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

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Top-Down Processes Control Flow and Geochemistry of a Watershed

- Wet/Dry catchments regulate water chemistry (DOC and O₂)
- Land uses regulate infiltration, chemistry, habitats
- Geomorphology
- Sediment
- Ecology
- Climate Type
- Extreme Events
- Fires
- Geology
- Discharge
- Infiltration regime
- Meanders
- Riparian habitat
- Sediment structure
- Banks/Thalwegs
- Agriculture/Pumping
- Hyporheic
- Invertebrates
- Algae
- Biofilms
- Microbes

Observations of cumulative effects

Water & DOC pulses

Food-web support

Flow & Reactions
Bottom-Up Feedbacks Contribute to Cumulative Effects

Weather Controls Bankfull Discharge Events

Chemistry

Local DOC Production, DO regulation

External DOC, NO₃ inputs

Microbial Transformation of DOC, NO₃ to CO₂, N₂, Bioclogging

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

GSD controls substrate transport through pores

With A Scouring Event

Without A Scouring Event

Fast Hydraulic K

GSD shifts after extreme events

Slow Hydraulic K

Geomorphology

Macrophytes and Algae
Vertical Exchange in the Hyporheic Zone

Losing: Dominant flow direction down (Mediterranean Climates)

Gaining: Dominant flow direction up (Wet, temperate climates)

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

~100% of river water is filtered.
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?
How do coupled hyporheic hydrological-biogeochemical feedbacks range between these conditions?
Temporal Dynamics of Hyporheic Processing

Climates and Catchments Control Availability and Initial Conditions

- Discharge
- IC of Sediments
- Minerals/Metals
- Invertebrate Grazers
- Phyto/Benthic GPP
- Supply of Nutrients
- Aerobic/Anaerobic Rates

Top-down control Patterns

Bottom-up feedback Processes

Ability to process N, C, volume H₂O

Stream Order
Downstream Higher Q

Vertical

Horizontal

East River, CO

Russian River, CA
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
Measurements

The graph shows the water level (masl) for different periods from April 2010 to November 2010. The lines represent:
- Red: Nearby groundwater well
- Green: River
- Blue: Pumping

The x-axis indicates the months from April 2010 to November 2010, while the y-axis shows the water level in meters above sea level (masl) ranging from 0 to 14 meters. The graph also plots the pumping rate (MGaI) on the right y-axis.
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)

Images from [Brunner et al. 2009]

Common in Mediterranean Climates
Field Site Data: Evidence for Bioclogging
Represent sediment parameters $K$ and $\Phi$ as Initial Conditions (IC) within a numerical model.
Linking Sediment Parameters to Climate

RELATIONSHIP BETWEEN TEXTURE AND INITIAL POROSITY AND PERMEABILITY

MEDIAN GRAIN SIZE--mm

1.0 0.5 0.25 0.125 0.064 0.044

EXTREMELY WELL
VERY WELL
WELL
MODERATE
POOR
VERY POOR

SORTING--S.

1.1 1.0 1.2 1.1 1.4 2.0 2.0 2.7 5.7

PERMEABILITY--Dk
400
200
100
50
25
40
38
34
32
28
26
28
5
2.5
1.0
0.5

POROSITY--% 42

COARSE MEDIUM FINE VERY FINE SILT

Dry Year Conditions

Strength of hydrological events

Number of hydrological events

Many Strong Flows

Many Weak Flows
Methods: Upscale a Bioclogging Pore-Network Model

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

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

Colonies Model:
\[ \Phi \text{ and } K = f(\text{microbial growth}) \]

- Theoretical permeability model
- Related laboratory experiments and pore-network models to theory
- Equations included in MIN3P**
- Loosely-coupled approach with Hydrus 1D
- Change initial riverbed conditions (K and \( \Phi \)) to represent antecedent winter river discharge

\(^2\)Thullner, M. et al. [2002]
1D Numerical Setup

- MIN3P and Hydrus-1D numerical code
- $K$ and $\Phi$ 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:**
- $\uparrow Q$, $\uparrow K$, $\uparrow \Phi$

**Dry year end-member:**
- $\downarrow Q$, $\downarrow K$, $\downarrow \Phi$
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

The graph illustrates the relationship between time (in days) and flux (in m/day) under different growth rates (day$^{-1}$). The growth rates are color-coded as follows:

- Green: 0 day$^{-1}$
- Purple: 0.005 day$^{-1}$
- Orange: 0.01 day$^{-1}$
- Yellow: 0.015 day$^{-1}$
- Blue: 0.02 day$^{-1}$
- Pink: 0.025 day$^{-1}$
- Red: 0.03 day$^{-1}$
- Gray: 0.04 day$^{-1}$

The black dots represent the peak fluxes for each growth rate condition. The constitutive model and colonies are also indicated on the graph.
## Results: Bioclogging Bottom-up Feedback

<table>
<thead>
<tr>
<th></th>
<th>w/ Unsaturated Conditions</th>
<th>w/o Unsaturated Conditions</th>
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</thead>
<tbody>
<tr>
<td><strong>Biomass Growth</strong></td>
<td>Losing-Disconnected River</td>
<td>Losing-Connected River</td>
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<tr>
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<td>Fast Water Table Drop</td>
<td>Slow Water Table Drop</td>
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<tr>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
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<td><img src="image3" alt="Graph" /></td>
<td><img src="image4" alt="Graph" /></td>
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<tr>
<td><strong>No Biomass Growth</strong></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
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<td><img src="image7" alt="Graph" /></td>
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Simulating bioclogging effects on dynamic riverbed permeability and infiltration

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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 groundwater (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...
Nutrient substrates for biomass growth + K, Φ

A novel approach in numerical models

- Measure C consumption, biomass growth, CO₂ and N₂ production across the spatial gradient

Processes to include in modeling
- Disconnection
- Pumping
- Initial sediment parameters
- Topography
- Bioclogging from DOC, NO₃
Pressure Head
Connected in Thalweg and Bank
Disconnected on outer Bank
River topography included

Develops an inverted water table
Linking Surface Ecology and Subsurface N,C Transformations

Microbes Grow

Algae growth

Riverbed

Sediment Parameters

Aerobic/Ane aerobic microbes consume C, N

Microbes Grow

Fill Pore Space

Reduce $\Phi$ and K

Reduce Infiltration

Feedback Effect: Unsteady nutrient supply

Carbon, Nitrogen

How much N, C transformed to CO$_2$ and N$_2$ and why?
Top-Down Controls: Stochastic Water Levels

Fourier spectrogram of pumping time series

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

- Long wet period
- Long dry period
- Average
- Fluctuations around Average

Water Table Elevation (m)

Time (Days)
Fluctuations Lead to Enhanced Bioclogging and Hastened Infiltration Decline

High K – earlier bioclogging

Low K – later & slower bioclogging
Results: Carbon Transformations are Dependent on River Sediment Structure

- High K: \( \Phi = 0.28 \)
- Low K: \( \Phi = 0.17 \)
- Low High: \( \Phi = 0.23 \)
Sediment Effects on CO₂ Gas Production

Dry End member

Wet End member

High range represents variation in frequency of pumping
Undergoes Disconnection

$\Phi = 0.17$

No Disconnection

$\Phi = 0.28$

O$_2$ Concentration

Low

Distance Across the River (m)

Elevation above msl (m)

High
Undergoes Disconnection

CO₂ Pressure

Φ = 0.17

No Disconnection

CO₂ Pressure

Φ = 0.28

CO₂ and Bioclogging hotspot

Elevation above msl (m)

Distance Across the River (m)

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
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?

Perturbations from hydrology?
Simulate spring/summer DO conditions

Implement as BC in MIN3P model

\[ h_m = 0.28 \left( \frac{U^2}{2g} \right) \left( \frac{H/d}{0.34} \right)^{3/8} \quad H/d \leq 0.34 \]

\[ h_m = 0.28 \left( \frac{U^2}{2g} \right) \left( \frac{H/d}{0.34} \right)^{3/2} \quad H/d \geq 0.34 \]
Without an Ecological Boundary

Anaerobic Biomass

Downwelling

Upwelling

Elevation

Anaerobic Biomass
Without an Ecological Boundary

[Table]

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<tr>
<th></th>
<th>AR (Moles)</th>
<th>DN (Moles)</th>
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<tbody>
<tr>
<td>Carbon</td>
<td>406.0</td>
<td>26.0</td>
</tr>
<tr>
<td>Nitrate</td>
<td>402.0</td>
<td>50.7</td>
</tr>
</tbody>
</table>

[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
• 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...