Cumulative Effects of Multiple Stream Restoration Projects on Flood Attenuation and Nitrate Removal at the Watershed Scale

ERICH HESTER, MICHAEL CALFE, CARLY FEDERMAN, LUKE GOODMAN, AND DURELLE SCOTT

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Background

Sources: Montgomery County MD, Fairfax County VA

Research Motivation


Eutrophication


Urban Flooding

Sources: Virginia Dept. of Health, Weather.gov

<u>Eutrophication and Flooding</u>

- Land use change (agriculture, urbanization), and climate change leads to
- Increased eutrophication leading to harmful algal blooms and “dead zones”
- Increased flooding

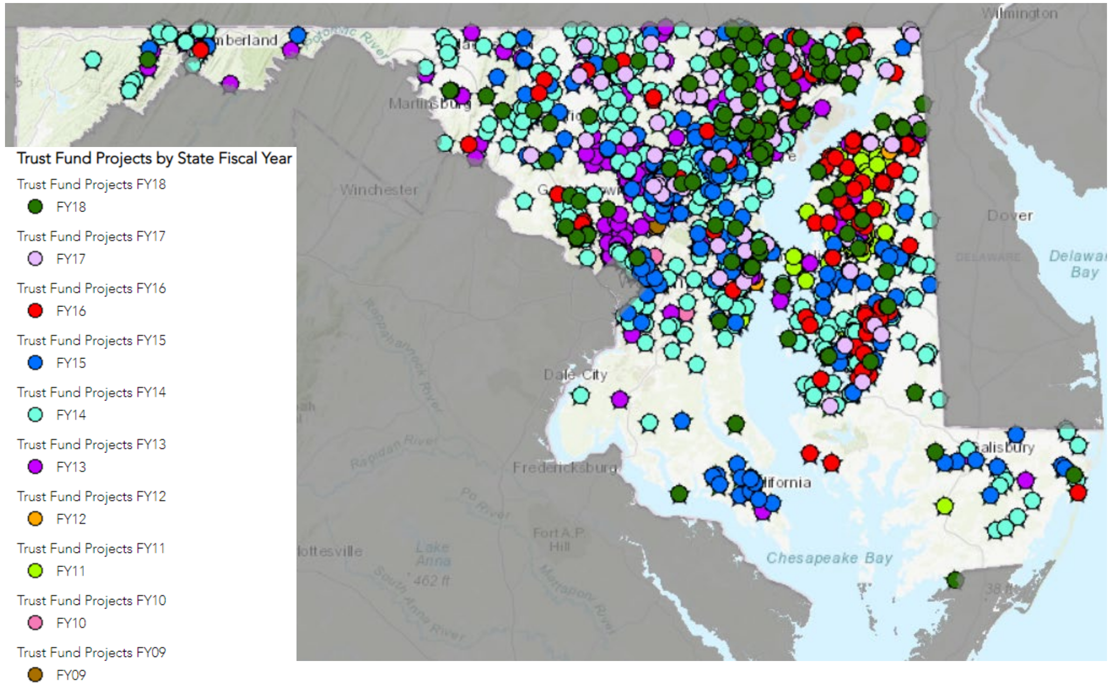
Research Motivation

Sources: USEPA, Montgomery County MD DEP, King County WA

Stream Restoration as a Solution

- Stream restoration for nitrate reduction
  - Channel restoration for hyporheic enhancement
  - Floodplain exchange enhancement (bankfull floodplain restoration, Stage 0 restoration)
- Stream restoration for flood attenuation
  - Floodplain exchange enhancement (bankfull floodplain restoration, Stage 0 restoration)
- Stage 0 implemented by raising streambed (RSB) and/or legacy sediment removal (LSR)

Research Motivation



Source: Maryland Trust Fund Restoration Mapper

State of Practice and Knowledge Gaps

- Insufficient knowledge of
  - Variation in project effects with location within watershed
  - Cumulative effects at watershed scale
  - Effect of Stage 0 restoration

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Current Modeling Projects

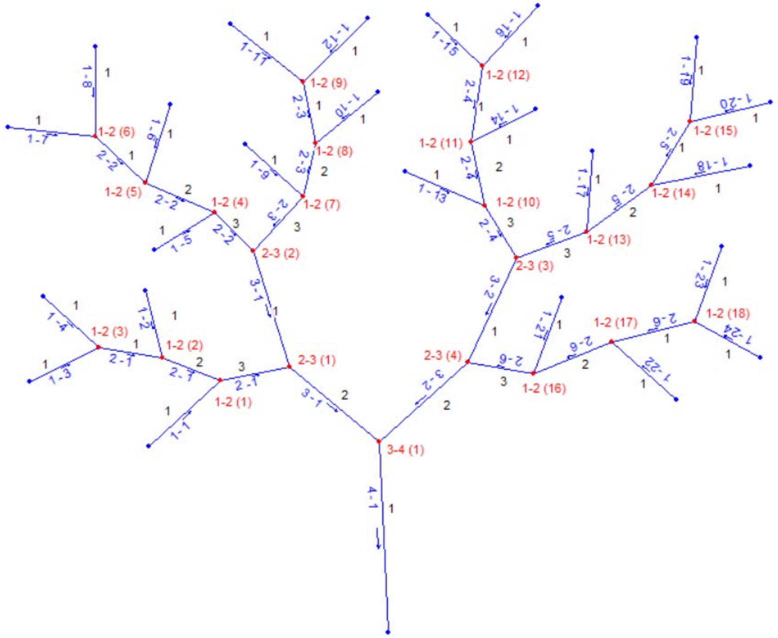
A. Effects of **channel restoration for hyporheic enhancement** on nitrate removal at watershed scale

B. Effects of **floodplain exchange enhancement** on flood attenuation at stream segment scale

Sources: USEPA, Montgomery County MD DEP, King County WA

A) Hyporheic Enhancement – Methods

Stream Order	Number of Channels	Representative drainage area (DA) [km²]	Bankfull Width (W) [m]	Bankfull Mean Depth (D) [m]	Bankfull Slope (S) [m/m]	Model Stream Length (L) [m]
1	24	1.8	3.4	0.2	0.0066	1,830
2	6	9.7	7.0	0.5	0.0043	5,030
3	2	47	13.7	0.8	0.0029	12,800
4	1	202	25.6	1.4	0.0020	30,790

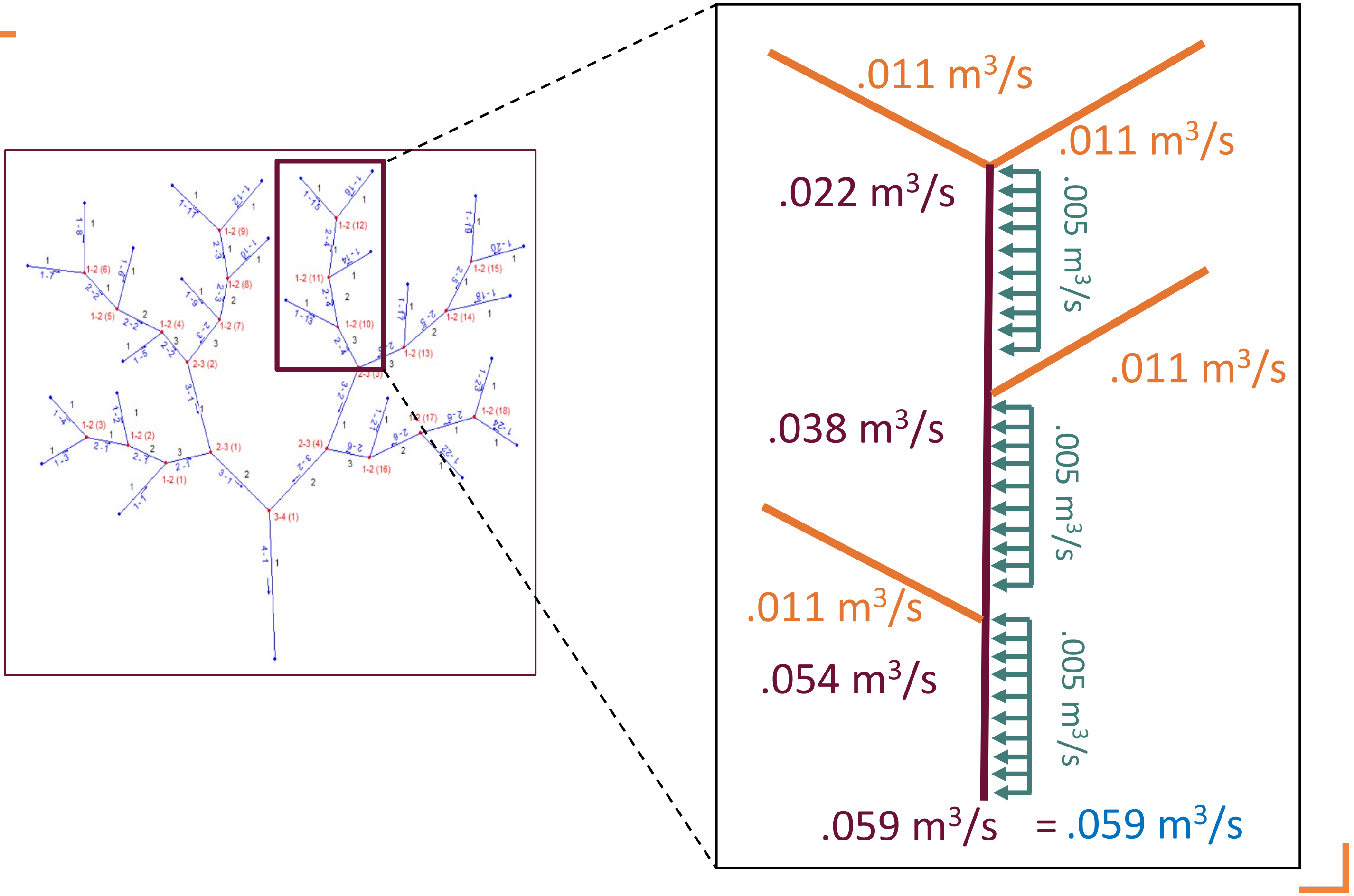


HEC-RAS Model Geometry

- Generic model for Piedmont physiographic province
- Strahler ordering
  - Bifurcation ratio
    - 4:1 1st Order to 2nd Order
    - 3:1 2nd Order to 3rd Order
    - 2:1 3rd Order to 4th Order
- Drainage basin area
  - USEPA NHD*Plus*
- Horton laws
  - Regional curves
    - W, D, S based on DA
  - Hack's law
    - L= $1.4DA^{0.6}$ (*Hack* 1957 for Piedmont Streams)

Source: Calfe, M.L., Scott, D.T., 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.

A) Hyporheic Enhancement – Methods



HEC-RAS Model Flow

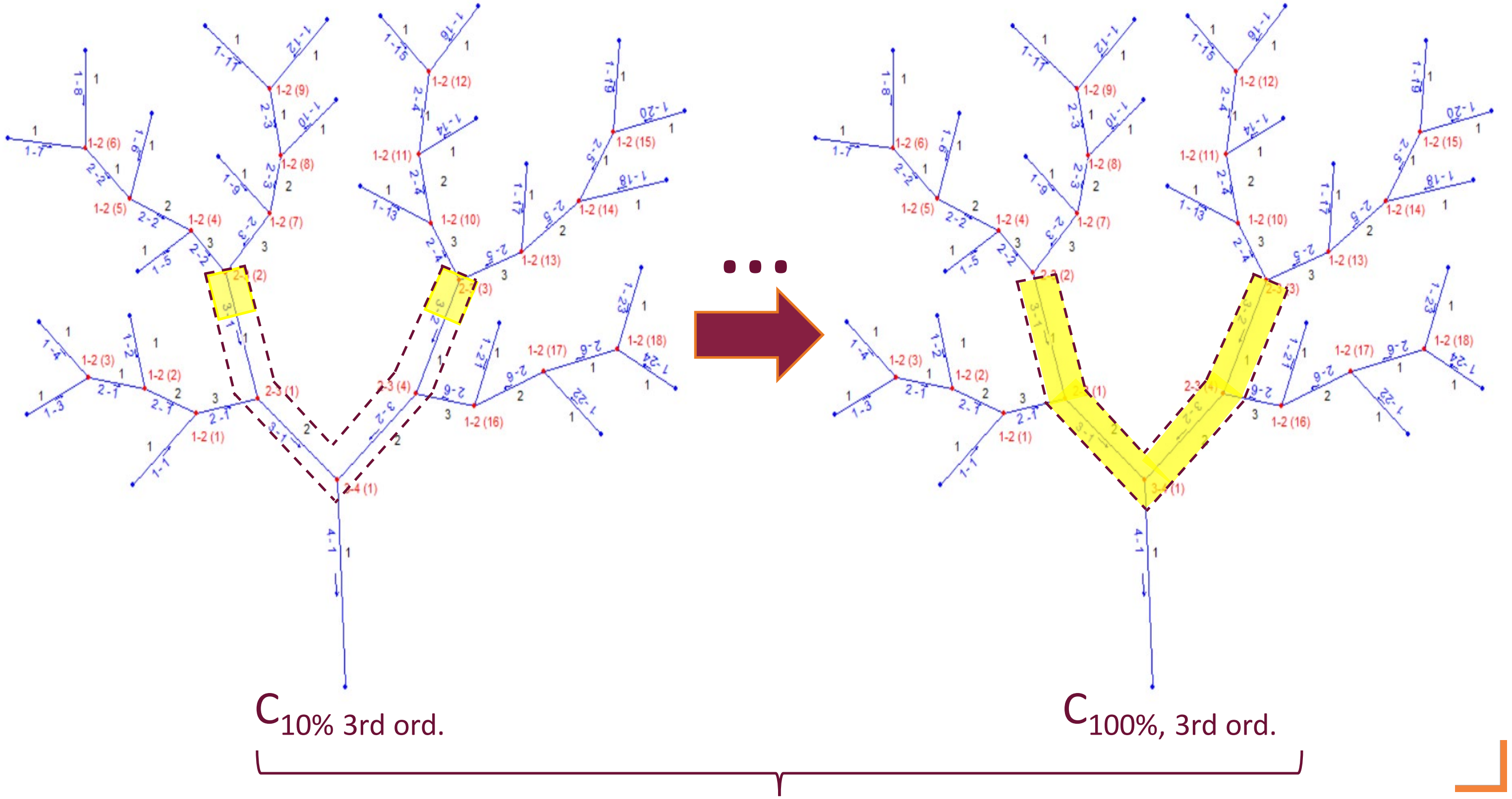
- Steady, long-term mean baseflow conditions
- Most effective flow conditions for hyporheic denitrification
- All reaches are mildly gaining to honor regional curve flows for each stream order watershed
- Groundwater is widely polluted with 1 mg/L nitrate

Source: Calfe, M.L., Scott, D.T., 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.

A) Hyporheic Enhancement – Methods

10% of total 3rd order reach length restored.

100% of total 3rd order reach length restored.



Determine percent reduction at different outlet locations

Experimental Design

Restoration scenarios:

1. Restore individual order channels in increments of 10% starting at the top of each reach and working down
2. Restore entire watershed

Determine nitrate load reductions at:

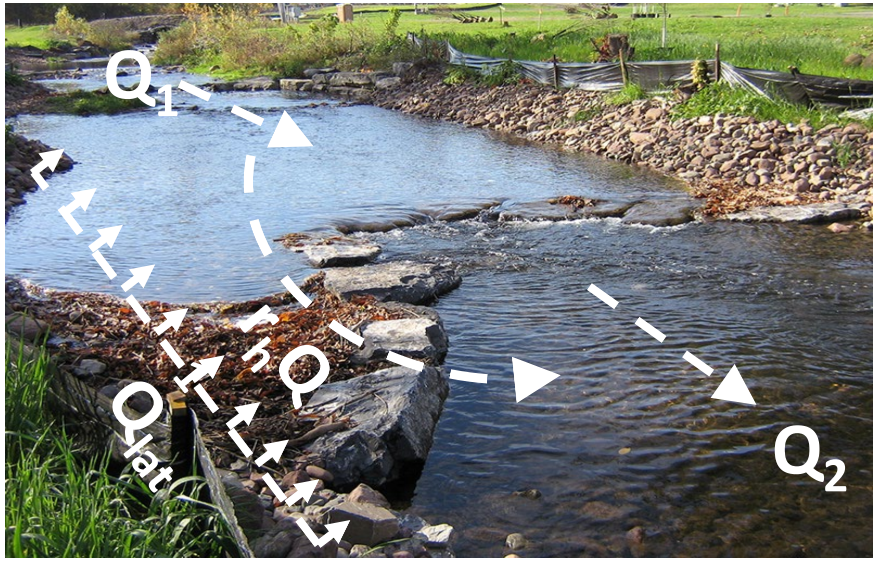
1. Individual stream order outlet(s)
2. 4th-order watershed outlet

Source: Calfe, M.L., Scott, D.T., 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.

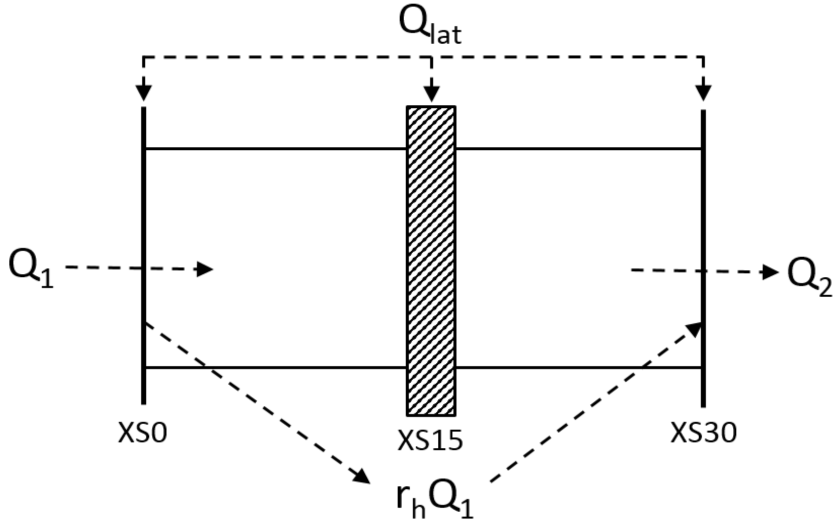
A) Hyporheic Enhancement – Methods

HEC-RAS + R Script to Simulate Hyporheic Exchange and Nitrate Removal

Conceptual model of hyporheic flow around a cross vane in nature (also represents meanders, gravel bars, pool-riffles, etc.)



HEC-RAS/R-Script computational model of hyporheic flow around a cross vane



Source: Calfe, Scott, and Hester. *Ecological Engineering*. 2022.

Q_1 = Upstream discharge Q_2 = Downstream discharge Q_{lat} = GW upwelling along reach

r_h = Percentage of surface water flowing through structure-induced hyporheic zone (0.3%, 0.03%)

- Sediment was sand/gravel with some or considerable fines [*Azinheira et al.* 2014; *Wondzell and Swanson* 1996; *Gordon et al.* 2013]
- Supply-limited denitrification, i.e. all nitrate entering hyporheic zone is denitrified [*Hester et al.* 2016; *Herzog et al.* 2016]

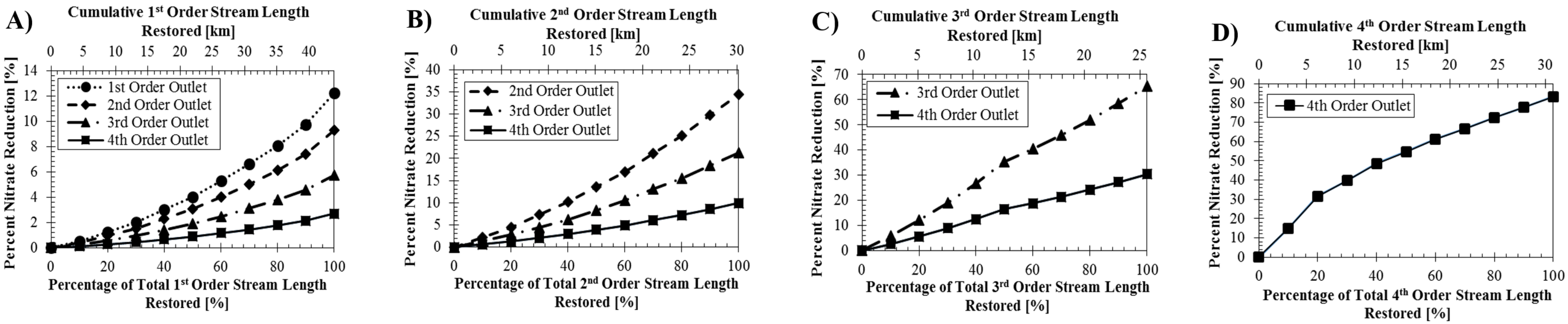
Source: Calfe, M.L., Scott, D.T., Hester, E.T., 2022. Nitrate removal by watershed-scale hyporheic stream restoration: Modeling approach to estimate effects and patterns at the stream network scale. *Ecological Engineering*, 175: 106498.

A) Hyporheic Enhancement – Results

Effect of Percent Restored on Nitrate Reduction

$r_h = 0.3\%$

1st order | 2nd order | 3rd order | 4th order



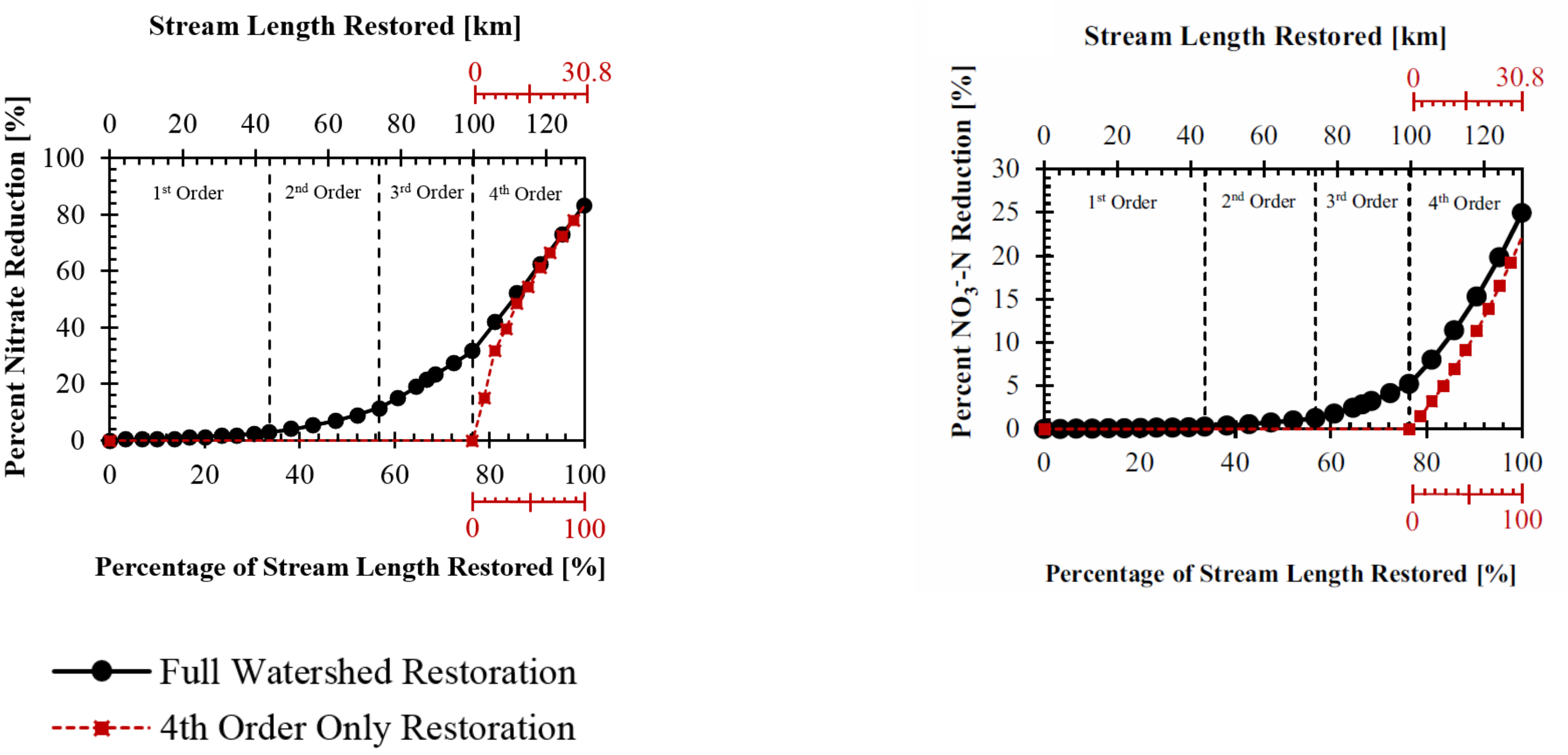
- Higher order channels more effective at removing nitrogen, both incrementally and cumulatively
- Change in concavity after instances of surface water recycling (incremental effect of individual project changes with amount already restored)

Source: Calfe, M.L., Scott, D.T., 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.

A) Hyporheic Enhancement – Results

Effect of Percent Restored on Nitrate Reduction

$r_h = 0.3\%$ $r_h = 0.03\%$

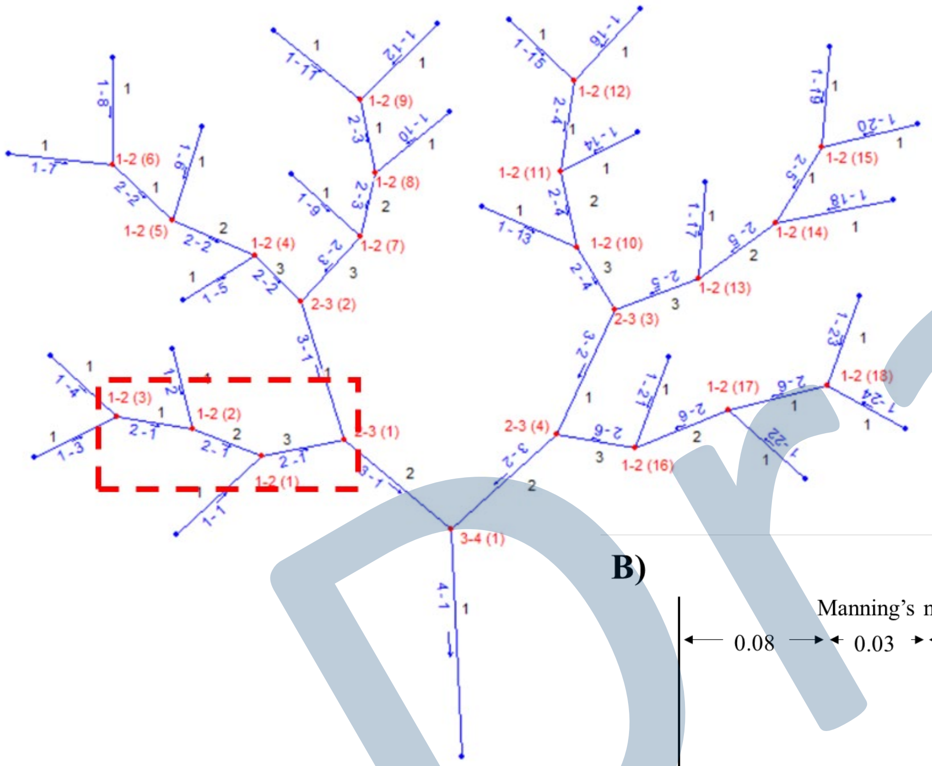


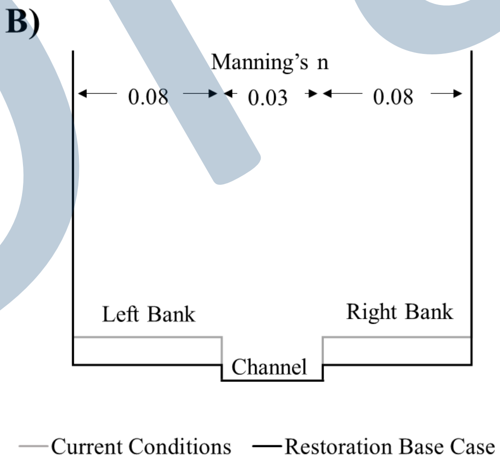
Source: Calfe, M.L., Scott, D.T., Hester, E.T., 2022. Nitrate removal by watershed-scale hyporheic stream restoration: Modeling approach to estimate effects and patterns at the stream network scale. *Ecological Engineering*, 175: 106498.

A) Hyporheic Enhancement – Conclusions

- Location in watershed affects both incremental and cumulative nitrate load reduction from restoration projects (more effective in larger streams)
- Length of channel already restored affects incremental nitrate load reduction from individual projects (different effects in small vs. large streams)
- Removal potential greater in larger streams, but larger streams have less removal rate data and harder to do restoration
- Results emphasize the importance of watershed-scale planning in stream restoration

B) Floodplain Exchange Enhancement – Methods





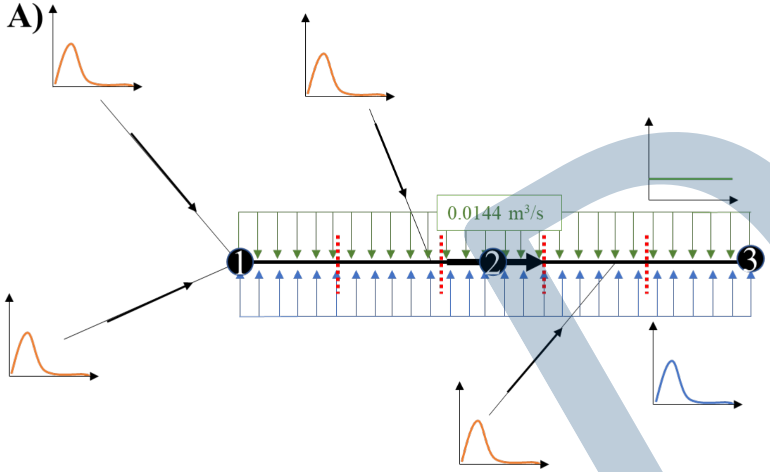
Source: Federman MS thesis, 2021

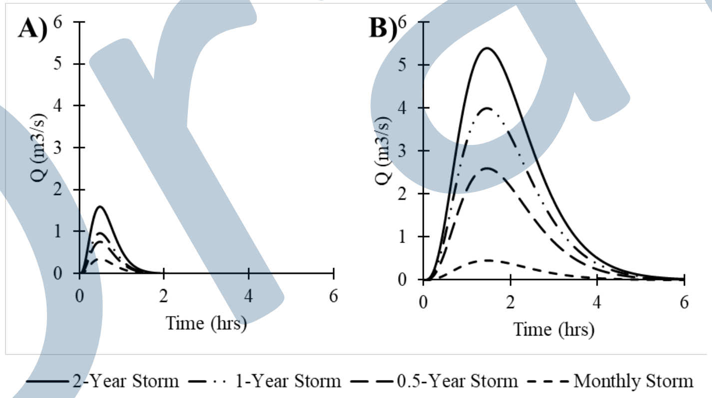
<u>HEC-RAS Model Geometry</u>

- Modified subset of earlier model as starting point
- Single representative 2nd-order channel
- Simplified floodplain on both banks
- Just hydraulics for now
- Output
  - Flood attenuation (reduced peak flow)
  - Floodplain exchange (relates to N removal)

B) Floodplain Exchange Enhancement – Methods

Recurrence Interval	Peak flow at the downstream end of stream (m^3/s)	
	1st-order	2nd-order
2-year storm	1.60	5.38
1-year storm	0.95	3.99
0.5-year storm	0.76	2.59
Monthly storm	0.34	0.45





Source: Federman MS thesis, 2021

HEC-RAS Model Flow

- Unsteady flow in 2nd order channel
- Peak flows and hydrographs from Piedmont physiographic province
- Added distributed stormflow (interflow, surface runoff, etc.) to calibrate to 2nd order hydrograph at downstream end

B) Floodplain Exchange Enhancement – Methods

Parameter	Range varied in sensitivity analysis	Increments used for sensitivity analysis	Base case restoration value
Percent of channel length restored	0% - 100%	20%	20%
Bank height	7.6 cm – 46 cm	7.6 cm	15.2 cm
Restoration location	Upstream portion (0 m – 1006 m) – Downstream portion (4025 m - 5030 m)	1006 m	Upstream portion (0 m – 1006 m)
Floodplain Manning's n	0.04 – 0.12	0.02	0.08
Floodplain width	0 m - 204.2 m	0, 10.42, 107.4, 204.2 m[1]	10.42 m

Source: Federman MS thesis, 2021

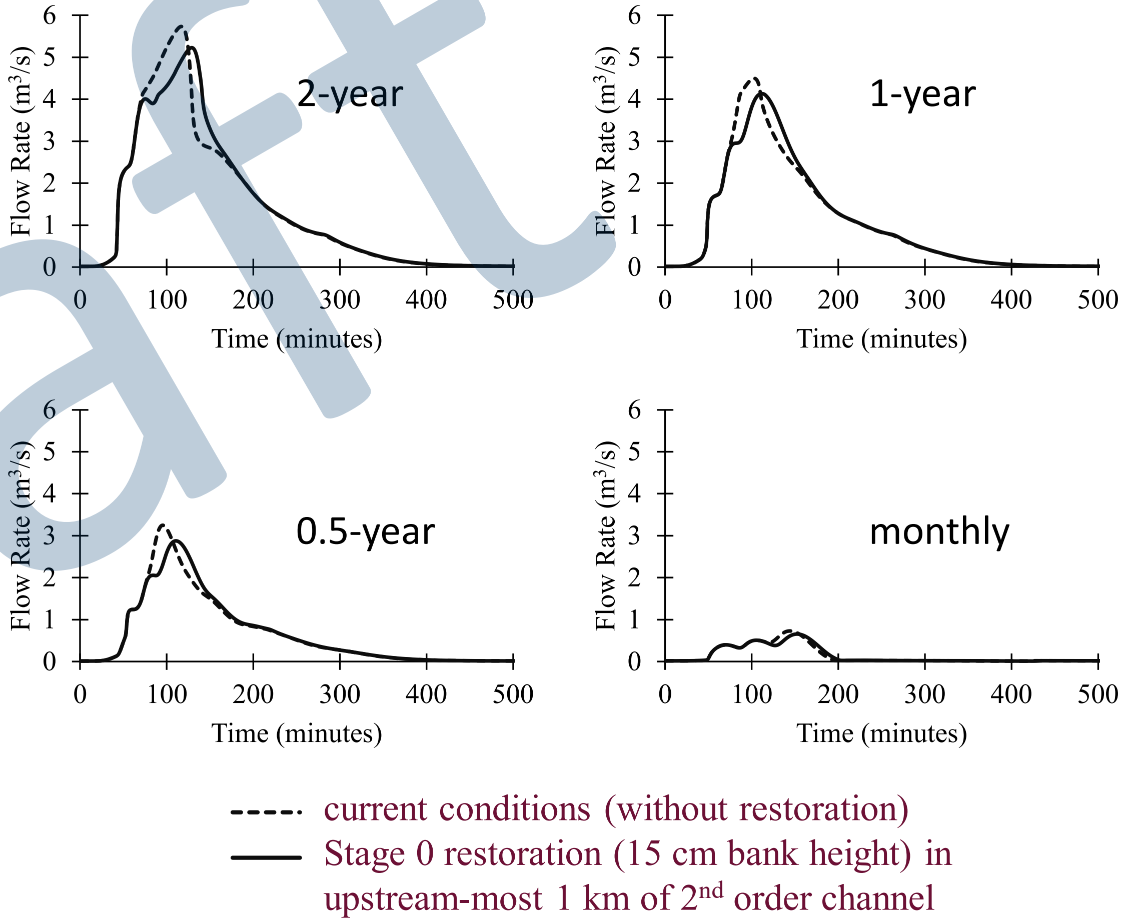
Model Sensitivity Analysis

- Varied percent channel length restored (as before)
- Varied design parameters, including bank height, restoration location, floodplain width, floodplain Manning's n
- Bank height range included Stage 0 (<15 cm) and conventional bankfull floodplain restoration (40-50 cm)

B) Floodplain Exchange Enhancement – Results

Example Output Hydrographs

- Flood attenuation = reduced peak flow rate at downstream end of 2nd order channel for restored conditions



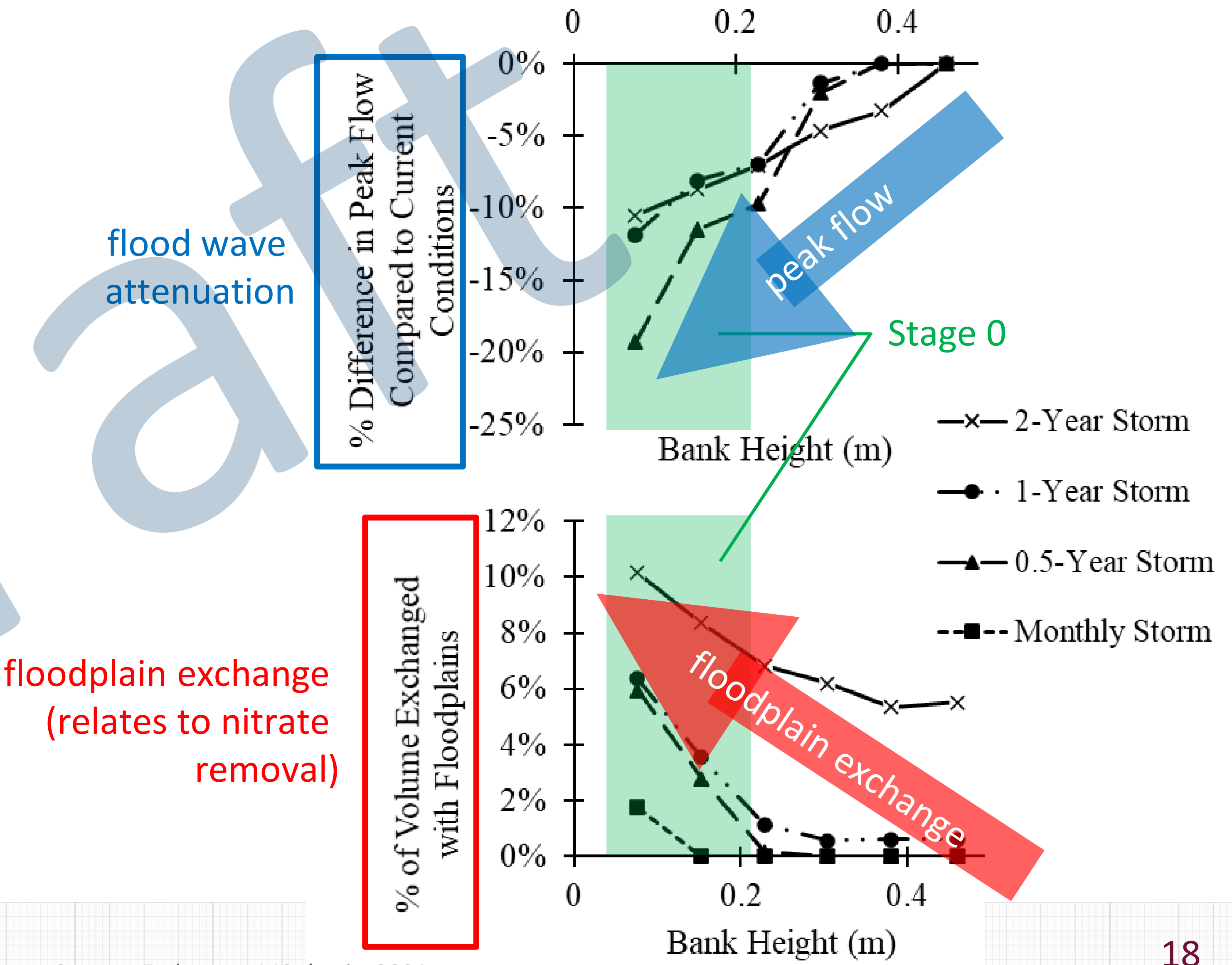
Source: Federman MS thesis, 2021

B) Floodplain Exchange Enhancement – Results

<u>Effect of Bank Height (Restoration Technique)</u>

- Stage 0 (low banks) more effective than high banks (bankfull floodplain)
- No tradeoff among restoration benefits; lower banks enhances both flood attenuation and floodplain exchange (water quality)

Stage 0 implemented by raising streambed (RSB) and/or legacy sediment removal (LSR)

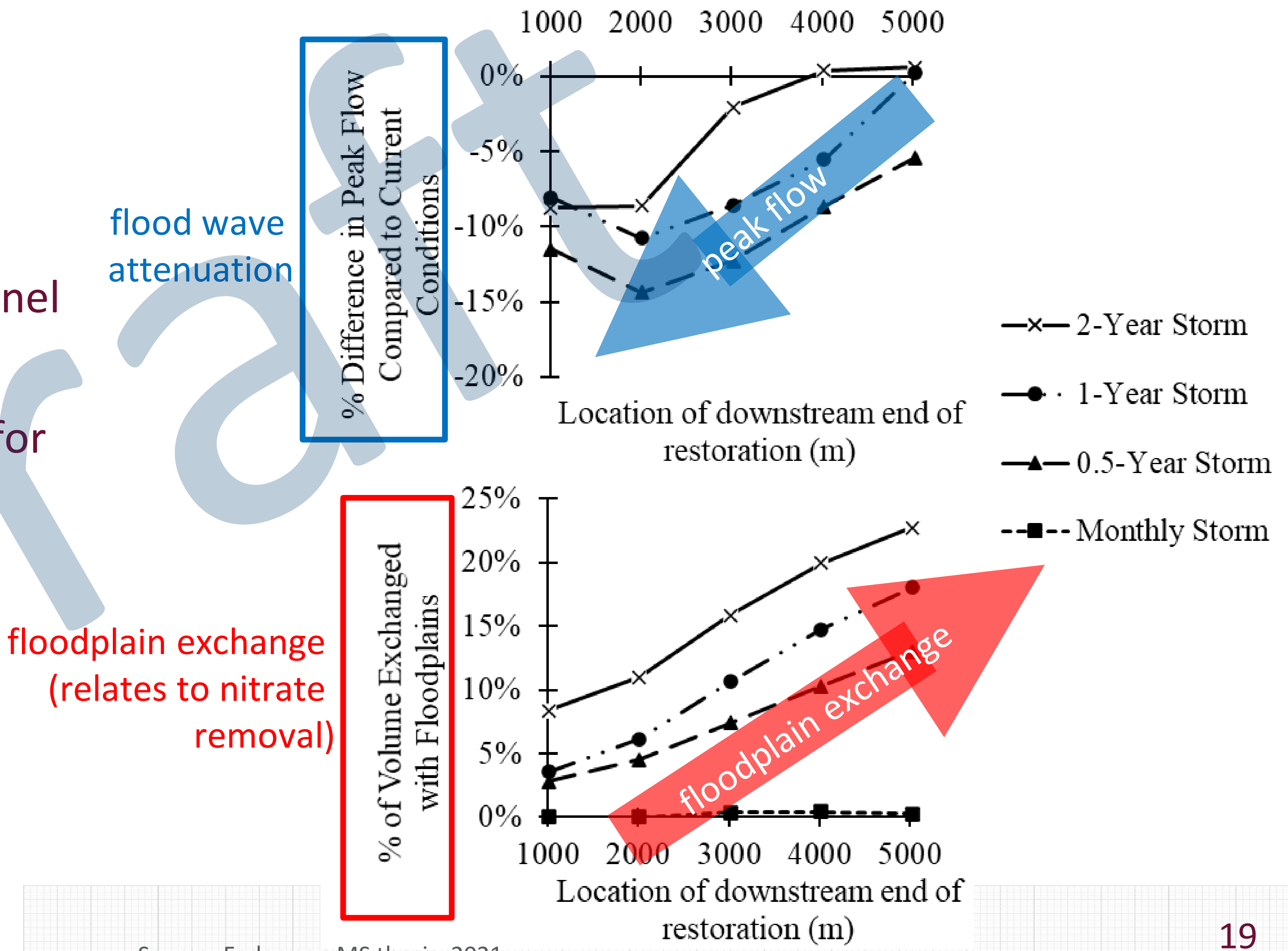


Source: Federman MS thesis, 2021

B) Floodplain Exchange Enhancement – Results

<u>Effect of Project Location</u>

- Individual projects were more effective if…
- …located upstream along channel (for flood wave attenuation)
- …downstream along channel (for floodplain exchange)
- Tradeoff between flood attenuation and floodplain exchange



Source: Federman MS thesis, 2021

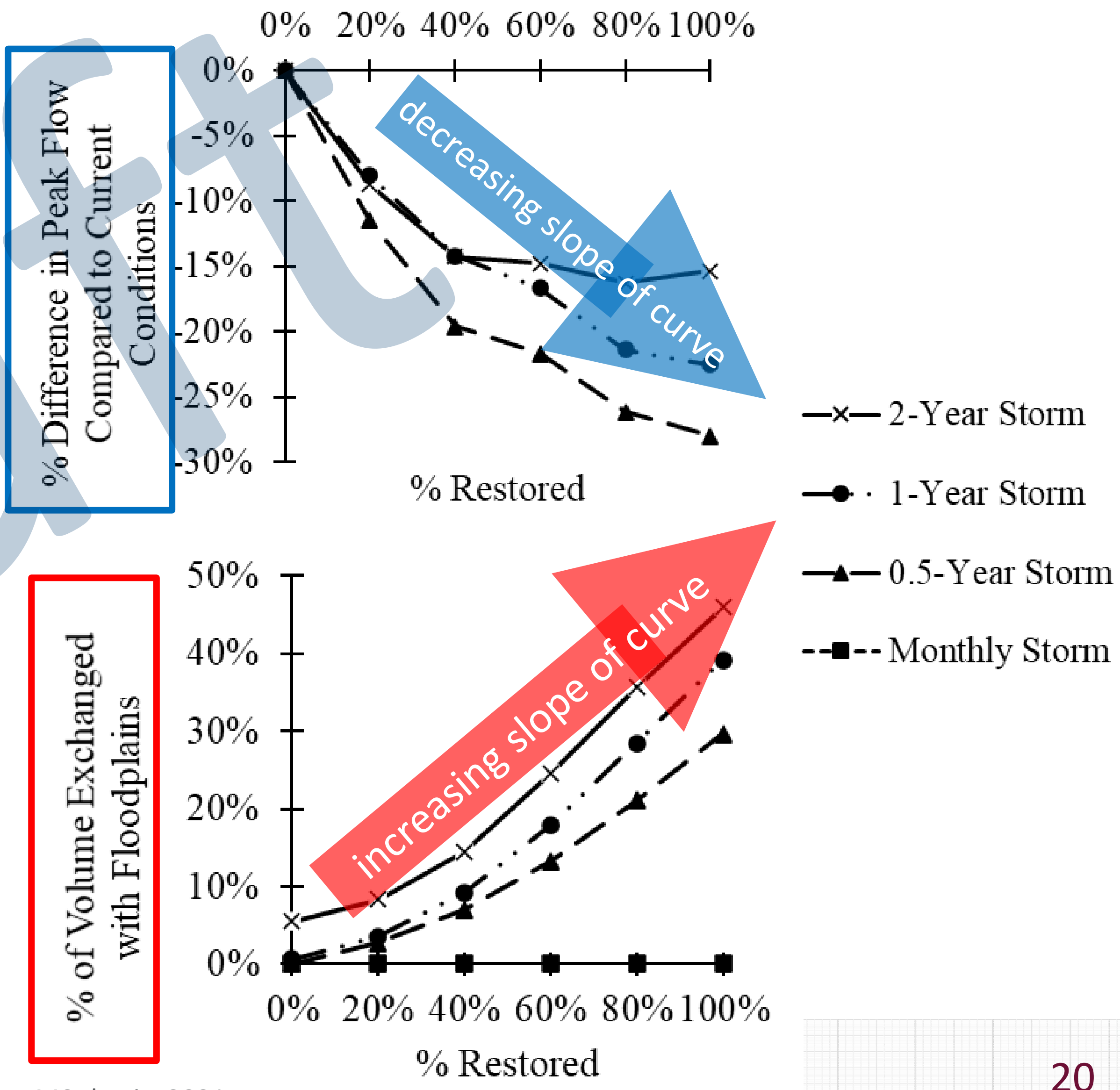
B) Floodplain Exchange Enhancement – Results

Effect of Percent Restored

- Individual projects were more effective (i.e. greater slope of curve) if…
- …less prior restoration (for flood wave attenuation)
- …more prior restoration (for floodplain exchange)
- Tradeoff between flood attenuation and floodplain exchange

flood wave attenuation

floodplain exchange (relates to nitrate removal)



Source: Federman MS thesis, 2021

3) Floodplain Exchange Enhancement – Conclusions

- Stage 0 restoration more effective than bankfull floodplain restoration
- Incremental flood attenuation/exchange benefits from individual projects depends on:
  - Length of channel already restored (greater effect on attenuation/exchange when less/more already restored, respectively)
  - Location of restoration along 2nd-order channel (greater effect on attenuation/exchange at upstream/downstream end, respectively)

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Next Steps

1. **Channel restoration for hyporheic enhancement:** Account for spatial variation of exchange, temporal variation of groundwater gaining

2. **Floodplain exchange enhancement:** Scale up to 4^{th}-order watershed, add nitrate transport and removal component

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Credits

- Funders: MD DNR, NFWF through US EPA Chesapeake Bay Program Office, Chesapeake Bay Trust, Charles E. Via Jr. Foundation at Virginia Tech
- Data: Natalie Kruse Daniels
- Guidance: Andy Miller, Art Parola, Bill Stack, Dave Goerman, David Wood, Drew Altland, Elizabeth Zinecker, Erik Michelsen, Jeff Hartranft, Jeremy Hanson, Joe Berg, Joe Sweeney, Josh Running, Ken Belt, Lisa Fraley-McNeal, Neely Law, Paul Mayer, Rich Starr, Roderick Lammers, Sean Crawford, Shannon McKenrick, Solange Filoso, Sujay Kaushal, Tammy Newcomer-Johnson, Tom Jordan

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