



Assessing 2035 Climate Change Risks to TMDL in the Rappahannock River using SCHISM



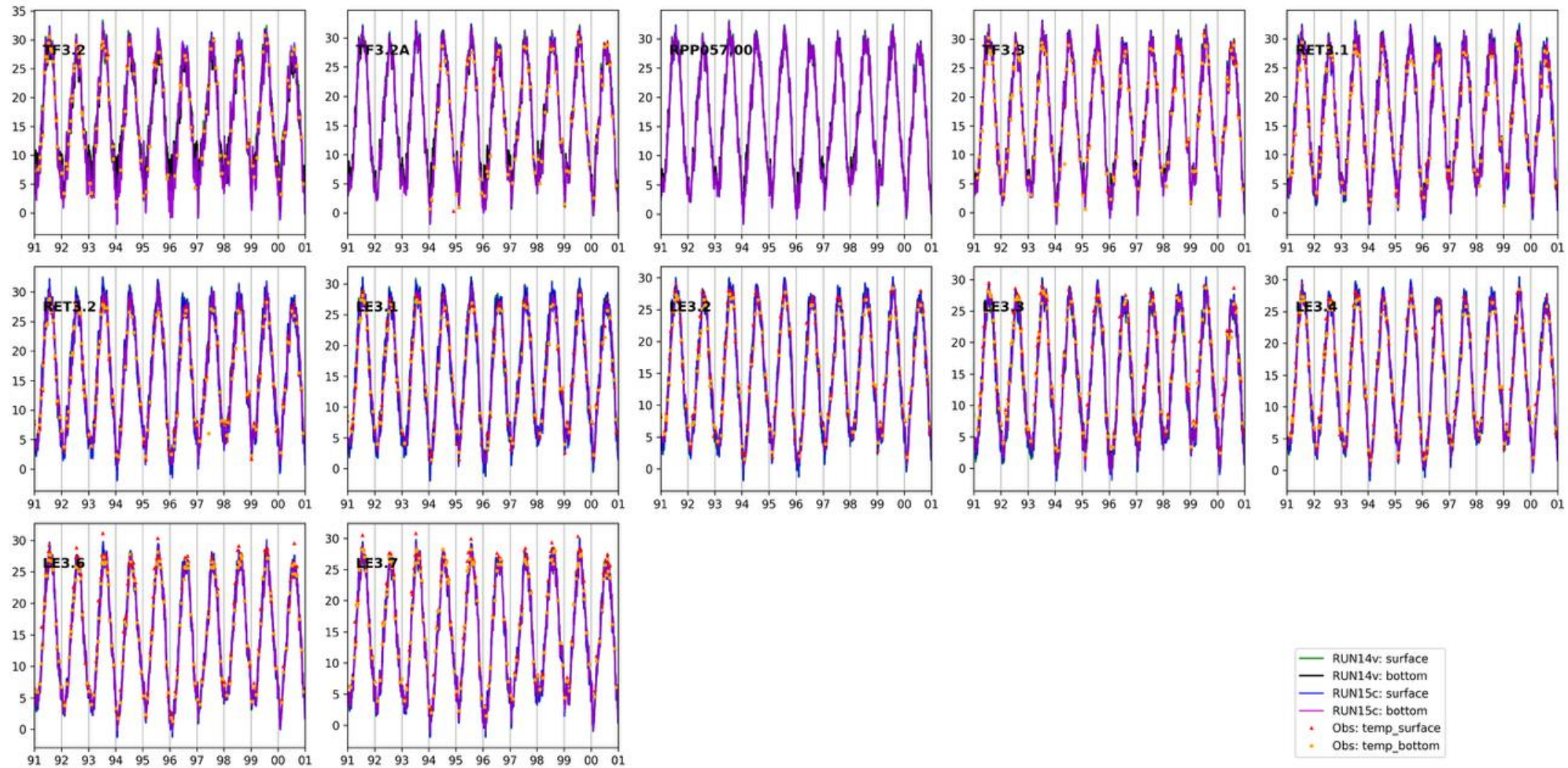
(co-)PIs: Qubin Qin, Jian Shen, Zhengui Wang, and Pierre St-Laurent
Advisory team: Joseph Zhang and Marjorie Friedrichs

CBP Modeling Quarterly Review
April 8, 2026

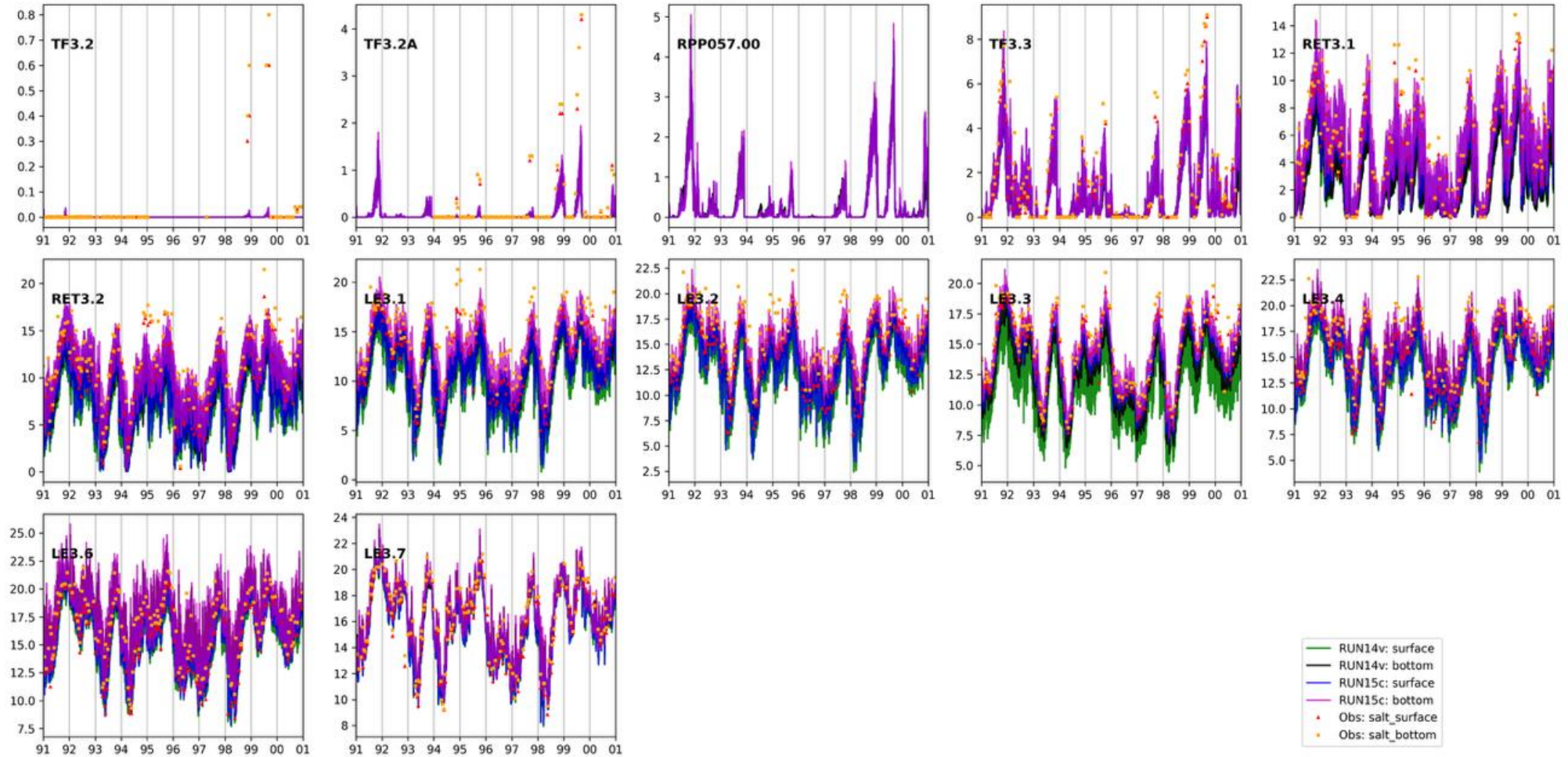
Progress of the Rappahannock MTM Development

- Both the hydrodynamic model and the ICM have been updated to align with the latest MBM configuration (Phase 7 loadings) and run successfully
- Here we show preliminary results

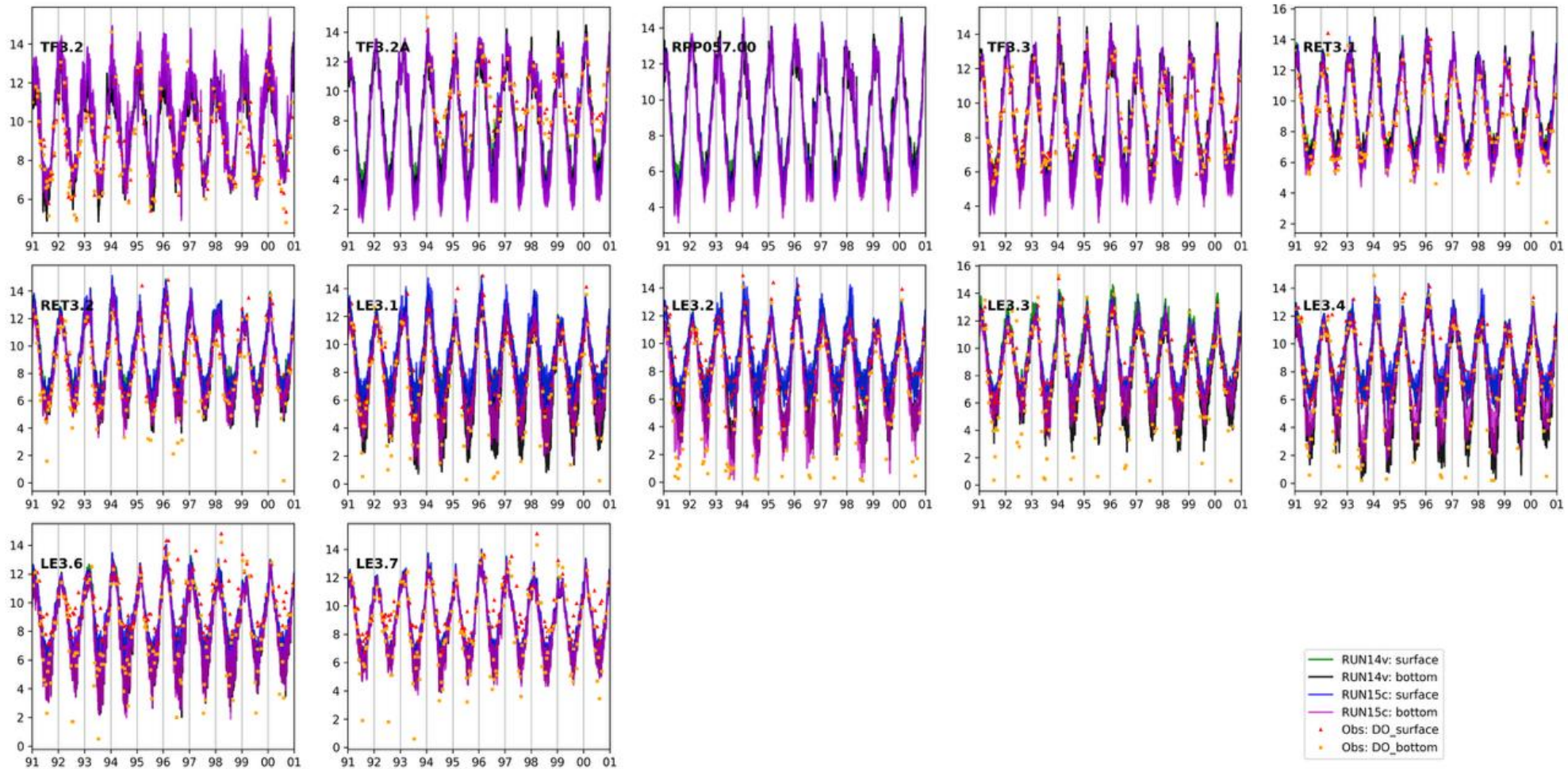
Rappahannock MTM model results from 1991 to 2000: temperature



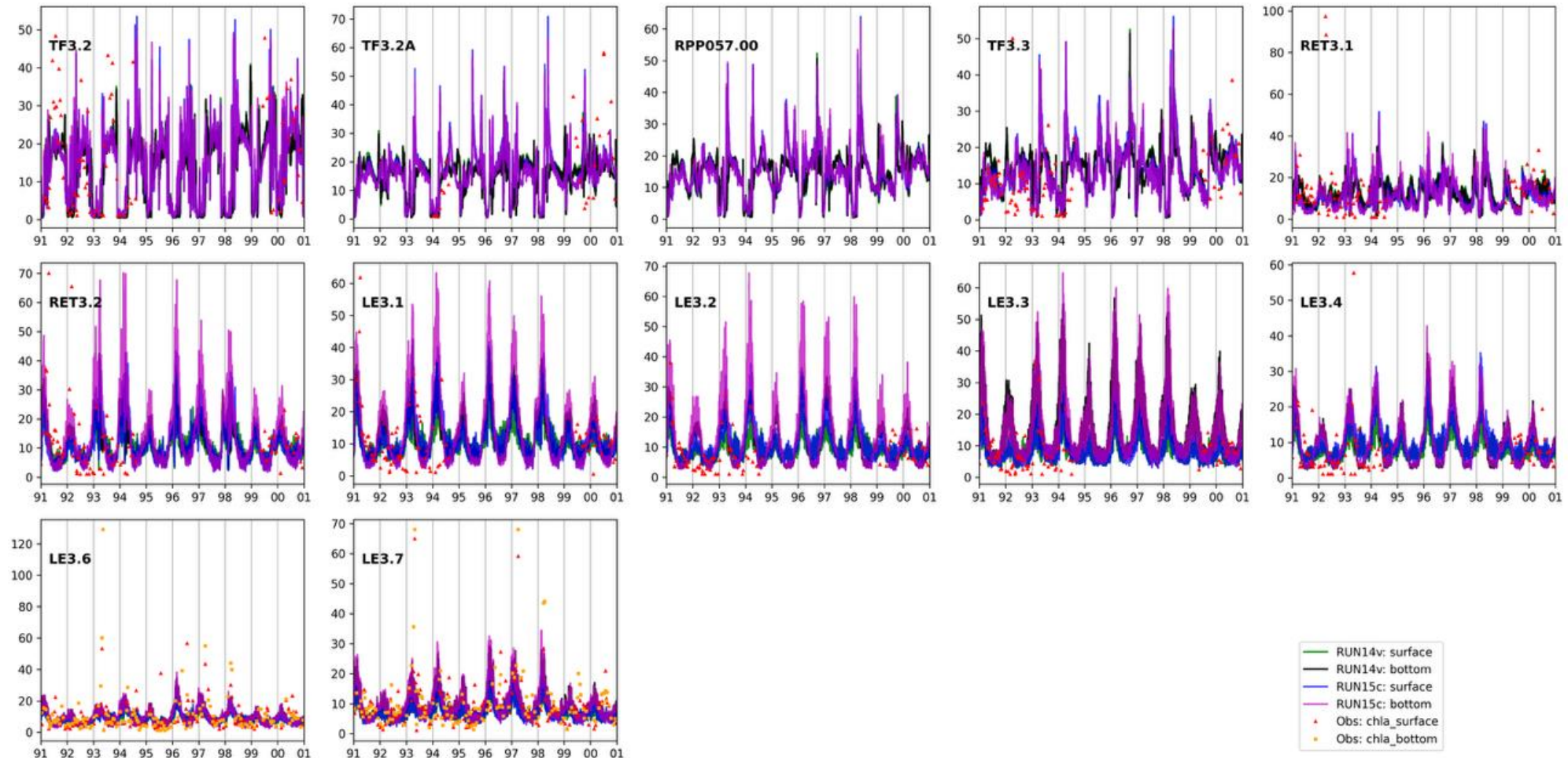
Rappahannock MTM model results from 1991 to 2000: Salinity



Rappahannock MTM model results from 1991 to 2000: Dissolved oxygen concentrations



Rappahannock MTM model results from 1991 to 2000: Chlorophyll-a concentrations



Riverine Freshwater Connectivity Among Major Tributaries in Chesapeake Bay

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¹East Carolina University

²Yale University

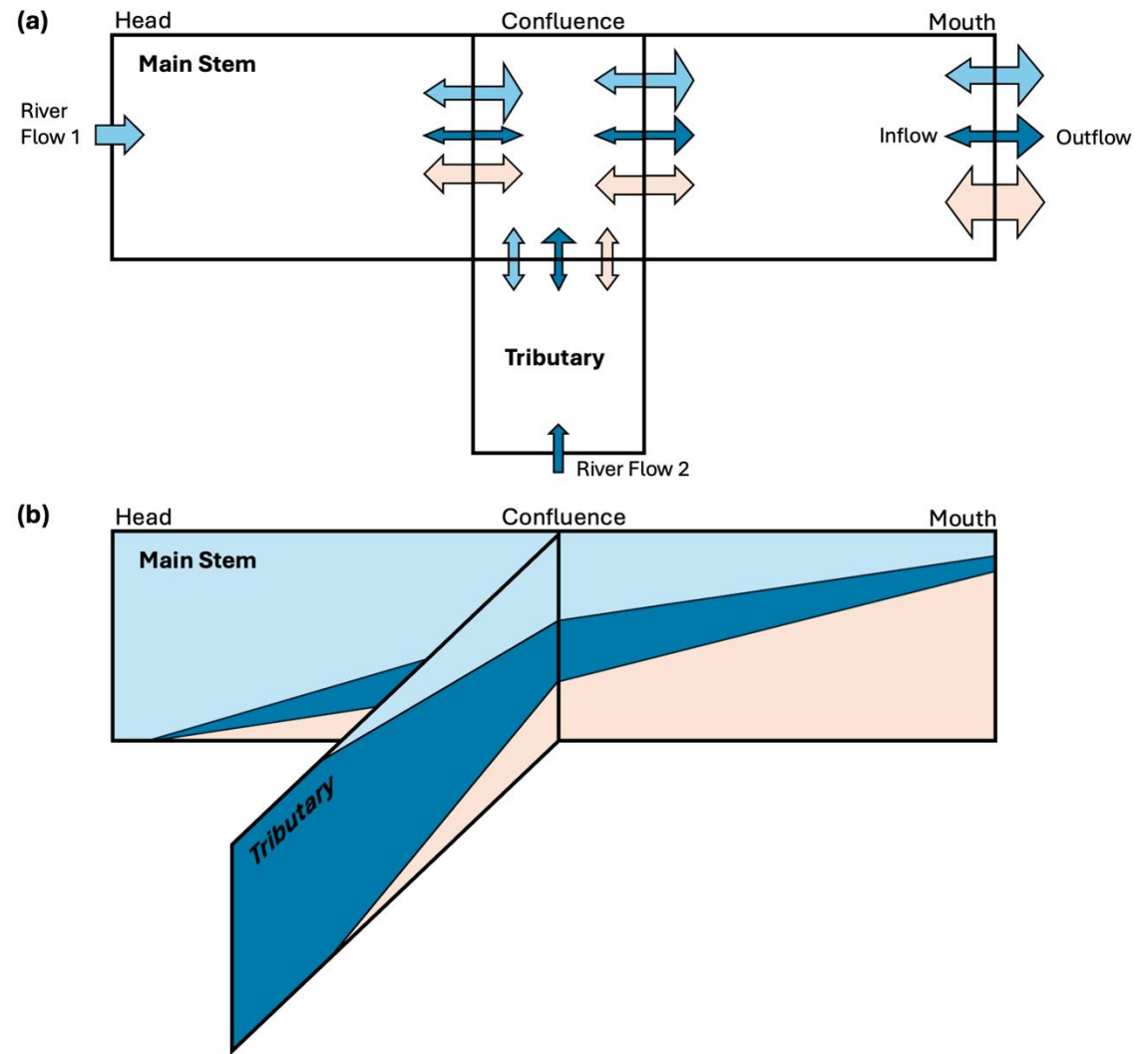
³Virginia Institute of Marine Science

⁴U.S. Environmental Protection Agency Chesapeake Bay Program Office

Introduction

Riverine freshwater connectivity:

the extent to which freshwater discharged from one tributary is transported to and influences other tributaries within the estuarine network.

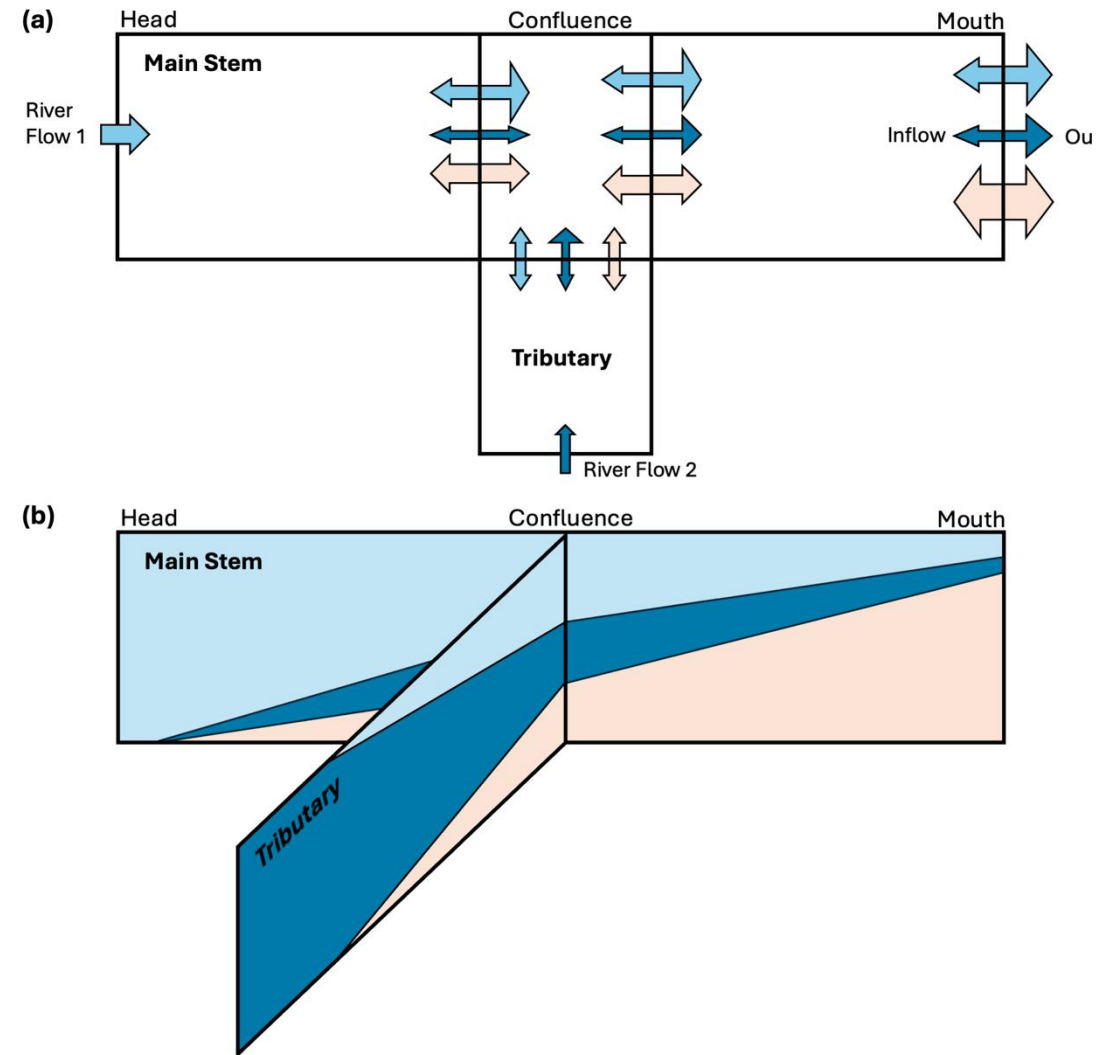


Conceptual Schematic of tributary-to-tributary freshwater connectivity in an estuarine system. (a) Volume fluxes of river inflow, inflow and outflow for two freshwater constituents (light and dark blue), and oceanic saltwater (orange). (b) Corresponding fractions of freshwater constituents and saltwater in total water composition, such that the sum of all fractions equals 1.

Introduction

Importance of Riverine freshwater connectivity:

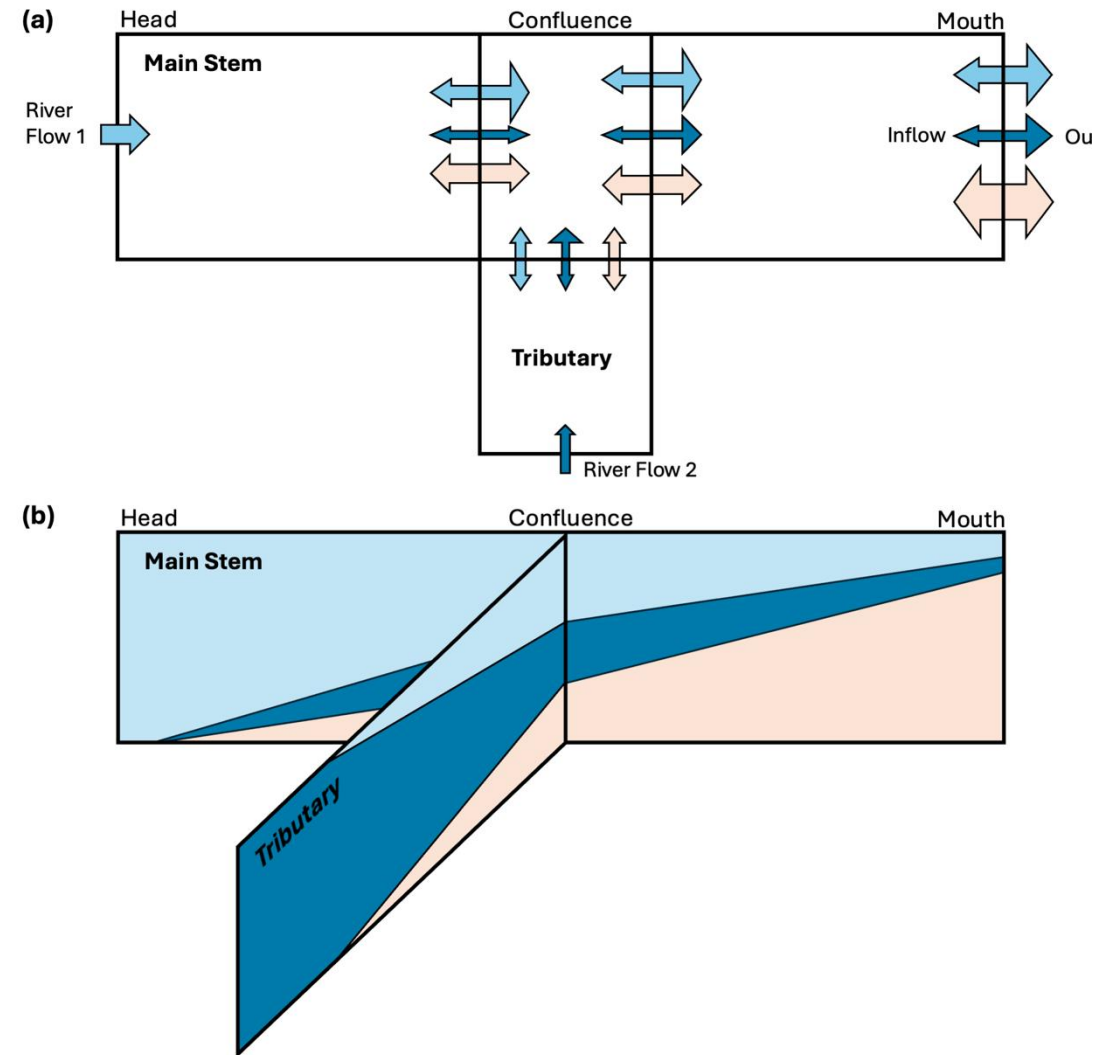
- Changes in discharge from one tributary can measurably alter salinity in another (Lin et al., 2024; Wang et al., 2017);
- Affect water availability for municipal and industrial use as well as ecological conditions including species distribution, productivity, and habitat quality (Jassby et al., 1995; Montagna et al., 2013; Odum, 1988);



Introduction

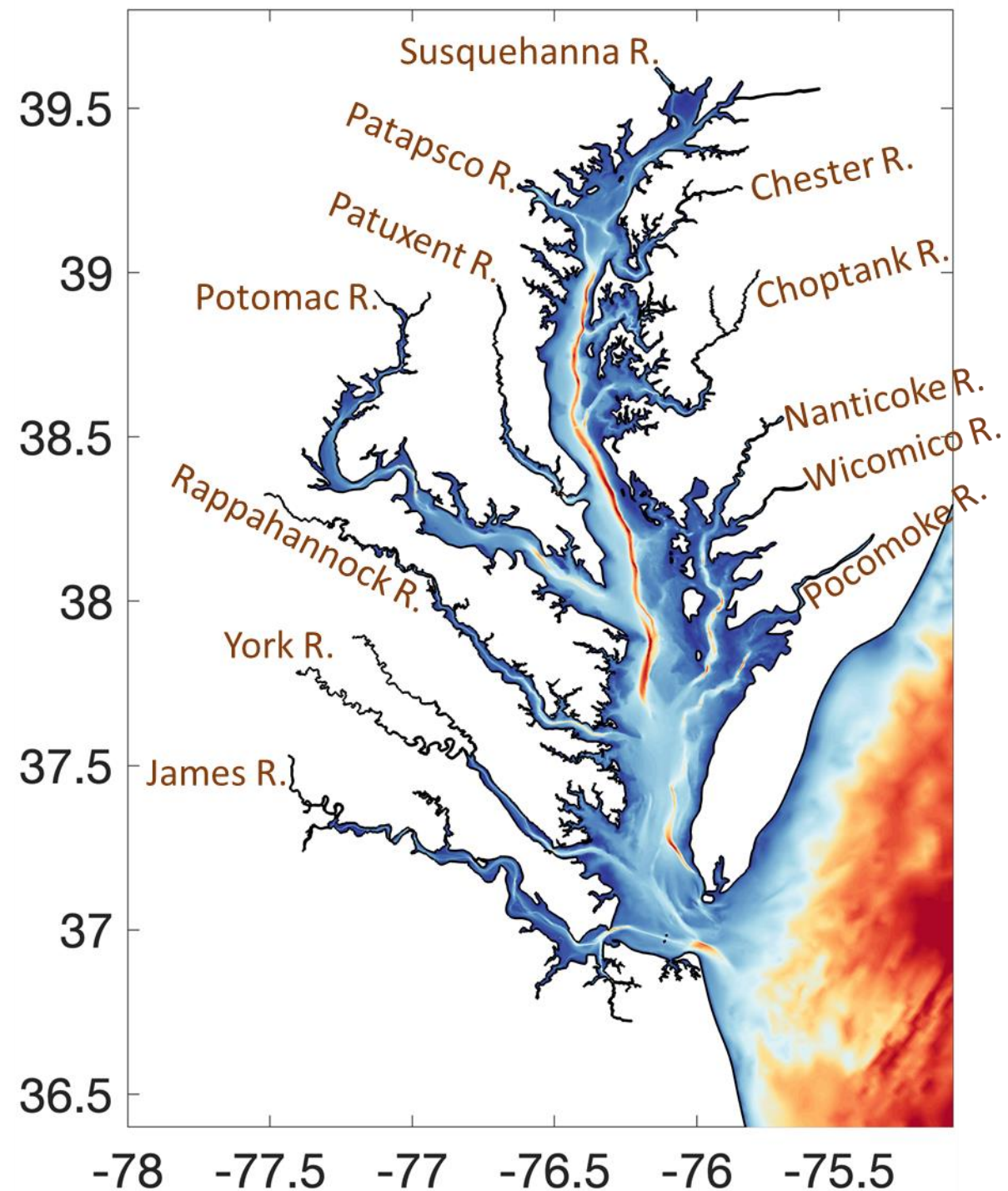
Importance of Riverine freshwater connectivity:

- Impact nutrient transport and retention (Du & Shen, 2017; Wild-Allen & Andrewartha, 2016),
- Impact autochthonous and allochthonous sources of carbon (Abrantes & Sheaves, 2010), hypoxia (Tyler et al., 2009), and
- Impact the movement of pollutants such PFAS, fecal coliform bacteria, and microplastics (Banas et al., 2015; Condie et al., 2018).
- Riverine freshwater exchange and connectivity represent a core mechanism linking hydrodynamic and ecological connectivity in estuarine environments (Conway-Cranos et al., 2015)



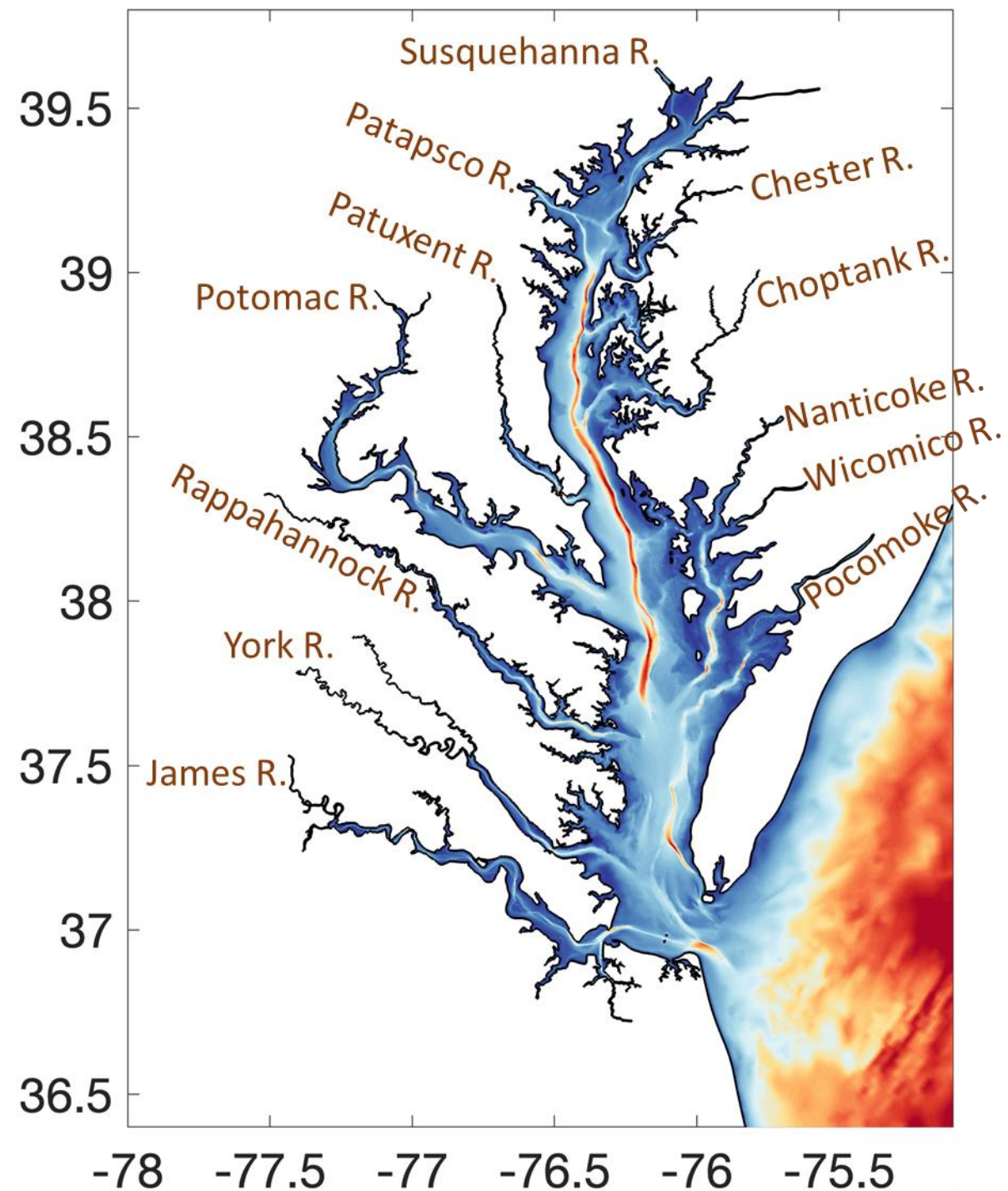
Introduction

- Systematic quantification of inter-tributary freshwater connectivity in Chesapeake Bay has not been well studied
- Riverine Freshwater Connectivity
 - *Exchange of freshwater between each pair of subestuaries (tributaries)*

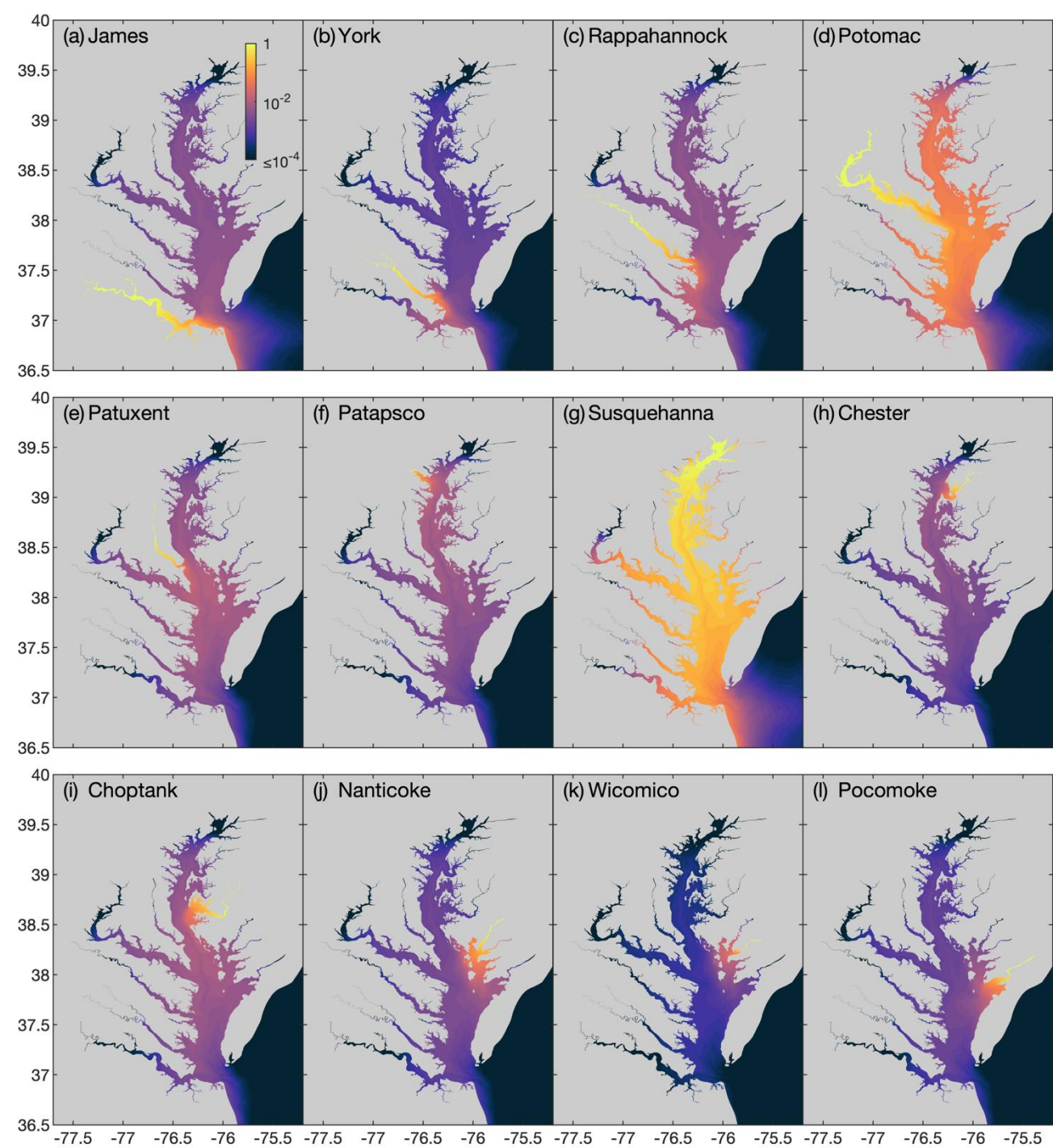
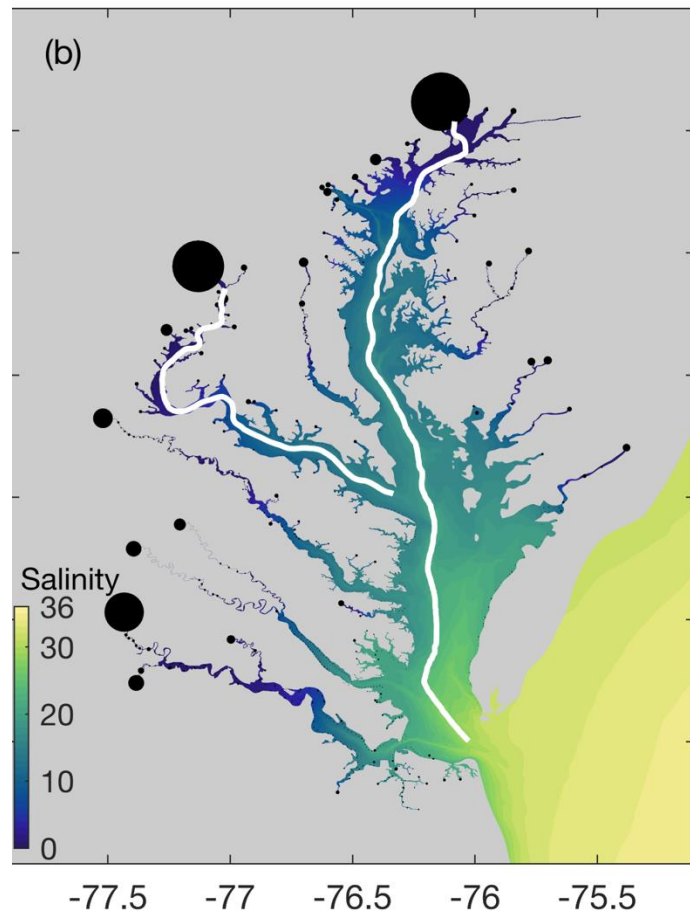


Methods

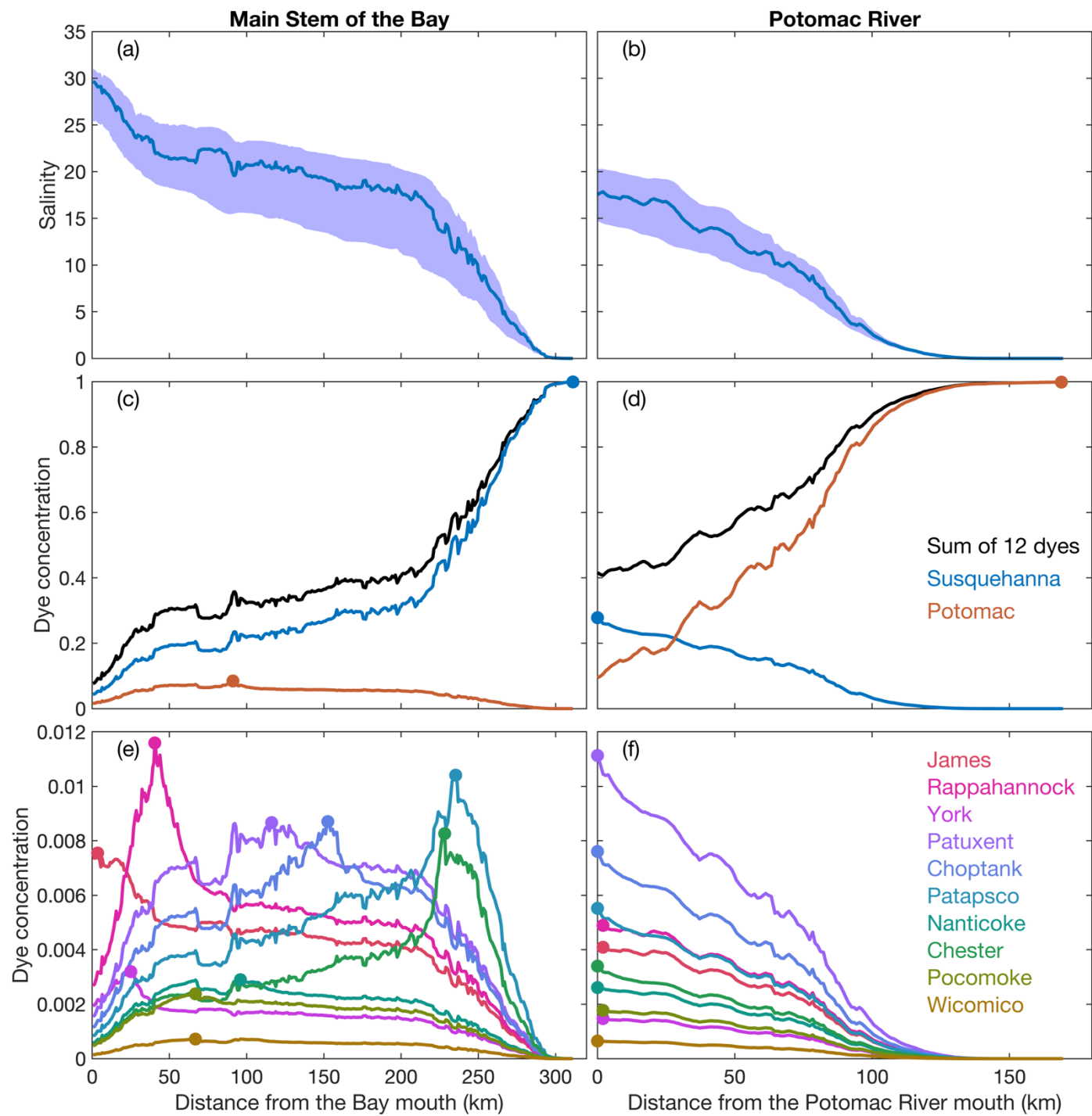
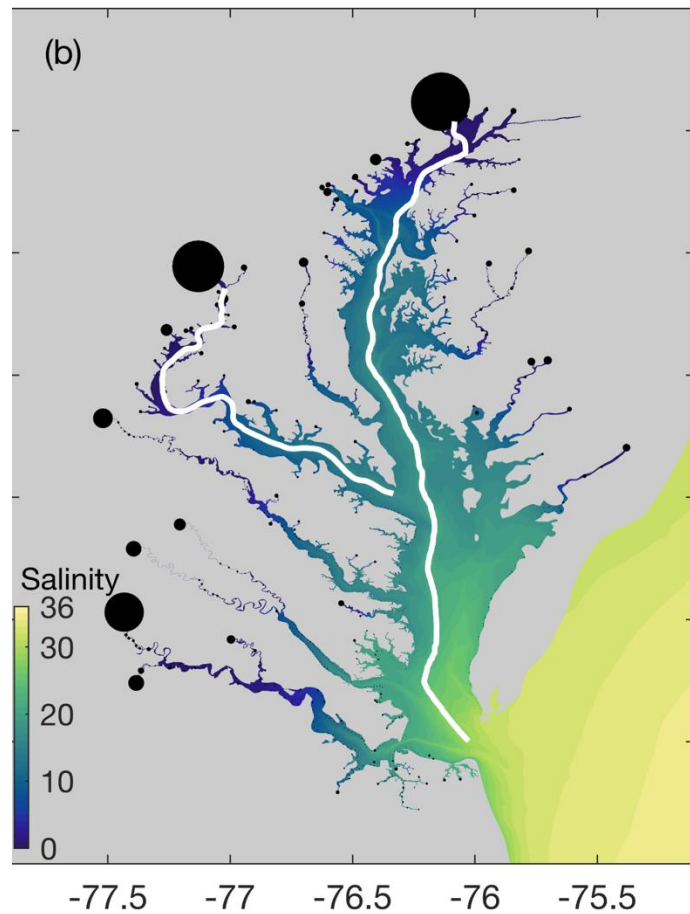
- Study region
 - Chesapeake Bay
 - Focused on 12 major sub-estuaries
 - Susquehanna River is the largest river
- SCHISM hydrodynamic model
 - Chesapeake Bay
 - Well calibrated
 - Ye et al. 2018; Cai et al. 2022, 2023
 - Refined in subestuaries
 - Hydrodynamics: 2010-2014
 - Dye study: 2011-2014



Results - Trace/dye study



Results - Trace/dye study

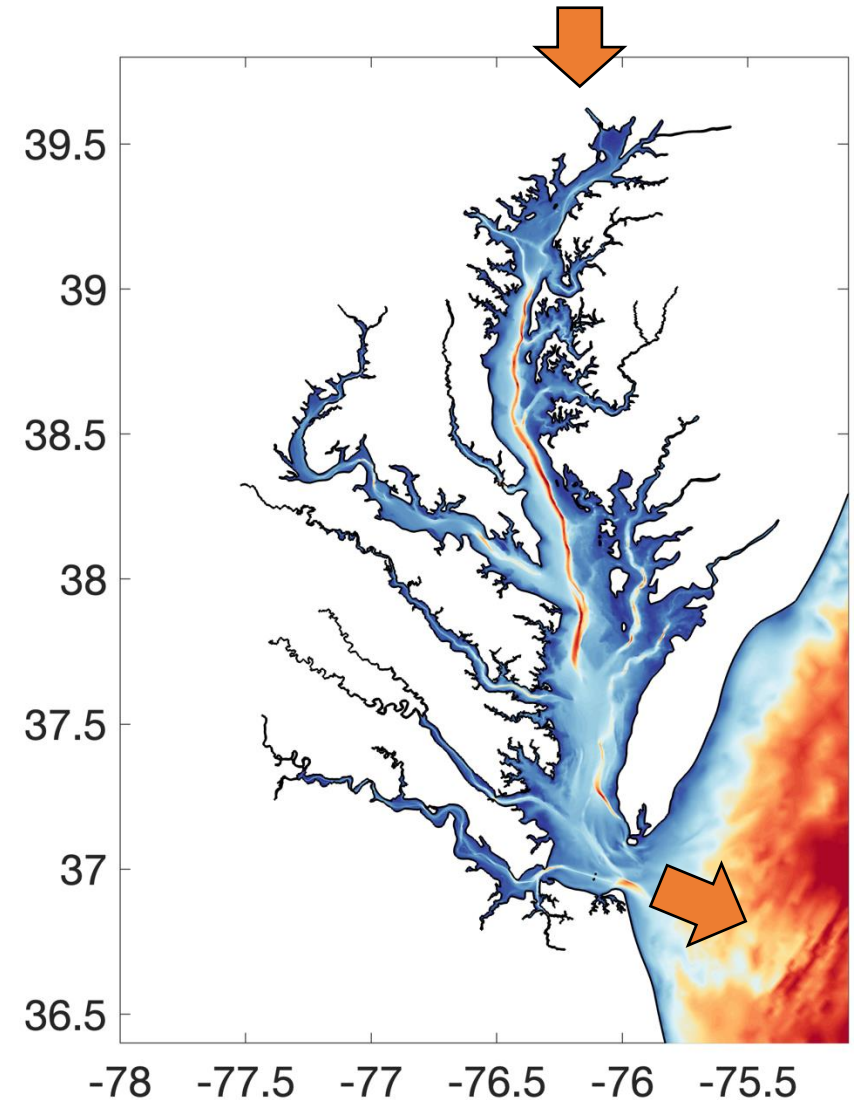


Two metrics for connectivity

Percentage Metric characterizes the distribution of freshwater originating from a specific supplying tributary throughout the estuarine system.

It is defined as the ratio of the total volume of freshwater from the supplying tributary present in a receiving tributary to the total volume of that freshwater constituent within the entire estuary.

$$\text{Percentage}_{i,j} = \frac{\text{Dye mass in Subestuary } j \text{ from Subestuary } i}{\text{Dye mass from Subestuary } i \text{ in the entire system}}$$

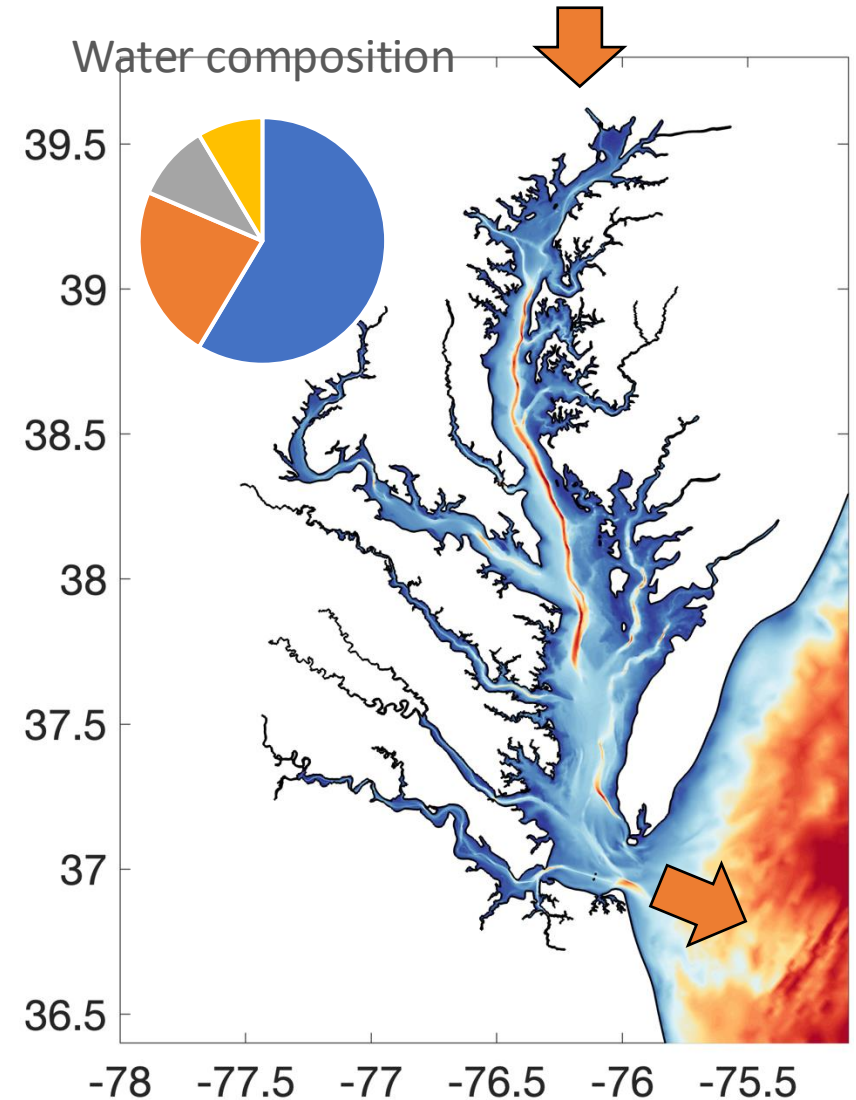
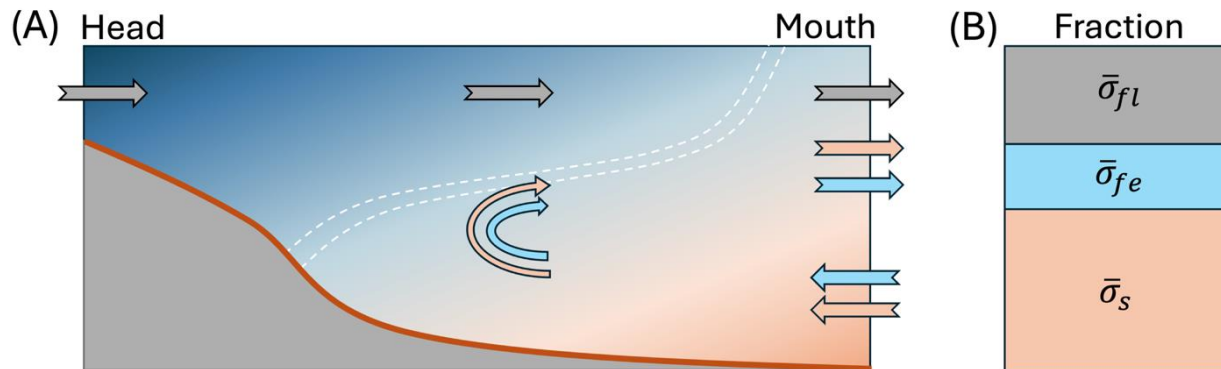


Two metrics for connectivity

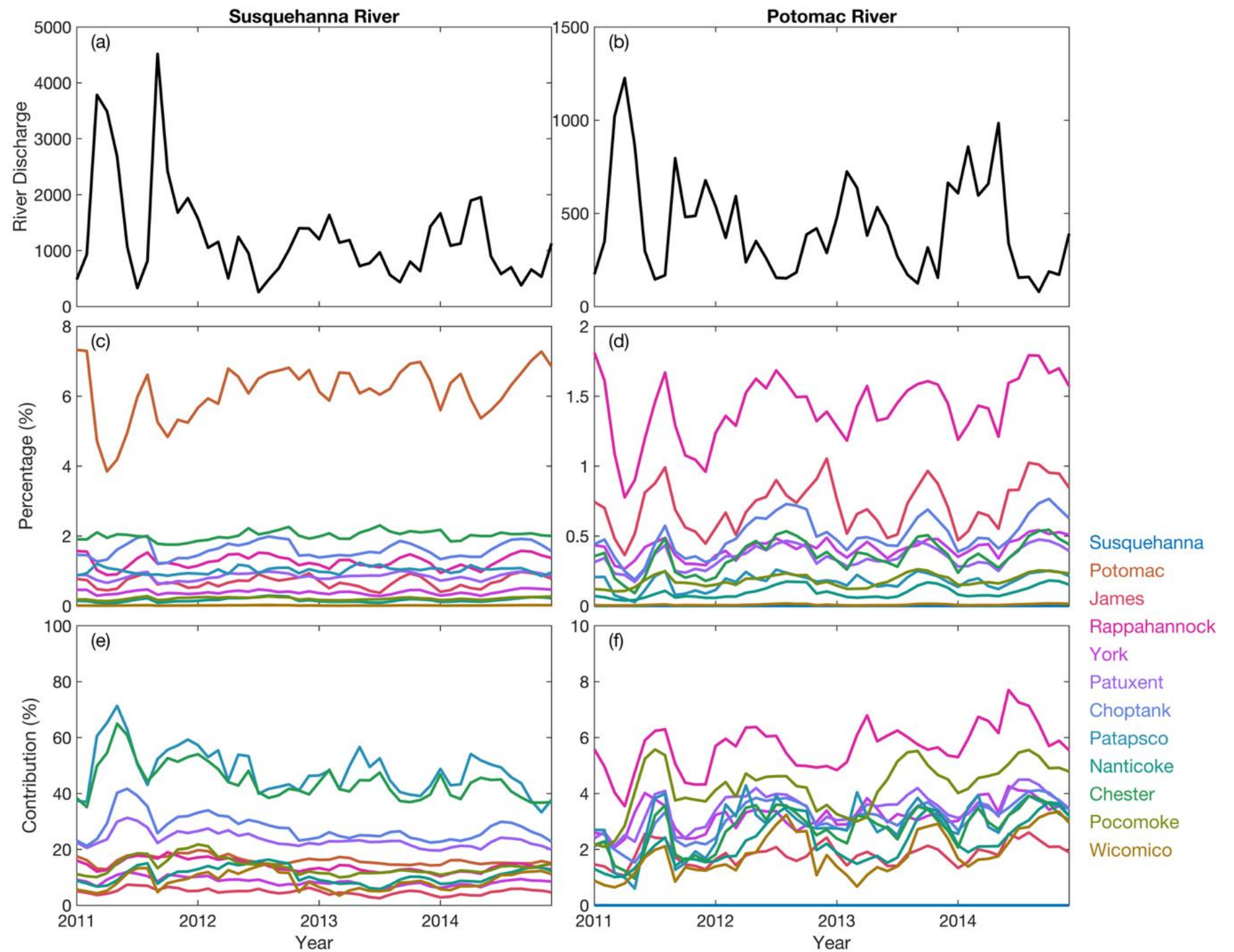
Contribution Metric characterized the influence of riverine freshwater from a supplying tributary i on the water composition of a receiving tributary j .

It is defined as the ratio of the freshwater constituent volume to the total water volume in the receiving tributary, which equals the average fraction of the freshwater constituent i in the receiving tributary j

$Contribution_{i,j} = \text{Dye concentration in Subestuary } j \text{ from Subestuary } i$

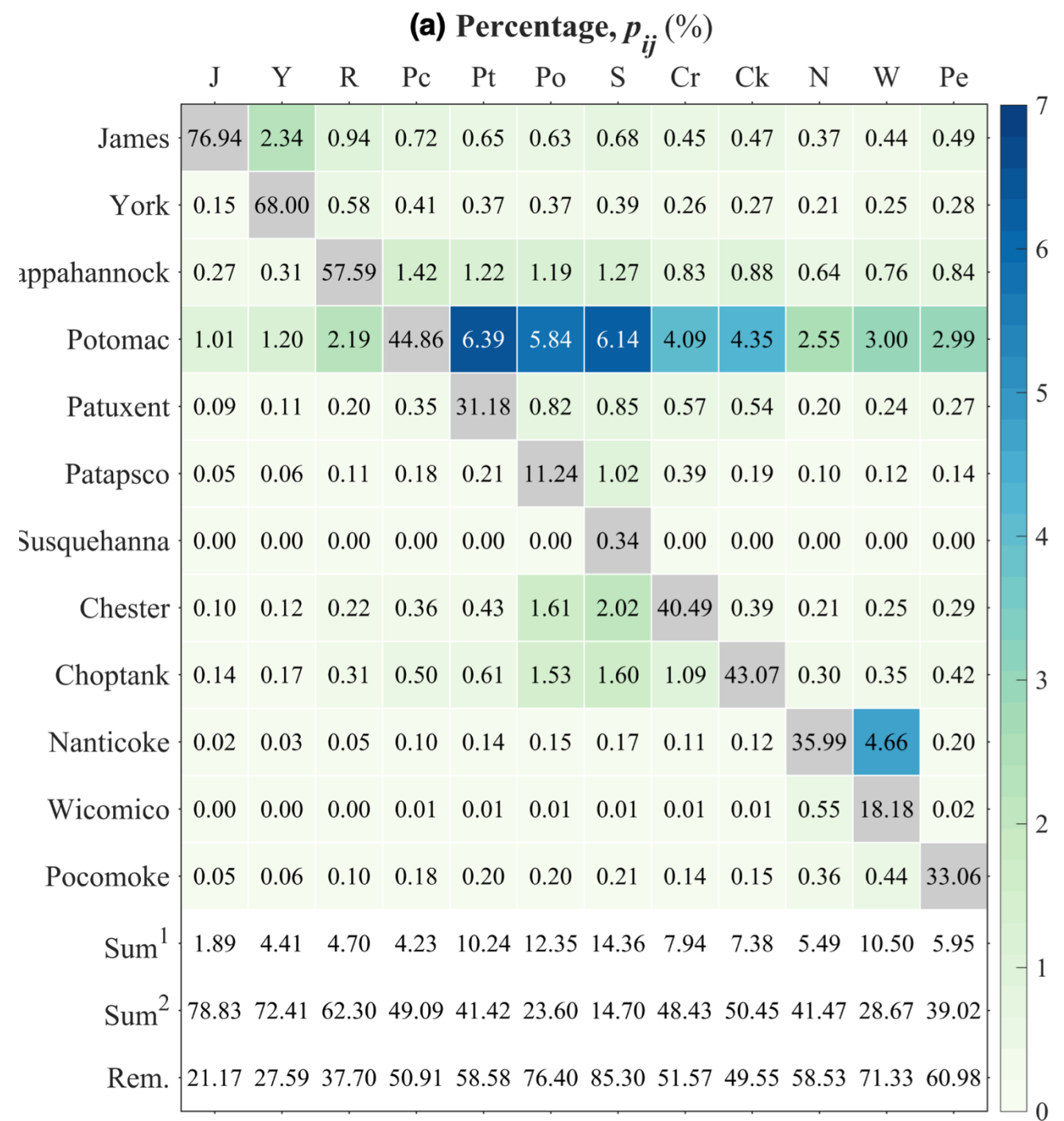


Results

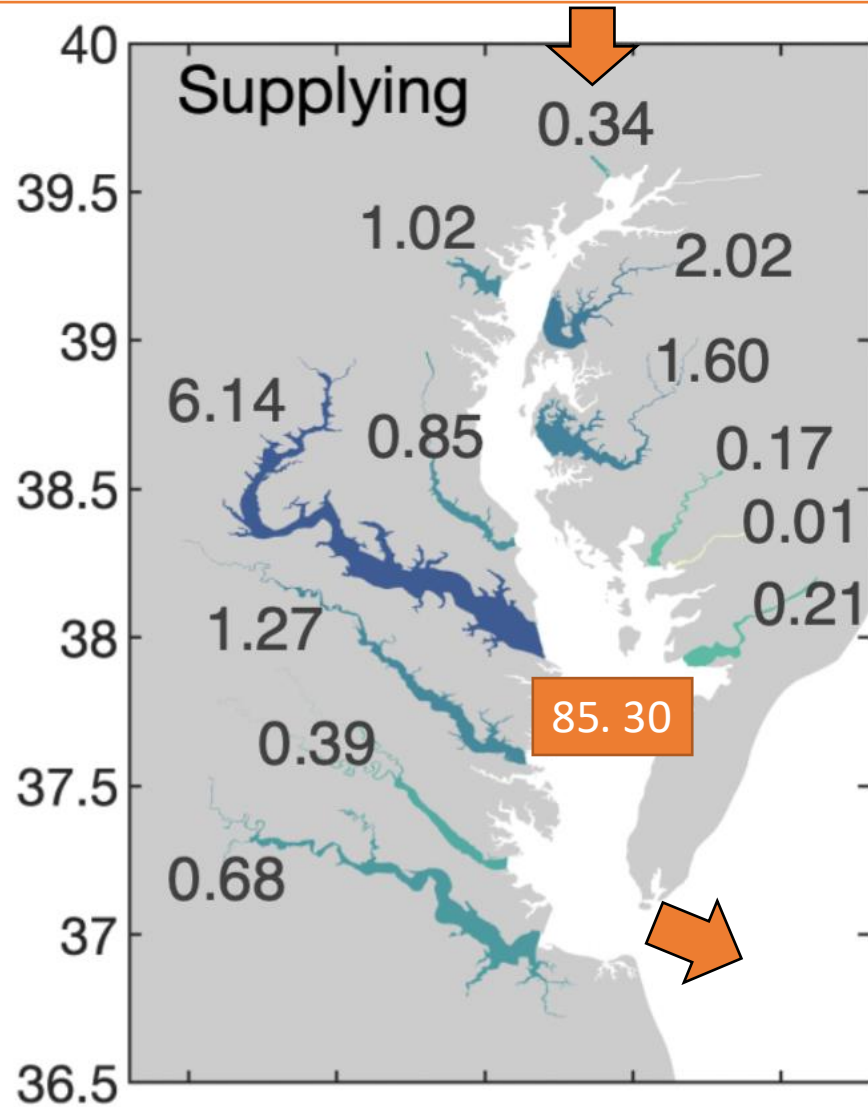


Results: Percentage Metric, multi-year mean (2011-2014)

Columns: the percentage of freshwater constituent from each supplying tributary retained within itself and exported to other tributaries



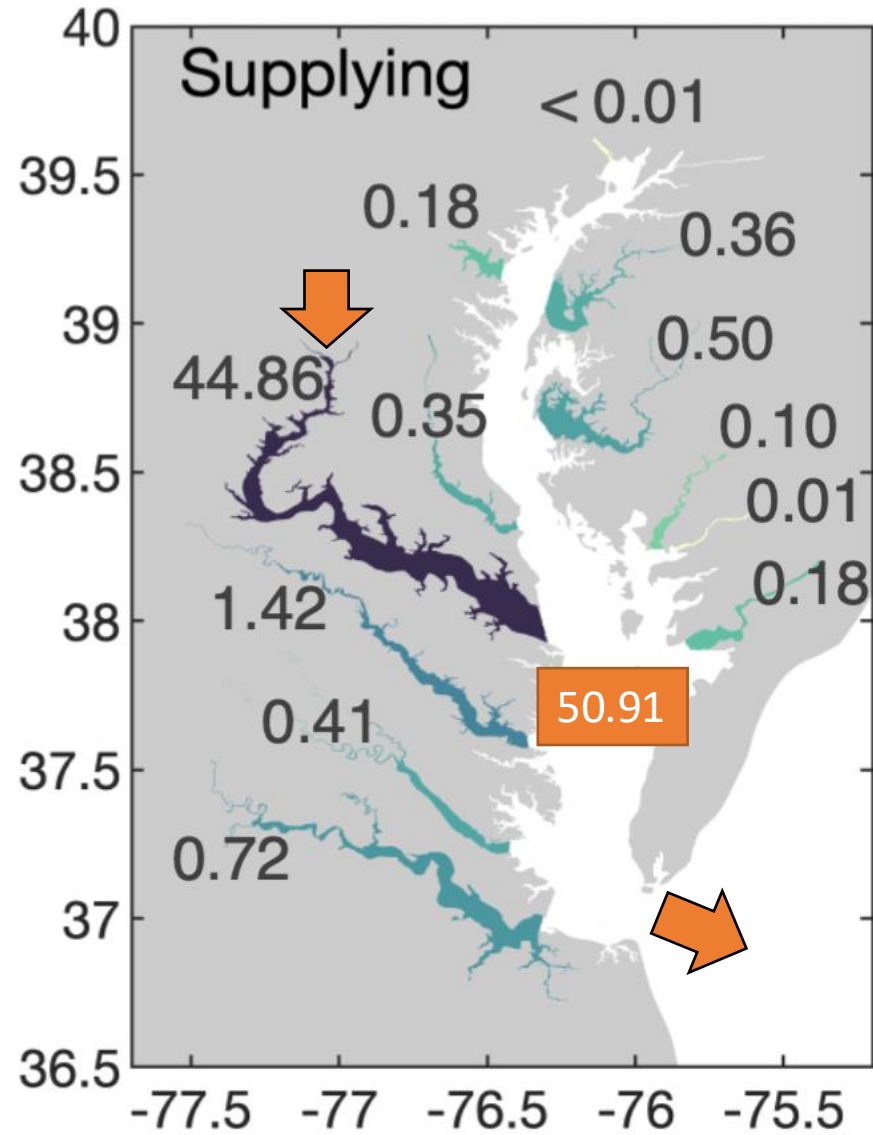
Percentage of freshwater discharged from the Susq. River entered other subestuaries



(a) Percentage, p_{ij} (%)

	J	Y	R	Pc	Pt	Po	S	Cr	Ck	N	W	Pe
James	76.94	2.34	0.94	0.72	0.65	0.63	0.68	0.45	0.47	0.37	0.44	0.49
York	0.15	68.00	0.58	0.41	0.37	0.37	0.39	0.26	0.27	0.21	0.25	0.28
Rappahannock	0.27	0.31	57.59	1.42	1.22	1.19	1.27	0.83	0.88	0.64	0.76	0.84
Potomac	1.01	1.20	2.19	44.86	6.39	5.84	6.14	4.09	4.35	2.55	3.00	2.99
Patuxent	0.09	0.11	0.20	0.35	31.18	0.82	0.85	0.57	0.54	0.20	0.24	0.27
Patapsco	0.05	0.06	0.11	0.18	0.21	11.24	1.02	0.39	0.19	0.10	0.12	0.14
Susquehanna	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00
Chester	0.10	0.12	0.22	0.36	0.43	1.61	2.02	40.49	0.39	0.21	0.25	0.29
Choptank	0.14	0.17	0.31	0.50	0.61	1.53	1.60	1.09	43.07	0.30	0.35	0.42
Nanticoke	0.02	0.03	0.05	0.10	0.14	0.15	0.17	0.11	0.12	35.99	4.66	0.20
Wicomico	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.55	18.18	0.02
Pocomoke	0.05	0.06	0.10	0.18	0.20	0.20	0.21	0.14	0.15	0.36	0.44	33.06
Sum ¹	1.89	4.41	4.70	4.23	10.24	12.35	14.36	7.94	7.38	5.49	10.50	5.95
Sum ²	78.83	72.41	62.30	49.09	41.42	23.60	14.70	48.43	50.45	41.47	28.67	39.02
Rem.	21.17	27.59	37.70	50.91	58.58	76.40	85.30	51.57	49.55	58.53	71.33	60.98

Percentage of freshwater discharged from the Potomac River entered other subestuaries



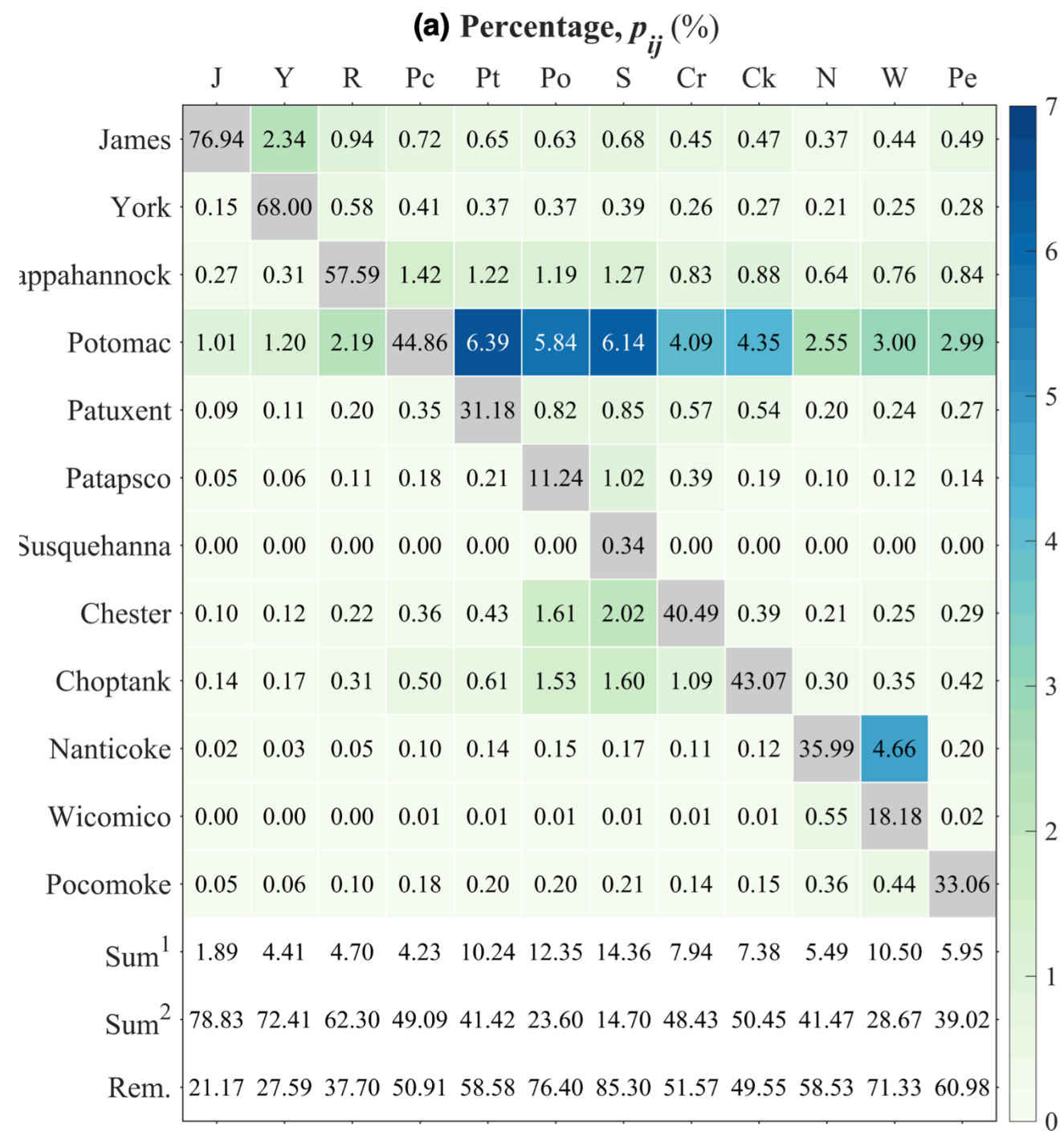
(a) Percentage, p_{ij} (%)

	J	Y	R	Pc	Pt	Po	S	Cr	Ck	N	W	Pe
James	76.94	2.34	0.94	0.72	0.65	0.63	0.68	0.45	0.47	0.37	0.44	0.49
York	0.15	68.00	0.58	0.41	0.37	0.37	0.39	0.26	0.27	0.21	0.25	0.28
Rappahannock	0.27	0.31	57.59	1.42	1.22	1.19	1.27	0.83	0.88	0.64	0.76	0.84
Potomac	1.01	1.20	2.19	44.86	6.39	5.84	6.14	4.09	4.35	2.55	3.00	2.99
Patuxent	0.09	0.11	0.20	0.35	31.18	0.82	0.85	0.57	0.54	0.20	0.24	0.27
Patapsco	0.05	0.06	0.11	0.18	0.21	11.24	1.02	0.39	0.19	0.10	0.12	0.14
Susquehanna	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00
Chester	0.10	0.12	0.22	0.36	0.43	1.61	2.02	40.49	0.39	0.21	0.25	0.29
Choptank	0.14	0.17	0.31	0.50	0.61	1.53	1.60	1.09	43.07	0.30	0.35	0.42
Nanticoke	0.02	0.03	0.05	0.10	0.14	0.15	0.17	0.11	0.12	35.99	4.66	0.20
Wicomico	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.55	18.18	0.02
Pocomoke	0.05	0.06	0.10	0.18	0.20	0.20	0.21	0.14	0.15	0.36	0.44	33.06
Sum ¹	1.89	4.41	4.70	4.23	10.24	12.35	14.36	7.94	7.38	5.49	10.50	5.95
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Results: Percentage Metric, multi-year mean (2011-2014)

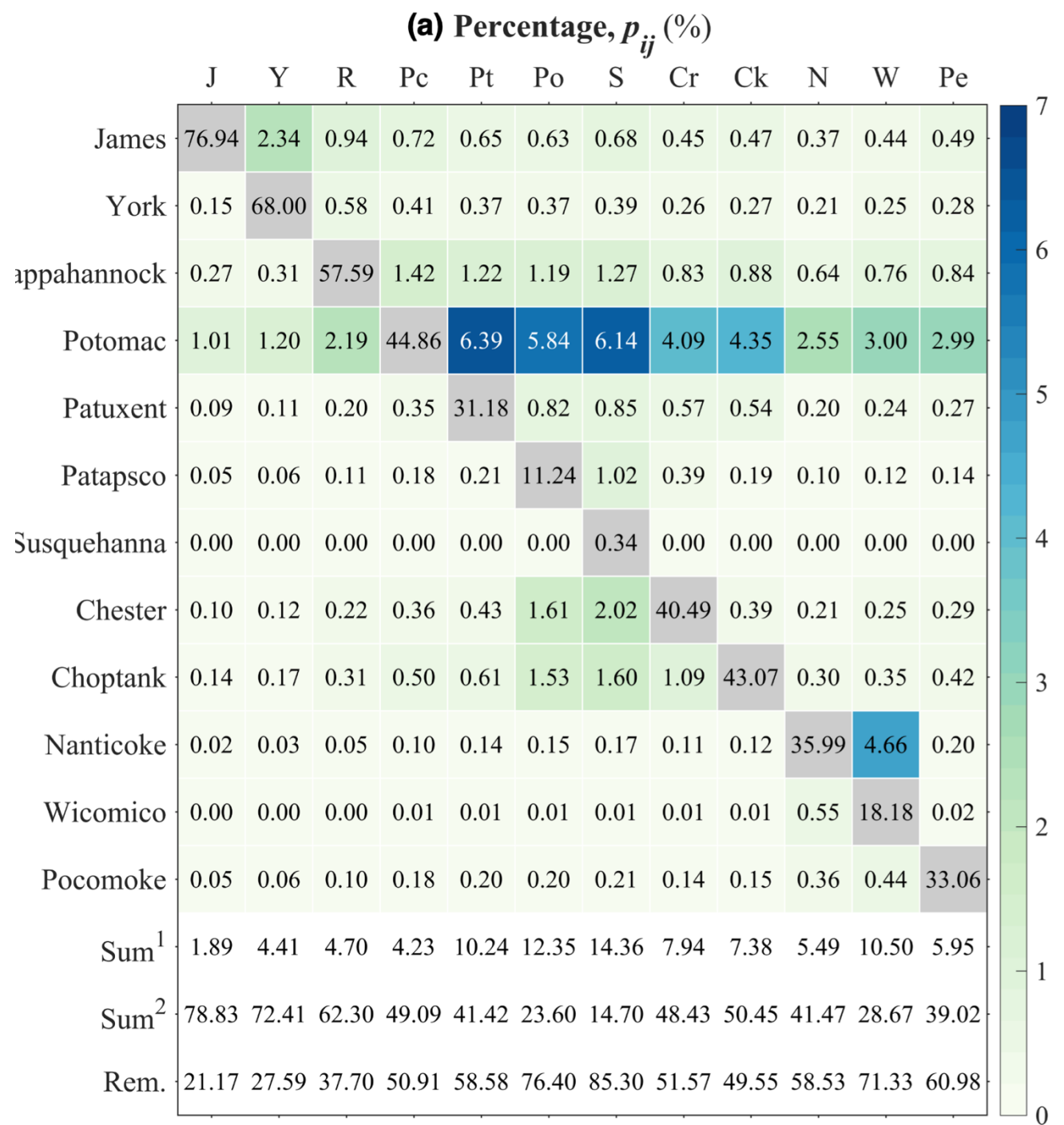
Columns: the percentage of freshwater constituent from each supplying tributary retained within itself and exported to other tributaries

- For freshwater from one river, the largest percentage it enters is either the subestuary itself or the mainstem
- The percentage of freshwater exported to other subestuaries remained generally low: < 10%, and in most cases, <1%.

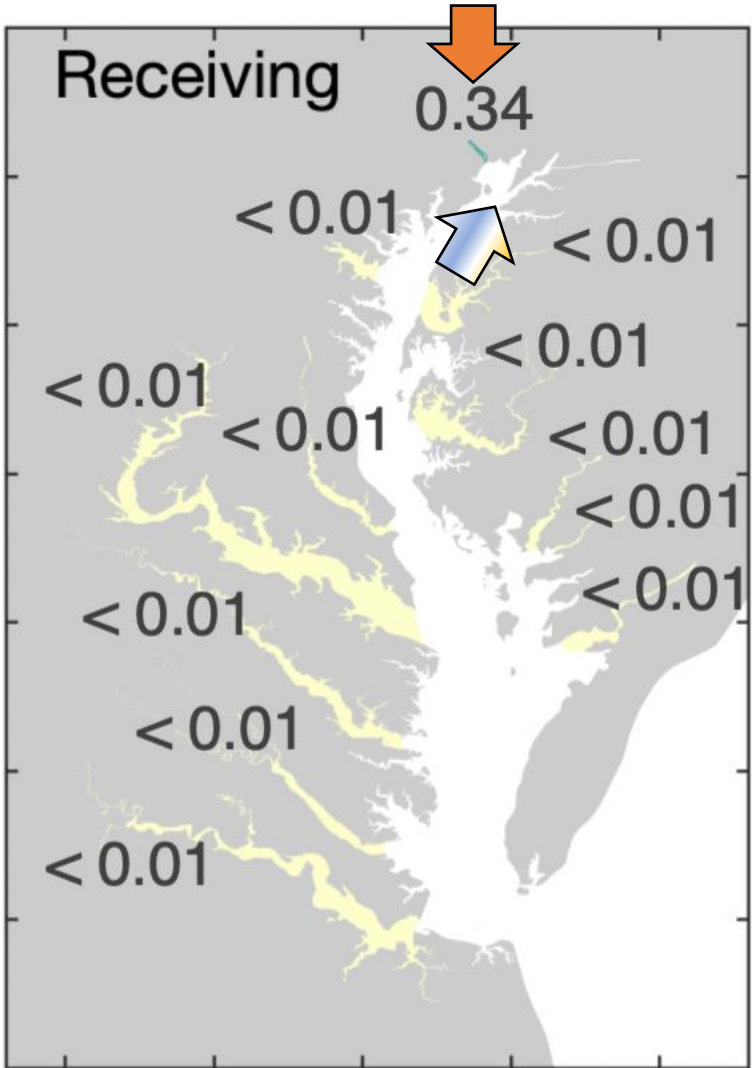


Results: Percentage Metric, multi-year mean (2011-2014)

Rows: Percentage of supplying tributary's freshwater constituent in each receiving tributary



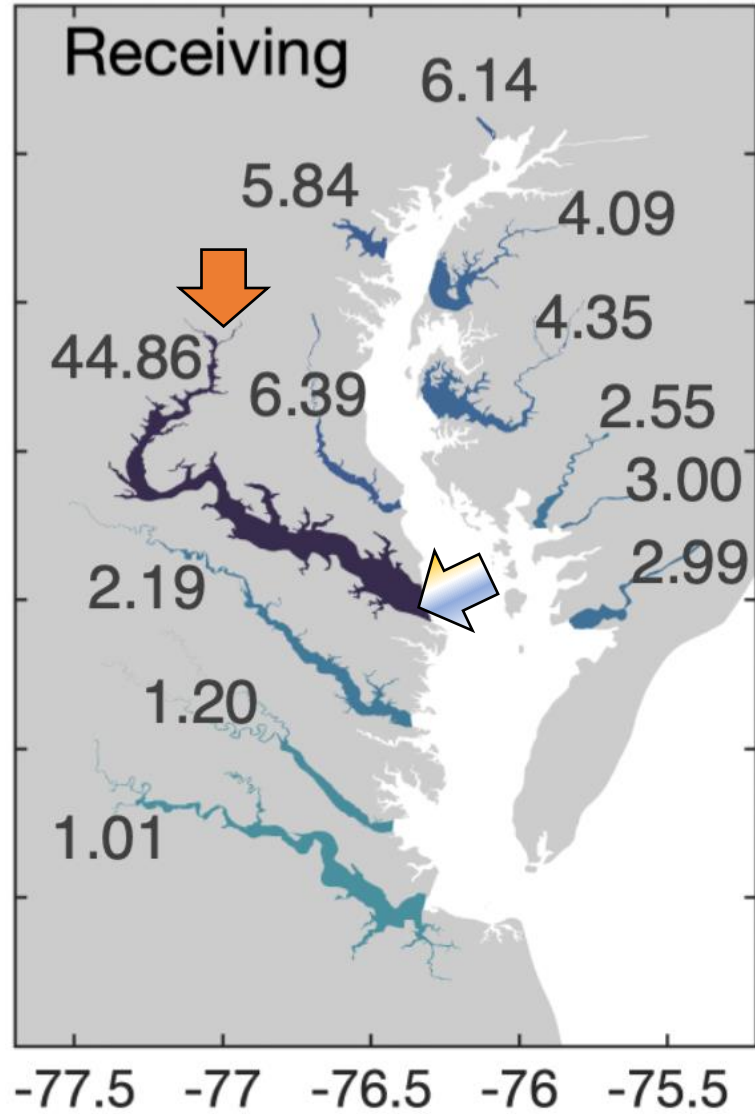
Percentage of freshwater discharged from other subestuaries into the Susq. River



(a) Percentage, p_{ij} (%)

	J	Y	R	Pc	Pt	Po	S	Cr	Ck	N	W	Pe
James	76.94	2.34	0.94	0.72	0.65	0.63	0.68	0.45	0.47	0.37	0.44	0.49
York	0.15	68.00	0.58	0.41	0.37	0.37	0.39	0.26	0.27	0.21	0.25	0.28
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Susquehanna	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00
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Choptank	0.14	0.17	0.31	0.50	0.61	1.53	1.60	1.09	43.07	0.30	0.35	0.42
Nanticoke	0.02	0.03	0.05	0.10	0.14	0.15	0.17	0.11	0.12	35.99	4.66	0.20
Wicomico	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.55	18.18	0.02
Pocomoke	0.05	0.06	0.10	0.18	0.20	0.20	0.21	0.14	0.15	0.36	0.44	33.06
Sum ¹	1.89	4.41	4.70	4.23	10.24	12.35	14.36	7.94	7.38	5.49	10.50	5.95
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Rem.	21.17	27.59	37.70	50.91	58.58	76.40	85.30	51.57	49.55	58.53	71.33	60.98

Percentage of freshwater discharged from other subestuaries into the Potomac River



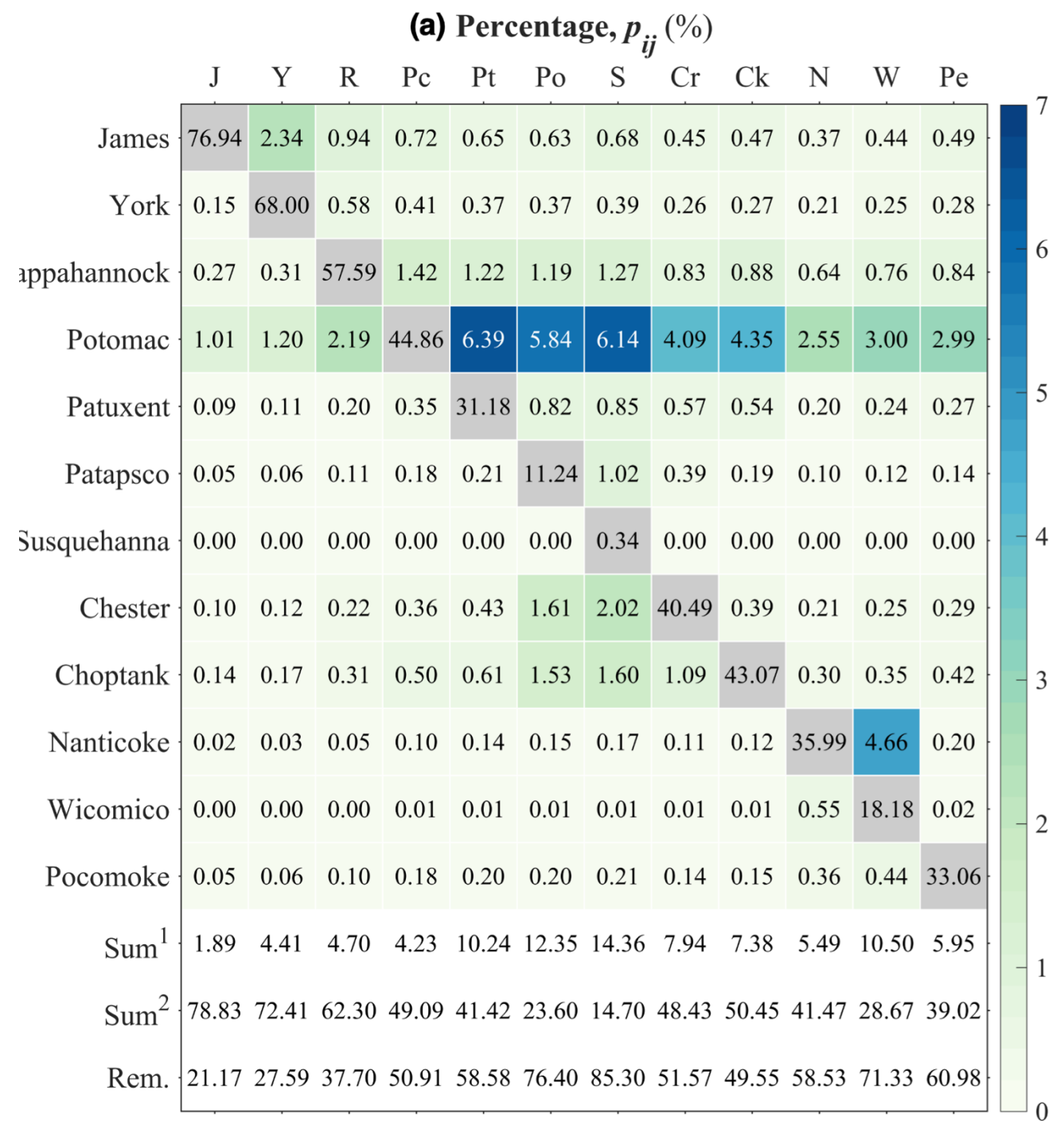
(a) Percentage, p_{ij} (%)

	J	Y	R	Pc	Pt	Po	S	Cr	Ck	N	W	Pe
James	76.94	2.34	0.94	0.72	0.65	0.63	0.68	0.45	0.47	0.37	0.44	0.49
York	0.15	68.00	0.58	0.41	0.37	0.37	0.39	0.26	0.27	0.21	0.25	0.28
Rappahannock	0.27	0.31	57.59	1.42	1.22	1.19	1.27	0.83	0.88	0.64	0.76	0.84
Potomac	1.01	1.20	2.19	44.86	6.39	5.84	6.14	4.09	4.35	2.55	3.00	2.99
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Patapsco	0.05	0.06	0.11	0.18	0.21	11.24	1.02	0.39	0.19	0.10	0.12	0.14
Susquehanna	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00
Chester	0.10	0.12	0.22	0.36	0.43	1.61	2.02	40.49	0.39	0.21	0.25	0.29
Choptank	0.14	0.17	0.31	0.50	0.61	1.53	1.60	1.09	43.07	0.30	0.35	0.42
Nanticoke	0.02	0.03	0.05	0.10	0.14	0.15	0.17	0.11	0.12	35.99	4.66	0.20
Wicomico	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.55	18.18	0.02
Pocomoke	0.05	0.06	0.10	0.18	0.20	0.20	0.21	0.14	0.15	0.36	0.44	33.06
Sum ¹	1.89	4.41	4.70	4.23	10.24	12.35	14.36	7.94	7.38	5.49	10.50	5.95
Sum ²	78.83	72.41	62.30	49.09	41.42	23.60	14.70	48.43	50.45	41.47	28.67	39.02
Rem.	21.17	27.59	37.70	50.91	58.58	76.40	85.30	51.57	49.55	58.53	71.33	60.98

Results: Percentage Metric, multi-year mean (2011-2014)

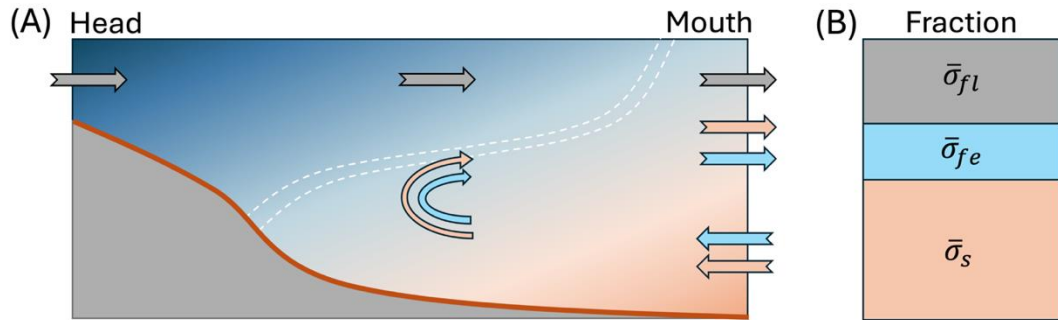
Rows: Percentage of supplying tributary's freshwater constituent in each receiving tributary

- **The Potomac** is the largest receiver of the freshwater from the other subestuaries, except the sources from the York and Wicomoco



Results: Contribution Metric, multi-year mean (2011-2014)

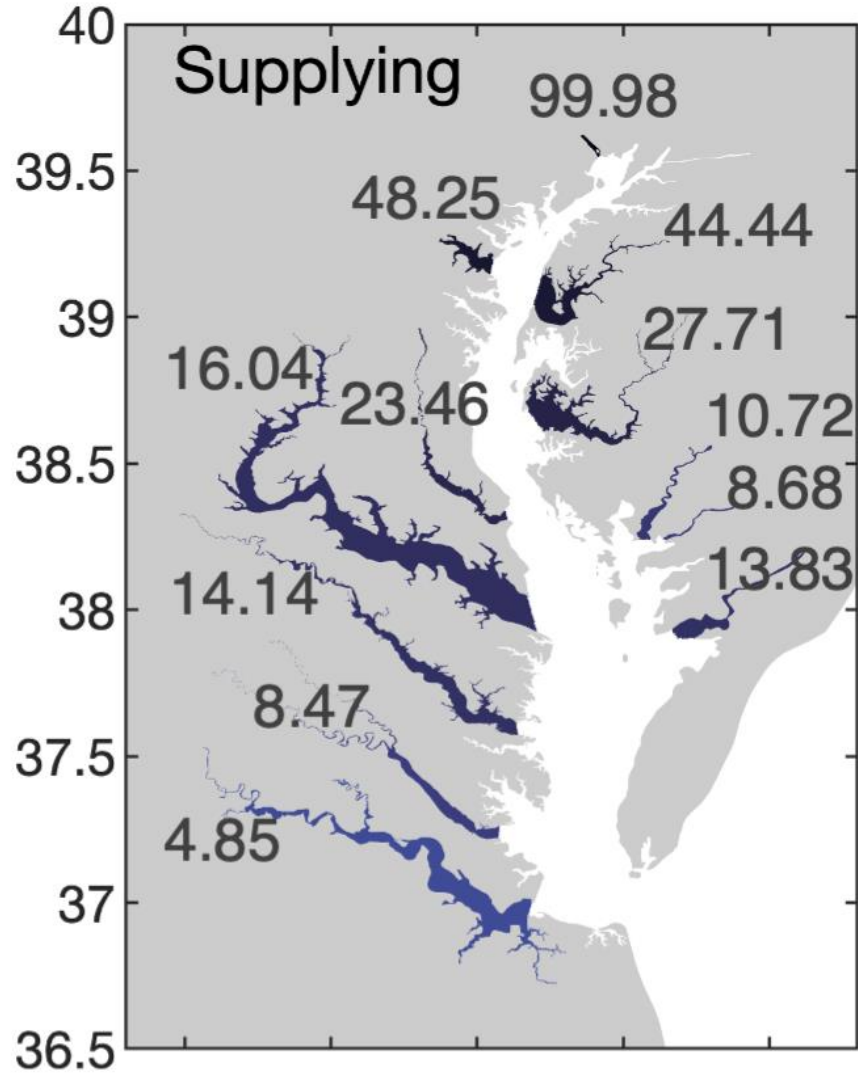
Columns: Contribution of discharge from one river to overall composition of water in subestuaries



(a) Contribution, q_{ij} (%)

	J	Y	R	Pc	Pt	PO	S	Cr	CK	N	W	Pe	Sum ¹	Sum ²	Rem.
James	55.16	0.50	0.36	1.84	0.17	0.09	4.85	0.06	0.13	0.06	0.02	0.05	8.13	63.29	36.71
York	0.32	44.26	0.67	3.22	0.31	0.16	8.47	0.10	0.23	0.11	0.03	0.09	13.71	57.98	42.02
Rappahannock	0.29	0.10	34.91	5.68	0.51	0.27	14.14	0.17	0.38	0.17	0.04	0.13	21.91	56.82	43.18
Potomac	0.26	0.09	0.31	43.03	0.64	0.32	16.04	0.20	0.44	0.16	0.04	0.11	18.62	61.65	38.35
Patuxent	0.25	0.09	0.29	3.45	33.17	0.47	23.46	0.29	0.58	0.13	0.03	0.11	29.15	62.33	37.67
Patapsco	0.22	0.08	0.26	2.92	0.37	11.03	48.25	0.34	0.34	0.12	0.03	0.10	53.04	64.07	35.93
Susquehanna	0.00	0.00	0.00	0.00	0.00	0.00	99.98	0.00	0.00	0.00	0.00	0.00	0.00	99.98	0.02
Chester	0.22	0.08	0.25	2.77	0.35	0.73	44.44	16.55	0.32	0.11	0.03	0.09	49.40	65.95	34.05
Choptank	0.24	0.08	0.28	3.09	0.39	0.55	27.71	0.34	29.26	0.12	0.03	0.10	32.94	62.20	37.80
Nanticoke	0.14	0.05	0.17	2.26	0.34	0.21	10.72	0.13	0.30	58.06	1.54	0.18	16.05	74.11	25.89
Wicomico	0.12	0.04	0.14	1.85	0.28	0.17	8.68	0.10	0.25	7.76	56.84	0.15	19.52	76.37	23.63
Pocomoke	0.32	0.11	0.35	4.28	0.48	0.27	13.83	0.16	0.37	0.57	0.15	30.95	20.89	51.85	48.15

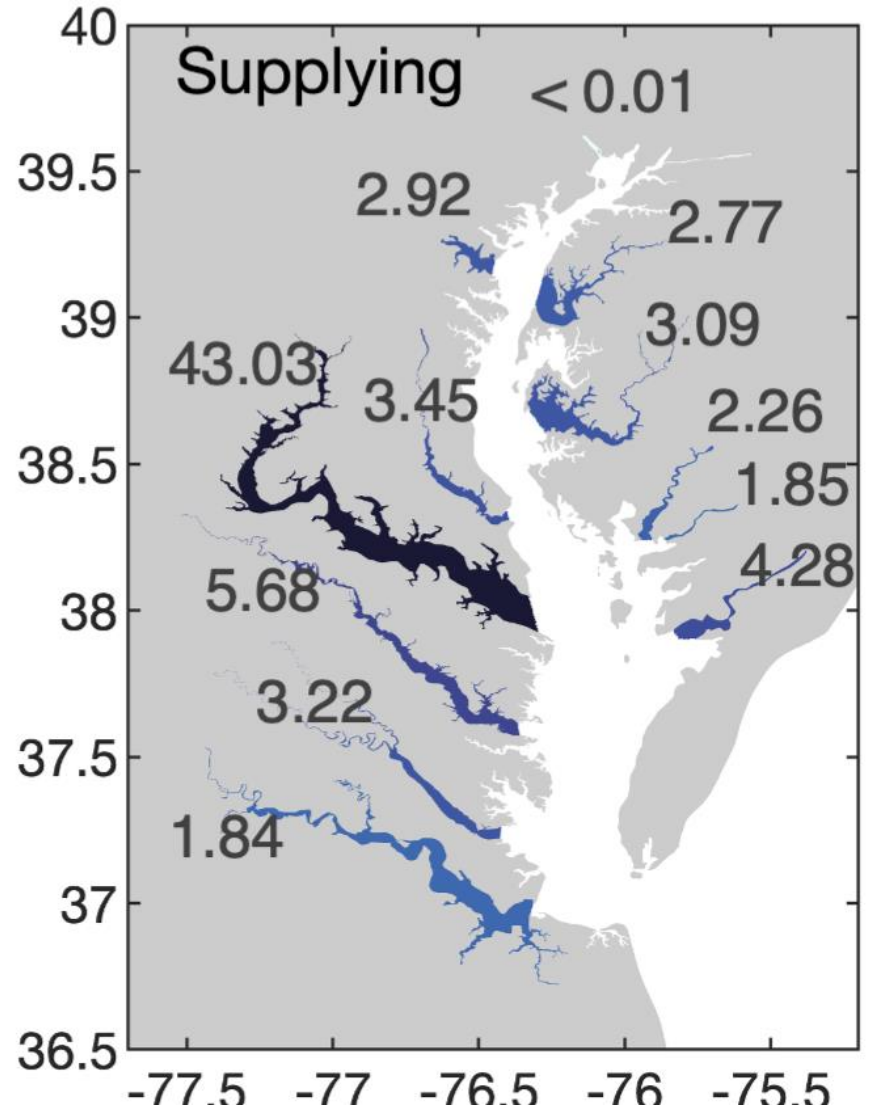
Contribution of the Susq. to other subestuaries



Contribution_{ij} (%)

	J.	Y.	R.	P.	P.	P.	S.	C.	C.	N.	W.	P.
James	55.16	0.50	0.36	1.84	0.17	0.09	4.85	0.06	0.13	0.06	0.02	0.05
York	0.32	44.26	0.67	3.22	0.31	0.16	8.47	0.10	0.23	0.11	0.03	0.09
Rappahannock	0.29	0.10	34.91	5.68	0.51	0.27	14.14	0.17	0.38	0.17	0.04	0.13
Potomac	0.26	0.09	0.31	43.03	0.64	0.32	16.04	0.20	0.44	0.16	0.04	0.11
Patuxent	0.25	0.09	0.29	3.45	33.17	0.47	23.46	0.29	0.58	0.13	0.03	0.11
Patapsco	0.22	0.08	0.26	2.92	0.37	11.03	48.25	0.34	0.34	0.12	0.03	0.10
Susquehanna	0.00	0.00	0.00	0.00	0.00	0.00	99.98	0.00	0.00	0.00	0.00	0.00
Chester	0.22	0.08	0.25	2.77	0.35	0.73	44.44	16.55	0.32	0.11	0.03	0.09
Choptank	0.24	0.08	0.28	3.09	0.39	0.55	27.71	0.34	29.26	0.12	0.03	0.10
Nanticoke	0.14	0.05	0.17	2.26	0.34	0.21	10.72	0.13	0.30	58.06	1.54	0.18
Wicomico	0.12	0.04	0.14	1.85	0.28	0.17	8.68	0.10	0.25	7.76	56.84	0.15
Pocomoke	0.32	0.11	0.35	4.28	0.48	0.27	13.83	0.16	0.37	0.57	0.15	30.95

Contribution of the Potomac to other subestuaries

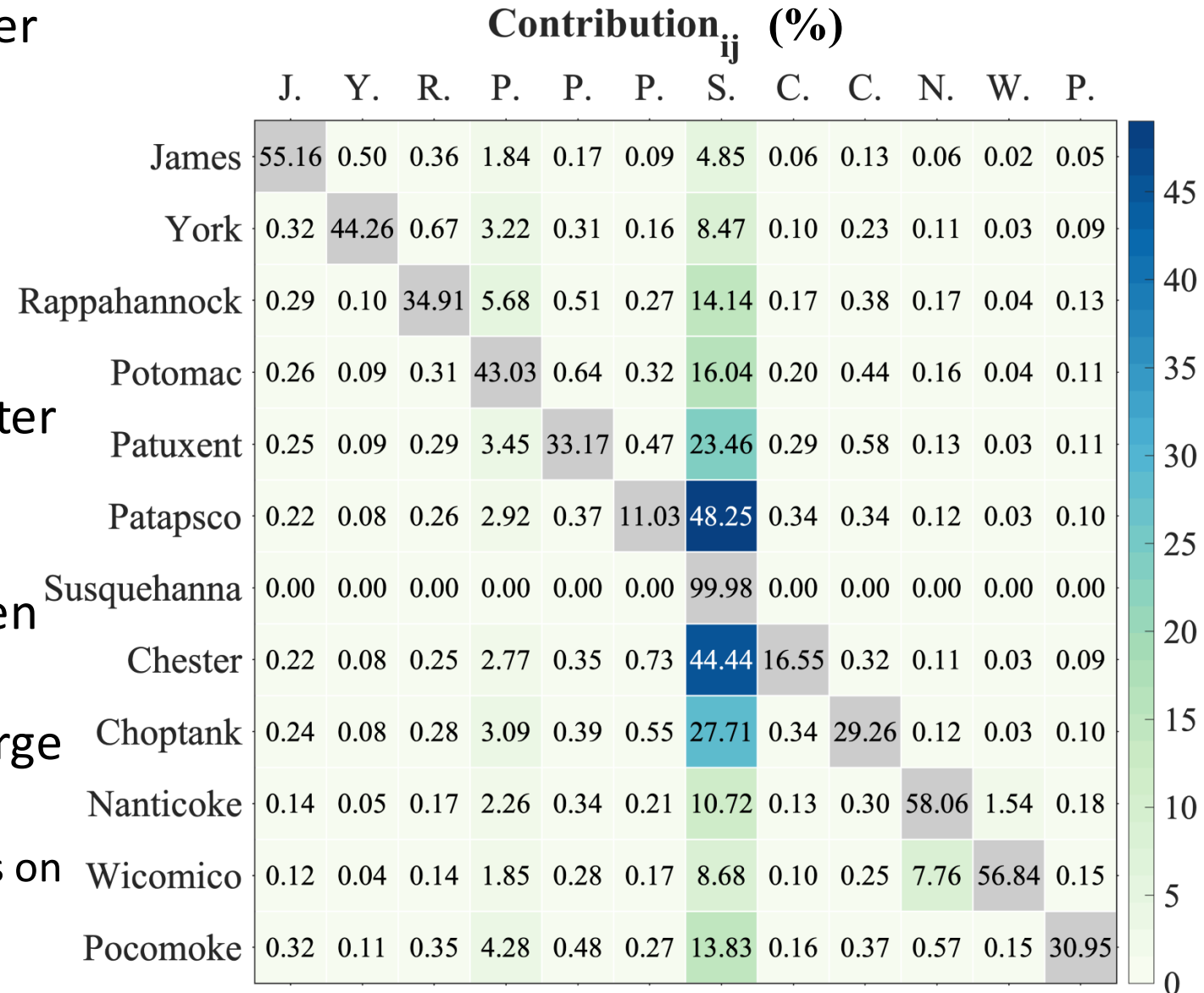


Contribution_{ij} (%)

	J.	Y.	R.	P.	P.	P.	S.	C.	C.	N.	W.	P.
James	55.16	0.50	0.36	1.84	0.17	0.09	4.85	0.06	0.13	0.06	0.02	0.05
York	0.32	44.26	0.67	3.22	0.31	0.16	8.47	0.10	0.23	0.11	0.03	0.09
Rappahannock	0.29	0.10	34.91	5.68	0.51	0.27	14.14	0.17	0.38	0.17	0.04	0.13
Potomac	0.26	0.09	0.31	43.03	0.64	0.32	16.04	0.20	0.44	0.16	0.04	0.11
Patuxent	0.25	0.09	0.29	3.45	33.17	0.47	23.46	0.29	0.58	0.13	0.03	0.11
Patapsco	0.22	0.08	0.26	2.92	0.37	11.03	48.25	0.34	0.34	0.12	0.03	0.10
Susquehanna	0.00	0.00	0.00	0.00	0.00	0.00	99.98	0.00	0.00	0.00	0.00	0.00
Chester	0.22	0.08	0.25	2.77	0.35	0.73	44.44	16.55	0.32	0.11	0.03	0.09
Choptank	0.24	0.08	0.28	3.09	0.39	0.55	27.71	0.34	29.26	0.12	0.03	0.10
Nanticoke	0.14	0.05	0.17	2.26	0.34	0.21	10.72	0.13	0.30	58.06	1.54	0.18
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Pocomoke	0.32	0.11	0.35	4.28	0.48	0.27	13.83	0.16	0.37	0.57	0.15	30.95

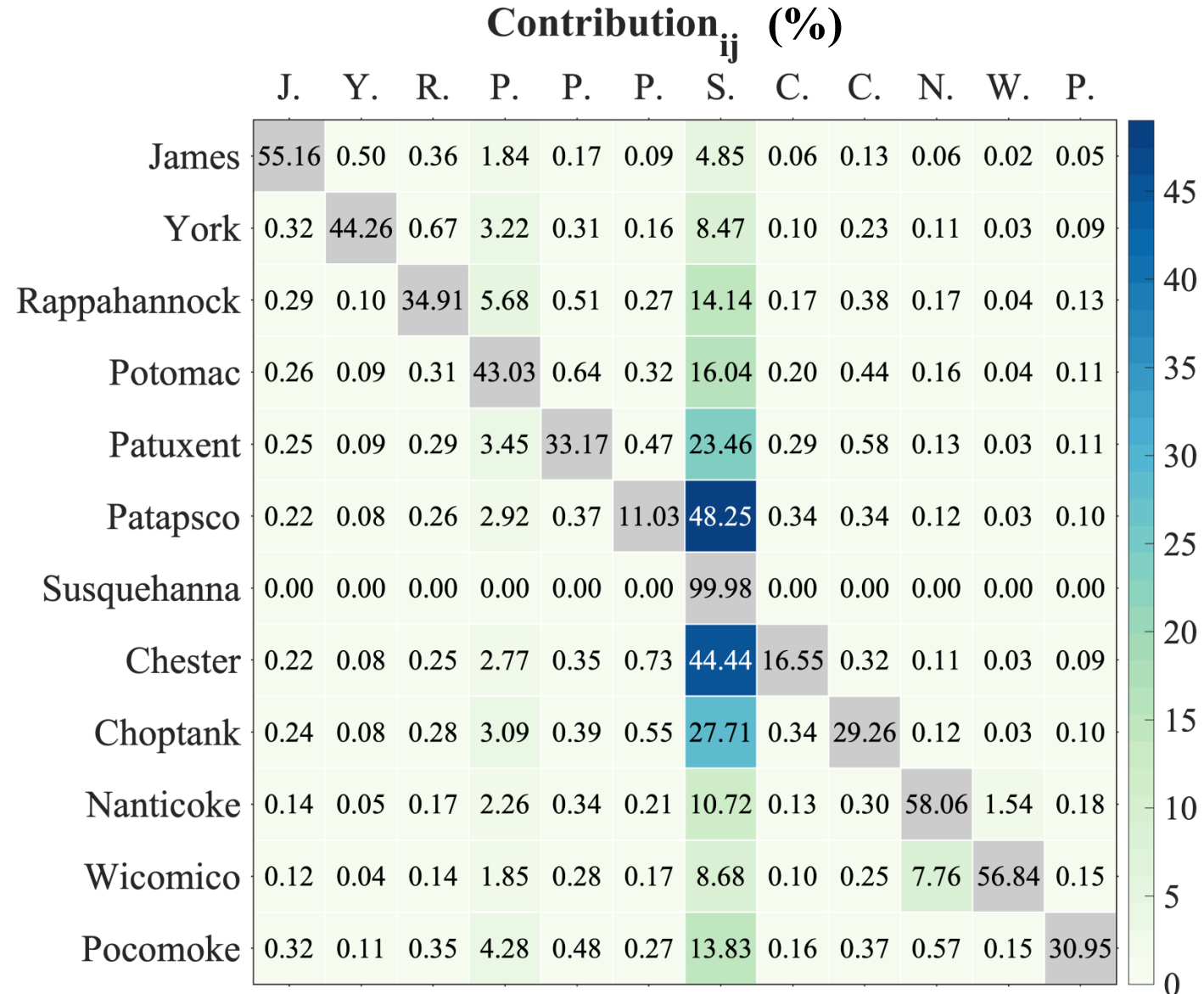
Columns: Contribution of discharge from one river to overall composition of water in subestuaries

- Each river contributes most to the water composition of itself
- The Susquehanna is a major freshwater source to other subestuaries;
- Other rivers contributes < 10% or even <1% to the water composition of another subestuary, even they are large rivers.
 - The contribution does not only depends on the **magnitude of discharge**, but also depends on **estuarine circulation**

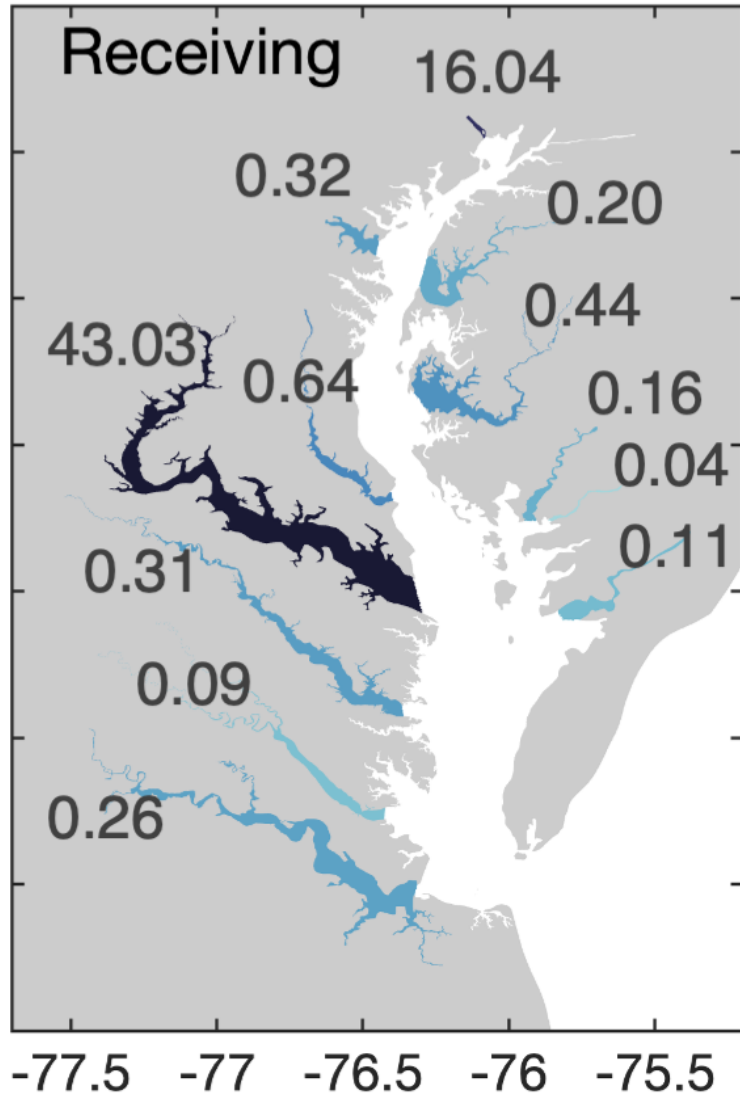


Results: Contribution Metric, multi-year mean (2011-2014)

Rows: freshwater composition in each tributary, showing the relative influence of each supplying tributary



Contribution of other rivers to the Potomac

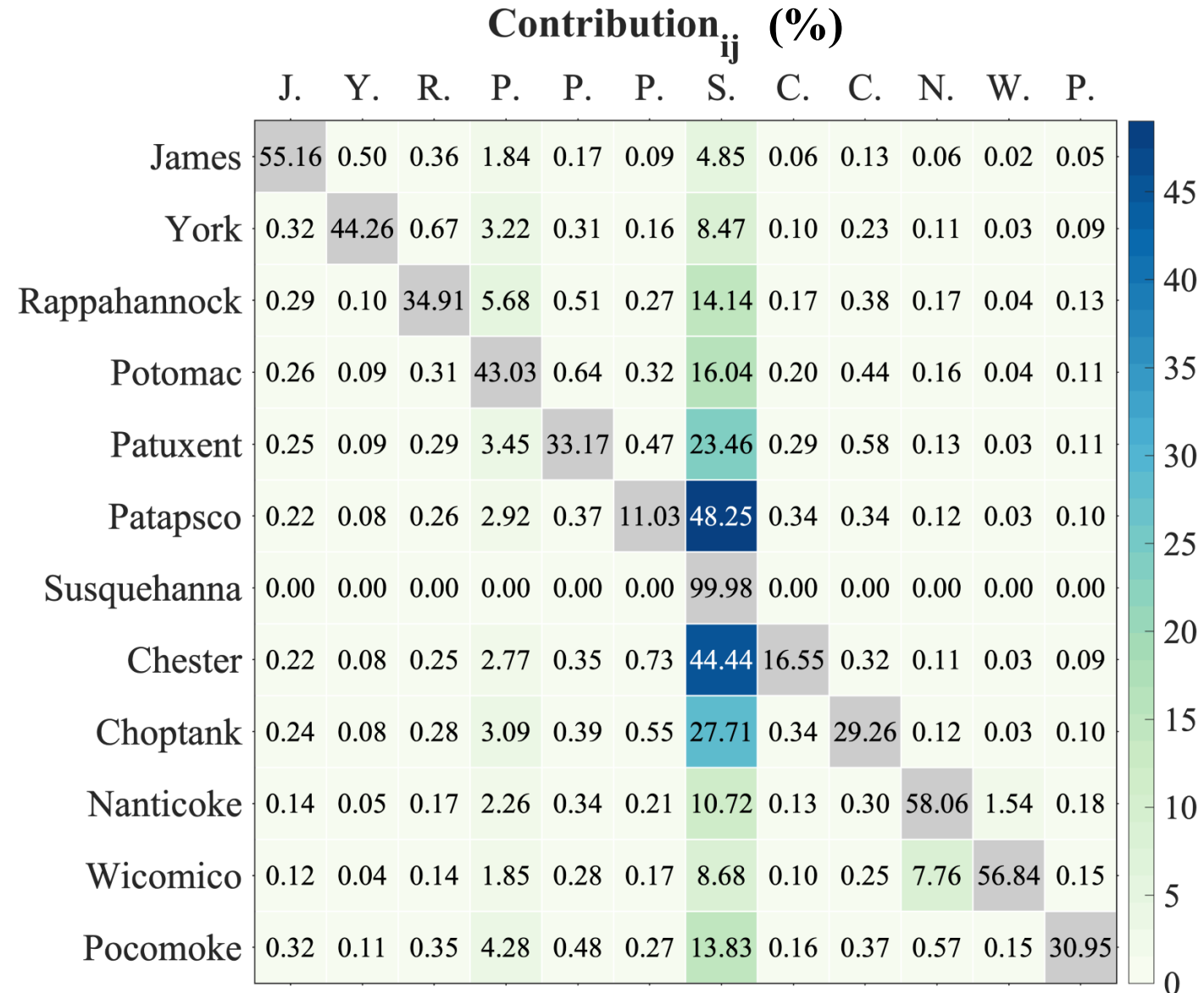


Contribution_{ij} (%)

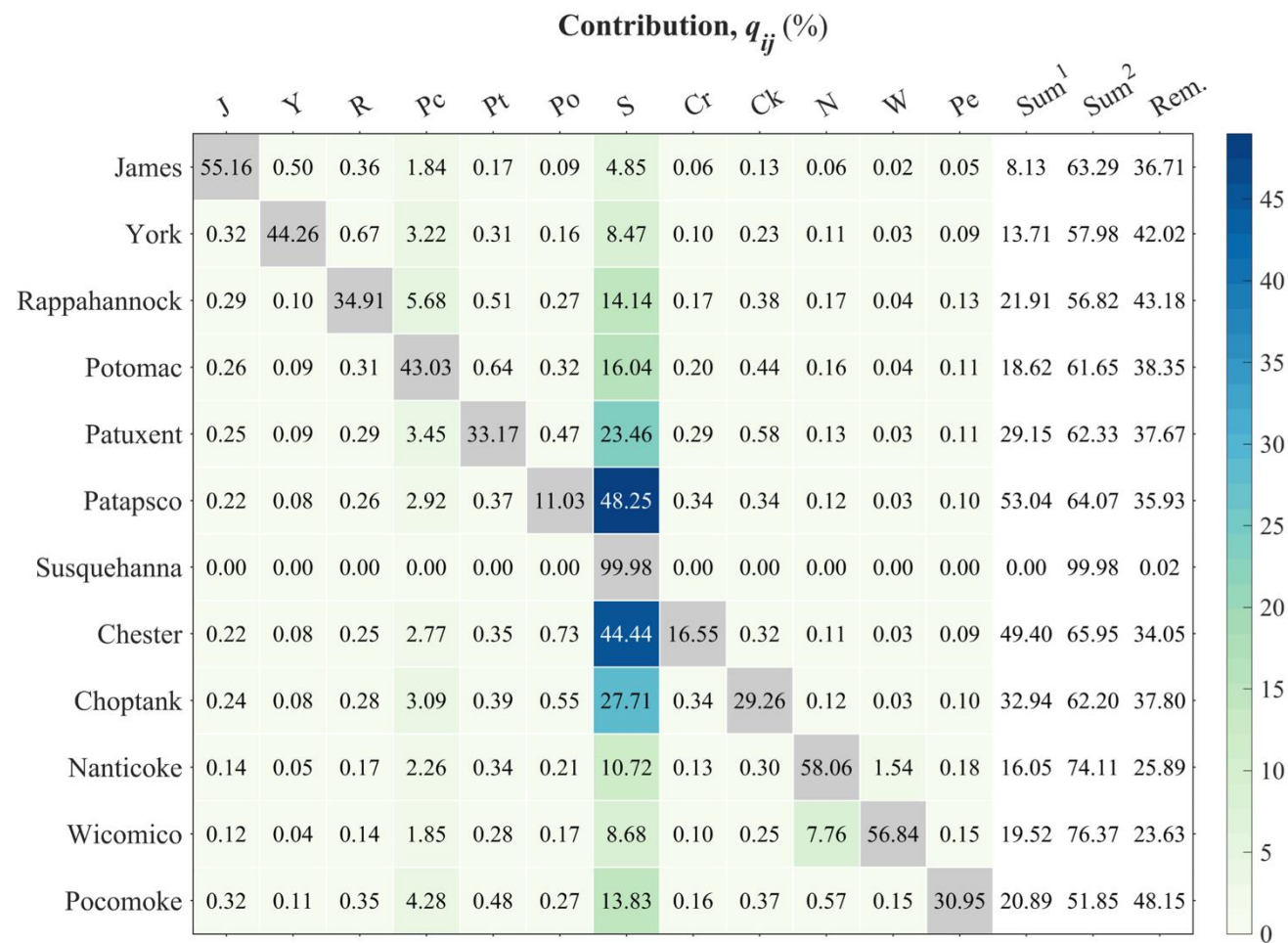
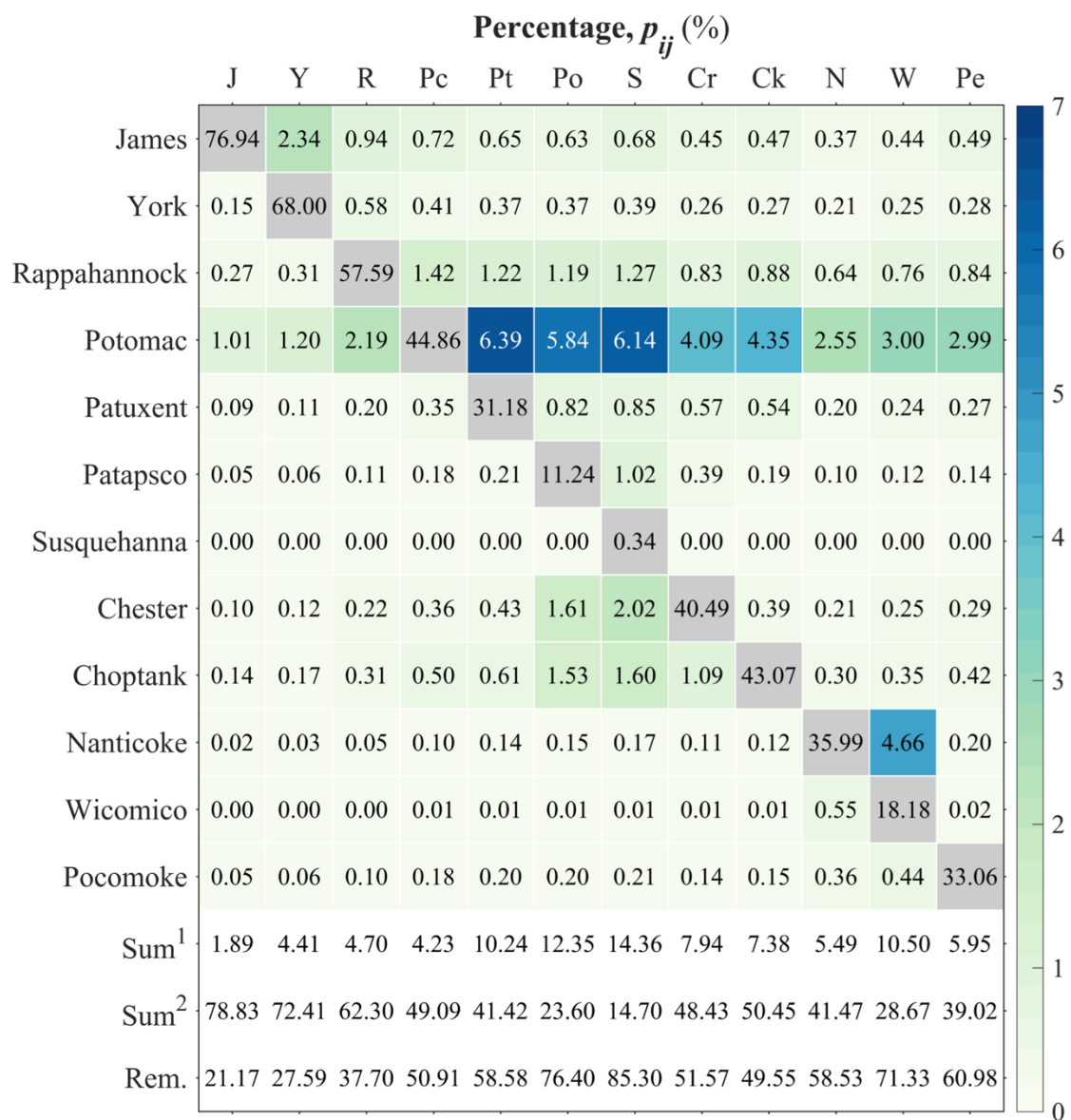
	J.	Y.	R.	P.	P.	P.	S.	C.	C.	N.	W.	P.
James	55.16	0.50	0.36	1.84	0.17	0.09	4.85	0.06	0.13	0.06	0.02	0.05
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Susquehanna	0.00	0.00	0.00	0.00	0.00	0.00	99.98	0.00	0.00	0.00	0.00	0.00
Chester	0.22	0.08	0.25	2.77	0.35	0.73	44.44	16.55	0.32	0.11	0.03	0.09
Choptank	0.24	0.08	0.28	3.09	0.39	0.55	27.71	0.34	29.26	0.12	0.03	0.10
Nanticoke	0.14	0.05	0.17	2.26	0.34	0.21	10.72	0.13	0.30	58.06	1.54	0.18
Wicomico	0.12	0.04	0.14	1.85	0.28	0.17	8.68	0.10	0.25	7.76	56.84	0.15
Pocomoke	0.32	0.11	0.35	4.28	0.48	0.27	13.83	0.16	0.37	0.57	0.15	30.95

Rows: freshwater composition in each tributary, showing the relative influence of each supplying tributary

- Freshwater coming from the head of this subestuary is the dominant source of the freshwater in that subestuary, except for the Patapsco and Chester, which are most close to the Susquehanna;
- For each subestuary, the Susquehanna is the freshwater source contributing most among all other rivers.



Results



Conclusions

- Inter-tributary freshwater connectivity in Chesapeake Bay was quantified using a 3D hydrodynamic model and two diagnostic metrics.
- Exchange among tributaries is generally low (<7%) but external freshwater can contribute up to 50% of water in some receiving tributaries.
- Clear asymmetry of freshwater connectivity among those subestuaries.

Qin, Q., Cai, X., Shen, J. and Linker, L.C. (In revision). Riverine Freshwater Connectivity Among Major Tributaries in a Large Estuary. Submitted to *Water Resources Research*.

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