Temporal organization of braided rivers through morphological states

Clemente GOTELLI

Christophe ANCEY

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What is a braided river?

Multiple definitions

"A system of channels, splitting and rejoining around islands" (Jagers, 2003);

"An unstable network of multiple channels separated by ephemeral bars" (P. Ashmore, 2024);

"A network of bars and interweaving channel threads" (Y. Wang et al., 2024);

"Multiple channel threads separated by mobile, inter-channel bars" (Li & Limaye, 2025).

Navisence River above Zinal. Bob de Graffenried, LHE-EPFL.

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WHY ARE THEY IMPORTANT?

- Present and future of braided rivers matter because:
  - Channel mobility
  - High sediment loads
  - Hazard to infrastructure
  - Flood conveyance
  - Economic impact
  - Ecological role
  - **Climate change sensitivity**
  - **Restoration priority**

2005 2010

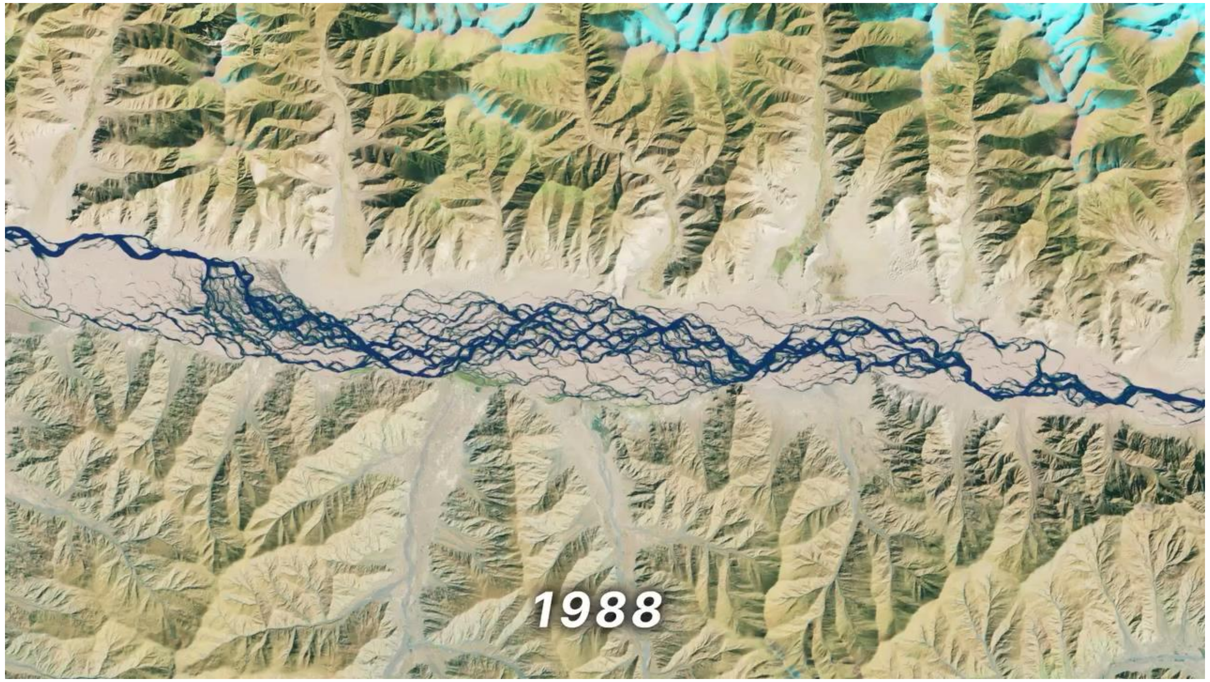
Mareiter Bach River, Italy. Vignoli et al. (2011)

We must understand how they work to be able to predict their behavior

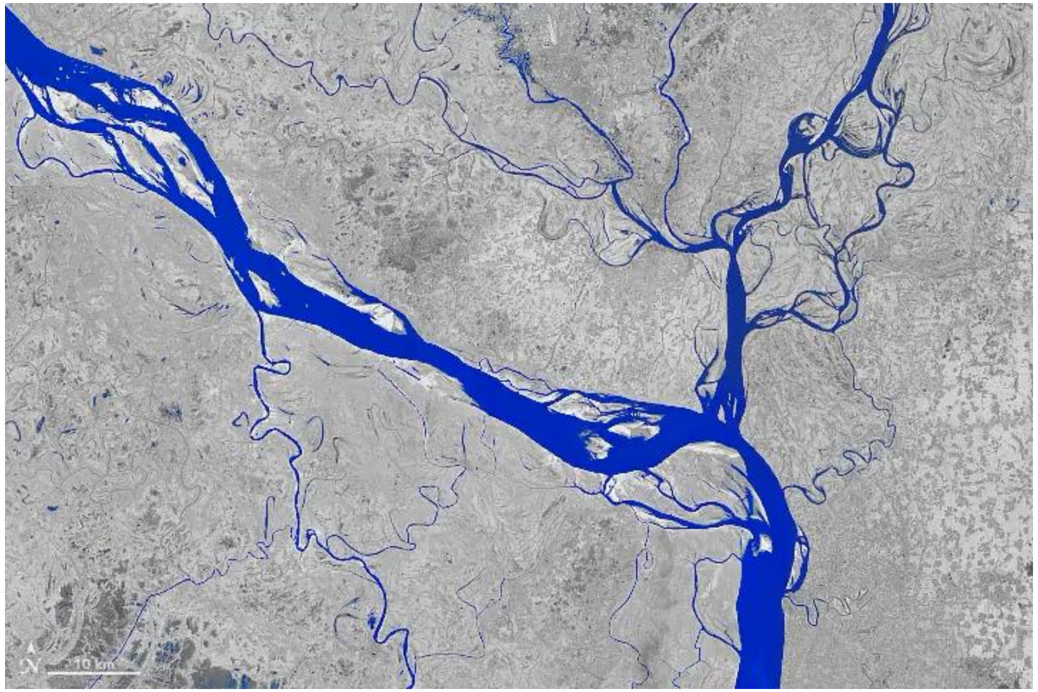
THE MODELING CHALLENGE

Channel morphology evolution is difficult to model

- Highly variable and non-linear behavior
- Strong fluctuations even under ≈ steady forcing



Yarlung Tsangpo River, China



Padma River, Bangladesh

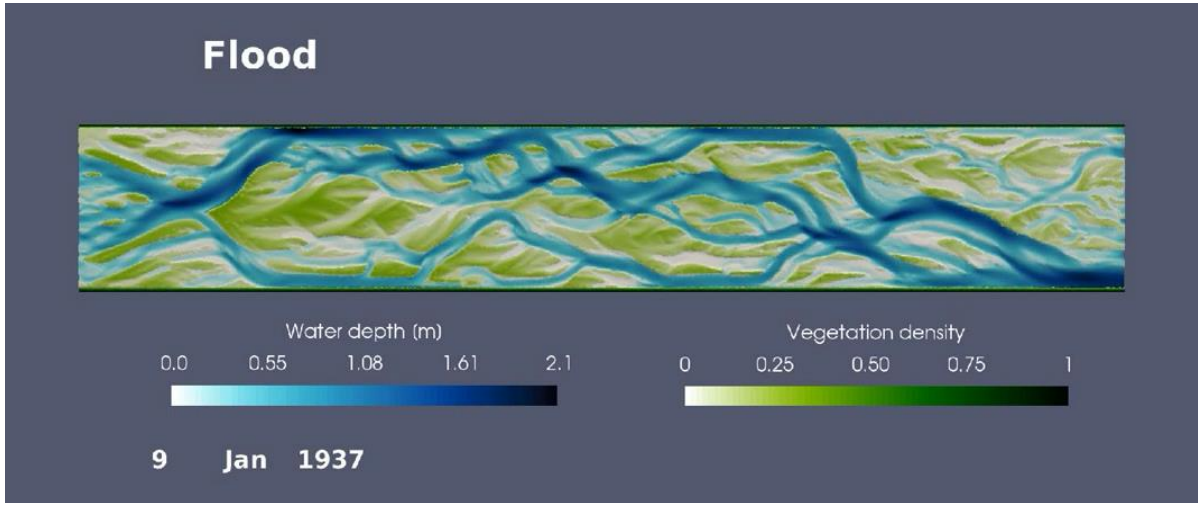
Modeling Strategies

Deterministic approach

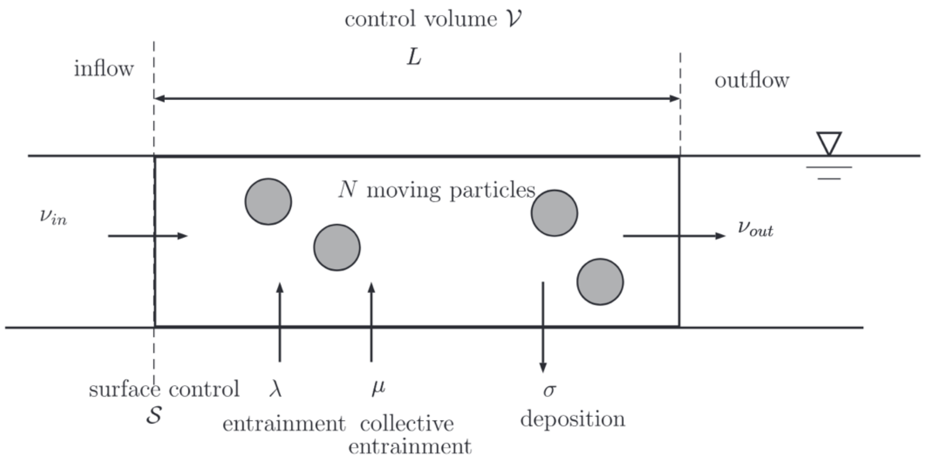
- Solve the equations for hydrodynamics and sediment transport.
- Simple and reliable.
- Sensitive to initial and boundary conditions.
- Computationally expensive.
- Single realizations only ← uncertainty!

Probabilistic approach

- Handle threshold behavior better
- They quantify uncertainty
- Only particle size models for now



Stecca et al. (2017)

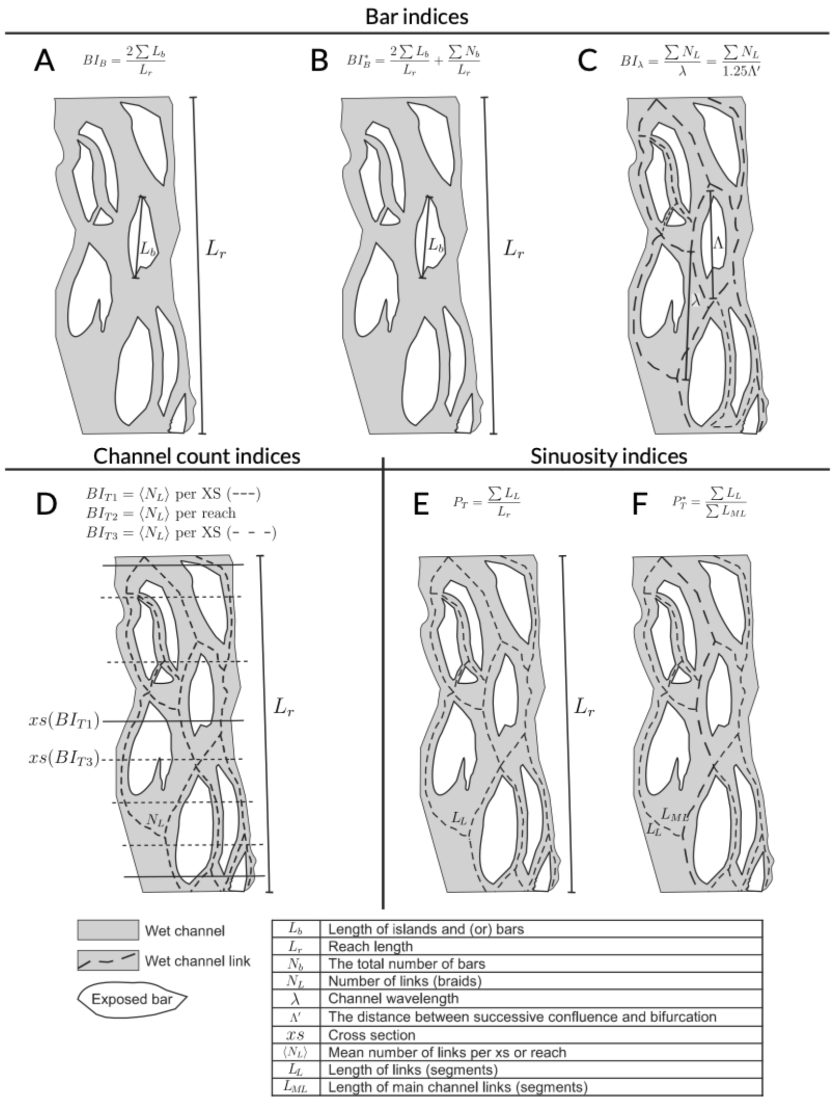


Ancey & Pascal (2020)

Modeling Strategies

Planform: the standard lens for braided river characterization

- At greater scale, planform metrics (BI, eBI, wetted width, etc.) have traditionally been used to characterize rivers.
- They are good for summarizing river geometry and sediment transport in mean values (Bertoldi, 2009)
- **They lack temporal description of river patterns and variability of sediment transport**



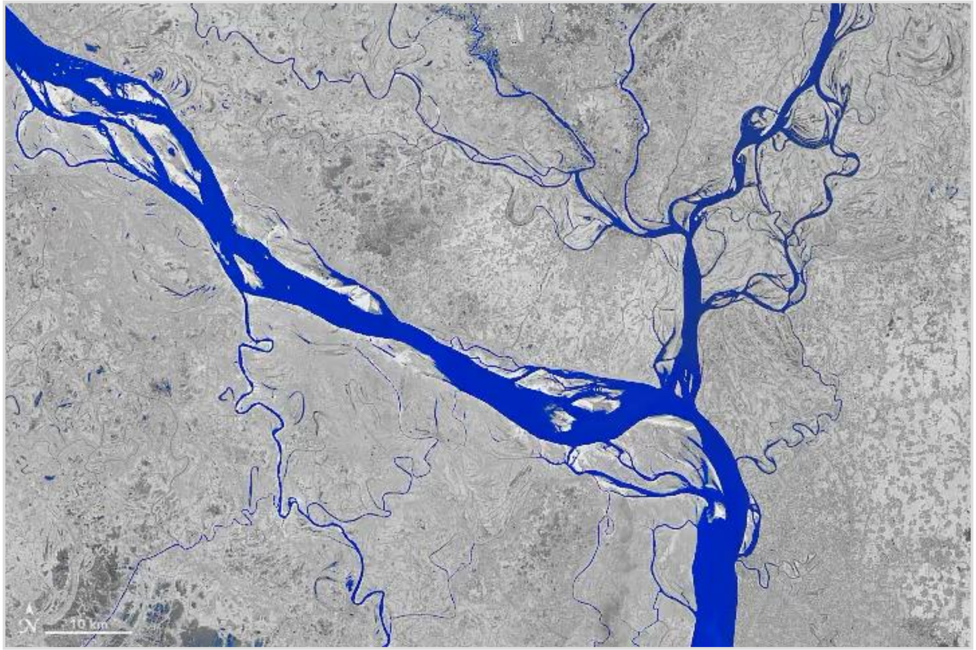
Egozi & Ashmore, 2008

From Continuous to Discrete

Rivers alternate among a finite set of recurrent morphologies

Based on experimental, numerical and field evidence:

- Planform metrics fluctuate even under steady conditions.
- Long records reveal alternation, not around a single value, but among a **limited set of recurrent configurations**.
- Link between metrics and planforms suggests that braided rivers evolve through a **limited catalogue of planforms instead of a continuous of planforms**
- Each planform can be seen as a **state** of the system: observable, **repeatable**, and linked to distinct transport behavior.



Padma River, Bangladesh

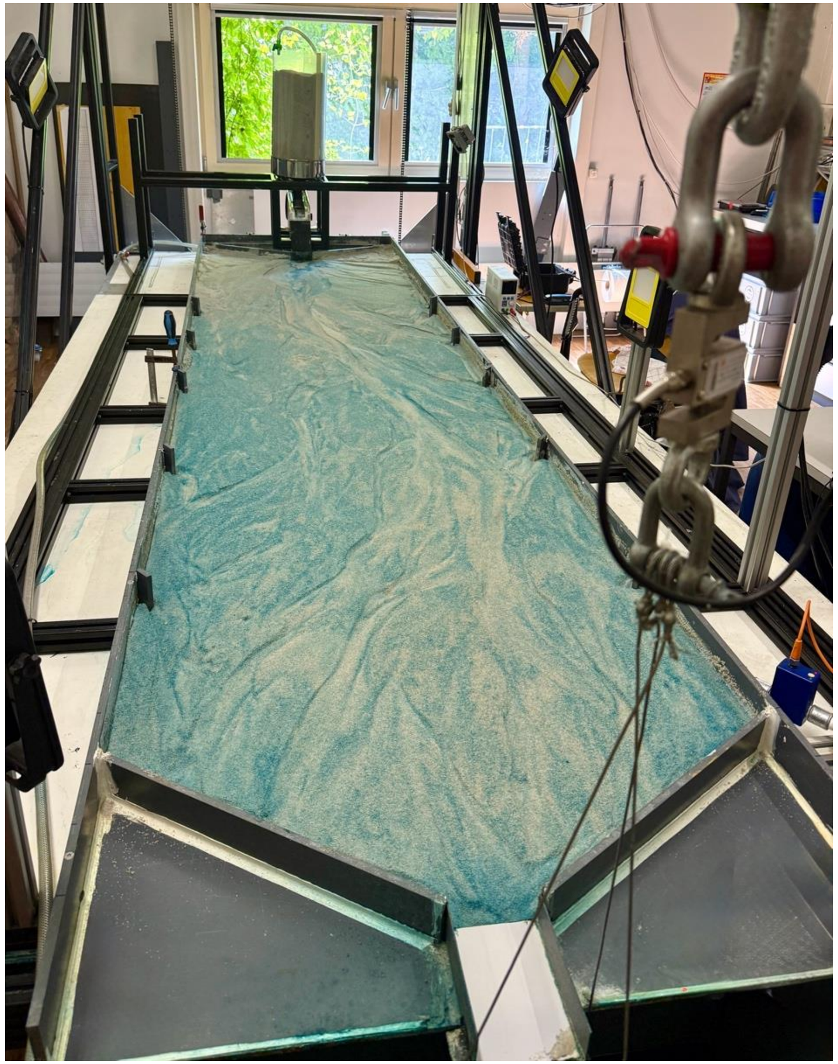
Our objective is to find if these states exist. If they exist, how do they behave and interact?

Experimental Setup

We need planforms + sediment.

- Experiment running continuously during $1{,}200$ h.
- All inputs are constant.
- One top view photo per minute → $72{,}000$ water masks
- Load cell for sediment transport records @ outlet

Parameter	Value
Length [m]	3.3
Width [m]	1.0
Slope [%]	3
Sediment type	Unimodal, d50 = 1mm
Flow rate [L/s]	0.15
Sediment feed rate [g/s]	1.5

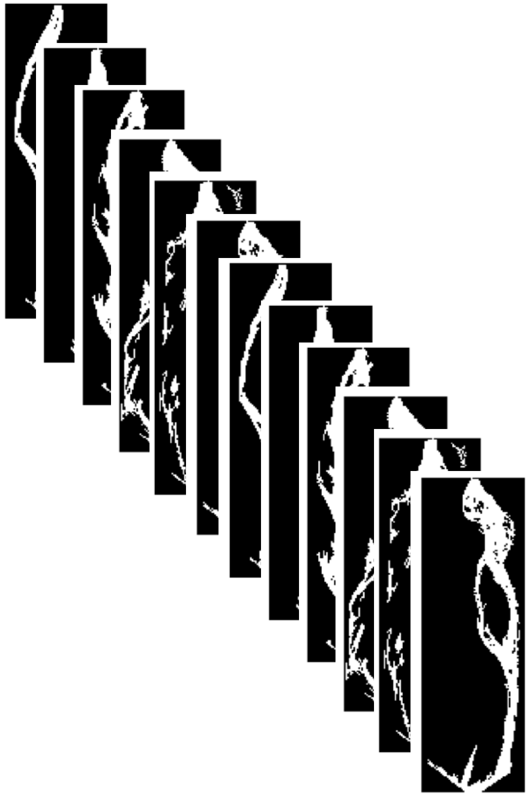


From Masks to Morphological States

- We must create the **morphological states** solely from masks
- We want to group planforms by similarity, but

  they are **too many** to group them manually!!
- We use computer vision algorithms
- The process is:

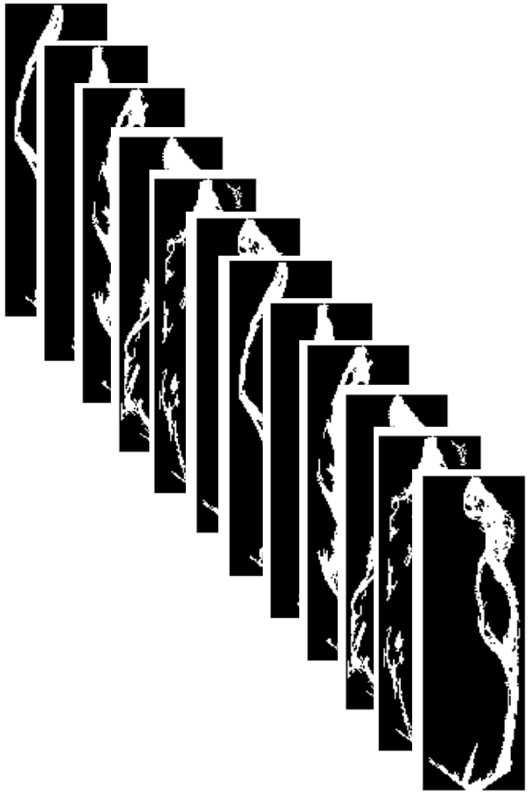
1. Compute the (dis)similarity between masks
2. Reduce the matrix dimensions to 3
3. Cluster them with machine learning



72,000 images

From Masks to Morphological States

- Compute distance + Dimension reduction + Clustering by density



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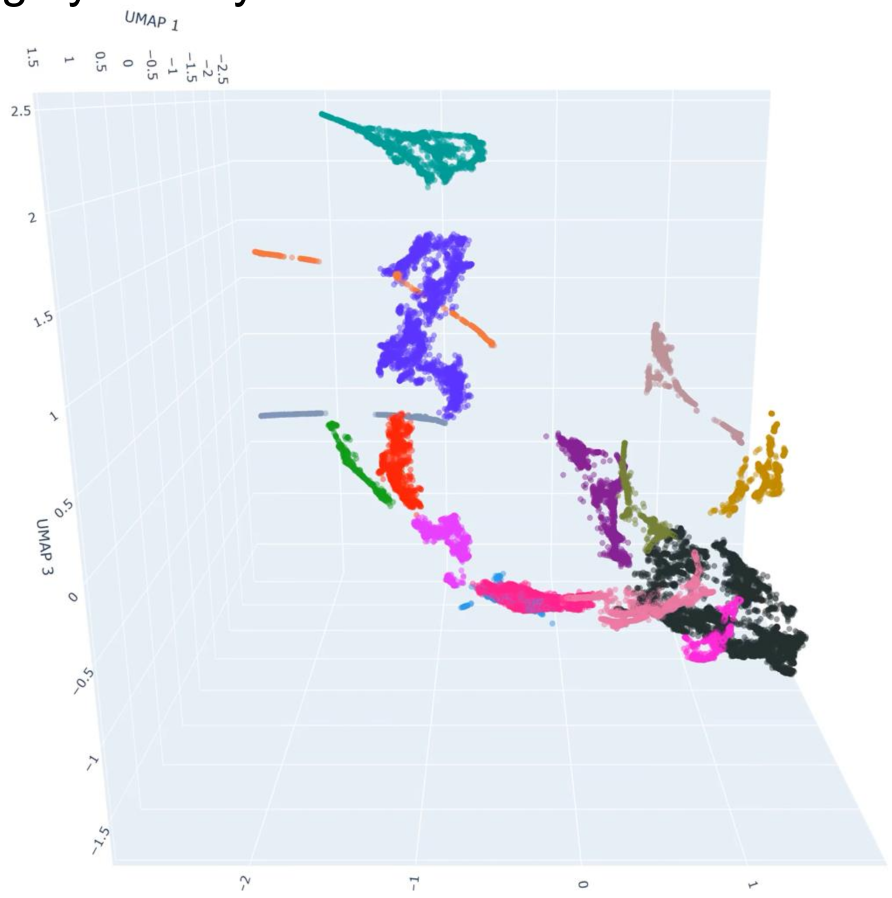
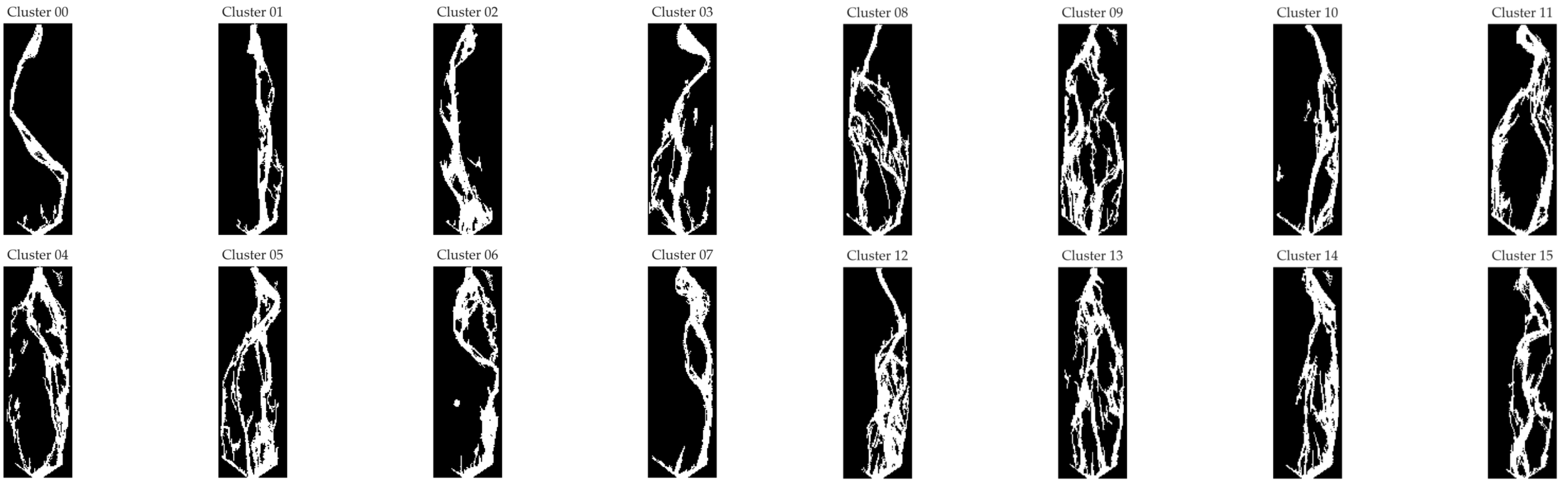


— 3D cloud of 72,000 points (1 per mask)
— 16 different clusters
— online version

Cluster Characterization

Morphological Description

- Sixteen medoids representative of each cluster
- Range from single-thread to braided
- Different levels of curvature, threads, bars and junctions.



Cluster Characterization

Morphological Description

Morphological metrics show:

- Image count is uneven.
- Wetted width and area doubles from single-thread to braided clusters.
- Sinuosity varies even more.
- Clusters capture the variety of planforms

Cluster	Image Count	Wetted Width (cm)	Wetted Area (m^2)	Sinuosity (–)	BI (–)	eBI (–)	BI/eBI (–)
cluster 0	1 954	30.92	0.93	11.79	1.77	1.53	1.11
cluster 1	2 108	19.70	0.59	11.90	1.76	1.54	1.10
cluster 2	4 237	31.30	0.94	26.98	2.85	2.36	1.18
cluster 3	3 481	41.95	1.26	30.51	3.04	2.42	1.21
cluster 4	2 290	67.25	2.02	58.51	4.32	3.38	1.30
cluster 5	2 978	66.37	1.99	73.31	5.38	4.26	1.28
cluster 6	2 262	52.41	1.57	34.02	3.28	2.66	1.23
cluster 7	4 393	34.11	1.02	20.24	2.32	1.98	1.15
cluster 8	3 252	70.20	2.11	49.25	3.71	3.05	1.20
cluster 9	7 212	68.84	2.07	76.83	5.40	4.25	1.28
cluster 10	5 133	44.84	1.35	28.73	3.07	2.51	1.21
cluster 11	13 729	64.06	1.92	47.90	3.92	3.18	1.22
cluster 12	7 931	48.78	1.46	26.00	2.89	2.37	1.20
cluster 13	4 828	68.84	2.07	52.42	4.37	3.47	1.27
cluster 14	3 416	58.79	1.76	35.48	3.62	2.94	1.23
cluster 15	2 796	50.29	1.51	39.05	3.73	3.03	1.24

CLUSTER CHARACTERIZATION

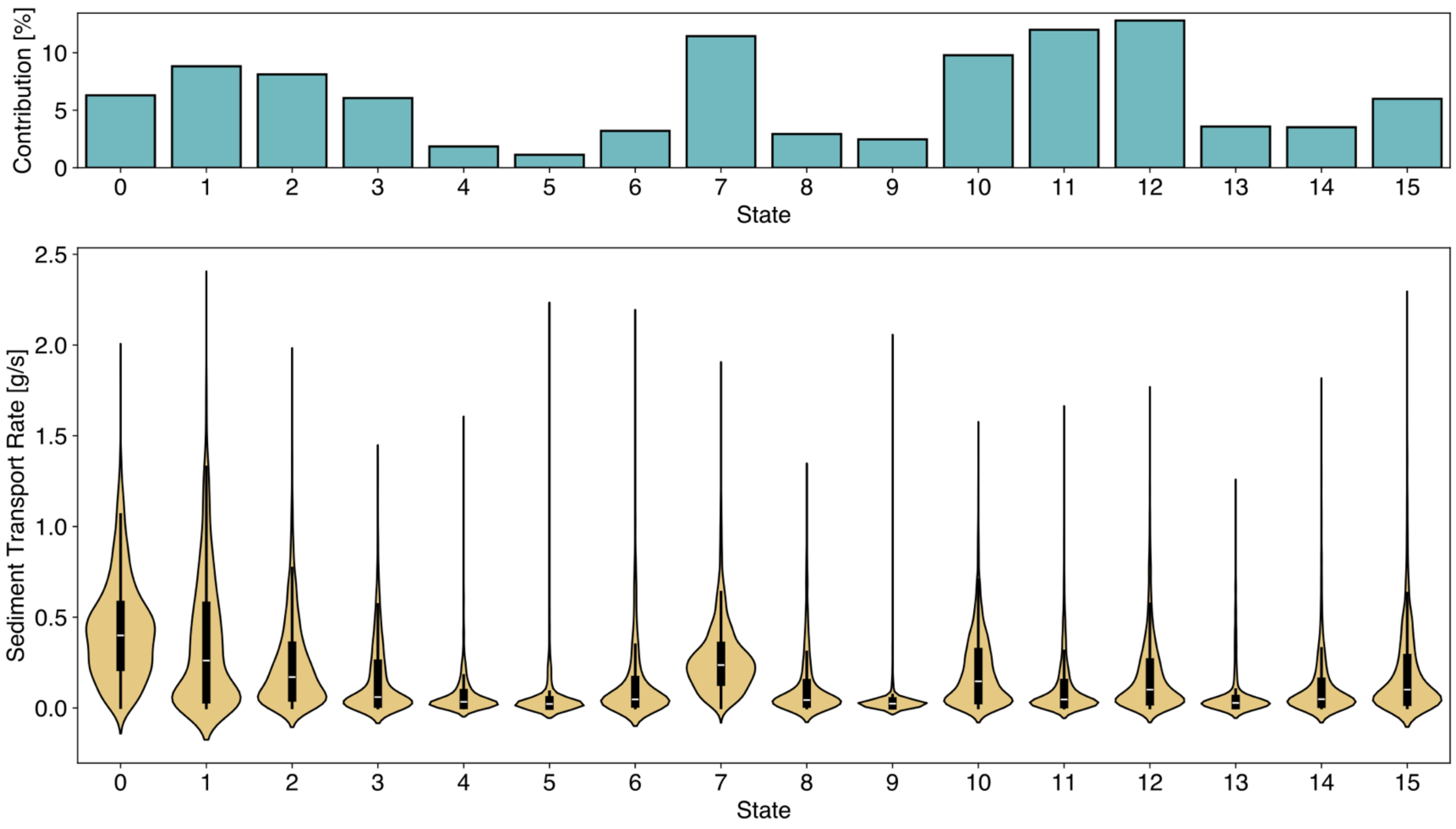
State-conditioned sediment transport

Violin plots show three main patterns:

- Compact body and thin tails
- Median changes with states
- Variability is uneven between states

Contribution to total sediment does not follow the same behavior

Sediment transport dynamics are state-dependent and unevenly distributed across the morphological spectrum.



Cluster Characterization

State-conditioned sediment transport

Correlation with morphological descriptors

- As wetted width, sinuosity, and braiding indices increase, transport decreases.
- Simple and narrow states transport more sediments with greater variability

Planform complexity increases

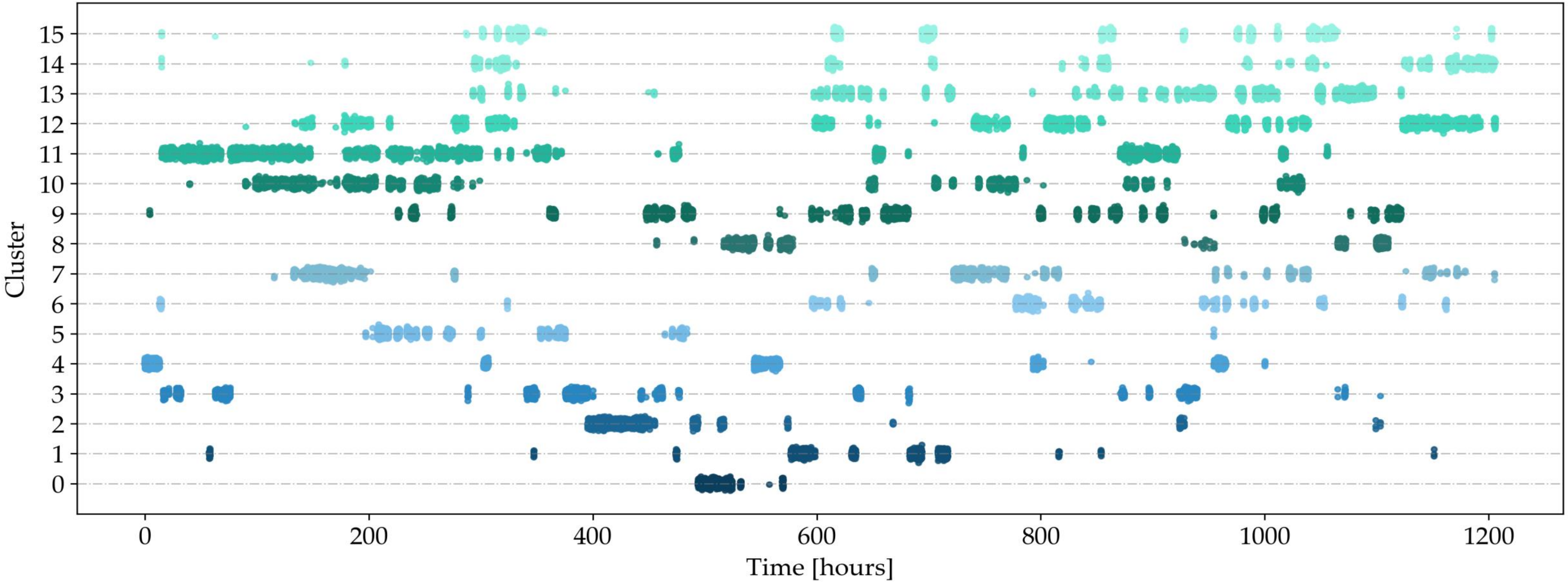
⇓

Transport decreases

TEMPORAL ORGANIZATION

State occupancy and persistence

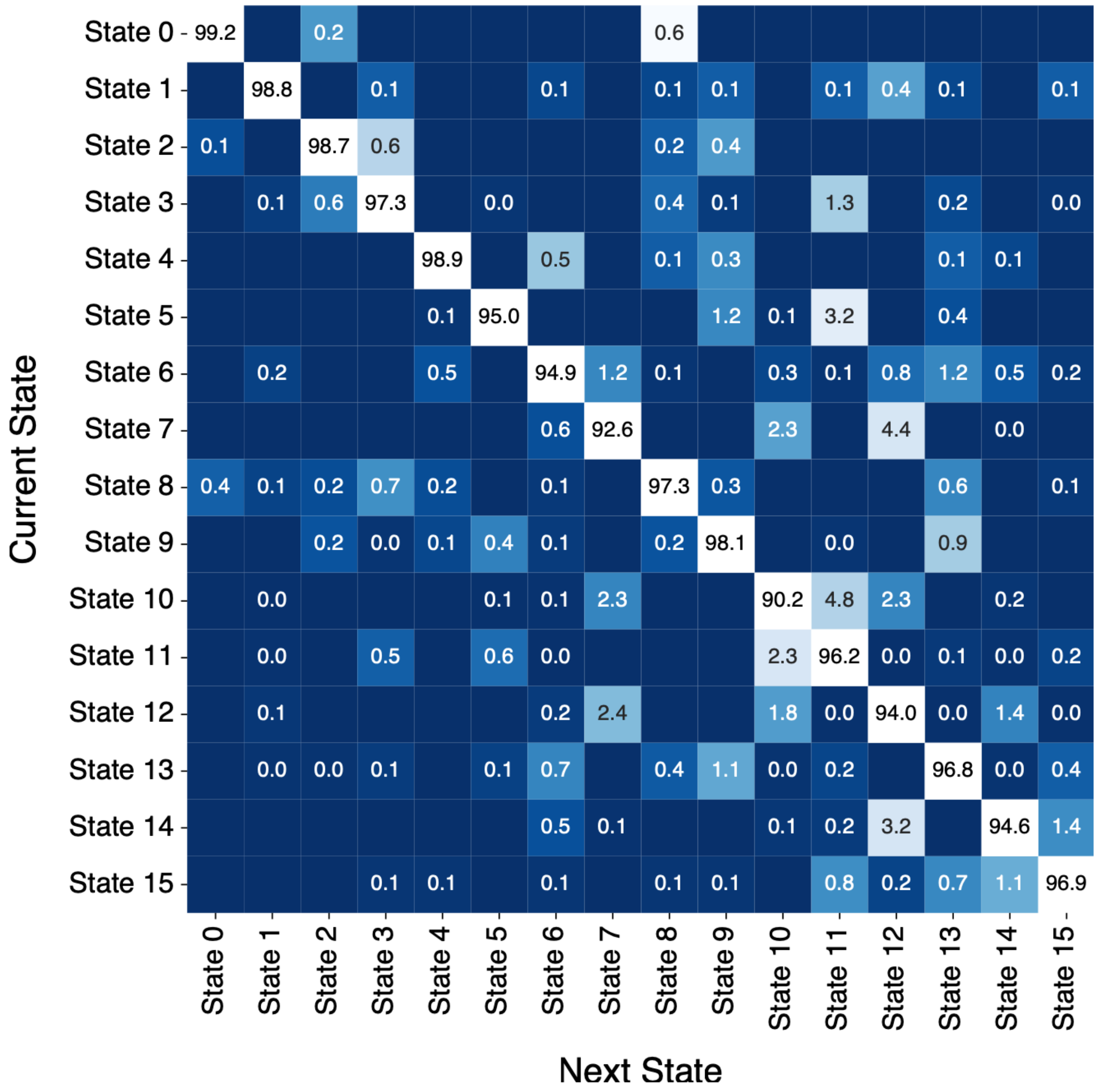
- Extended intervals during which the system remains in a single configuration, interrupted by shorter periods of rapid switching among states.



Temporal Organization

Transition structure

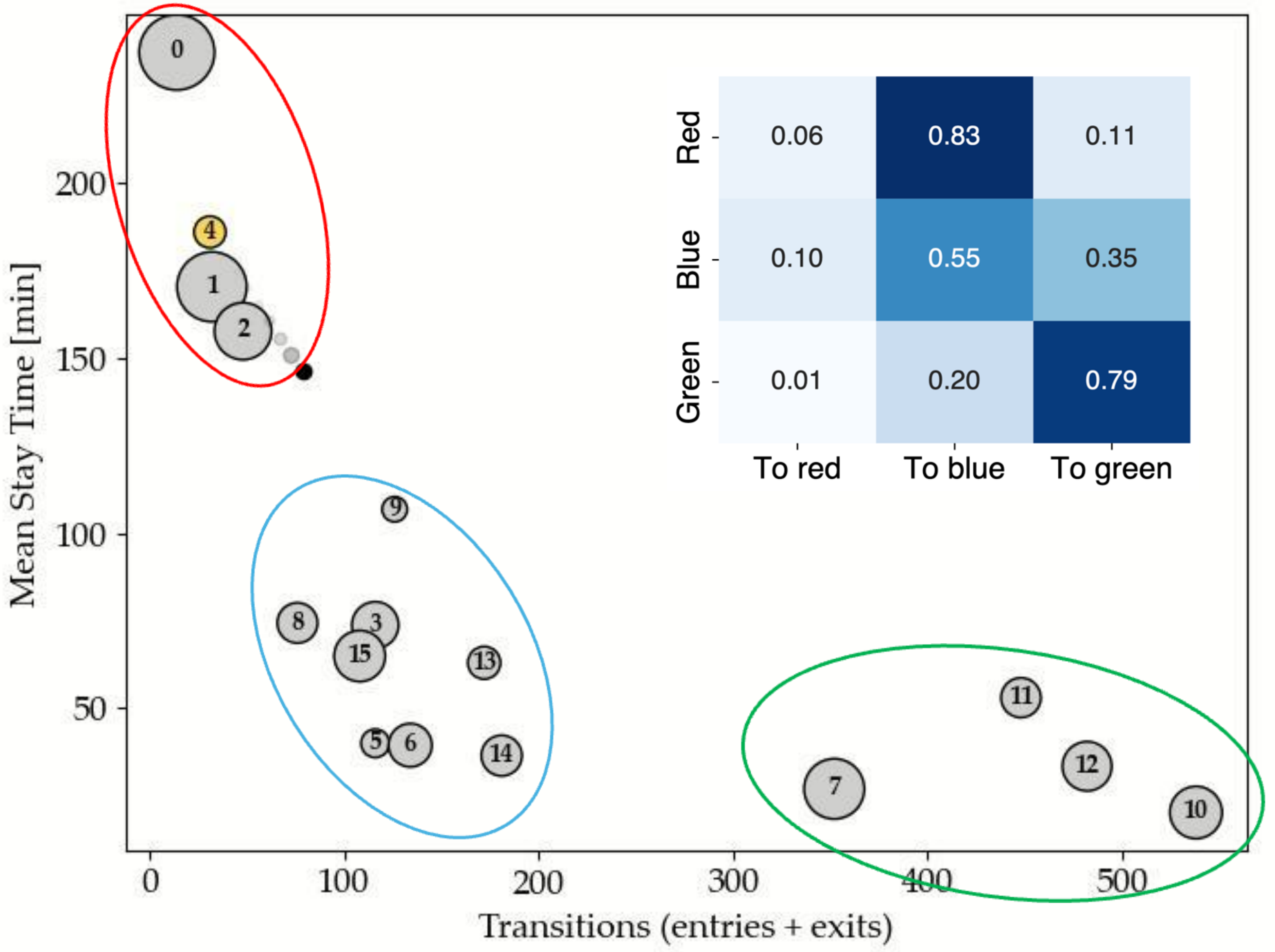
- Transitions are not uniformly distributed across the state space.
- Higher transition probabilities tend to cluster near the diagonal: small incremental changes between timesteps
- Distant jumps are rare. When they occur, there is no return travel.
- Some states more “friendly” than others.



TEMPORAL ORGANIZATION

Transition structure

- Three groups coexist:
  - **Red:** low activity and long stays. Varied transport.
  - **Blue:** moderate transitions and stay time. Mediator between other two.
  - **Green:** short stays and high activity. Greater contribution to total sediment.
- Planform evolution unfolds through a heterogeneous sequence of state occupations and transitions.



CONCLUSIONS

1. Braided rivers can be described in terms of a set of distinct morphological states
2. These states are functionally meaningful: morphology structures define sediment transport behavior
3. States with similar morphometrics behave differently in their time organization
4. No single morphology dominates the system
5. The system has a structured temporal architecture with preferred planform states and certain pathways of reorganization.
6. Our approach is a physically interpretable way to connect morphology and transport without requiring explicit resolution of all local processes.

Next step: use this approach to predict sediment transport.

Preprint available!

Thank you