PULSE-SHUNT CONCEPT

HYDROLOGICAL AND BIOGEOCHEMICAL CONTROLS ON WATERSHED DISSOLVED ORGANIC MATTER TRANSPORT

RAYMOND ET AL., 2016

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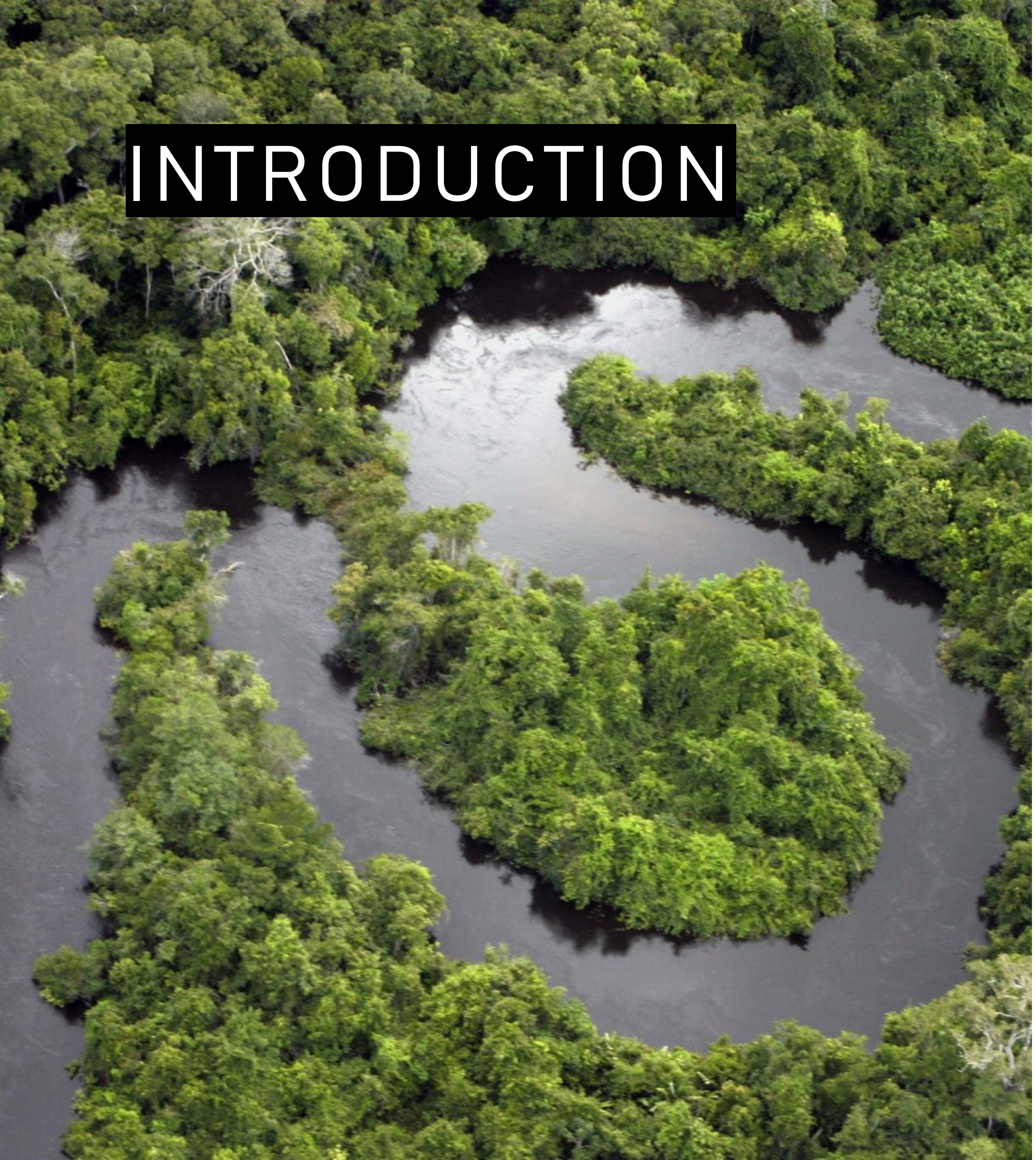
Global Change Ecology & Fluvial Ecosystems



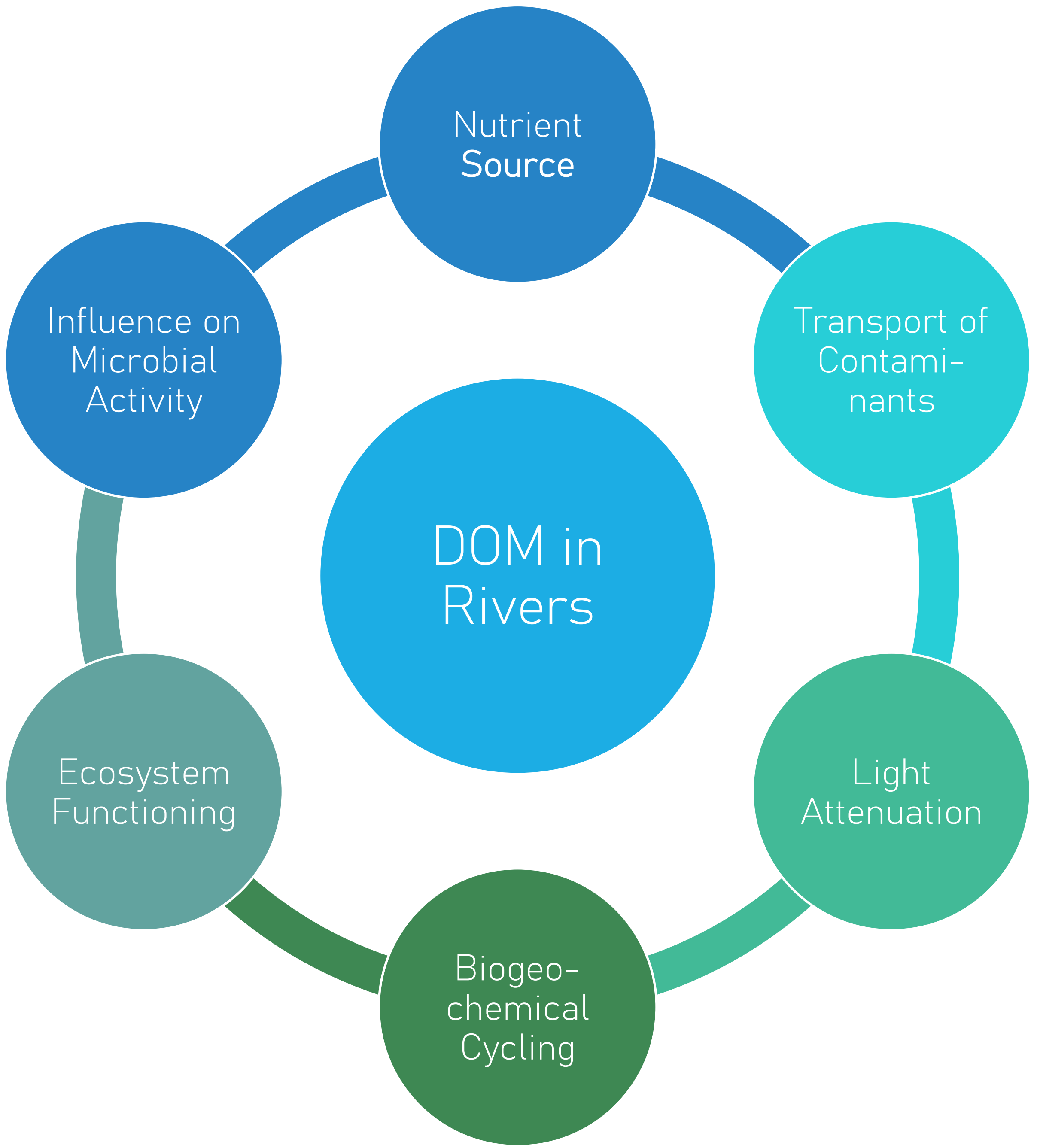
INTRODUCTION

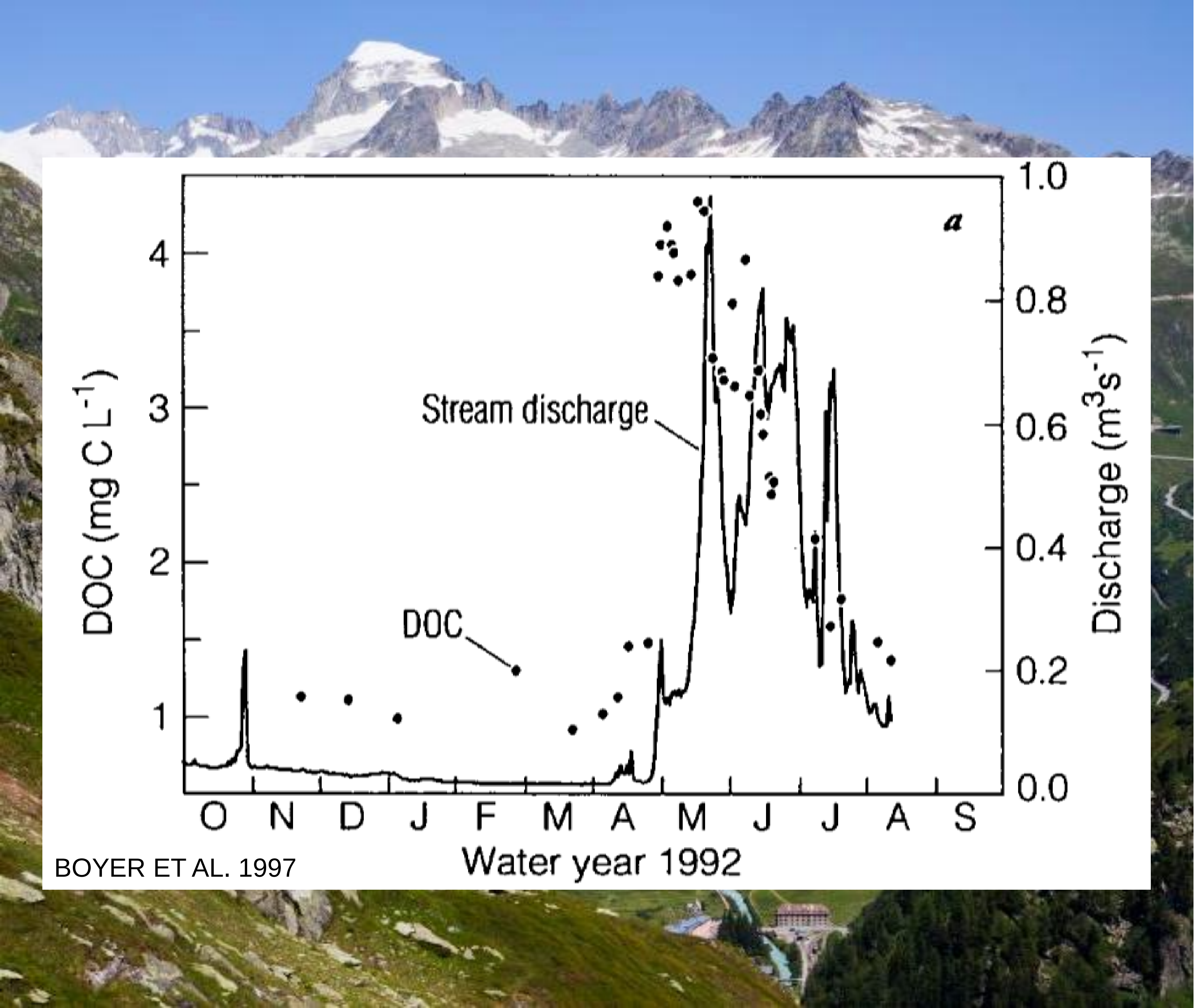
- Model to estimate the **export** of DOM
- Explore **importance** of
  - **hydrologic event intensity** and
  - **stream connectivity**

  for regulating DOM fluxes
- Provides a **quantitative framework** to evaluate the relationships among
  - **flow**,
  - **DOM supply, and**
  - **utilization**

  in drainage networks
- Important for **advancing our understanding** of nutrient dynamics in aquatic systems

INTRODUCTION



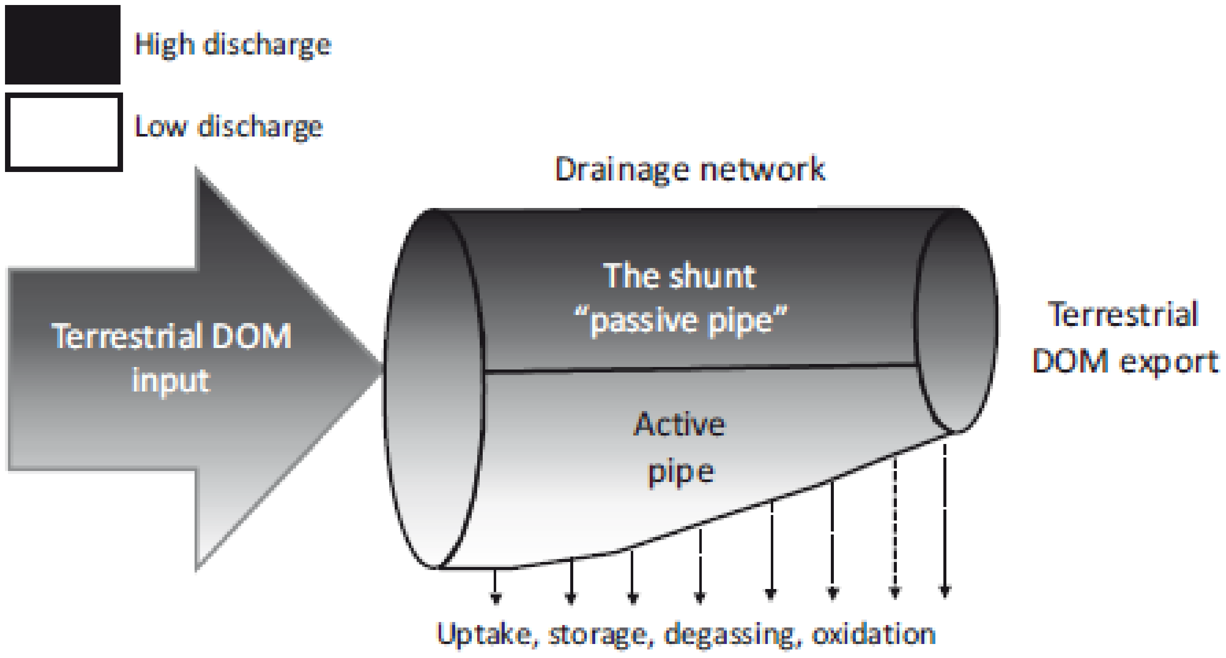


BOYER ET AL. 1997

- **Sudden and significant release of DOM**
- Significant hydrological events
- Increase of concentration in rivers from terrestrial landscape
- Infrequent but high magnitude

- Rapid transport of DOM bypassing headwater streams
- Due to increased velocity
- Affects regional biogeochemical cycles

PULSE AND SHUNT



MOTIVATION – WHY DO WE NEED THE PSC

- Importance of DOM pulses and hydrologic variation recognized:
  - Hydrologic events: 86% of annual forested DOC export
    - Large hydrologic events (5% of days/year): 60% of annual forested DOC export
- Other models: RCC (River continuum concept) & RES (Riverine ecosystem synthesis)

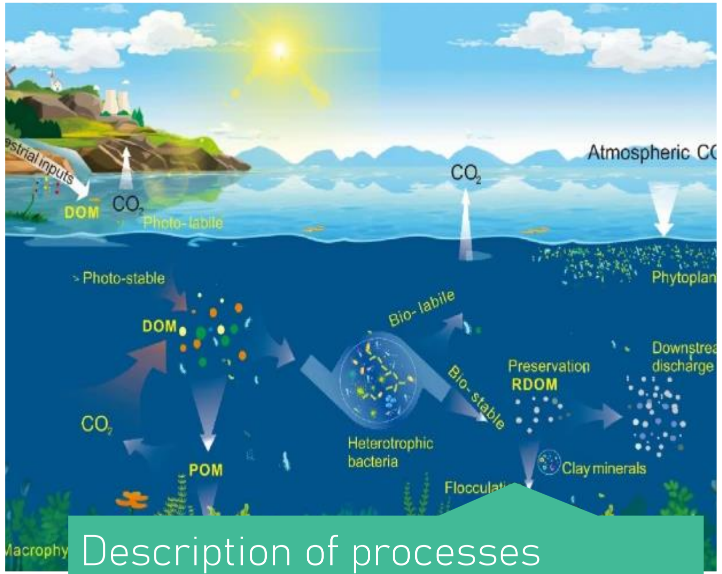
→ don't integrate pulse & shunt into their models

Assumptions of the model

- 200 000 km² temperate forest watershed
- 8th order drainage network w/ main-stream length of 500 km

River network attributes

- Drainage network connectivity & geomorphology
- Hydraulic geometry



Description of processes

- Concentration & discharge relationships
- Bioreactivity
- Transfers and downstream subsidies

METHODS

RIVER NETWORK ATTRIBUTES

DRAINAGE NETWORK CONNECTIVITY & GEOMORPHOLOGY

Stream Segments

$$R_n = \frac{n_{o+1}}{n_o}$$

Stream lengths

$$R_L = \frac{L_{o+1}}{L_o}$$

Scale of watershed areas

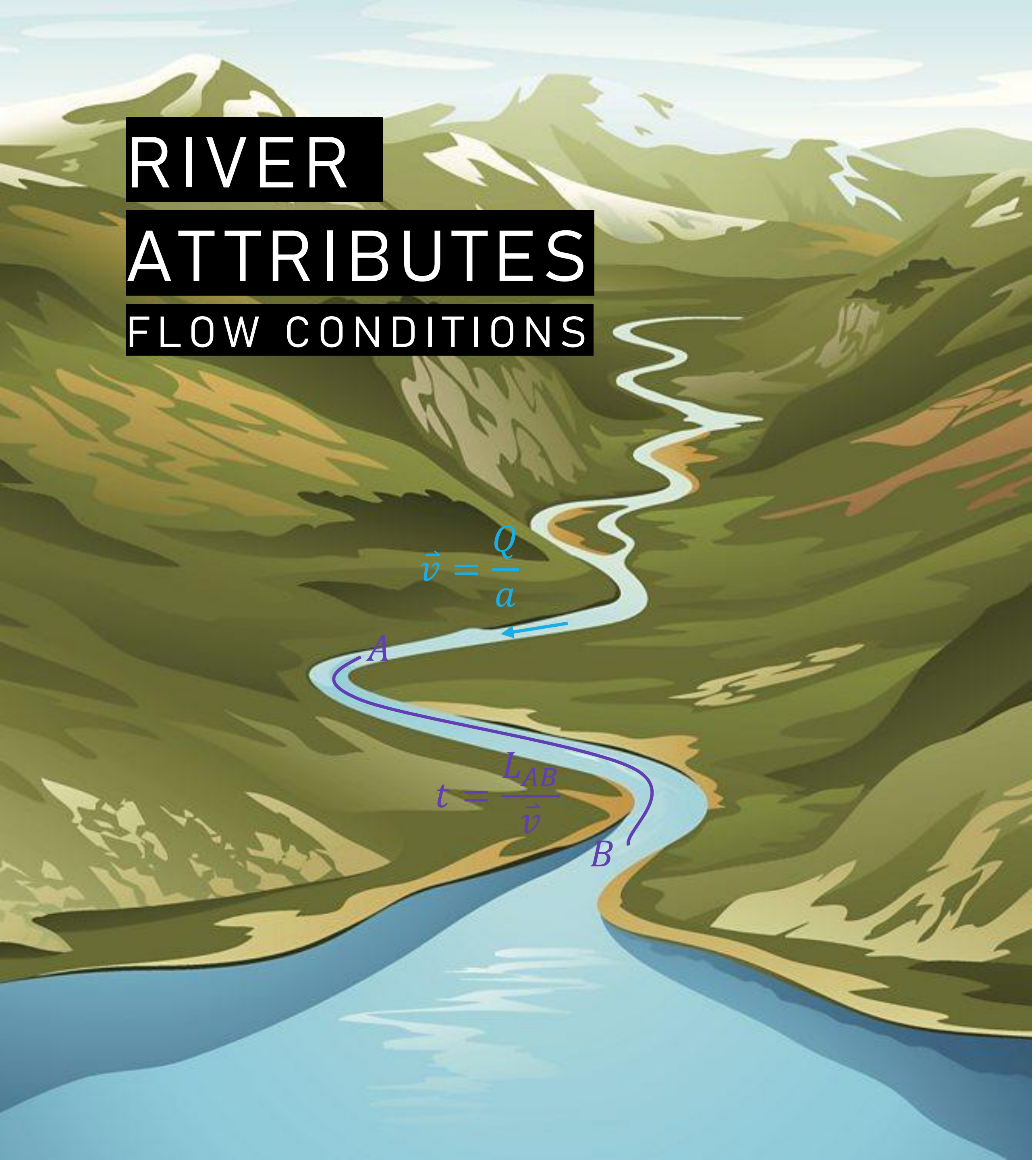
$$R_a = \frac{a_{o+1}}{a_o}$$

Number of connections

$$T_v = T_1(R_t)^{0-1}$$

RIVER ATTRIBUTES

FLOW CONDITIONS



Stream water velocity

Estimated for various discharge conditions (Q) and stream orders:

$$V_o = aQ^b$$

with

a ≈ -1,35

b ≈ 0,02

Residence time

for each stream order

$$T_o = \frac{L_o}{V_o}$$

with

L_o – segment length

RIVER NETWORK ATTRIBUTES

TABLE 1. River network attributes for a hypothetical eighth-order forested New England watershed.

Order	No. stream segments	Mean length (km)	Mean basin area (km^2)	Velocity (m/s) for $Q = 0.83$	Residence time (d) for $Q = 0.83$	Velocity (m/s) for $Q = 0.1$	Residence time (d) for $Q = 0.1$
1	25 581	5.6	8	0.26	0.25	0.17	0.36
2	5561	10.6	21	0.31	0.40	0.21	0.58
3	1209	20.2	97	0.41	0.57	0.28	0.85
4	263	38.4	447	0.55	0.80	0.37	1.21
5	57	72.9	2055	0.76	1.10	0.49	1.71
6	12	138.5	9452	1.07	1.50	0.68	2.37
7	3	263.2	43 478	1.51	2.01	0.93	3.24
8	1	500.0	200 000	2.18	2.65	1.32	4.37

Notes: Stream number, length, and basin area approximate data from NHDplus Hydrosheds (http://www.horizon-systems.com/nhdplus/). Also provided are the velocity and residence time for stream orders for discharge (Q; cm/d) at the effective discharge for dissolved organic carbon (DOC) assuming annual discharge data from three forested headwater streams in New England (Fig. 2) and a nominal discharge of 0.1 cm/d.

DESCRIPTION OF PROCESSES

DOM CONCENTRATION AND DISCHARGE RELATIONSHIPS

1. **Discharge variability**

   Empirical value from flow-frequency curves → likelihood f(Q) and discharge Q

2. **Concentration of DOM** in 1st order streams

$$c_1^{in} = gQ^h$$

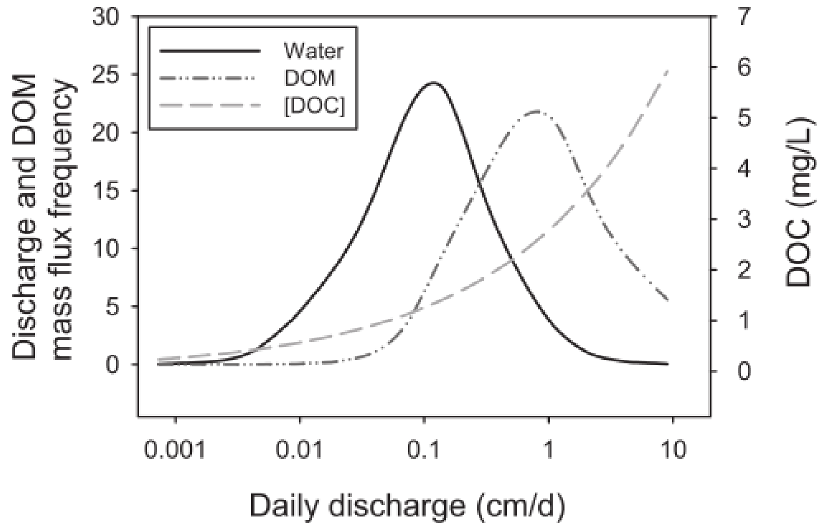
   with

   Q – volumetric discharge per watershed area,

   g = 1,02 and h = 0,345 (empirical)

3. **Decomposition** (linear kinetics reaction)

$$c_1^{out} = c_1^{in} e^{-kT_1}$$



DESCRIPTION OF PROCESSES

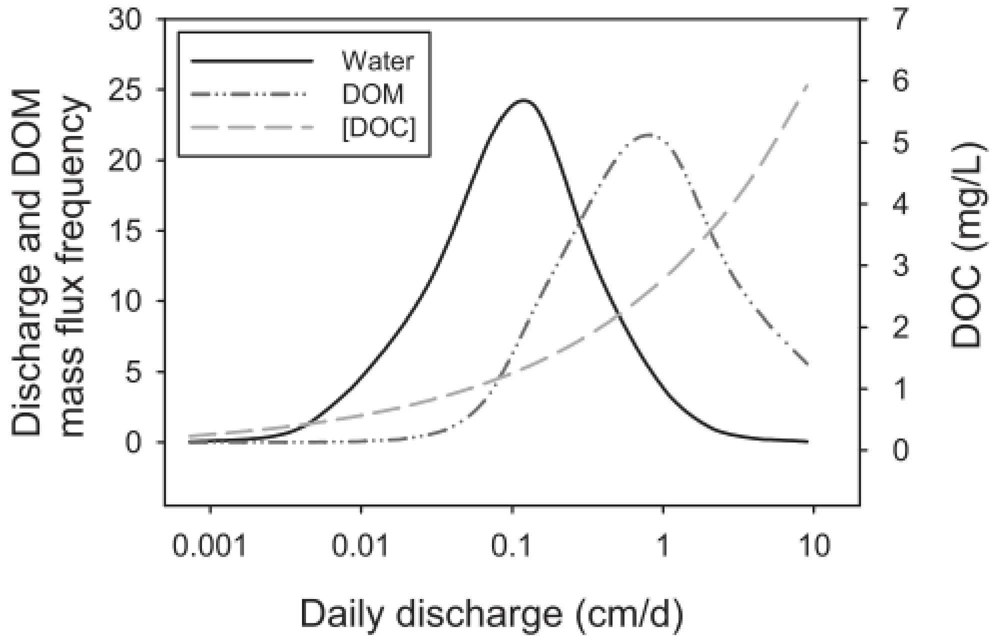
DOWNSTREAM DOM TRANSFER BETWEEN STREAM ORDERS

$$F_1^{out} = A_1 \int_{Q_{1a}}^{Q_{1b}} f(Q_1) c_1^{out} \, dQ_1$$

- A_1: river cross section
- $f(Q_1)$: discharge frequency
- dQ_1: volumetric discharge
- Q_{1a}, Q_{1b}: discharge interval of the flow-frequency curve
- c_1^{out}: DOM concentration after decomposition

$$F_o^{out} = F_o^{in} e^{-k_o T_o}$$

- T_o: residence time in segment
- k_o: decay rate = 0.22 /d



Ganges River delta. GETTY IMAGES

PSC model reveals macrosystem watershed properties.

- DOM subsidies
- Importance of event frequency and size
- Influence of seasonality

RESULTS: DOM SUBSIDIES

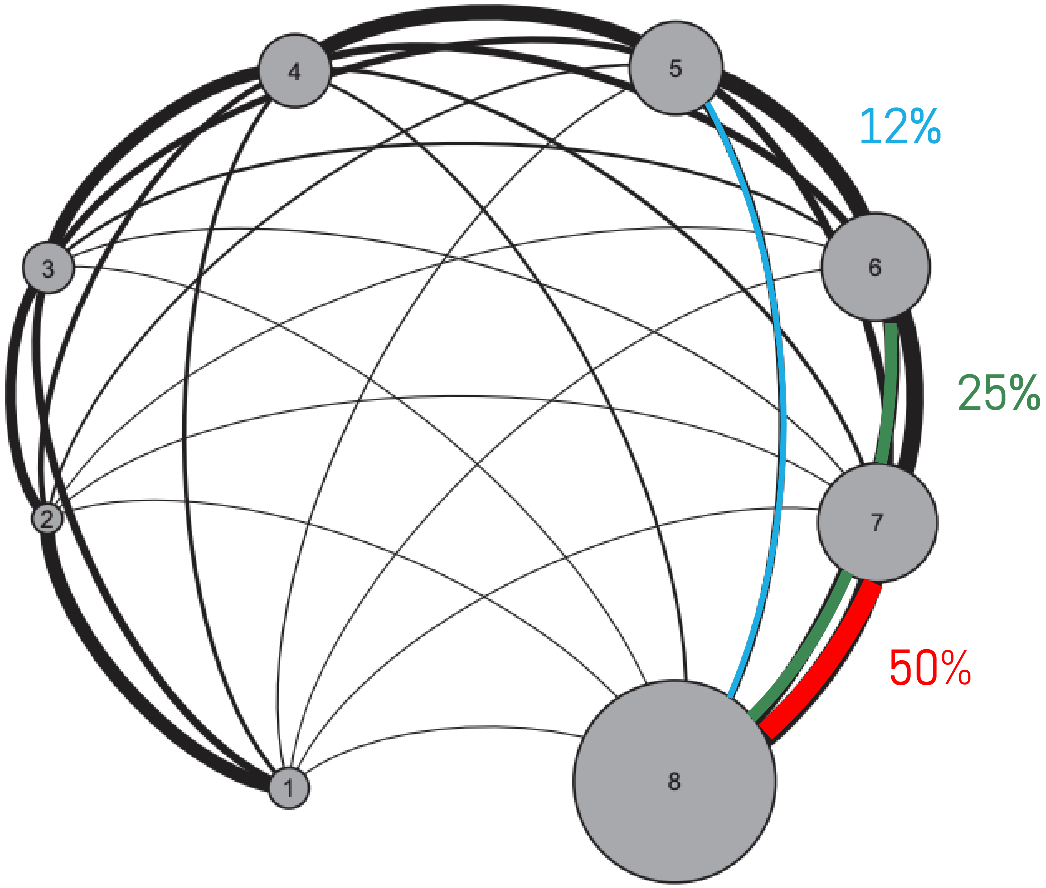


FIG. 3. A network graph for predicted annual uptake of terrestrial DOC among stream orders for a hypothetical large forested watershed using the pulse-shunt concept (PSC) modeling framework and assumptions outlined in this study.

- Largest removal of DOM in higher order streams.
- Preceding 3 orders transfer most of the DOM.

Law of Stream Subsidies:

$$R_s = \frac{F_{o+1}}{F_o}$$

RESULTS: EVENT FREQUENCY & INTENSITY

TABLE 3. The impact of discharge event size on fluxes of DOC off the landscape and to the ocean.

Size of event (cm/d)	Annual number of events	Terrestrial DOC input ($g \cdot m^{-2} \cdot yr^{-1}$)	Removal (%)	Export to ocean ($g \cdot m^{-2} \cdot yr^{-1}$)
0.2 (Light rain or drizzle)	500	1.59	85	0.23
0.5	200	2.12	79	0.45
1 (Steady snowmelt or moderate rain)	100	2.77	74	0.71
5	20	4.83	61	1.87
10 (Major Storm)	10	6.14	56	2.73

x 1.7

x 2.7

total mass processed by the river increases, but % of DOM removed decreases,

RESULTS: SEASONALITY EFFECTS

Decomposition:

$$c_1^{out} = c_1^{in} e^{-kT_1}$$

DOM processing adjusted for temperature:

$$c_1^{in} = gQ^h + (W_t - 15) \times 0.15$$

Water Temperature

Base case temperature (C°)

Emperical factor (Raymond & Saiers, 2010)

TABLE 4. Results from an analysis where both the concentration of DOC and the decomposition constant (k) were allowed to vary as a function of temperature.

Flux	5°C	15°C	25°C
Terrestrial DOC input ($mg \cdot m^{-2} \cdot d^{-1}$)	48.8	82.5	116.3
Terrestrial DOC uptake ($mg \cdot m^{-2} \cdot d^{-1}$)	16.3	45.7	92.3
Terrestrial DOC export ($mg \cdot m^{-2} \cdot d^{-1}$)	32.5	36.8	24
DOC (mg/L)	2.2	3.7	5.2
Uptake (%)	33	55	79

RESULTS: SEASONALITY EFFECTS

- More DOC is delivered in the water months
- Higher DOC retention in warmer months
- Suggests that there is an "optimized T" for DOM export
- Seasonal variability plays a crucial role in carbon dynamics.

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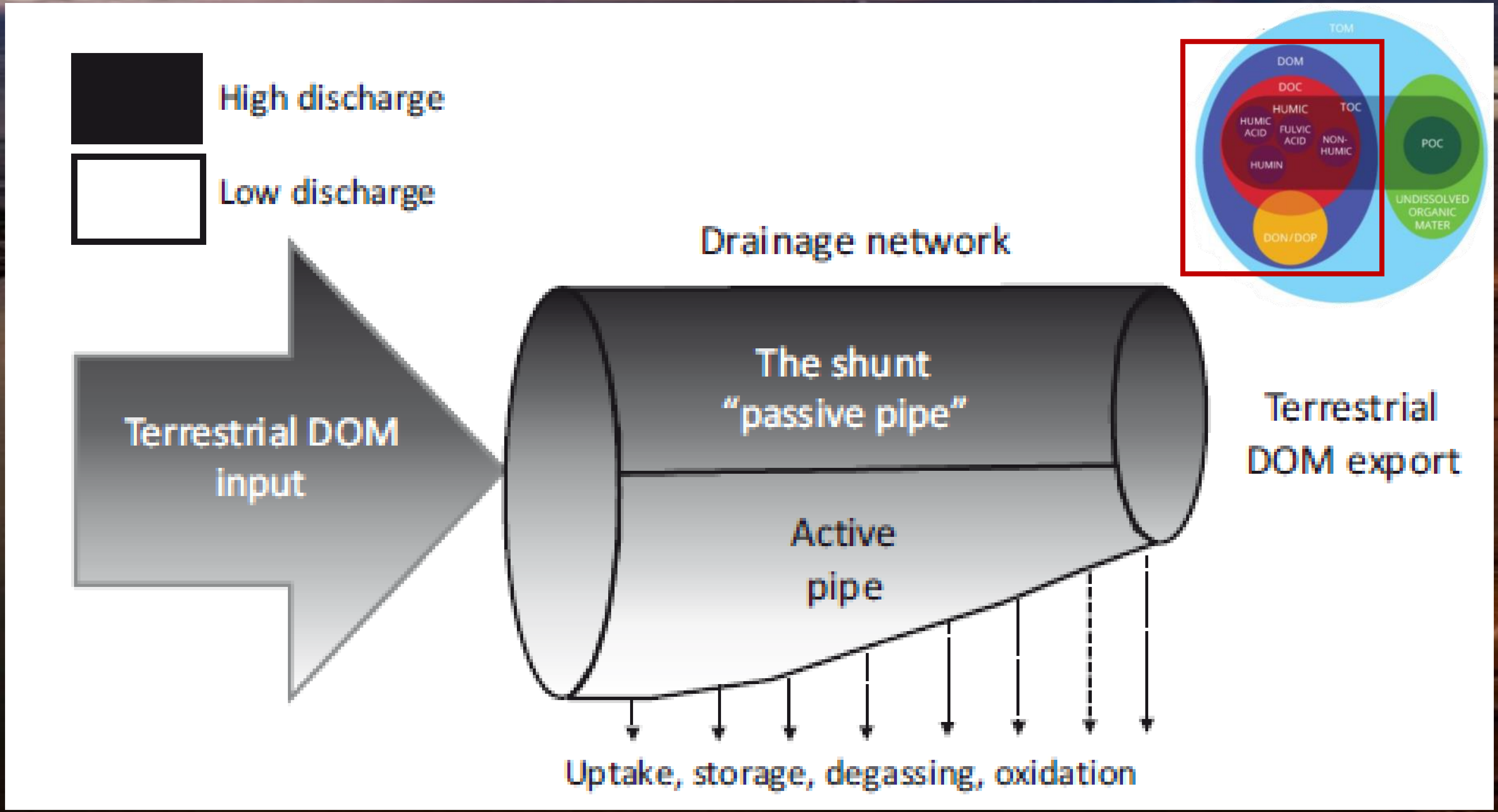
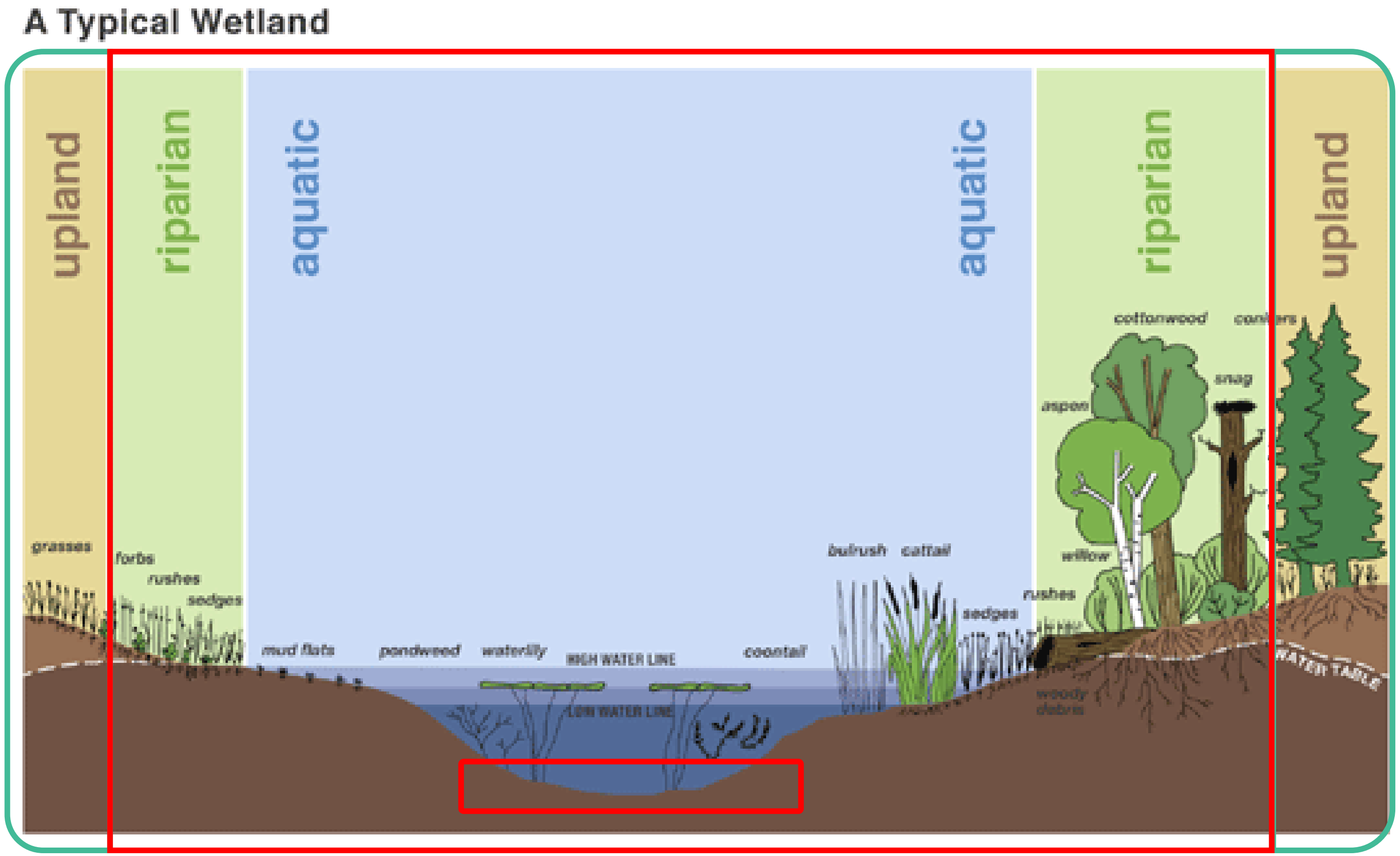
POSSIBLE PSC ADAPTATIONS



FUNCTIONAL LANDSCAPE UNITS



(Pamela A mason, 2016))

- Preliminary PSC model focuses on on **upland areas** and **does not incorporate other key functional landscape units.**
  - **Wetlands & riparian** zones contribute DOM all along the continuum
  - **Reservoirs, hyporheic zones, and floodplains** as they impact DOM pathways

OTHER POSSIBLE ADAPTATIONS

1. Biotic & Abiotic Factors

- Temperature
- DOM composition
- Light availability
- Different microbial communities

2. Small River Contributions

- Headwater streams
- Spring-fed streams

3. Autochthonous Terrestrial Sources

- Algal Blooms
- Aquatic Vegeation
- Periphyton (biofilms)

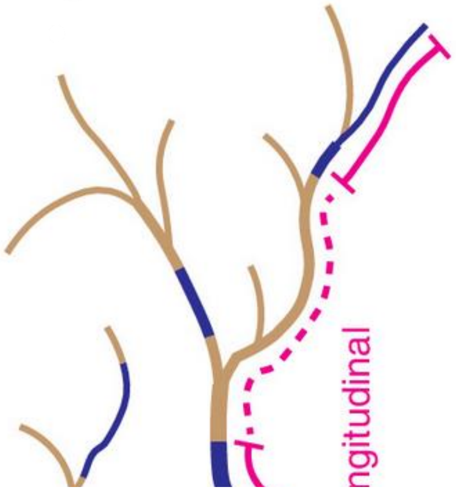
PULSE-SHUNT-STORAGE

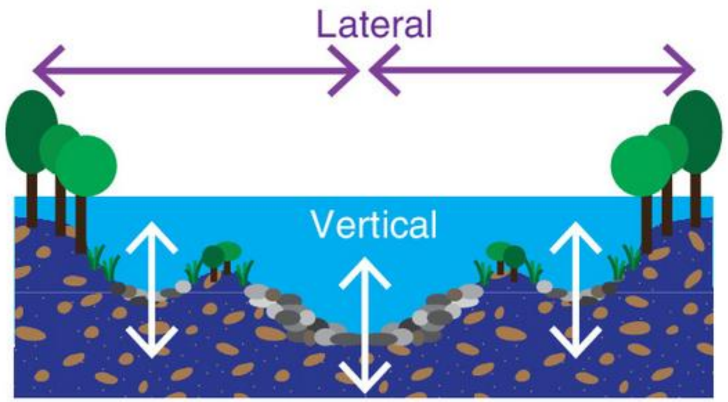
(CATALAN ET AL., 2022)

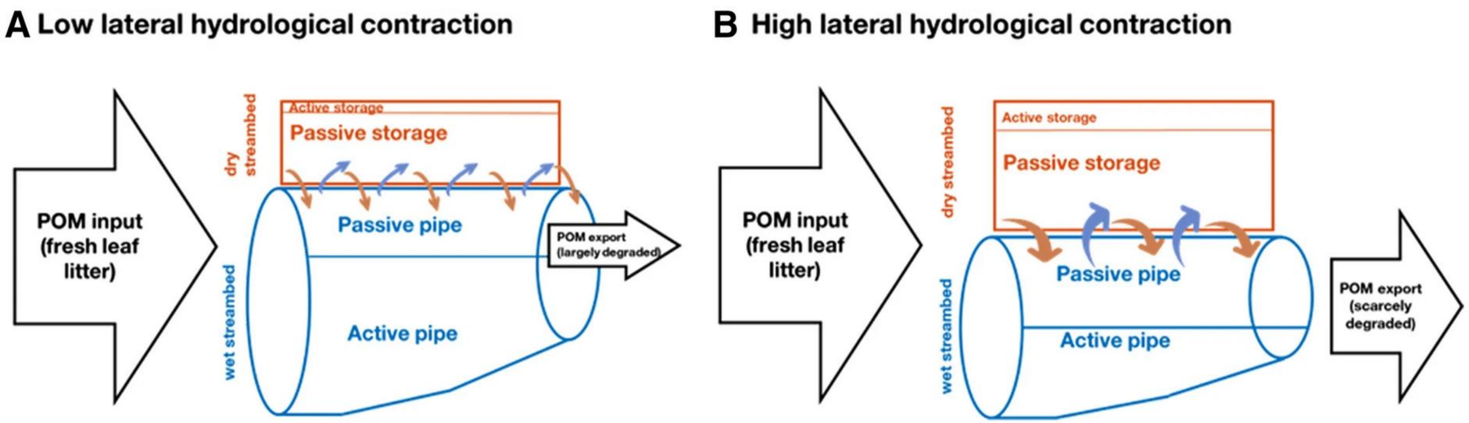
Non-perennial river networks:

- high hydrological contraction

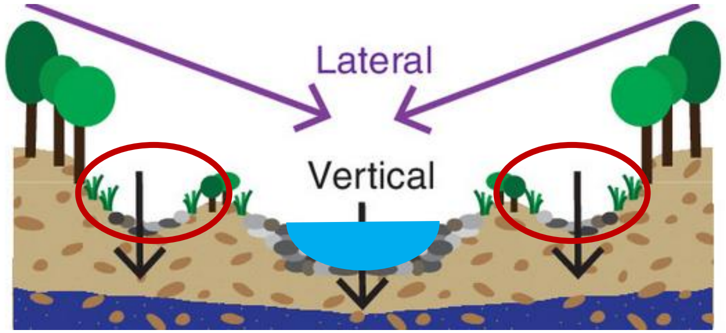
→ Storage and dry-processing of POM (particulate organic matter)





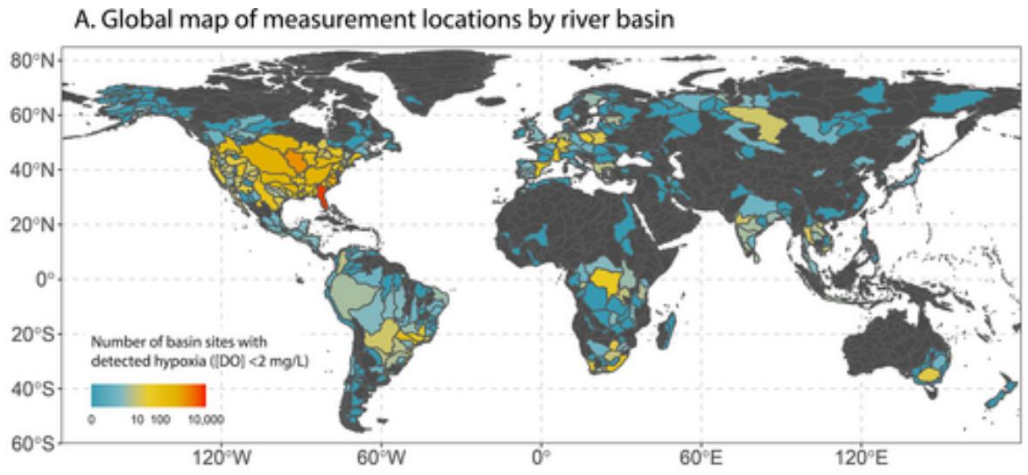


Dry season:



Adapted from Allen D. et al, 2020

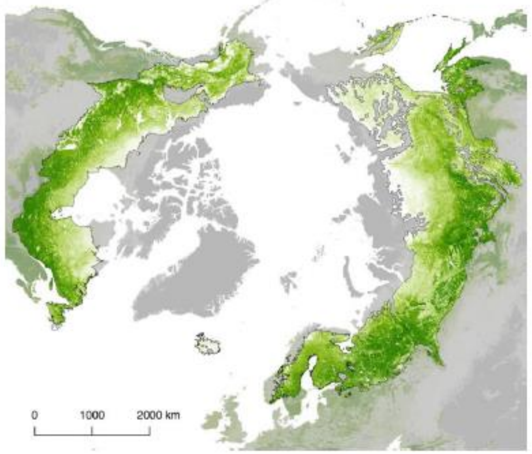
INTEGRATING THE PSC TO WHAT WE ALREADY KNOW: HYPOXIA IN RIVER NETWORKS



From Blaszczak J. R. et al., 2022

- Hypoxia especially problematic in summers
- Storms: higher DOM export and concentration
- Some rivers might be more prone to hypoxia than expected with old models
- → underestimation of hypoxia

Using the PSC to understand the browning of rivers with climate change

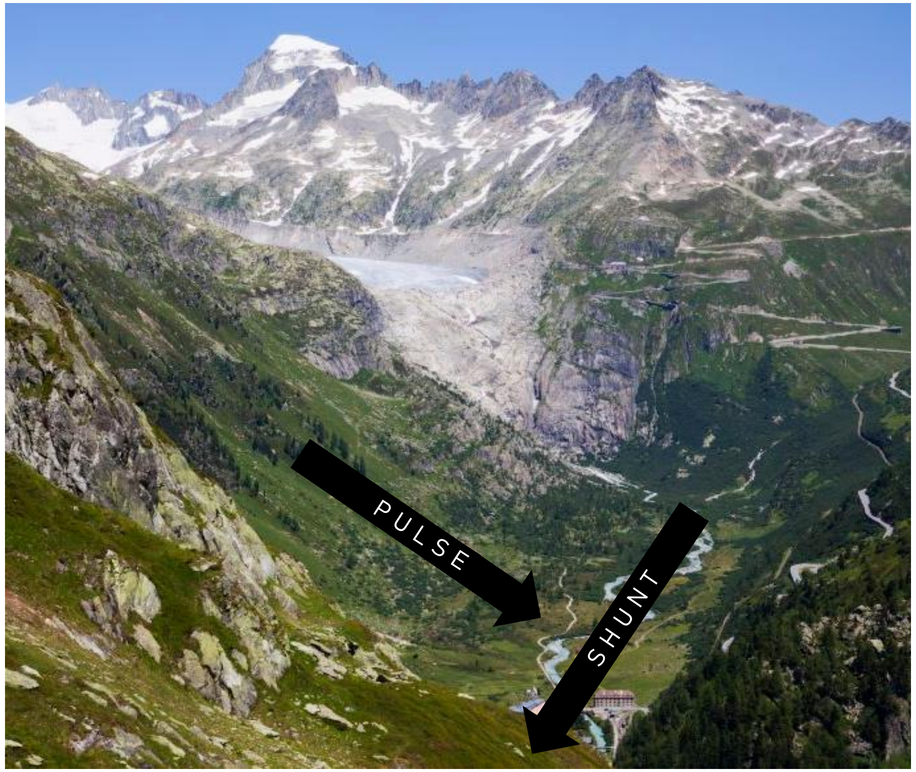


Greening of the boreal landscape

- Large amounts of soil organic carbon mobilized and entering streams and rivers
- Humic and fulvic acids (degradation product of vascular plant material) induce browning of surface waters
- Increases in water DOC concentration

- Greening: increase in DOM
- → Increased frequency of big hydrologic events: more pulse and shunt of DOM
- Together with higher water temperatures: Threat of hypoxia

CONCLUSIONS



- Frequency and size of hydrological events is crucial to predict DOM fluxes.
- PSC shows fluxes of DOM across stream orders
- Could be expanded to incorporate multiple landscape functional units, for example with a storage component
- Underscores the power of integrating scaling laws into biogeochemical research
- Research gaps: decomposition constants & residence times
- Provides a better conceptualization of the role of river networks in the global C cycle considering influence of hydrologic variability


THANK YOU

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