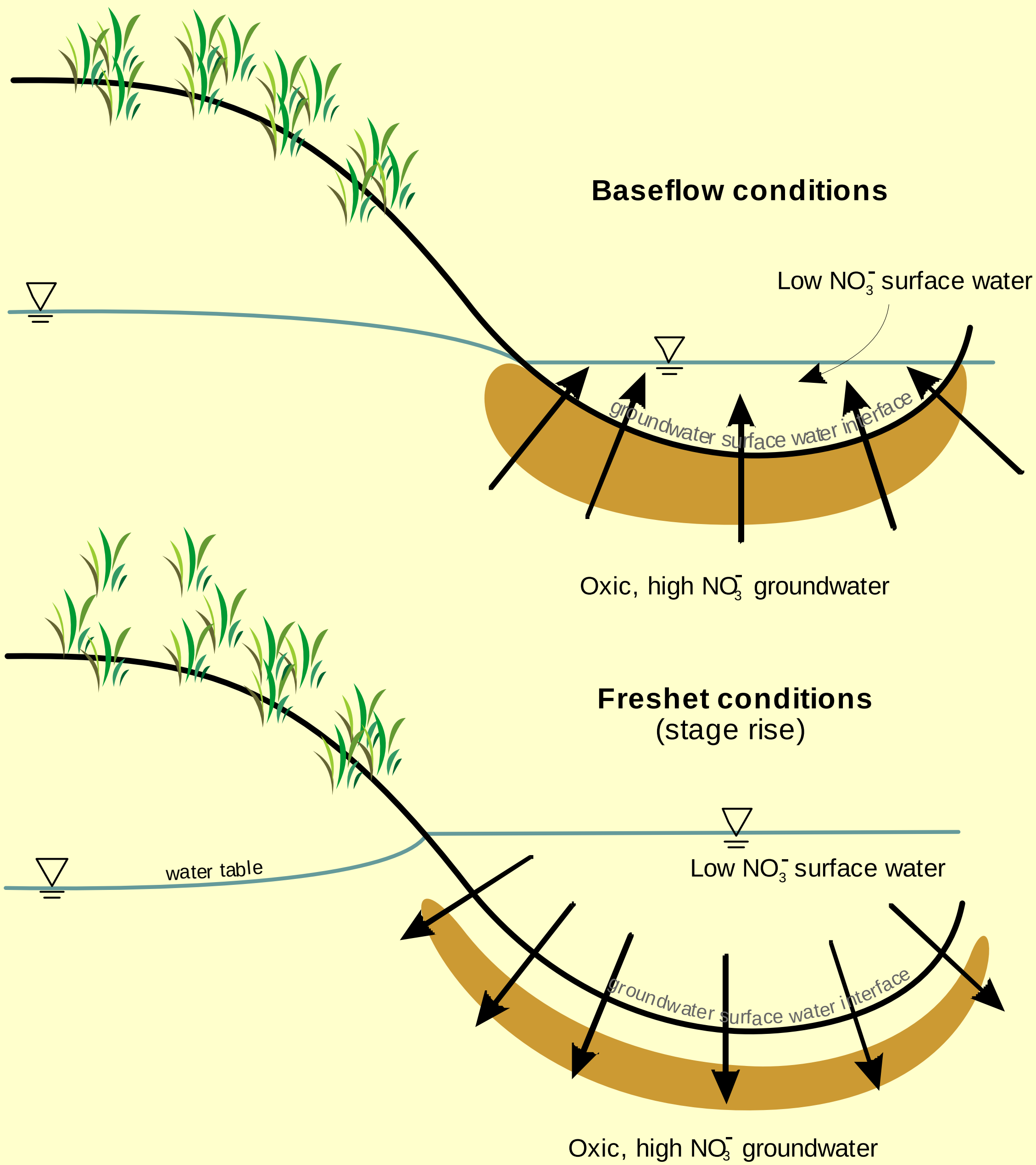
A Damkohler number (ratio of travel time to reaction time scale) and a Peclet number (ratio of advective time scale to dispersive time scale) control the removal fraction. One possibility for synthesis would be to relate these time scales to physical and biological catchment characteristics that determine these time scales.





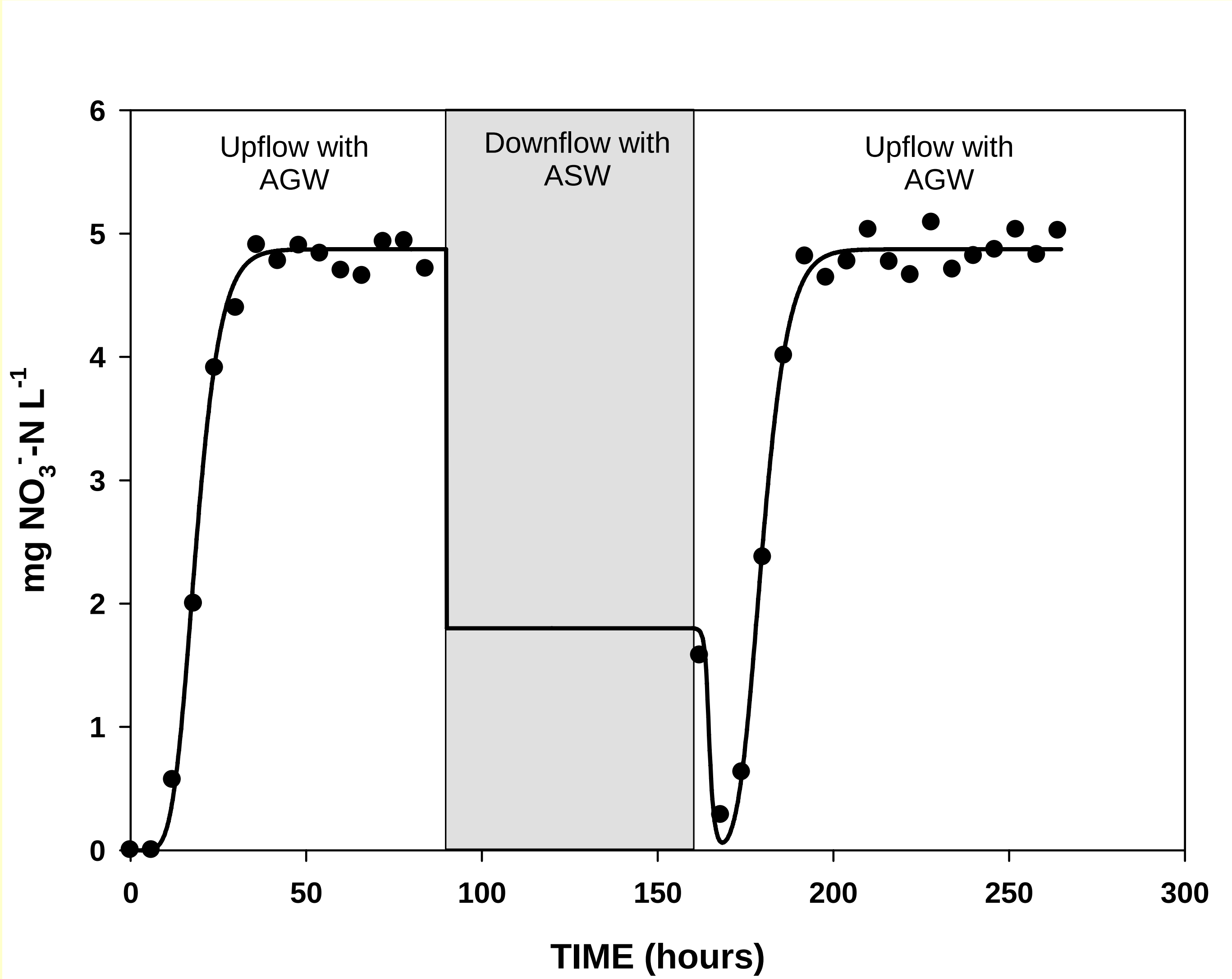

Base figure from Ocampo et al. 2006. *Water Resources Research 42*: W01408, doi:10.1029/2004WR003773

Question: Can the conceptual approach outlined by Vidon and Hill (2006, *JAWRA 42*: 1099-1112) be made quantitative using dimensionless groups related to landscape characteristics?



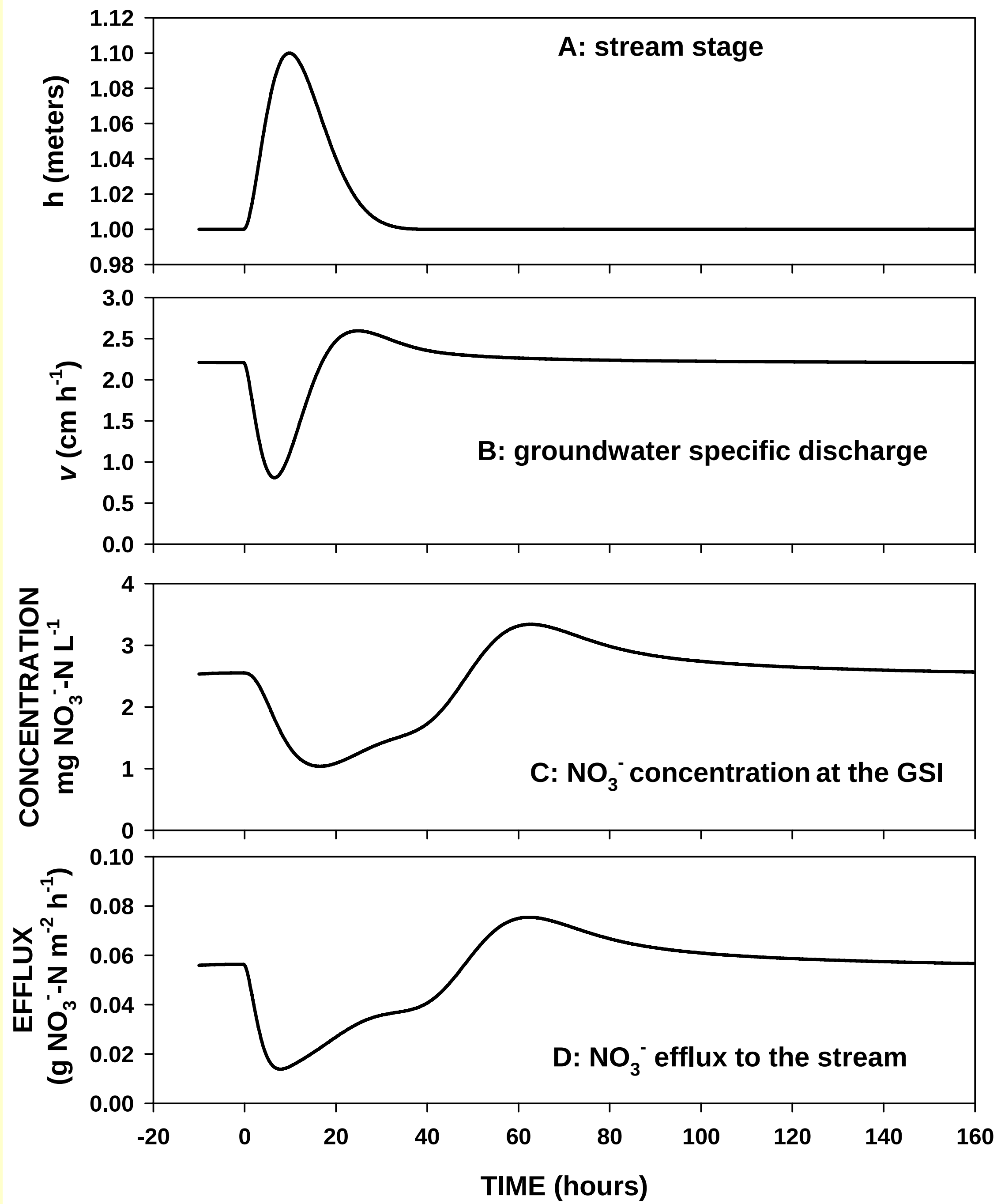

# But how do transient conditions affect nitrate transport? If events are large enough, flow can be reversed and surface water can be pushed into the sediments.

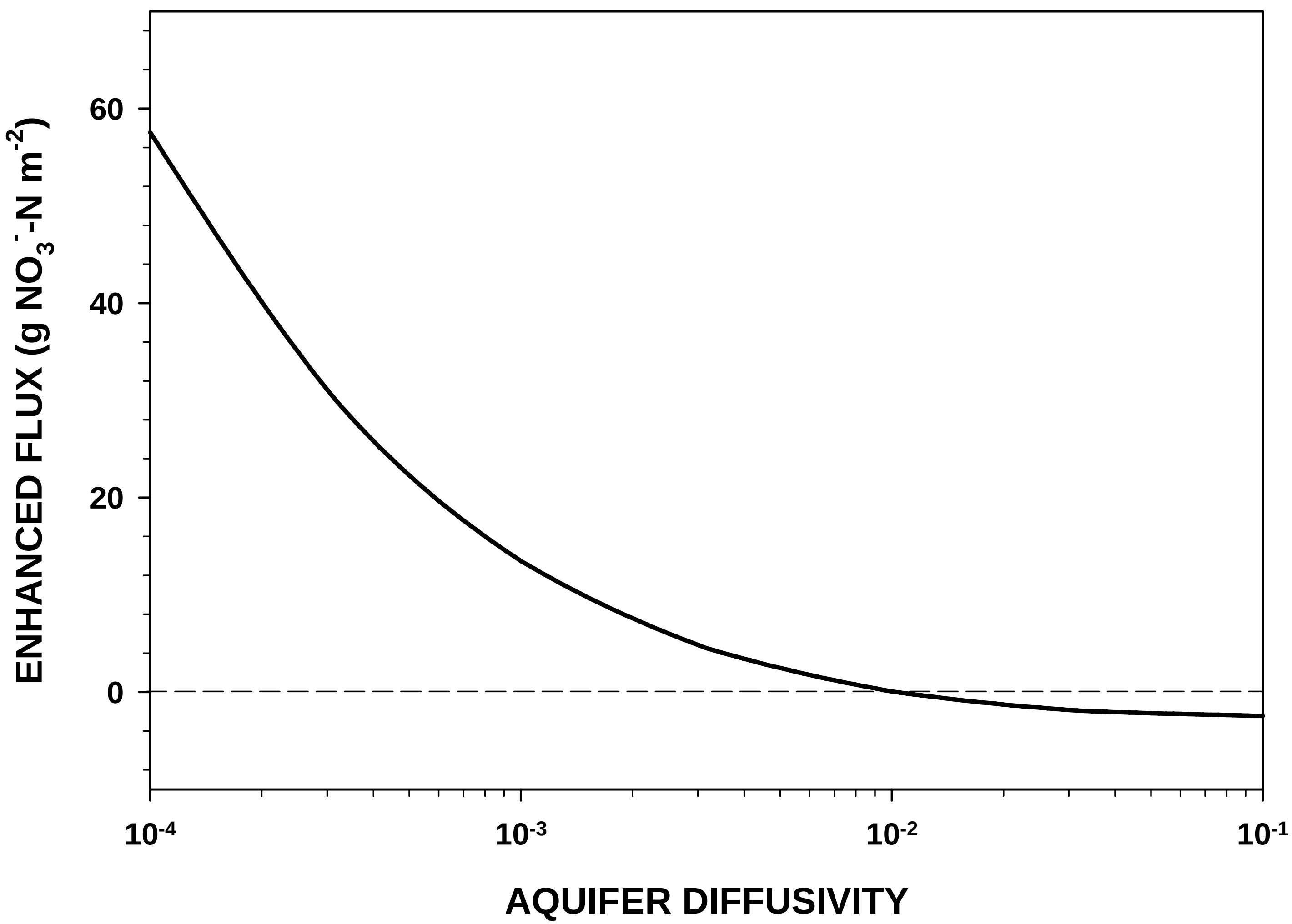
Gu, C., Hornberger, G.M., Mills, A.L., and J.S. Herman. The Effect of Freshets on the Flux of Groundwater Nitrate Through Streambed Sediments, ***Water Resour. Res.***, In review



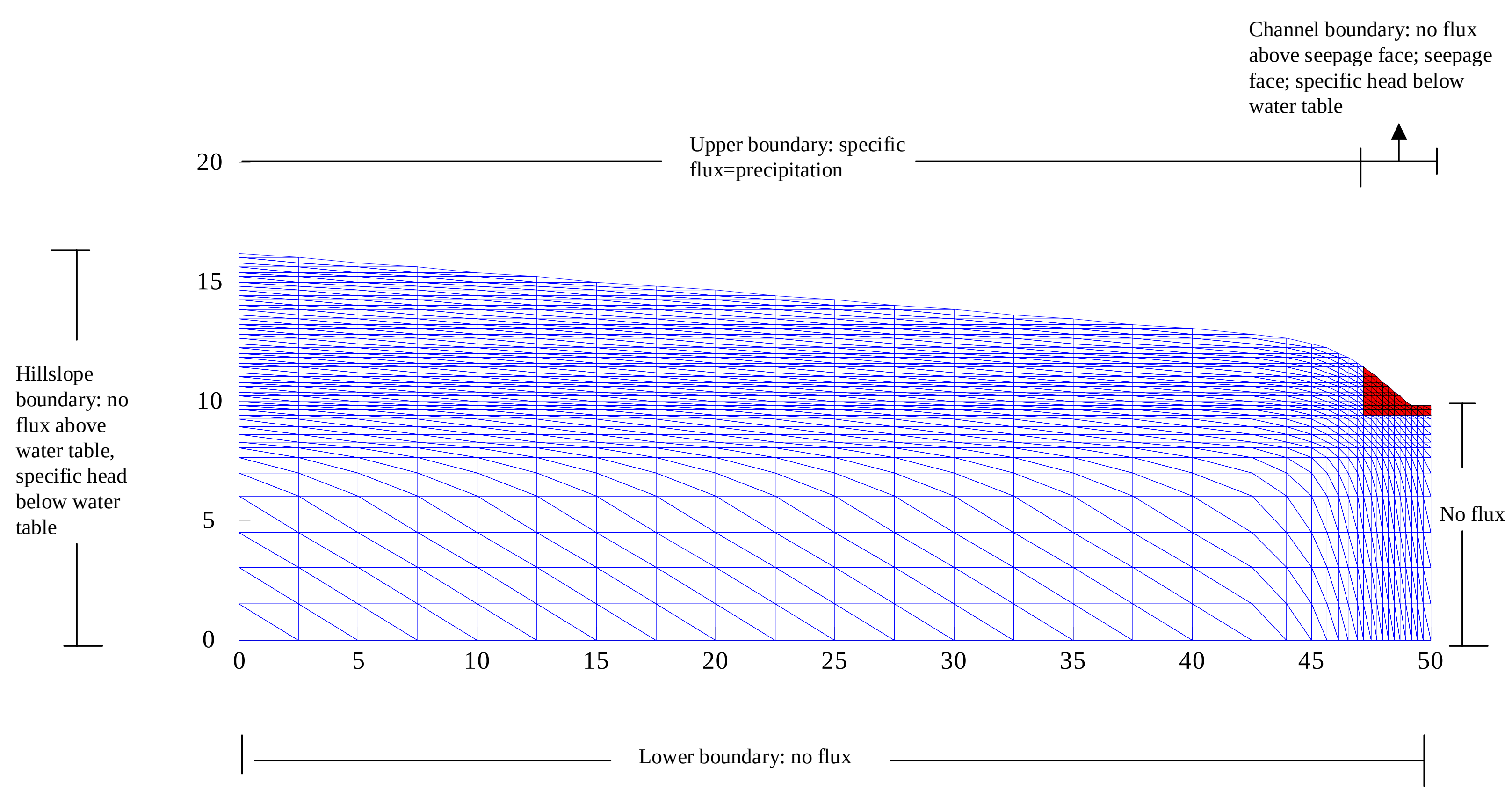

The mathematical model, calibrated with experiments with flow in one direction successfully described results for experiments simulating flow reversal during a freshet.

Model results indicate that one effect can be that nitrate flux is first reduced (even if flow is not reversed but just slowed) but later increases because the streamward gradient following the peak in the freshet is greater than the prestorm conditions thus reducing the residence time in the sediments, decreasing the Damkohler number and thus the nitrate removal.



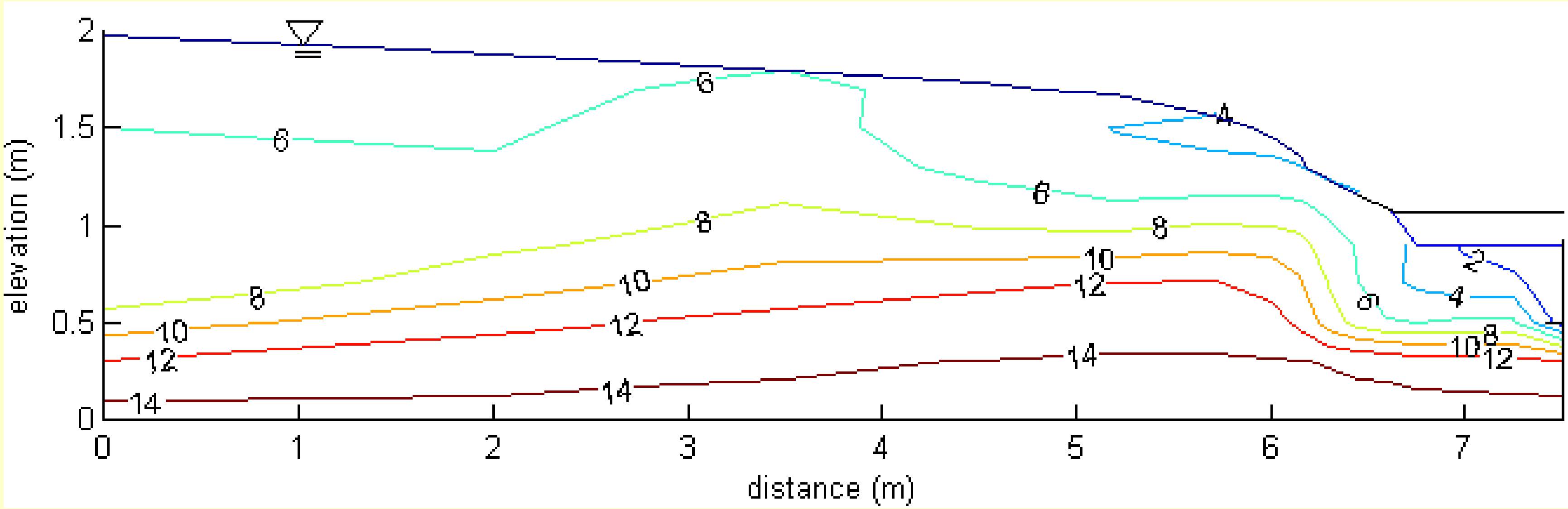



The net effect – whether total load is increased or decreased by a freshet – depends on the properties of the sediments but the most likely case is a slight overall decrease in load.

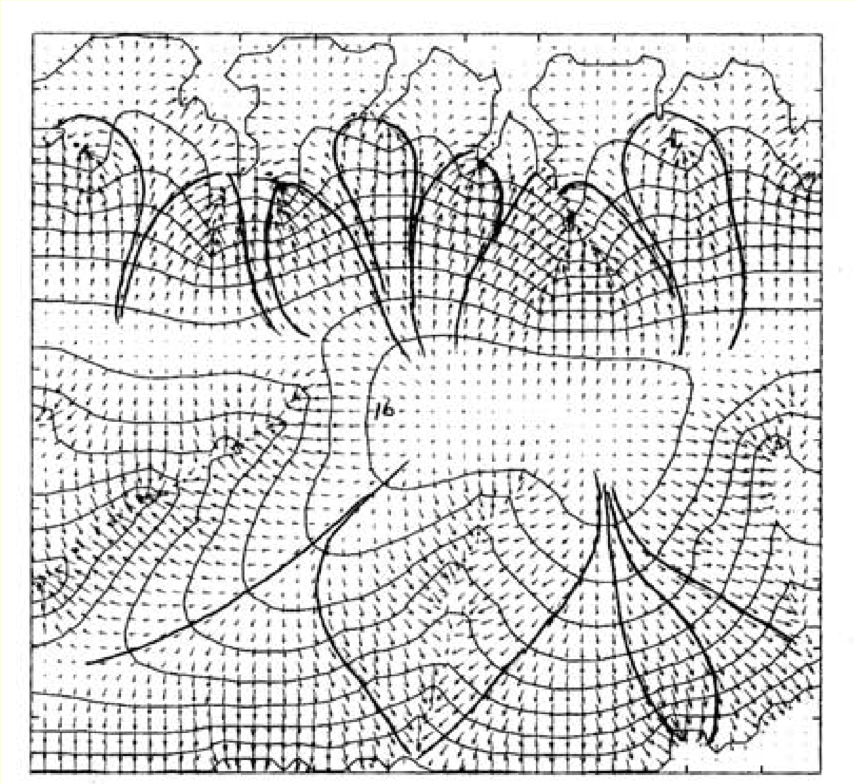



Extension of the model to a two-dimensional hillslope has been accomplished. Finite element meshes and boundary conditions constructed for the transect consist of 1068 nodes and 2004 linear triangular finite elements.

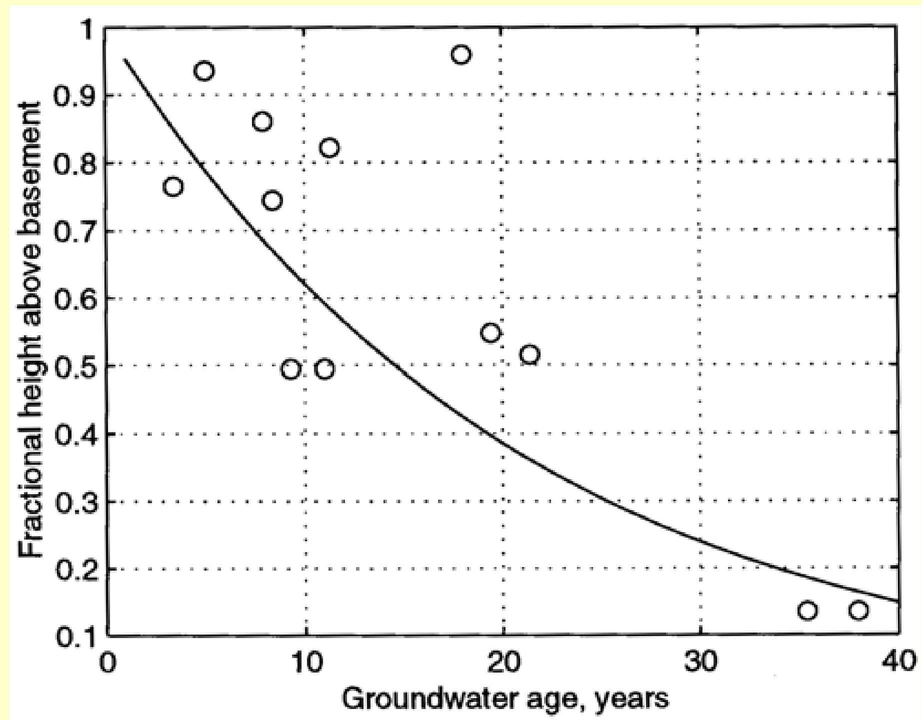

Gu et al. Influence of stream-aquifer interaction on $NO_3^-$ flux to a stream through a riparian zone: Cobb Mill Creek, VA. ***WRR***, In review.




Simulated nitrate concentrations on the hillslope (shown above) were in reasonable agreement with measurements from the piezometer nests. Results indicate that the “dilution” observed over storm events actually includes a denitrification component due to increases in residence times in the sediment due to transient flow conditions.



Phillips (2003, *Wat. Resour. Res. 39*: 1149, doi:10.1029/2001WR001261) proposed an approach for relating groundwater travel times to topography on the Delmarva peninsula.

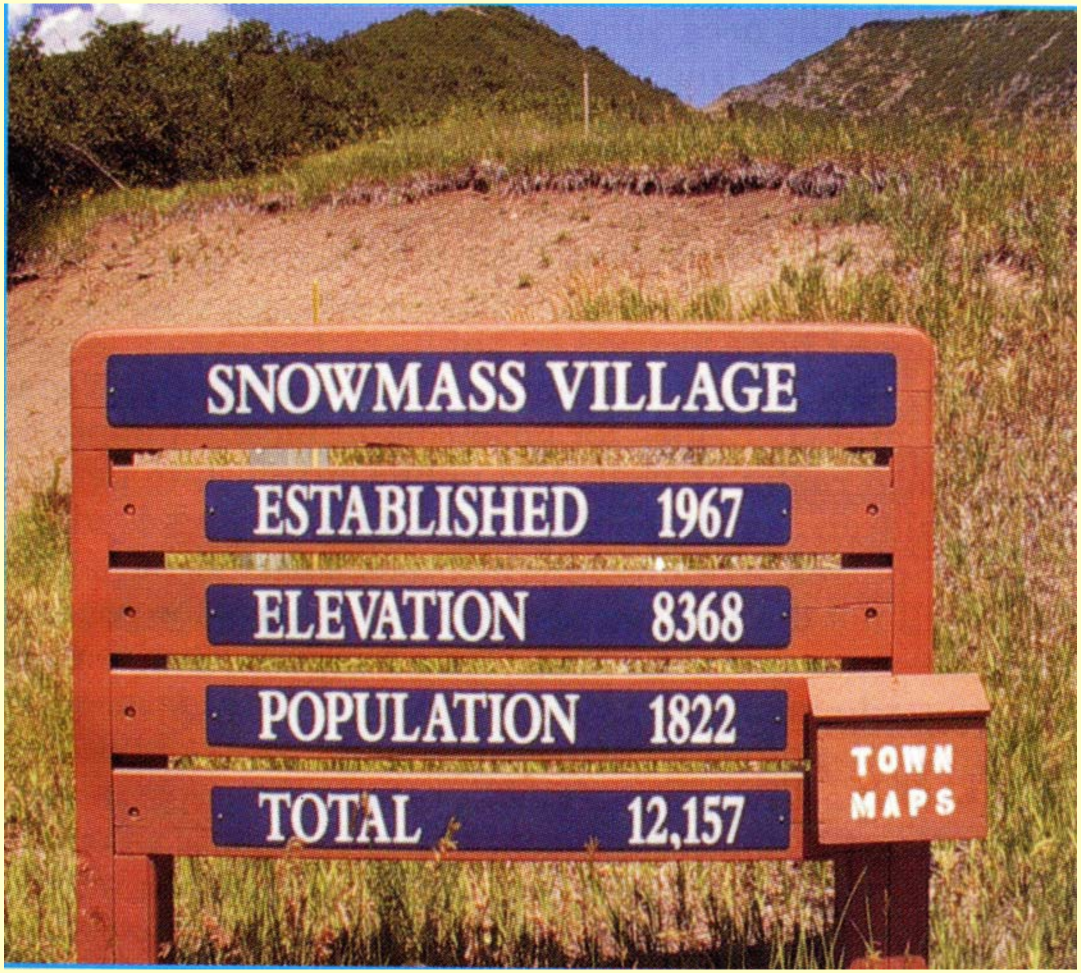



Question: Can a regional approach such as that suggested by Phillips be used to extend the “just so” story about transient effects?

## Recall the plea for a "taxonomy" to include catchment hydrochemical functioning --

"With such a [*catchment*] taxonomy …, researchers for a particular watershed could investigate where their watershed might be classified within the scheme and they could relate results of their specific experiments to experiments performed by researchers at other (perhaps quite distant) sites. If the researchers at different sites had similar types of watersheds … and observed similar results from similar experiments, then this would serve to corroborate their conclusions. If the researchers had drawn different conclusions from the similar results, the use of the taxonomy could lead to profitable discussions as to why."

Church MR 1997. ***Annual Review of Earth and Planetary Sciences 25***: 23-59.




So, although we need to be careful in how we make calculations, I argue that we must continue to find ways to generalize results and avoid relying exclusively on "just-so" stories. The details of how we do this remain a challenge for the field.