WATERSHED EFFECTS ON SUCCESS OF STREAM RESTORATION FOR EXCESS NITROGEN MITIGATION

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General Restoration Questions from RFP:

1. What are the cumulative effects of watershed restoration activities within a watershed?
2. What percentage of a catchment needs to be treated…? Does the location of [stream restoration] practices within the catchment make a difference…?

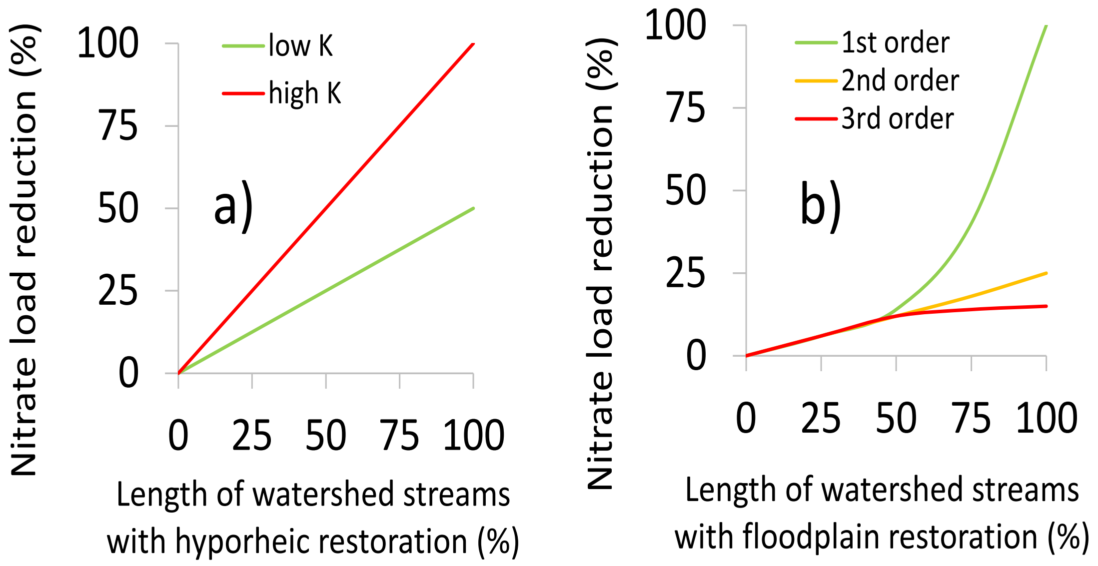
Research Questions and Hypotheses

Restoration Questions from Proposal

1. What is the slope and shape of the relationship between percent of stream network restored and percent nitrate load reduction at the watershed outlet (i.e., linear, exponential, levelling off)?

2. How do the answers to Question #1 above vary with w
   - Distribution of nitrate sources in the watershed
   - Restoration technique
   - Restoration location
   - Watershed topography
   - Soil type

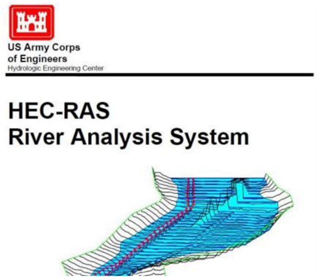
Example Graphic **Hypotheses**



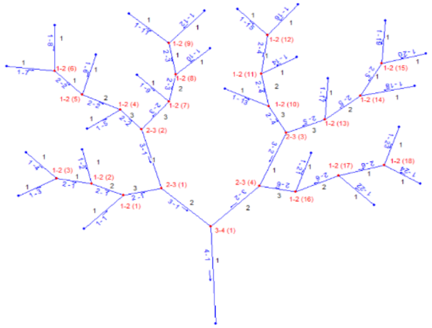
Project Tasks (all completed)

Task 1. Generate literature database of nitrate removal rates.

Task 2. Select model software (1D HEC-RAS w/auxiliary R script).



Task 3. Model generic watershed with literature rates to answer research questions.



Task 4. Model case study watershed to demonstrate applied value.

Task 1: Nitrate Removal Rates

Quantified variability of nitrate removal rates with key controlling factors beyond those studied in prior work (Newcomer Johnson et al. 2016, Lammers and Bledsoe 2017):

- Restoration status (e.g., restored or not)
- Restoration technique (e.g., channel or floodplain)
- Hydrologic status (baseflow vs stormflow)
- Stream order
- Season
- Sample location (e.g., floodplain or channel)

Quantitative Synthesis from Literature

- 701 nitrate removal rates from 55 publications
- Random forest (RF) followed by artificial neural network (ANN), predictability quantified by Nash-Sutcliffe Efficiency (NSE)
- Subset into six dataframes for analysis

Analysis	Nitrate removal rate type	Reaches included	Nitrogen concentration	n	Median NSE	Performance[1]
A	Actual	All	Yes	114	0.1712	Not satisfactory
B	Actual	All	No	114	0.5563	Very good
C	Actual	Restored	Yes	78	0.5772	Very good
D	Actual	Restored	No	78	0.6659	Very good
E	Potential	All	No	183	0.2758	Satisfactory
F	Potential	Restored	No	100	0.3116	Satisfactory

[1] From Moriasi et al. (2015).

Actual = in-situ
Potential = in lab

Task 1: Key Outcomes

- Hydrologic condition (baseflow vs. storm flow) was the most important variable, rates higher during baseflow
- Stream order also relatively important, rates higher in headwater streams
- Season relatively unimportant

However

- Lack of data for larger streams, n<=20 for all orders > 1
- Large variability in rates within relative to between categories (using traditional stats)
- Therefore, varying model rates (for Tasks 3-4) not justified among stream orders, seasons, or between restored and unrestored conditions

Task 3: Simulated nitrate removal from Stage 0/ floodplain restoration in generic 4th-order watershed

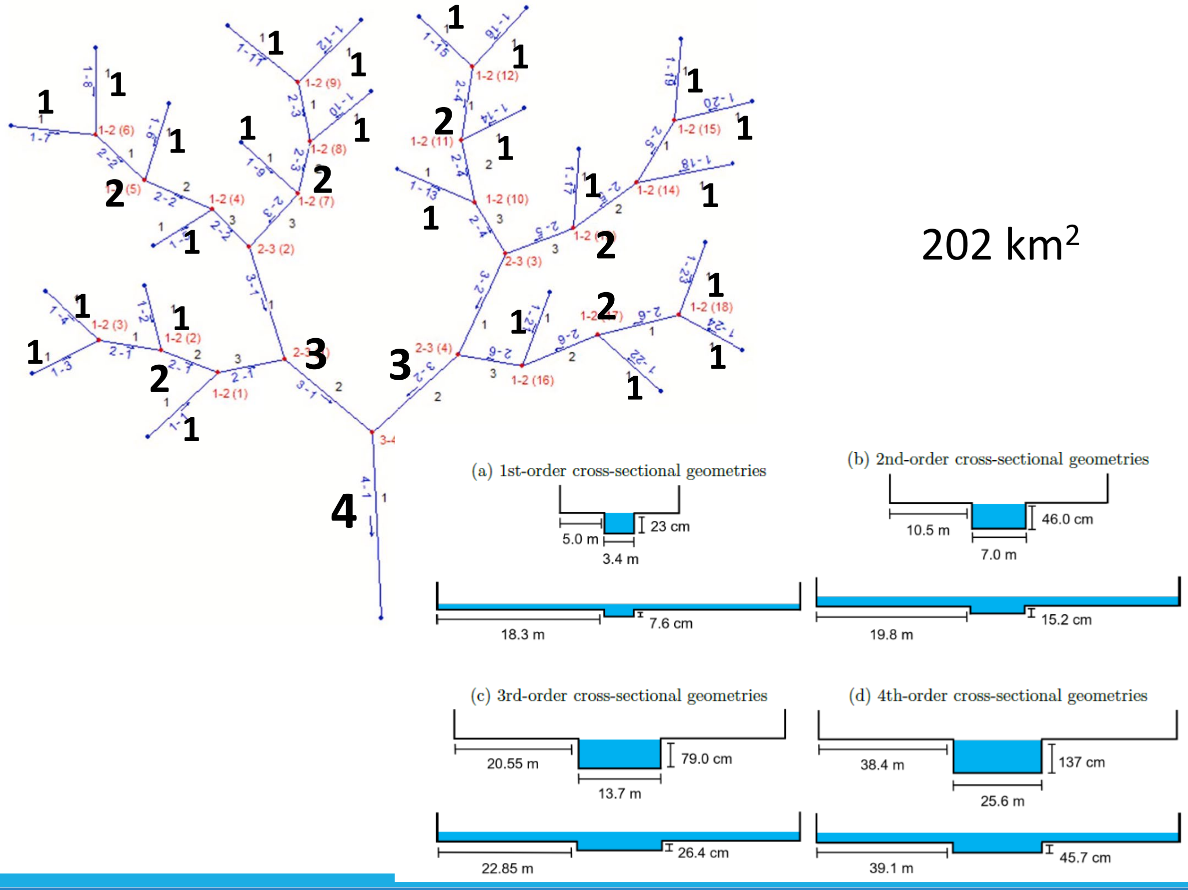
HEC-RAS model of storm flow hydraulics:

- Channel network geometry average for VA Piedmont
- Unsteady hydrology from VA Piedmont USGS gages and Snyder unit hydrograph
- No SW-GW exchange in floodplain

Varied:

- Stream order restored
- % channel length restored
- Storm size (monthly, 0.5 year, 1 year, and 2 year storms)

HEC-RAS model channel schematic and cross sections



Task 3: Simulated nitrate removal from Stage 0/ floodplain restoration in generic 4th-order watershed

R code calculated nitrate removal:

- 1 mg/L background sources in SW and GW
- Transport limited
- Constant/uniform zero-order areal removal rate from Task 1, 10th, 50th (median) and 90th percentile of actual rates
- Multiplied by floodplain inundation area and duration from HEC-RAS

Varied:

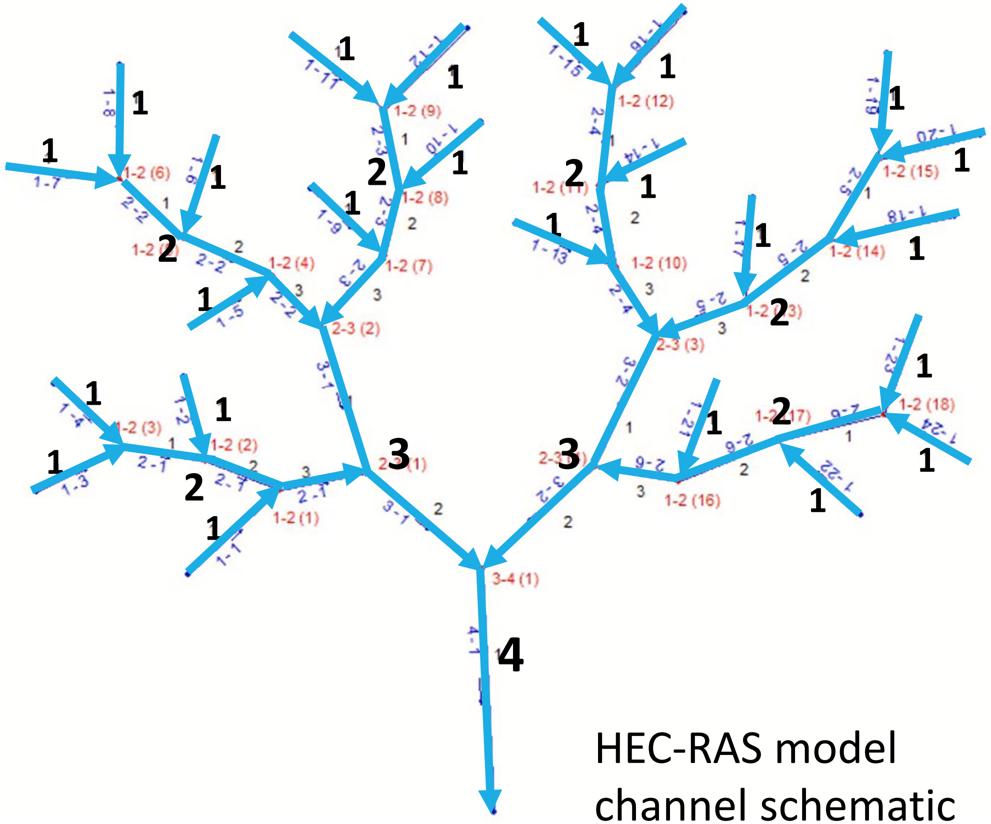
- Nitrate removal rate

Floodplain Nitrate Removal Rates $\left[\frac{mg-N}{m^2\,hr}\right]$	
10th percentile (k_{10})	0.072
Median (k_m)	0.66
90th Percentile (k_{90})	14

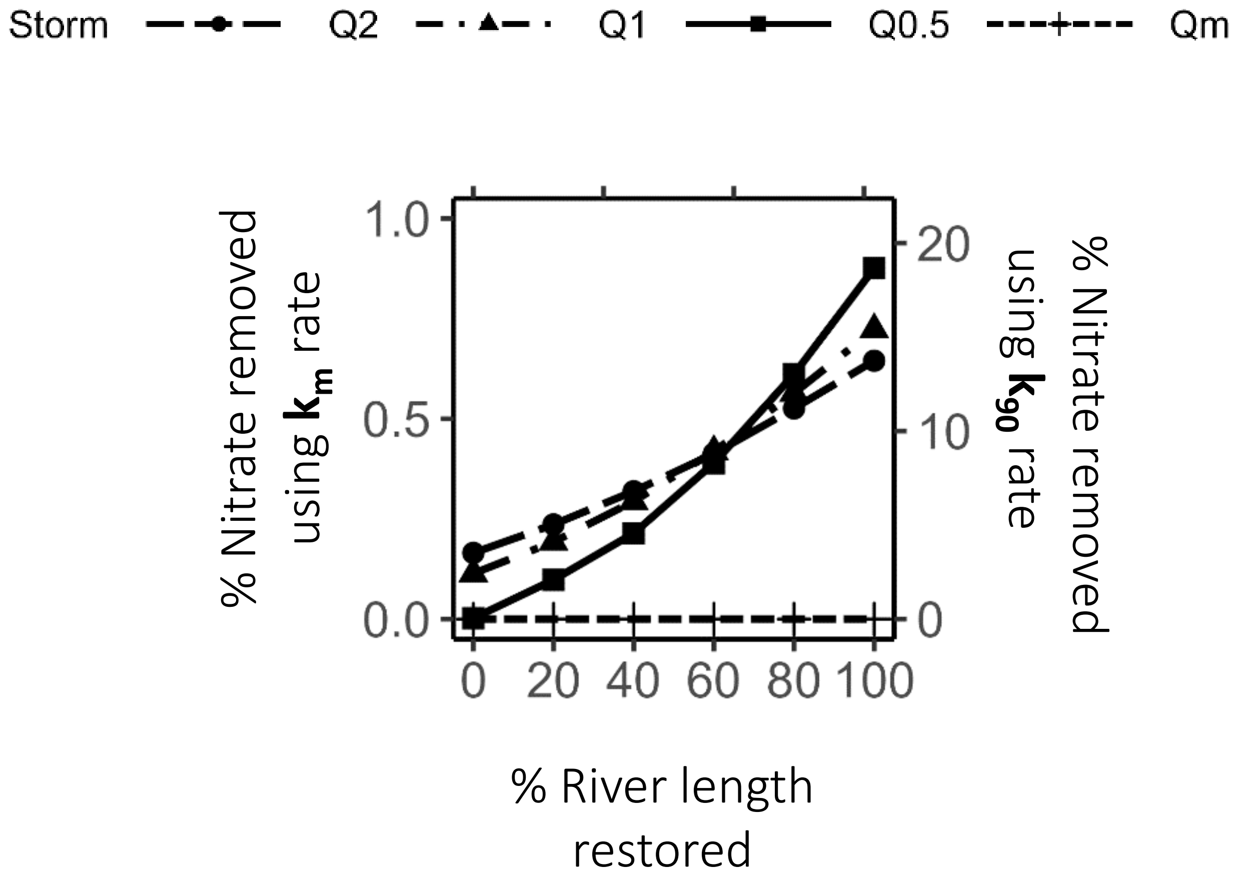
Nitrate removal = $k \cdot t \cdot A$

$$\%\ Removal = \frac{Nitrate\ Removal}{Nitrate\ Load} \cdot 100$$

Cumulative Single Order Restoration

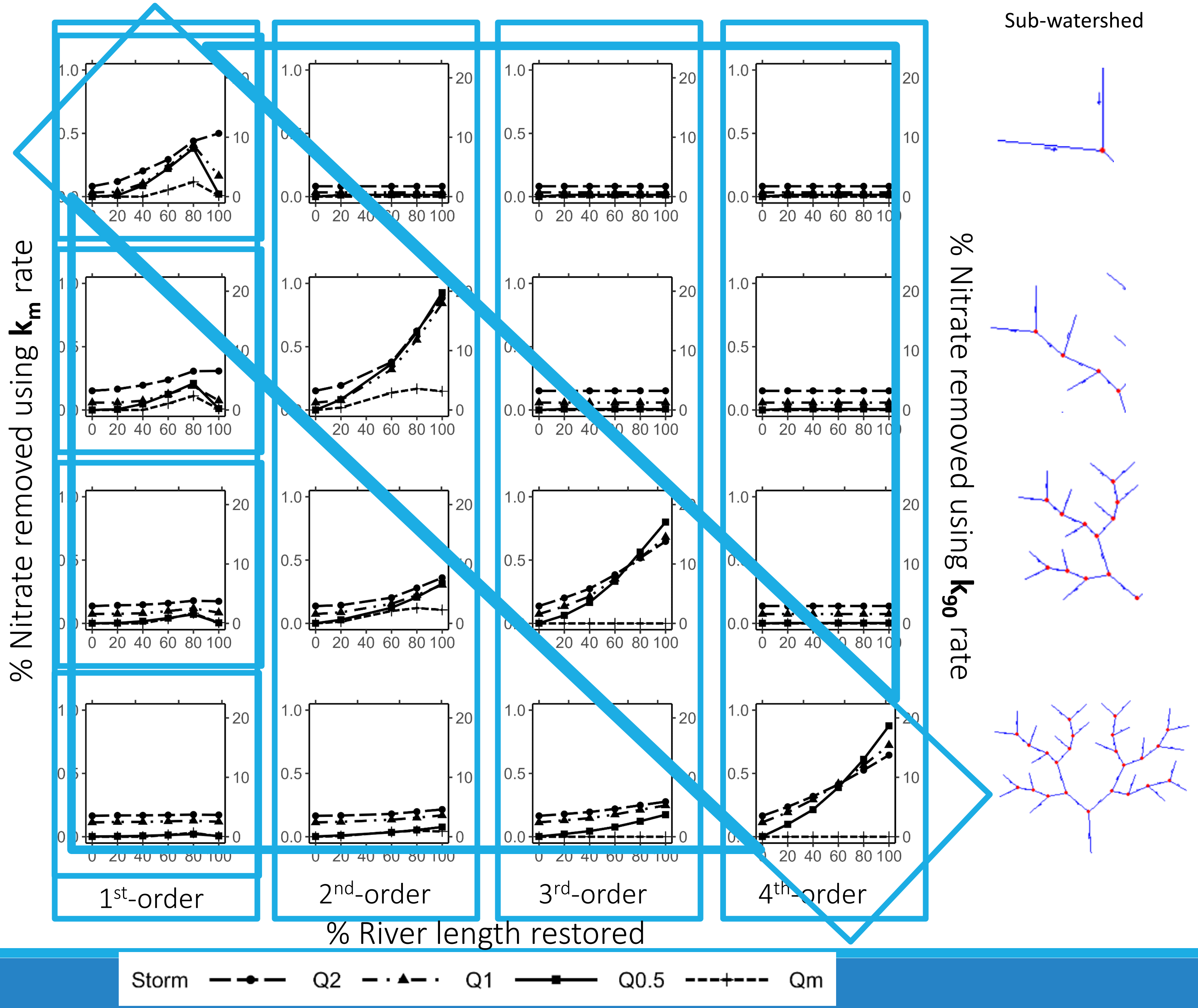


HEC-RAS model channel schematic

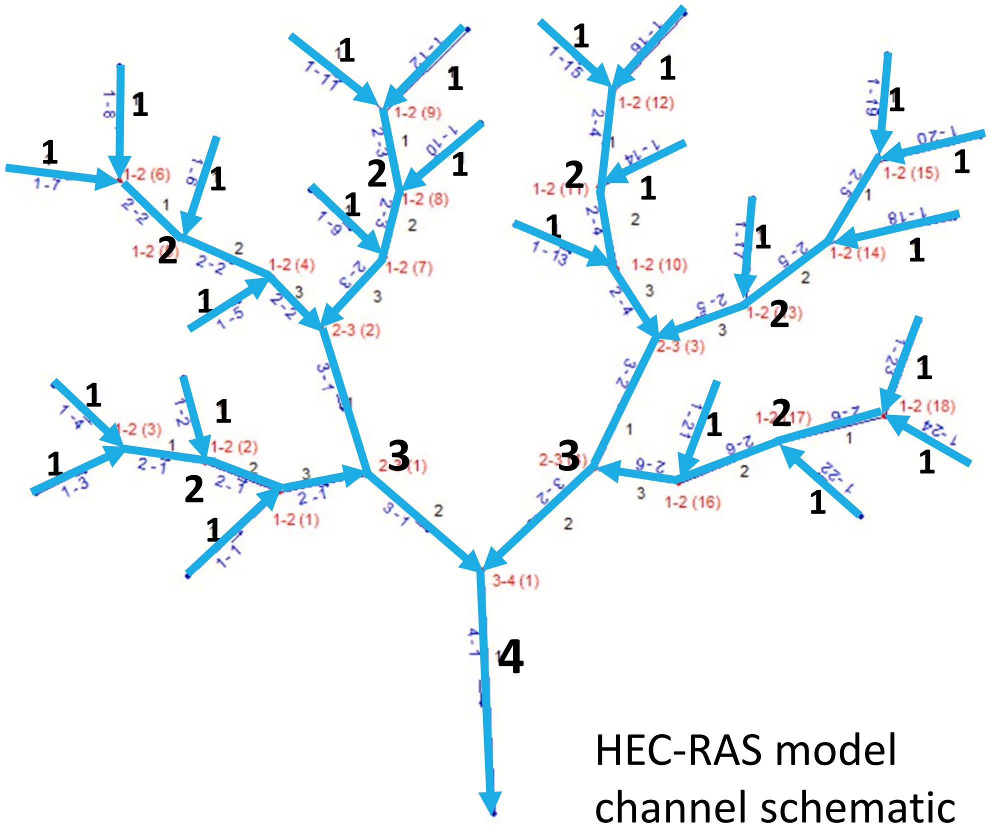


Nitrate Removal for Single Order Restoration

- Removal greatest where restoration occurred
- Removal greatest for restoration of full river lengths
- Reduced effects downstream
- Removal greatest for half-year storm
- Significance of removal dependent on removal rate



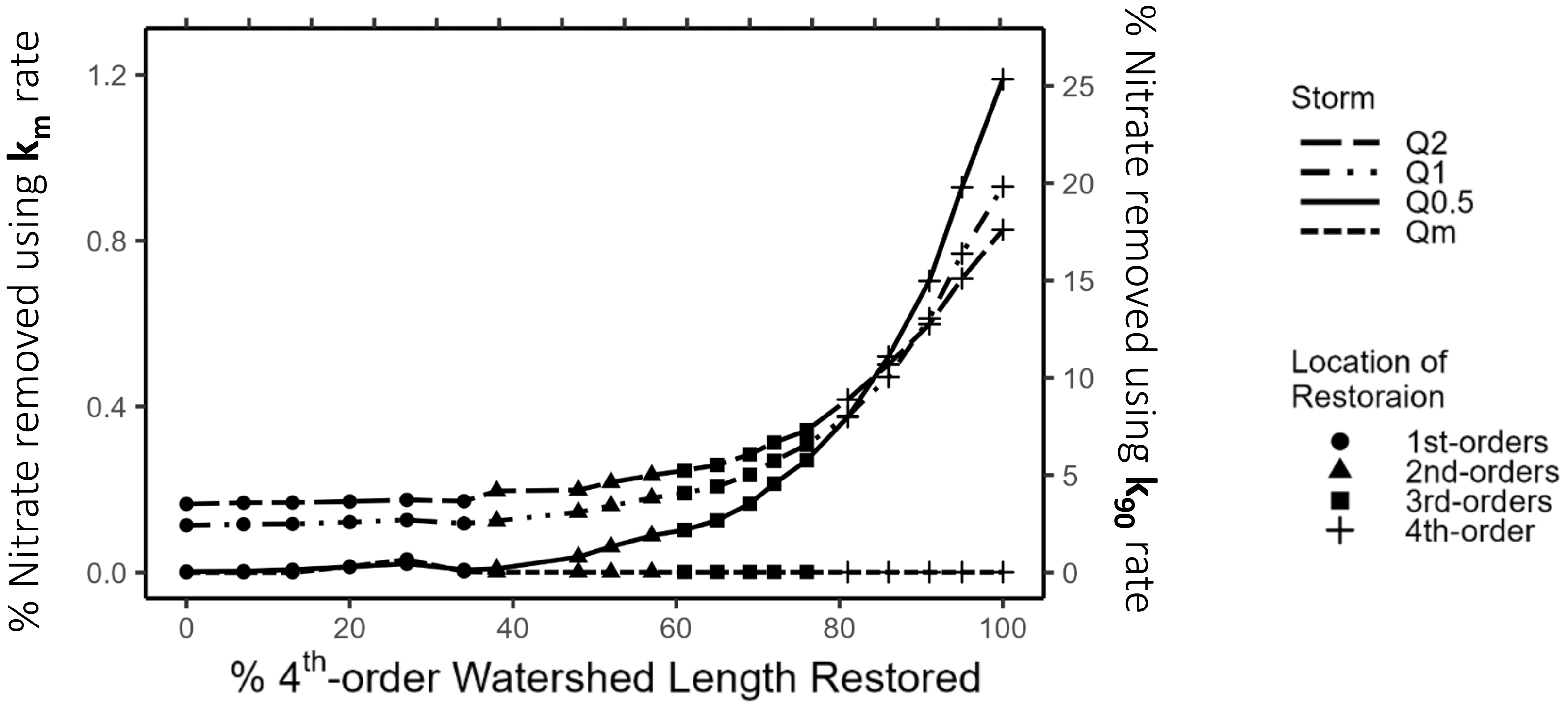
Cumulative Full Watershed Restoration



HEC-RAS model channel schematic

Nitrate Removal for Cumulative Full Watershed Restoration

- Maximum removal 1.2% or 25%
- 4^{th}-order river more efficient at nitrate removal



Annual Removal Simulation

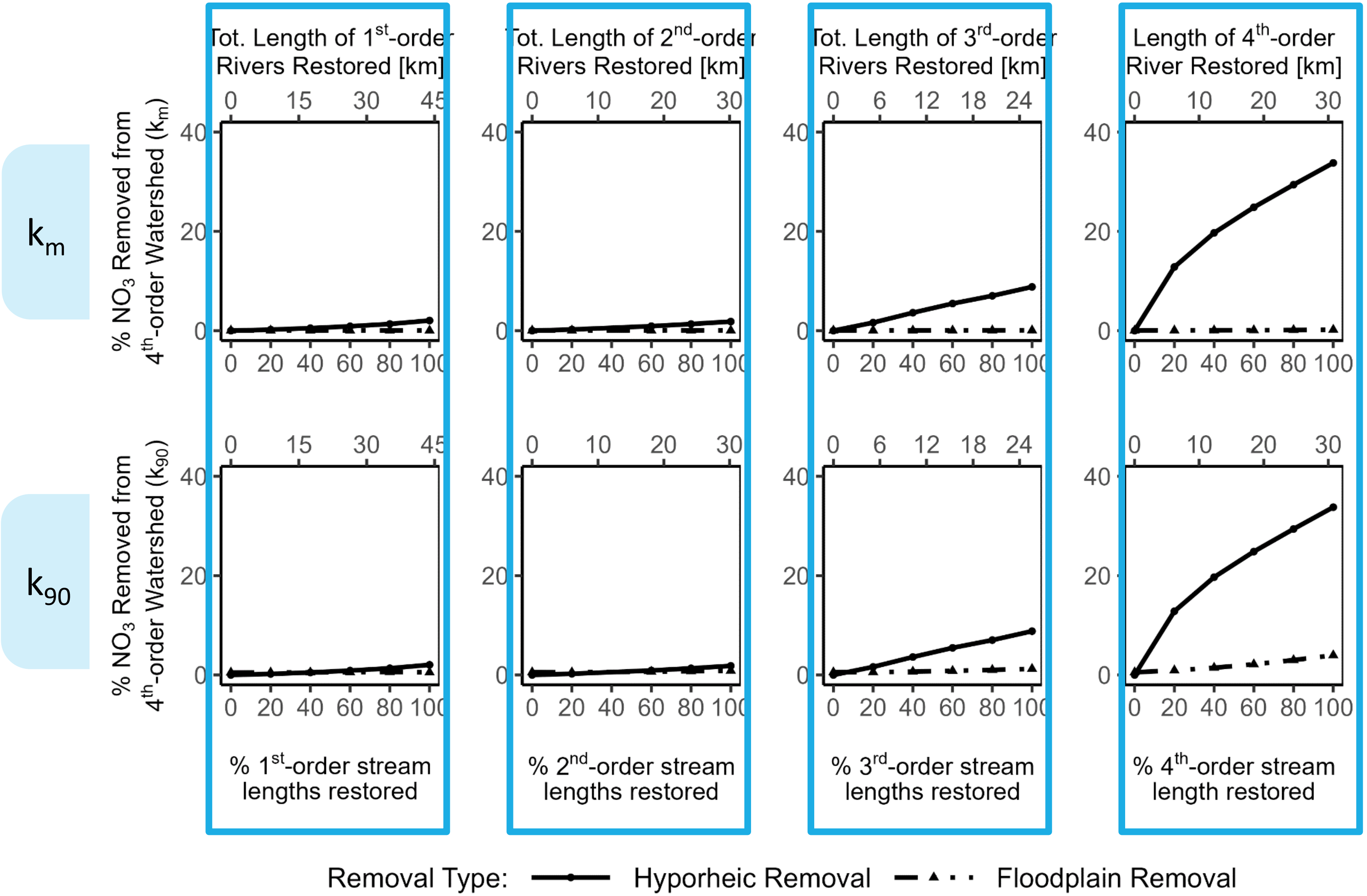
- Compared hyporheic and floodplain restoration techniques
- Scaled cumulative single order restoration results to an annual basis
  - Extracted baseflow hyporheic nitrate removal due to in-channel hyporheic enhancement from Calfe et al. (2022)
  - Scaled floodplain removal to a synthetic annual hydrograph

Number of Storms	Recurrence Interval Storm
12	Monthly
2	Half-year
1	1-year
1	2-year

Calfe, M.L., D.T. Scott, Hester, E.T. 2022. Nitrate removal by watershed-scale hyporheic stream restoration: Modeling approach to estimate effects and patterns at the stream network scale. *Ecological Engineering* 175:106498.

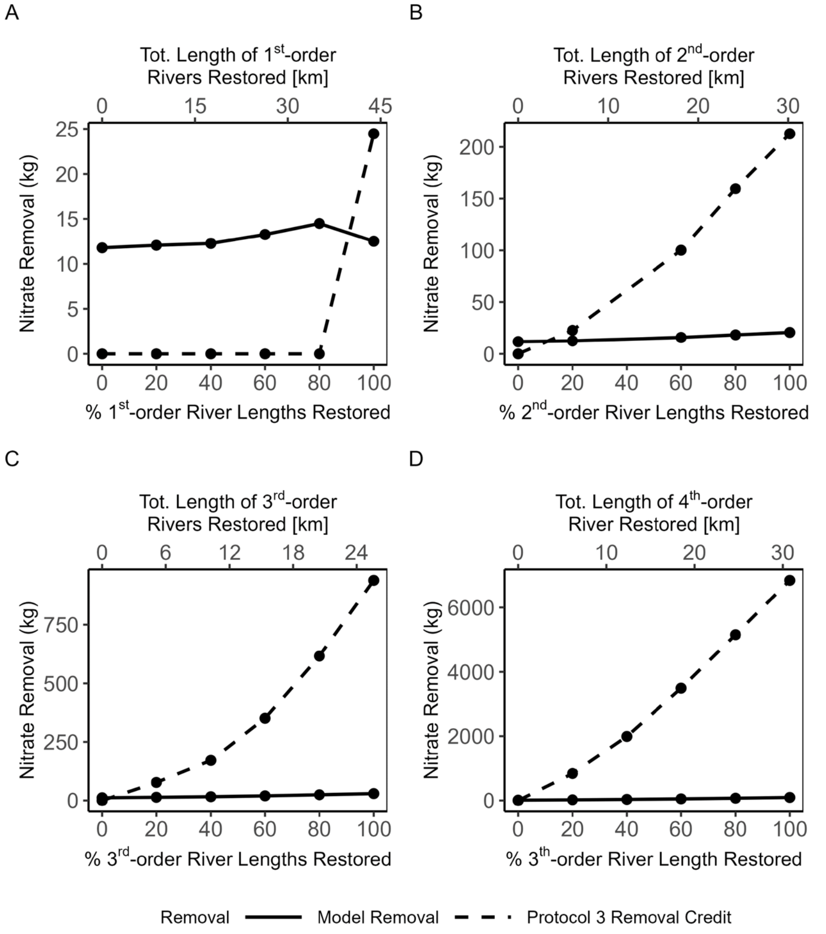
Annual Removal Simulation

- Hyporheic removal was greater than floodplain
- Floodplain removal limited by inundation frequency
- A combination of restoration techniques will provide greater nitrate removal



Comparison to Chesapeake Protocol 3

- Annual removal
- Using k_m and average Protocol 3 efficiency, Protocol 3 removals are generally higher than our model
- When include full range of our removal rates and Protocol 3 efficiencies, result is more muddled
- Clear need for more systematic nitrate removal data from field studies



Task 3: Key Outcomes

- Watersheds are complex: results depend on both restoration and measurement locations
- Key controls on watershed scale nitrate removal in floodplains include
  - Restoration length → restoration of full river lengths is needed for significant nitrate removal
  - Stream order → removal increased with stream order; restoration more effective in higher order rivers
  - Removal rate → controlled significance of removal
  - Storm size → intermediate sized storms removed the most nitrate
- Floodplain restoration less effective than hyporheic enhancement on annual basis
- Chesapeake Bay Protocol 3 often overpredicts our results
- Does not include pulsed hyporheic exchange in floodplain

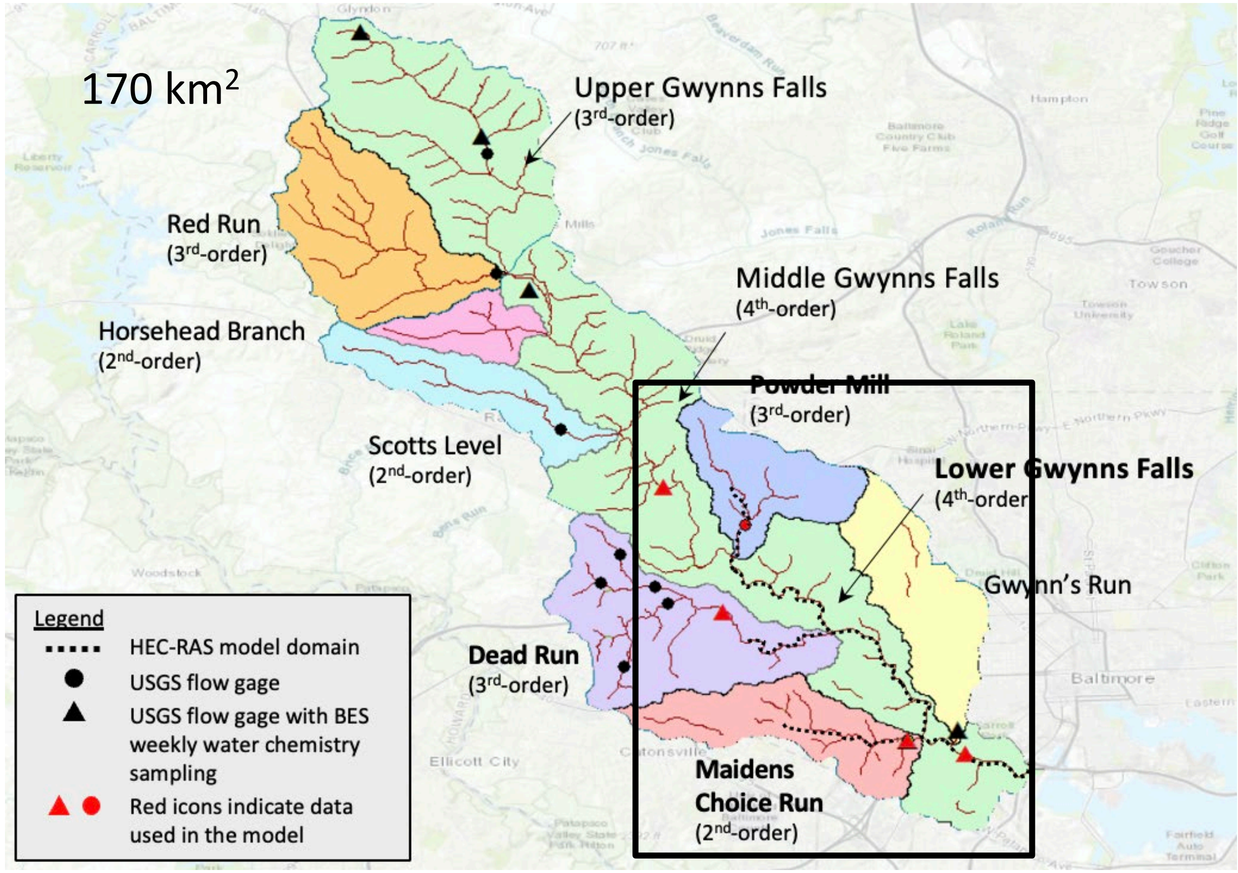
Task 4: Simulated nitrate removal from *hypothetical* Stage 0/ floodplain restoration in Gwynns Falls

HEC-RAS model of storm flow hydraulics:

- Existing channel network geometry from MDE
- Unsteady hydrology from USGS gages and Snyder unit hydrograph

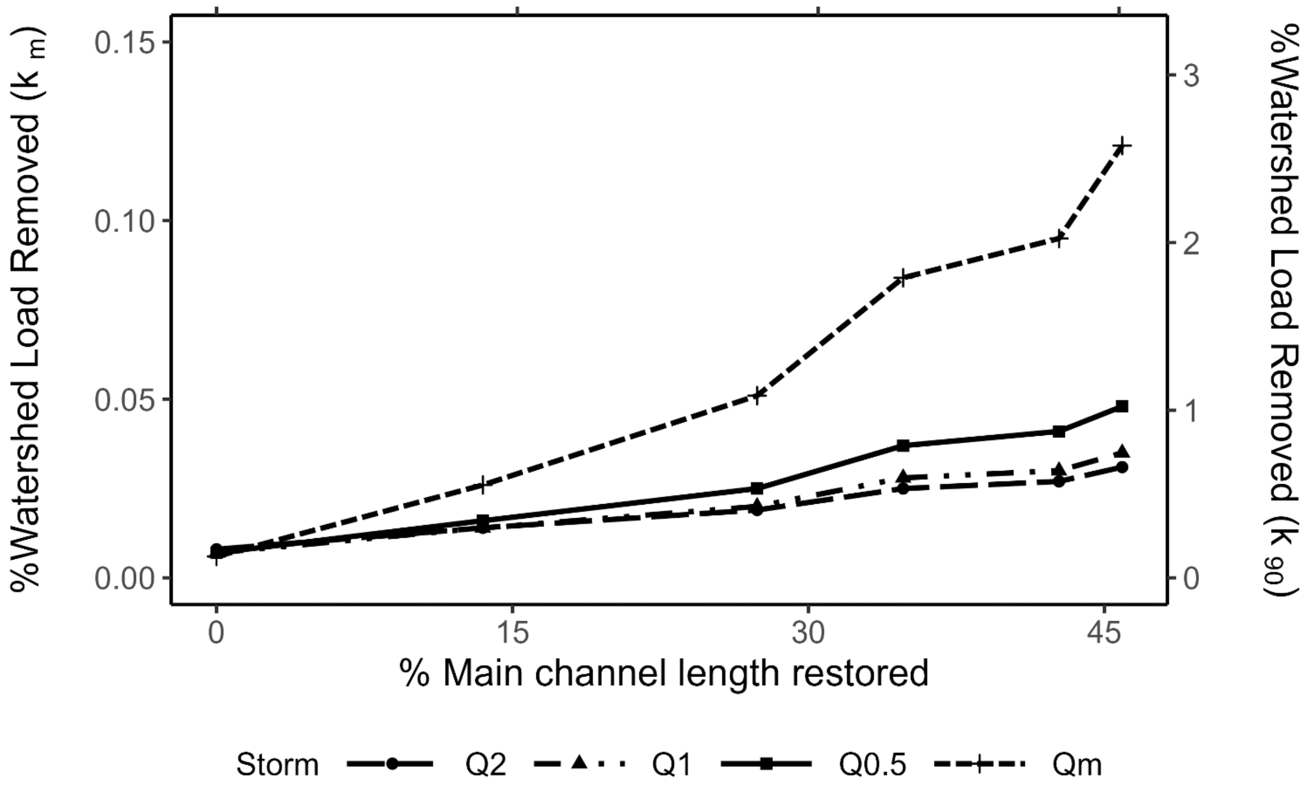
Varied:

- Up to 46% mainstem length restored (hypothetical legacy sediment removal)
- Storm size (monthly, 0.5 year, 1 year, and 2 year storms)



Nitrate Removal

- Minimal nitrate removal from restoration
- Significance of restoration was limited by existing infrastructure
- Up to 21% of full main channel restored



Task 4: Key Outcomes

- Small effect of restoration on nitrate removal
- Additional restoration lengths are required to increase nitrate removal and flood reduction, but even modeled restoration would be expensive
- Again, does not include pulsed hyporheic exchange in floodplain
- Watershed scale modeling is important but cost effectiveness of this approach may be highly variable given data availability

Publications

Journal Articles (so far):

Calfe, M.L., D.T. Scott, and E.T. Hester. 2022. Nitrate removal by watershed-scale hyporheic stream restoration: Modeling approach to estimate effects and patterns at the stream network scale. *Ecological Engineering* 175:106498

Federman, C.E., D.T. Scott, and E.T. Hester. 2023. Impact of floodplain and Stage 0 stream restoration on flood attenuation and floodplain exchange during small frequent storms. *Journal of the American Water Resources Association* 59:29–48

Theses:

Calfe, M. L. 2019. Cumulative Impacts of Watershed-Scale Hyporheic Stream Restoration on Nitrate Loading to Downstream Waterbodies. Virginia Tech, Blacksburg, VA.

Federman, C. 2021. Impact of Stream Restoration on Flood Attenuation and Channel-Floodplain Exchange During Small Recurrence Interval Storms. Virginia Tech, Blacksburg, VA.

Goodman, L. 2023. Cumulative Impacts of Stream Restoration on Watershed-Scale Flood Attenuation, Floodplain Inundation, and Nitrate Removal. Virginia Tech, Blacksburg VA.

Oehler, M. A. 2024. Watershed Scale Impacts of Floodplain Restoration on Nitrate Removal and the Practical Applications of Modeling Cumulative Floodplain Restoration Hydraulics Virginia Tech, Blacksburg, VA.

Thank you

The Chesapeake Bay Trust and partners the Maryland Department of Natural Resources, the National Fish and Wildlife Foundation through the Environmental Protection Agency's Chesapeake Bay Program Office, the Maryland Department of Transportation State Highway Administration, and the Montgomery County Department of Environmental Protection

Charles E. Via Endowment at Virginia Tech

Joe Berg of Biohabitats for translation

Translation Slides

I’m glad I’m a Practitioner!

Trying to model complex watersheds and processes is not easy and it may be even harder to extract useful insights into optimizing restoration efforts.

What does this mean for me?

Longer restoration projects deliver greater benefits than shorter ones, all else being equal-not a surprise

Generally, we see better N processing with treatment of baseflow (hyporheic processing)-this shouldn't be a surprise as this work is being done 24/7/365, with favorable water volume to hyporheic bed volume

The prediction that less N processing is occurring with floodplain reconnection may be the result of how the analysis was conducted-we might expect a longer lag time on the order of weeks for floodplain N processing through infiltration, movement through the lateral hyporheic bed, as well as the dynamic nature of floodplain performance, e.g., width of wetted floodplain, retention time/volume, frequency of storm connection to the floodplain, etc.

Are headwater restorations or 4th order stream restorations more important for N processing- I'm not sure the results answer this question authoritatively

What does this mean for me?

What do I take from this if I am a practitioner:

I need to continue to look through the literature for studies that measure actual project performance

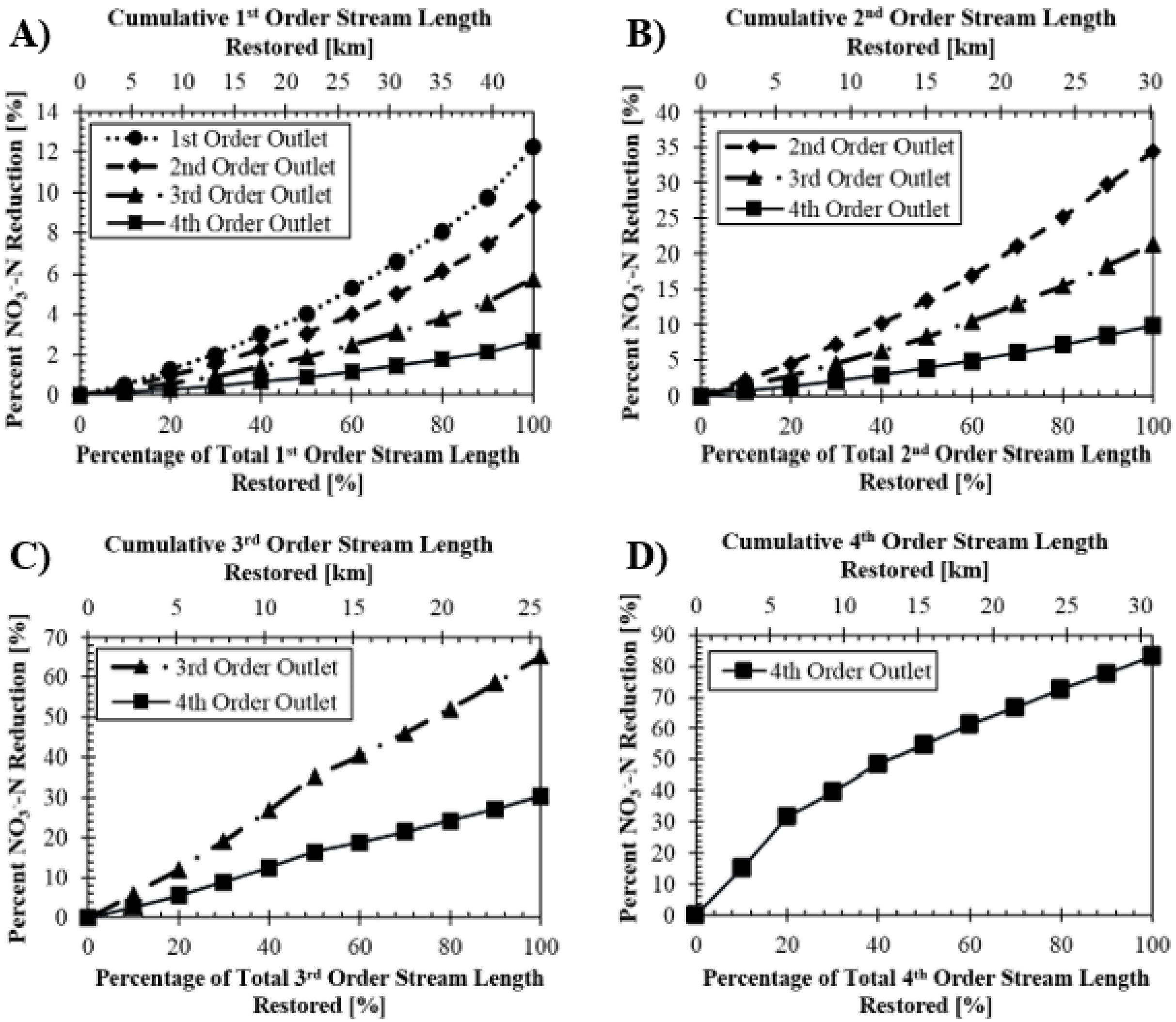
I appreciate the challenge of developing models that we can use to answer important questions as those evaluated in this project, but its clear that developing such a model is not a quick, easy, or inexpensive approach-it will require more $ and more calendar time

What do I take from this if I am a regulator:

I need to continue to look through the literature for studies that measure actual project performance.

Everyone in this field is working hard to improve our understanding of stream restoration performance.

Leftover slides



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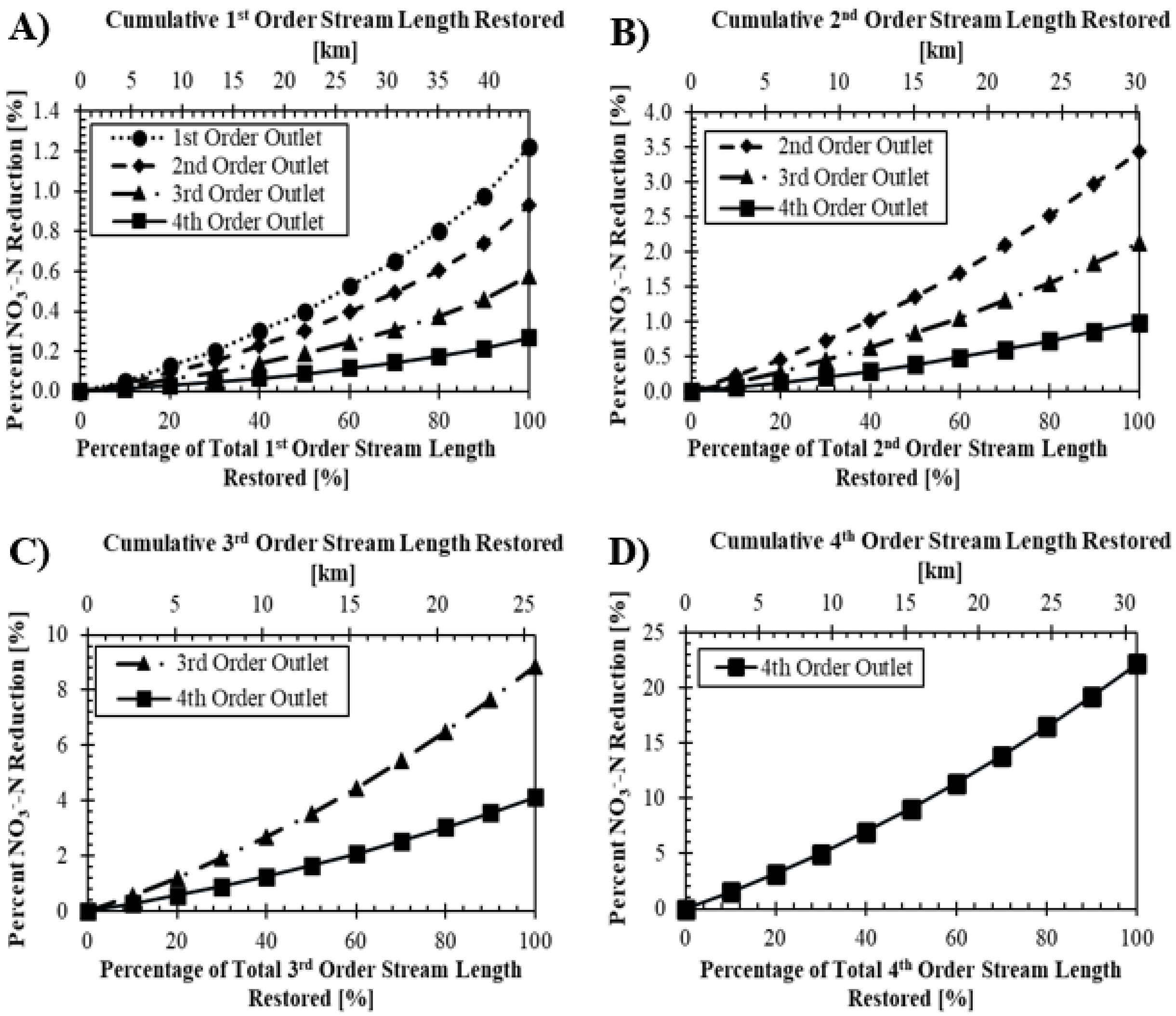

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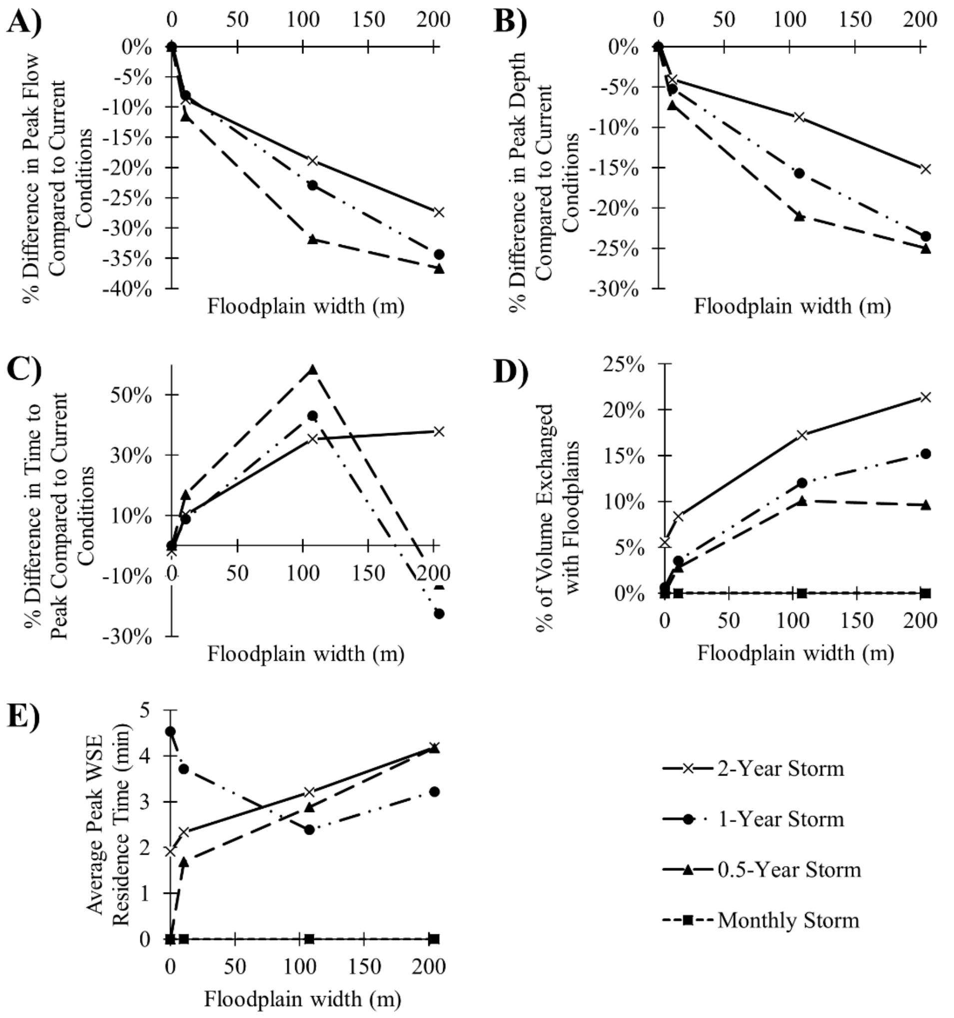

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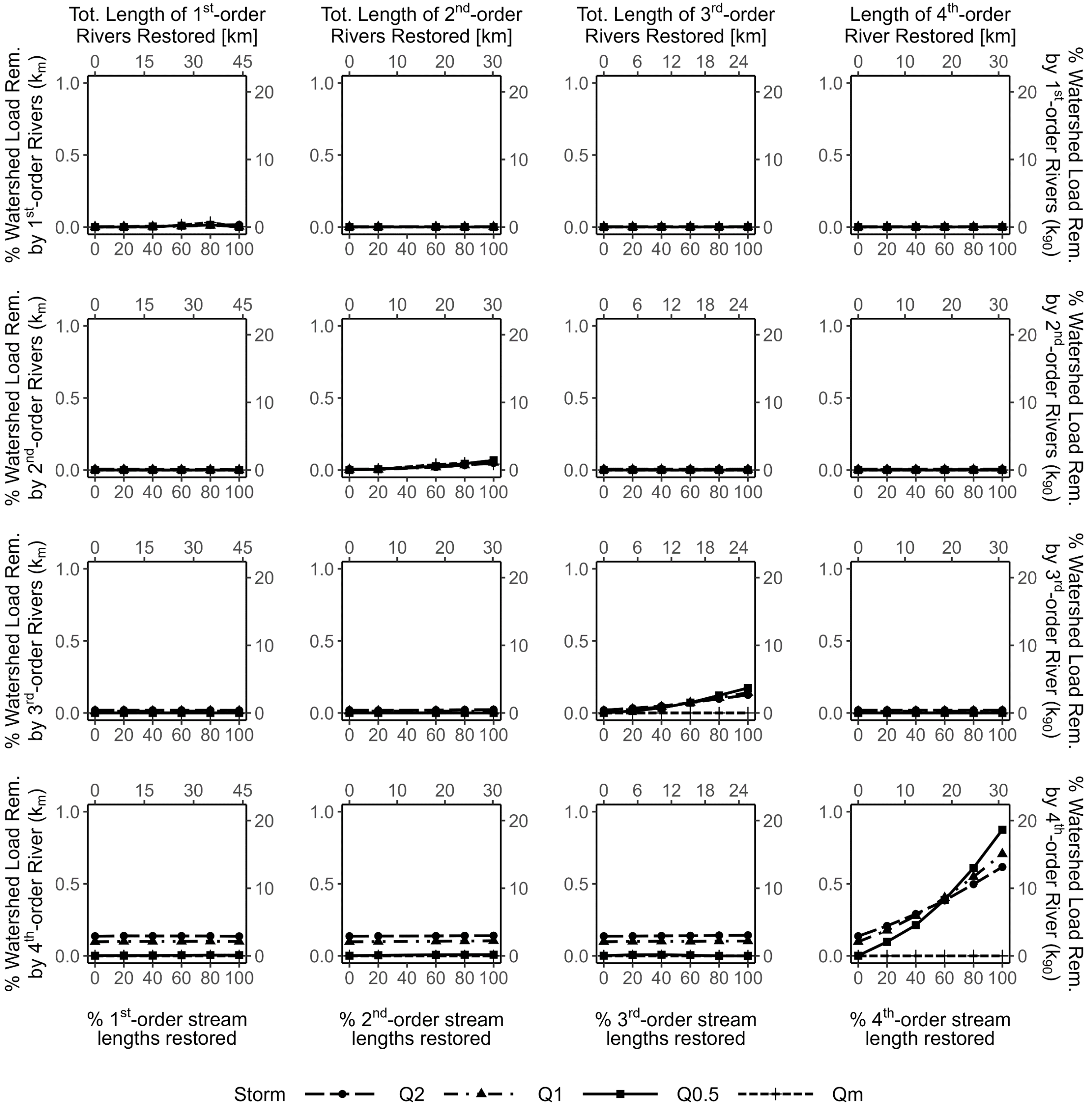
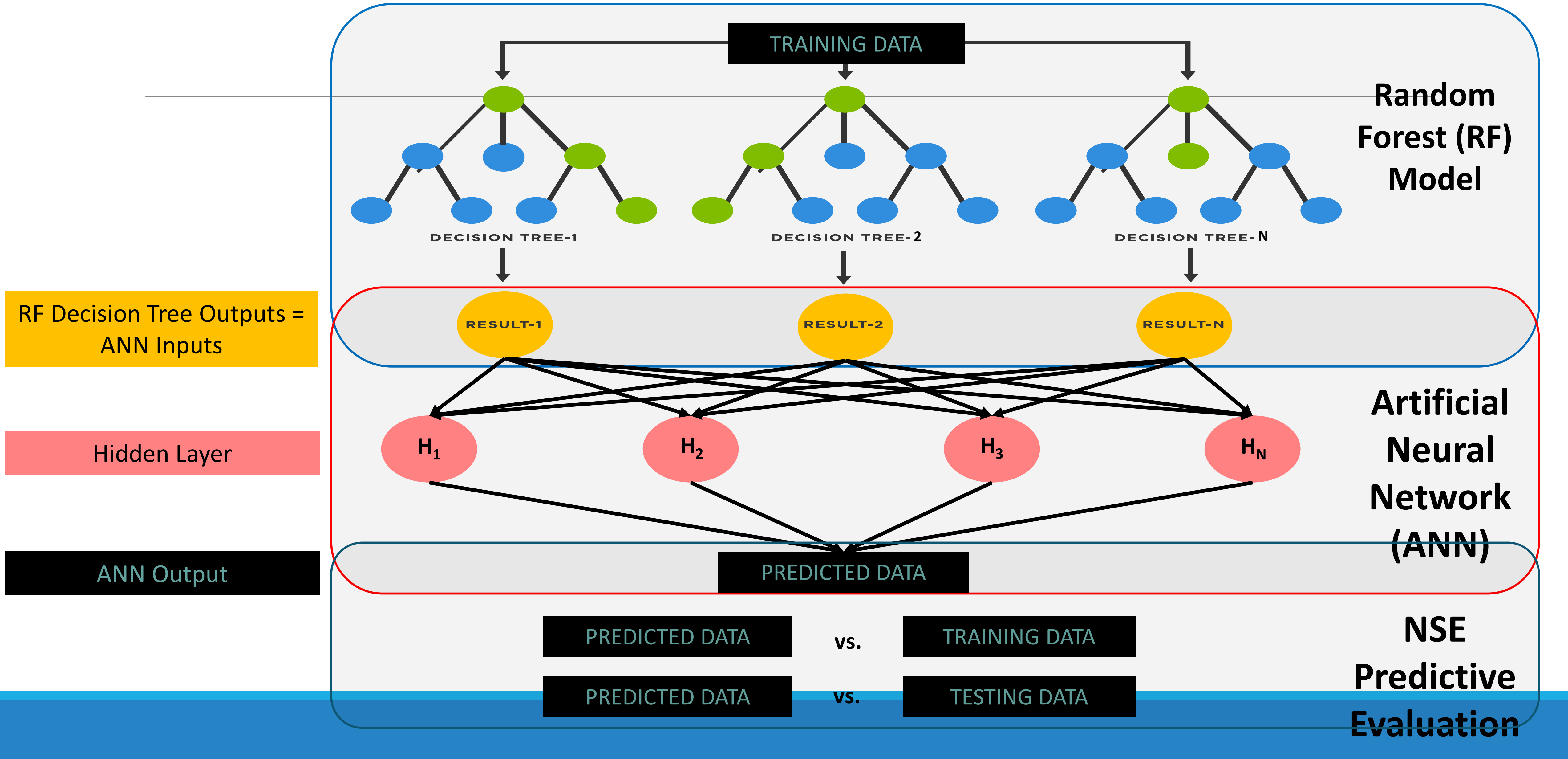


Tot. Length of 1st-order Rivers Restored [km]
Tot. Length of 2nd-order Rivers Restored [km]
Tot. Length of 3rd-order Rivers Restored [km]
Length of 4th-order River Restored [km]
% Watershed Load Rem. by 1st-order Rivers (km)
% Watershed Load Rem. by 2nd-order Rivers (km)
% Watershed Load Rem. by 3rd-order Rivers (km)
% Watershed Load Rem. by 4th-order River (km)
% Watershed Load Rem. by 1st-order Rivers (k90)
% Watershed Load Rem. by 2nd-order Rivers (k90)
% Watershed Load Rem. by 3rd-order River (k90)
% Watershed Load Rem. by 4th-order River (k90)
% 1st-order stream lengths restored
% 2nd-order stream lengths restored
% 3rd-order stream lengths restored
% 4th-order stream length restored
Storm
Q2
Q1
Q0.5
Qm

Random Forest-Artificial Neural Network Coupled Analysis



Model Performance

Model performance by Median Testing NSE

Analysis	Nitrate removal rate type	Reaches included	Nitrogen concentration	n	Median NSE	Performance[1]	Mean predicted nitrate removal rate ($mg/m^2/hr$)
A	Actual	All	Yes	114	0.1712	Not satisfactory	2.683
B	Actual	All	No	114	0.5563	Very good	1.980
C	Actual	Restored	Yes	78	0.5772	Very good	1.937
D	Actual	Restored	No	78	0.6659	Very good	2.718
E	Potential	All	No	183	0.2758	Satisfactory	2.389
F	Potential	Restored	No	100	0.3116	Satisfactory	2.066

[1] From Moriasi et al. (2015).

Table 2.2: NSE performance criteria for watershed-scale nitrogen models (Moriasi et al., 2015).

Not satisfactory	**Satisfactory**	**Good**	**Very good**
NSE $\leq$ 0.25	0.25 $<$ NSE $<$ 0.40	0.40 $\leq$ 0.40 NSE $\leq$ 0.55	NSE $>$ 0.55

Variable Importance

Data used for each analysis

Analysis	Nitrate removal rate type	Reaches included	Nitrogen concentration
A	Actual	All	Yes
B	Actual	All	No
C	Actual	Restored	Yes
D	Actual	Restored	No
E	Potential	All	No
F	Potential	Restored	No

With vs. Without N conc; Actual rates; *All reaches*

	Analysis A		Analysis B	
Rank	Variable	VI	Variable	VI
1	Hydrologic condition	1.242	Hydrologic condition	1.697
2	Nitrogen concentration	1.179	Specific runoff	1.326
3	Stream order	0.993	Stream order	0.855
4	Specific runoff	0.609	Restoration status	0.074
5	Restoration status	0.060	Season	0.067
6	Season	0.051	NA	NA

Potential rates; Restored vs. All reaches

	Analysis E		Analysis F	
Rank	Variable	VI	Variable	VI
1	Specific runoff	0.736	Specific runoff	0.555
2	Stream order	0.287	Stream order	0.282
3	Season	0.155	Season	0.145
4	Sample location	0.148	Restoration type	0.101
5	Restoration status	0.101	Hydrologic condition	0.059
6	Hydrologic condition	0.045	Sample location	0.042

With vs. Without N conc; Actual rates; *Restored reaches*

	Analysis C		Analysis D	
Rank	Variable	VI	Variable	VI
1	Hydrologic condition	1.225	Hydrologic condition	1.203
2	Restoration type	0.808	Restoration type	0.796
3	Stream order	0.733	Stream order	0.517
4	Specific runoff	0.428	Specific runoff	0.373
5	Nitrogen concentration	0.364	Season	-0.001
6	Season	0.002	NA	NA

Variable Importance

Data used for each analysis

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A	Actual	All	Yes
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With vs. Without N conc; Actual rates; *Restored reaches*

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Predicted Nitrate Removal Rates

Hydrologic Condition

Hydrologic condition	Mean predicted nitrate removal rate ($mg/m^2/hr$) A	B	C	D	E	F
Baseflow	4.605	3.201	3.172	4.008	2.104	2.114
Stormflow	1.550	1.588	1.801	0.696	4.211	1.983

Stream Order

Stream order	Mean predicted nitrate removal rate ($mg/m^2/hr$) A	B	C	D	E	F
1st	1.151	4.119	4.274	4.766	2.739	2.260
2nd	3.714	1.813	3.641	4.226	5.941	4.713
3rd	1.918	2.156	2.378	1.969	1.338	0.624
4th	5.405	2.334	2.642	2.143	NA*	0.749
5th	NA*	NA*	NA*	NA*	6.119	4.839
6th	0.867	0.568	0.783	0.544	1.929	1.402
7th	0.939	NA*	1.225	0.696	2.184	2.467
8th	NA*	NA*	NA*	NA*	4.849	NA*

*NAs are due to an insufficient amount of input data.

Restoration Status and Type

(a) Restored and unrestored reach mean predicted nitrate removal rates

Restoration status	Mean predicted nitrate removal rate ($mg/m^2/hr$) A	B	E
Restored	2.586	1.263	2.573
Unrestored	3.891	3.620	1.670

(b) Floodplain vs. channel restoration mean predicted nitrate removal rates

Restoration type	Mean predicted nitrate removal rate ($mg/m^2/hr$) C	D	F
Floodplain	1.279	1.431	1.980
Channel	1.597	2.393	2.558

Variable Ranking and Predicted Nitrate Removal Rate Trends

Importance of hydrologic factors:

Facilitates **hydrologic exchange** with floodplain soils, increasing nutrient removal and processing (Berg et al., 2013; Hester et al., 2016; Mahl et al., 2015; Newcomer Johnson et al., 2014, 2016; Roley et al., 2012)

Potential rates: specific runoff, stream order, and season were most important

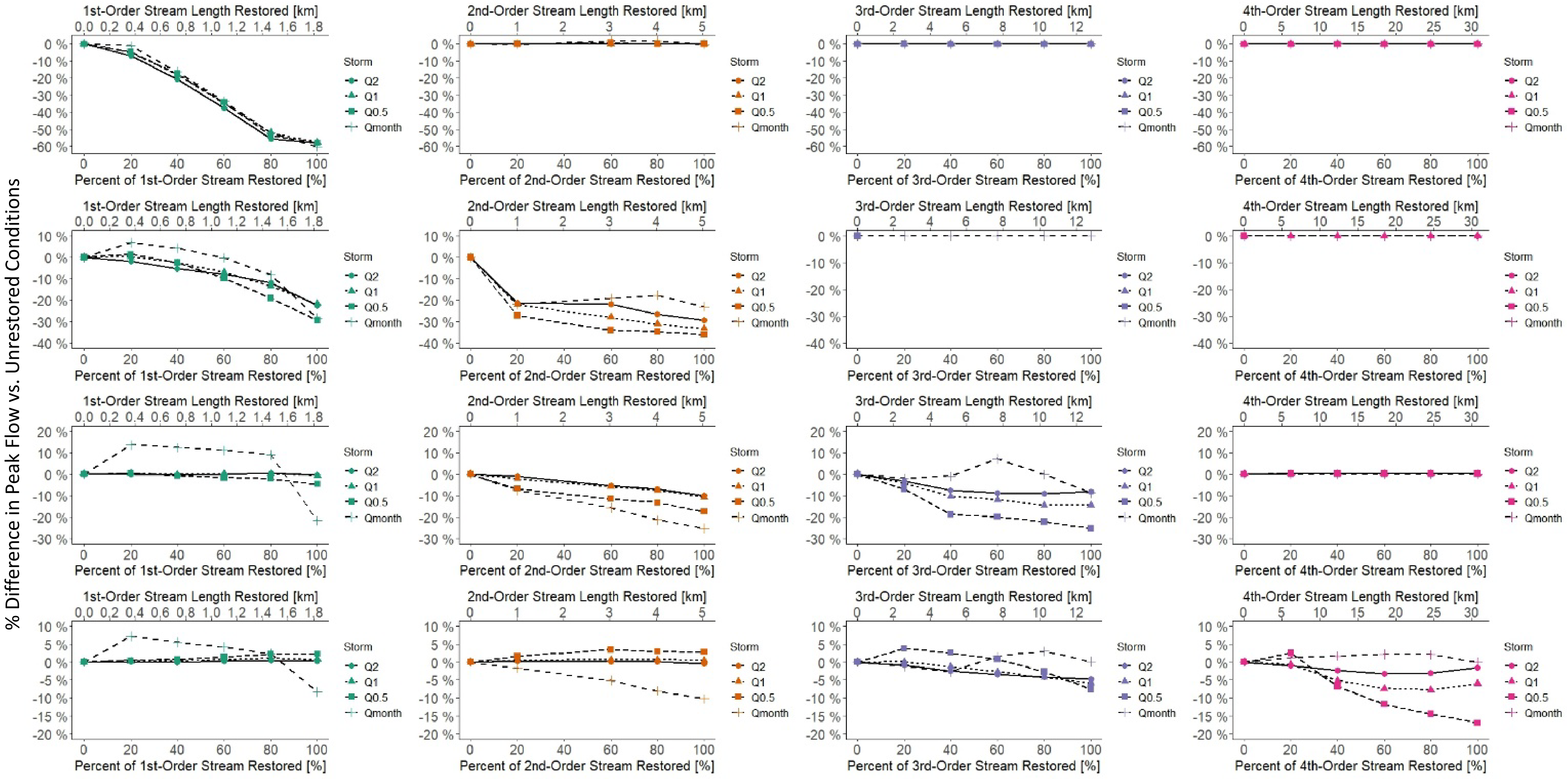
Reflective of **spatial** and **temporal** variations in **soil** or **sediment** properties

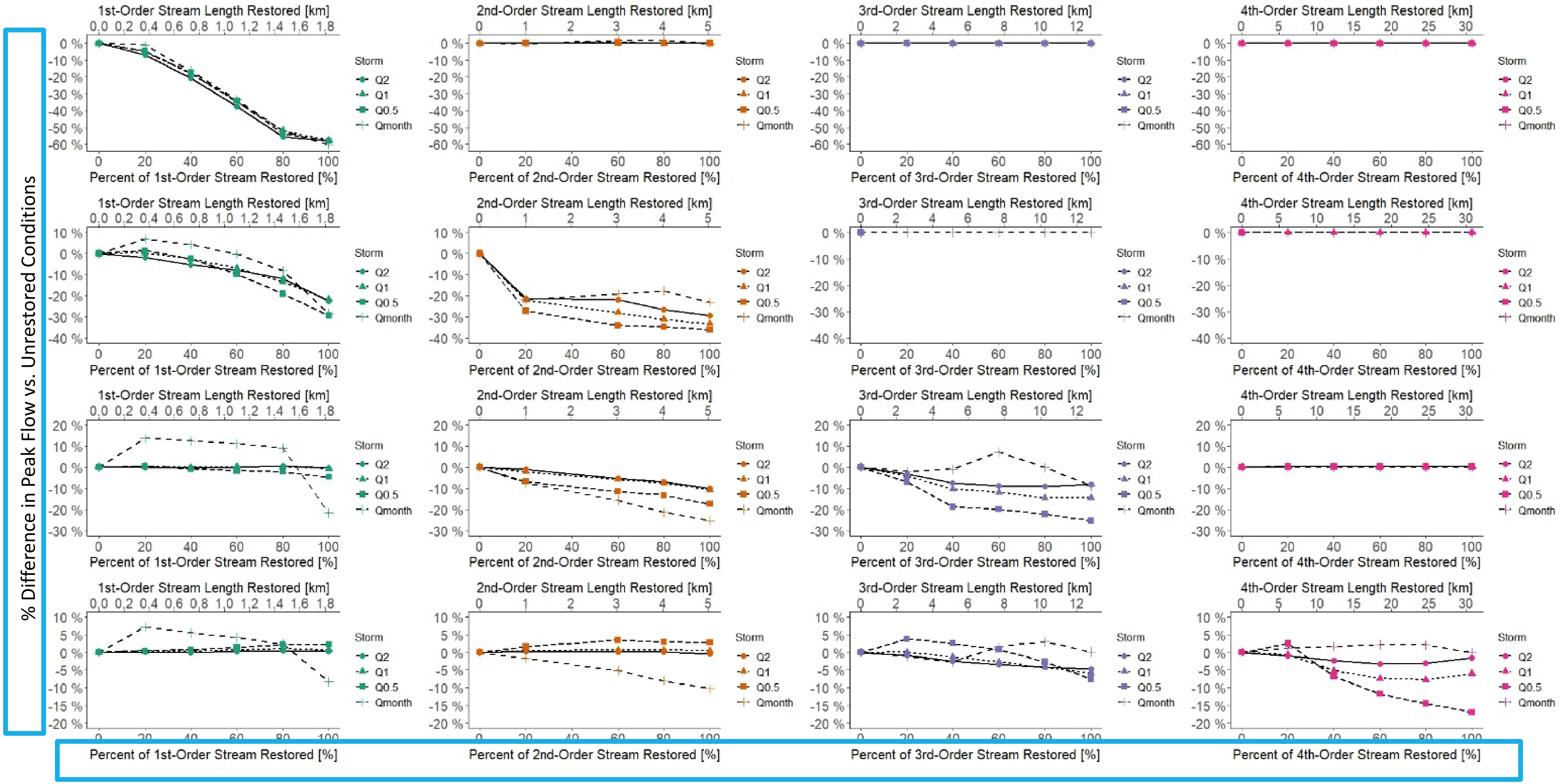
N concentration was less influential for predicting actual nitrate removal rates when compared to other factors (Jones et al. 2015)

Limitations

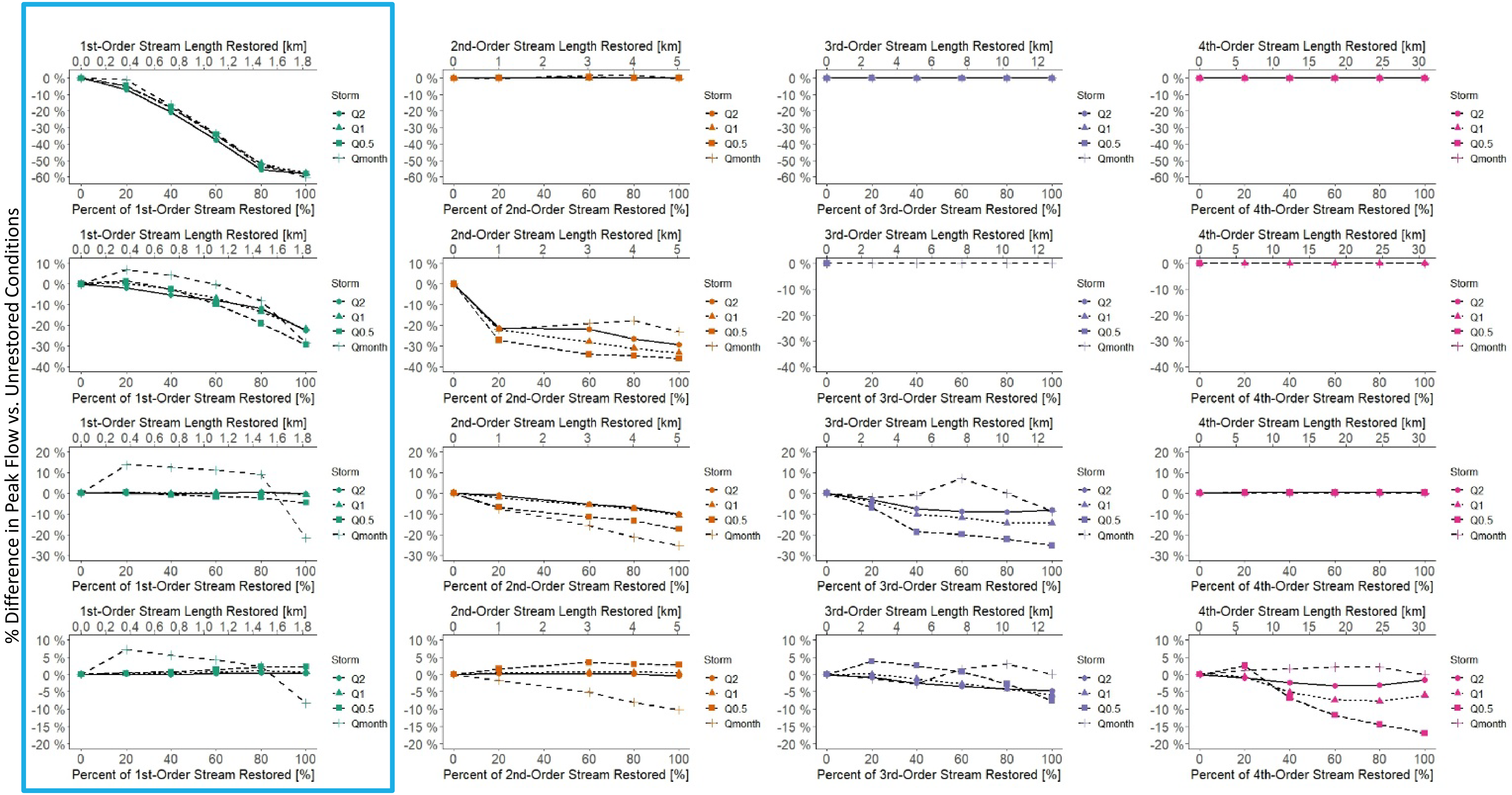
Lack of input data for larger stream orders

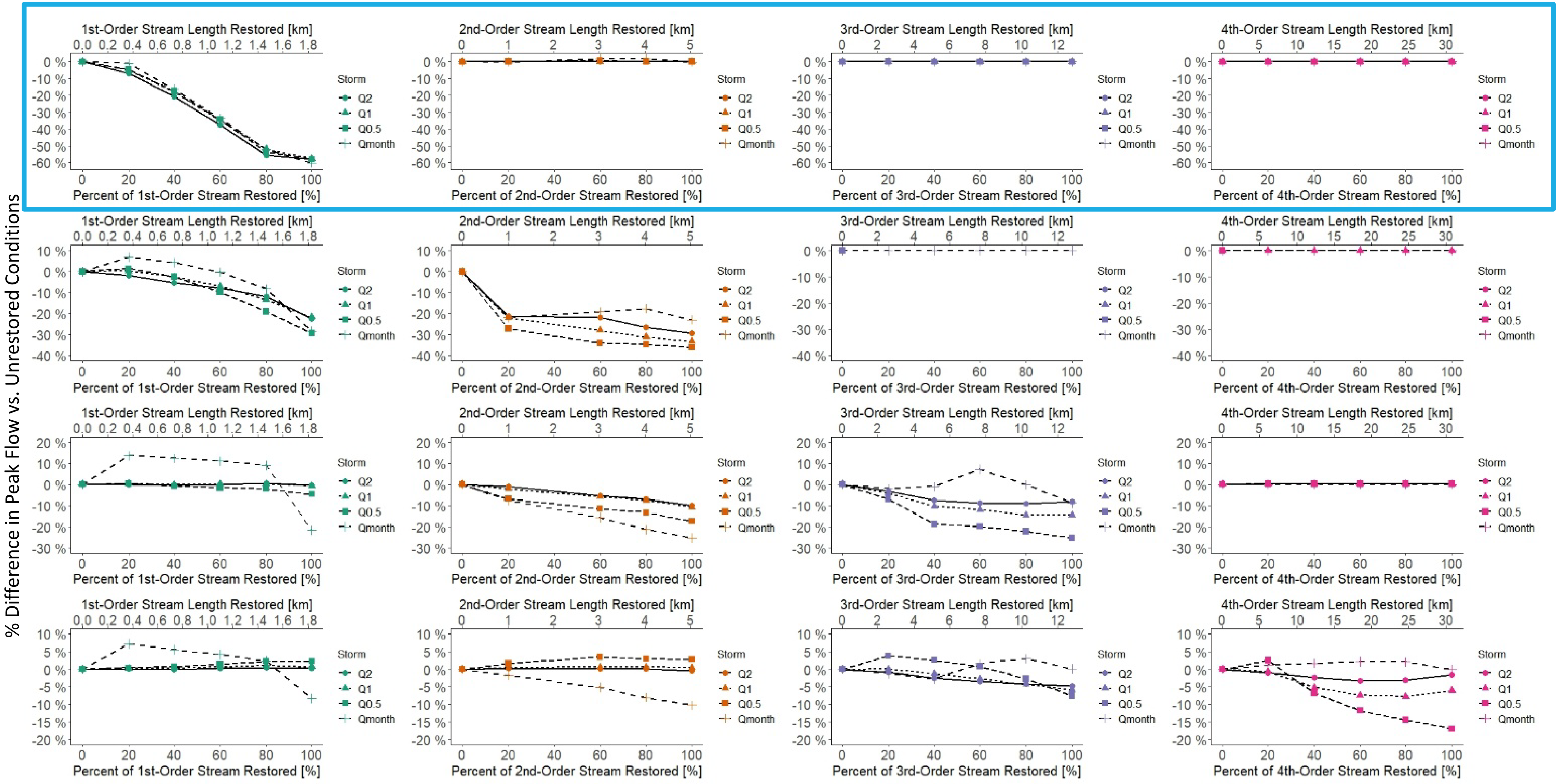
Binning restoration practices into two categories


% Difference in Peak Flow vs. Unrestored Conditions
1st-Order Stream Length Restored [km]
Percent of 1st-Order Stream Restored [%]
2nd-Order Stream Length Restored [km]
Percent of 2nd-Order Stream Restored [%]
3rd-Order Stream Length Restored [km]
Percent of 3rd-Order Stream Restored [%]
4th-Order Stream Length Restored [km]
Percent of 4th-Order Stream Restored [%]
Storm
Q2
Q1
Q0.5
Qmonth

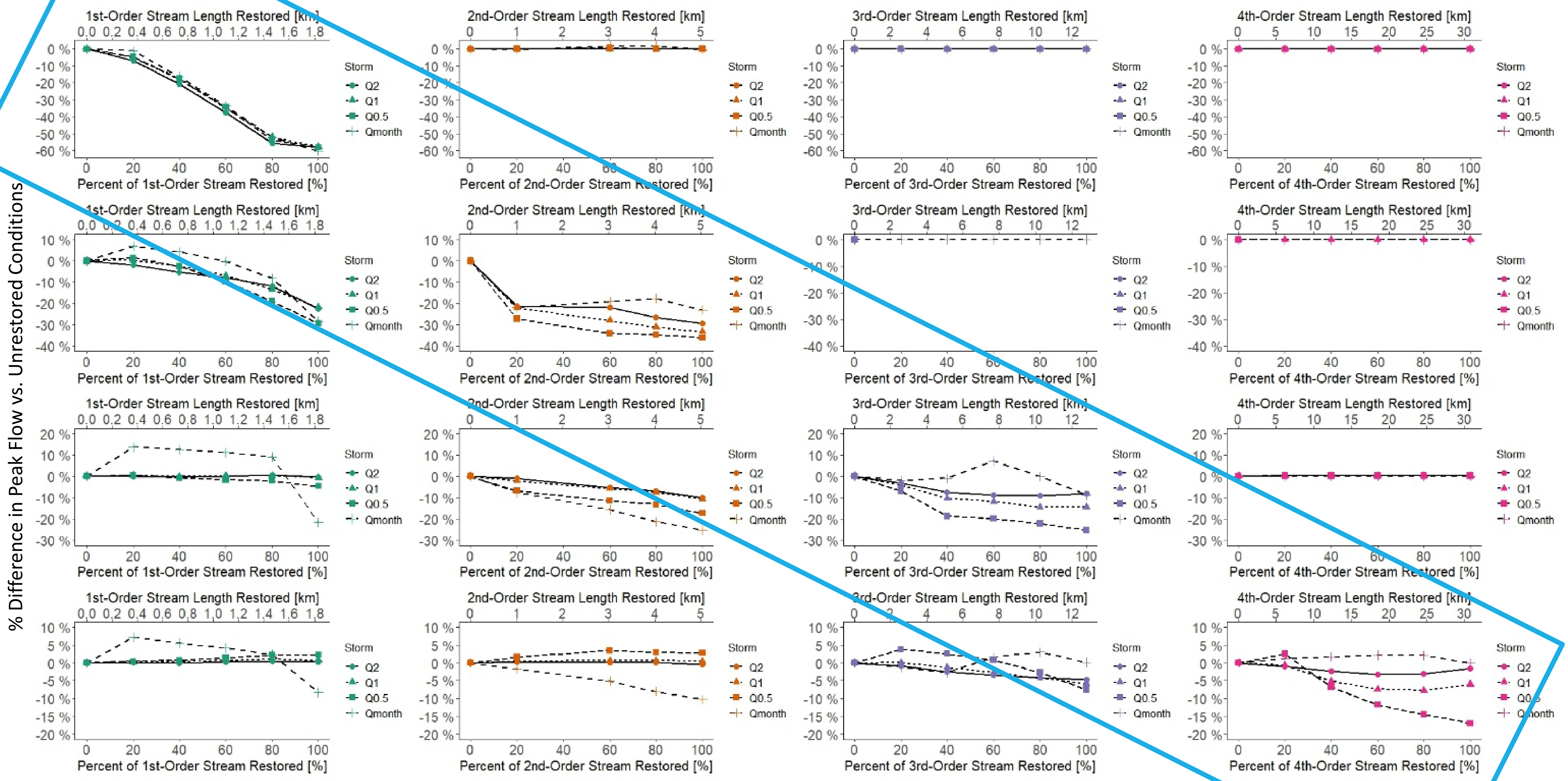


% Difference in Peak Flow vs. Unrestored Conditions
1st-Order Stream Length Restored [km]
2nd-Order Stream Length Restored [km]
3rd-Order Stream Length Restored [km]
4th-Order Stream Length Restored [km]
Percent of 1st-Order Stream Restored [%]
Percent of 2nd-Order Stream Restored [%]
Percent of 3rd-Order Stream Restored [%]
Percent of 4th-Order Stream Restored [%]
Storm
Q2
Q1
Q0.5
Qmonth


% Difference in Peak Flow vs. Unrestored Conditions
1st-Order Stream Length Restored [km]
2nd-Order Stream Length Restored [km]
3rd-Order Stream Length Restored [km]
4th-Order Stream Length Restored [km]
Percent of 1st-Order Stream Restored [%]
Percent of 2nd-Order Stream Restored [%]
Percent of 3rd-Order Stream Restored [%]
Percent of 4th-Order Stream Restored [%]
Storm
Q2
Q1
Q0.5
Qmonth



% Difference in Peak Flow vs. Unrestored Conditions
1st-Order Stream Length Restored [km]
Percent of 1st-Order Stream Restored [%]
2nd-Order Stream Length Restored [km]
Percent of 2nd-Order Stream Restored [%]
3rd-Order Stream Length Restored [km]
Percent of 3rd-Order Stream Restored [%]
4th-Order Stream Length Restored [km]
Percent of 4th-Order Stream Restored [%]
Storm
Q2
Q1
Q0.5
Qmonth


% Difference in Peak Flow vs. Unrestored Conditions
1st-Order Stream Length Restored [km]
2nd-Order Stream Length Restored [km]
3rd-Order Stream Length Restored [km]
4th-Order Stream Length Restored [km]
Percent of 1st-Order Stream Restored [%]
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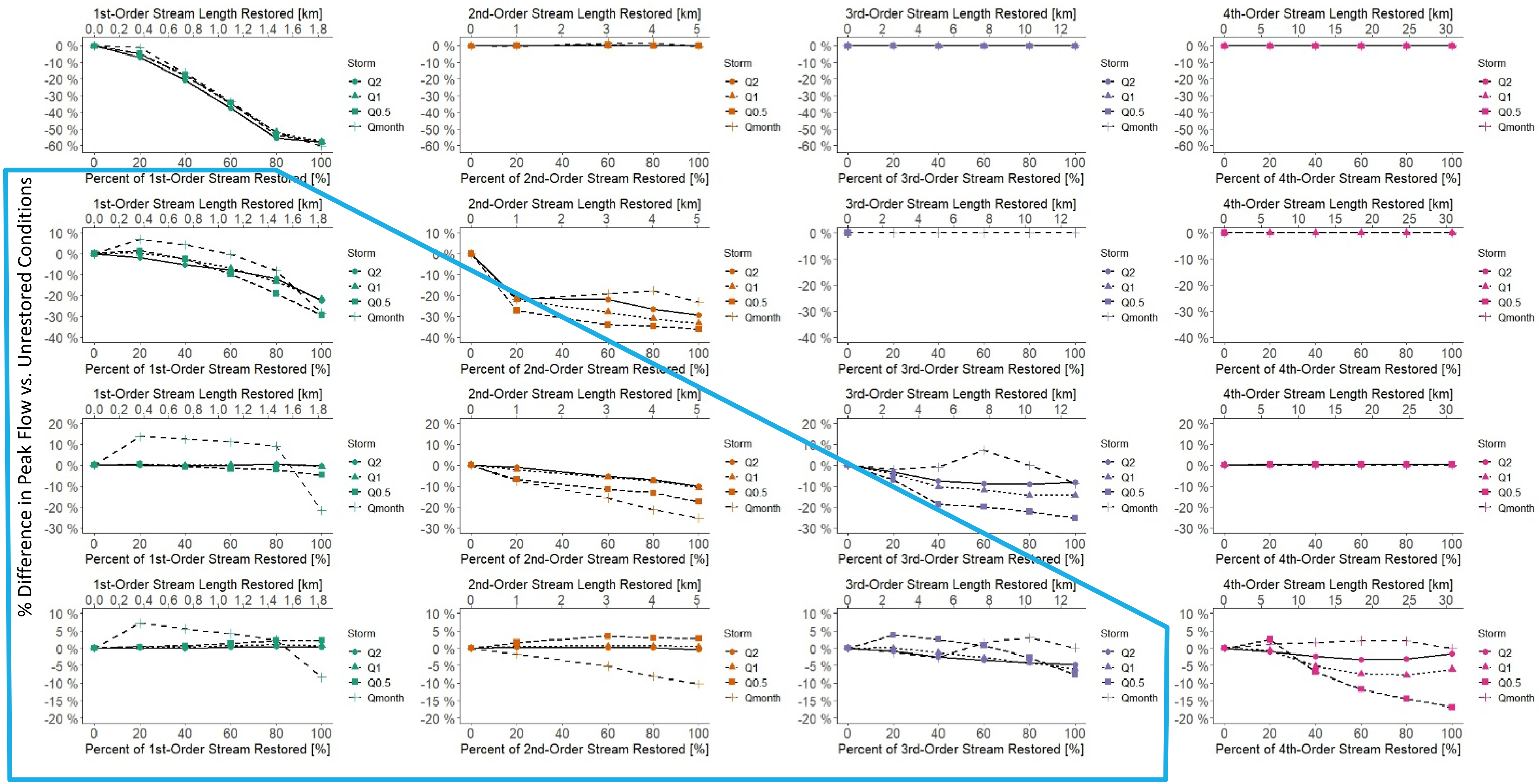
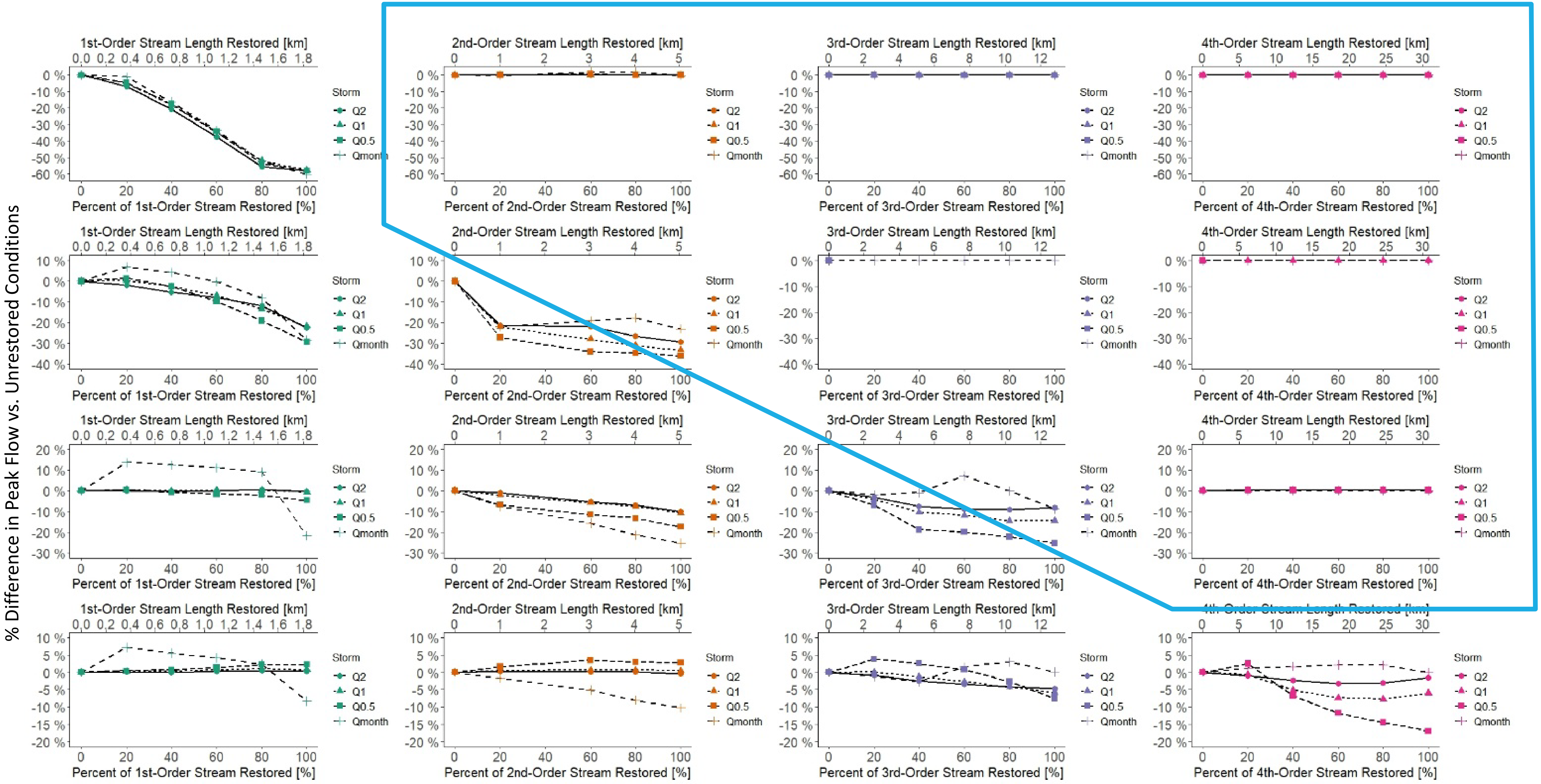
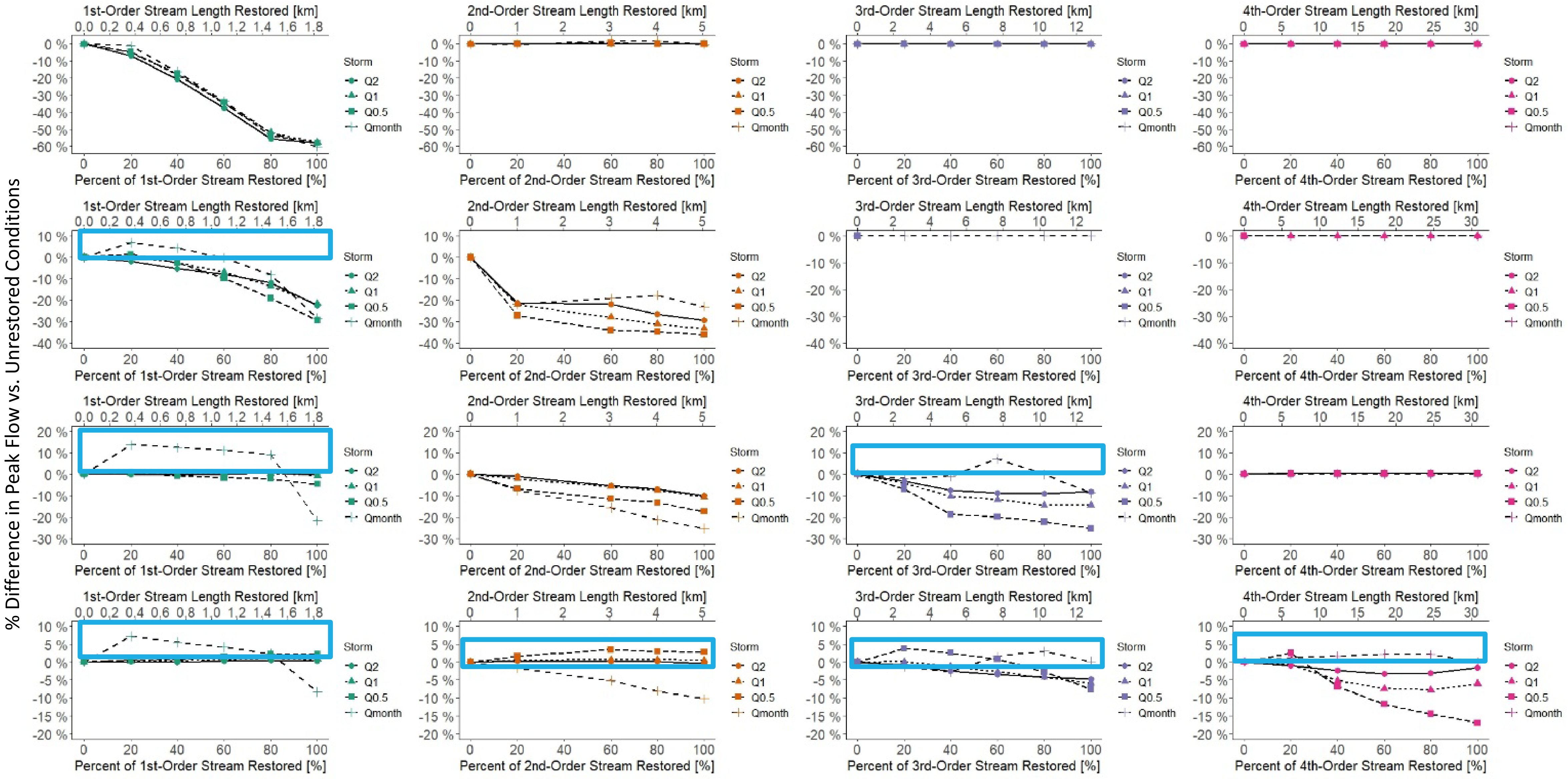
Percent of 3rd-Order Stream Restored [%]
Percent of 4th-Order Stream Restored [%]
Storm
Q2
Q1
Q0.5
Qmonth



% Difference in Peak Flow vs. Unrestored Conditions
1st-Order Stream Length Restored [km]
Percent of 1st-Order Stream Restored [%]
2nd-Order Stream Length Restored [km]
Percent of 2nd-Order Stream Restored [%]
3rd-Order Stream Length Restored [km]
Percent of 3rd-Order Stream Restored [%]
4th-Order Stream Length Restored [km]
Percent of 4th-Order Stream Restored [%]
Storm
Q2
Q1
Q0.5
Qmonth


% Difference in Peak Flow vs. Unrestored Conditions
1st-Order Stream Length Restored [km]
0,0 0,2 0,4 0,6 0,8 1,0 1,2 1,4 1,6 1,8
Percent of 1st-Order Stream Restored [%]
2nd-Order Stream Length Restored [km]
0 1 2 3 4 5
Percent of 2nd-Order Stream Restored [%]
3rd-Order Stream Length Restored [km]
0 2 4 6 8 10 12
Percent of 3rd-Order Stream Restored [%]
4th-Order Stream Length Restored [km]
0 5 10 15 20 25 30
Percent of 4th-Order Stream Restored [%]
0 20 40 60 80 100
Storm
Q2
Q1
Q0.5
Qmonth
0 % -10 % -20 % -30 % -40 % -50 % -60 %
10 % 0 % -10 % -20 % -30 % -40 %
20 % 10 % 0 % -10 % -20 % -30 %
10 % 5 % 0 % -5 % -10 % -15 % -20 %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2nd-Order Stream Length Restored [km]
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Percent of 2nd-Order Stream Restored [%]
Percent of 3rd-Order Stream Restored [%]
Percent of 4th-Order Stream Restored [%]
Storm
Q2
Q1
Q0.5
Qmonth

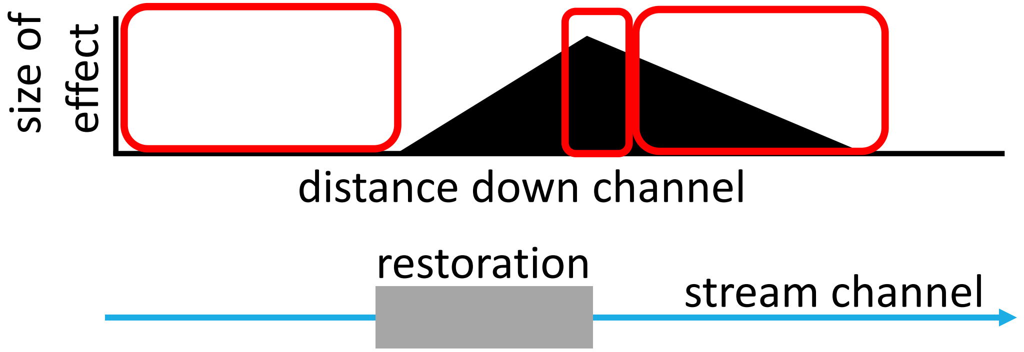
Generic model conclusions

Watershed context irreducibly complex

Greatest effect just downstream of restoration

Decreasing effect with distance downstream

No effects upstream



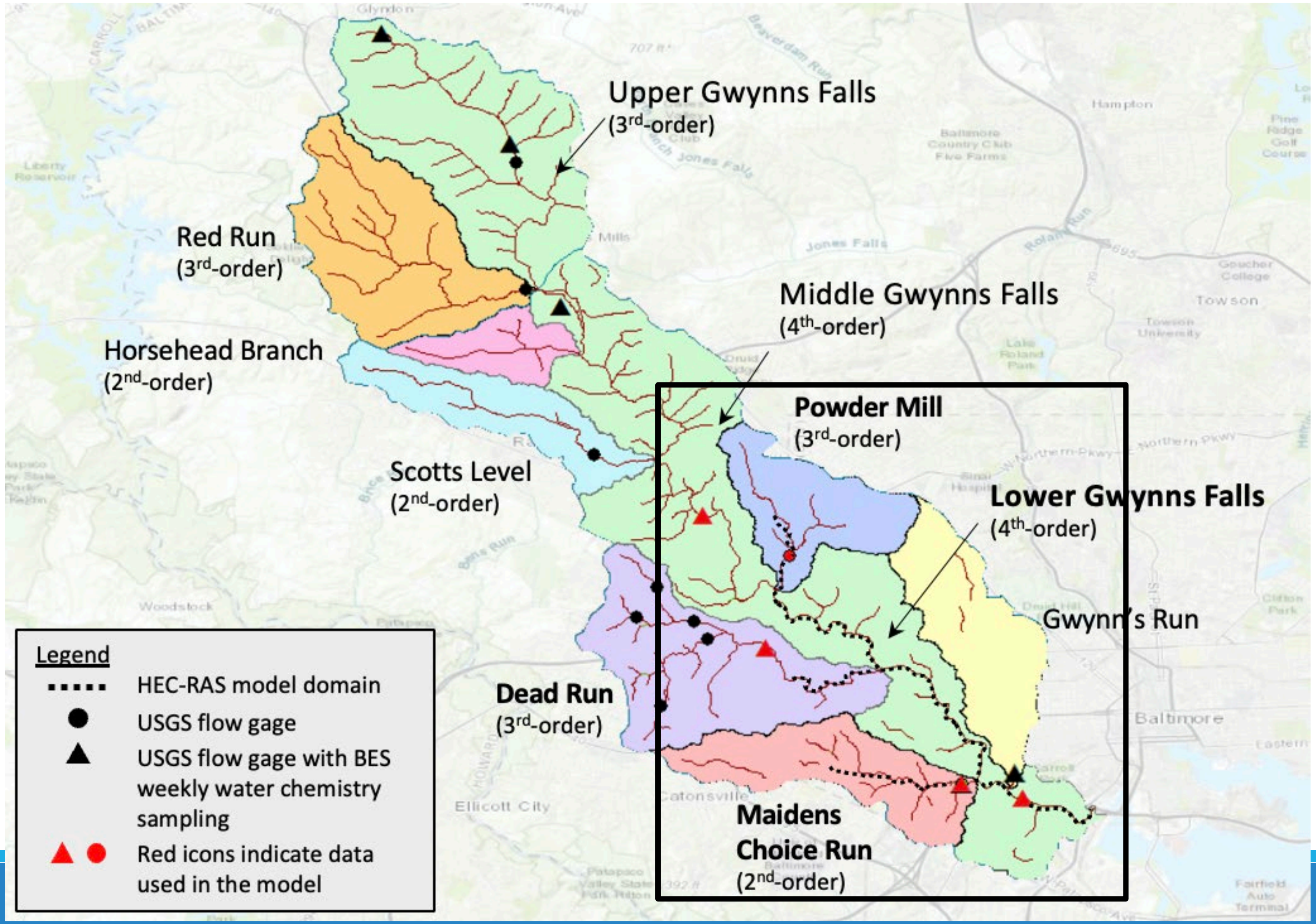
Largest decreases often for

- smaller order channels
- smaller storms

Mostly decrease in flood peaks, but some increases

Task 4: Simulated flood attenuation and nitrate removal from Stage 0/ floodplain restoration in Gwynns Falls

- Near Baltimore, MD
- 170 km^2 drainage area
- Urban (79%), forest (17%), agriculture (3%)
- Modeled because of ample data available and location within the Chesapeake Bay Watershed

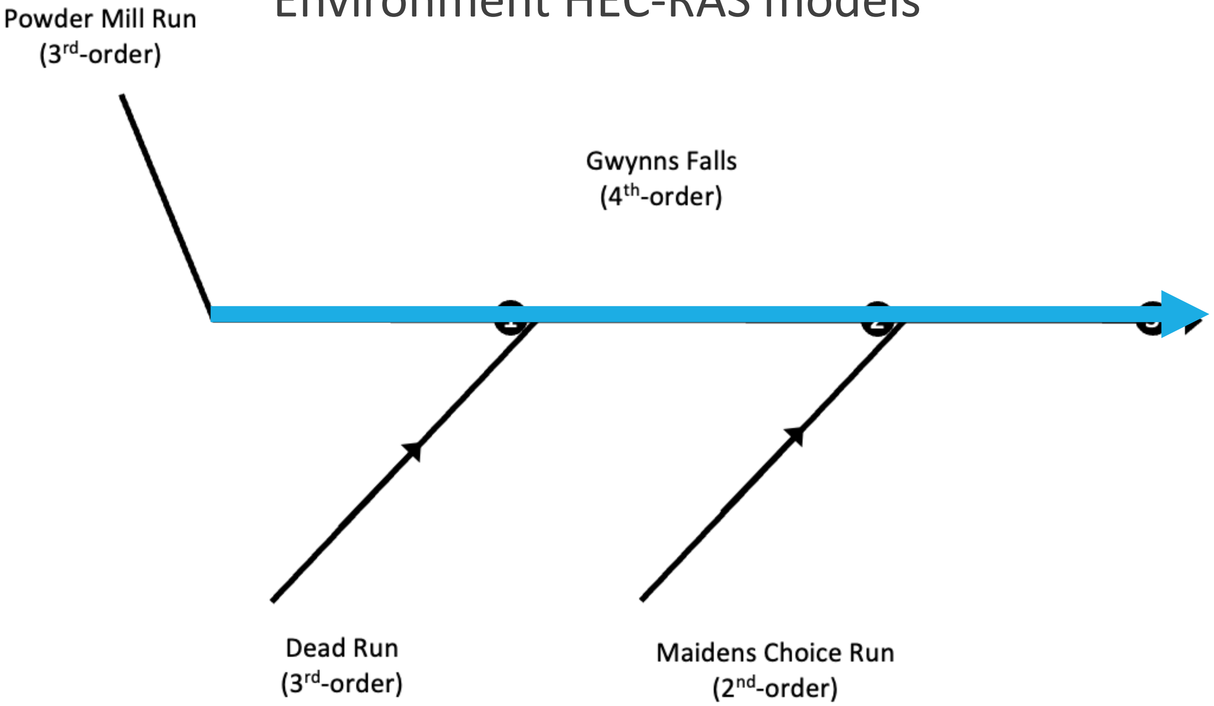


Geometry

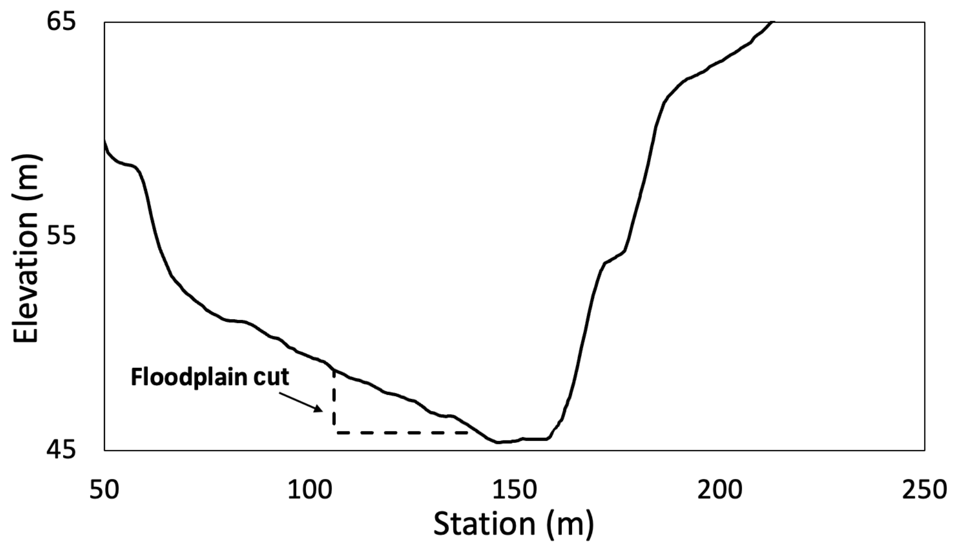
Flow

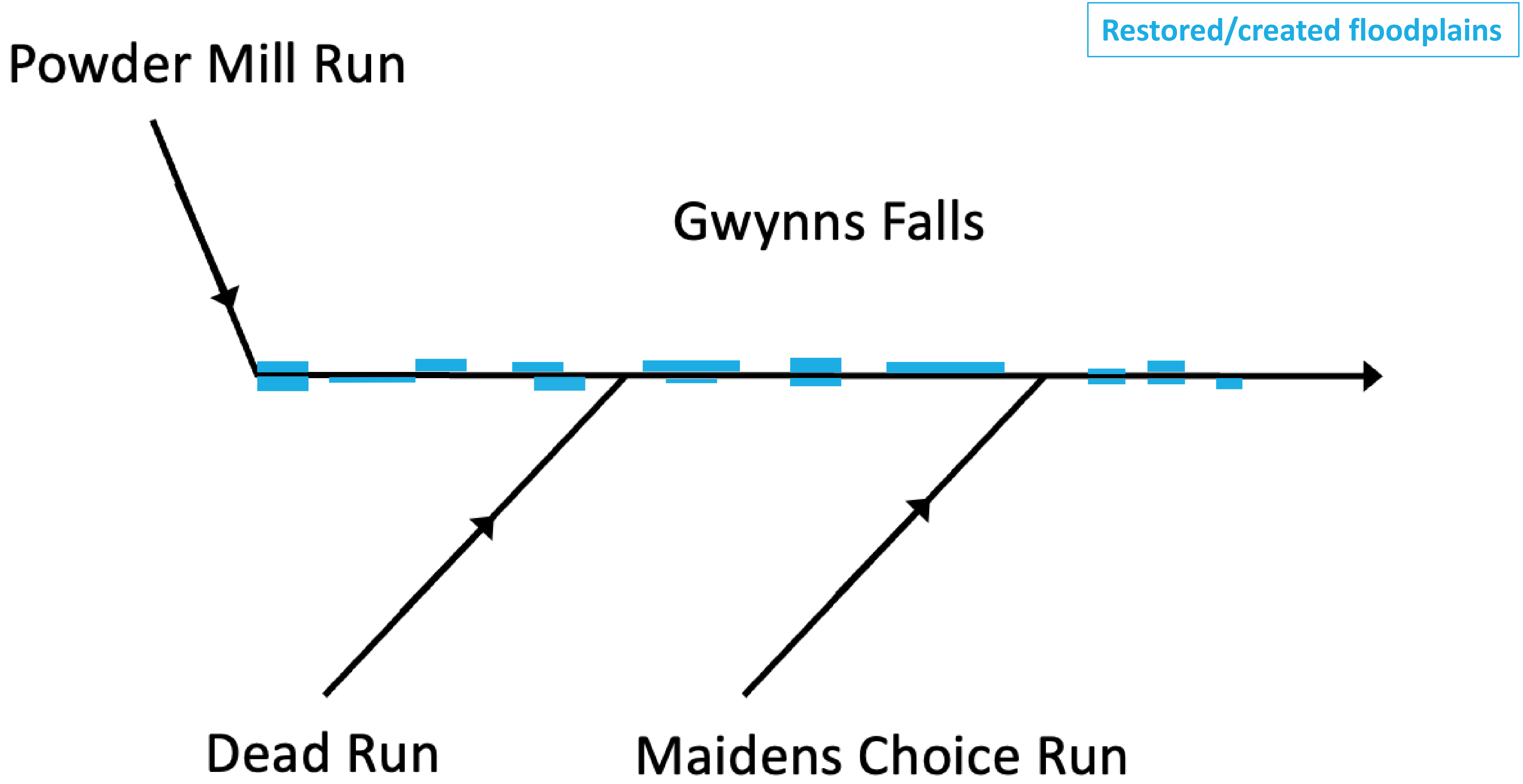
Gwynns Falls HEC-RAS Model - Geometry

- Unrestored geometry
  - Maryland Department of the Environment HEC-RAS models



- Restored geometry
  - Floodplain cut using HEC-RAS channel modification tool
  - Up to 46% of model main channel restored

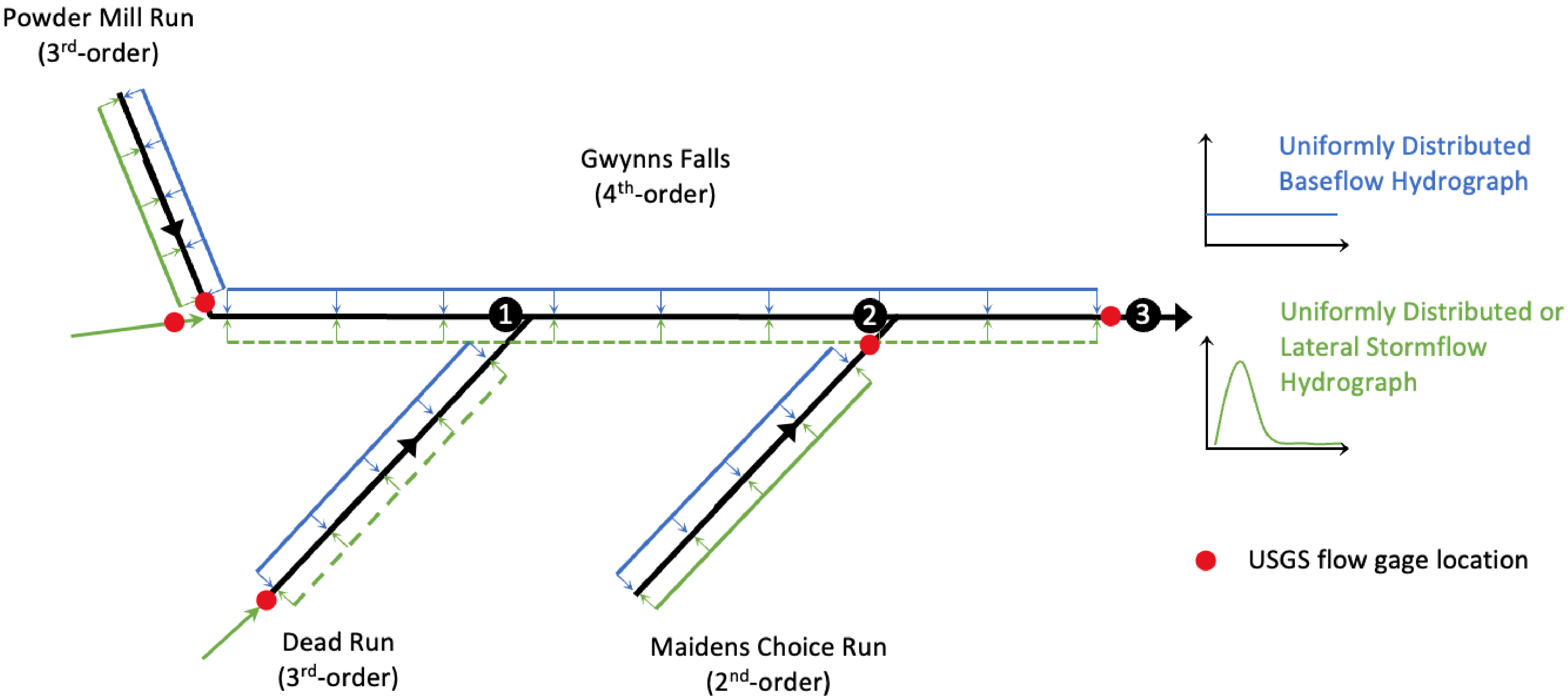



Restored/created floodplains
Powder Mill Run
Gwynns Falls
Dead Run
Maidens Choice Run

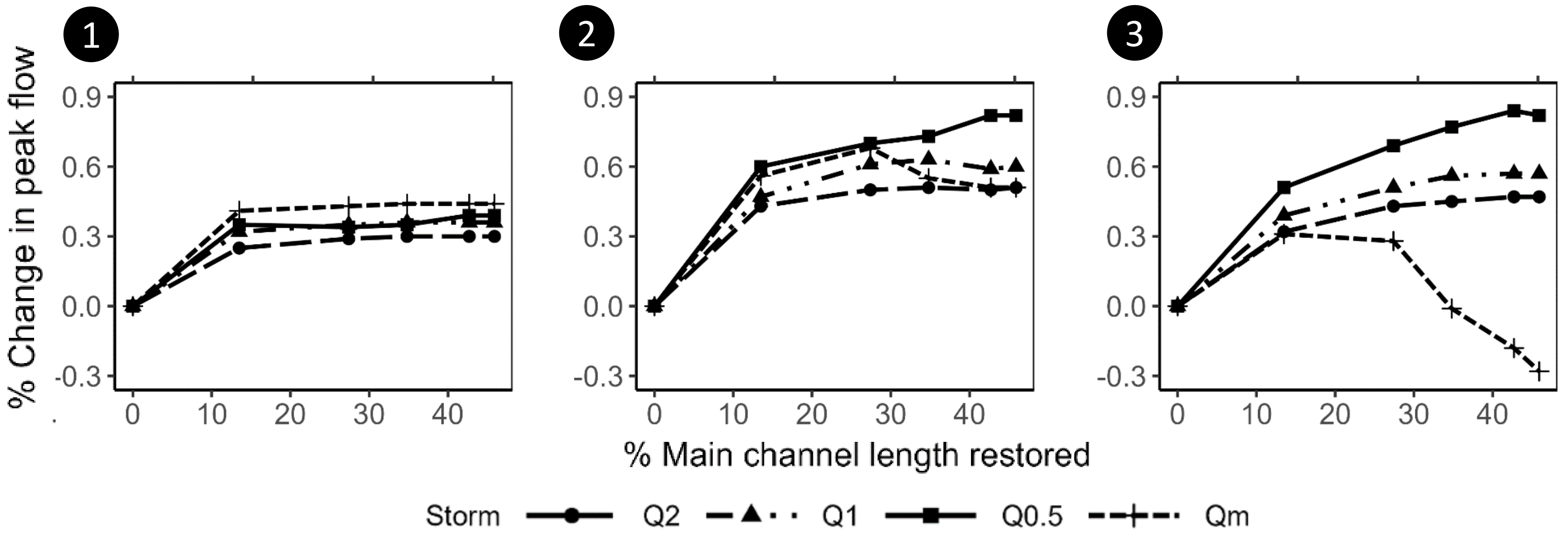
Gwynns Falls HEC-RAS Model - Flow

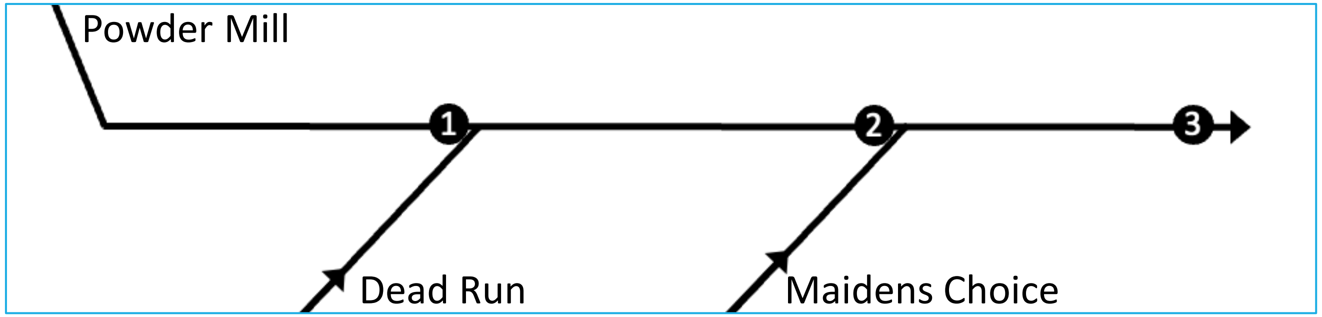
- Baseflow
  - USGS monthly baseflow for Maryland stream gages
  - Calibrated to the expected baseflow at the watershed outlet
- Stormflow
  - Synthetic hydrographs from USGS flow gages
  - Monthly [Qm], half-year [Q0.5], 1-year [Q1], and 2-year [Q2] recurrence interval storm
  - Calibrated to the synthetic hydrograph created for the gage at the outlet

Model Flow Boundary Conditions



Restoration *Increased* Peak Flow





- Restoration caused unintentional increases in peak flow

Peak Flow Asymmetry and Synchronization

- Hydrograph peak asymmetry
- Tributary synchronization