Comparing Reach Scale Nitrate Removal of Instream Restoration Techniques

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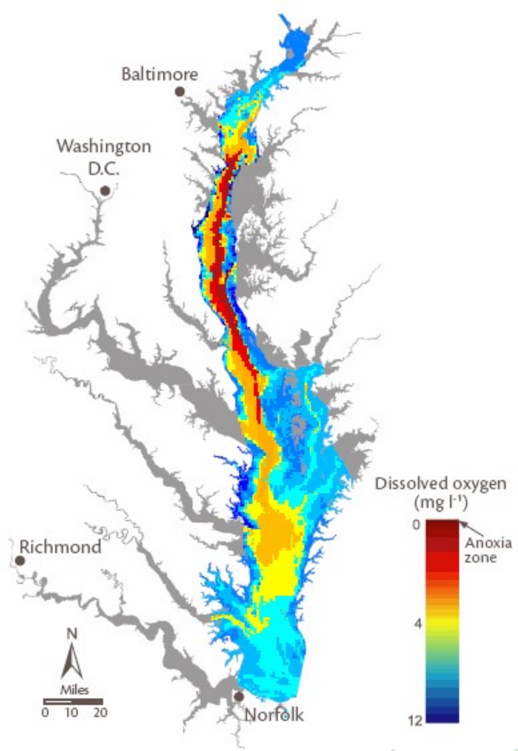
Outline

- Background
- Methods
- Results
- Conclusions and Application
- Credits

Background

Stream Restoration and Water Quality

- Growing interest in stream restoration for water quality
- Chesapeake Bay Program (CBP) protocols give nitrogen credit for specific restoration practices
  - Chesapeake Bay TMDL 2010
  - CBP Protocol 2: Removal in hyporheic zone during baseflow
- Nitrogen issues in NC rivers as well (e.g., Neuse River TMDL)

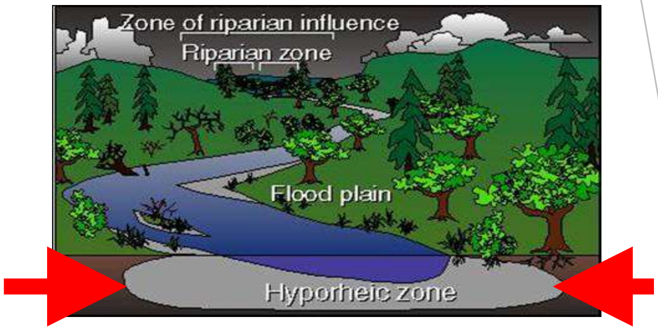


"red is dead"

cbf.typepad.com

Hyporheic exchange and denitrification

- Hyporheic exchange is where water leaves channels, enters sediment, and returns to channel in short distance
- Once channel water is in the sediment, nitrate can be removed by denitrification (anoxic conditions)
- CBP Protocol 2: Credit for nitrate removal within hyporheic zone (hyporheic box) during baseflow



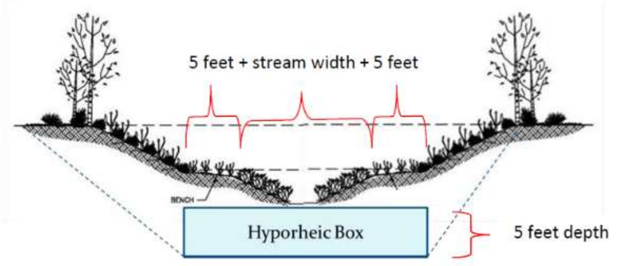


Figure 3 of Berg et al. 2014

Berg, J., J. Burch, D. Cappuccitti, S. Filoso, L. Fraley-McNeal, D. Goerman, N. Hardman, S. Kaushal, D. Medina, and M. Meyers (2014). Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects. Chesapeake Bay Program.

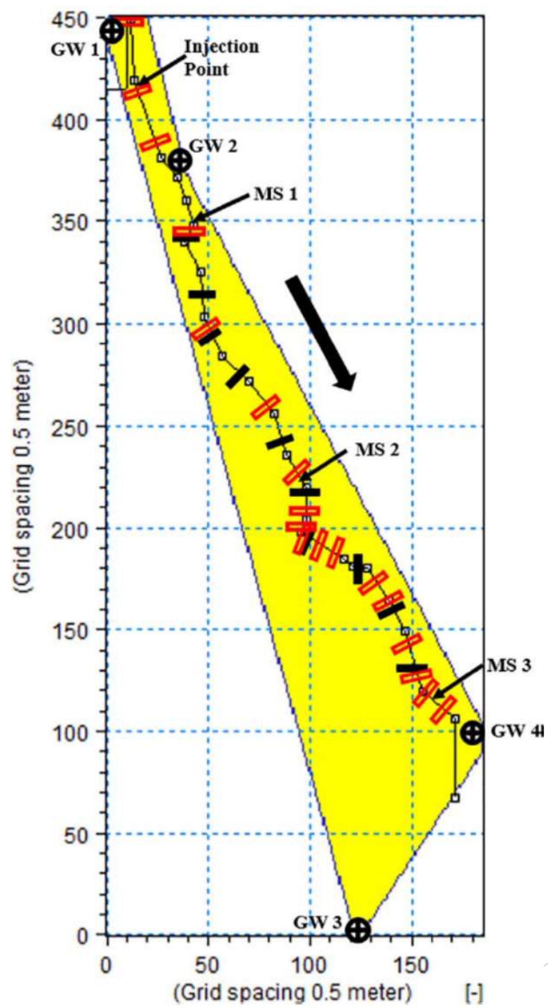
Knowledge Gaps (Nitrate)

- Do not know relative efficacy of different types of in-stream structures
  - Log dams, boulder weirs
  - Buried structures
- More importantly, do not know how efficacy varies in time and space:
  - Channel discharge (season)
  - Sediment characteristics (watershed location)
  - Groundwater heads (season, watershed location)
- CBP Protocol #2 is important advance, but need to understand how efficacy varies in time and space

Methods

Software and model domain

- MIKE SHE (Danish Hydraulic Institute) software
- 3D groundwater flow, 2D overland flow, solute transport and reaction
- 200 m stream reach in Jefferson National Forest, SW Virginia
- 18 surveyed cross sections
- 10 in-stream structures
- Gaining at very upstream end, neutral in upper middle, losing for at least downstream half (set as basecase in sensitivity analysis)
- Computation grid: 0.5 by 0.5 m horizontally
- Saturated zone is divided into 25 computational layers



In-stream structures: fully spanning weirs

Natural

Engineered
(Stream Restoration)

source: NRCS Stream Restoration Design Handbook

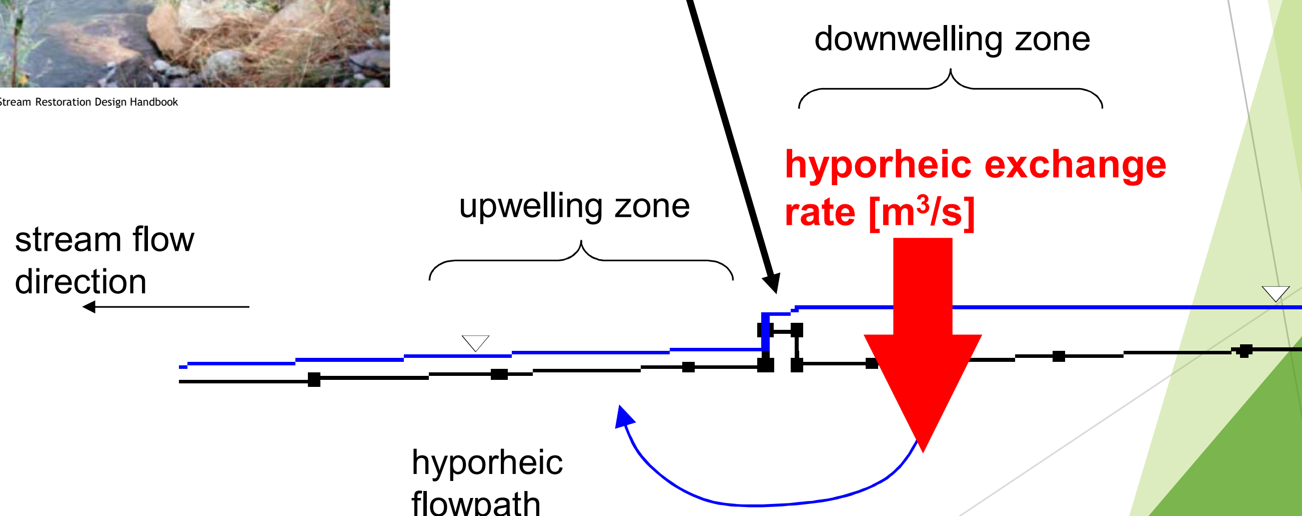
e.g., log dam, debris dam, large wood, boulder weir, cross vane, upstream V

Weirs induce hyporheic exchange

(circumneutral case)

NRCS Stream Restoration Design Handbook

weir



In-stream structures: buried structures

- Most in-stream structures are in the channel
- New idea: buried structures, beneath the channel
- Also induce hyporheic exchange
- Advantages: less erosion/scour, less maintenance
- Areas of different sediment hydraulic conductivity (K) in streambed induces exchange

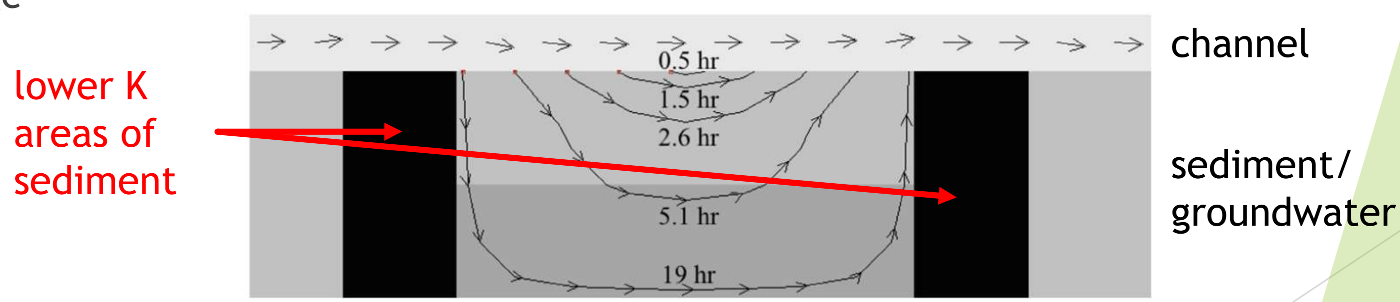


Fig. 4. Example flow paths and RTs within BEST at 1% slope and $K = 5.8 \times 10^{-3}\ ms^{-1}$

Herzog, S. P., C. P. Higgins, and J. E. McCray. 2016. Engineered Streambeds for Induced Hyporheic Flow: Enhanced Removal of Nutrients, Pathogens, and Metals from Urban Streams. Journal of Environmental Engineering **142**.

Field data and calibration

- Second order stream in Jefferson National Forest
- Groundwater levels, slug test data to determine hydraulic conductivity, stream flow measurements, tracer experiment data, and stream surveys
- Calibrated surface water and groundwater hydraulics and surface water transport

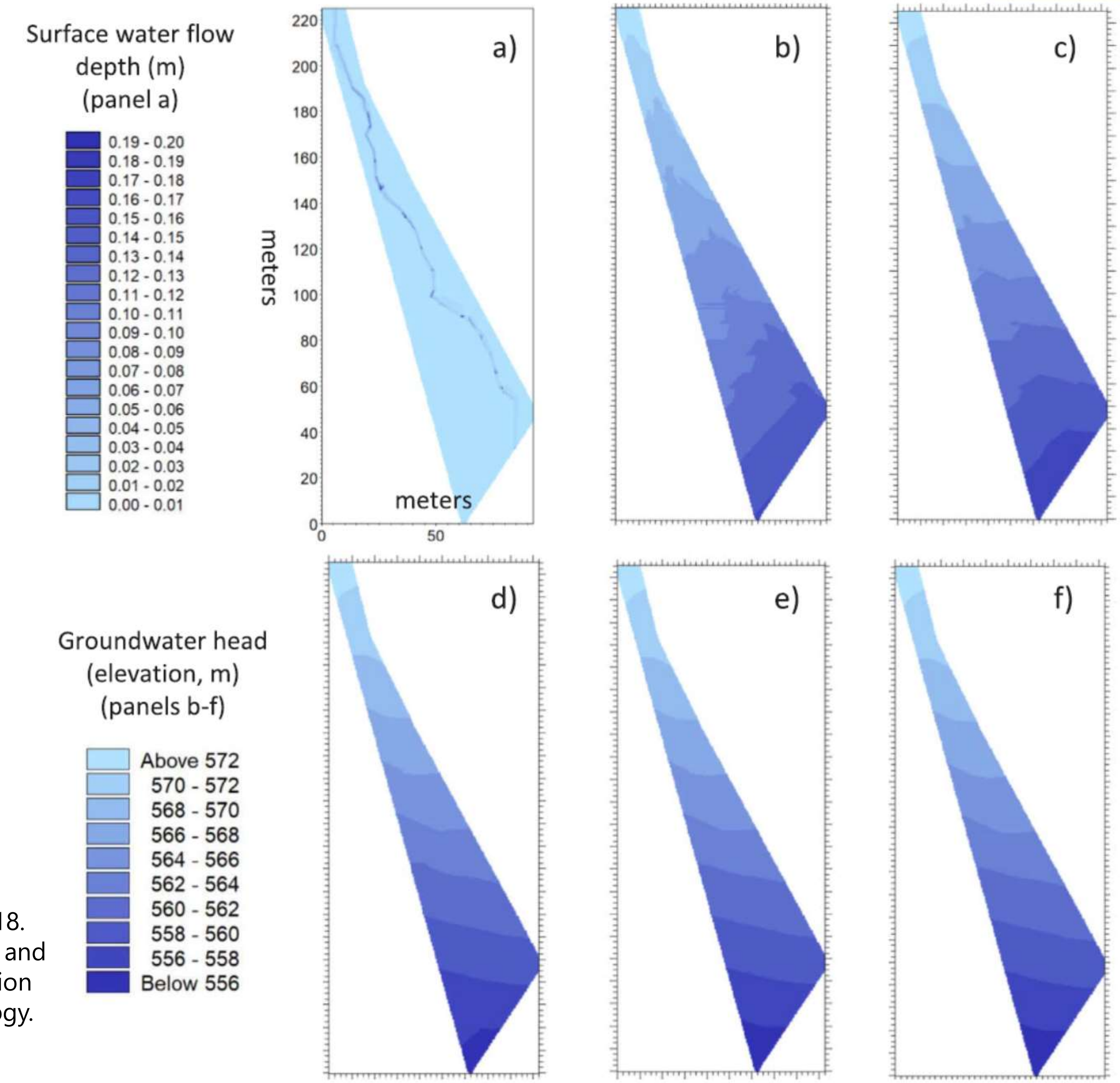
Sensitivity Analysis

Parameter	Description	Base Case	Minimum Value	Maximum Value	Groundwater Conditions
Groundwater Levels	Varied so that stream changed from overall losing to overall gaining conditions	Losing	Losing (10 L/s from stream to groundwater)	Gaining (78.3 L/s from groundwater to stream)	Varied parameter
Reaction Rate	Variation based on Hester et al (2016)	6 d^{-1}	0.6 d^{-1}	36 d^{-1}	Only run under base case (losing) conditions
Discharge	Varied to be similar to lowest, average, and highest discharges from field experiments	9 L/s	6 L/s	13 L/s	Only run under base case (losing) conditions
Hydraulic Conductivity (K)	Varied from that of fine gravel to silt	10^{-3} m/s	10^{-6} m/s	10^{-2} m/s	Run under all three conditions (losing, neutral, gaining)
Type of Structures	Fully channel-spanning weirs, partially channel-spanning weirs, and buried structures	Fully channel-spanning weirs	N/A	N/A	Run under all three conditions (losing, neutral, gaining)
Number of Structures	Number of fully channel-spanning weirs added to stream	10	0	20	Run under all three conditions (losing, neutral, gaining)

Results

Hydraulics

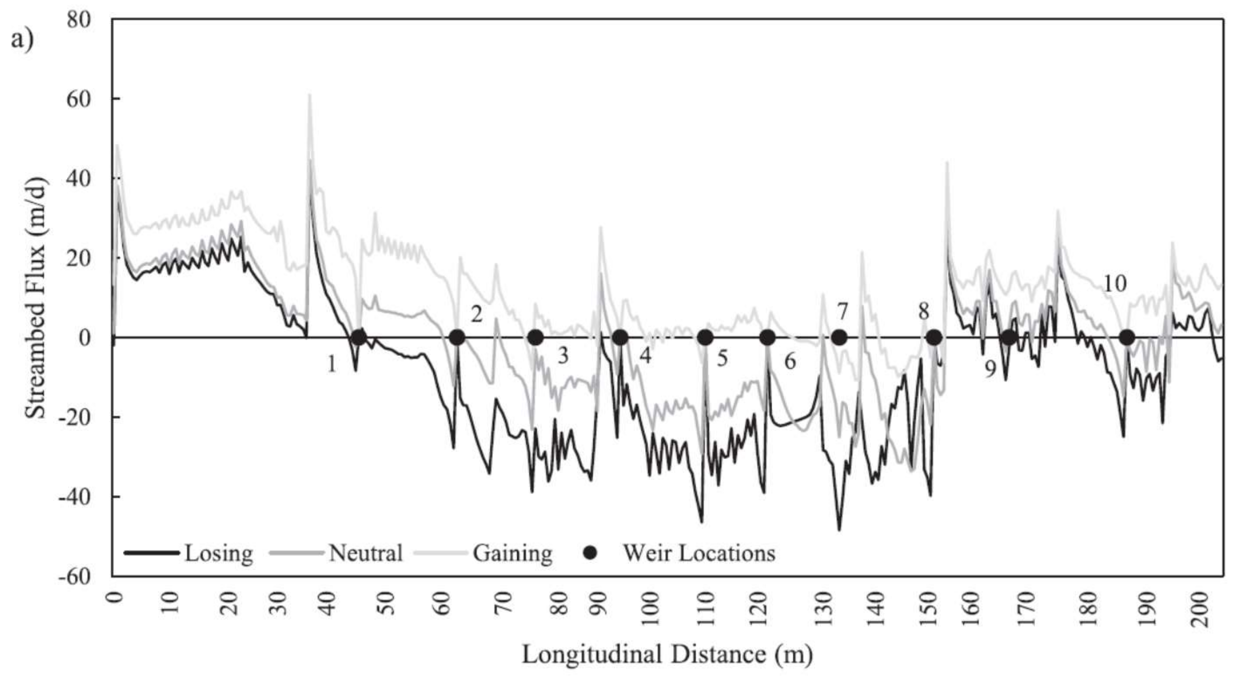
- Plan view
- Channel typically about 10 cm deep
- Groundwater generally headed downhill/ downstream



Hester, E. T., K. E. Brooks, and D. T. Scott. 2018. Comparing reach scale hyporheic exchange and denitrification induced by instream restoration structures and natural streambed morphology. *Ecological Engineering* 115:105-121.

Hydraulics

- Longitudinal profile of water exchange along the channel
- Strong effect of groundwater heads
- Gaining=high groundwater heads and vice versa
- Weirs shown as numbered dots



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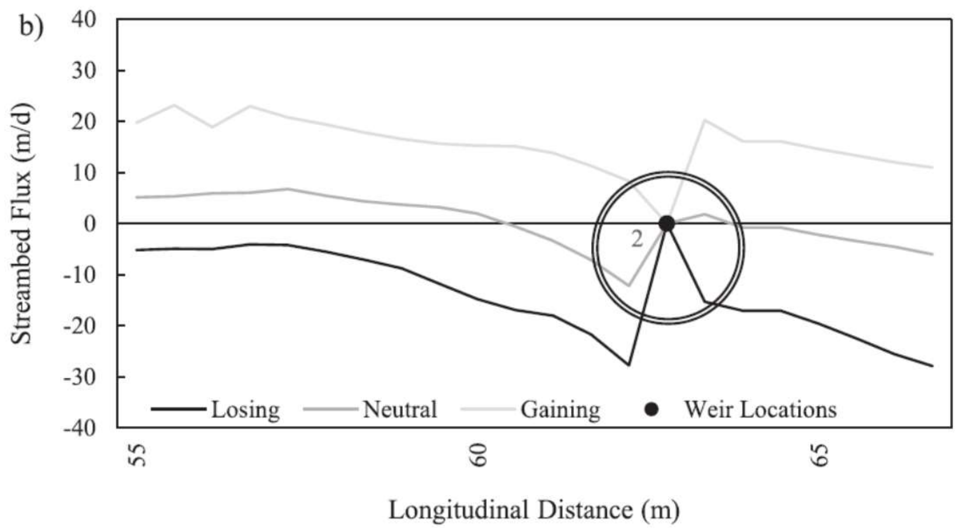
Hydraulics

- Zoom in of single weir
- Shows downwelling upstream of the structure and downwelling downstream



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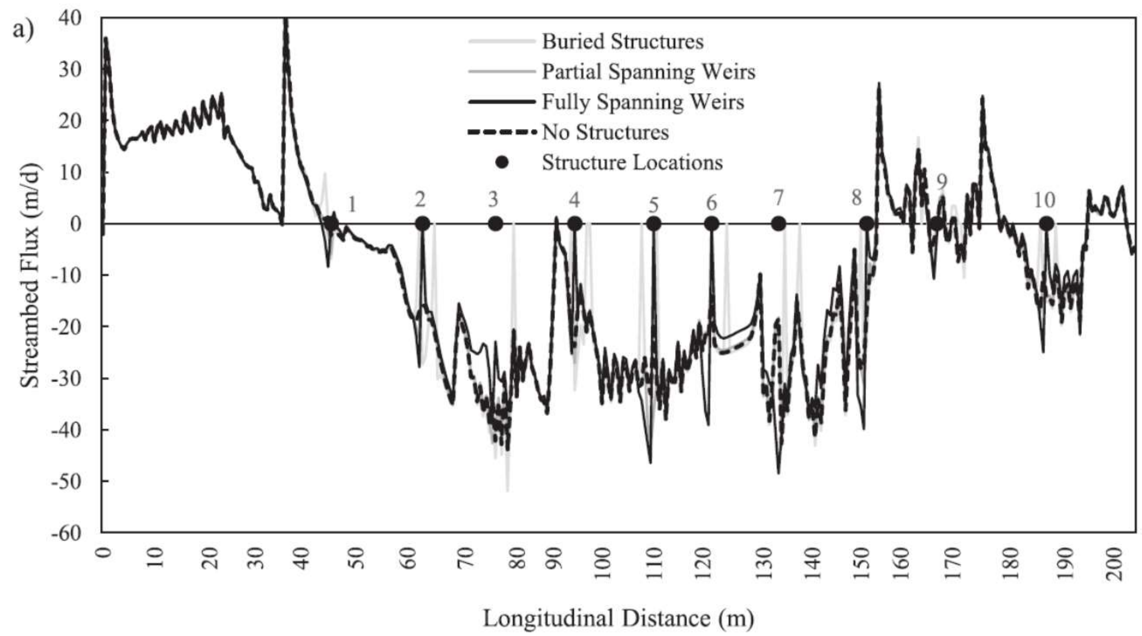
Hydraulics

- Longitudinal profile of water exchange along the channel
- Weak effect of structure types
- Weak effect of structure presence
- Weirs shown as numbered dots



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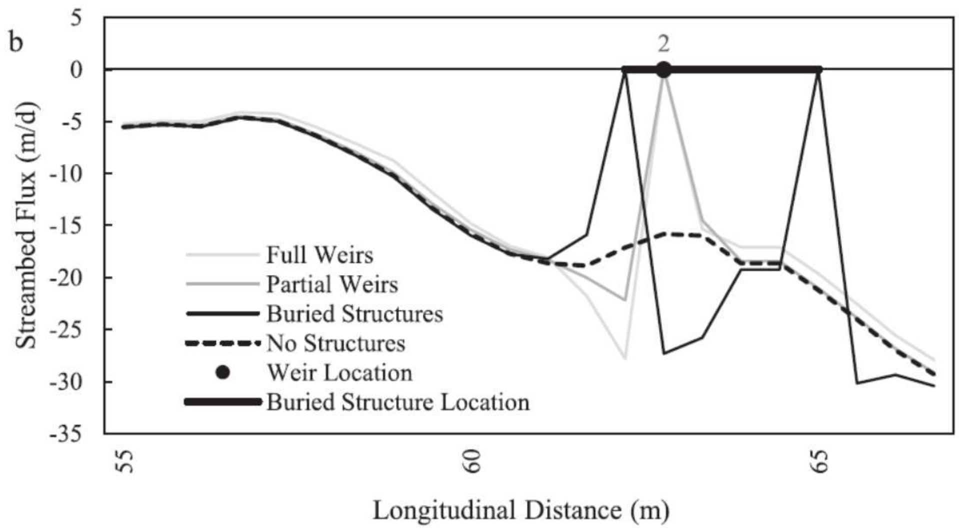
Hydraulics

- Zoom in of single structure
- Different patterns for different structure patterns, but overall net effect similar



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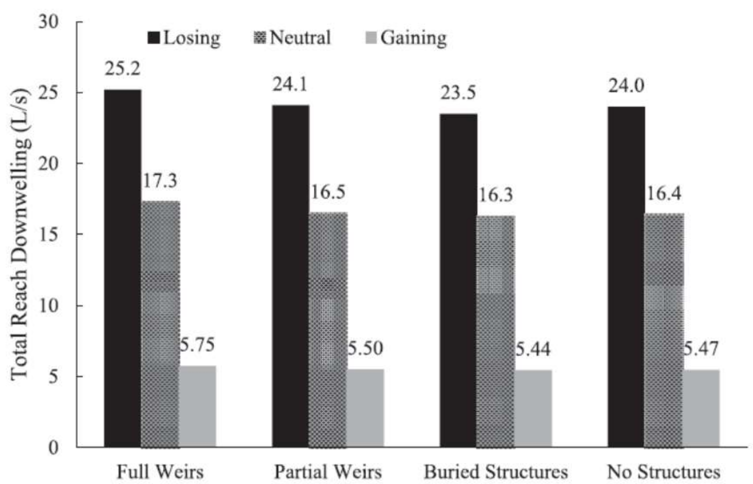
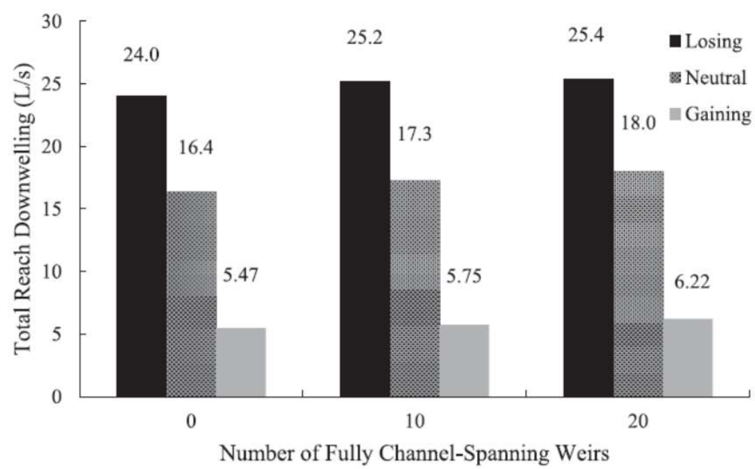
Hydraulics

- Net reach scale effect
- Little effect of structure type
- Little effect of number of structures
- Big effect of groundwater heads (gaining = high GW heads and vice versa)





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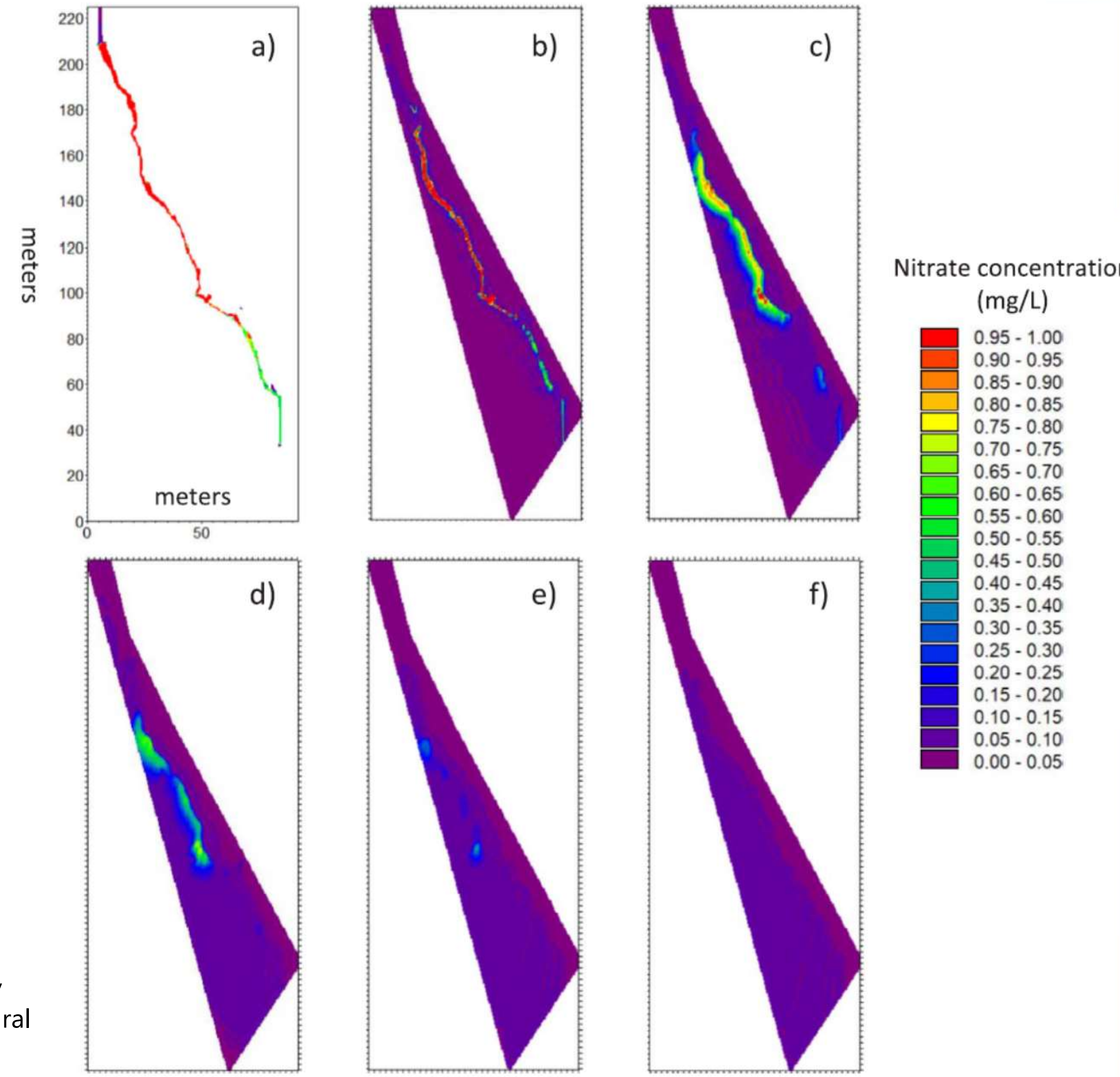
Nitrate

- Plan view
- Decreasing concentrations downstream in the channel
- Basecase (losing) conditions
- Nitrate transfer from channel to groundwater followed by denitrification



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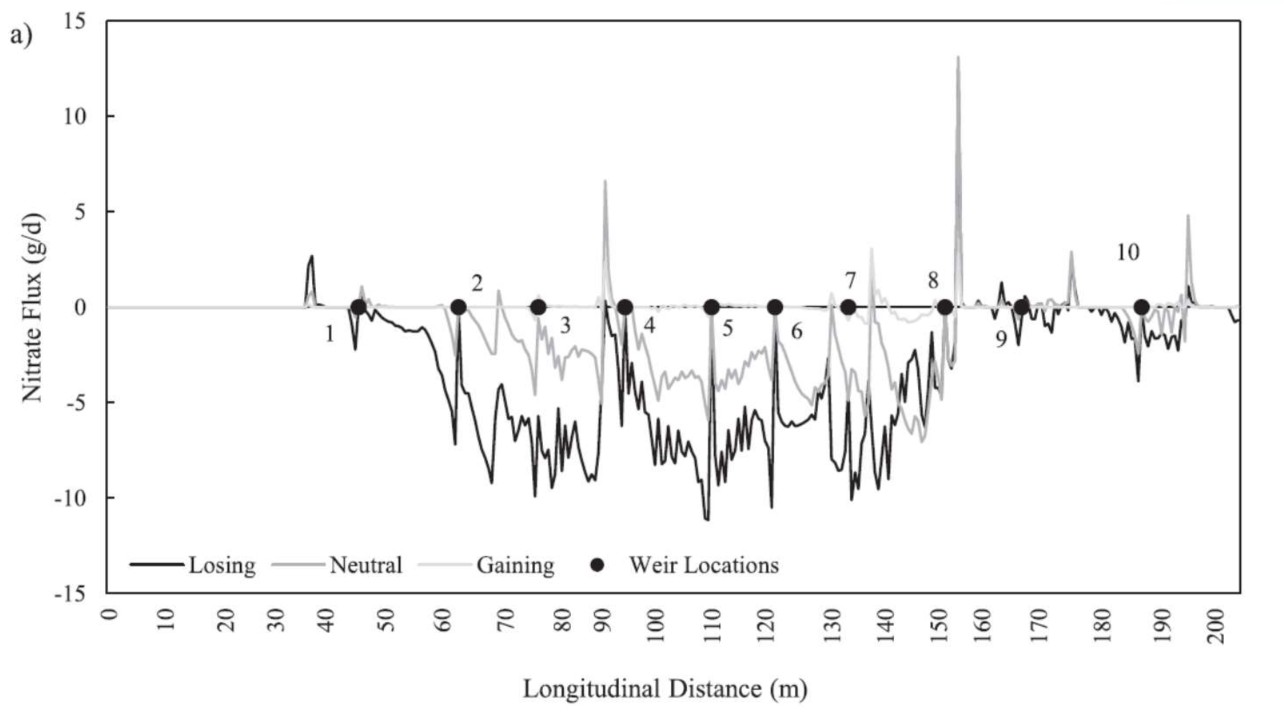
Nitrate

- Longitudinal profile of nitrate exchange along the channel
- Strong effect of groundwater heads
- Almost no exchange in gaining conditions
- Little upwelling nitrate even in gaining conditions due to loss to denitrification in groundwater



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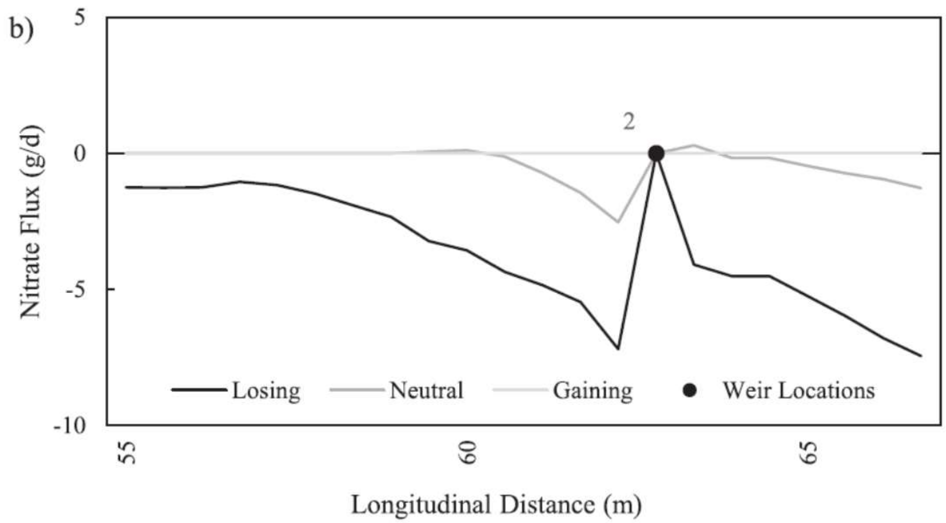
Nitrate

- Zoom in of single weir
- Gaining condition shows neither loss to groundwater or return to surface water



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- Weak effect of structure types
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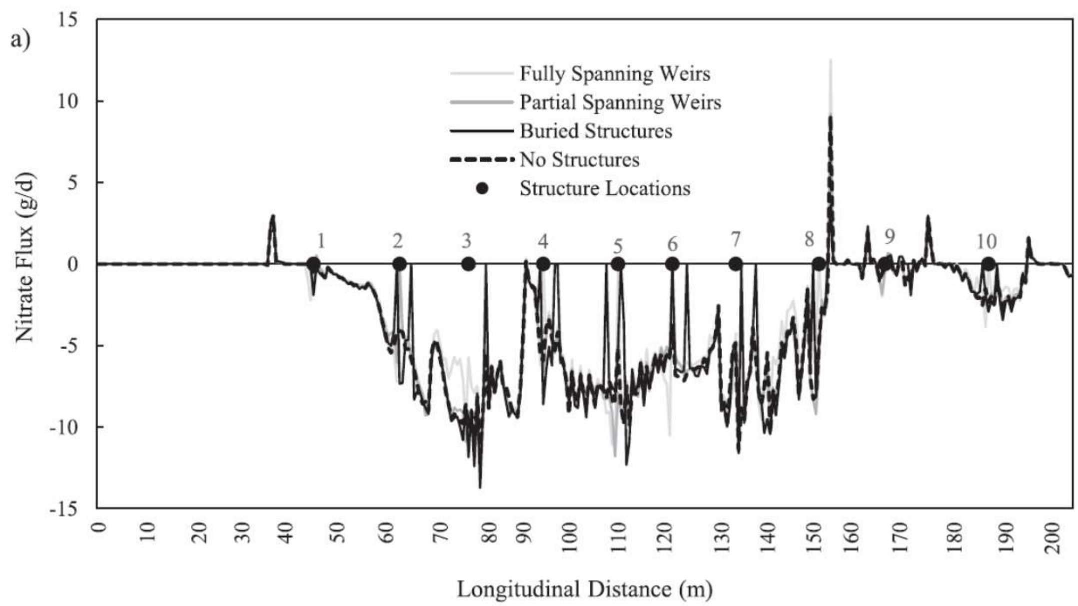
- Weirs shown as numbered dots



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Nitrate

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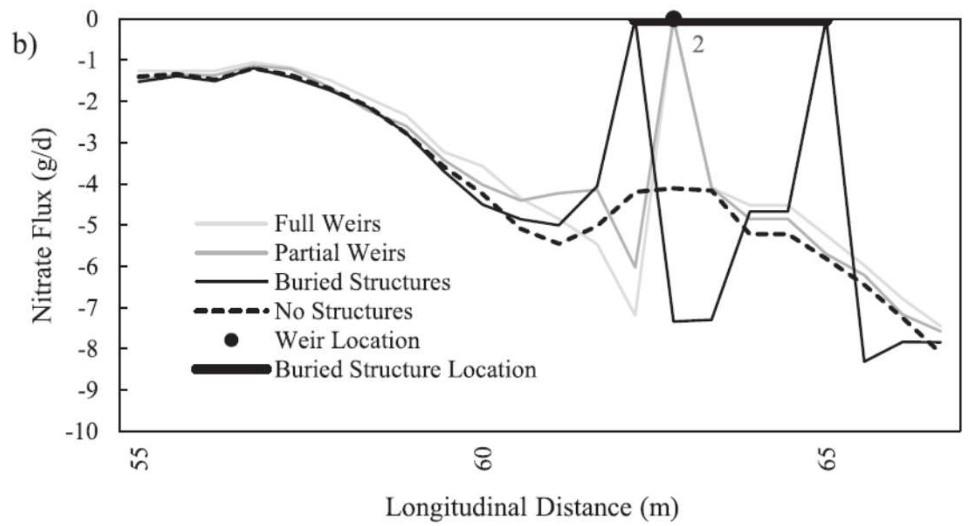

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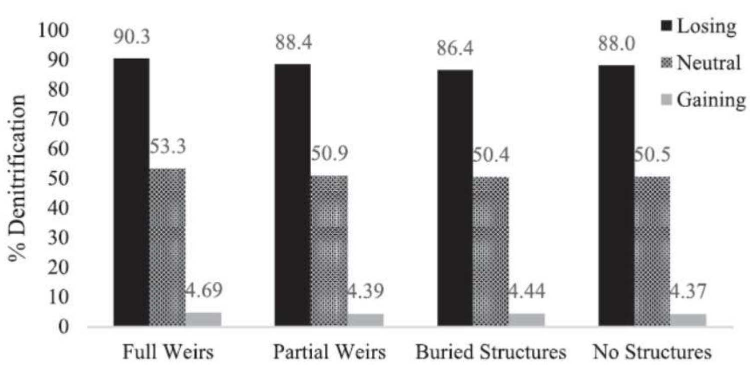
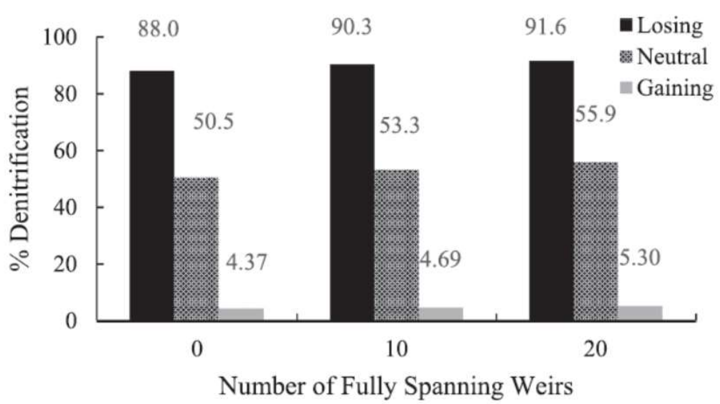
Nitrate

- Net reach scale effect, percent nitrate loss in channel
- Little effect of structure type
- Little effect of number of structures
- Big effect of groundwater heads (gaining = high GW heads and vice versa)





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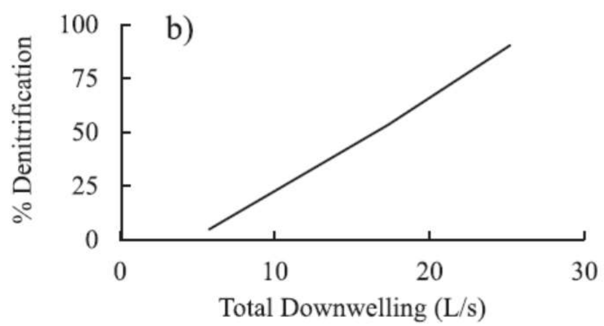
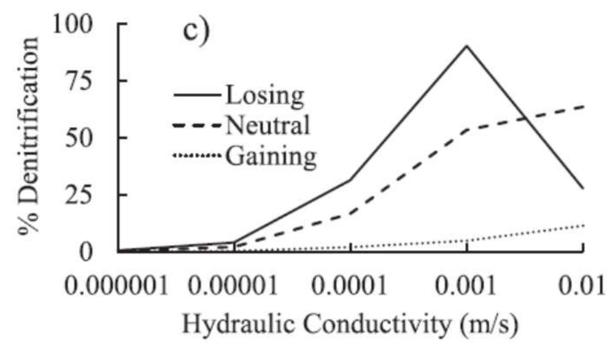
Nitrate

- Net reach scale effect, percent nitrate loss in channel
- Big effect of groundwater heads (losing = low GW heads = more downwelling, and vice versa)
- Big effect of sediment texture (hydraulic conductivity)

Groundwater Heads
(Downwelling = Losing)



Hydraulic Conductivity



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Conclusions and Application

Study conclusions

Less effect on denitrification

- In stream structure type (despite title of talk)
- Number of structures and even presence of structures

More effect on denitrification

Depend on location in watershed

Depends on time of year

- Reach characteristics
  - Groundwater levels (i.e. gaining/losing)
  - Sediment texture (hydraulic conductivity)
  - Streambed topography at larger scales than structures (reach scale)
- In other words, getting nitrate into groundwater is the key, and losing conditions and high hydraulic conductivity accomplished that

Application

- Watershed position more important than engineering design:
  - Watershed location affects groundwater levels and hydraulic conductivity
  - Human land use affects both
    - e.g., urbanization can increase or decrease groundwater levels
    - e.g., urban construction and agriculture can increase fine sediment loading
  - Climate change?
- Can we engineer these things?
  - We can engineer coarser channels (although may not last if watershed remains unchanged)
  - Can we engineer losing reaches?
    - Long pool/riffles?
- Or is it more a question of site selection?
  - But site selection is difficult (many constraints)
- Chesapeake Bay Program removal credits for enhancement of hyporheic exchange may be not be generally applicable to all sites

Credits

- Danish Hydraulic Institute
- Via Endowment in the Department of Civil and Environmental Engineering at Virginia Tech
- The National Science Foundation
- Many field helpers

Publications

Hester, E. T., K.E. Brooks, and D.T. Scott. 2018. Comparing reach scale hyporheic exchange and denitrification induced by instream restoration structures and natural streambed morphology. *Ecological Engineering* 115: 105-121.

Hester, E.T., B. Hammond, and D.T. Scott. 2016. Effects of inset floodplains and hyporheic exchange induced by in-stream structures on nitrate removal in a headwater stream. *Ecological Engineering* 97:452-464.

Jones, C.N., D.T. Scott, C.R. Guth, E.T. Hester, and W.C. Hession. 2015. Seasonal variation in floodplain biogeochemical processing in a restored headwater stream. *Environmental Science & Technology* 49:13190−13198.

Azinheira, D.L., D.T. Scott, W.C. Hession, and E.T. Hester. 2014. Comparison of effects of inset floodplains and hyporheic exchange induced by in-stream structures on solute retention. *Water Resources Research* 50(7):6168-6190.

I am happy to email copies of any of these publications (ehester@vt.edu)

Literature comparison

Table 5
Comparison of induced hyporheic flow and denitrification among different studies of instream restoration structures.

Study	Herzog et al. (2016), buried structures	Current study, buried structures	Hester et al. (2016) fully channel-spanning weirs	Current study, fully channel-spanning weirs
Induced Flows	0.023–0.151 L/s downwelling for 1 structure	0.01 L/s less downwelling per buried structure	–	0.09 L/s more downwelling per full weir
Induced Denitrification	1–2% for 1 structure	0.01% less denitrification per buried structure	1.5% per full weir	0.28% per full weir

Literature comparison

- Other studies have noted the importance of groundwater levels for hyporheic exchange (Azinheira et al, 2014; Hester and Doyle, 2008; Malzone et al, 2016; Lewandowski and Nützmann, 2010; Mayer et al, 2010); stream topography (Kasahara and Wondzell, 2003; Gooseff et al, 2006; Harvey and Bencala, 1993), and K (Azinheira et al, 2014; Hester and Doyle, 2008; Ward et al, 2011; Rahimi et al, 2015).
- Other studies have found similar effects of groundwater levels on nitrate (Rahimi et al, 2015) and K (Hester et al, 2014; Menichino and Hester, 2014; Hester et al 2016)