URBANIZATION EFFECTS ON NITRATE-DISCHARGE RELATIONSHIPS AND NITRATE CONCENTRATION IN BOZEMAN CREEK

by

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LIST OF ABBREVIATIONS

Abbreviation	Full Terminology
AICc	Corrected Akaike Information Criterion
AOV	Analysis of Variance
C-Q	Concentration to Discharge
N-Q	Nitrate Concentration to Discharge
mg/l	milligrams per liter

ABSTRACT

Water quality issues can arise in rapidly growing micropolitan cities like Bozeman, Montana. Bozeman has experienced a population growth rate ranging from 1 to 7% in the last decade, and that growth has been accompanied by an increase in impervious area and stormwater infrastructure. In this paper I investigate how urban growth can potentially impact local streams by means of altering discharge and runoff contamination. To examine how stream nitrate concentration-to-discharge (N-Q) relationships and nitrate concentration relate to the expansion of urban area in Bozeman, I selected three sites in Bozeman Creek to collect and analyze data. I collected data using Montana State University Extension's Water Quality Data Hub. My objectives were to assess nitrate concentration and discharge for three sites that represent an urbanization gradient along Bozeman Creek and to determine if nitrate concentrations and N-Q relationships have a positive, neutral, or negative trend. Analysis of Variance (AOV) tests for N-Q relationships identify a significant overall negative linear correlation between nitrate concentration and discharge ($p < 0.001$). The tests also suggest that this relationship varies by site ($p = 0.04$), with the upstream site having a more negative relationship than the downstream sites ($p = 0.06$). Sample size corrected Akaike Information Criterion (AICc) test scores suggest that a simple model that does not specify site-specific N-Q relationships is the optimal model, but also provides some support for a model that allows the N-Q relationship to vary by site. AOV tests for mean annual nitrate concentration suggest significant differences in mean values by site ($p < 0.001$) and year ($p = 0.007$). A Tukey's HSD test suggests that mean annual nitrate concentration is higher at two downstream sites than at the upstream site ($p < 0.001$), but it does not provide clear evidence for trends across years. Therefore, the evidence suggests that all monitoring sites exhibit a clear dilution-type N-Q relationship, while the rate of nitrate dilution decreases from upstream to downstream. Additionally, the evidence suggests that mean annual downstream nitrate concentrations are higher than upstream. Because the data span from June October, inferences about patterns are constrained to that period. My study shows that urbanization may result in downstream consequences to water quality and freshwater habitat. Further studies using more robust data would help in more thoroughly understanding ecological impacts of urban growth on local streams, which would provide more accurate information on how to mitigate potentially negative consequences to water quality of freshwater habitat.

INTRODUCTION

Urbanization in Bozeman

Bozeman, Montana was one of the fastest growing micropolitan cities in the United States (Mackun et al., 2021; Miller & Shelly, 2021). Its annual population grew consistently over the last couple of decades, with an average annual growth rate of 3.5% between 2001 and 2021, and a high of 7% from 2019 to 2020 (Figure 1) (Billings Gazette, n.d.; U.S., n.d.). Rapid urbanization changes the way water moves through a landscape by increasing impervious area and creating more direct pathways for the conveyance of stormwater to streams, which can alter runoff timing and intensity (Bajracharya et al., 2016; Li et al., 2018). This altered response often increases stream discharge flashiness and runoff volume, increases the mobility of stormwater contaminants, and reduces the potential for chemical or biological transformation and uptake of contaminants (Qinqin et al., 2015; Wang et al., 2011).

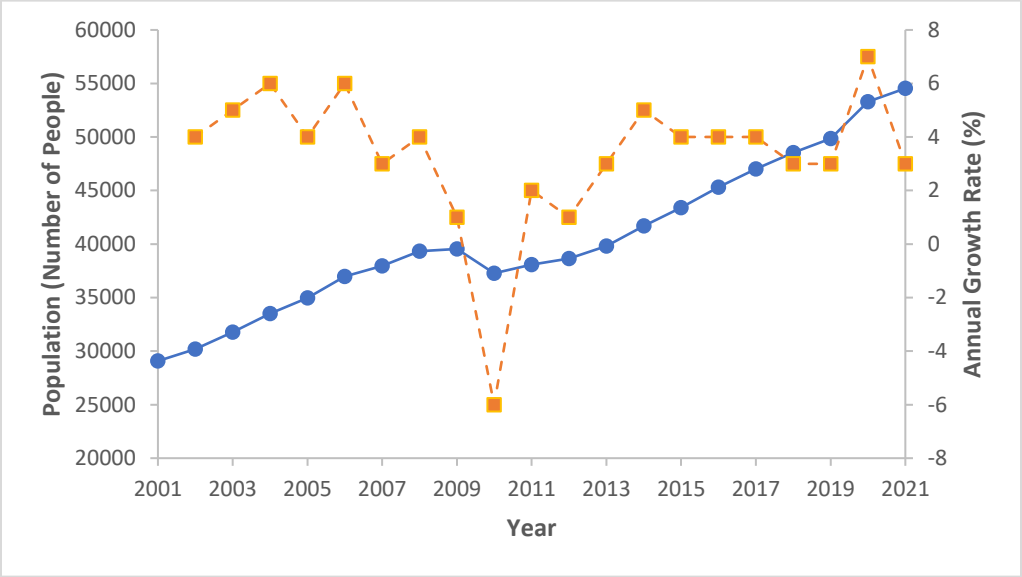


Figure 1. Bozeman's Annual Population (N) and Growth rate (% of N) from 2001 to 2021 with a solid blue line representing annual population trend and a dashed orange line representing annual growth rate (Billings Gazette, n.d.; U.S., n.d.).

Impacts of Urbanization on Small Local Streams

Several meta-analyses suggest that as urban areas continue to grow, there are many possible consequences for stream corridor ecology, hydrology, and water quality (Hansen et al., 2005; McKinney; Ruas et al., 2022). Replacing natural areas with impervious surfaces can result in increased stream contamination due to a reduced reactive capacity of stormwater along flow paths from vegetation and soil infiltration (McKinney, 2002; Onandia et al., 2019). Further, stormwater inlet systems can act as a stream contaminant funnel by collecting and routing sediment and solutes because event runoff volume and flashiness can increase their mobilization (Wang et al., 2011). These mechanistic changes can result in greater amounts of contaminants ultimately reaching local streams, degraded water quality, and impaired freshwater habitat (Gao et al., 2022).

The capacity for settling, filtration, or biological processing of contaminants along flow paths is also reduced by urbanization, with pronounced effects on the transport of biologically reactive solutes, such as nutrients. Streams and landscape features, such as detention swales, parks, and riparian corridors, often support nutrient cycling, stormwater filtration, and solute retention (Gurevitch et al., 2021; Stelzer et al., 2019; Onandia et al., 2019). Riparian corridors in particular can act as a buffer against nitrate-contaminated stormwater by retaining nitrate in soils and processing them biologically (Stelzer et al., 2019; Wherry et al., 2022). Buffering can also be achieved by reducing surface water flow by allowing for subsurface infiltration, thereby reducing snowmelt and precipitation-event driven nutrient loading to streams and mitigating the severity of algal blooms and nutrient toxicity (Stelzer et al., 2019; Wherry et al., 2022). One study examining stream nitrate concentration near agricultural land observed that the lowest modeled stream nitrate concentrations were associated with substantial riparian cover (Wherry et al., 2022).

Stream Concentration to Discharge Relationships

The relationships between stream solute concentration to discharge (C-Q) (Figure 2) allows scientists to make inferences on drivers of nitrate storage, transport and release, and in-stream processes affecting solute concentration (Gorski & Zimmer, 2021; Mehdi et al., 2021; Marinos et al., 2020). C-Q relationships can be classified into two types that indicate the solute concentration variability relative to the discharge variability: chemostatic and chemodynamic (Godsey et al., 2009; Marinos et al., 2020). A chemostatic C-Q relationship describes a setting where solute concentration variability is close to zero as discharge increases (Godsey et al.,

2009; Marinos et al., 2020). A chemodynamic C-Q relationship describes a setting where solute concentration varies with a positive or negative correlation to discharge, and a linear or non-linear association with discharge (Godsey et al., 2009; Marinos et al., 2020). A chemostatic relationship is often found where nitrate availability is uniformly high across a landscape, such as leaching groundwater fertilizer compounds from intensive agriculture, or effluent from a water treatment facility.

C-Q Relationship Settings

A chemostatic relationship can also be found where relatively low influxes of nitrate exist in natural/undisturbed settings (Marinos et al., 2020). Chemodynamic relationships are often found where nitrate availability varies substantially across a landscape, such as places where non-point source contamination is prevalent (Marinos et al., 2020). Further, a chemodynamic relationship can contain one of two trends: dilution (a negative C-Q correlation), and mobilization (a positive C-Q correlation) (Knapp et al., 2020). Dilution can be seen during spring months with ample runoff, and where nitrate supply is limited or controlled (Mehdi et al., 2021); an example is being near a contamination point-source that occasionally releases waste into a stream. Mobilization can be found during fall months, where landscape solute retention is saturated and baseflow is an important contributor, and where contamination rates are variable and uncontrolled (Mehdi et al., 2021); an example is non-point-source contamination, such as urban stormwater solutes.

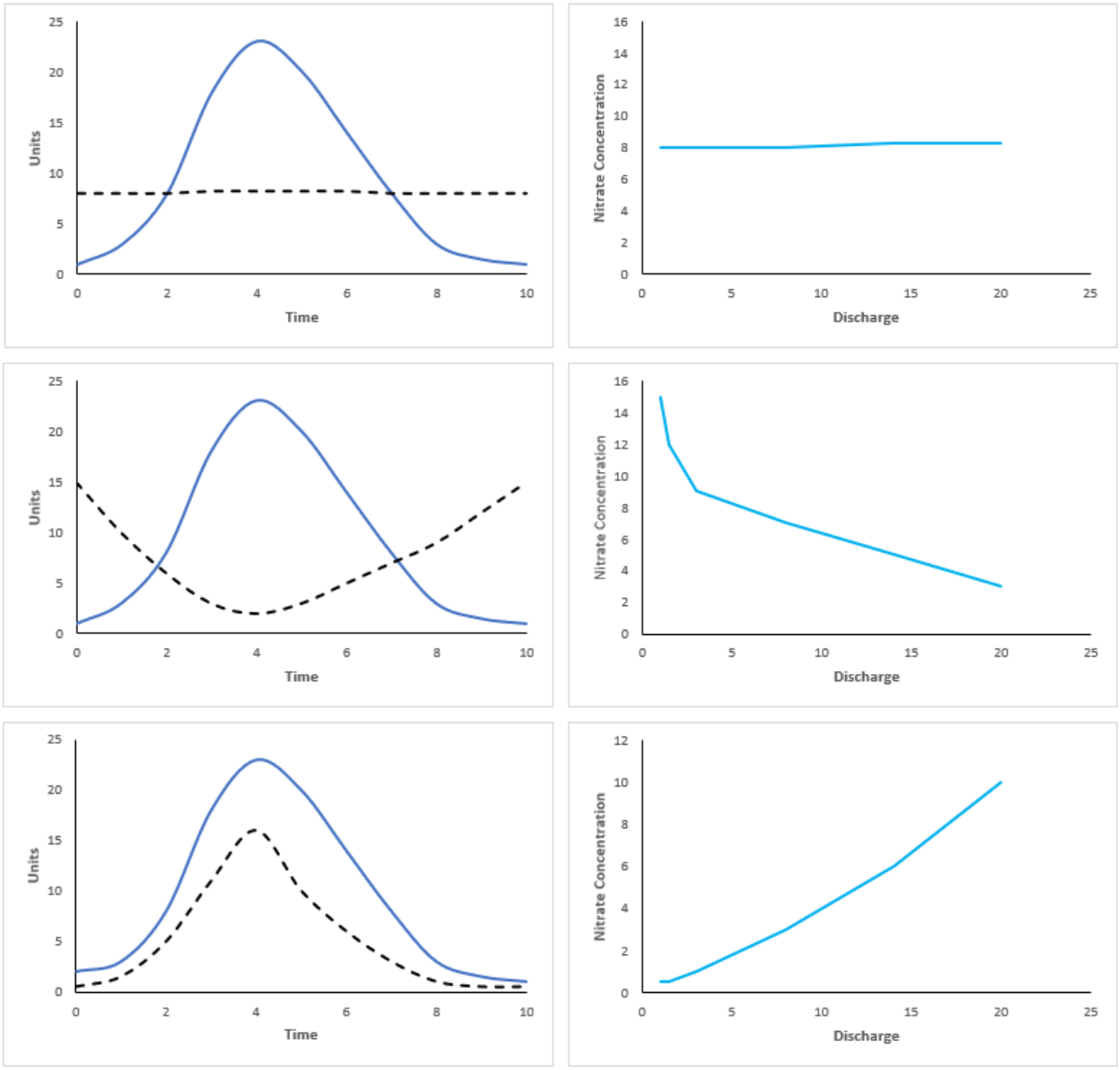


Figure 2. An Example of Stream Solute C-Q Relationships (images to the right) by Precipitation-Event Hydrograph Interaction (images to the left) with a solid dark blue line representing discharge, a dashed black line representing nitrate concentration, and a solid light blue line representing the N-Q relationship; showing a chemostatic-type (top), a dilution-type (middle), and a mobilization-type (bottom) (Author's diagram).

Research Question

The City of Bozeman has experienced a prolonged period of substantial urbanization. This increase in urban area likely corresponds with altered stormwater runoff pathways, which may contribute to nutrient concentration issues on the East Gallatin River. To understand these important dynamics in greater mechanistic detail, my paper examines how urbanization in Bozeman relates to N-Q relationships and nitrate concentrations through space and time.

Due to the potential relationship between urbanization and stormwater runoff pathways in Bozeman, I hypothesize that the nitrate buffering capacity of Bozeman Creek's riparian ecosystem corridor is reduced. Secondly, I hypothesize that this reduction in buffering capacity has led to increasing nitrate concentrations in Bozeman Creek near its confluence with the East Gallatin River. If the first hypothesis is correct, I expect to see a shift in N-Q slope from dilution towards mobilization across a spatial or temporal urbanization gradient. If the second hypothesis is correct, I expect to see an increasing trend of nitrate concentrations near the confluence over the 2012-2021 study period.

Objectives

To address these questions and hypotheses, my study assesses nitrate concentration and discharge for three monitoring sites that represent a spatial urbanization gradient along Bozeman Creek, and determines if nitrate concentrations and N-Q relationships have a positive, neutral, or negative trend.

CHAPTER ONE: METHODS

Study Area

I selected the City of Bozeman to study due to its recent history of rapid growth. With the exception of 2010, the annual population of Bozeman has increased steadily, with growth rates from 1 to 7%. Due to this recent growth, Bozeman is a good case study for examining the relationship between rapid urbanization and water quality. My paper examines three monitoring sites along Bozeman Creek (an urban stream that flows through the City of Bozeman) (Figure 3). I selected sites that represent a spatial urbanization gradient. In a downstream direction, from south to north, the sites increase in urbanization and are named: Tuckerman Park, City Hall, and the Mouth. This gradient will support the analysis of detecting potential N-Q slope shifts and changes in nitrate concentrations.

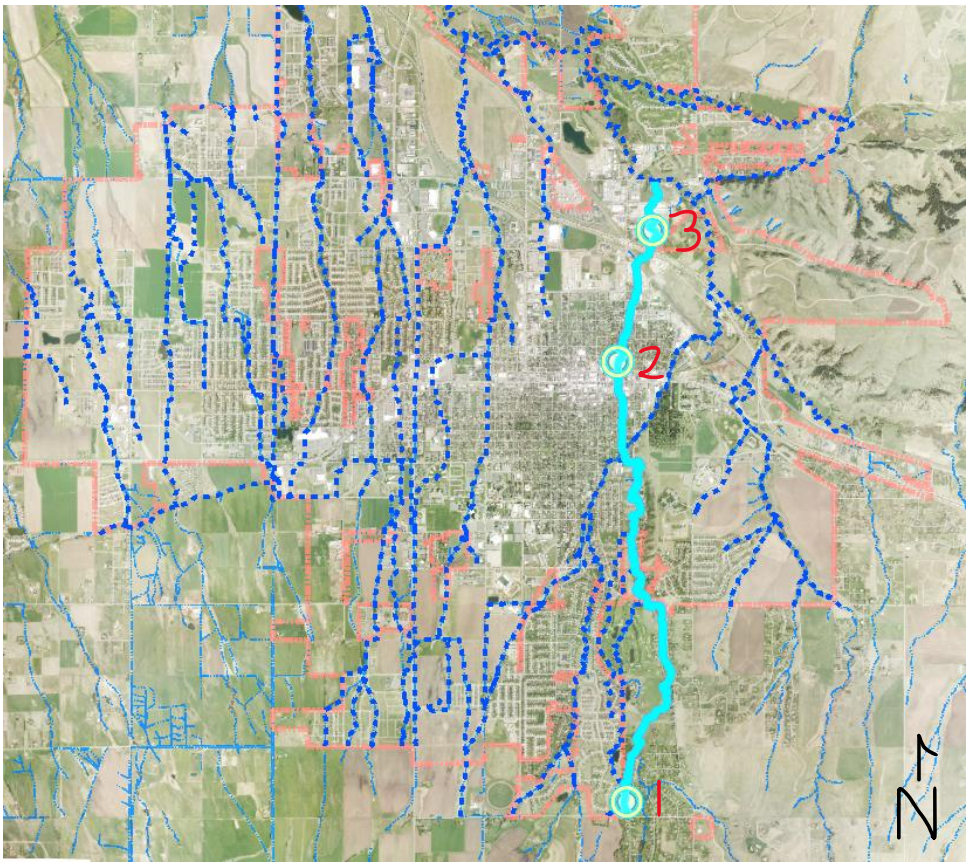


Figure 3. Map of Bozeman with dashed dark blue lines representing urban streams and ditches, a solid light blue line representing Bozeman Creek, three green circles representing the monitoring sites, and red dashed lines representing city limits; Streamflow direction is due north, monitoring site names (as indicated in red) are: Tuckerman Park (1), City Hall (2), the Mouth (3) (City of Bozeman, n.d.).

Data Availability & Acquisition

I collected nitrate concentration and discharge data from Montana State University Extension's Water Quality Data Hub (Monana State University, n.d.). The data span from June through October, and from 2012 through 2021 (Table 1). I downloaded raw data from the Hub as a csv file, which I then filtered using Microsoft Excel by deleting superfluous data fields (e.g. pH

and water temperature). I then used this condensed file for analysis in R statistical software (Posit Team, 2023).

Table 1. Number of Data Points by Year per Monitoring Site for Bozeman Creek.

	Data Points per Monitoring Site									
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Tuckerman Park		3	3	3		3	4		3	4
City Hall		3				3				
The Mouth	3	3	3	3	2	3	4			

Data Analysis

I analyzed the data for two purposes: 1) to compare nitrate concentration across space and time, and 2) to compare N-Q slope shifts across space and time. Because there were limited data points for a meaningful analysis of N-Q slope per individual site and year, I normalized the data. I implemented this process to preserve the raw overall N-Q relationship while allowing for individual site and year relationships to be comparable to each other. First, I grouped the data by site and year (e.g. City Hall 2013) in a new data frame to calculate mean values for nitrate concentration and discharge per group category. I then merged this data frame to the original, and calculated nitrate concentration and discharge indexes by dividing the original data from each row (i.e. each pair of site and year) by the corresponding site-year mean.

I produced three plots: a fitted N-Q relationship using all data, a fitted N-Q relationship by site, and data distribution for nitrate concentration by site across the applicable years.

Statistical Analysis

N-Q Relationships

I used a series of statistical tools to interpret the significance of the hypothesized trends in the data. First, I developed a global model that allowed for a different N-Q relationship for each combination of site and year. I then compared the performance of this global model to the performance of simpler models representing the effects of site and year on the N-Q relationship by using the MuMIn ('Multi Model Inference') package, version 1.15 (Barton, 2016) for R statistical software (Posit Team, 2023). This method calculated AICc scores for each model. I then used these AICc scores to identify which combinations of explanatory terms provided the best description of the N-Q relationships. Finally, I used AOV tests to determine the fit of the models for the N-Q relationships indexed by site and year.

In the first, simplest linear regression model, normalized nitrate concentration is related only to normalized flow:

$$N_n = I + \beta_q Q_n, \quad (1)$$

where N_n is the normalized nitrate concentration (mg/l), I is the intercept, and β_q and Q_n are the slope coefficient and value for normalized streamflow in cubic feet per second (cfs), respectively. For clarity, I term this the **'flow only model'**.

Adding the potential effects of site to the flow only model yields a **'flow and site model'**:

$$N_n = I + I_s + (\beta_q + \beta_{qs})Q_n, \quad (2)$$

where I_s and β_{qs} modify the intercept and slope of the N-Q relationship, respectively, and take on distinct fitted values for each categorical value of site. In this model, the intercept and slope of the N-Q relationship can vary between sites.

Adding the potential effects of year to the flow only model yields a **'flow and year model'**:

$$N_n = I + I_y + (\beta_q + \beta_{qy})Q_n, \quad (3)$$

where I_y and β_{qy} modify the intercept and slope of the N-Q relationship, respectively, and take on distinct fitted values for each categorical value of year. In this model, the intercept and slope of the N-Q relationship can vary between years.

Adding the potential effects of year to the flow and site model yields a **'flow-site-year model'**:

$$N_n = I + I_s + I_y + (\beta_q + \beta_{qs} + \beta_{qy})Q_n, \quad (4)$$

Where I_y and β_{qy} describe change in the intercept and the slope of the N-Q relationship, respectively, and take on different fitted values for each year. In this model, the slope of the N-Q relationship can vary for each combination of site and year due to the interaction between N_n and site and year. This model also serves as the global model for the AICc analysis.

Nitrate Concentration

I conducted an AOV test to examine the association between site and year and raw (not normalized) nitrate concentration measurements. A Tukey's HSD test was then used to see which of these groups had significantly different means.

In the simple linear regression model, nitrate concentration is related to the potential effects of site and year:

$$N = I + \beta_s Site + \beta_y Year, \quad (5)$$

where N is nitrate concentration (mg/l), I is the intercept, β_s and $Site$ describe the slope coefficient and identity of the sampling site, and β_y and $Year$ describe the slope coefficient and identity of the sampling year. As site and year are categorical variables, β_s and β_y take on a different value for each site and year, respectively.

CHAPTER TWO: RESULTS

N-Q Relationships

The flow only model uses all nitrate concentration and discharge indexes to form one fitted regression to represent an overall N-Q relationship across the three sites and all years. This model therefore does not reveal potential differences in N-Q slope by site and year. The flow and site model uses site-specific indexes to form fitted regressions that represent potential differences in N-Q slope per site. Nitrate concentration index values for Bozeman Creek appear to be similar to those found in literature, however direct comparisons are somewhat limited because most of the studies reviewed for my paper use logarithmic values or different normalization schemes.

Flow Only Model

There is a clear negative relationship between normalized nitrate concentration and discharge across all sites and years (Figure 4). Linear regression indicates that this relationship has an intercept of 1.51 and a slope of -0.51, and it provides evidence ($p < 0.001$) for the significance of this negative slope. Variation in normalized discharge, as fitted in this simple model, explains 60% of the observed variation in normalized nitrate concentration. This result indicates that regardless of potential site and year variation, Bozeman Creek exhibits a dilution-type N-Q relationship.

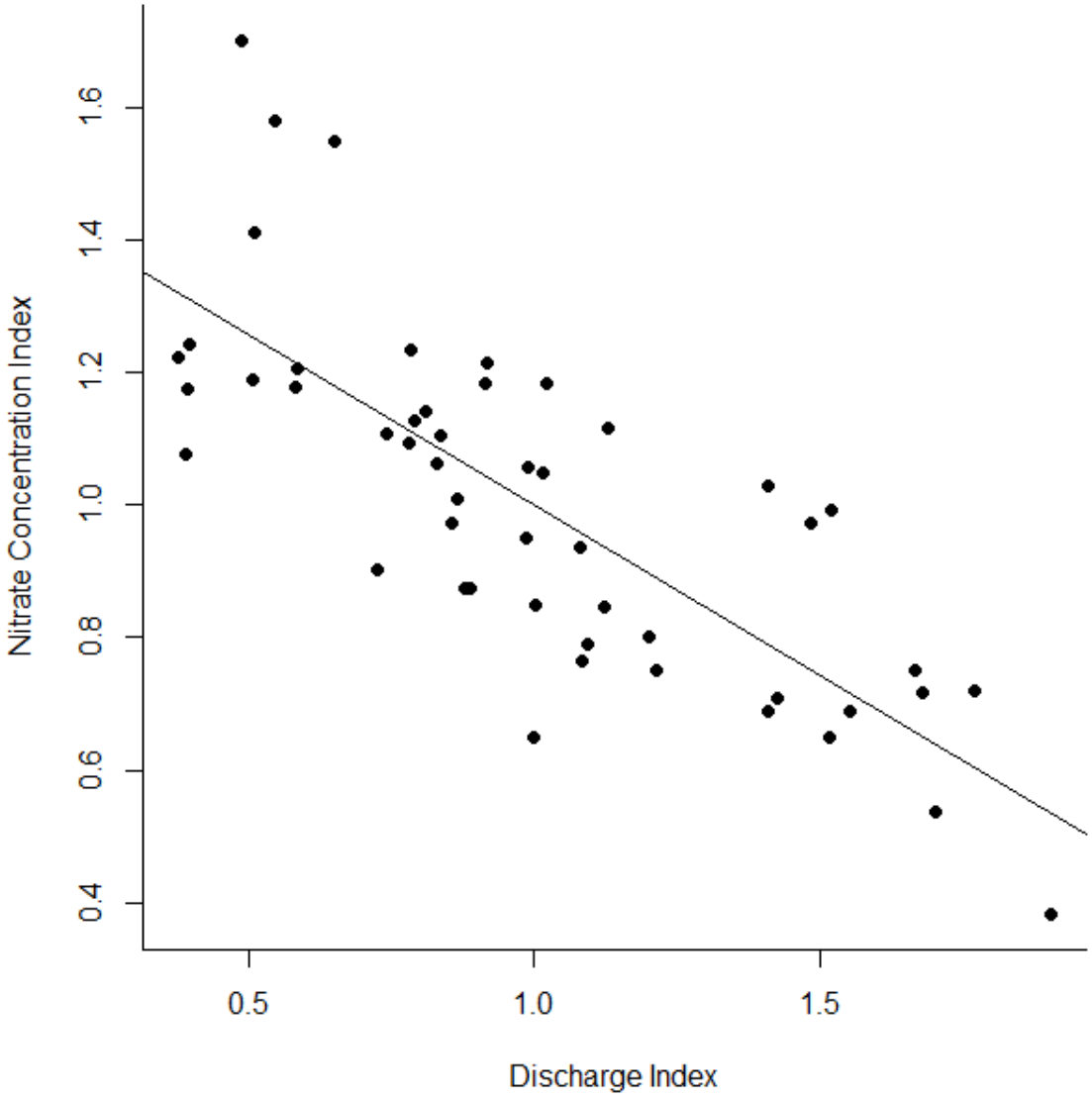


Figure 4. Normalized Nitrate to Discharge Relationship in Bozeman Creek for all Sites and Years.

Identification of Optimal Models

The AICc scores (Table 2) for the component models of the flow-site-year model suggest that the flow only model is the optimal model, which explains 60% of the observed variation in normalized nitrate concentration. However, the AICc scores also indicate some support (ΔAICc = 2.83) for the flow and site model (equation 2), which explains 62% of the observed variation in

normalized nitrate concentration. The flow and year model (equation 3), and all other models incorporating year, or site and year, performed poorly in the AICc analysis.

Table 2. Summary of AICc Analysis Results of Global N-Q Relationship Model.

Model Name	**Degrees of Freedom**	**ΔAICc**
Flow Only	3	0
Flow & Site	7	2.83
Flow & Year	19	47.93

Flow & Site Model

The AOV test results suggest that the association between site and N-Q relationship is significant ($p = 0.04$). Further, the AOV results suggest that the N-Q relationship for Tuckerman Park is different from that of City Hall and the Mouth ($p = 0.06$), but the results do not suggest that the N-Q relationship for City Hall is different from that of the Mouth ($p = 0.98$). Due to these results, City Hall and the Mouth were combined into one group for the flow and site model, and Tuckerman Park formed the other group.

There are clear negative relationships between normalized nitrate concentration and discharge across all years for Tuckerman Park and the City Hall-Mouth group (Figure 5). Linear regression indicates that this relationship for Tuckerman Park (shown as a solid black line in figure 5) has an intercept of 1.51 and a slope of -0.65 ($R^2 = 0.68$), and it provides evidence ($p < 0.001$) for the negative slope. The N-Q relationship for the City Hall-Mouth group (shown as a dashed green line in figure 5) has an intercept of 1.35 and a slope of -0.35 ($R^2 = 0.51$), and it provides evidence ($p = 0.06$) for the negative slope. These results suggest that both Tuckerman Park and City Hall-Mouth exhibit a dilution-type N-Q relationship. Additionally, they suggest that the fitted City Hall-Mouth N-Q relationship has a less negative than the fitted Tuckerman

Park N-Q relationship. This provides a moderate degree of support for my first hypothesis, that the nitrate buffering capacity of Bozeman Creek's riparian ecosystem corridor is reduced.

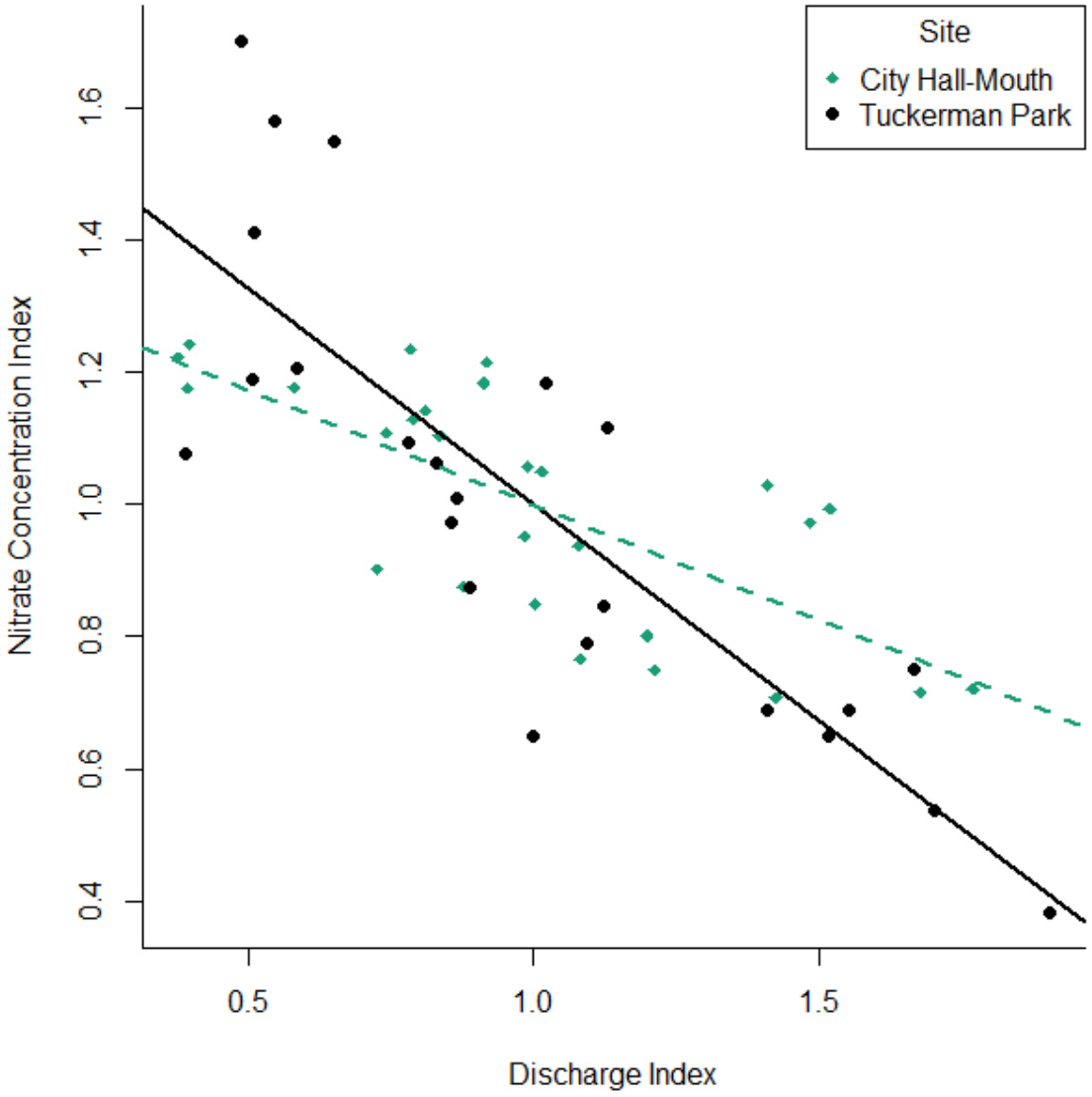


Figure 5. Normalized Nitrate to Discharge Relationships in Bozeman Creek for Tuckerman Park (solid black regression) and City Hall-Mouth (dashed green regression).

Nitrate Concentration

Nitrate Concentration by Site & Year

There appears to be a negative relationship between mean annual nitrate concentration and years for Tuckerman Park, and a positive relationship between mean annual nitrate concentration and years for the City Hall-Mouth group (Figure 6). A regression was not fitted to the data due to lack of sufficient measurements. The AOV test (using equation 5) suggests that there is evidence that at least one site-specific mean annual nitrate concentration is significantly different from the others ($p < 0.001$), and it suggests that there is at least one year-specific mean annual nitrate concentration that is significantly different from the others ($p = 0.007$).

Tukey's HSD Test

Evidence suggests a difference in mean annual nitrate concentration of -0.33 mg/l ($p < 0.001$) between Tuckerman Park and the Mouth, and suggests a difference of -0.26 mg/l ($p < 0.001$) between Tuckerman Park and City Hall. There is insufficient evidence to suggest a difference of 0.07 mg/l ($p = 0.44$) between the Mouth and City Hall. These results suggest that downstream mean annual nitrate concentration is higher than upstream, which is consistent with my second hypothesis, that the reduction in buffering capacity has led to increasing nitrate concentrations in Bozeman Creek near its confluence with the East Gallatin River.

Evidence suggests a difference in mean annual nitrate concentration for four-out-of-36 year-pairs. These are -0.21 mg/l between 2015 and 2013 ($p = 0.058$), -0.22 mg/l between 2015 and 2014 ($p = 0.073$), 0.25 mg/l between 2018 and 2015 ($p = 0.016$), and 0.18 mg/l between 2018 and 2017 ($p = 0.078$). The evidence does not suggest a consistent year-to-year change (increase or decrease) in nitrate concentration. Therefore, the results do not clearly support the second hypothesis, that the reduction in buffering capacity has led to increasing nitrate concentrations in Bozeman Creek near its confluence with the East Gallatin River.

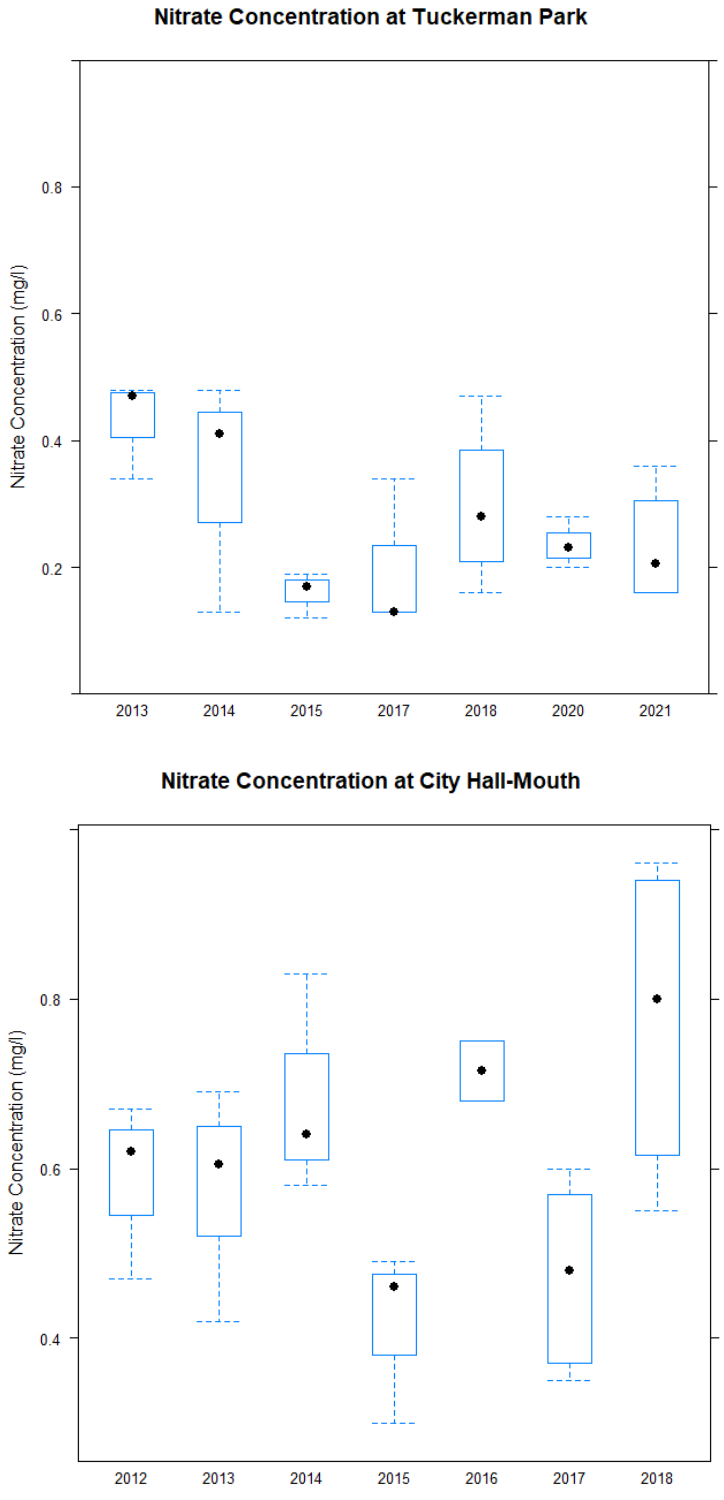


Figure 6. Nitrate Concentration Distribution Box-and-whisker Plots for Tuckerman Park (top plot) and City Hall-Mouth group (bottom plot) by Site and Year. Center points indicate mean annual nitrate concentration.

CHAPTER THREE: DISCUSSION

N-Q Relationships

Bozeman Creek exhibited linear dilution-type N-Q relationships during the summer and fall. The relationships were captured fairly well by simple linear regression models using normalized nitrate concentration (N_n) and discharge (Q_n), and a site-specific slope coefficient (β_s), indicated by the moderately strong performance of equations 1 and 2. The flow only model, and flow and site model, illustrate a dilution-type pattern (negative slope), with a less negative slope downstream than upstream. These results are consistent with previously studied N-Q relationships over multi-year periods, and where baseflow is the primary driver of discharge (e.g. Gorski & Zimmer, 2021; Knapp et al., 2020), which is not surprising.

The shift in normalized N-Q slope from -0.65 (Tuckerman Park) to -0.35 (City Hall-Mouth) indicates that nitrate concentration at City Hall and the Mouth decreases at a slower rate relative to increasing discharge than at Tuckerman Park, which is consistent with my first hypothesis, that the nitrate buffering capacity of Bozeman Creek's riparian ecosystem corridor is reduced. This shift could be associated with a reduction in the nitrate buffering capacity of Bozeman Creek's riparian ecosystem corridor at City Hall and the Mouth in relation to urbanization (Hansen et al., 2005; Onandia et al., 2019). Along Bozeman Creek, the City Hall and the Mouth monitoring sites represent arguably the highest degree of urban development. They exhibit the most impervious area for collecting contaminated stormwater, the most stormwater infrastructure outflows, and the least amount of vegetated area that allows for infiltration, filtering, and processing of stormwater. Conversely, the Tuckerman Park monitoring

site likely represents the lowest degree of urban development, and thus the riparian ecosystem corridor's nitrate buffering capacity is likely least affected.

The dilution-type pattern of Tuckerman Park and the City Hall-Mouth sites could be explained by the time of season and related precipitation, by the capacity of riparian vegetation and nearby landscapes to buffer runoff, or by the amount of nitrate entering the stream in proportion to the stream's size. To address the first point, it could be that dilution-type relationships are seen because the data represent samples from only June through October, which excludes spring high flow periods driven by snowmelt and rainfall that might exhibit a stream corridor system experiencing nitrate mobilization (delivery-limited) patterns (Gorski & Zimmer, 2021; Knapp et al., 2020; Steltzer et al., 2019). Conversely, summer and fall precipitation events in this region are typically infrequent, short in duration, and mild in total depth, and can explain a stream corridor system experiencing nitrate dilution (supply-limited) patterns. To address the second point, regardless of precipitation event intensity, the vegetation that exists within the stream corridor system might have sufficient capacity to buffer enough stormwater runoff such that urban flow rarely achieves a magnitude to allow for stream nitrate mobilization, and the runoff does not overwhelm the stream corridor system (Gao et al., 2022; Godsey et al., 2009; Onandia et al., 2019). This idea is somewhat related to the third point, that the size of the stream corridor system could be sufficient to accommodate for its capacity to filter and process runoff contaminants (Marinos et al., 2020). These inferences are important because N-Q relationships of local urban streams can impact larger water bodies, such as the East Gallatin River, which hosts a variety of aquatic life and has historical issues with algal blooms, and high levels of the

nitrate. These issues resulted in the development of a Total Maximum Daily Load (TMDL) for nitrate concentration in the East Gallatin River (Schmidt et al., 2013).

Inferences on this system's behavior, related to N-Q relationships, are somewhat limited due to the dataset and methods used. For example, the fitted linear regressions explain 60 to 62% of the observed N-Q relationship plot, with which is reasonable to make inferences. However, the data were normalized to account for differences in nitrate concentration and discharge that could be due to inherent physical differences per site (more stormwater outlets, more contamination sources, stream morphology and riparian characteristics) and per year (more precipitation or less precipitation). There could be more detailed factors, like amount of precipitation and a broader time period that captures peak runoff that could aid in making more accurate inferences. Additionally, the data only represents June through October, which is most of the falling limb for the year.

Nitrate Concentration

Bozeman Creek exhibited two different linear site-specific nitrate concentration trends (Tuckerman Park and the City Hall-Mouth group) during the summer and fall that were captured by the simple linear regression model using a site-specific slope coefficient (β_s). Nitrate concentration trends were not explained well by using a year-specific slope coefficient (β_y). The linear regression model (equation 4) suggests that the site-specific slopes of nitrate concentration are significant, however a regression was not fitted to plotted data because there were insufficient points to produce meaningful statistical results. Thus, the box-and-whisker plots suggest that mean annual nitrate concentrations at Tuckerman Park exhibit a decreasing trend

across years, while the mean annual nitrate concentrations at City Hall-Mouth exhibit an increasing trend across years. These results make sense given the setting of Tuckerman Park (an upstream, relatively undisturbed area with few inputs of stormwater runoff) and the City Hall-Mouth group (a downstream, largely urban area with many sources of inputs of stormwater runoff). This finding is consistent with my second hypothesis, that the reduction in buffering capacity has led to increasing nitrate concentrations in Bozeman Creek near its confluence with the East Gallatin River over time.

If the plots are reasonably accurate at portraying mean annual stream nitrate concentration trends, the decreasing trend seen at Tuckerman Park could be explained by less precipitation and snowmelt conveying less stormwater into the stream, and/or runoff entering the stream being considerably less than the amount which infiltrates the soil and is processed and filtered by the riparian ecosystem (Gao et al., 2022; Onandia et al., 2019). It could also be that more data would shift the apparently negative slope at Tuckerman Park. The increasing trend seen at City Hall and the Mouth could be explained by greater inputs of stormwater contamination, such as sediment, oil, and debris (Bajracharya et al., 2016; Li et al., 2018; Qinqin et al., 2015). Additionally, it could be a result of the sites being more exposed to runoff from an expanding stormwater infrastructure grid.

The degree to which inferences can be accurately made about these results and this system is very limited, however, because there is no validated regression to interpret, and like the N-Q relationship results, every year of data covers only five months, excluding peak runoff season. To this extent, inferences can be made about patterns in mean annual values and

distributions, compared by site, but should stay within the June-October period. Without a more robust dataset, in-depth interpretations could be inaccurate.

Lessons & Study Limitations

The data points that I used in my study were constrained to observations with both nitrate concentration and discharge values because examining N-Q relationships was the primary goal for analysis. Due to this, and the relatively small dataset, I made conservative inferences from statistical tests and plot analyses were made. The weakest section of data is represented by the City Hall site, although sufficient data exist for my overall analysis.

Because N-Q relationships are affected by many variables, and I used multiple sites, I conducted my analysis using normalized data to account for differences in nitrate concentration and discharge by site and year. I am interested in site because the three monitoring sites could have unique nitrate and discharge inputs. I am interested in year of data because each year can fluctuate between wet and dry precipitation seasons. Two variables that I did not include in normalization, but could add more accuracy to assessing the data for change by year and site, are amount of precipitation (e.g. daily depth), and groundwater interaction.

One aspect of my study that could have strongly impacted my analysis is having peak runoff data. N-Q relationships in urban settings can be very dynamic near high runoff events, and when discharge is flashy (Gorski & Zimmer, 2021; Knapp et al., 2020; Steltzer et al., 2009). The data that I used in my study represent early-summer (June) to mid-fall (October) only. Assessing data that focused on, or incorporated, spring runoff and high-intensity precipitation events could be more helpful in answering the questions that I posed in my study.

Because stage data were not available for Bozeman Creek, and many measurements contained only nitrate concentration or discharge, options for assessing nitrate concentration trends were limited. Ideally, the majority of a site's hydrograph would be used for an accurate analysis of stream nitrate behavior, where discharge could be estimated from stage. I decided that the most meaningful examination of the data, given the limitation, was to view mean annual concentration trends, but this gives only one perspective to the overall behavior of the system.

CHAPTER FOUR: CONCLUSION

Normalizing stream nitrate concentration and discharge by categorical variables that may impact their magnitude (potential variation due to site and time), while weighting the influence of potential factors (how site and year interactions can affect the fitted linear regression) provided a simple and effective regression model for describing the N-Q relationships of my study system. This approach is likely useful in other systems that are interconnected with urban areas with varying stormwater runoff inputs and stream system characteristics. Using a small nitrate concentration dataset was sufficient for providing simple preliminary statistical results (suggesting significance of model factors like site influence), however it limited the degree to which accurate, nuanced inferences of the system could be made, in part by impairing the feasibility of a meaningful fitted regression.

I examined meaningful relationships using linear regression, however, the strength of my inferences were limited due to using available seasonal data (June through October) that did not contain major hydrograph features, such as the rising limb, peak discharge, and the beginning of the falling limb. This constrained my interpretations about relationships to being within the end of significant runoff events, and the majority of baseflow.

In my study system, a difference in normalized N-Q slope, due to site within a city, was suggested by linear regression using the flow and site model. Tuckerman Park exhibited a negative, moderately steep regression slope, while the City Hall-Mouth group exhibited a negative, less steep regression slope. This result suggests that downstream nitrate concentration does not dilute as fast with higher discharge than upstream nitrate concentration. Similar to the results for N-Q relationships, a difference in raw nitrate concentration, due to site within a city,

was suggested by analysis of the nitrate-site-year model. The model suggests that mean annual nitrate concentration has increased over the study period (2012-2021) at City Hall and the Mouth, while it has decreased at Tuckerman Park.

Bozeman is one of many rapidly growing cities that is susceptible to potentially negative impacts of ecological stressors, such as urbanization on N-Q relationships and downstream nitrate concentration. My study shows that urbanization may result in downstream consequences to water quality and freshwater habitat. Although N-Q relationship studies are not a novel science, few thorough examinations have been conducted into how they can change in urban settings and how that can impact stream ecosystems. Further studies using more robust data would help in more thoroughly understanding potential ecological impacts of urban growth on local streams, which would provide more accurate information on how to mitigate potentially negative consequences to water quality of freshwater habitat.

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