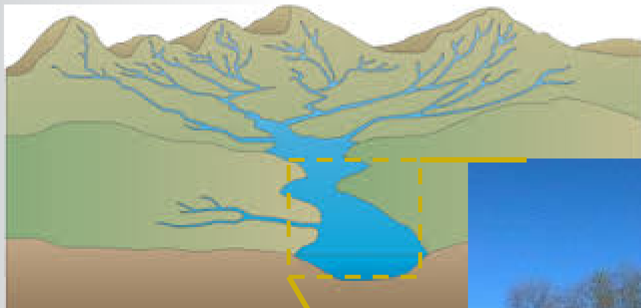
Climate and Hydrological Controls on Riverbed Bioclogging and Implications for Water Resources and Quality

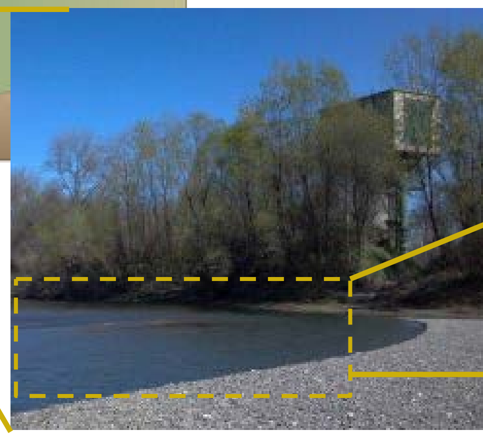
Collaborators:
Susan Hubbard, Yoram Rubin,
Jan Fleckenstein, Uli Maier,
Mary Power, Nigel Chen,
Dipankar Dwivedi, Craig Ulrich

Michelle Newcomer
Geological Post-Doctoral Fellow LBNL

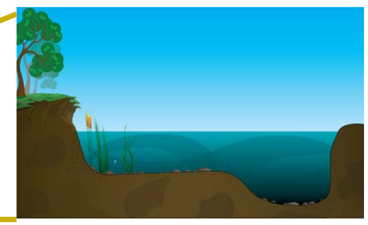
Top-Down Processes Control Flow and Geochemistry of a Watershed



- **Wet/Dry catchments regulate water chemistry (DOC and O_2)**



- **Land uses regulate infiltration, chemistry, habitats**



- **Geomorphology**
- **Sediment**
- **Ecology**

- Climate Type
- Extreme Events
- Fires
- Geology
- Discharge

Water & DOC pulses

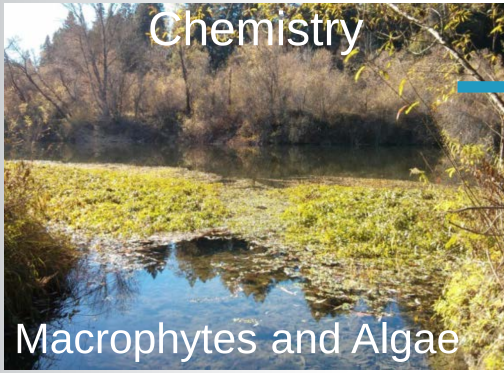
- Infiltration regime
- Meanders
- Riparian habitat
- Sediment structure
- Banks/Thalwegs
- Agriculture/Pumping

Food-web support

- Hyporheic
- Invertebrates
- Algae
- Biofilms
- Microbes

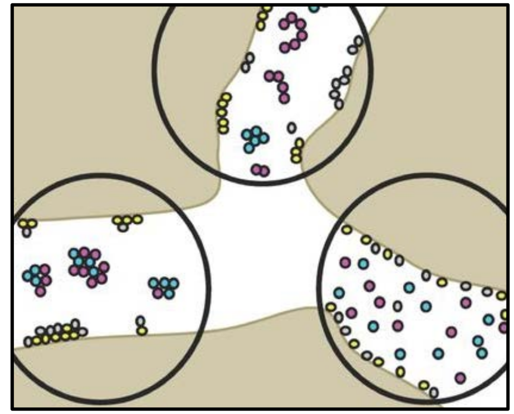
Observations of cumulative effects ↔ **Flow & Reactions**

Bottom-Up Feedbacks Contribute to Cumulative Effects



Local DOC Production, DO regulation

Pore-Scale Processing of N,C:
Aerobic respiration **(AR)**
Anaerobic denitrification **(DN)**



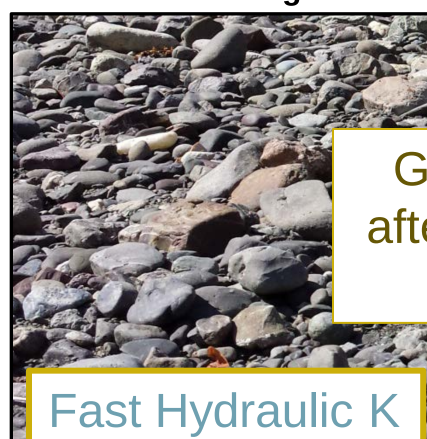
Microbial Transformation of DOC, NO_3 to CO_2, N_2, Bioclogging

GSD controls substrate transport through pores

External DOC, NO_3 inputs

Weather Controls Bankfull Discharge Events

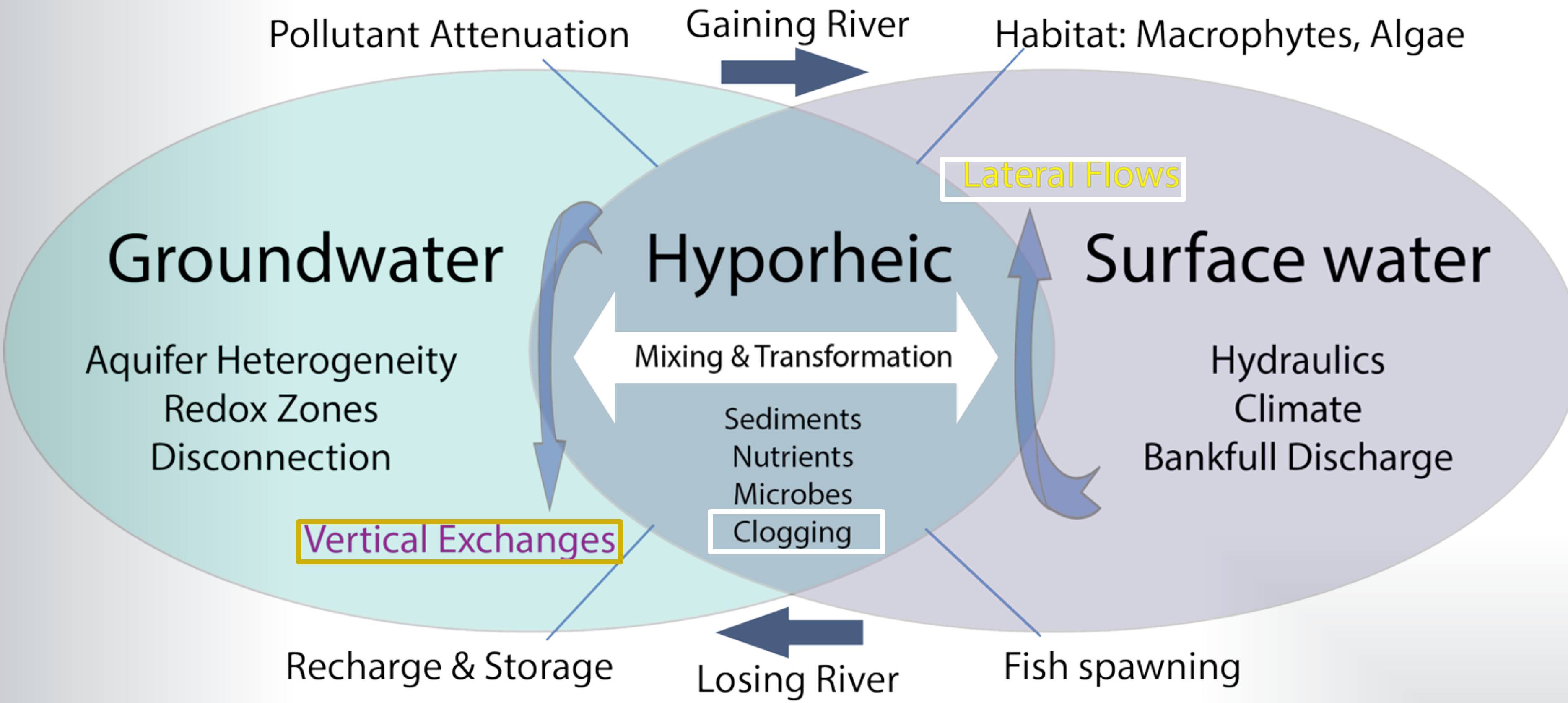
With A Scouring Event



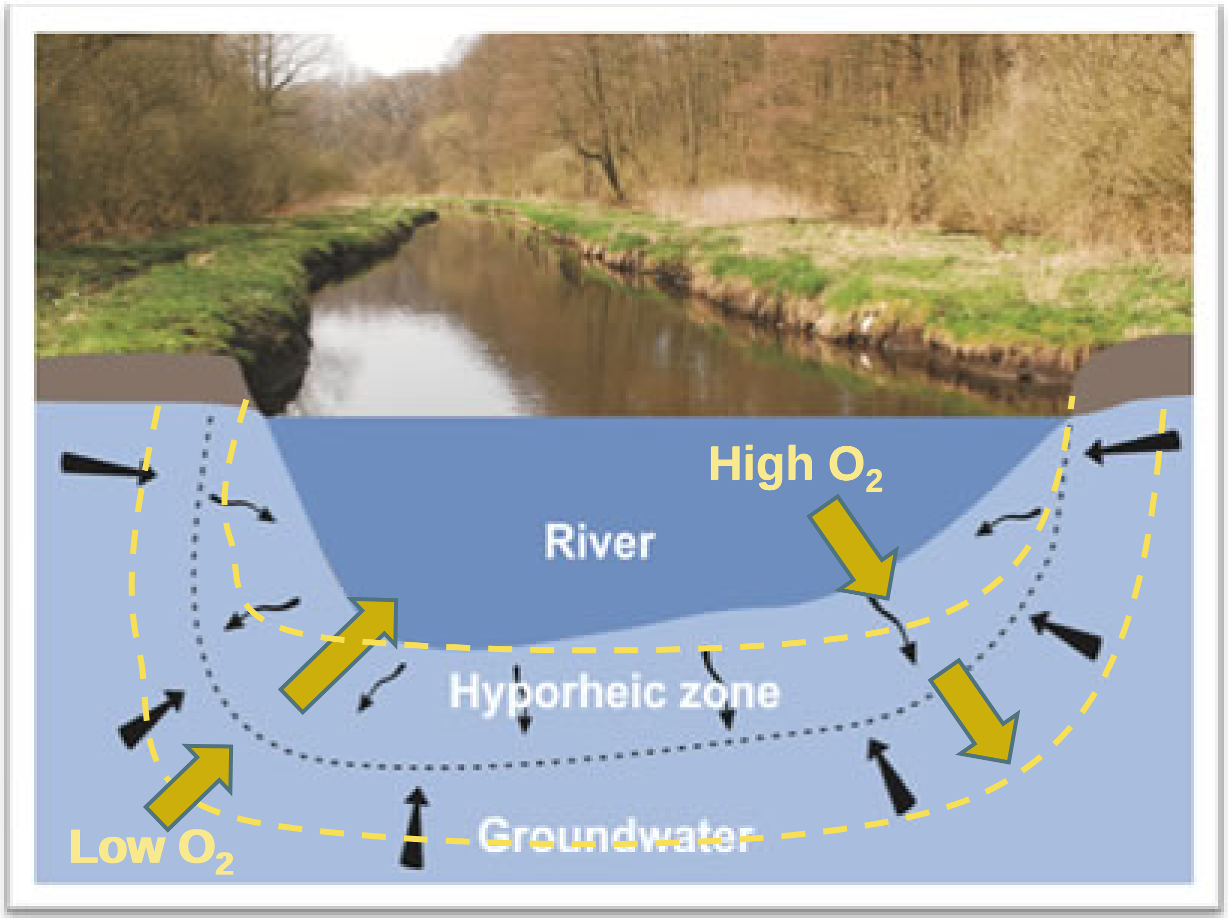
Without A Scouring Event

GSD shifts after extreme events

Hydrological Connectivity: The Hyporheic Zone as an Organizing Concept



Vertical Exchange in the Hyporheic Zone

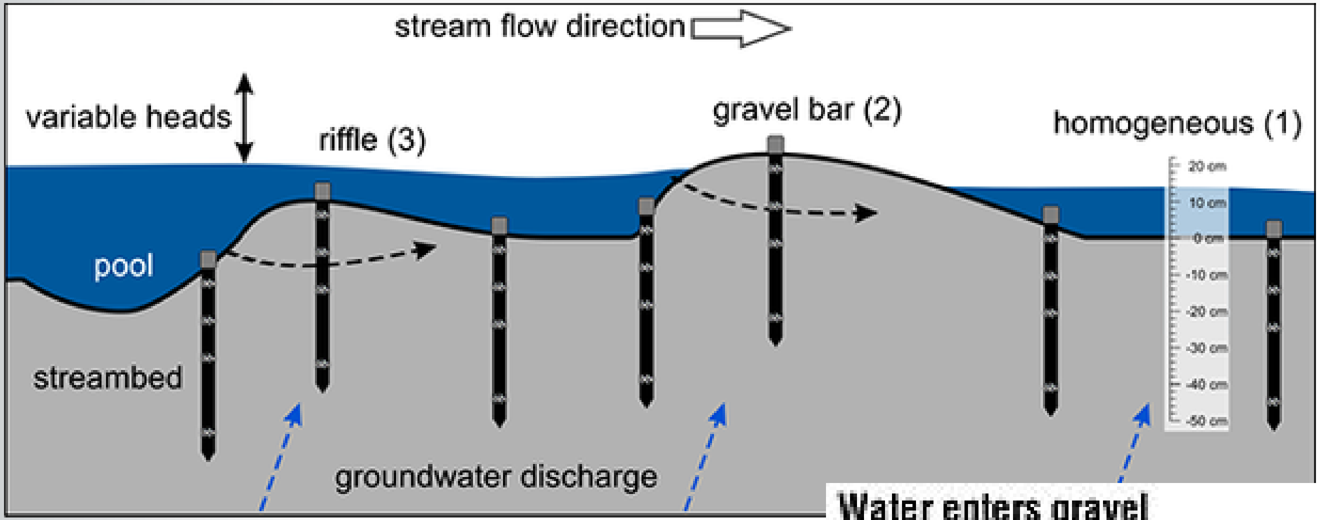


<u>Losing:</u>
Dominant flow direction down (Mediterranean Climates)

<u>Gaining:</u>
Dominant flow direction up (Wet, temperate climates)

- Controls on Recharge, Well Production, Drinking Water Quality, Redox Zonation, Groundwater levels

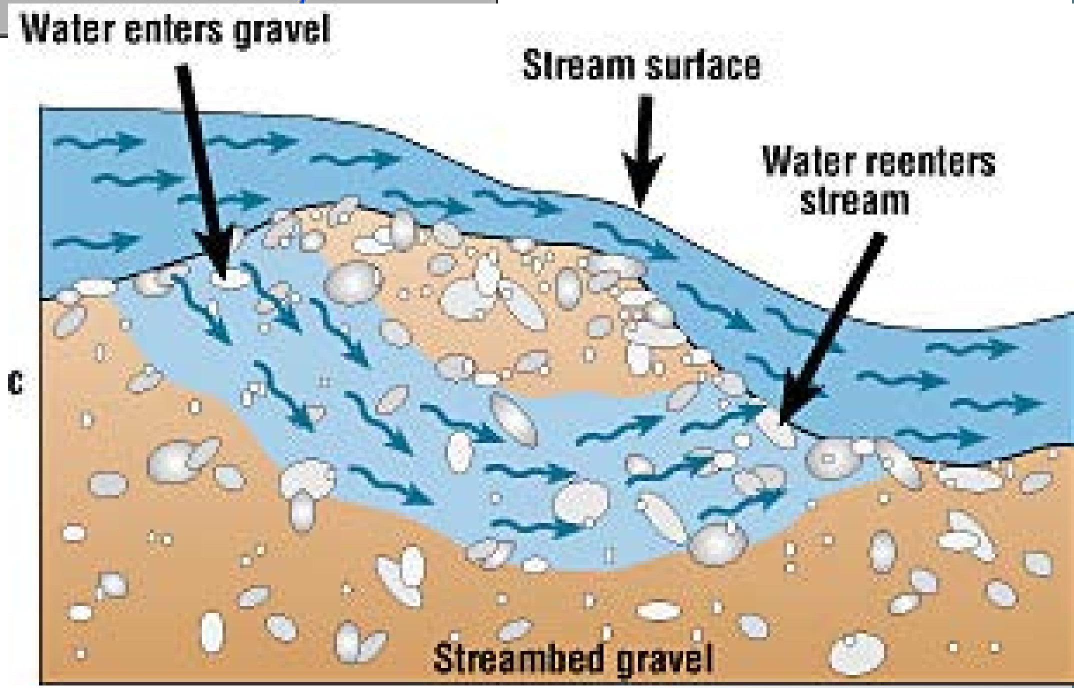
Horizontal Flow in the Hyporheic Zone



~100% of river water is filtered

- Microbes uptake nutrients and contaminants (C,N) and grow (bioclogging)

When 10% of the pore-space is occupied by microbes, conductivity is reduced by 80%



Major Research Questions

- What are the controlling effects of climates and river sediments on the Carbon cycle (C) and Nitrogen cycle (N) in the hyporheic zone?
- Using these feedbacks, can we better predict cumulative watershed effects?
- What are the subsurface contributions to CO_2, N_2 measured in river settings?
- How do top-down extreme events regulate subsurface microbial reactions?

Managed System

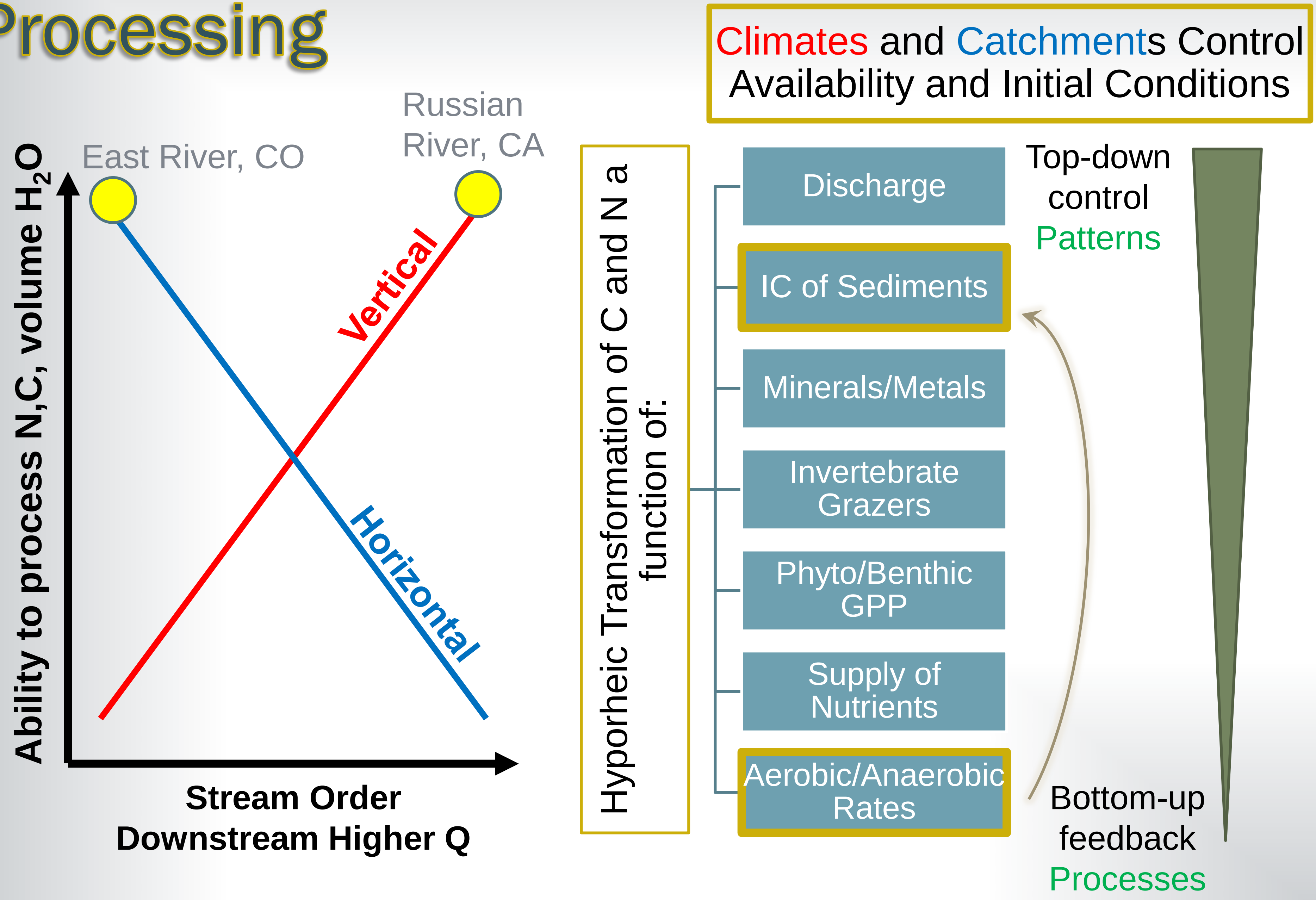
Russian River, CA
Riverbank Filtration
Mediterranean climate
Losing river (Vertical)

Natural System

East River, CO
SFA Watershed (Upper Colorado)
Semi-arid, Montane climate
Horizontal fluxes

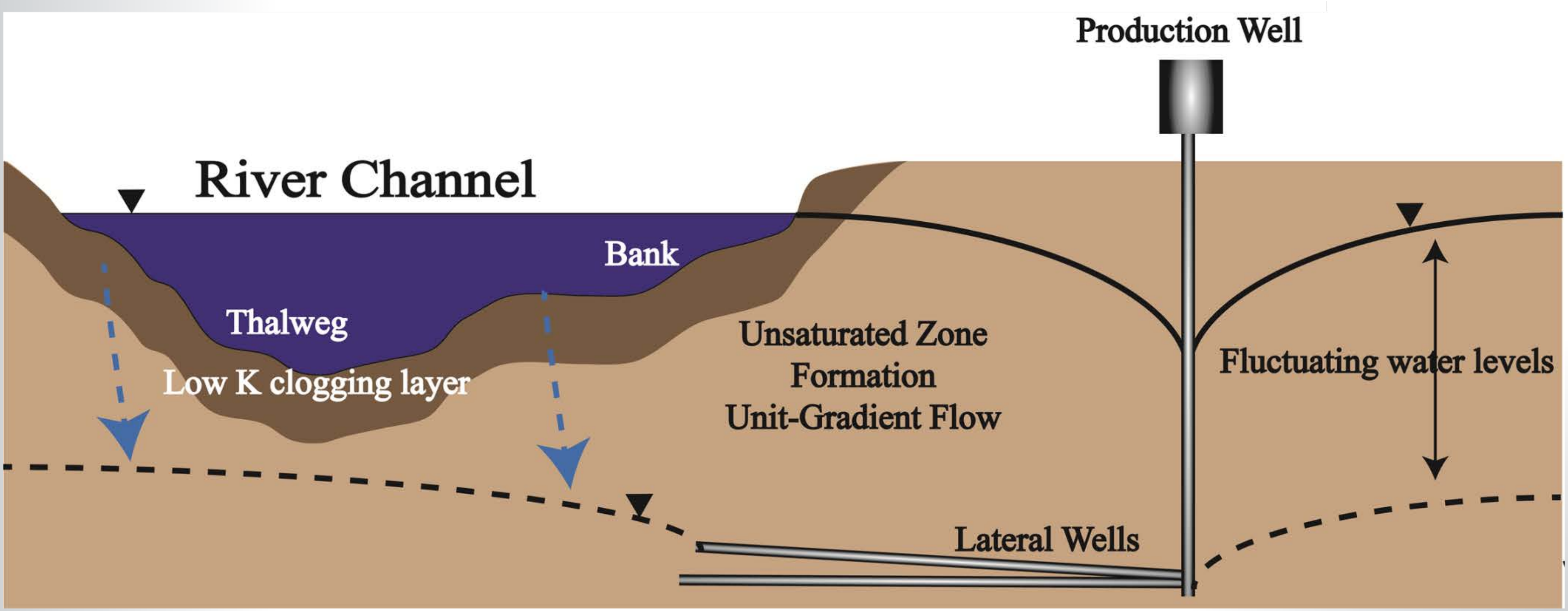
How do coupled hyporheic hydrological-biogeochemical feedbacks range between these conditions?

Temporal Dynamics of Hyporheic Processing

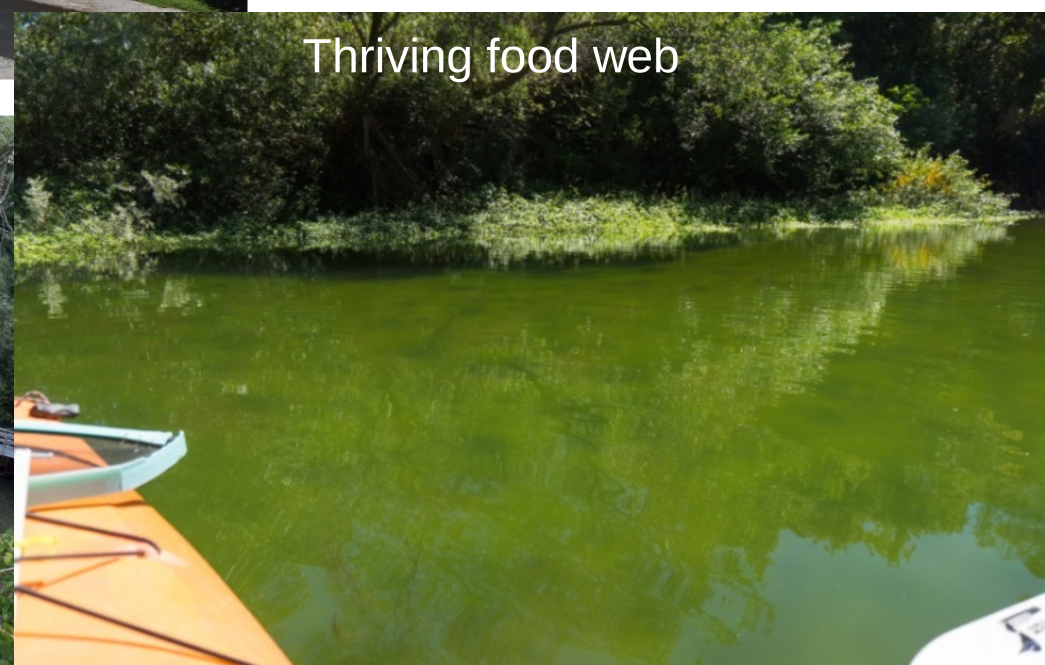


The Role of Rivers in Mediating These Interactions is Dynamic

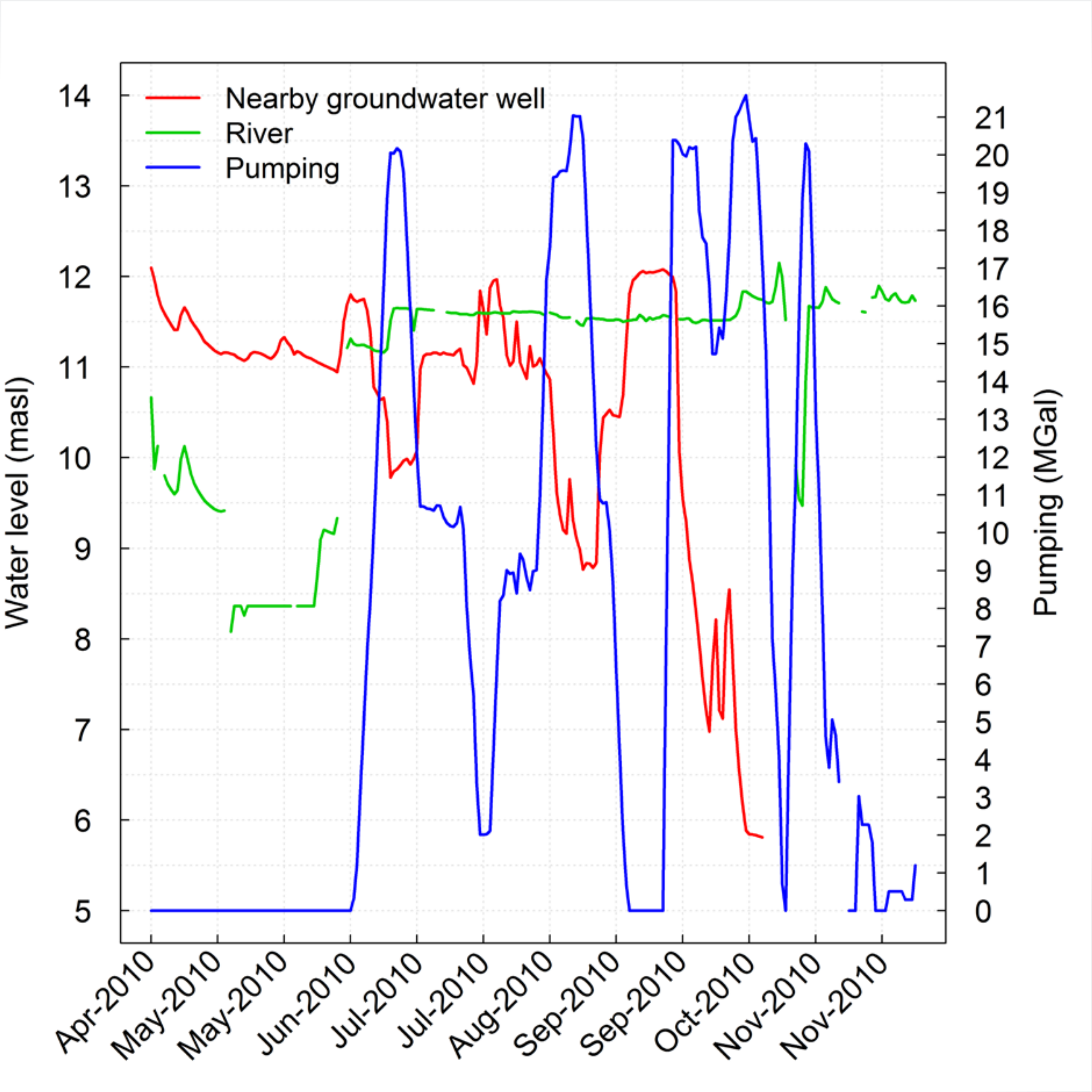
- **Russian River, CA:** Pumping causes water table fluctuations
- Dominantly Losing (Gaining in the Winter)
- Shifting redox zones
- Full disconnection (unsat. zone) during summer



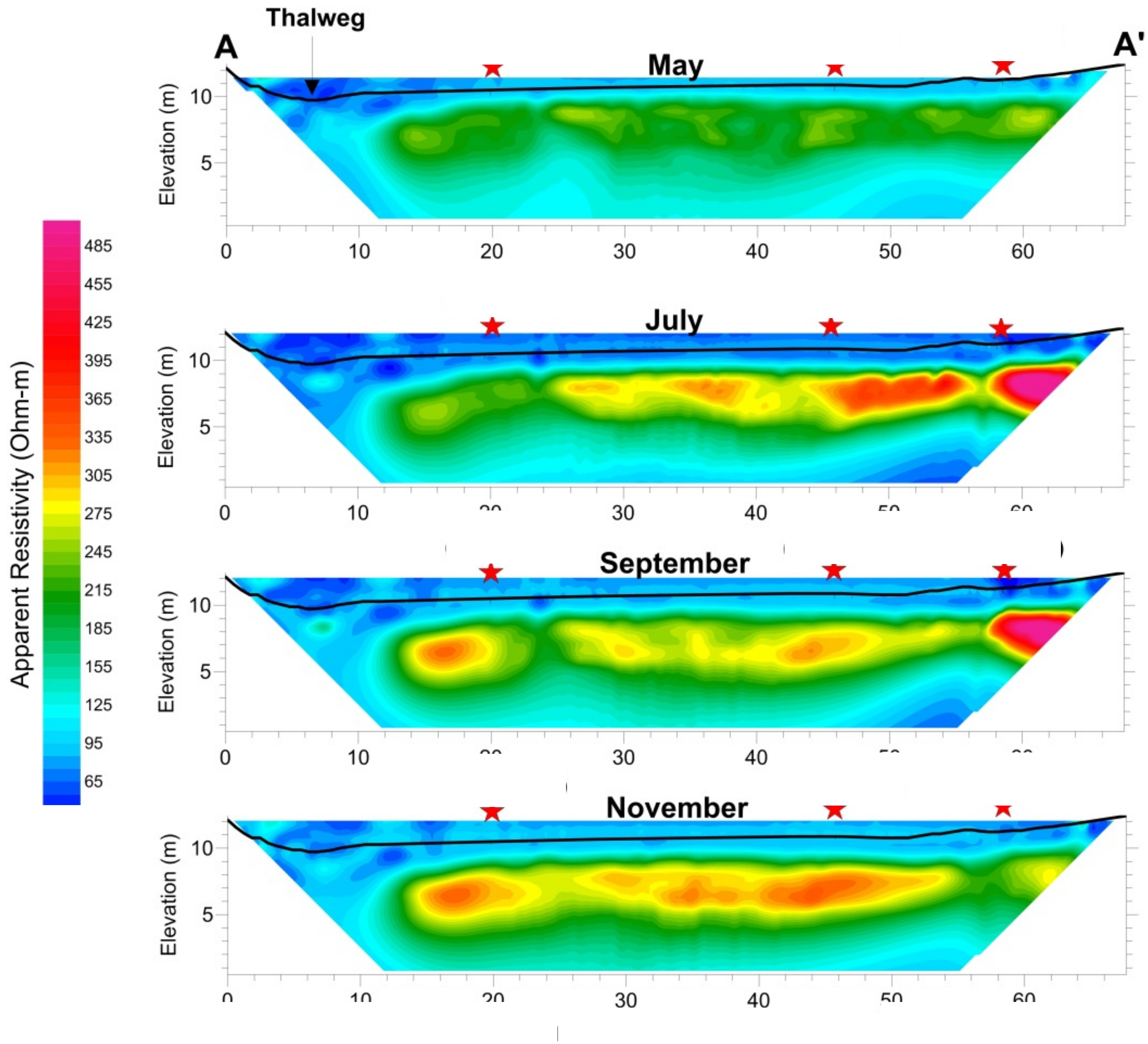
Russian River, CA



Measurements



A View of the Subsurface: Evidence of Disconnection

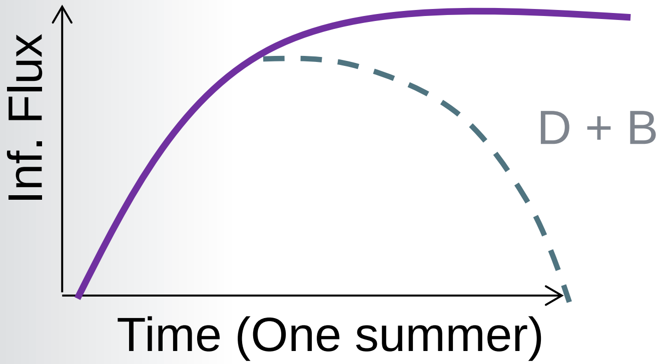


A Strongly Losing River Can Have an Unsaturated Zone

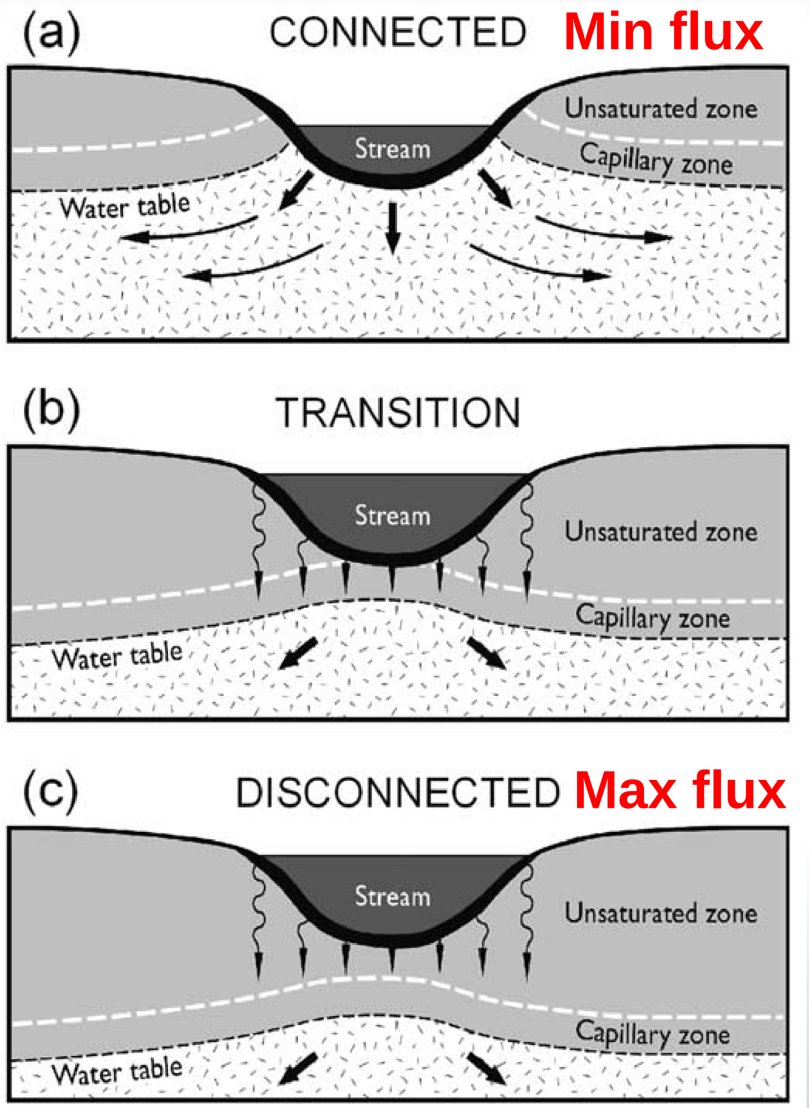
Disconnection

- Seepage is maximized when the unsaturated zone becomes fully developed (higher nutrient fluxes)
- Bioclogging (B) limits flux (dynamic permeability)

Max Flux at steady state when disconnected

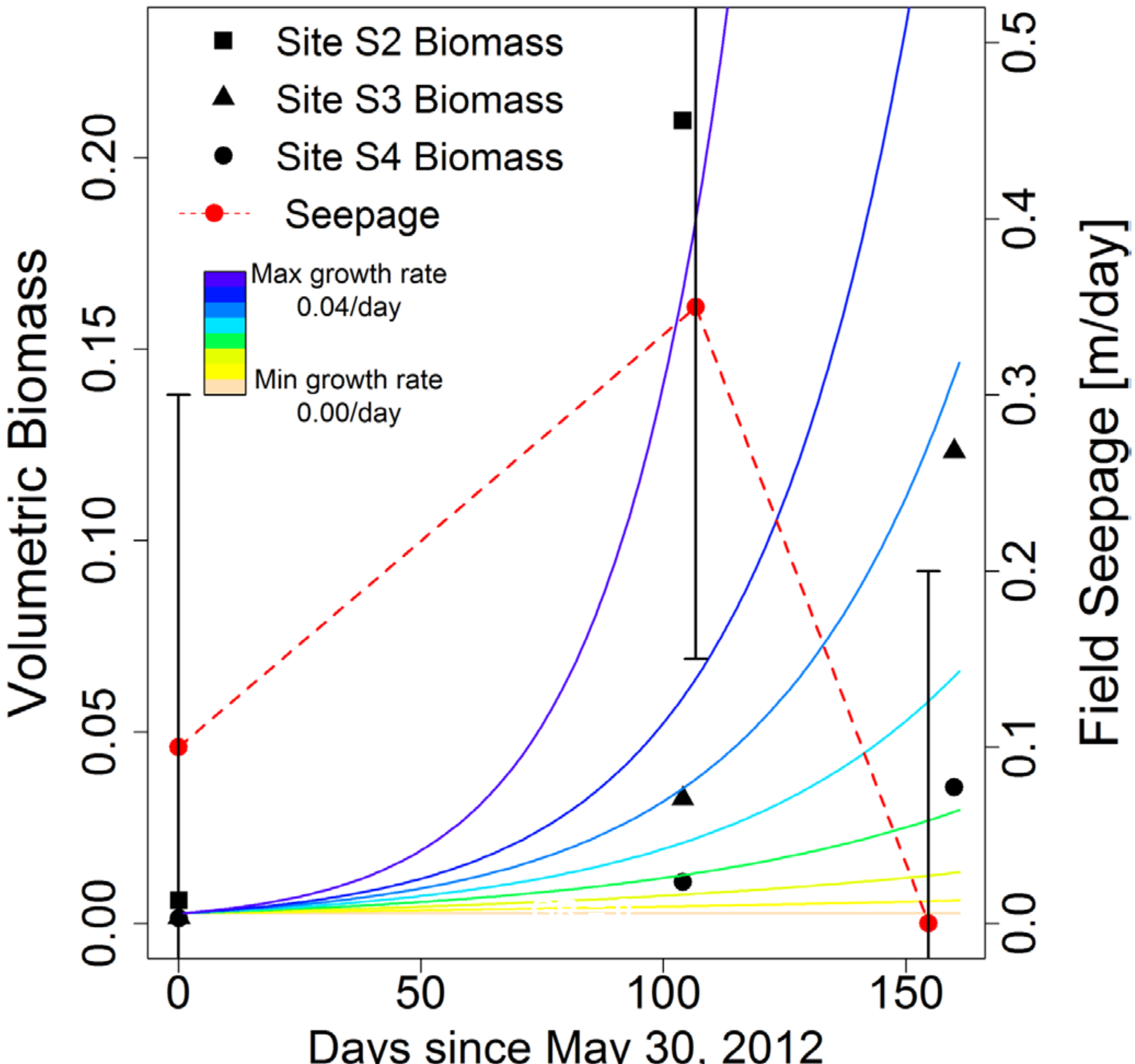


Common in Mediterranean Climates

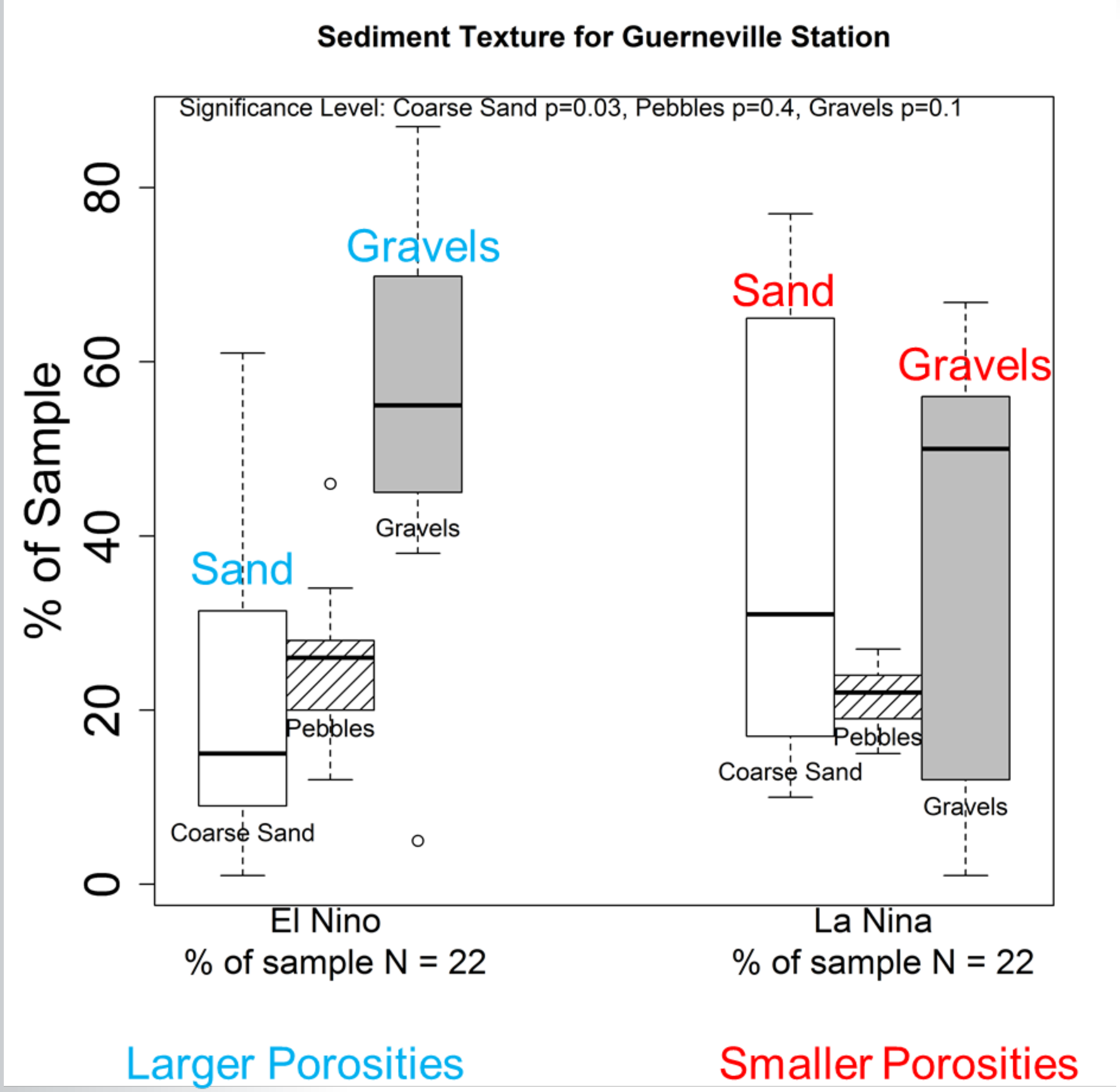


Images from [Brunner et al. 2009]

Field Site Data: Evidence for Bioclogging

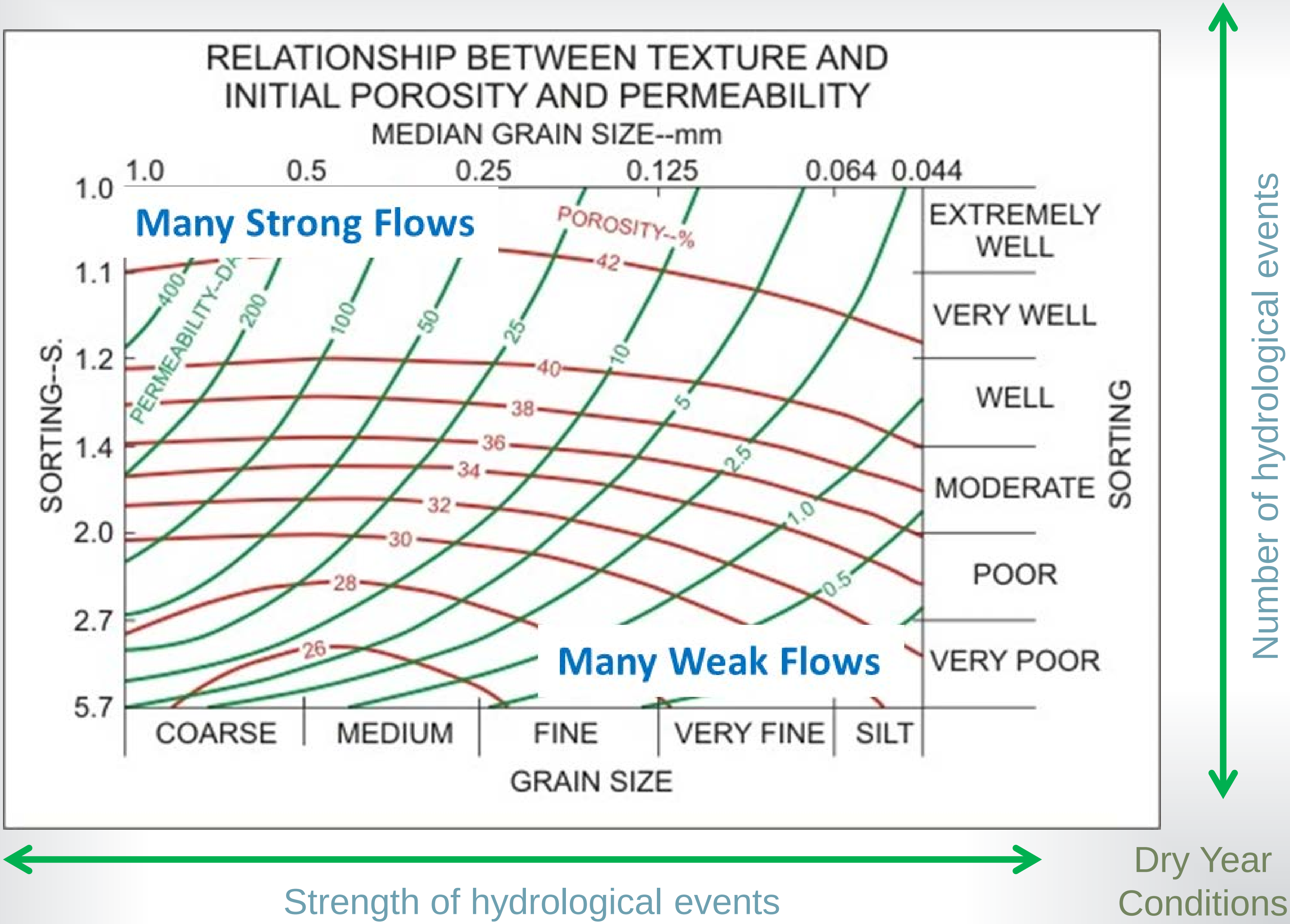


Top-Down Controls: Climatic Regulation of Sediments



Represent sediment parameters K and Φ as Initial Conditions (IC) within a numerical model

Linking Sediment Parameters to Climate



Dry Year Conditions

Methods: Upscale a Bioclogging Pore-Network Model

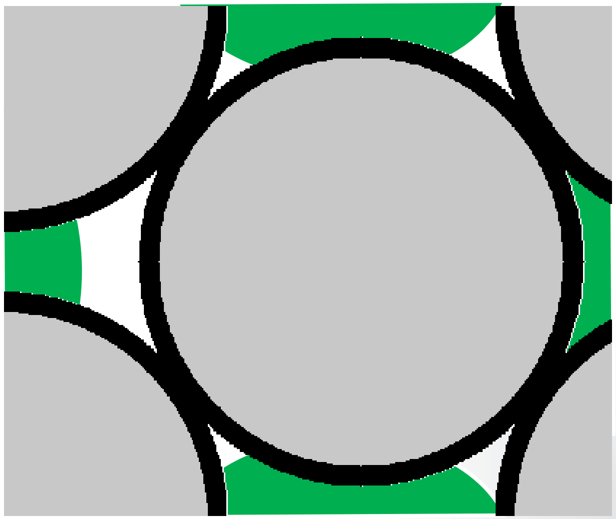
Colonies Model:
Φ and K = f(microbial growth)

- Theoretical permeability model[2]
- Related laboratory experiments and pore-network models to theory

Monod Kinetics:
Aerobic respiration **(AR)**
Anaerobic denitrification **(DN)**

$$K_{rel} = \left[\left(\frac{n_{rel} - n_0}{1 - n_0} \right)^b + K_{min} \right] * \frac{1}{1 + K_{min}}$$

- Equations included in MIN3P**
- Loosely-coupled approach with Hydrus 1D
- Change initial riverbed conditions (K and Φ) to represent antecedent winter river discharge



[2]Thullner, M. et al. [2002]

1D Numerical Setup

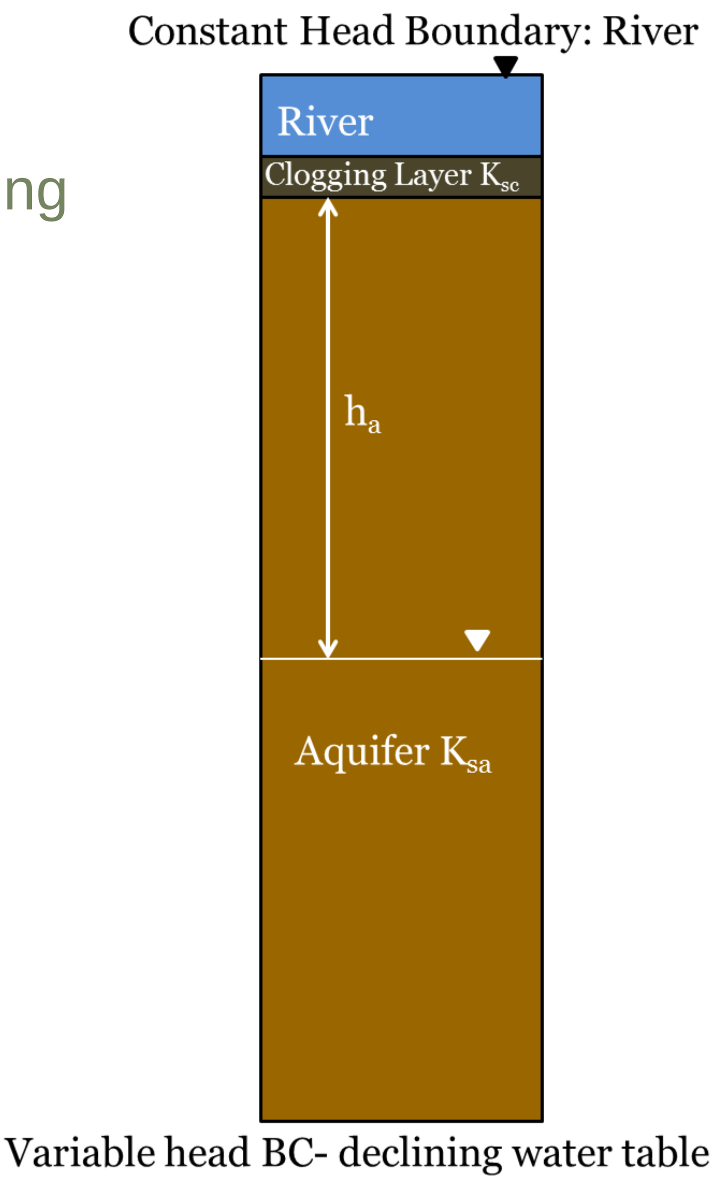
- MIN3P and Hydrus-1D numerical code
- K and Φ change over time in the clogging layer
- Lowering water table from pumping
- Fast vs. slow pumping
- Fast vs. slow biomass growth

Wet year end-member:

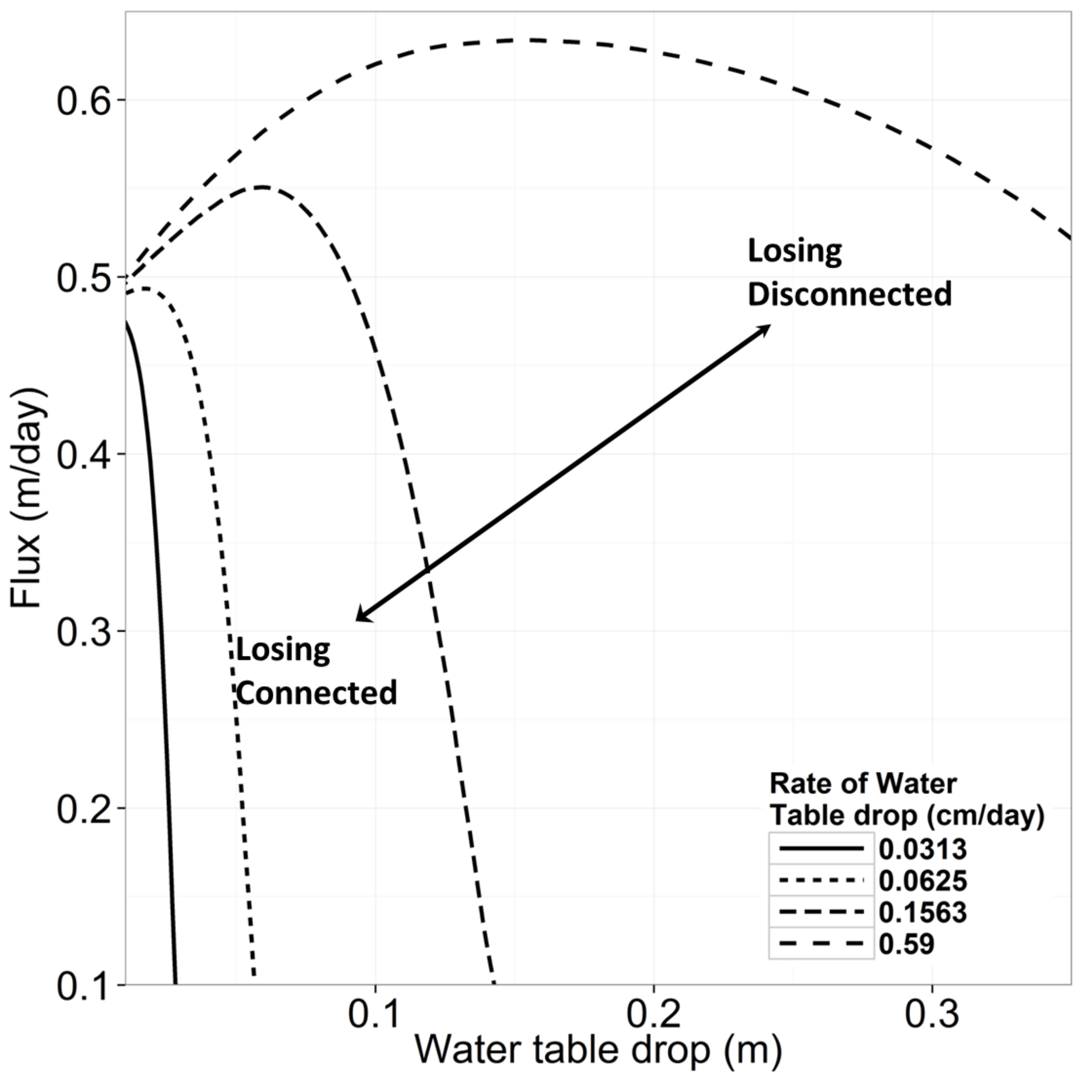
↑Q, ↑K, ↑Φ

Dry year end-member:

↓Q, ↓K, ↓Φ



Results: Fast vs. Slow Pumping

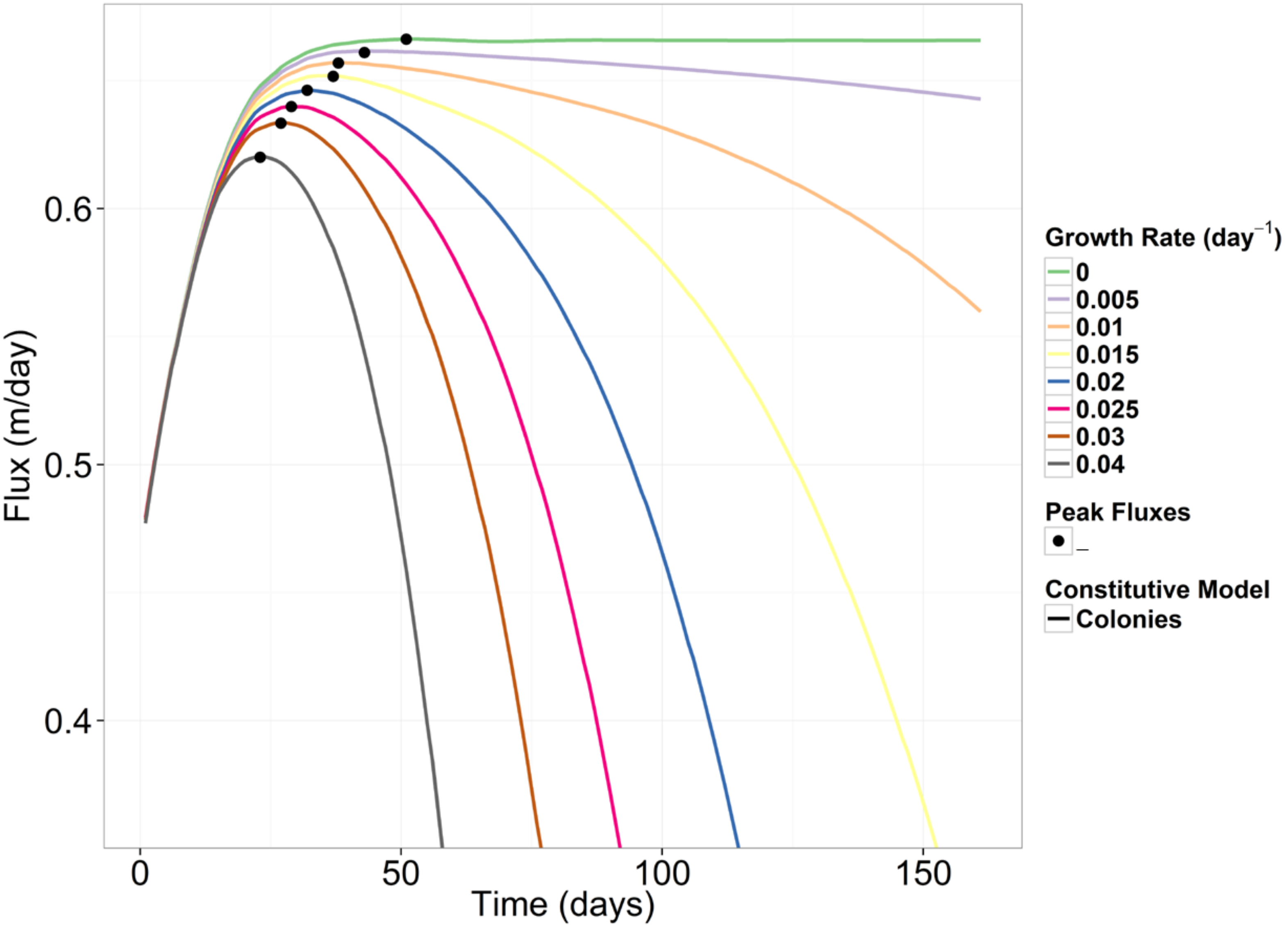


Processes Included

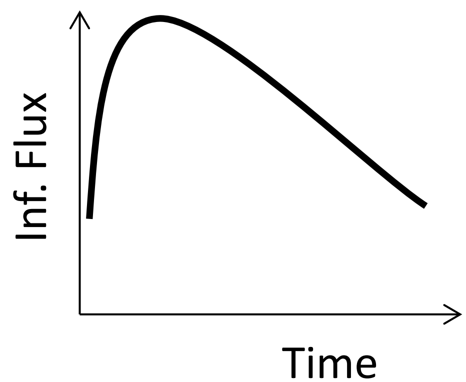
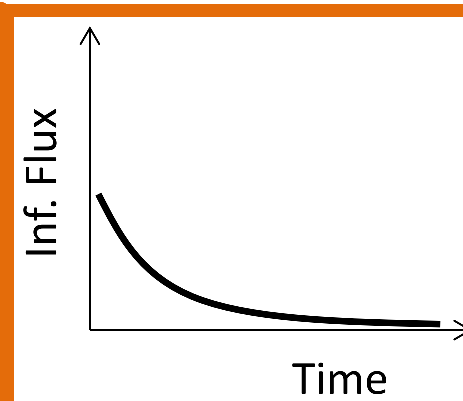
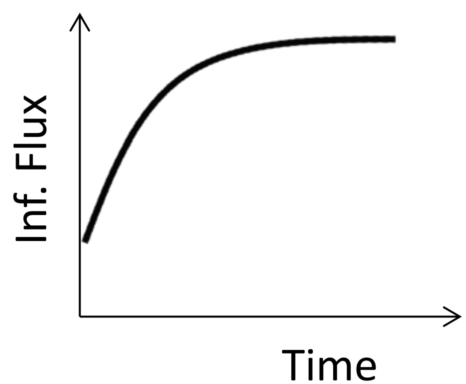
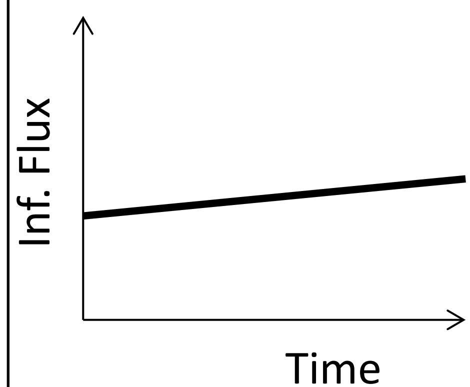
- Losing/Gaining
- Disconnection
- IC sediment parameters
- Topography
- Bioclogging

- Including these hydrological and biological processes was enough to predict seasonal trend

Key Findings



Results: Bioclogging Bottom-up Feedback

	w/ Unsaturated Conditions	w/o Unsaturated Conditions
	Losing-Disconnected River Fast Water Table Drop	Losing-Connected River Slow Water Table Drop
Biomass Growth		
No Biomass Growth		

New Paper!

AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2015WR018351

Key Points:

- Riverbed bioclogging is a key control on infiltration in losing rivers
- River infiltration gains from disconnection can offset riverbed permeability declines caused by bioclogging
- Permeability reduction can hasten the onset of disconnection

Supporting Information:

- Supporting Information S1
- Data Set S1

Correspondence to:
Y. Rubin,

Simulating bioclogging effects on dynamic riverbed permeability and infiltration

Michelle E. Newcomer[1,2], Susan S. Hubbard[3], Jan H. Fleckenstein[2], Ulrich Maier[2], Christian Schmidt[2], Martin Thullner[4], Craig Ulrich[3], Nicolas Flipo[5], and Yoram Rubin[1]

[1]Department of Civil and Environmental Engineering, University of California, Berkeley, Berkeley, California, USA, [2]UFZ-Helmholtz Centre for Environmental Research, Department of Hydrogeology, Leipzig, Germany, [3]Lawrence Berkeley National Laboratory, Earth Sciences Division, Berkeley, California, USA, [4]UFZ-Helmholtz Centre for Environmental Research, Department of Environmental Microbiology, Leipzig, Germany, [5]Geosciences Department, MINES ParisTech, PSL Research University, Paris, France

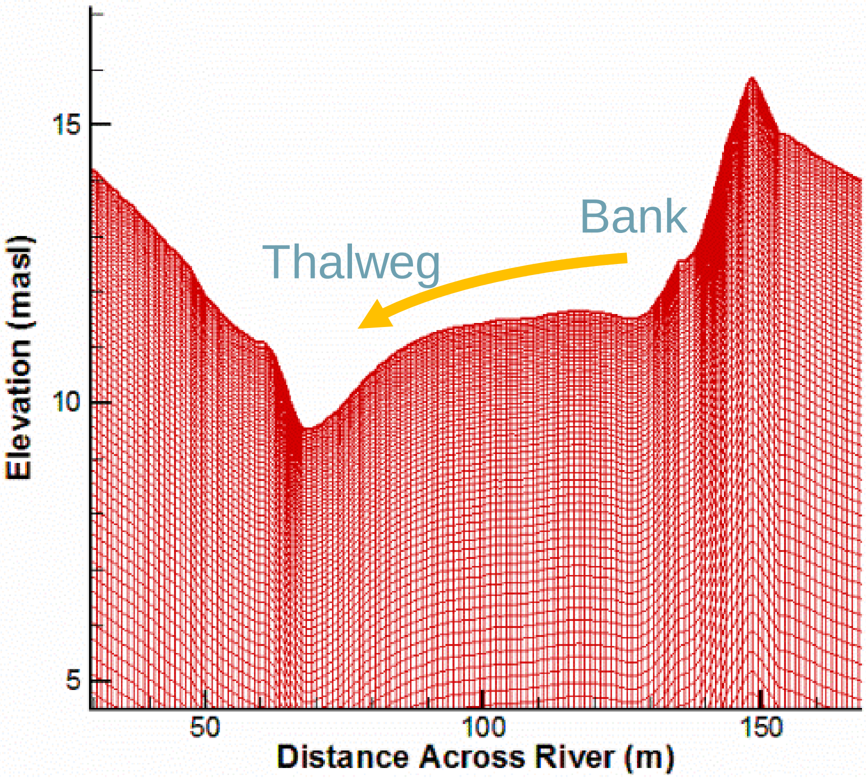
Abstract Bioclogging in rivers can detrimentally impact aquifer recharge. This is particularly so in dry regions, where losing rivers are common, and where disconnection between surface water and ground-water (leading to the development of an unsaturated zone) can occur. Reduction in riverbed permeability due to biomass growth is a time-variable parameter that is often neglected, yet permeability reduction

Feedbacks within the numerical model MIN3P

- Nutrient substrates for biomass growth + K, Φ

→ A novel approach in numerical models

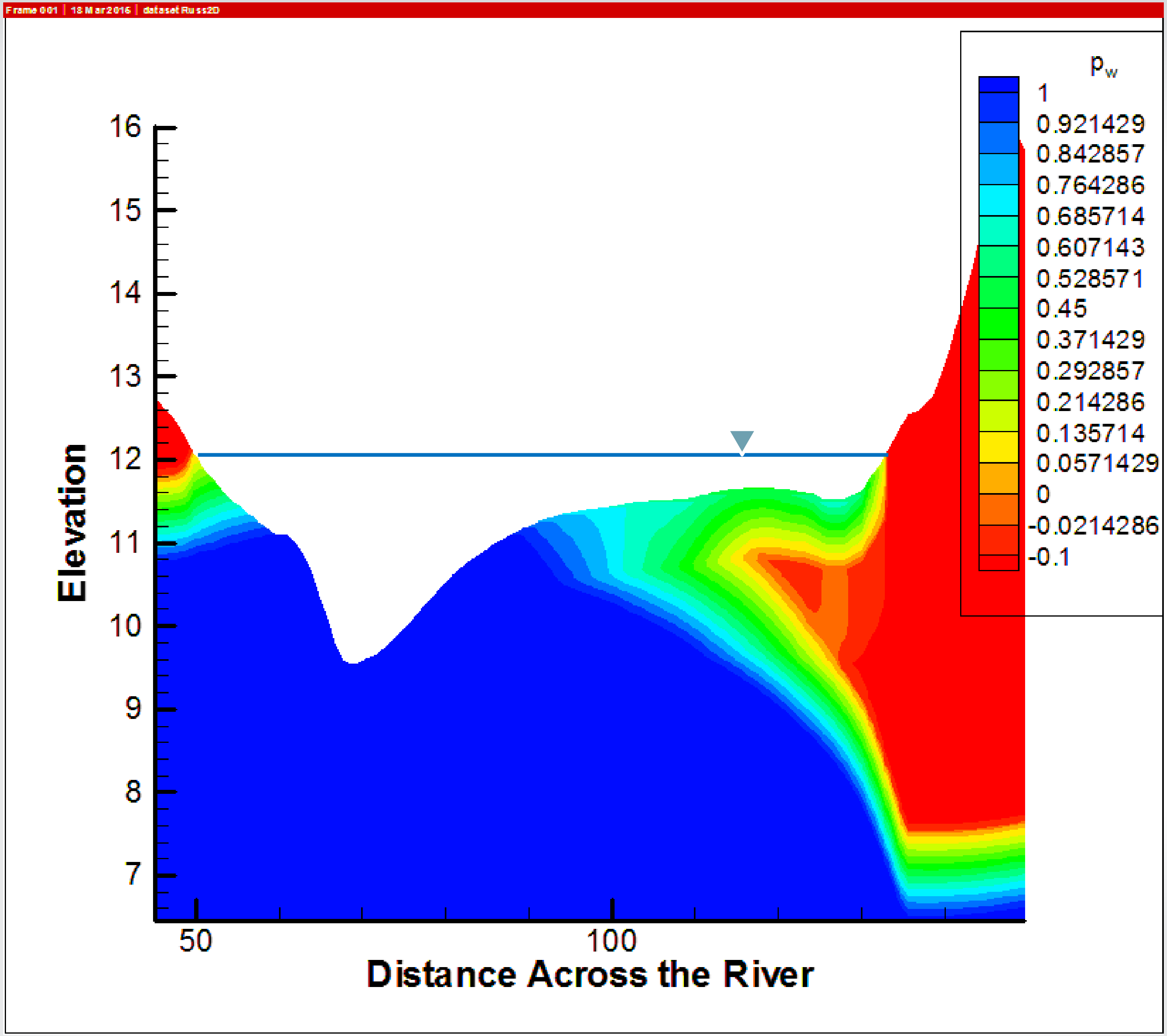
  - Measure C consumption, biomass growth, CO_2 and N_2 production across the spatial gradient



Processes to include in modeling

- Disconnection
- Pumping
- Initial sediment parameters
- Topography
- Bioclogging from DOC, NO3

Develops an inverted water table



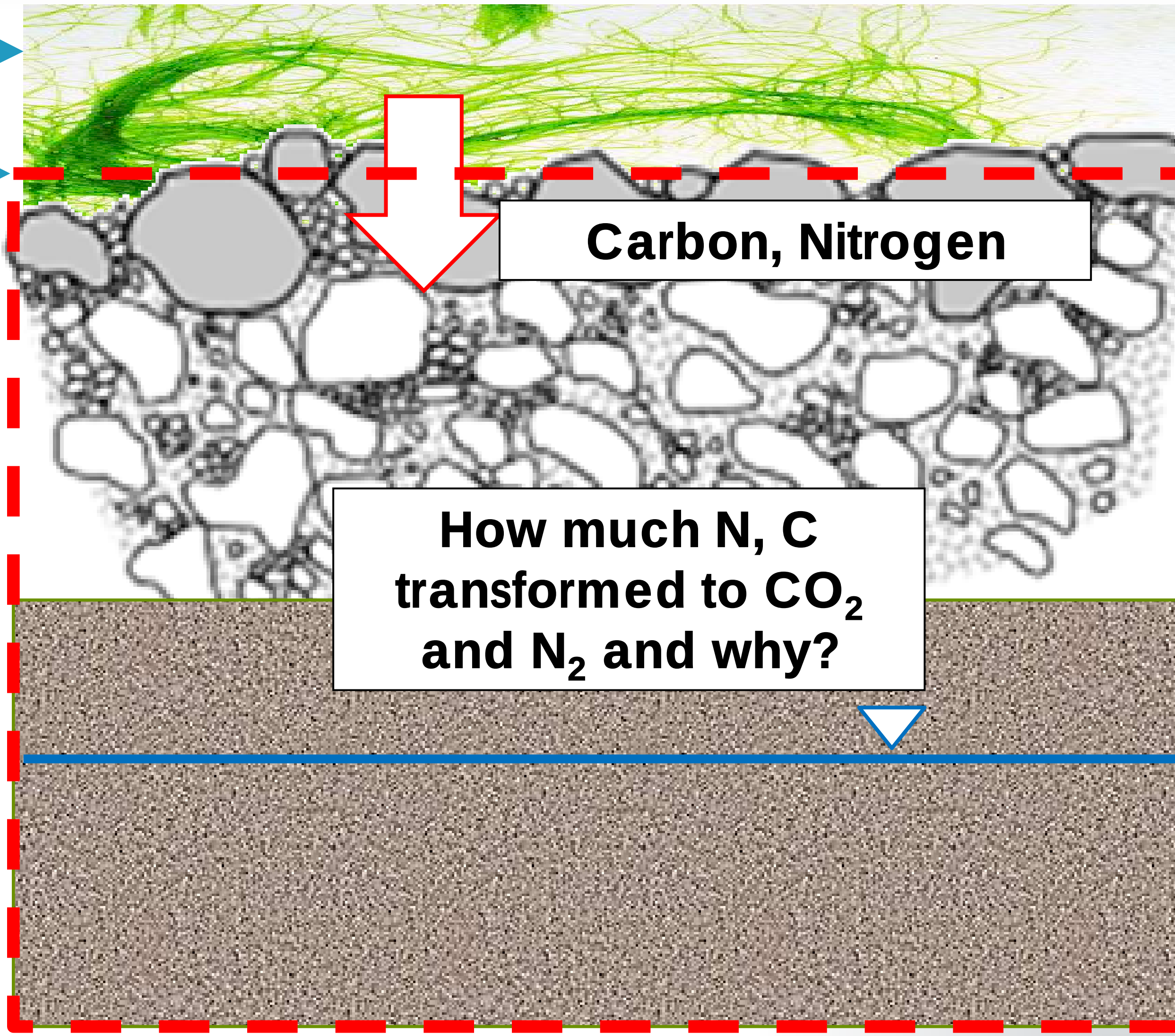
Linking Surface Ecology and Subsurface N,C Transformations

Algae growth

Riverbed

Sediment Parameters

Aerobic/Anaerobic microbes consume C, N



Microbes Grow → **Fill Pore Space** → **Reduce Φ and K** → **Reduce Infiltration**

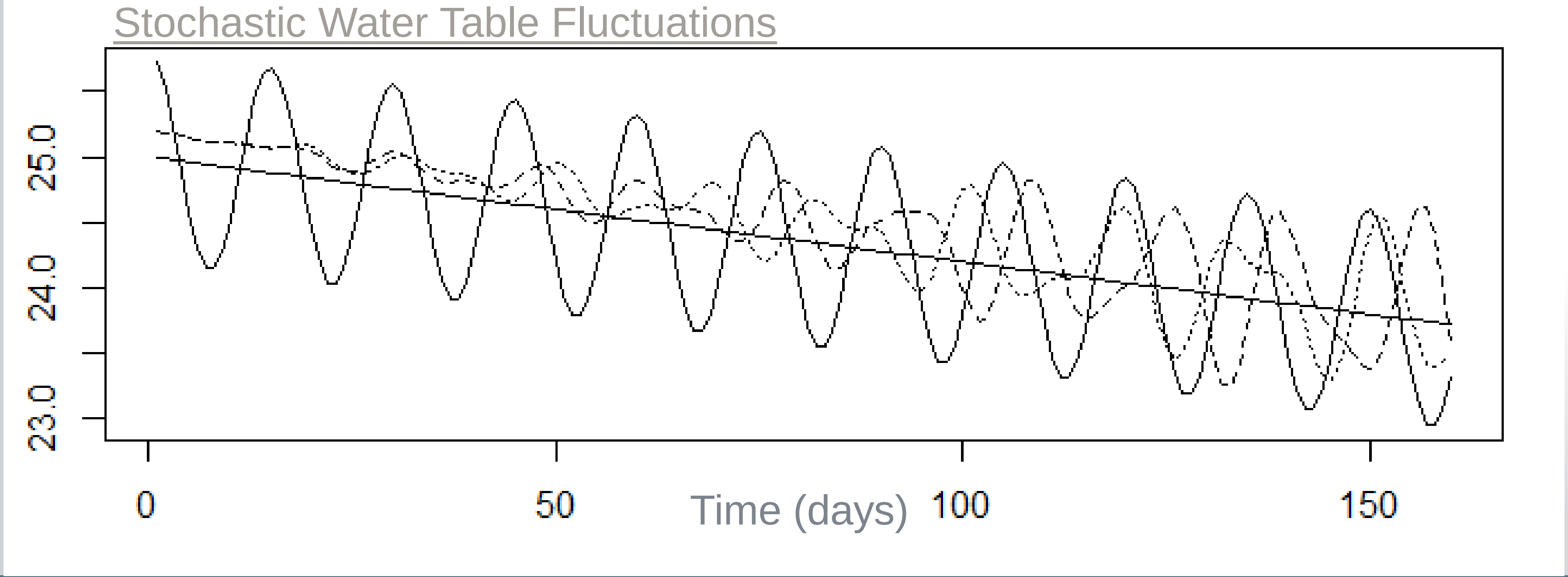
Feedback Effect: Unsteady nutrient supply

Top-Down Controls: Stochastic Water Levels

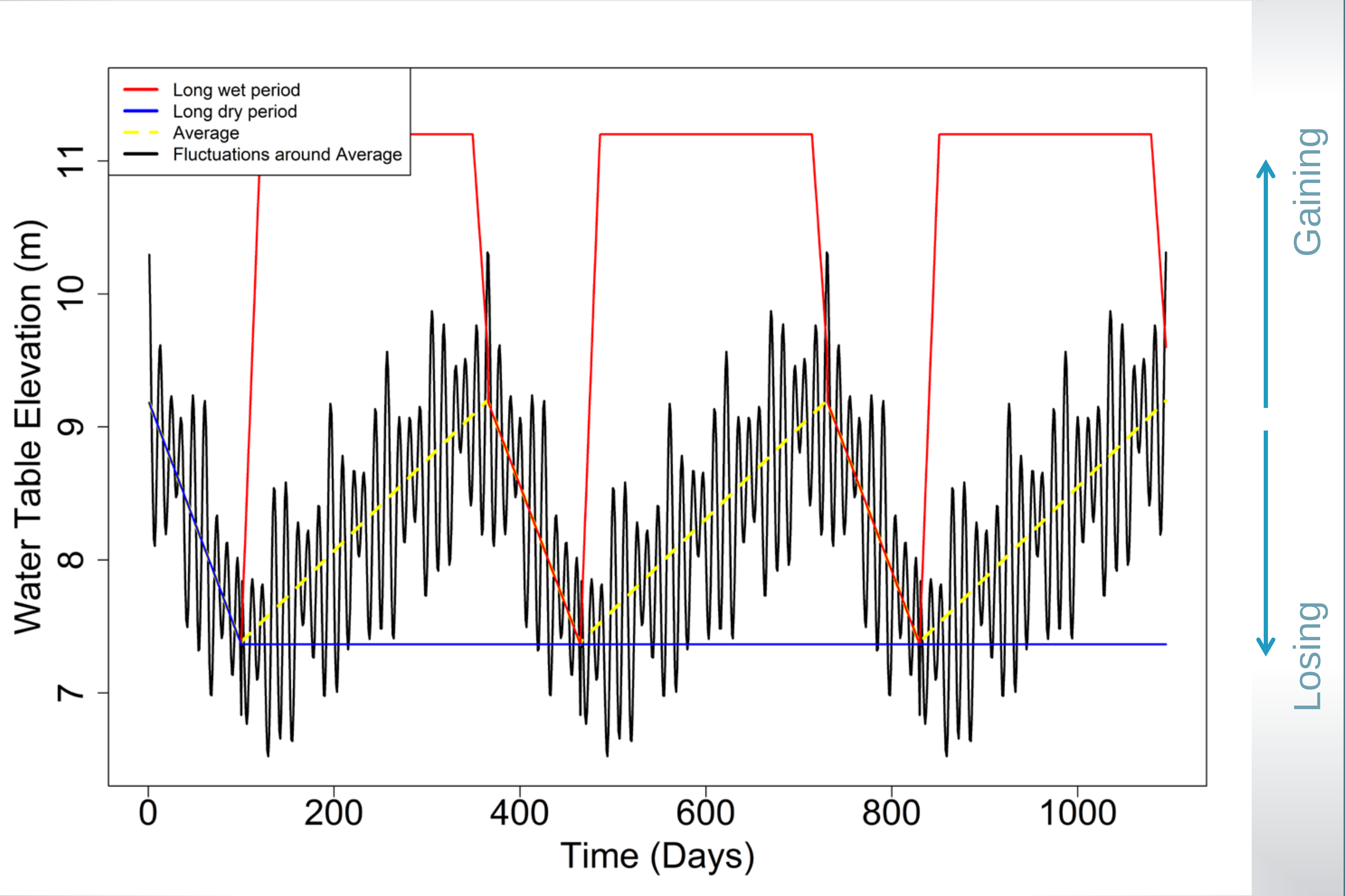
Fourier spectrogram of pumping time series → Extract dominant frequencies and create pdf

Sample pdf and reconstruct water levels with imposed dominant frequencies (fast/slow, losing/gaining)

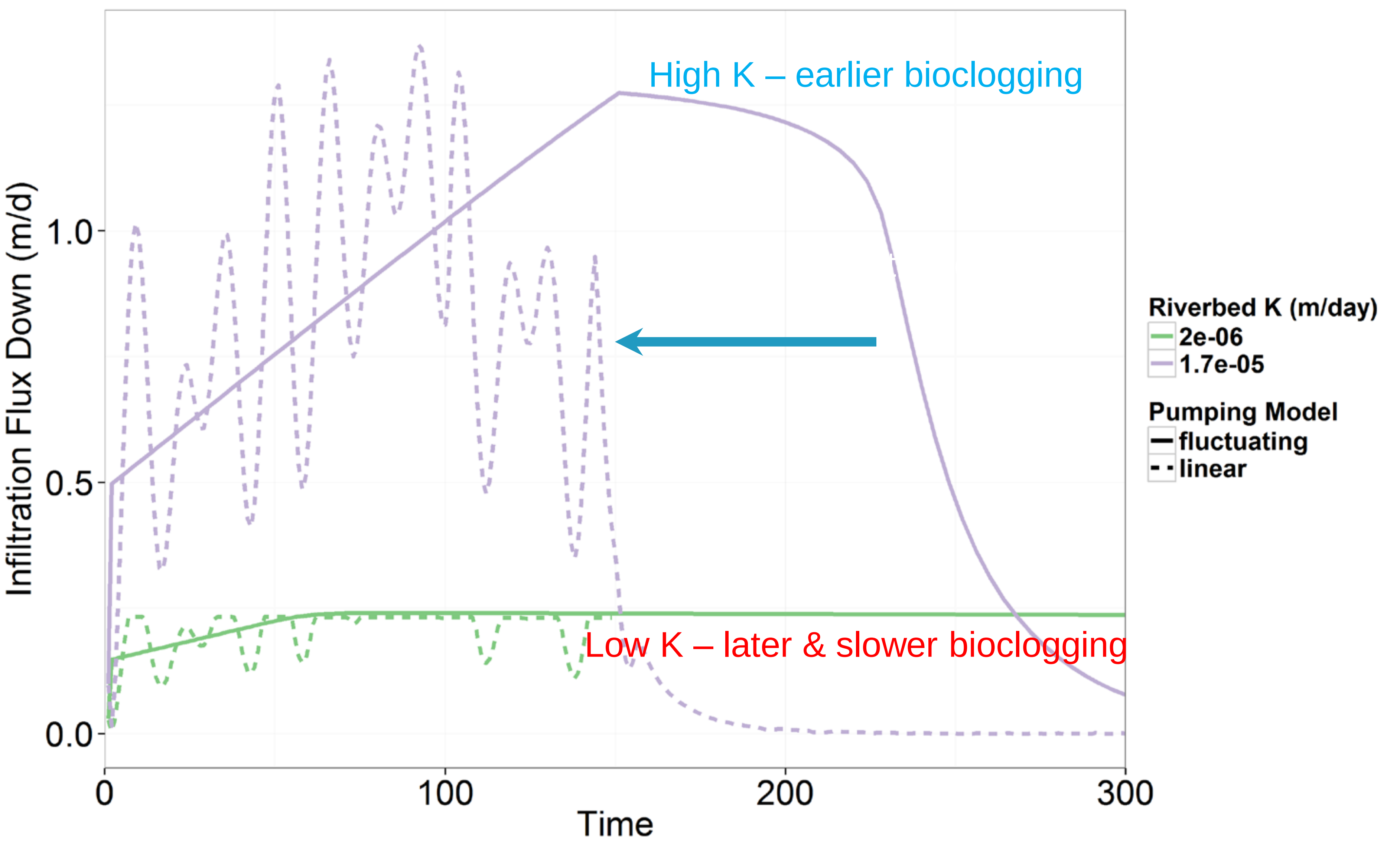
- What is the effect on C, N processing, bioclogging hotspots?



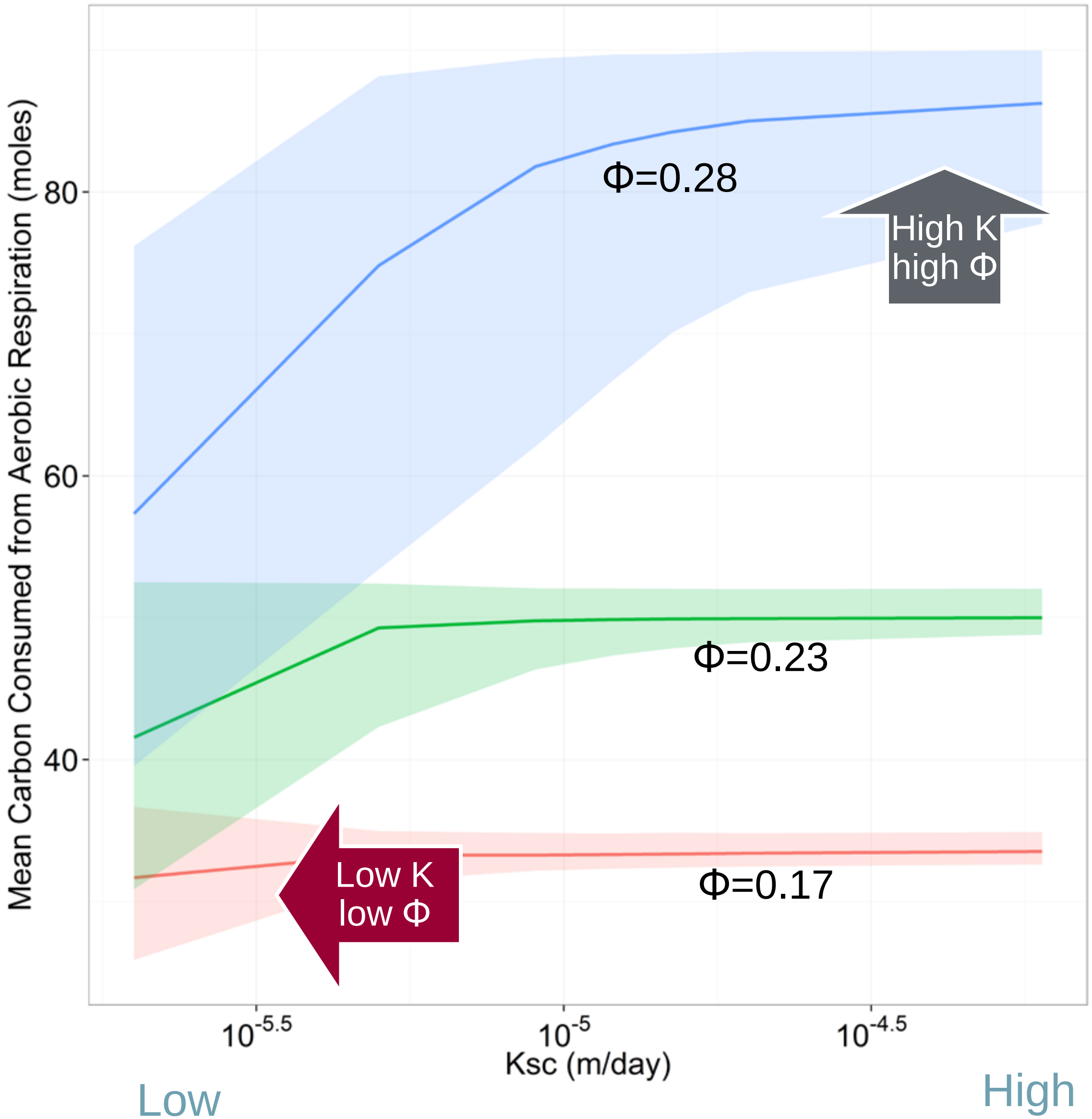
Groups Based on Climate & Seasonality



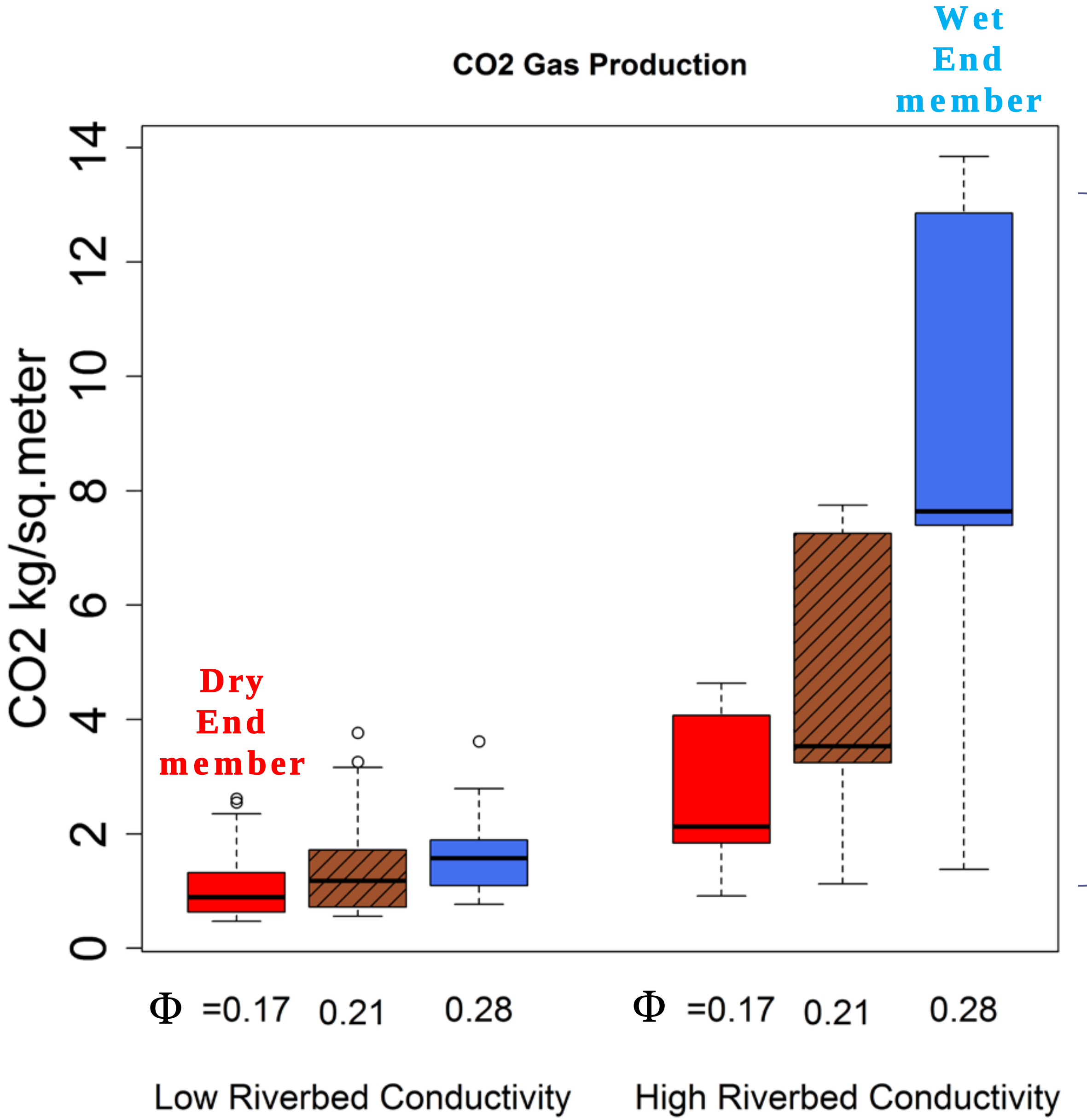
Fluctuations Lead to Enhanced Bioclogging and Hastened Infiltration Decline



Results: Carbon Transformations are Dependent on River Sediment Structure



Sediment Effects on CO_2 Gas Production



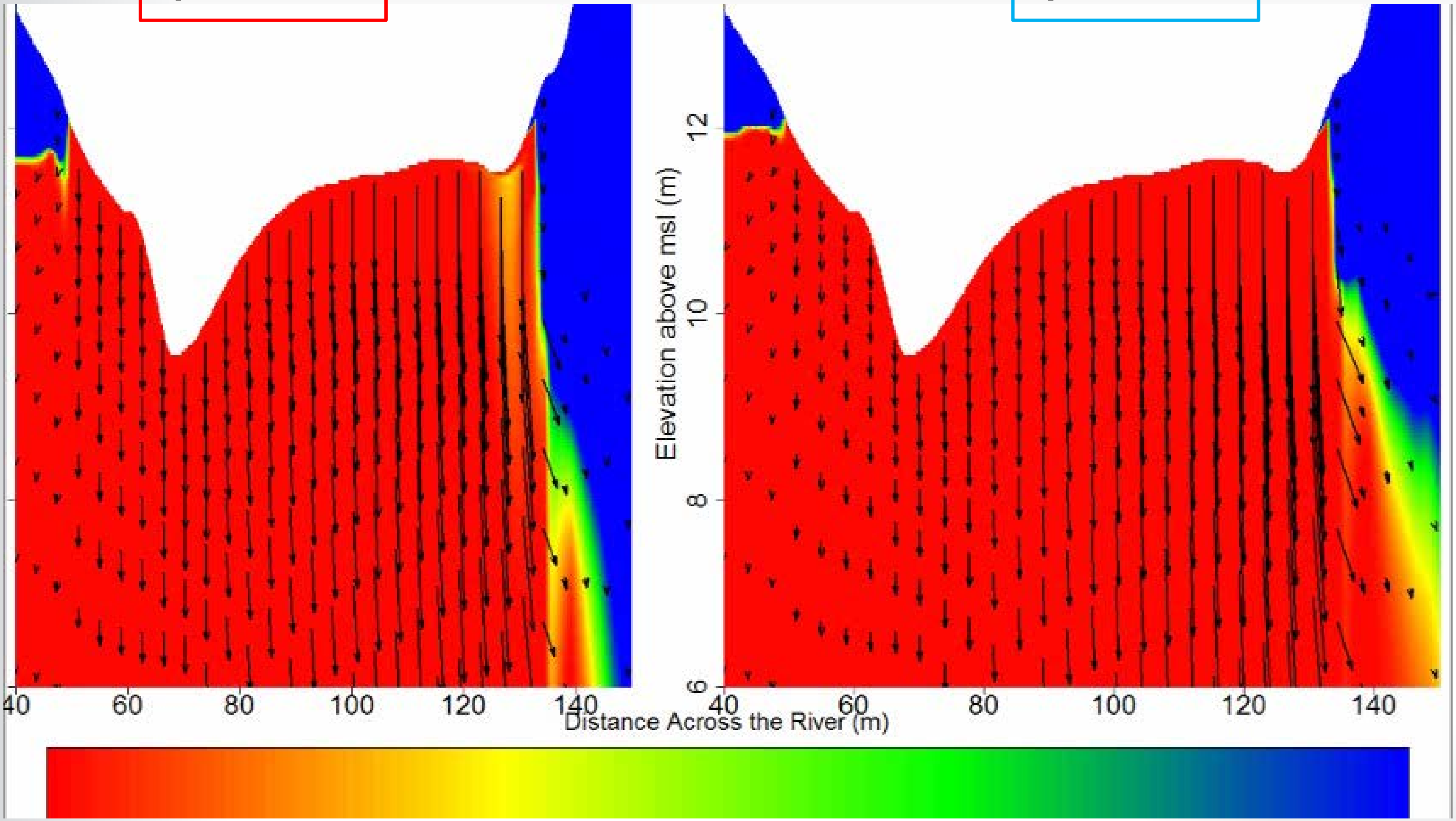
High range represents variation in frequency of pumping

Undergoes Disconnection

$\Phi = 0.17$

No Disconnection

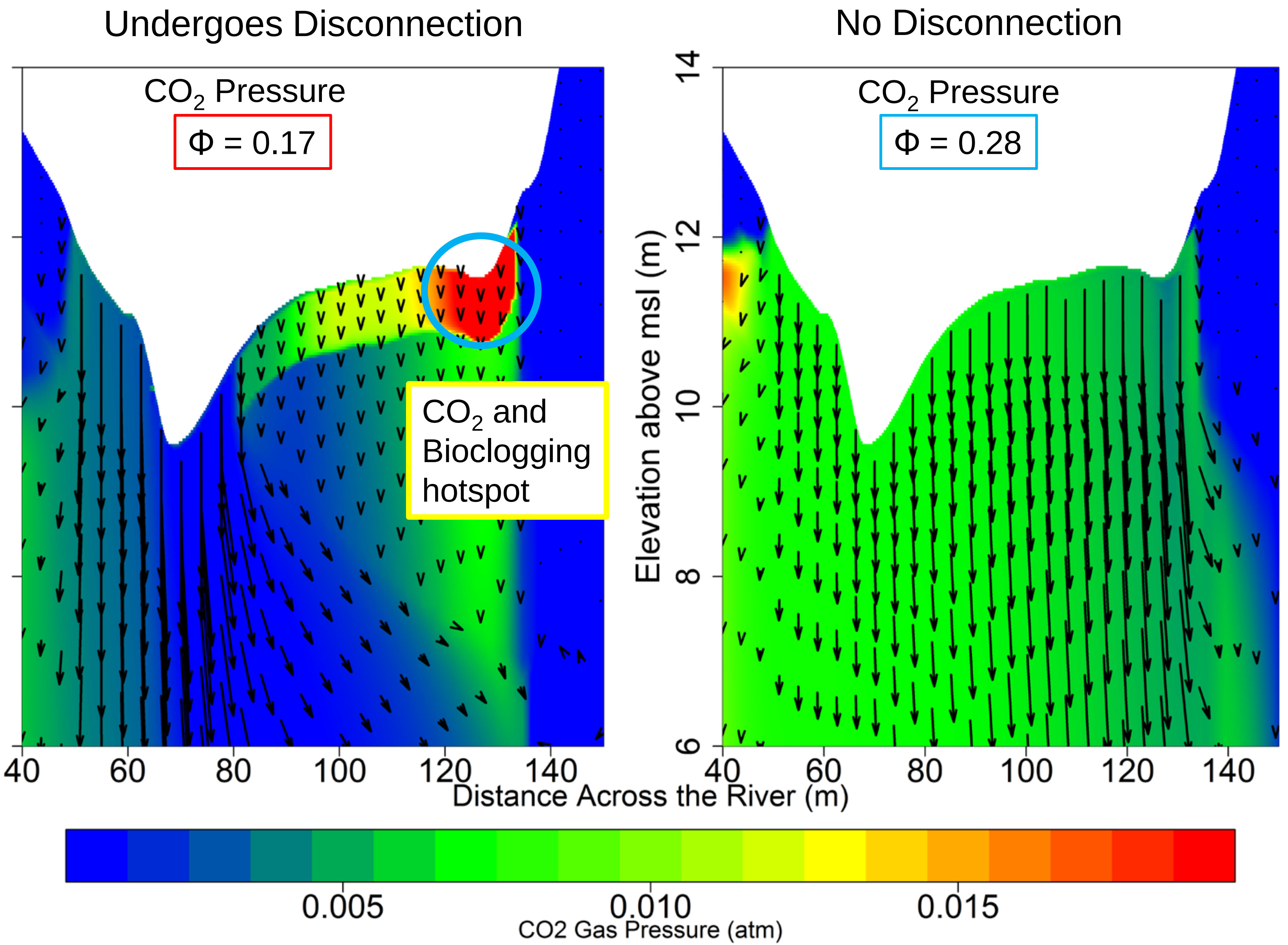
$\Phi = 0.28$



Low

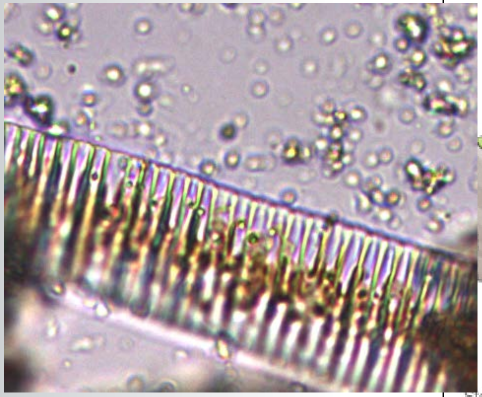
High

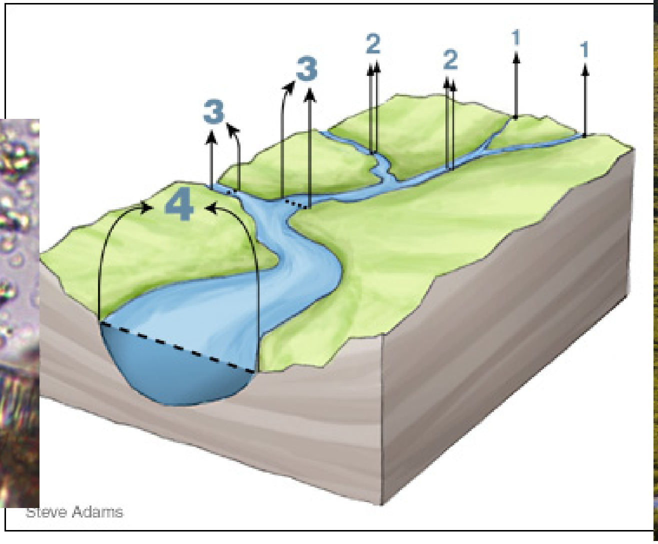
O_2 Concentration

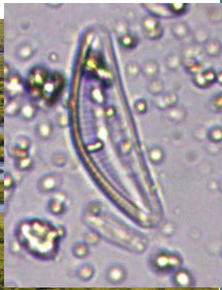

Undergoes Disconnection
No Disconnection
CO2 Pressure
Φ = 0.17
CO2 Pressure
Φ = 0.28
CO2 and Bioclogging hotspot
Elevation above msl (m)
6
8
10
12
14
40
60
80
100
120
140
Distance Across the River (m)
0.005
0.010
0.015
CO2 Gas Pressure (atm)

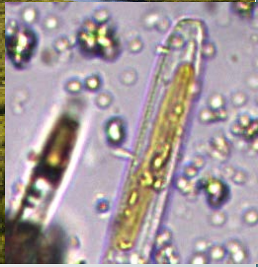
Top-Down Controls: Surface Ecology Stimulates Subsurface Activity

- Lateral hyporheic flow model implemented in MIN3P for the East River Catchment, CO
- Montane, Semi-Arid Climate (Dry winter, wet summer): Climate scenarios projected to reduce streamflow
- Surface Ecology as a source of C and N for subsurface microbes









Benthic Algae Growth and Phytoplankton

- Top-down, hydro-ecological controls on subsurface bioclogging

Winter with at least one storm that resets bed sediments

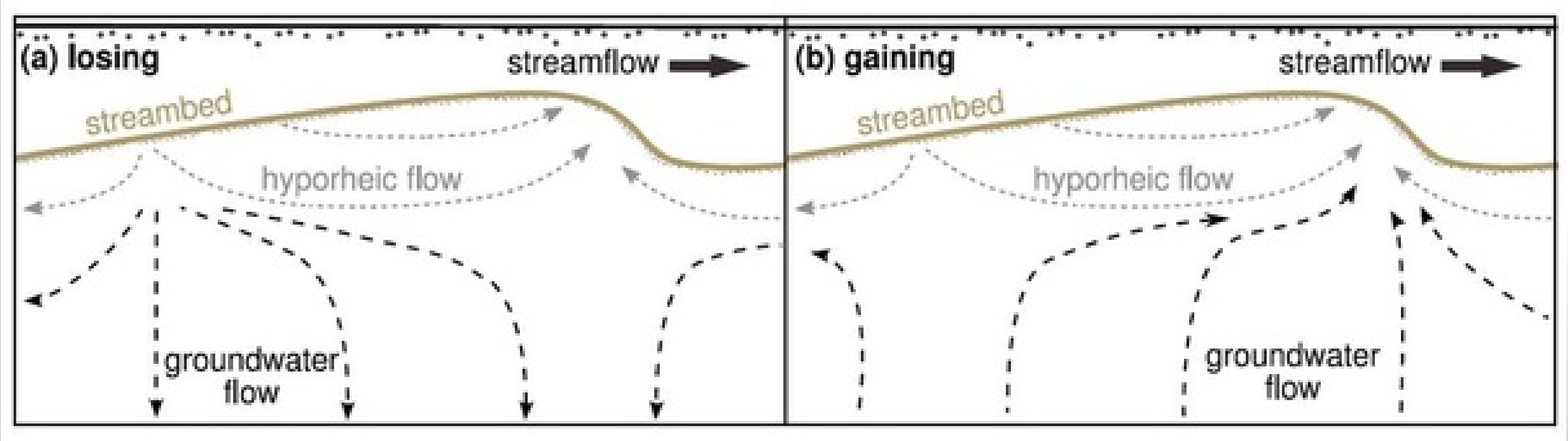
More discharge → Resetting of bed sediments → Loss of grazers that eat algae → More algae growth → ↑Substrate for heterotrophic bacteria

No storms that reset bed sediments

Less discharge → No scour of sediment → Large population of grazers → Less algae growth → ↓Substrate for bacteria

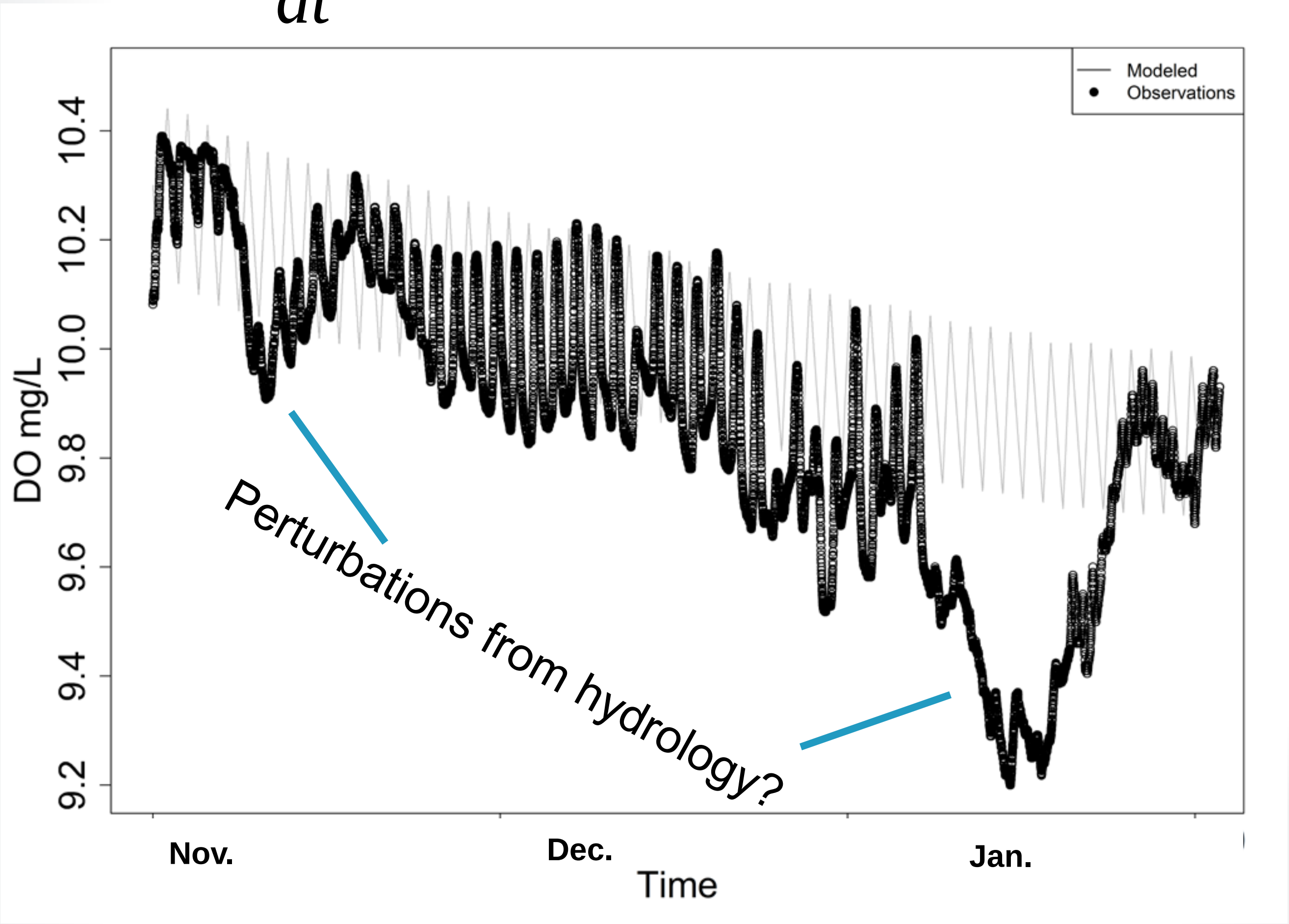
Representing Horizontal Hyporheic Fluxes

- Simulate spring/summer primary productivity
- Seasonal climatic DOC and DO in surface water
- What happened in the previous winter affects the next spring



The East River: Primary Productivity

$$\frac{dO}{dt} = D(O_s - O) + P - R - HO$$



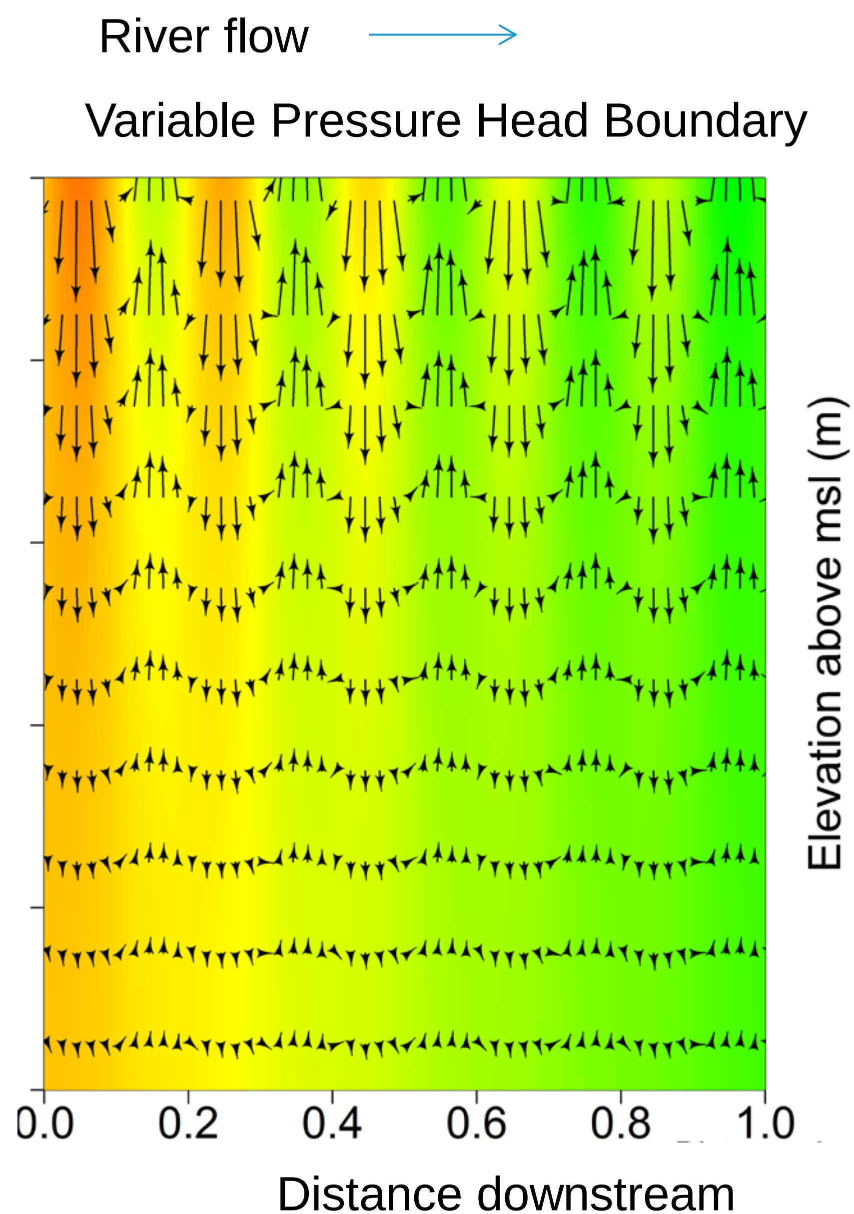
Groundwater Discharge?
Lagged pulses?

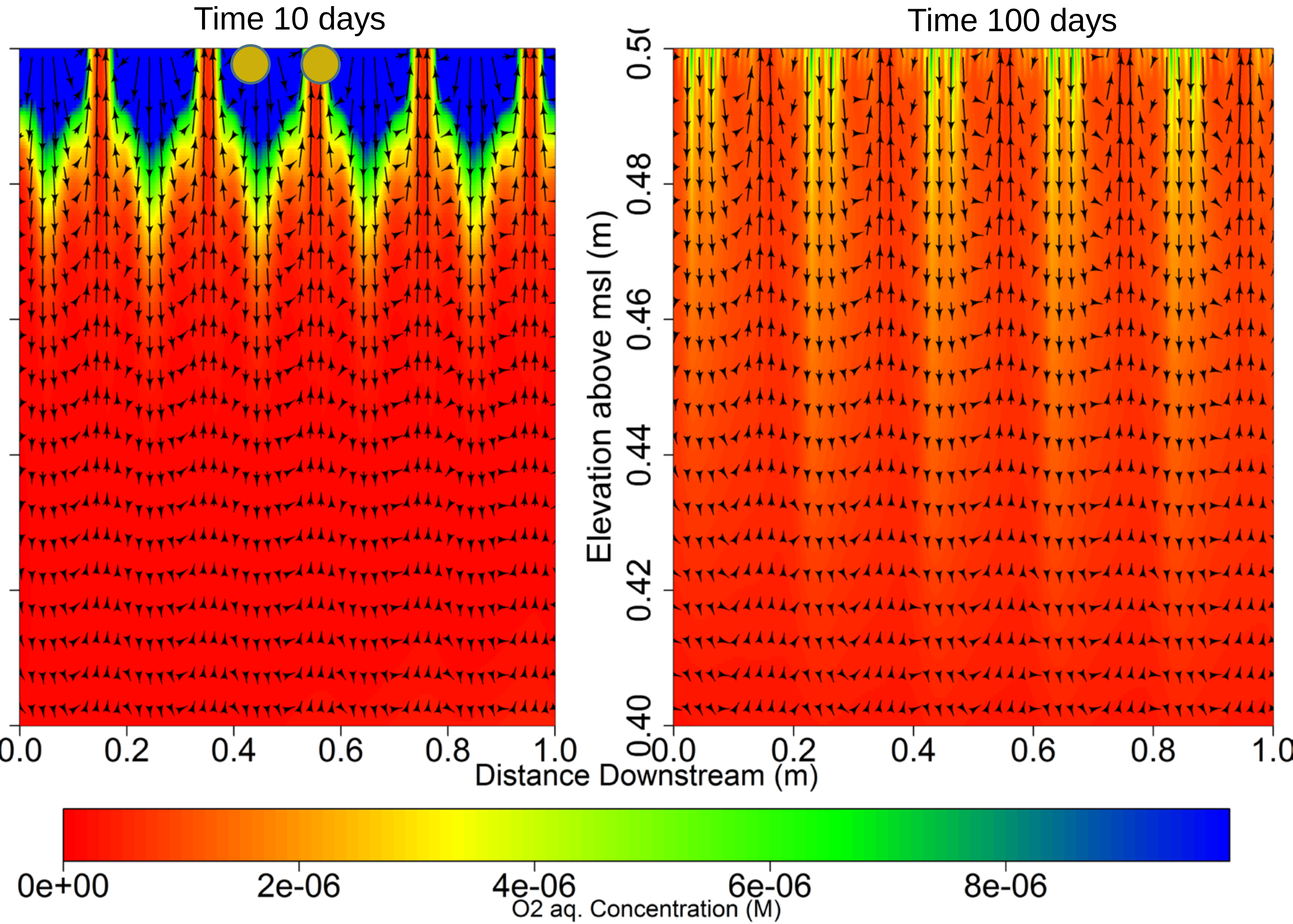
Lateral Hyporheic Flow Model with Primary Productivity

- Simulate spring/summer DO conditions
- Implement as BC in MIN3P model

Elliott & Brooks Head Boundary

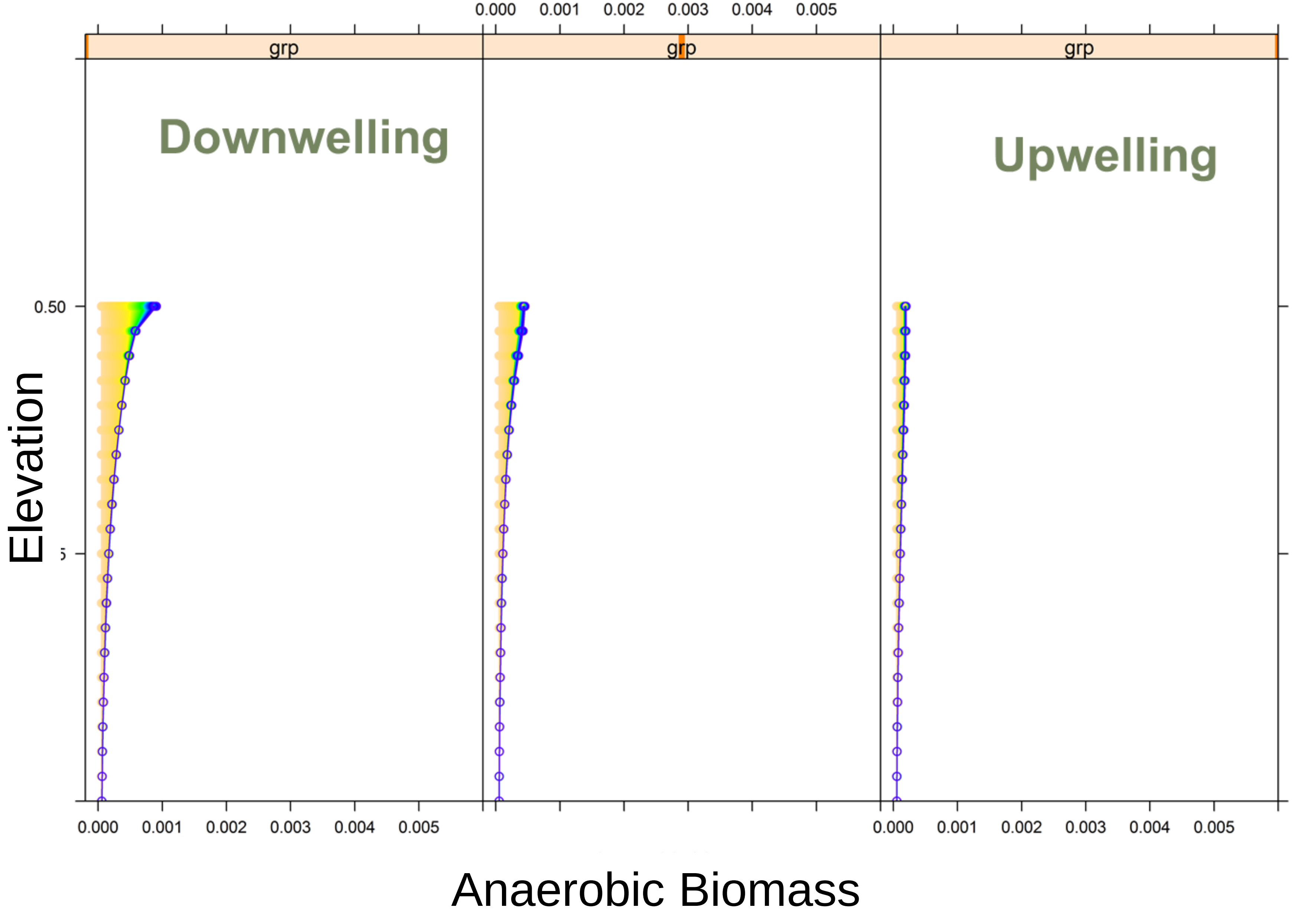
$$h_m = 0.28 \frac{U^2}{2g} \begin{cases} \left(\frac{H/d}{0.34}\right)^{3/8} & H/d \le 0.34 \\ \left(\frac{H/d}{0.34}\right)^{3/2} & H/d \ge 0.34 \end{cases}$$



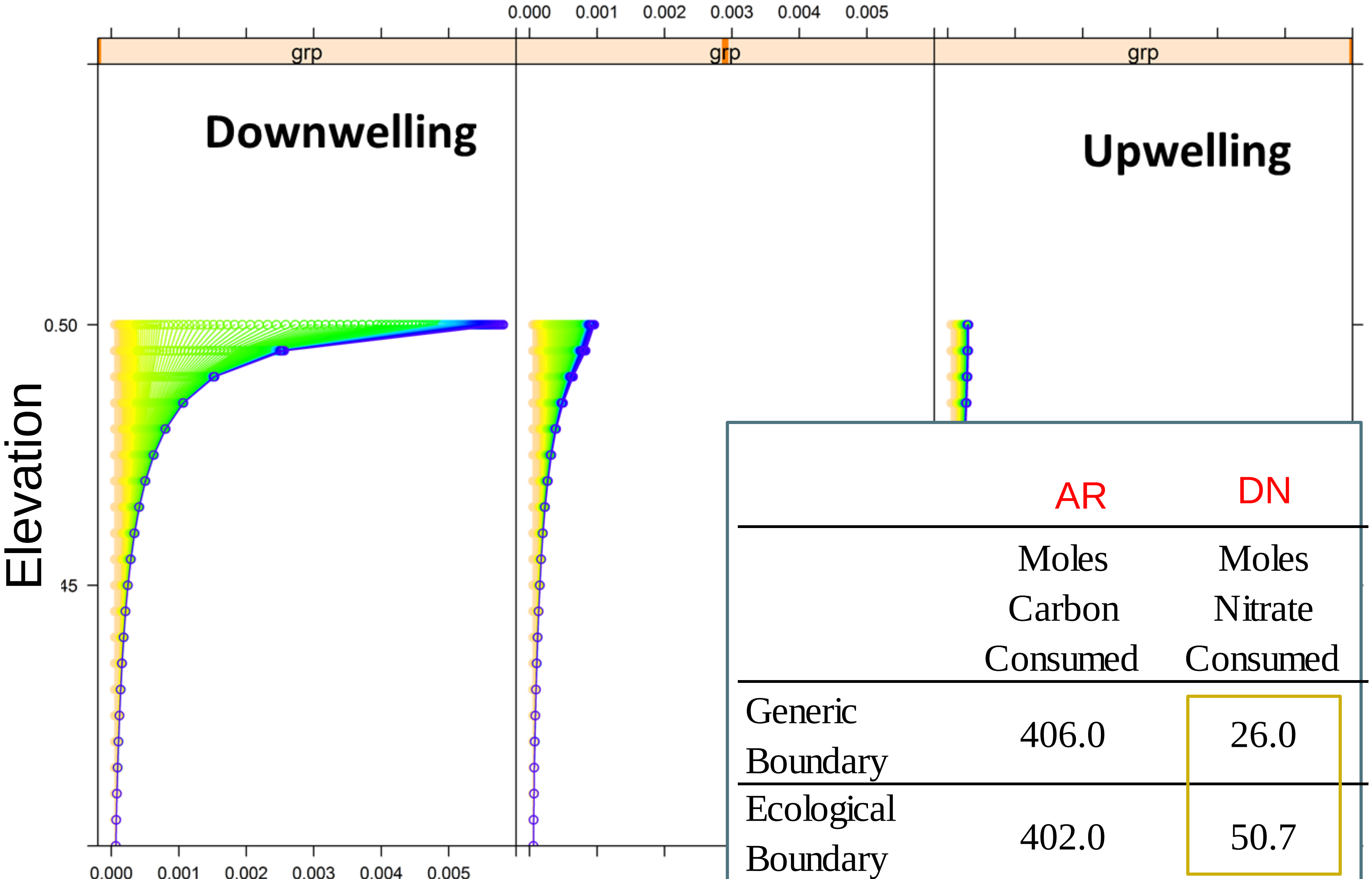


Time 10 days
Time 100 days
Elevation above msl (m)
0.50
0.48
0.46
0.44
0.42
0.40
0.0
0.2
0.4
0.6
0.8
1.0
Distance Downstream (m)
0e+00
2e-06
4e-06
6e-06
8e-06
O2 aq. Concentration (M)

Without an Ecological Boundary



Without an Ecological Boundary



	AR	DN
	Moles Carbon Consumed	Moles Nitrate Consumed
Generic Boundary	406.0	26.0
Ecological Boundary	402.0	50.7

Anaerobic Biomass

[Hinkle et al., 2001]. Linking hyporheic flow and Nitrogen cycling. JOH

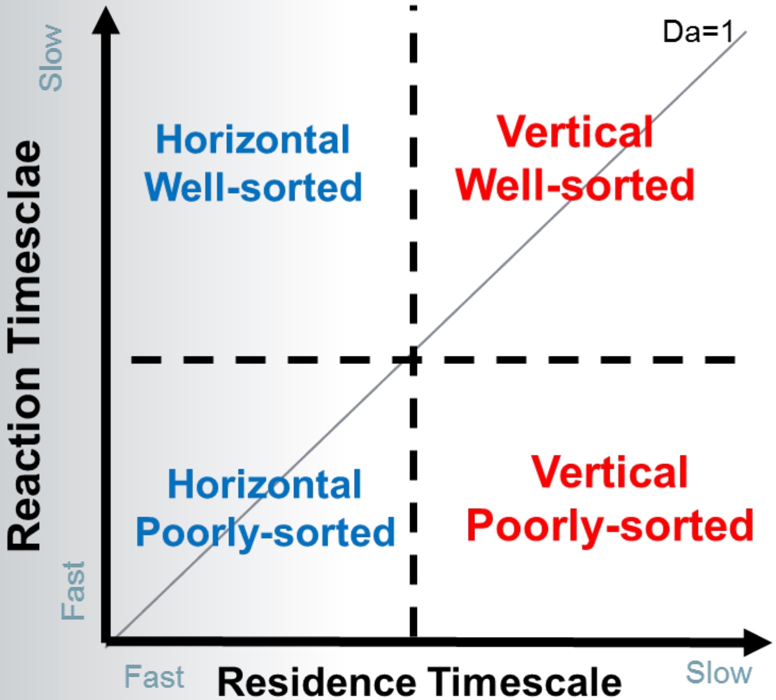
Important Implications

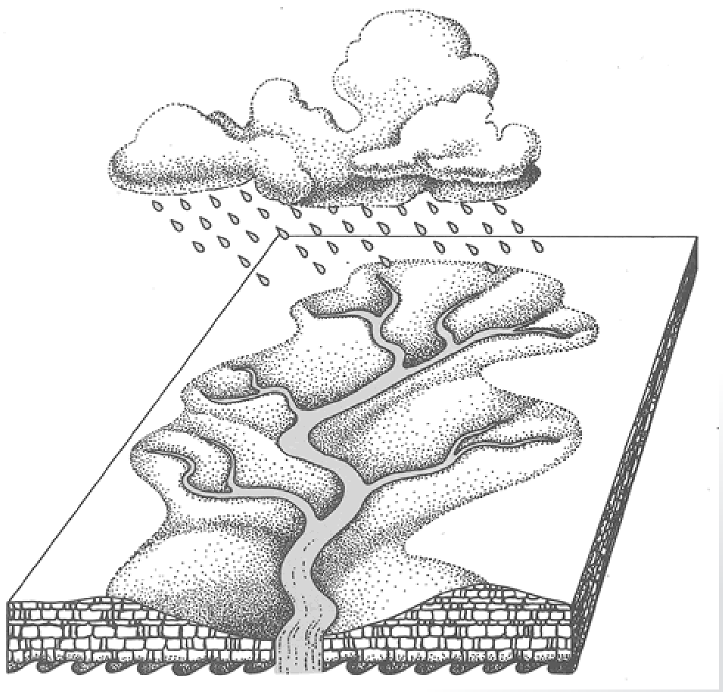
- Coupled biological, ecological, and physical processes at river beds influence critical ecosystem services:

1) Aerobic subsurface respiration contributing to NPP

2) Anaerobic subsurface denitrification

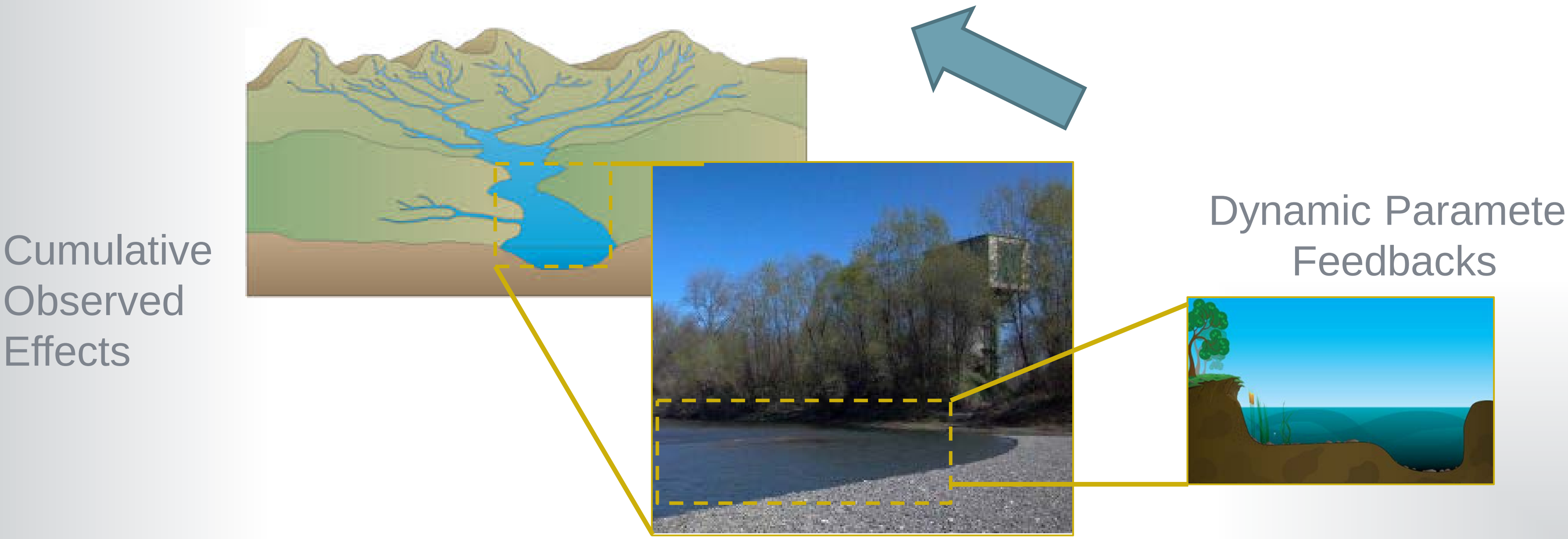
3) Total infiltration and recharge for ET





Upscaling to the Watershed

- New approaches needed to allow dynamic parameter feedbacks in models
  - Migration to PFLOTRAN
  - Effect on larger scale net primary productivity in rivers?
  - → New methods to exchange parameter models and flow models



A special thanks…

SONOMA COUNTY WATER AGENCY

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

THE UNIVERSITY OF CALIFORNIA 1868 LET THERE BE LIGHT

HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ

MINES ParisTech