Final Report for

WATERSHED EFFECTS ON SUCCESS OF STREAM RESTORATION FOR EXCESS NITROGEN MITIGATION

Virginia Tech

Award #18006

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1. EXECUTIVE SUMMARY

Excess nutrients cause dead zones in estuaries, collapse of fisheries, and toxic dinoflagellate blooms. Stream restoration is a multibillion-dollar industry whose goals increasingly focus on removing excess nutrients through watershed mitigation efforts. Stream restoration can improve water quality by increasing exchange of water between channels and both hyporheic zones and floodplains, with innovative crediting protocols developed by the Chesapeake Bay Program. Yet current restoration crediting does not account for the high variability in nutrient effects among project locations.

In this study, we simulated the cumulative effect of multiple stream restoration projects on nitrate removal within a 4th-order watershed. We evaluated 1) effects of in-channel hyporheic enhancement at baseflow using a steady-state HEC-RAS model plus an R script, and 2) effects of floodplain/Stage 0 restoration during storm events using an unsteady HEC-RAS model plus other R scripts. We also evaluated the impact of floodplain/Stage 0 restoration projects on flood attenuation at the same spatial scales. Finally, we conducted a literature review and analysis of nitrate removal rates from field studies to provide nitrate removal rate input data for the floodplain/Stage 0 restoration simulations.

Our model results of in-channel hyporheic enhancement under baseflow conditions indicated that restoration could remove substantial nitrate if implemented widely throughout a channel network. By contrast, our model results of floodplain/Stage 0 restoration during storm events indicated that while Stage 0 generally had a greater nitrate removal effect than bankfull floodplain restoration, in both cases watershed nitrate removal was overall of small magnitude. Nevertheless, both types of restoration were more effective at nitrate removal when implemented in higher-order (larger, more downstream) channels than in lower-order (headwater) channels. This sets up a tradeoff, as restoration of larger order channels is more expensive and often more constrained by infrastructure. Therefore, restoration practitioners should consider restoration of larger channels before investing in small-scale projects that may have little impact at the watershed scale.

When comparing nitrate removal from in-channel hyporheic enhancement to that from floodplain/Stage 0 restoration on an annual basis, we found that hyporheic enhancement was substantially more effective. This is likely the effect of greater duration of baseflow and larger percent of surface water cycling through the hyporheic zone relative to overbank flow, but may also be affected by our floodplain simulations not directly simulating groundwater nitrate removal.

Our model results of floodplain/Stage 0 restoration during storm events indicated that such restoration practices generally provide the additional benefit of flood attenuation downstream. These practices thus have potential to mitigate increases in peak flows due to urbanization and climate change. Flood attenuation was generally greatest in the same stream order as the location of the restoration project(s), and was more minor in downstream larger order channels. This local effect was greatest in lower-order channels. In a sensitivity analysis of additional possibly controlling factors, restored floodplain width was one of the most important in controlling flood attenuation. Nevertheless, we note that restoration did increase peak flows in a minority of cases, particularly for the monthly storm. This indicates that floodplain/Stage 0 restoration can make flooding worse. This effect is likely due to peak flow synchronization, which can only be simulated using a channel network model rather than a smaller-scale stream reach or segment model.

Our results demonstrate the importance of watershed-scale simulations during design and planning to fully evaluate potential project effects. Yet we acknowledge that developing such complex models can be difficult and expensive. To address these concerns, public data can be used to reduce the model development times, for example in our case study we used HEC-RAS geometry files available from Maryland Dept of Environment. Nevertheless, not all watersheds and jurisdictions will have such data available. Among model parameters, removal rate was one of the most important in controlling the amount of removal from restoration, but the relative dearth of existing field data results in considerable scatter and an inability to assign varying removal rates for varying conditions such as steam order, flow conditions, or season. Thus there is a clear need for more systematic field measurements of nitrate removal rate in restored floodplains, particularly in higher-order channels and over seasons.

Overall, watersheds are irreducibly complex, and effects of restoration projects in that context depend on the locations of both the restoration projects and the measurements of those effects within the channel network. Thus, large-scale watershed/channel network models are necessary in the design and planning process. Yet while restoration can induce significant watershed-scale flood attenuation and nitrate removal, often the effects are fairly small for nitrate removal even with extensive restoration, and in some cases, restoration can unintentionally increase peak storm flows. It is important to manage expectations for project results with clear benefits potentially requiring extensive restoration and effects dependent on watershed parameters such as channel network position and prior restoration.

2. INTRODUCTION

2.1 Literature Context

Stream restoration is a multibillion-dollar industry (Bernhardt et al. 2005) whose goals increasingly focus on excess nutrients in inland and estuarine waters (Craig et al. 2008, Hester and Gooseff 2010, Lawrence et al. 2013, Calfe et al. 2022) through watershed mitigation efforts such as Total Maximum Daily Loads (TMDLs) and water quality trading (USEPA 2013, Water Environment Federation (WEF) 2015). Excess nutrients cause dead zones in estuaries, collapse of fisheries, and toxic dinoflagellate blooms (Alexander et al. 2000, Burkholder and Glasgow 2001, USEPA 2010). Stream restoration has potential to improve water quality by increasing exchange of water between the channel and more reactive off-channel areas, such as hyporheic zones and floodplains (Craig et al. 2008, Azinheira et al. 2014, Harvey 2016, Christopher et al. 2017). The Chesapeake Bay Program has developed innovative protocols that offer pollution mitigation credit for stream restoration practices (Berg et al. 2014, Altland et al. 2020) in response to the monumental Chesapeake Bay TMDL for nitrogen, phosphorous, and sediment (USEPA 2010).

Nevertheless, current restoration practice does not account for the high variability among project locations in terms of potential to enhance nutrient uptake. Key controlling factors may include a) where in the watershed a project is implemented (i.e. stream order) and also b) how much prior restoration has occurred (i.e. cumulative effects). In other words, incremental effects of an individual stream restoration project on nutrient uptake could vary depending on watershed context. This knowledge is critical for wisely managing scarce resources available for restoration projects, in order to ensure that projects achieve maximum possible benefit.

2.2 Key Research Questions

Our key restoration questions investigate watershed-scale controls on stream restoration effectiveness in reducing nitrate loads, including cumulative effects of multiple projects on reduction of watershed loads. We are especially interested in restoration of hyporheic and floodplain exchange, which increase contact of channel water with off-channel reactive surfaces where denitrification occurs. Our research questions for this study were:

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 watershed conditions such as
    a. Distribution of nitrate sources in the watershed (headwaters vs. along larger channels)
    b. Restoration technique, (hyporheic restoration vs. floodplain restoration)
    c. Restoration location (headwaters vs. along larger channels)
    d. Watershed topography (overall topographic relief which controls degree of gaining and hence potential for hyporheic restoration, and valley type/width of valley floors which controls room for floodplains and hence potential for floodplain restoration)
    e. Soil type (hydraulic conductivity which controls potential for hyporheic restoration)

These questions aligned with Key Restoration Question A1 and parts of A2 in the FY2020 Chesapeake Bay Trust (CBT) Restoration Research Award Program RFP.

2.3 Hypotheses

Monitoring studies alone cannot adequately determine the effect of cumulative stream restoration projects on pollutant load reductions within a watershed, while teasing out the effects of potential controls such as restoration project location. Due to the difficulty of uncontrolled factors among watersheds (i.e. data collected under varying soil type, location of nitrogen sources, hydrologic state (storm vs. baseflow), climate/season, etc.), such a study would require an almost intractable amount of data to provide sufficient statistical power to confidently determine the effects of key controls. Thus, answering the key restoration questions outlined above requires a numerical model, where parameters can be varied independently. Such models can represent a range of real watersheds by drawing on the large number of more modest monitoring studies that together provide sufficient data for parameterization.

We focused on nitrogen, because it is the primary limiting factor for eutrophication in coastal areas where dead zones are major drivers for TMDL development (Sinha et al. 2017), flushing of nitrogen to waterways is expected to increase with climate change more than phosphorous (Paerl et al. 2016, Sinha et al. 2017), and nitrogen is in excess relative to phosphorus for the Susquehanna River (ratio of TN:TP loads > 22; ratio of dissolved N: dissolved P > 80), which represents over 60% of the total N input into the Chesapeake Bay (Zhang et al. 2015). We focused on nitrate in particular, because nitrate is generally the largest fraction of in-stream nitrogen within human impacted systems (Vilmin et al. 2018), and our model was best constrained for nitrate because nitrate data are by far the most abundant. We primarily focused on nitrate removal via denitrification but also plant uptake where significant.

We focused on the relationships between percent of a stream channel network in a watershed that is restored (both hyporheic and floodplain restoration) and net watershed nitrate load reduction (primarily by denitrification). In particular, we hypothesized that:

H1. The slopes of these relationships increase with key watershed-scale controls such as width of valley floor (floodplain restoration), sediment hydraulic conductivity (hyporheic restoration); and decrease with key watershed-scale controls such as stream order.

H2. The shapes of these relationships go from levelling off to linear to exponential as the majority of watershed nitrate sources shift from headwaters to larger channels downstream in the watershed channel network. We hypothesize that this shift in shape occurs sooner for hyporheic restoration during baseflow than for floodplain restoration during storms.

2.4 Project Tasks

Our approach entailed four tasks that together answered the key restoration questions and tested the hypotheses listed above.

Task 1. Generate nitrate removal rate database. Upscaling point-scale or reach-scale data on stream restoration effects on nitrate to the watershed-scale model in later tasks required gathering nitrate concentration and reaction data and converting them into removal (denitrification + plant uptake) rates needed for modeling. We did a thorough review of peer-reviewed scientific literature, and also governmental and consulting documents to the extent feasible.

Task 2. Select model software. We used stakeholder feedback on model software selection to choose HEC-RAS and auxiliary scripts written in R.

Task 3. Use 1D flow and transport model to answer research questions listed above. We used the hydrologic and water quality capabilities of the model codes selected in Task 2, together with the removal rates developed in Task 1, to evaluate stream restoration effects on nitrate to answer questions and test hypotheses listed above. Because the models used to calculate nitrate removal by necessity include hydrologic models, and given the value of flood reduction as another applied goal of stream restoration, we also evaluated stream restoration effects on flood attenuation.

Task 4. Demonstrate value of removal rate database and modeling approach developed in Tasks 1-3 via case study. We applied our developed approach to a case study 4th order watershed in the MD portion of Chesapeake Bay watershed (Gwynn's Falls).

3. METHODS

In this section we summarize the methods used for each of the project tasks listed in Section 2.4 above. Given the complexity of hydrologic and water quality processes in full watersheds, the methods used were by necessity quite complex. For this reason, it was not practical to provide here all details necessary to replicate our approach. For additional details, we refer the reader to the original documents, which are incorporated into this report in the Supporting Documents (separate zipped folder) or by reference.

3.1 Nitrate Removal Rate Database (Task 1)

Task 1 entailed performing a literature review of the effects of stream channel and floodplain restoration practices on nitrate removal, and analyzing the resulting database of recorded nitrate removal rates for variation with key controlling parameters of interest.

3.1.1 Literature Review

A key outcome of Task 1 is a comprehensive database to explore patterns of nitrate removal rates with controlling factors. This database is of value on its own as a source of information for practitioners and researchers. Prior meta-analysis studies have summarized nutrient removal data associated with stream restoration practices, focusing on potentially controlling factors including study ecosystem (i.e., river, wetland, ditch, stream, floodplain, riparian zone), denitrification measurement method, land use, nitrate concentration, climate, and management actions (i.e., restoration, engineering, or rehabilitation) (Newcomer Johnson et al. 2016, Lammers and Bledsoe 2017). Lammers and Bledsoe (2017) concluded that certain restoration strategies may be more effective for enhancing nutrient retention and removal in streams versus riparian systems; however, they did not have enough evidence to determine the reasons for differences in nitrate removal efficacy across restoration strategies. Newcomer Johnson et al. (2016) found that limited hydrologic connectivity can reduce the effectiveness of floodplains in retaining and removing nutrients. They also concluded that combining multiple hydrologic reconnection restoration practices increases the likelihood of nutrient removal on a watershed scale.

Task 1 went beyond these prior studies by focusing on potentially controlling factors such as stream order where restoration occurs, flow conditions, and seasonality that are important when considering cumulative impact of multiple restoration projects at the watershed channel network scale and net project effects over annual and longer timescales. The database generated by Task 1 also aimed to more specifically prepare for modeling in Task 3 by providing input values and identifying controlling factors that could be used as explanatory variables for nitrate removal rates. Specific potentially controlling factors for which we gathered relevant data from the studies included in the database included:

a) Restoration: Restored, unrestored, and reference
b) Restoration technique: Various techniques for restoring channel and/or floodplain
c) Hydrologic status of stream during nitrate removal sampling event(s) Baseflow versus stormflow
d) Stream order: Location within the watershed channel network
e) Seasonality: Season of the year
f) Nitrate removal sample location within the system: Floodplain or in-stream (channel)

Stream restoration typically enhances nitrate removal from water flowing down the channel network by increasing hydrologic connectivity with off-channel storage zones via hyporheic and floodplain exchange (Berg et al. 2014, Hester et al. 2016). There are a wide range of specific stream restoration techniques that enhance hyporheic and/or floodplain exchange. However, to allow quantitative analysis of the removal rates in the database, we lumped specific practices into three categories, including in-channel restoration, bankfull floodplain restoration, and Stage 0 restoration. In-channel restoration techniques consisted of any type of channel engineering that increases hyporheic exchange between the surface water and channel bed or banks. This included the restoration, construction, or alteration of any type of in-stream structures (e.g., boulder weirs, log dams, sills, cross vanes), altering channel morphology (e.g., pool-riffle sequences, channel bars, and meanders), and modifying the streambed (e.g., raising, lowering, changing streambed substrate to alter hydraulic conductivity) (Hester and Gooseff 2011). Bankfull floodplain restoration techniques included any practices that reconnect the channel with a floodplain that experiences overbank flow typically from a few times a year to, on average, once every two years (Jones et al. 2015). This increases the volume of water that can access the floodplain during stormflow conditions. Stage 0 restoration is a newer technique that aims to bring streams back to a pre-colonial state in which bank heights are lowered, the streambed is raised, and/or legacy sediment is removed from the floodplain (Powers et al. 2019). This causes overbank flow that is more frequent than a stream that has undergone typical floodplain restoration (Cluer and Thorne 2014), often at stages just above baseflow. This enhances flood wave attenuation in the downstream direction, which decreases hydrograph flashiness downstream, and slows the flow of water traveling downstream through the channel and floodplain (Berg et al. 2020). Stage 0 approaches also raise the water table in the floodplain near to the land surface and increases exchange between surface water and groundwater within the floodplain soils (Flitcroft et al. 2022).

We confined our literature search to studies that focused on restoration practices with bidirectional flow between the channel and floodplain because we are interested in practices that remove nitrate from water flowing down the channel network. The literature we used for our review consisted of scholarly articles from peer reviewed scientific journals that were published between 1995 and 2020. In total, our completed database contains 63 studies that include 109 unique stream reaches. We excluded some data from our statistical analysis where rates that were zero (skewed random forest analysis), negative, or we were unable to calculate rates due to lack of sufficient data necessary to convert all rates to the same units. After removing data that did not fit our nitrate removal rate criteria, 701 out of 763 data points remained. We retained 55 out of 63 studies, and 98 out of 109 unique stream reaches. We searched globally for studies, which allowed us to include data from the U.S., Canada, Australia, New Zealand, and Europe (Austria, France, Denmark, England, Switzerland, Spain, and Ireland). However, we emphasized finding studies that were conducted within the Chesapeake Bay watershed, since Task 3 and 4 modeling used input data from Chesapeake Bay watershed.

Additional detail on background and methods can be found in “Literature Review of Nitrate Removal Rates by Stream Restoration Practices and Summary of Removal Rate Database.pdf” among the supporting files.

3.1.2 Data Analysis

The database resulting from the literature search discussed in Section 3.1.1 above contained actual and potential rates associated with different stream restoration scenarios, watershed conditions, and seasonality, among other variables. Actual nitrate removal rates are measured in- situ and represent the nitrate removal rate actually occurring in the system of interest accounting for limiting conditions present (i.e., nitrogen availability, flow rate, etc.) (Mulholland et al. 2008). Potential nitrate removal rates are ex-situ measurements determined by soil or sediment samples originally collected from the field. These samples are taken to a lab where the acetylene block technique is applied (Hanson et al. 1994). They represent the maximum nitrate removal rate without limiting conditions.

Understanding the influence that these variables have on nitrate removal rates through the use of traditional statistical approaches (e.g., ANOVA, linear regression) does not work due to covariation among "independent" variables, hence, negating their independence. When testing for covariance within our database, we found that many of the variables that we wanted to test against our nitrate removal rates were significantly correlated with one another, and this was especially true for stream order. Therefore, we elected to use a random forest (RF) machine learning approach because this approach does not require variable independence. RF allows understanding patterns in nitrate removal rates that cannot be easily distinguished using traditional statistical methods. RF machine learning has shown to be a valuable method for performing data classification analyses using pattern recognition algorithms (Chen et al. 2013). Its effectiveness is attributed to its foundation in simple mathematical theory, fast computation times, stable outputs, insensitivity to noise, minimal risk of overfitting, and an automatic compensation mechanism for biased group sample sizes (Amaratunga et al. 2008).

Rodriguez-Galiano et al. (2015) and Nitze et al. (2012) found that RF outperformed other machine learning algorithms, including regression trees and support vector machines, by showing greater stability of results. Their results, along with other RF studies focusing on landscape-level environmental data (Mohammady et al. 2019, Ahmed et al. 2021, Price et al. 2021), provided justification for RF being a good methodological approach for our study. We then coupled the outputs of our RF models with artificial neural networks (ANNs) to formulate predicted nitrate removal rates based on specific temporal, spatial, hydrologic, and restoration criteria, as well as testing the predictive power of our RF-ANN coupled models.

Hereafter, we differentiate between a "database" and a "dataframe" by defining our nitrate removal database as all of the data obtained during our data collection phase. This database contains 701 potential and actual nitrate removal rates with 62 additional columns of data associated with the rates. However, not all nitrate removal rates were used in the analyses due to insufficient data for variables of interest associated with the nitrate removal rates. The "dataframes" refer to subsets of the nitrate removal database that are complete dataframes of the variables of interest (i.e., no NAs) and contain specific nitrate removal rates for each random forest analysis. Random forest analyses were performed on six distinct dataframes, all of which contained the same associated variables (i.e., variables other than nitrate removal rates), but different subsets of nitrate removal rates. We performed six different RF and ANN analyses (Table 1), each using different subsets of nitrate removal rate data because (1) we cannot include actual and potential rates in the same analysis, (2) we wanted to analyze restored streams and all available streams (i.e., restored, unrestored, reference) separately, and (3) we wanted to see the effect of including versus excluding nitrogen concentration for actual rates. Actual and potential nitrate removal rates cannot be included in the same analysis because they are inherently different measurements. The predictive capabilities of the RF-ANN coupled models were measured with a Nash-Sutcliffe efficiency (NSE) value, which is commonly used to evaluate the predictive capabilities of hydrologic and water quality models including RF (Moriasi et al. 2007, Moriasi et al. 2015, Shortridge et al. 2016, Fang et al. 2021). NSE values range from negative infinity to 1.0. Higher NSE values (>0.25) are a sign of satisfactory model performance for watershed-scale nitrogen models (Moriasi et al. 2015). However, an NSE value at or very close to 1.0 indicates that a model is overfit. Out of the six random forest-artificial neural network (RF-ANN) analyses, all but one performed satisfactorily (median NSE > 0.25 yet well below 1.0) during the testing phase (Table 1). This "performance" column in Table 1 is thus based on a well-established quantitative measure of information content in the dataframes, and is therefore a rigorous method by which to determine which results are reliable.

Table 1. Description of data used for each random forest-artificial neural network coupled analysis. "All" in the "Reaches included" column indicates that the analysis included unrestored, restored, and reference reaches. The n column indicates the total number of nitrate removal rates included in the dataframe. The n values vary based on the data availability for predictor variables, because only complete dataframes could be used. Analyses A and B contained the same nitrate removal rate data to allow for comparison. The same is true for Analyses C and D.

Analysis	Nitrate removal rate type	Reaches included	Nitrogen concentration	n	Median NSE	Performance[1]	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).

Additional detail on background and methods can be found in Luke Goodman's thesis among the supporting files.

3.2 Generic Watershed Model (Task 3)

Task 3 entailed using a series of generic watershed models to answer the key research questions and test the hypotheses presented in Section 1. For this reason, this section is the longest, and involved the theses of four separate graduate students. Use of a generic model rather than a site-specific model allows our results to be more widely applicable rather than limited to a specific watershed. Nevertheless, our modeling approach was constrained by a lot of data, using averages parameter values for many streams/rivers in the Virginia Piedmont, so it is based solidly in the reality of Chesapeake Bay region streams. Our ultimate focus here is on watershed-scale effects of restoration on nitrate removal, yet hydraulic simulations are necessary to conduct the nitrate removal modeling. The hydraulic simulations included steady-state baseflow models used to simulate effects of hyporheic enhancement on nitrate removal, and unsteady flood wave propagation simulations to simulate effects of floodplain and Stage 0 restoration on nitrate removal. The hydraulic simulations for the floodplain restoration scenarios also allowed us to calculate the watershed-scale effects of restoration on flood attenuation.

The modeling approach entailed use of the U. S. Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS) 1D model, together with a series of R scripts. We used a generic 4th-order watershed (Figure 1) with average values for channel network layout (e.g., channel lengths and bifurcation ratios), channel dimensions (e.g., bankfull depth and width), watershed area, and baseflows (Table 2). Model flows were calibrated first to baseflow conditions (steady-state model) using regional low flow equations and then to storm flows (unsteady model) using USGS gage data and the Snyder Unit Hydrograph. Additional detail on background and methods can be found in Michael Calfe's and Carly Federman's theses, as well as the journal articles that were derived from those theses (Calfe et al. 2022, Federman et al. 2023), among the supporting files.

Table 2. Channel network characteristics and baseflow (steady-state) hydrology. From Calfe et al. (2002).

Stream order	Representative drainage area (km^2)	Bifurcation ratio with next higher-order channel (-)	Bankfull width (m)	Bankfull mean depth (m)	Bankfull slope (m/m)	Total channel length (m)	Channel baseflow at each outlet (m^3/s)	Baseflow gaining along each channel (m^3/s)
1	1.77	4.0	3.40	0.23	0.00656	1,830	0.0113	0.00850
2	9.74	3.0	7.00	0.46	0.00429	5,030	0.0596	0.0144
3	46.9	2.0	13.7	0.79	0.00289	12,800	0.289	0.110
4	202		25.6	1.4	0.00200	30,790	1.24	0.662

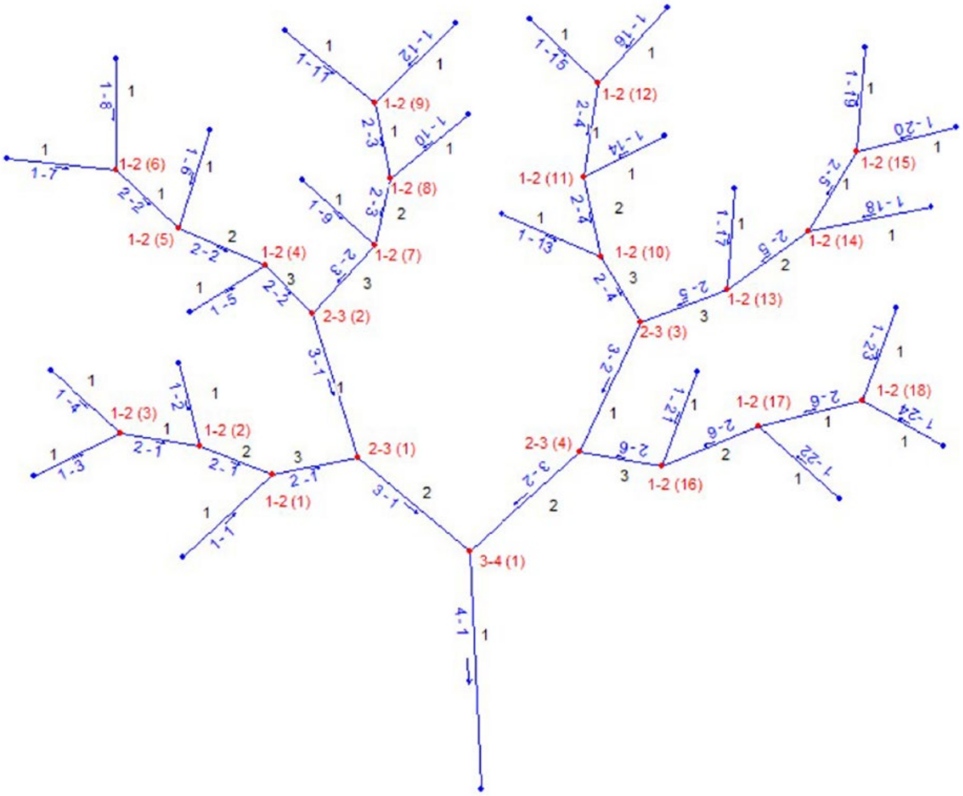


Figure 1. Plan view schematic of HEC-RAS channel network (not to scale). Reprinted from Calfe et al. (2022), copyright 2022, Elsevier.

3.2.1 Flood Attenuation

Floods provide beneficial ecosystem services (e.g., processing pollutants, transferring nutrients and sediment, supporting biodiversity), but they can also damage infrastructure and result in the loss of human life. The effects of human actions on channel network hydrology are numerous. Land use change increases peak flows with variable effect on low flows. Climate change also increases peak flows, with variable effects (but often a decrease) on baseflows. Dams and reservoirs typically decrease peak flows and increase baseflows. Groundwater pumping can decrease or increase baseflow, depending on whether the channel is closer to the extraction well or the application of the water. These effects on hydrology then affect humans and ecosystems. Increased peak flows threaten infrastructure, including prior restoration projects. Decreased low flows reduce habitat and affect migration.

The effects of Floodplain/Stage 0 Restoration on channel network hydrology are complex as well. Restoration typically decreases peak flows by increasing surface water and groundwater storage, but can also increase peak flows with asymmetric (in time) flow hydrographs or unintentional peak flow synchronization between tributary and mainstem. Floodplain restoration can also affect low flows, with potential to both increase low flows due to more groundwater storage or decrease low flows through enhanced evapotranspiration (Hammersmark et al. 2008, Nash et al. 2018, Nash et al. 2020, Ohara et al. 2014, Tague et al. 2008). We simulated unsteady flood hydraulics in preparation for simulating nitrate removal from floodplain and Stage 0 restoration. Because unsteady simulations are complex, we started by simulating just a single 2nd-order channel from the larger 4th-order channel network before scaling our model up to the full 4th-order watershed. We simulated relatively frequent storm events (i.e., 2-year, 1-year, 0.5-year, and monthly recurrence intervals).

3.2.1.1 Flood Attenuation by Restoration along Single 5-km long 2nd-order Channel

1D unsteady HEC-RAS was used to simulate small storms (monthly, 0.5-year, 1-year, and 2-year storms, Figure 2) in a 5 km-long, second-order generic stream from the Virginia Piedmont portion of the Chesapeake Bay watershed (red dashed area in Figure 3). Percent channel restored (starting at the upstream end), restoration location, restoration bank height (distinguishes bankfull from Stage 0 restoration), and floodplain width/Manning's n were varied in a sensitivity analysis (Table 3). In particular, Stage 0 entailed lower bank heights with more frequent floodplain inundation imitating pre-colonization conditions, achieved by legacy sediment removal (LSR) in floodplain or raising the streambed (RSB). By contrast, bankfull floodplain restoration entailed higher bank heights with floodplain inundation ~1/year.

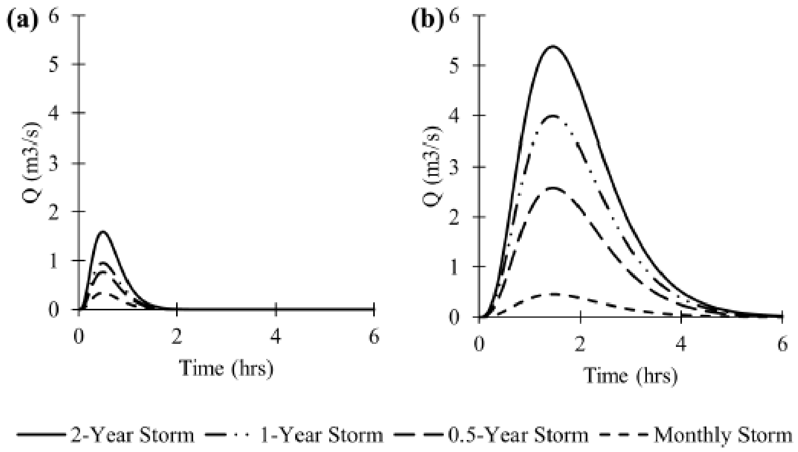
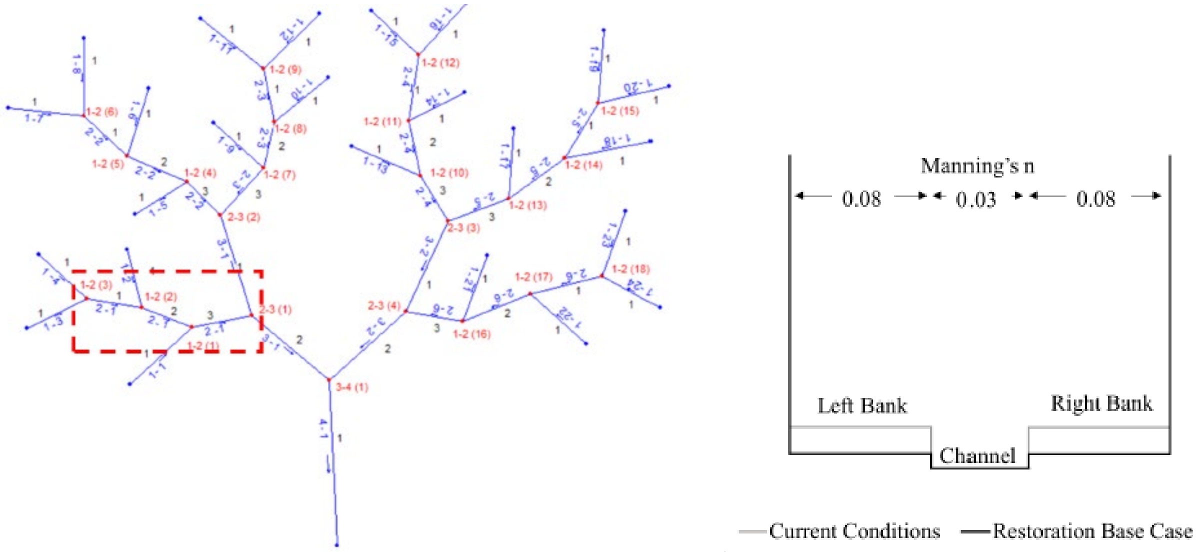


Figure 2. Dimensioned hydrographs (a) at the downstream end of a first-order river, and (b) at the downstream end of a second-order river. From Federman et al. (2023).



a)

b)

Figure 3. a) Second-order stream sub-model of the larger 4th-order generic HEC-RAS model in Calfe et al. (2022). Figure adapted from Figure 1 published in Calfe et al. (2022). The red-dashed box shows the second-order stream used in our model. b) Conceptual cross sections of current conditions and for the restoration base case (Stage-0). From Federman et al. (2023).

Table 3. Modeling Parameters for Sensitivity Analyses. From Federman et al. (2023).

Parameter	Range varied in sensitivity analysis	Increments used for sensitivity analysis	Base case restoration value
Percent 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)
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	10.42 m

Additional detail on background and methods can be found in Federman et al. (2023) and Carly Federman's thesis, both among the supporting files.

3.2.1.2 Flood Attenuation by Restoration throughout Full 4th-order Watershed

We next extended our approach to the full 4th-order watershed used by Calfe et al. (2022), again using average network, channel, and hydrologic parameters for the Virginia Piedmont region. We varied restoration location by stream order and cumulatively (Figure 4, Table 4).

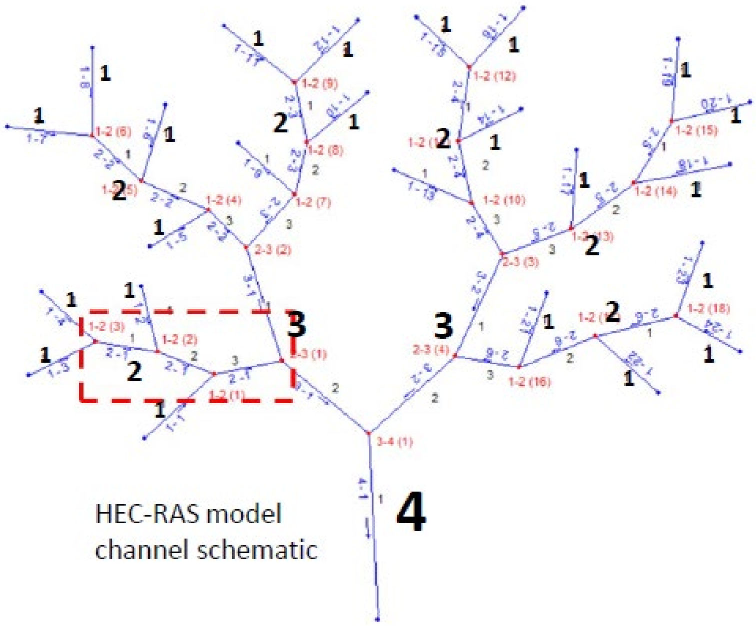


Figure 4. Fourth-order HEC-RAS channel network with stream orders shown.

Table 4. First- through 4th-order floodplain widths and bank heights for both unrestored conditions and with floodplain restoration.

Stream order	Unrestored floodplain width (m)	Restored floodplain width (m)	Unrestored bank height (cm)	Restored bank height (cm)
1	10.0	36.6	23	7.6
2	21.0	39.6	46	15.2
3	41.1	45.7	79	26.4
4	76.8	78.2	137	45.7

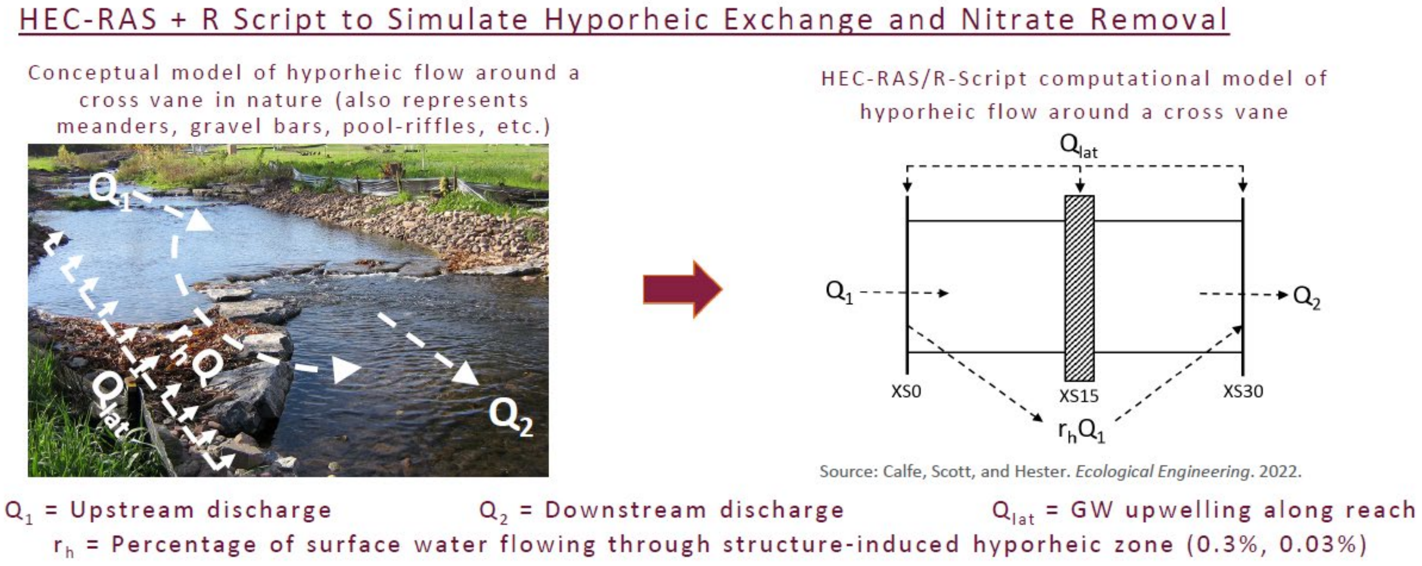
Additional detail on background and methods can be found in Luke Goodman's thesis among the supporting files.

3.2.2 Nitrate Removal

We implemented nitrate removal simulations as auxiliary R codes using the output from the HEC-RAS hydraulic simulations. Nitrate removal at baseflow by in-channel hyporheic enhancement used the steady-state baseflow hydraulic model. Nitrate removal during storm events by floodplain (bankfull and Stage 0) restoration used the unsteady storm flow hydraulic model.

3.2.2.1 Nitrate Removal during Baseflow by In-Channel Hyporheic Enhancement

The research project described here (nitrate removal by in-channel hyporheic enhancement) was wrapping up when the CBT-funded project that is the main subject of this final report was beginning. It used a steady-state 1D HEC-RAS baseflow model to simulate the effects of in-channel hyporheic enhancement on nitrate removal within a 4th-order watershed. Hyporheic enhancement entailed anything that increases hyporheic exchange primarily within the channel, such as in-channel structures, pool-riffle sequences, gravel bars, and meander bends. Location and extent of restoration was varied throughout the 4th-order channel network as described previously for flood attenuation (Section 3.2.1, above). An R script was run to calculate nitrate removal by restoration-enhanced hyporheic exchange using the output of the hydraulic model (Figure 5). We assumed 0.3% of surface flow in the channel cycles through the hyporheic zone per 30 meters of restored channel. All nitrate cycling through the hyporheic zone was assumed to be removed. Groundwater in the watershed was assumed widely polluted with excess nitrate, such that the main nitrate source to the channel network was baseflow gaining.



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%)

Figure 5. Schematic of R script used to calculate nitrate removal due to in-channel hyporheic enhancement techniques.

Additional detail on background and methods can be found in Michael Calfe's thesis among the supporting files.

3.2.2.2 Nitrate Removal during Storms by Floodplain (Bankfull, Stage 0) Restoration

A nitrate removal model was written in R using the output of the unsteady watershed HEC-RAS hydraulic model of cumulative and spatially varying restoration. Nitrate removal was calculated as the product of inundation and inundation area (from HEC-RAS) and nitrate removal rate (0^{th}-order, from nitrate removal database generated in Task 1). Nitrate removal rates used were the 10^{th} percentile, median, and 90^{th} percentile of all of the actual (vs potential) rates in the database for floodplain restoration (Table 5). Percent removal was calculated as the nitrate removal (described above) divided by nitrate loading to the watershed and multiplied by 100.

We chose to not vary removal rates with stream order in our floodplain nitrate removal modeling (Table 5). While the Random Forest-Artificial Neural Network analysis in Task 1 was able to determine the most important factors controlling nitrate removal rates, the variation of rates was not statistically significant among stream orders. In other words, the variability in nitrate removal rates within each stream order was large relative to differences between stream orders. This high variability was quantified with the coefficient of variation, which was >1 for all sub-categories, indicating a wide spread in the data (see Tables A-2 and A-3 in Morgan Oehler's thesis among the supporting files for details).

Table 5. Removal Rates Used in Nitrate Removal Modeling. Statistics were calculated using Goodman's (2023) nitrate removal rate database for actual (in-situ) measurements, floodplain restoration, all seasons, and all stream orders.

Nitrate removal rates [(mg-N)/(m^2-hr)]	
10th percentile (k_{10})	0.072
Median (k_m)	0.66
90th Percentile (k_{90})	14

Net removal was also calculated across a full annual cycle due, including both floodplain/Stage 0 restoration during a series of storm events and in-channel hyporheic enhancement during intervening baseflow periods. Baseflow hyporheic nitrate removal results were extracted from the R code that used the results of the steady-state model, and floodplain/Stage 0 removal results were extracted from the unsteady model. A synthetic annual hydrograph was created using 12 monthly storms, 2 half-year storms, a single 1-year storm and a single 2-year storm, with the remaining portion of the year assigned to baseflow conditions.

Additional detail on background and methods can be found in Morgan Oehler's thesis among the supporting files.

3.3 Case Study Watershed Model (Task 4)

The goal of the case study watershed model in Task 4 was to test the modeling approach developed for the generic model in Task 3 using a real case study watershed, particularly to assess the value and challenges of applying our approach to specific watersheds. The Gwynns Falls watershed near Baltimore MD (Figure 6) was chosen because it was within the Chesapeake Bay watershed, had considerable available hydrologic and water quality data, and was similar in size to the generic 4th-order watershed used in Task 3. The unrestored version of the hydraulic model was constructed in HEC-RAS using georeferenced model geometries from the Maryland Department of the Environment. At the time of model construction, such geometry files were only available for the lower third of the Gwynn's Falls mainstem and some associated tributaries, which become the model domain. Within this domain, the restored geometry was created by modifying the unrestored geometry via floodplain cut along 46% of the main channel length (Figure 6). Restoration was constrained by existing infrastructure, including buildings, roadways, and utilities. Unsteady stormflow hydraulics were simulated for the same small and sub-annual storms as used for Task 3 (e.g., 2-year, 1-year, half-year, and monthly), using USGS data for calibration. The effects of cumulative Stage-0 floodplain restoration on the lower mainstem (4th-order channel) were evaluated for effects on flooding and nitrate removal.

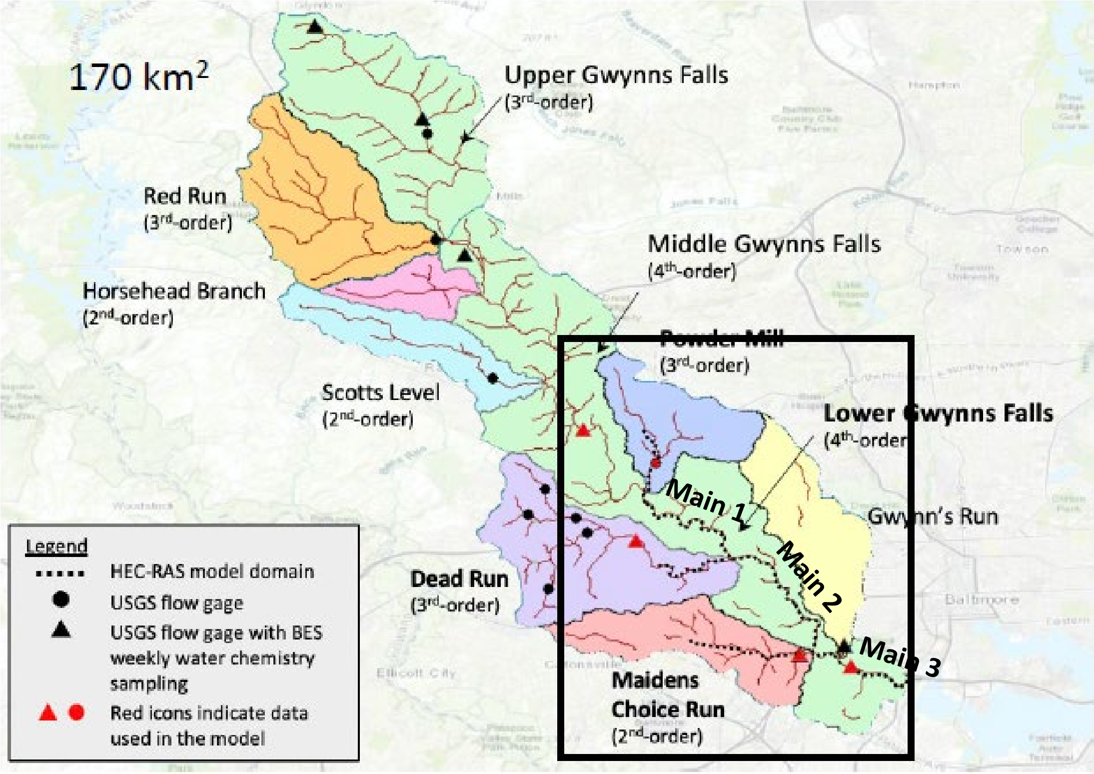


Figure 6. Gwynn's Falls watershed near Baltimore, MD showing Task 4 HEC-RAS model domain. The watershed has a 170 km^2 drainage area and includes urban (79%), forest (17%), and agriculture (3%) land uses. Black box indicates the extent of case study watershed modeled.

Additional detail on background and methods can be found in Morgan Oehler's thesis among the supporting files.

4. RESULTS

The goal of this project was to evaluate the watershed-scale effects of stream restoration on nitrate removal, including the cumulative effects of multiple restoration projects, and the effects of project location within a watershed. This evaluation, including answering the key research questions and testing the hypotheses listed in Section 2.2 above, was primarily accomplished using a generic watershed model in Task 3. Thus, we first present results from Task 3 here in Section 4.1. Section 4.2 then presents supporting or auxiliary findings resulting from Tasks 1 and 4. These auxiliary results were necessary either as input to Task 3 methods (Task 1) or were otherwise promised in the proposal (Task 4).

We emphasize that this project generated a large volume of results. To enhance reader understanding, here we present only a summary of the most important and germane results. This summary is drawn from a series of interim deliverables and reports, published articles, student theses, and presentations. For additional details, we refer the reader to the original documents, which are incorporated into the final deliverables for this project in the Supporting Documents (separate zipped folder) or by reference.

4.1 Results that Answer Key Research Questions (Task 3)

Here we present answers to the key research questions listed in Section 2.2. To make these questions easy to find in this document, we highlight them below in <u>*italics and underline*</u>. In addition to presenting nitrate removal results to directly answer the key research questions, we also present results of our modeling assessment of watershed-scale effects of floodplain restoration on flood attenuation. The effect of restoration on flood attenuation is an important applied concern in the Chesapeake Bay Watershed on its own, therefore these results will likely be of interest to many stakeholders in the region. We present these flood attenuation results together with the nitrate removal rates (rather than separating the two) because the hydraulic modeling that generated the flood attenuation results was a necessary precursor to the nitrate modeling that generated the nitrate removal results for floodplain restoration during storm events, and the resulting findings are best understood together.

4.1.1 Flood Attenuation

4.1.1.1 Flood Attenuation by Restoration along Single 5-km long 2nd-order Channel

We started by modeling the effects of floodplain/Stage 0 restoration projects along a single 2nd-order channel (Section 3.2.1). Our results indicated that restoration reduced peak flow. In particular, here we define flood attenuation as reduced peak flow rate at downstream end of the 2nd-order channel (Figure 7).

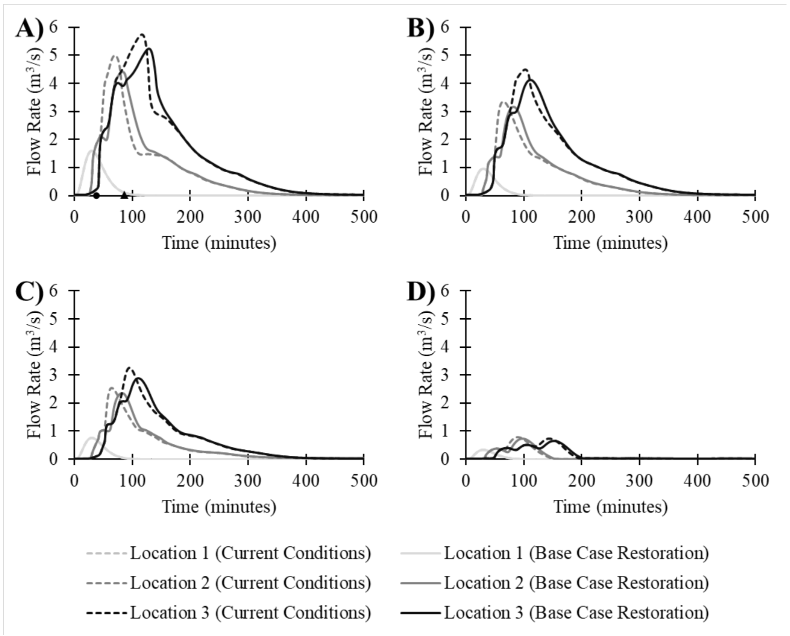


Figure 7. Hydrographs for the A) 2-year, B) 1-year, C) 0.5-year, and D) monthly (1/12-year) storms for current conditions and base case restoration scenarios. Locations 1, 2, and 3 are the upstream, midpoint, and downstream ends of the 5-km long channel model domain, respectively. Solid circle and triangle on x-axis in panel A indicate t = 45 minutes and t = 90 minutes. From Federman thesis.

Project effectiveness varied with restoration technique (Figure 8). In particular, Stage 0 (low banks) was more effective than high banks (bankfull floodplain). There was no tradeoff among restoration benefits, in that lower banks enhance both flood attenuation and floodplain exchange (water quality).

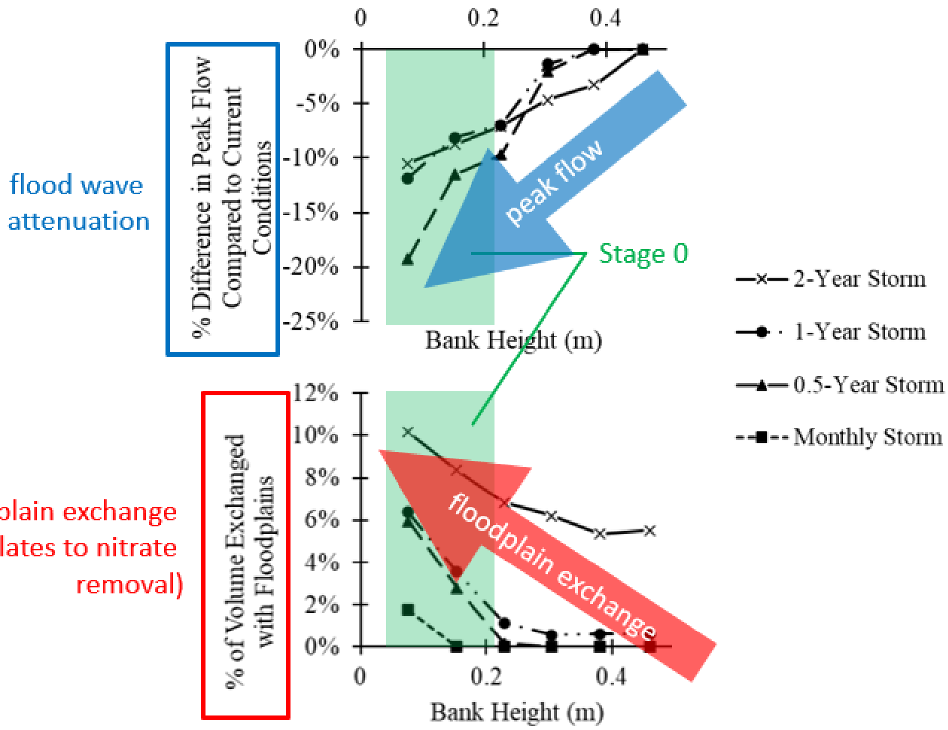


Figure 8. Effect of restoration bank height on flood wave attenuation (top) and floodplain exchange (bottom).

Project effectiveness also varied with restoration project location along channel (Figure 9). In particular, individual projects were more effective if located upstream along channel (for flood wave attenuation) or downstream along channel (for floodplain exchange). Thus there was a tradeoff between flood attenuation and floodplain exchange in terms of project location.

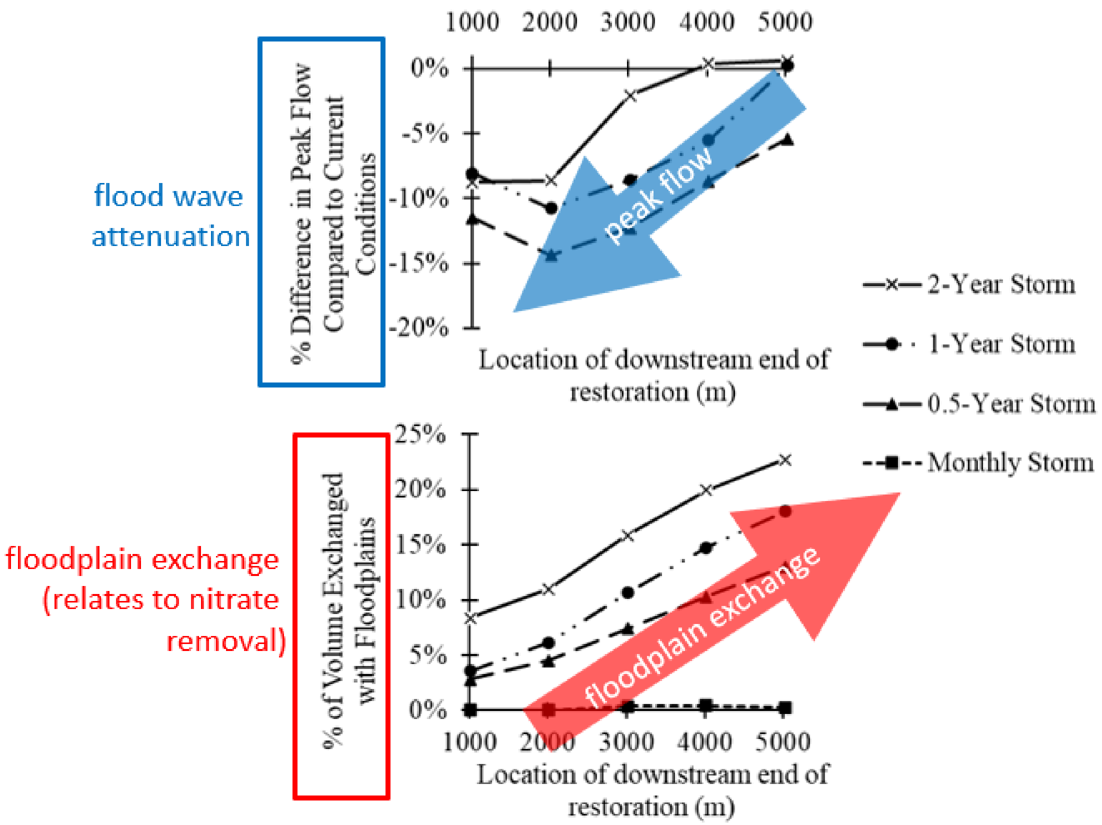


Figure 9. Effect of restoration project location along 5-km 2nd-order channel on flood wave attenuation (top) and floodplain exchange (bottom).

Finally, project effectiveness varied with percent of stream network restored (Figure 10). In particular, individual projects were more effective (i.e. greater slope of curve) if there was less prior restoration (for flood wave attenuation) or more prior restoration (for floodplain exchange). Thus, there was a tradeoff between flood attenuation and floodplain exchange for percent prior restoration. Note that this result (i.e. the shape of these curves) probably depends on the shape of the curves in Figure 9 and thus the direction in which restoration increased along the channel.

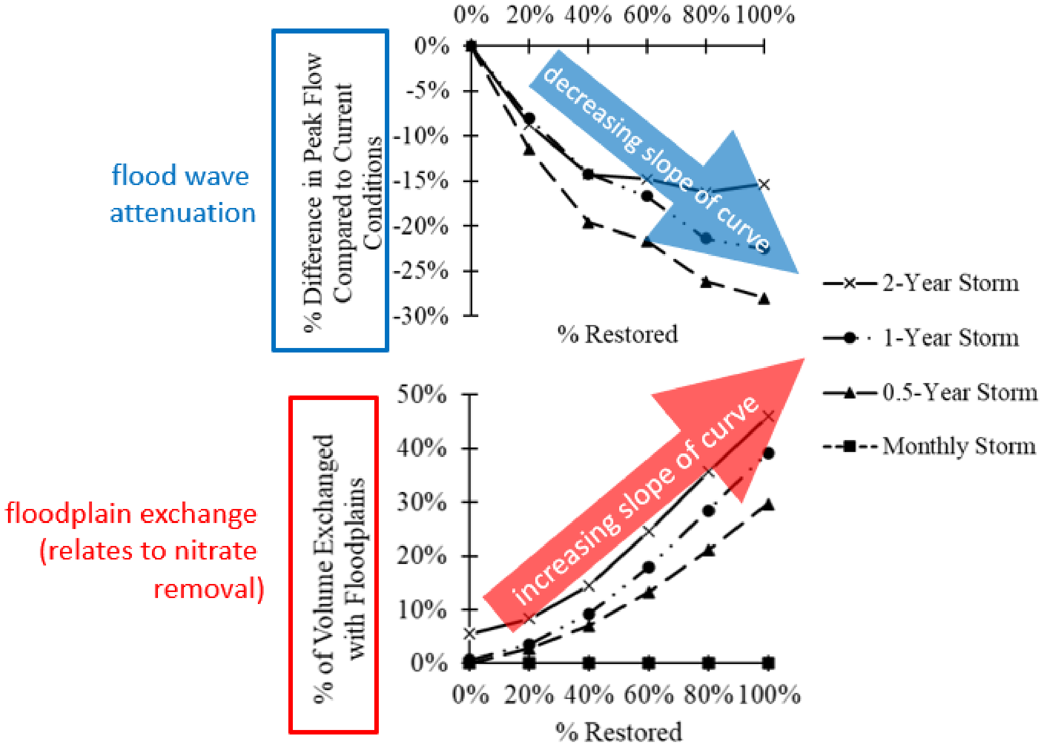


Figure 10. Effect of amount of prior restoration along 5-km 2nd-order channel on flood wave attenuation (top) and floodplain exchange (bottom).

We also varied a series of other potentially controlling factors. Of these, restored floodplain width was one of the most important in controlling flood attenuation.

<u>How do the answers to Research Question #1 (Section 2.2) vary with watershed conditions such as valley width?</u>

Increasing the floodplain width increased the area of floodplain inundation (not shown, but obvious because increasing floodplain width directly increases the area of inundation), the amount of water exchanged between the channel and the floodplain (Figure 11d), and to a lesser extent the residence time of water in the floodplain (Figure 11e). While we did not explicitly model the effect of floodplain width on nitrate removal, the equation we used to estimate nitrate removal involved multiplying a nitrate removal rate by floodplain area and residence time. As a result, the trends discussed above provide strong evidence that floodplain nitrate removal would increase with floodplain width.

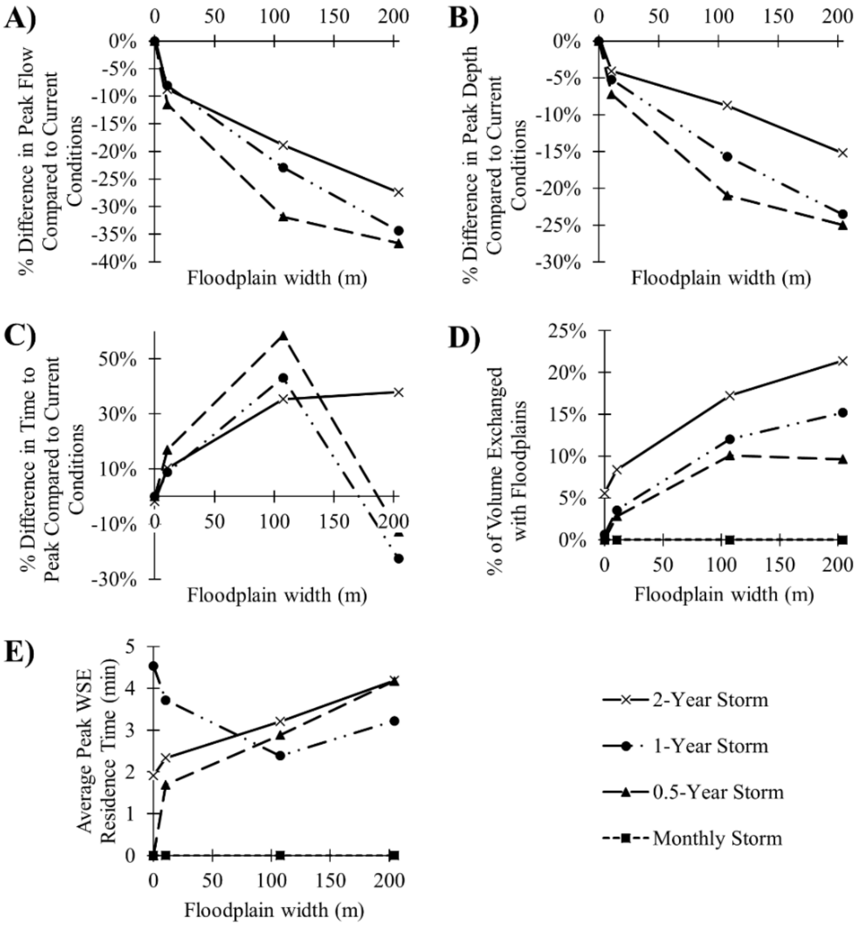


Figure 11. Effect of floodplain width on each side of the channel on A) peak flow, B) peak depth, C) time to peak, D) cumulative exchange, and E) residence time at downstream end of model domain. Widths are for one side of channel, and totals for both sides are double the values shown. During the monthly storm overtopping was so small that HEC-RAS output it as 0, but it still had a slight effect on the peak values causing the trends look inconsistent from large to small storm size. Panel D shows cumulative channel-floodplain exchange occurring over the duration of each scenario, calculated as the ratio of the total volume inundating the floodplains and the total volume in the model domain at each time step, and was used to estimate residence times. From Federman et al. (2023).

Additional detail on results, interpretation, and significance can be found in Federman et al. (2023) and Carly Federman's thesis, both among the supporting files.

4.1.1.2 Flood Attenuation by Restoration throughout Full 4th-order Watershed

Results indicated that restoration generally induced decreases in flood peaks, but there were some increases, particularly for the monthly storm (Figure 12). The greatest flood attenuation effect occurred just downstream of the restoration, with decreasing effect with distance further downstream, and no effects upstream. The largest decreases in peak flows were often for smaller-order channels and small to medium sized storms. Flood attenuation and floodplain exchange both increased with percent of channel network restored (Figures 12, 13). Stage 0 techniques (1st- and 2nd-order channels) were more effective at inducing floodplain exchange and flood wave attenuation than bankfull floodplains (3rd- and 4th-order channels), as expected. The incremental effect of an individual restoration project varied depending on where it was in the 4th-order channel network, and on the amount of previous restoration that had already occurred in the watershed, with tradeoffs between enhancing flood attenuation and enhancing floodplain exchange for some parts of the watershed/channel network (e.g., 2nd-order) but not others (e.g., 4th-order). Relationships between percent restored and flood attenuation were often highly nonlinear (Figure 12), meaning the incremental effect of a given restoration project on flood attenuation depended on the degree of prior restoration. Whether the effect increased or decreased as percent restored increased depended on watershed location (i.e. stream order) of project. Relationships between percent restored and floodplain exchange were roughly linear but incremental effects were sometimes larger at higher percent restored (Figure 13). This means that incremental effect of given project on floodplain exchange often depended less on degree of prior restoration than did flood attenuation. The incremental effect of a given individual project and floodplain exchange in particular increased with stream order (projects were more effective in larger streams).

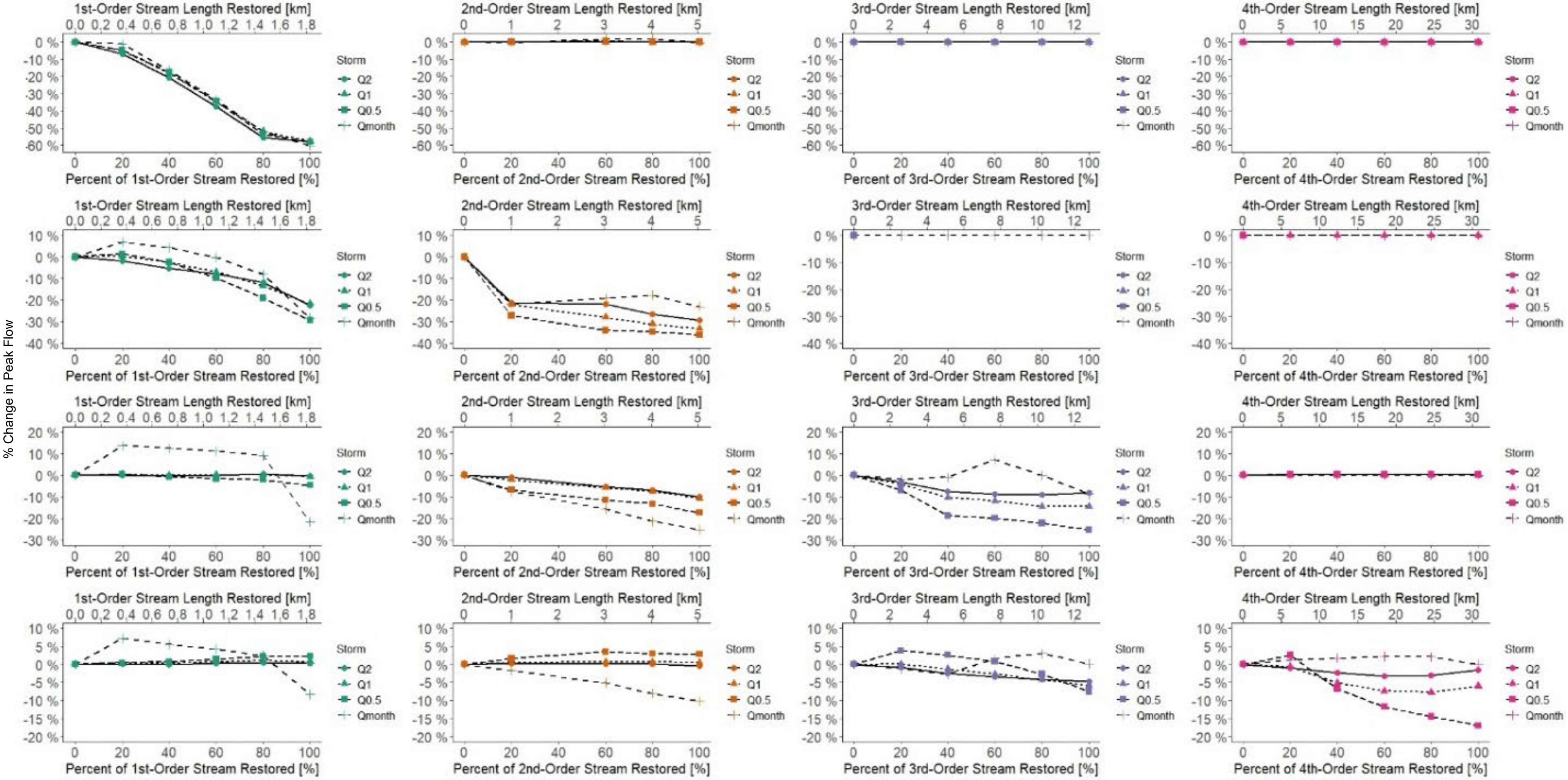
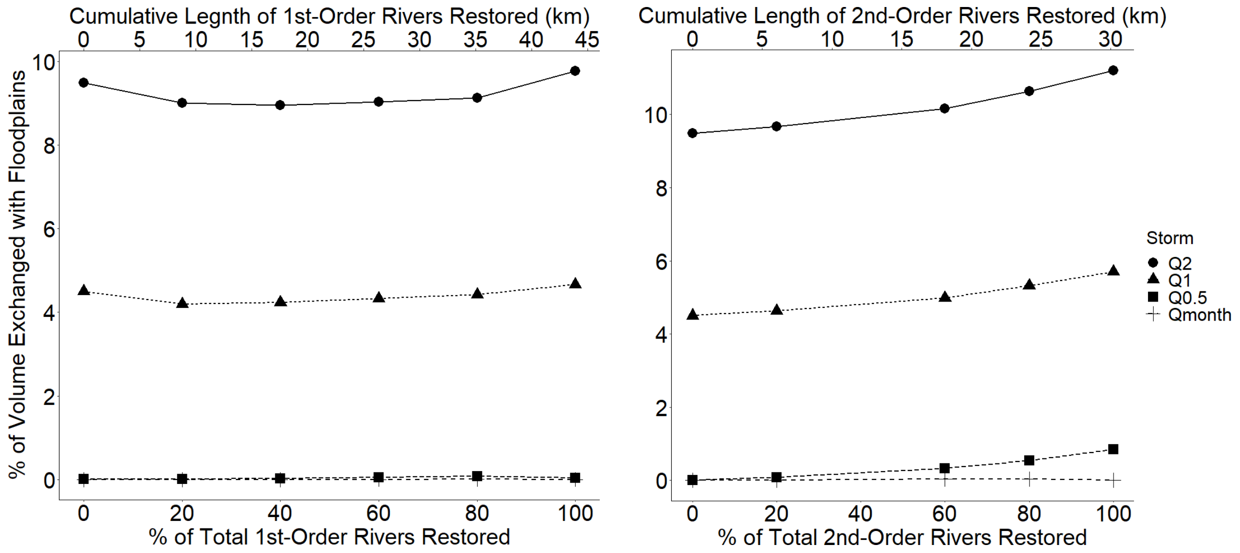
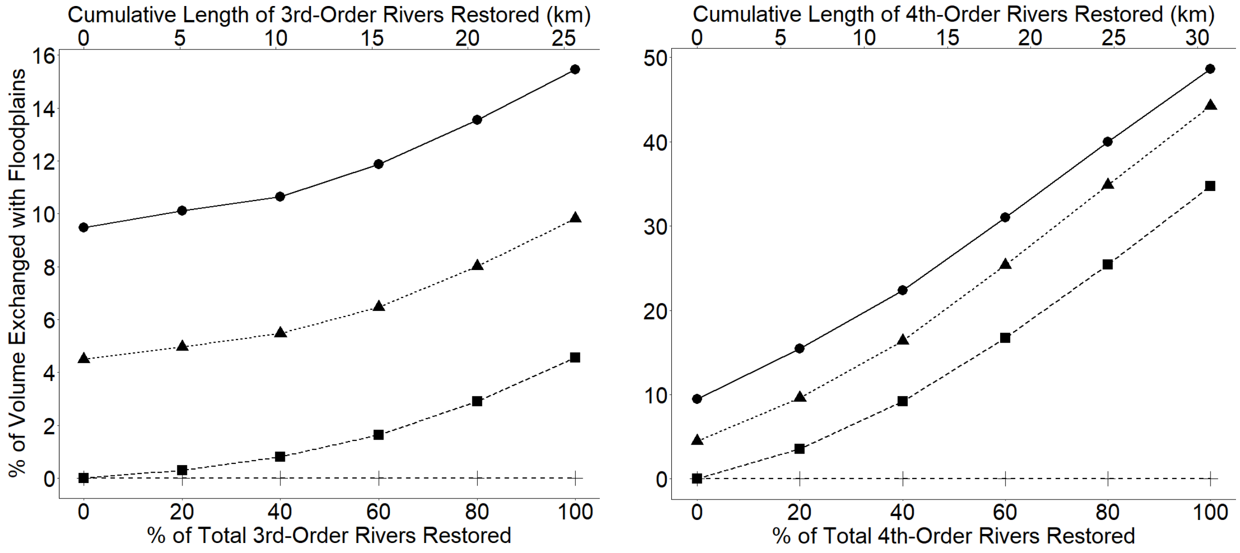


Figure 12. Effect of restoration project location (i.e. stream order), percent of prior restoration, and storm size on flood attenuation quantified as percent reduction in peak storm discharge relative to unrestored condition. Rows differ in terms of the location where flood attenuation was quantified (i.e. downstream end of 1st-, 2nd-, 3rd-, and 4th-order channels, respectively


(a) 1st-order restoration

(b) 2nd-order restoration


(c) 3rd-order restoration

(d) 4th-order restoration

Figure 13. Effect of restoration project location (i.e. stream order), percent of prior restoration, and storm size on total floodplain exchange within 4th-order watershed.

Overall, our results support the conclusion that watershed context is irreducibly complex, such that a channel network model is necessary to understand the effect of floodplain restoration projects on flows in the channel network. Additional detail on background, methods, results, interpretation, and significance can be found in Luke Goodman's thesis among the supporting files.

4.1.2 Nitrate Removal

4.1.2.1 Nitrate Removal during Baseflow by In-Channel Hyporheic Enhancement

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)?

The shape of the relationship varied from exponential for headwater streams (e.g., 1st-order, Figure 14a) to approximately linear for 3rd-order (Figure 14c) and levelling off for the largest streams we simulated (4th-order, Figure 14d). This indicates that the length of channel already restored affects incremental nitrate load reduction from individual projects. Cumulative restoration of all the channels in the full 4th-order watershed did not increase removal much beyond just restoring the 4th-order channel, although concavity was reversed (Figure 15).

Thus, location in the watershed (i.e. stream order) affected both incremental and cumulative nitrate load reduction from restoration projects. In particular, higher-order channels were more effective at removing nitrate (Figure 15). The reasons for this include spatial variations of the following within the watershed: a) amount of hydrologic gaining (amount of nitrate source upstream of restoration) and b) prevalence of “recycling” of surface water multiple times through hyporheic zone. Nevertheless, while removal potential was greater in larger streams, larger streams also had less removal rate data and would be harder/more expensive locations to do restoration.

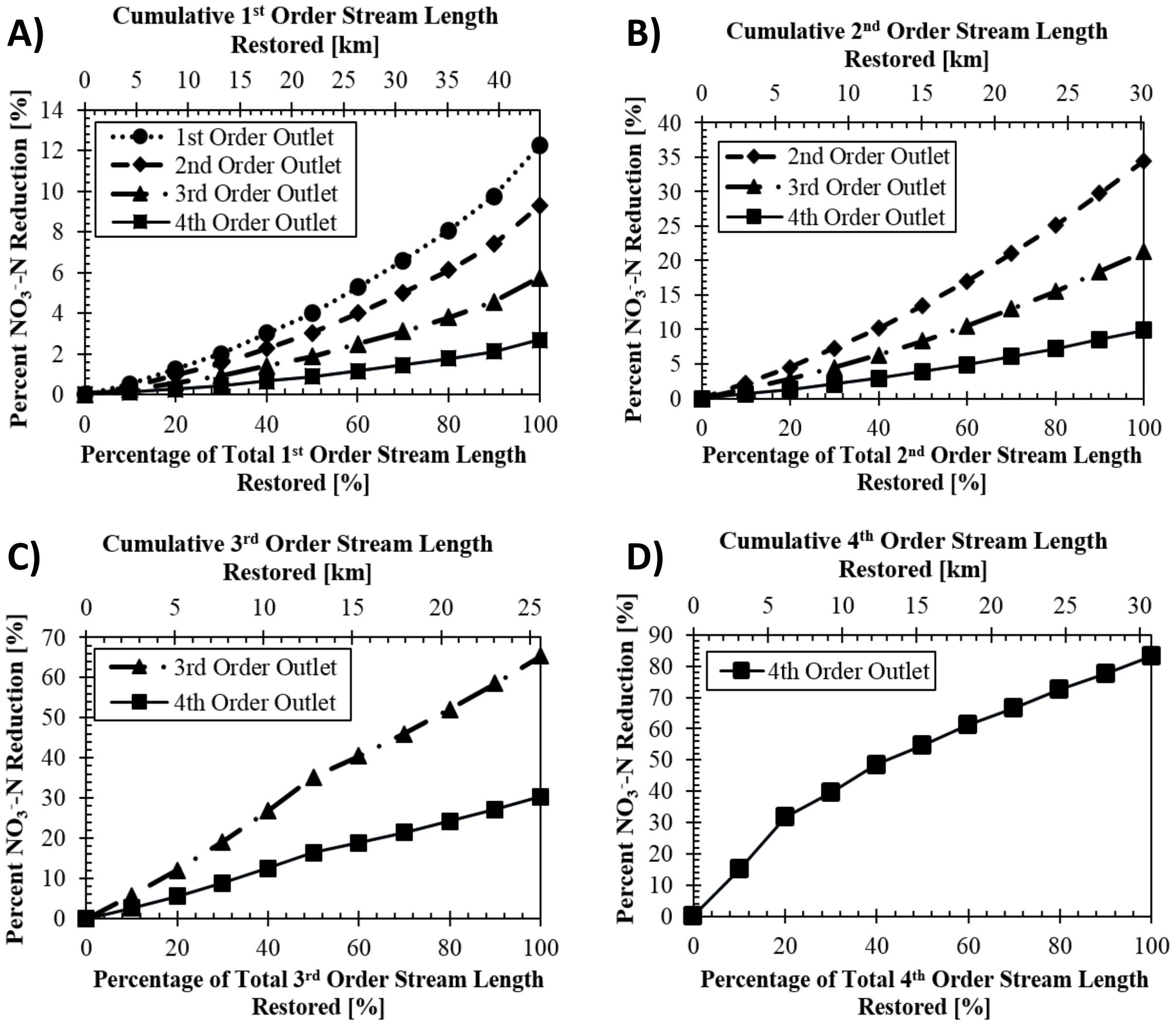


Figure 14. Percent nitrate (NO3--N) reduction in both concentration and mass at the furthest downstream cross section of the A) 1st-order rivers, B) 2nd-order rivers, C) 3rd-order rivers, and D) 4th-order river due to [hyporheic] restoration [induced by in-channel features] only in that respective stream order (rh = 0.3%). All Y-axis percent reductions are on both a concentration and load basis since we used a base concentration of 1 mg/L. X-axis is percent of the cumulative channel length of that stream order that was restored, which is equal to the percent restored of each individual river. Here we use official HEC-RAS terms where “river” means one individual channel, and “reach” means the parts of that river after being split by tributary junctions. Reprinted from Calfe et al. (2022), copyright 2022, Elsevier.

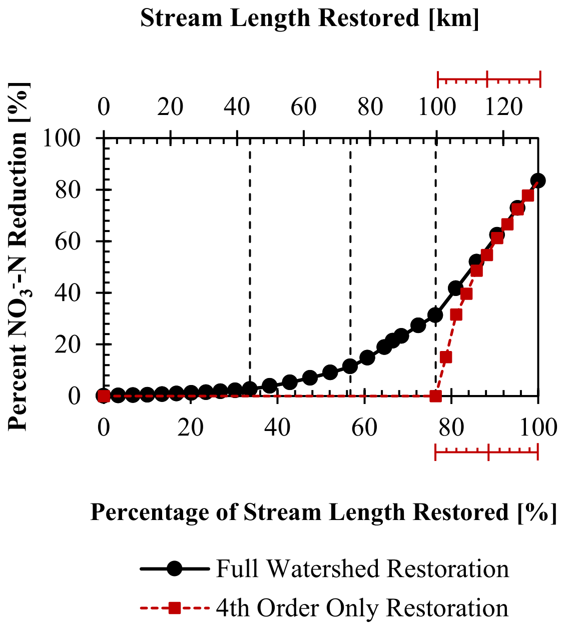


Figure 15. Percent nitrate-nitrogen (NO3-N) load/concentration reductions at the 4th order watershed outlet resulting from increasing percentages of the overall watershed restored, i.e. starting in the 1st order rivers and moving down to the outlet of the respective watershed. The red dashed line is for the individual 4th order restoration by itself as a comparison, and corresponds to the red x-axes. Reprinted from Calfe et al. (2022), copyright 2022, Elsevier.

<u>How do the answers to Question #1 above vary with watershed conditions such as degree of gaining?</u>

Increasing the degree of gaining clearly shuts off hyporheic flow (Hester and Doyle 2008, Azinheira et al. 2014), which would reduce nitrate removal induced by in-channel hyporheic restoration. The opposite would be true with decreasing the degree of gaining, where increasing the potential for hyporheic flow would occur. Nevertheless, we did test the effect of reducing the amount of hyporheic exchange induced by restoration by an order of magnitude, and found it reduced nitrate removal, but by less than an order of magnitude (compare Figures 14 and 16).

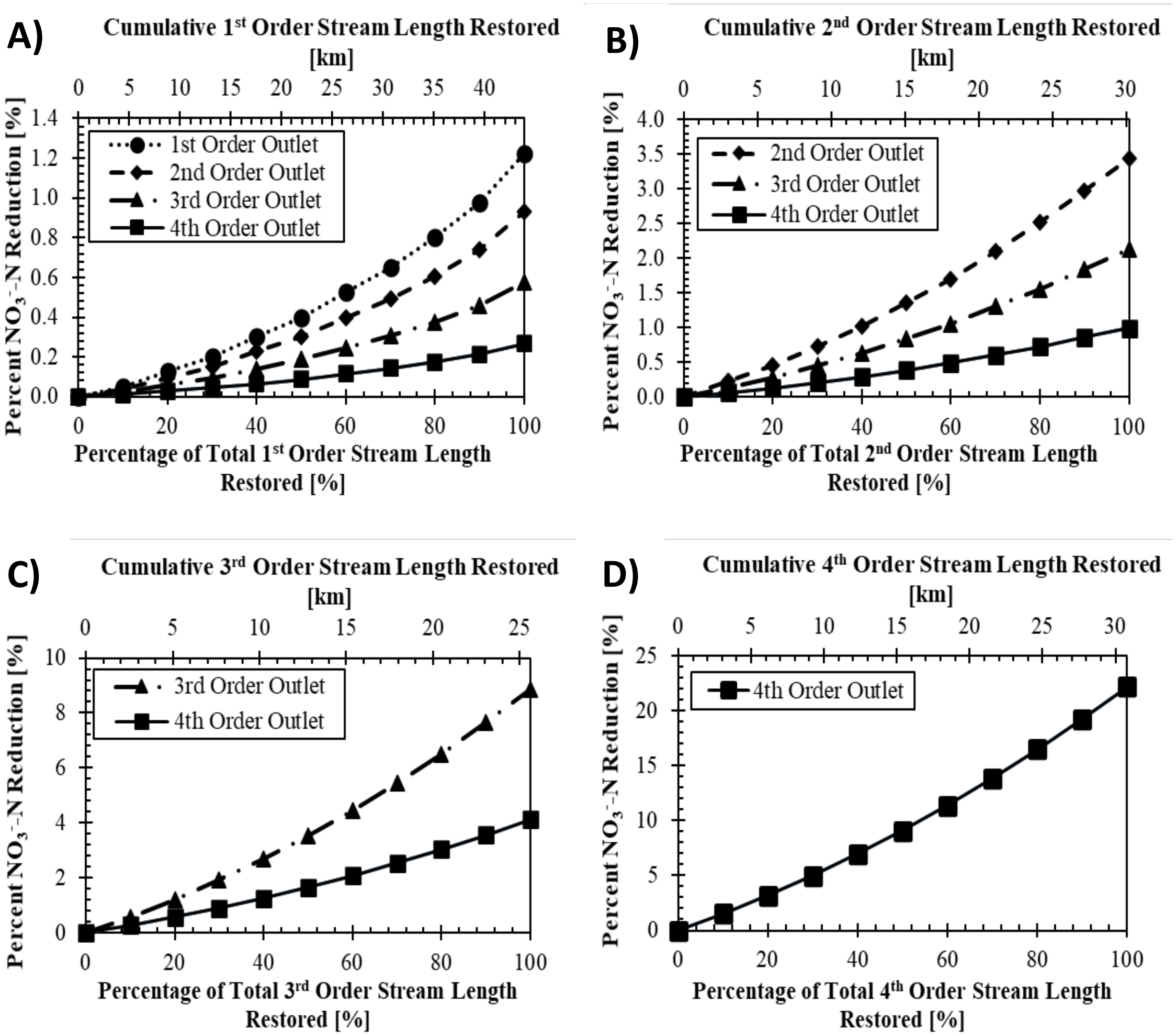


Figure 16. Percent nitrate-nitrogen (NO3-N) reduction in both concentration and mass at the furthest downstream cross section of the A) 1st-order rivers, B) 2nd-order rivers, C) 3rd-order rivers, and D) 4th-order river due to [hyporheic] restoration [induced by in-channel features] only in that respective stream order (rh = 0.03%). All Y-axis percent reductions are on both a concentration and load basis since we used a base concentration of 1 mg/L. X-axis is percent of the cumulative channel length of that stream order that was restored, which is equal to the percent restored of each individual river. Here we use official HEC-RAS terms where "river" means one individual channel, and "reach" means the parts of that river after being split by tributary junctions. Reprinted from Calfe et al. (2022), copyright 2022, Elsevier.

How do the answers to Question #1 above vary with watershed conditions such as soil type (hydraulic conductivity which controls potential for hyporheic restoration)?

According to Darcy's Law, hyporheic exchange is directly proportional to hydraulic conductivity (Hester and Doyle 2008). Because we assumed hyporheic nitrate removal is transport limited (Calfe et al. 2022), nitrate removal would also be proportional to hydraulic conductivity. Therefore, our simulations that reduced the amount of hyporheic exchange induced by restoration by an order of magnitude were equivalent to reducing the hydraulic conductivity of sediments by the same amount. The result was a reduction in nitrate removal, but by less than an order of magnitude (compare Figures 14 and 16).

Overall, these results emphasize the importance of watershed-scale planning in stream restoration. Additional detail on background, methods, results, interpretation, and significance can be found in Calfe et al. (2022).

4.1.2.2 Nitrate Removal during Storms by Floodplain (Bankfull, Stage 0) Restoration

Results of floodplain/Stage 0 restoration indicated that watershed nitrate removal could be significant, and increased with percent of channel length restored. Yet removal was generally small overall, ranging up to 1% or 19% of the watershed load, depending on use of a median or 90th-percentile removal rate, respectively. Removal varied depending on the location of restoration in the watershed and where removal was evaluated, with greatest effects in the stream order where restoration occurred, and diminishing effects downstream. Also, removal increased with stream order/channel size due to greater inundation times in larger rivers. Intermediate storm sizes (e.g., half-year storm) had the largest removal percentages due to the greater significance of removal compared to the watershed load. Finally, the removal rate strongly controlled overall degree of removal, and given the high degree of uncertainty of this parameter, indicates the need for more systematic field measurements of nitrate removal rate in restored floodplains, particularly throughout watersheds and over seasons.

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)?

Similarly to hyporheic restoration (Figure 14), for floodplain/Stage 0 restoration, the shape was often exponential, but also linear, levelling off, and even humped (Figure 17).

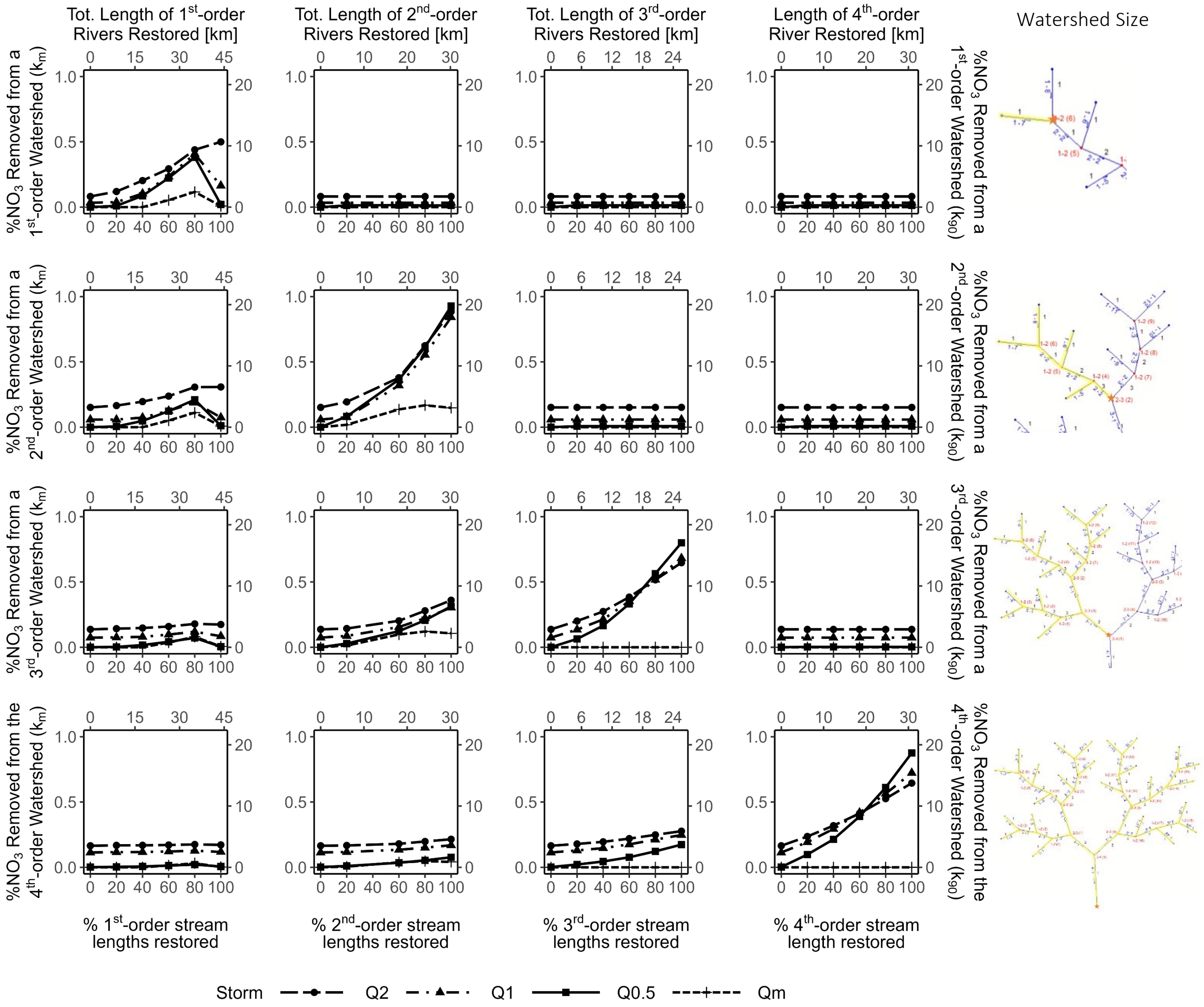


Figure 17. Percent nitrate removal from 1st-, 2nd-, 3rd-, and 4th-order watersheds due to varying location (stream order) and percent of channel length floodplain restored. By column, the stream order location of restoration changes and by row the watershed size where nitrate removal is evaluated changes. The yellow highlighted area in the "Watershed Size" column is where removal and input loads occur for that row. The two y-axes represent percent nitrate removal using the median (left) and 90th-percentile (right) removal rate. Restored length is a sum of all restored river lengths within an order.

How do the answers to Question #1 above vary with watershed conditions such as restoration technique (hyporheic restoration vs. floodplain restoration)?

See answers above regarding the shape of the relationships between percent restored and nitrate removal (Figures 14, 17). Additionally, we found that hyporheic restoration induced by in-channel features was generally more effective at removing nitrate than floodplain restoration (Figure 18) over an annual cycle. Yet a combination of restoration techniques will provide greater nitrate removal.

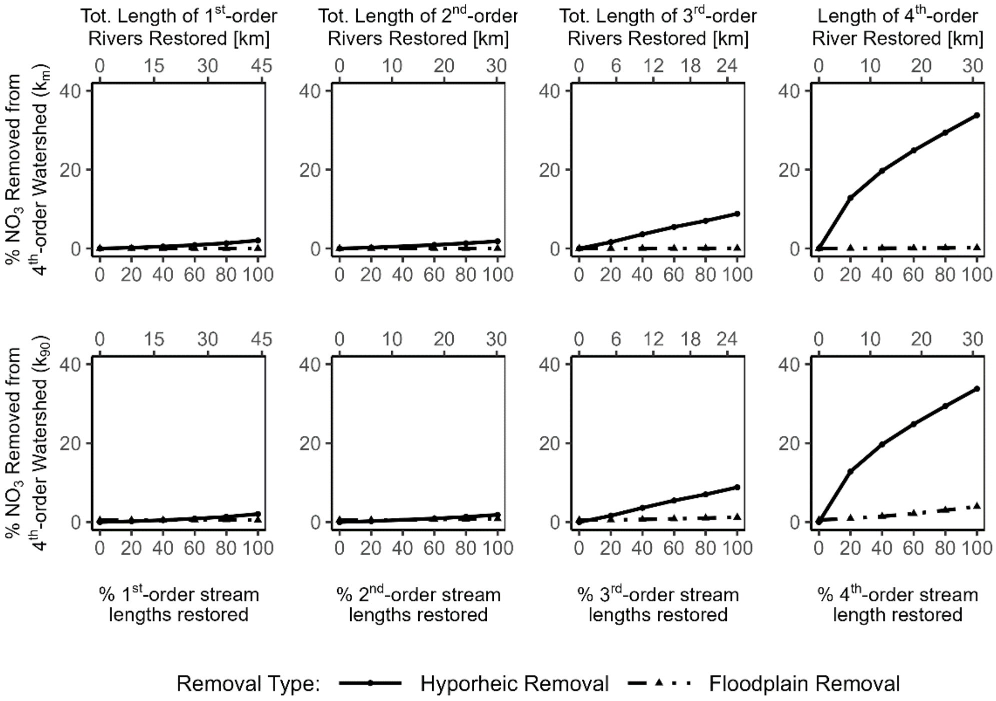


Figure 18. Comparison of results of hyporheic restoration induced by in-channel features from (Calfe et al. 2022) to floodplain restoration results using a synthetic annual hydrograph of 12 monthly storms, two half-year storms, one 1-year storm, one 2-year storm, and the remainder of time at baseflow. Simulation shows nitrate removal due to cumulatively restoring the length of each individual stream order. The first row shows percent 4th-order watershed nitrate removed using the median floodplain nitrate removal rate and the second shows removal for the 90th-percentile floodplain nitrate removal.

How do the answers to Question #1 above vary with watershed conditions such as restoration location (headwaters vs. along larger channels)?

We found that both hyporheic restoration induced by in-channel features and floodplain/Stage 0 restoration were most effective at removing nitrate on a watershed-scale basis when restoration occurred in the highest-order (largest) channel we simulated (4th-order, Figures 14, 19). Cumulative restoration of all the channels in the full 4th-order watershed did not increase removal much beyond just restoring the 4th-order channel, although concavity was reversed (Figure 20). Thus, restoring just the 4th-order river would be more efficient at nitrate removal than restoring all the channels in the full 4th-order watershed.

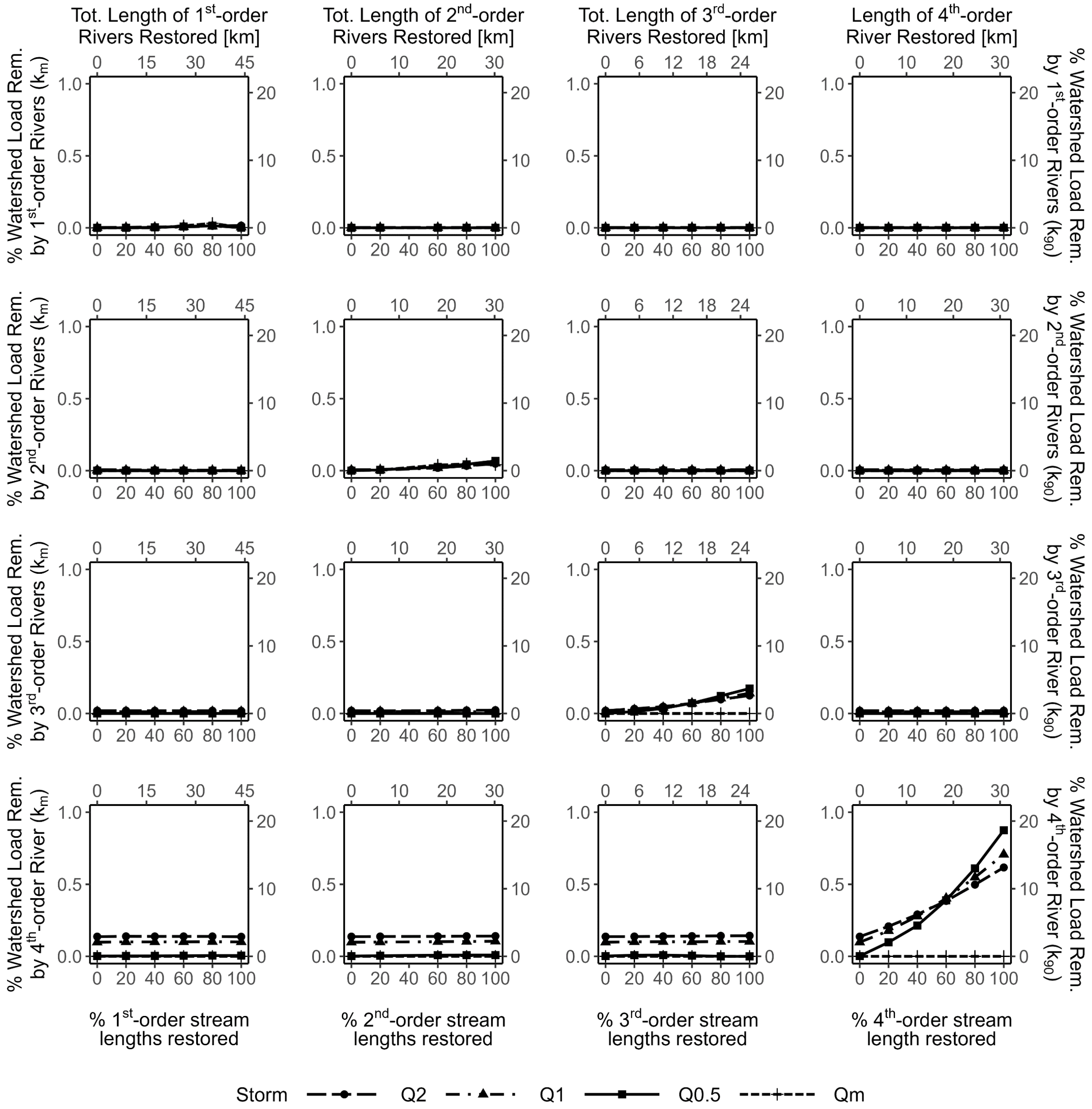


Figure 19. Percent of the 4th-order watershed nitrate load removed by each stream order due to varying restoration location (stream order) and cumulative length restored. By column the stream order location of restoration changes and by row the stream order where nitrate removal is evaluated changes. The rows represent removal of the 4th-order watershed load by (1) all 24 1st-order rivers, (2) all six 2nd-order rivers, (3) both 3rd-order rivers, and (4) the 4th-order river. The two y-axes represent percent nitrate removal using a median (left) and 90th-percentile (right) removal rate. Restored length is a sum of all restored river lengths within a stream order.

Additional detail on results, interpretation, and significance can be found in Morgan Oehler's thesis among the supporting files.

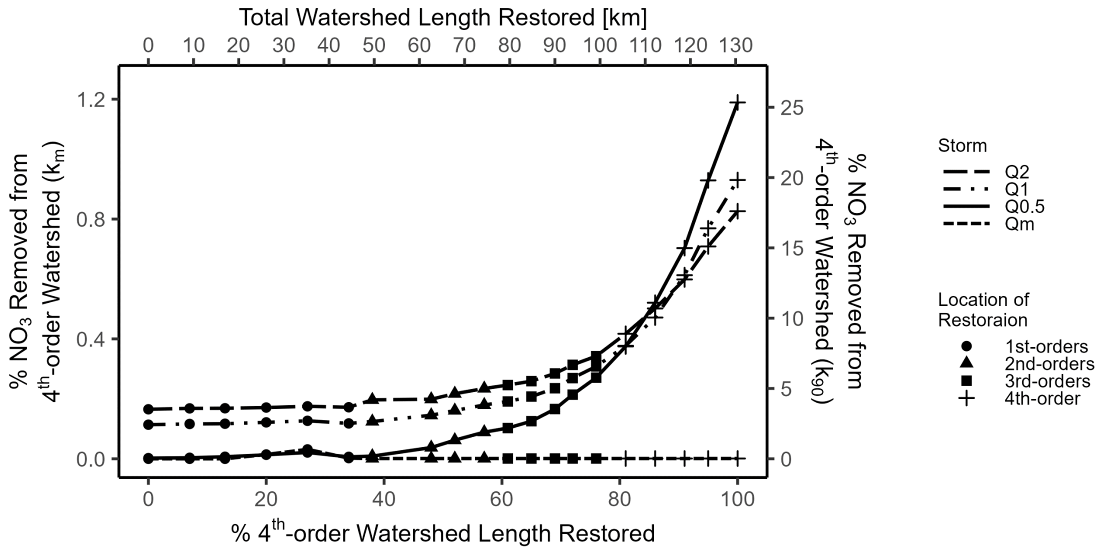


Figure 20. Percent of the 4th-order watershed load removed due to cumulative restoration of the full 4th-order watershed length. Restoration began at the upstream end of the first order rivers and was increased cumulatively through the 4th-order watershed outlet.

4.2 Results that Support or Supplement Key Research Questions (Tasks 1, 4)

4.2.1 Nitrate Removal Rate Database (Task 1)

Task 1 entailed performing a literature review of the effects of stream channel and floodplain restoration practices on nitrate removal, and analyzing the resulting database of recorded nitrate removal rates for variation in with key controlling parameters of interest.

4.2.1.1 Literature Review

One of the main findings from the literature review is that nearly all rates are for small (1^{st}-3^{rd} order) streams (Table 6). There were also no studies that systematically looked at variation throughout large (>3^{rd} order) watersheds. Thus, there is a need for more systematic studies on channel networks in larger systems.

Table 6. Number of locations with floodplain and channel engineering restoration practices in our database broken down by stream order.

Stream order	Bankfull floodplain restoration project locations	Channel engineering restoration project locations	Stage 0 restoration project locations
1	9	13	0
2	3	16	2
3	4	7	0
4	2	2	0
5	3	2	0
6	5	2	0
7	5	0	0
8	1	0	0
9	2	0	0
10	3	3	0
NA*	30	12	0
Total	67	57	2

* stream order could not be determined

Additional detail on results, interpretation, and significance can be found in “Literature Review of Nitrate Removal Rates by Stream Restoration Practices and Summary of Removal Rate Database.pdf,” and the database itself can be found in “Literature Removal Rate Database.xls” among the supporting files.

4.2.1.2 Data Analysis

Key outcomes of the Random Forest-Artificial Neural Network (RF-ANN) analysis were that hydrologic condition (baseflow vs. storm flow) was the most important variable (highest Variable Importance, or VI) (Tables 7, 8), with rates higher during baseflow. Stream order also relatively important, with rates higher in headwater streams. Season of the year was relatively unimportant.

Table 7. Variable importance (VI) scores and ranking of predictor variables associated with nitrate removal rates for Analysis A vs. B: with versus without nitrogen concentration, including all restoration statuses (actual nitrate removal rates). VI values were selected from the model with the median NSE for each analysis.

	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	1.242	Season	0.067
6	Season	1.179		

Table 8. Variable importance (VI) scores and ranking of predictor variables associated with nitrate removal rates for Analysis C vs. D: with versus without nitrogen concentration, including only restored reaches (actual nitrate removal rates). VI values were selected from the model with the median NSE for each analysis.

	Analysis C		**Analysis D**	
Rank	Variable	VI	Variable	VI
1	Hydrologic condition	1.225	Hydrologic condition	1.203
2	Restoration type	0.808	Restoration status	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		

Additional detail on results, interpretation, and significance can be found in Luke Goodman's thesis among the supporting files.

4.2.2 Case Study Watershed Model (Task 4)

4.2.2.1 Flood Attenuation

Results indicated that restoration mainly increased peak flow on the main channel (Figure 21). This effect was small (up to 0.9%), but clearly not a decrease in flow. The few exceptions were for the monthly storm for the greater restoration lengths at the downstream end of modeled reach. This increase in peak flow from restoration was due to slowing of the flood wave on the main channel which was then better synchronized with tributary inflows.

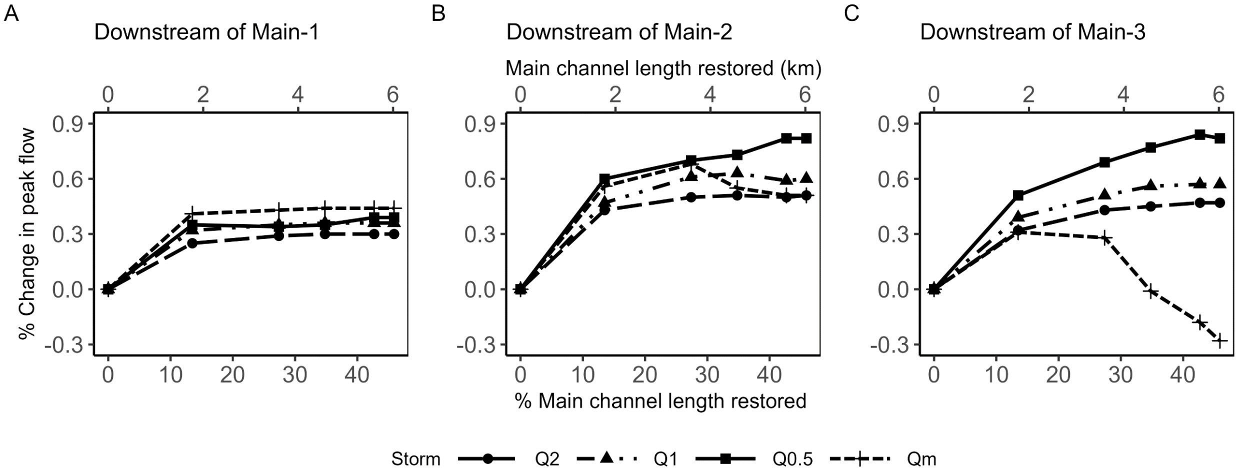


Figure 21. Percent change in peak flow from unrestored conditions at three locations on the main channel (Figure 6): (A) downstream end of Main-1 (just upstream of Dead Run confluence) (B) downstream end of Main-2 (just upstream of Maiden's Choice Run confluence) and (C) the watershed outlet. Note restoration lengths increase upstream to downstream cumulatively on the main channel. Thresholds in A and B are after the upstream lengths were fully restored.

4.2.2.2 Nitrate Removal

Restoration increased nitrate removal but at low levels (up to 0.12% or 2.6% removal for a median and 90th-percentile removal rate respectively) (Figure 22). This minimal effect was due to the small footprint of restoration in the watershed (up to 21.4% of the main channel was restored), which was due in turn to modeling limitations (HEC-RAS geometry files were available for a minority of the mainstem length) and practical restoration limitations by existing infrastructure in an urban watershed.

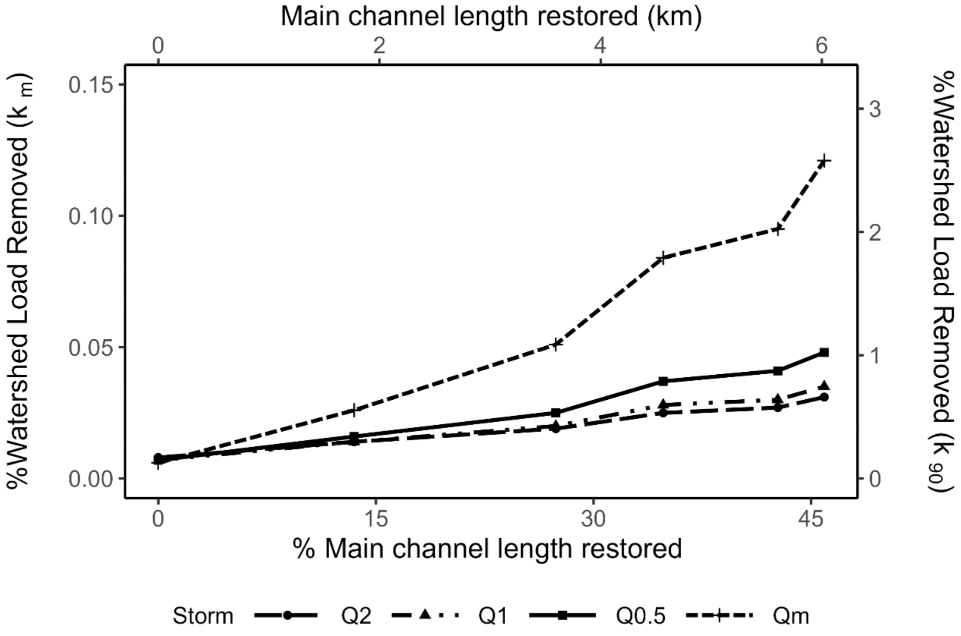


Figure 22. Percent of the Gwynns Falls watershed nitrate removed in the model domain due to cumulative restoration of the main channel. The watershed load includes loads upstream of our model domain. Watershed removal includes removal in tributary floodplains.

4.2.2.3 Methodological Results

Restoration effects were limited by existing infrastructure, yet earth moving and hence restoration costs would still be substantial. This argues for larger-scale solutions to address watershed-scale water quality and flooding issues, yet the required resources may be beyond typical practice, requiring re-evaluation against other societal needs. Time-efficient modeling of a complex watershed was facilitated by HEC-RAS model geometries being available from a public source (Maryland Department of the Environment) but was limited by the fact that only a certain fraction of the full watershed channel network was available at the time of modeling. We also benefited from extensive flow and water quality data, which may not be available for all projects. Watershed-scale modeling is necessary to understand channel network effects such as peak flow synchronization, but cost effectiveness of this approach may be highly variable given data availability.

Additional detail on background, methods, results, interpretation, and significance can be found in Morgan Oehler's thesis among the supporting files.

5. DISCUSSION

5.1 Controls on Nitrate Removal from Restoration

This study answered a number of important questions about how the effects of individual restoration projects on flood attenuation and nitrate removal add up at larger watershed or channel network scales. Key conclusions include that the incremental benefit of individual projects depend upon both where in the watershed the restoration occurs, but also how much restoration has happened already in the watershed. While restoration can induce significant watershed-scale flood attenuation and nitrate removal, often the effects are fairly small for nitrate removal even with extensive restoration, and in some cases, restoration can unintentionally increase peak storm flows.

A key limitation on success of extensive in-channel hyporheic enhancement for nitrate removal is the recycling of water that occurs when surface water cycles through the hyporheic zone multiple times. This effect increases in the downstream direction from 1st-order to 4th-order channels and implies a maximum possible removal at the watershed scale, but will only occur at restoration levels that are beyond what is likely to be achieved in real watersheds in the near term (Calfe et al. 2022).

Floodplain and Stage 0 restoration had a significant effect on flood attenuation with potential to mitigate from increases in peak flows due to climate change (Katz et al. 2002, Donat et al. 2016, Pendergrass et al. 2017, Cook et al. 2020). Stage 0 generally had a greater effect than bankfull floodplain restoration on flood attenuation and nitrate removal due to greater overbank inundation and residence times. Flood attenuation was greatest if there was minimal overbank flow prior to restoration and significant overbank flow after restoration. This occurred primarily for small to intermediate storms such as the 0.5-year event and carried over into the nitrate removal results as well.

Effects of floodplain and Stage 0 restoration were generally greatest on flood attenuation in the same stream order where restoration occurred. This local effect was greatest in lower-order channels. On the other hand, when looking at the effect of restoring individual stream orders on the larger watershed, restoring the 2nd-order channels was the most effective. Many of these effects can be attributed to relatively greater reduction in bank heights for the 1st- and 2nd-order channels than the higher-order channels.

A key factor controlling the overall level of flood attenuation and nitrate removal simulated in our study is floodplain area relative to watershed area. We strongly constrained the lateral width of our restored floodplains in the model because we were often simulating substantial lengths of restoration, and we felt that wider floodplain widths are not realistic along large channel lengths or substantial fractions of watershed channel networks. But increasing floodplain width is another way to increase flood attenuation or nitrate removal without increasing channel length restored. Among the stream orders we simulated, nitrate removal was limited by inundation time in lower-order rivers (1st- and 2nd-order) and by inundated area in higher-order channels (3rd- and 4th-order).

Floodplain restoration of higher-order channels removed more nitrate during storms than lower-order channels at the 4th-order watershed scale regardless of the location of restoration. Since the inundated areas across all stream orders were similar for all restoration scenarios, removal at the 4th-order watershed outlet was greatest in the 4th-order channel due to longer inundation times. Lower order-channels did not have significant impacts on watershed nitrate removal because of their limited inundation durations. Similarly, our model results indicated that hyporheic enhancement within larger channels could have as much or more nitrate removal as restoring all the lower-order channels (Calfe et al. 2022). Thus a tradeoff was revealed, where restoration of larger channels is typically more expensive, but more effective at nitrate removal. By contrast, restoration on low order rivers is typically less expensive, but less effective. Ultimately, at least some restoration on higher-order channels may necessary to achieve substantial nitrate reduction objectives.

In our annual simulation, hyporheic restoration removed substantially more nitrate than floodplain restoration for multiple reasons. First, baseflow occurred for greater duration during the annual cycle compared to flood flow, therefore hyporheic flow had more active removal time. Second, hyporheic structures were assumed to induce complete removal in any flow cycled through the bed, whereas our floodplain removal was limited by the removal rate. Third, hyporheic restoration induced greater percent exchange of channel flow than floodplain restoration. Although hyporheic removal from removal was generally greater, floodplain removal was greater at unrestored conditions because our model assumed no hyporheic removal in the unrestored watershed.

5.2 Applied Significance of Findings

Here we summarize the helpful translation efforts of David Hirschman (Hirschman Water and Environment, LLC and National Fish and Wildlife Foundation Liaison), Shannon McKenrick (Maryland Dept of the Environment, Watershed Protection Restoration and Planning Program) and Joe Berg (BioHabitats) at the 2022, 2023, and 2024 Pooled Monitoring Forums, respectively.

The nitrate removal database was acknowledged as a valuable dataset for evaluating stream restoration effectiveness at varying scales and considering design context. However, it also showed the limitations of existing data, and pointed to future data collection in that area (Section 5.3, below). Regarding the generic watershed modeling that addressed the key research questions in Section 2 above, a number of findings were valuable:

- It is clear from both the flood attenuation and nitrate removal simulations that spatially longer restoration projects deliver greater benefits than shorter ones, all else being equal. This is not a surprise, but is useful in supporting recent pushes toward longer restoration projects.
- The finding that greater nitrate removal generally occurred with treatment of baseflow (hyporheic processing) than storm flow (floodplain processing) over an annual timescale should also generally not be a surprise because hyporheic processing occurs almost continually relative to storm events with favorable water volume to hyporheic bed volume.
- Outcomes for both flood attenuation and nitrate removal vary depending on where restoration takes place along the stream corridor.
- The finding that headwater restorations are less important than 4th-order stream restorations for nitrate removal processing relates to an important debate currently occurring in the practitioner community, and should be evaluated against other studies and evidence. Restoring larger channels, particularly floodplains, is often not possible due to much large 100-year floodplain in higher-order channel relative to lower-order channels, and the associated increased difficulty of getting landowner agreement. Furthermore, lowering floodplain surfaces

along larger channels more likely creates flooding issues for infrastructure and FEMA map revisions.
- There are trade-offs in thinking about the effectiveness of individual projects vs. cumulative watershed affects.

A number of methodological insights were also derived:

- The prediction that less nitrate removal occurs with floodplain reconnection than expected or relative to that from in-channel hyporheic enhancement at baseflow may be the result of how the analysis was conducted. In particular the fact that the model simulated surface water floodplain inundation but not any subsequent flood water infiltration into the floodplain may have underestimated the net nitrate removal expected from reconnection.
- Developing complex models of this kind to answer important questions as those evaluated in this project is a challenge. It is not a quick, easy, or inexpensive approach, and thus will require considerable funds and time.

When considering planning, permitting, development of regulations, and development of practitioner guidance, a number of findings were of value. Understanding the performance of an individual project requires understanding how individual projects fit into a watershed framework. A key question is how to evaluate projects while taking into account cumulative watershed restoration impacts? This has implications for what information is needed from project design documents and analysis to determine whether desired outcomes are likely and achievable. It also has implications for the personnel expertise needed to examine designs. In both cases, evaluating the benefit of an individual project may require a larger-scale simulation that accounts for influences at the watershed/channel network scale. Incorporating this watershed context into the regulatory process may entail a shift in perspective.

When considering design of future restoration projects, a related set of findings were of value:

- For floodplain restoration projects, low bank height (i.e. Stage 0 rather than bankfull floodplain) was beneficial, regardless of the benefit of interest (flood attenuation, nitrate removal).
- The design approach should be nested within the watershed context: where, how much restored, optimization of peak flow reduction, watershed storage, water quality, habitat, etc. Important to pick the best location in addition to picking the best technique, and the best location may vary depending on which of the benefits stated above is of most interest.
- It is important to manage expectations for design results given outcomes are dependent on design type, location related to channel, location within watershed, stream order, etc.
- Evaluating the benefit of an individual project may require a larger-scale simulation that accounts for influences at the watershed/channel network scale. There are ways to reduce the expense of such simulations (e.g., HEC-RAS geometry files available from Maryland Dept of Environment).
- Models may be required to evaluate design alternatives at watershed scales, but practitioners also need to continue to look through the literature for studies that measure actual project performance.

The value of the findings for researchers are mainly in that these results point to the critical importance of watershed-scale analyses to really understand the impact of restoration projects and to move the field forward.

5.3 Method Limitations and Future Directions

As a first effort to simulate the effect of varying large-scale spatial patterns of multiple stream restoration locations throughout watersheds, we necessarily needed to limit the number of key controlling variables that we varied in our sensitivity analysis. This approach also allowed us to generalize our results to the broader Chesapeake Bay Watershed. Nevertheless, the effects of variation in other parameters could be pursued in the future, for example more nuanced spatial variation in channel dimensions or sediment texture, or floodplain dimensions and slopes. Furthermore, we limited our simulations to a 4th-order channel network for reasons of model tractability (even our 4th-order model had substantial run times) but also because nitrate removal data are largely unavailable for larger channels. Yet our approach could be extended to larger channel networks as computational power continues to increase, and if data become available for larger channels.

For the steady-state model of baseflow conditions used to simulate nitrate removal by in-channel hyporheic enhancement, we assumed circumneutral hydraulic gradients between surface water and groundwater and uniform hydraulic conductivity of sediments. More strongly gaining or losing conditions would reduce induced hyporheic exchange, and variation of hydraulic conductivity among stream orders could alter the distribution of nitrate removal within the watershed. We also assumed no hyporheic exchange prior to restoration, which if not true would reduce the calculated nitrate removal benefit of restoration.

For the unsteady model of storm conditions used to simulate nitrate removal and flood attenuation by floodplain and Stage 0 restoration, we did not simulate surface water-groundwater interaction. This interaction would potentially increase the flood attenuation predicted, although the effect would likely vary significantly with sediment hydraulic conductivity and groundwater gradients. Furthermore, this approach lumped any subsurface floodplain infiltration and nitrate removal processes into the area nitrate removal applied in the model. While the removal rates from the literature likely do account for some subsurface removal potential at these restoration sites, simulating such removal explicitly would allow a sensitivity analysis with more granular variation in floodplain hydrologic processes.

An important implication of our literature review and analysis of nitrate removal rates (Task 1), and our attempt to use the results in the modeling (Tasks 3-4), is that nitrate removal rate is one of the single biggest drivers of the overall level of nitrate reduction that occurs due to floodplain/Stage 0 restoration. Yet nitrate removal is quite poorly constrained by data, particularly for larger channels (> 3rd-order), and among seasons. There is still fairly little data and thus significant noise exists among available data. For this reason, a critical need is a systematic study of how nitrate removal rates vary among floodplain restoration settings, throughout watersheds/channel networks, and across seasons. A key driving factor for this variability is likely hydrology, specifically how nitrate removal rate varies with channel flow conditions. While our RF-ANN analysis indicated that nitrogen concentration was often not among the most important factors controlling nitrate removal rate, a more complete analysis could quantify variation with this key parameter, with the purpose of incorporating such information into models that explicitly incorporate Monod kinetics. More complete future nitrate removal datasets would also enable a more rigorous stochastic approach where a full probability distribution function of nitrate removal rates could be used in Monte Carlo simulations to better understand uncertainty in our results.

While our NSE values indicate our RF-ANN analysis was not overfitted, care should be taken with such issues in any future analyses of this kind.

Lastly, we only simulated movement and removal of inorganic nitrate. This choice was justified for a first effort given that nitrate typically makes up the bulk of nitrate migration in impacted watersheds. Yet incorporation of other forms of inorganic as well as organic nitrogen are necessary for a full picture. Simulating other nutrients such as phosphorous could follow.

6. CONCLUSIONS

We simulated the cumulative effect of multiple stream restoration projects within a channel network of a 4th-order watershed on nitrate removal. We evaluated effects of in-channel hyporheic enhancement at baseflow using a steady-state HEC-RAS model plus an R script, and floodplain/Stage 0 restoration during storm events using an unsteady HEC-RAS model plus other R scripts. We also evaluated the impact of multiple floodplain/Stage 0 restoration projects on flood attenuation at the same spatial scales. In order to provide nitrate removal rate data for the floodplain/Stage 0 restoration simulations, we conducted a literature review of nitrate removal rates from field studies and analyzed those rates using a Random Forest approach followed by an Artificial Neural Network (RF-ANN) modeling.

Our model results of in-channel hyporheic enhancement under baseflow conditions indicated that restoration of higher-order (larger, more downstream) channels was more effective at removing nitrate than restoration of lower-order (headwater) channels. In fact, restoring just the 4th-order channel alone could cause similar nitrate removal as restoring all the lower-order channels combined. Reducing the amount of hyporheic exchange induced by restoration (representing a decrease in hydraulic conductivity or increase in channel hydrologic gaining) predictably reduced nitrate removal.

Our model results of floodplain/Stage 0 restoration during storm events indicated that both bankfull floodplain and Stage 0 restoration generally attenuated flooding downstream (reduced peak flows), yet Stage 0 (low banks) was generally more effective than bankfull (high banks). These practices thus have potential to mitigate increases in peak flows due to urbanization and climate change. Flood attenuation was greatest if there was minimal overbank flow prior to restoration and significant overbank flow after restoration, which occurred primarily for small to intermediate storms such as the 0.5-year event. Flood attenuation was generally greatest in the same stream order as the restoration, this local effect was greatest in lower-order channels, and was diminished in larger-order channels downstream. In a sensitivity analysis of possibly controlling factors, restored floodplain width was one of the most important in controlling flood attenuation. Nevertheless, we note that restoration increased peak flows in a minority of cases, particularly for the monthly storm. This indicates that restoration could make flooding worse in certain locations, which is likely due to peak flow synchronization. Importantly, such synchronization can only be simulated using a channel network model.

Our model results of floodplain/Stage 0 restoration during storm events indicated that watershed nitrate removal could be significant, and increased with percent of channel length restored, but was overall of small magnitude. Stage 0 generally had a greater effect than bankfull floodplain restoration on nitrate removal due to greater overbank inundation and residence times. Similarly to flood attenuation, nitrate removal was greatest at the location of restoration and decreased downstream, but unlike flood attenuation (but similar to in-channel hyporheic enhancement), removal was greater when restoration occurred in higher-order channels. Also similarly to flood attenuation, nitrate removal was greatest if there was minimal overbank flow prior to restoration and significant overbank flow after restoration (i.e. during small to intermediate storms). Therefore, restoration practitioners should consider restoration of larger rivers before investing in small-scale projects that may have negligible impact at the watershed scale. From an implementation standpoint, restoration benefits will often be limited by existing infrastructure, yet earth moving and hence restoration costs can be substantial even to restore relatively smaller percentages of channel networks. This argues for larger-scale solutions to address watershed-scale water quality and flooding issues, yet the required resources may be beyond typical practice, requiring evaluation against other societal needs.

Our results demonstrate the importance of simulating complete watersheds to understand the effects of proposed restoration projects, but developing such complex models can be difficult and expensive. Yet there are ways to reduce the expense of such simulations, for example in our case study using HEC-RAS geometry files available from Maryland Dept of Environment. Nevertheless, not all watersheds and jurisdictions will have such data available, thus yield heterogeneous results. Among model parameters, removal rate was one of the most important in controlling the degree of removal, but the relative dearth of existing field data results in an inability to assign varying removal rates for varying conditions such as steam order, flow conditions, or season. Thus there is a clear need for more systematic field measurements of nitrate removal rate in restored floodplains, particularly in higher-order channels and over seasons.

When comparing nitrate removal from in-channel hyporheic enhancement to that from floodplain/Stage 0 restoration on an annual basis, we found that hyporheic enhancement was substantially more effective. This is likely the effect of the greater duration of baseflow and larger percent of surface water cycling through the hyporheic zone compared to overbank flow, but may also be affected by our floodplain simulations not directly simulating groundwater nitrate removal.

Overall, we conclude that watersheds are irreducibly complex, and effects of restoration projects in that context depend on the locations of both restoration projects and where effects are measured within the channel network. Thus, large-scale watershed/channel network models are indispensable in this context to assess the effects of proposed restoration projects. Yet while restoration can induce significant watershed-scale flood attenuation and nitrate removal, often the effects are fairly small for nitrate removal even with extensive restoration, and in some cases, restoration can unintentionally increase peak storm flows. A consistent finding during both baseflow and storm conditions was that restoration of higher-order channels was more effective for nitrate removal at the watershed scale than was restoration of lower-order channels. This sets up a tradeoff, as restoration of larger order channels is more expensive and often more constrained by infrastructure. It is important to manage expectations for design results with outcomes dependent on watershed parameters such as channel network position and prior restoration.

REFERENCES

Ahmed, A. A. M., R. C. Deo, Q. Feng, A. Ghahramani, N. Raj, Z. L. Yin, and L. S. Yang. 2021. Deep learning hybrid model with Boruta-Random forest optimiser algorithm for streamflow forecasting with climate mode indices, rainfall, and periodicity. Journal of Hydrology **599**.

Alexander, R. B., R. A. Smith, and G. E. Schwarz. 2000. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. Nature **403**:758-761.

Altland, D., C. Becraft, J. Berg, T. Brown, J. Burch, D. Clearwater, J. Coleman, S. Crawford, B. A. Doll, J. H. Geratz, J., J. Hartranft, J. Hottenstein, S. Kaushal, S. Lowe, P. Mayer, G. Noe, W. Oberholzer, A. Parola, D. Scott, B. Stack, B. W. Sweeney, and J. White. 2020. Consensus Recommendations to Improve Protocols 2 and 3 for Defining Stream Restoration Pollutant Removal Credits. Prepared by David Wood and Tom Schueler, Chesapeake Stormwater Network. October 27, 2020.

Amaratunga, D., J. Cabrera, and Y. S. Lee. 2008. Enriched random forests. Bioinformatics **24**:2010-2014.

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**:6168-6190.

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.

Berg, J., D. Streaker, and C. Streb. 2020. Stream Restoration Using Engineered Wood Structures Harvested from On-site: The Past and Future of Streams. Ecological Restoration **38**:257-264.

Bernhardt, E. S., M. A. Palmer, J. D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G. M. Kondolf, P. S. Lake, R. Lave, J. L. Meyer, T. K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth. 2005. Ecology - Synthesizing US river restoration efforts. Science **308**:636-637.

Burkholder, J. M., and H. B. Glasgow. 2001. History of toxic Pfiesteria in North Carolina estuaries from 1991 to the present. Bioscience **51**:827-841.

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.

Chen, T. L., Y. Cao, Y. N. Zhang, J. J. Liu, Y. Q. Bao, C. R. Wang, W. P. Jia, and A. H. Zhao. 2013. Random Forest in Clinical Metabolomics for Phenotypic Discrimination and Biomarker Selection. Evidence-Based Complementary and Alternative Medicine **2013**.

Christopher, S. F., J. L. Tank, U. H. Mahl, H. Yen, J. G. Arnold, M. T. Trentman, S. P. Sowa, M. E. Herbert, J. A. Ross, M. J. White, and T. V. Royer. 2017. Modeling nutrient removal using watershed-scale implementation of the two-stage ditch. Ecological Engineering **108**:358-369.

Cluer, B., and C. Thorne. 2014. A STREAM EVOLUTION MODEL INTEGRATING HABITAT AND ECOSYSTEM BENEFITS. River Research and Applications **30**:135-154.

Cook, B. I., J. S. Mankin, K. Marvel, A. P. Williams, J. E. Smerdon, and K. J. Anchukaitis. 2020. Twenty-First Century Drought Projections in the CMIP6 Forcing Scenarios. Earths Future **8**.

Craig, L. S., M. A. Palmer, D. C. Richardson, S. Filoso, E. S. Bernhardt, B. P. Bledsoe, M. W. Doyle, P. M. Groffman, B. A. Hassett, S. S. Kaushal, P. M. Mayer, S. M. Smith, and P. M. Wilcock. 2008. Stream restoration strategies for reducing river nitrogen loads. Frontiers in Ecology and the Environment **6**:529-538.

Donat, M. G., A. L. Lowry, L. V. Alexander, P. A. O'Gorman, and N. Maher. 2016. More extreme precipitation in the world's dry and wet regions. Nature Climate Change **6**:508-+.

Fang, H., B. Jamali, A. Deletic, and K. F. Zhang. 2021. Machine learning approaches for predicting the performance of stormwater biofilters in heavy metal removal and risk mitigation. Water Research **200**.

Federman, C., 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.

Flitcroft, R. L., W. R. Brignon, B. Staab, J. R. Bellmore, J. Burnett, P. Burns, B. Cluer, G. Giannico, J. M. Helstab, J. Jennings, C. Mayes, C. Mazzacano, L. Mork, K. Meyer, J. Munyon, B. E. Penaluna, P. Powers, D. N. Scott, and S. M. Wondzell. 2022. Rehabilitating Valley Floors to a Stage 0 Condition: A Synthesis of Opening Outcomes. Frontiers in Environmental Science **10**.

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

Hanson, G. C., P. M. Groffman, and A. J. Gold. 1994. DENITRIFICATION IN RIPARIAN WETLANDS RECEIVING HIGH AND LOW GROUNDWATER NITRATE INPUTS. Journal of Environmental Quality **23**:917-922.

Harvey, J. W. 2016. Hydrologic exchange flows and their ecological consequences in river corridors.*in* J. B. Jones and E. H. Stanley, editors. Stream ecosystems in a changing environment. Academic Press, London, U.K.

Hester, E. T., and M. N. Gooseff. 2010. Moving Beyond the Banks: Hyporheic Restoration Is Fundamental to Restoring Ecological Services and Functions of Streams. Environmental Science & Technology **44**:1521-1525.

Hester, E. T., and M. N. Gooseff. 2011. Hyporheic Restoration in Streams and Rivers.*in* A. Simon, S. J. Bennett, and J. M. Castro, editors. Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools American Geophysical Union, Washington, DC.

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., C. G. Guth, D. T. Scott, 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.

Katz, R. W., M. B. Parlange, and P. Naveau. 2002. Statistics of extremes in hydrology. Advances in Water Resources **25**:1287-1304.

Lammers, R. W., and B. P. Bledsoe. 2017. What role does stream restoration play in nutrient management? Critical Reviews in Environmental Science and Technology **47**:335-371.

Lawrence, J. E., M. E. Skold, F. A. Hussain, D. R. Silverman, V. H. Resh, D. L. Sedlak, R. G. Luthy, and J. E. McCray. 2013. Hyporheic Zone in Urban Streams: A Review and Opportunities for Enhancing Water Quality and Improving Aquatic Habitat by Active Management. Environmental Engineering Science **30**:480-501.

Mohammady, M., H. R. Pourghasemi, and M. Amiri. 2019. Land subsidence susceptibility assessment using random forest machine learning algorithm. Environmental Earth Sciences **78**.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the Asabe **50**:885-900.

Moriasi, D. N., M. W. Gitau, N. Pai, and P. Daggupati. 2015. HYDROLOGIC AND WATER QUALITY MODELS: PERFORMANCE MEASURES AND EVALUATION CRITERIA. Transactions of the Asabe **58**:1763-1785.

Mulholland, P. J., A. M. Helton, G. C. Poole, R. O. Hall, S. K. Hamilton, B. J. Peterson, J. L. Tank, L. R. Ashkenas, L. W. Cooper, C. N. Dahm, W. K. Dodds, S. E. G. Findlay, S. V. Gregory, N. B. Grimm, S.

L. Johnson, W. H. McDowell, J. L. Meyer, H. M. Valett, J. R. Webster, C. P. Arango, J. J. Beaulieu, M. J. Bernot, A. J. Burgin, C. L. Crenshaw, L. T. Johnson, B. R. Niederlehner, J. M. O'Brien, J. D. Potter, R. W. Sheibley, D. J. Sobota, and S. M. Thomas. 2008. Stream denitrification across biomes and its response to anthropogenic nitrate loading. Nature **452**:202-U246.

Newcomer Johnson, T. A., S. Kaushal, P. M. Mayer, R. M. Smith, and G. M. Sivirichi. 2016. Nutrient retention in restored streams and rivers: A global review and synthesis. Water **8**:1-28.

Nitze, I., U. Schulthess, and H. Asche. 2012. Comparison of machine learning algorithms random forest, artificial neural network and support vector machine to maximum likelihood for supervised crop type classification. . Proceedings of the 4th GEOBIA, Rio de Janeiro, Brazil **79**:3540.

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.

Paerl, H. W., W. S. Gardner, K. E. Havens, A. R. Joyner, M. J. McCarthy, S. E. Newell, B. Qin, and J. T. Scott. 2016. Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. Harmful Algae **54**:213-222.

Pendergrass, A. G., R. Knutti, F. Lehner, C. Deser, and B. M. Sanderson. 2017. Precipitation variability increases in a warmer climate. Scientific Reports **7**.

Powers, P. D., M. Helstab, and S. L. Niezgoda. 2019. A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network. River Research and Applications **35**:3-13.

Price, A. N., C. N. Jones, J. C. Hammond, M. A. Zimmer, and S. C. Zipper. 2021. The Drying Regimes of Non-Perennial Rivers and Streams. Geophysical Research Letters **48**.

Rodriguez-Galiano, V., M. Sanchez-Castillo, M. Chica-Olmo, and M. Chica-Rivas. 2015. Machine learning predictive models for mineral prospectivity: An evaluation of neural networks, random forest, regression trees and support vector machines. Ore Geology Reviews **71**:804-818.

Shortridge, J. E., S. D. Guikema, and B. F. Zaitchik. 2016. Machine learning methods for empirical streamflow simulation: a comparison of model accuracy, interpretability, and uncertainty in seasonal watersheds. Hydrology and Earth System Sciences **20**:2611-2628.

Sinha, E., A. M. Michalak, and V. Balaji. 2017. Eutrophication will increase during the 21st century as a result of precipitation changes. Science **357**:405-408.

USEPA. 2010. Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment. December 29, 2010. U.S. Environmental Protection Agency, Region 3.

USEPA. 2013. Impaired Waters and Total Maximum Daily Loads. United States Environmental Protection Website. http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/index.cfm Reference January 3, 2013.

Vilmin, L., J. M. Mogollon, A. H. W. Beusen, and A. F. Bouwman. 2018. Forms and subannual variability of nitrogen and phosphorus loading to global river networks over the 20th century. Global and Planetary Change **163**:67-85.

Water Environment Federation (WEF). 2015. Advances in water quality trading as a flexible compliance tool. A special publication. Water Environment Federation, Alexandria, VA.

Zhang, Q., D. C. Brady, W. R. Boynton, and W. P. Ball. 2015. Long-Term Trends of Nutrients and Sediment from the Nontidal Chesapeake Watershed: An Assessment of Progress by River and Season. Journal of the American Water Resources Association **51**:1534-1555.

APPENDIX A. DOCUMENTATION AND DISSEMINATION

Project results have been (or in some cases will be) disseminated via Pooled Monitoring Forum presentations, conference presentations, CBT reporting, peer-reviewed scientific journal articles, and MS theses. Given their collective size, none of the documents referred to below have been directly incorporated into this document. Instead, they have been collected into a Support Documents zipped archive with folders named according to the subsections below.

A.1 Pooled Monitoring Forum presentations

Presentations were given to the Pooled Monitoring Forum in 2022, 2023, and 2024.

A.2 Conference presentations

Presentations were given at the following conferences, primarily for the practitioner and regulatory communities:

1. Oehler, M., D. Scott, and E.T. Hester. 2024. Watershed-scale effects of floodplain and Stage 0 restoration on nitrate removal. National Stream Restoration Conference, New Orleans, LA. June 25, 2024.
2. Hester, E.T., S. Welch, C. Federman, L. Goodman, M. Oehler, and D.T. Scott. 2024. Watershed-scale effects of floodplain and Stage 0 restoration on hydrologic attenuation. National Stream Restoration Conference, New Orleans, LA. June 25, 2024.
3. Hester, E.T., S. Welch, C. Federman, L. Goodman, M. Oehler, and D.T. Scott. 2024. Watershed-scale effects of floodplain and Stage 0 restoration on hydrologic attenuation. River Restoration Northwest, Skamania, WA. February 7, 2024.
4. Hester, E.T., C. Federman, L. Goodman, and D.T. Scott. 2023. Watershed-scale effects of floodplain and stage 0 restoration on flood attenuation and floodplain exchange. River Restoration Northwest, Skamania, WA. February 8, 2023.
5. Hester, E.T., M. Calfe, C. Federman, L. Goodman, and D.T. Scott. 2022. Cumulative impacts of watershed-scale hyporheic stream restoration on nitrate loading to downstream waterbodies. National Stream Restoration Conference, Nashville, TN. August 1, 2022.
6. Goodman, L., C. Federman, D.T. Scott, N. Kruse Daniels, and E.T. Hester. Cumulative effects of stream restoration and watershed characteristics on watershed-scale nitrate removal. World Environmental and Water Resources Congress (American Society of Civil Engineers, Environmental and Water Resources Institute), Atlanta, GA. June 7, 2022.
7. Hester, E.T., M. Calfe, C. Federman, L. Goodman, and D.T. Scott. 2022. Cumulative effects of multiple stream restoration projects on nitrate removal at the watershed scale. River Restoration Northwest, Skamania, WA. February 9, 2022.
8. Hester, E.T., M. Calfe, C. Federman, L. Goodman, and D. T. Scott. 2021. Cumulative effects of stream restoration on nitrate removal at the watershed scale: data synthesis and numerical modeling (invited). American Geophysical Union Fall Meeting. December 14, 2021.

A.3 CBT reporting

The documents in this subsection have been requested by CBT, but have not been disseminated elsewhere.

A.3.1 Literature Review (Task 1)

Task 1 entailed a literature review of nitrate removal rates from field measurements or sampling. It included the results rates in an Excel file, and a description of the literature review methods and results in Word document. These were submitted to CBT as files attached to status reports for prior reporting periods.

A.3.2 R codes

The following R codes were generated:

- Task 1: The random forest analysis was conducted using an R script.
- Task 3:
    - Nitrate removal during baseflow from in-channel hyporheic enhancement was calculated using output from the steady-state baseflow HEC-RAS model.
    - Nitrate removal during storm events from floodplain/Stage 0 restoration was calculated using output from the unsteady storm event HEC-RAS model. There are two codes, one for individual stream orders and one for the fully restored watershed.
- Task 4: Nitrate removal during storm events from floodplain/Stage 0 restoration was calculated using output from the unsteady storm event HEC-RAS model.

A.4 Peer-reviewed scientific journal articles

The following peer-reviewed scientific articles have been published so far. Others will be submitted later this year (2024).

1. 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. Link to open access article.
2. 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.

A.5 MS theses

The following MS theses were supported at least in part by this CBT grant, or their publication in the scientific literature was supporting part by this CBT grant, and together provide the basis for all results presented in this report.

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

2. Federman, C. 2021. Impact of Stream Restoration on Flood Attenuation and Channel-Floodplain Exchange During Small Recurrence Interval Storms. Virginia Tech, Blacksburg, VA.
3. Goodman, L. 2023. Cumulative Impacts of Stream Restoration on Watershed-Scale Flood Attenuation, Floodplain Inundation, and Nitrate Removal. Virginia Tech, Blacksburg VA.
4. 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.