IJHSR
ijhighschoolresearch.org
RESEARCH ARTICLE

Effects of Urbanization on a North Carolina Piedmont Stream

Yasmine P. Ackall, Katherine M. Lopez, Pristine C. Onuoha, Micah E. van Praag
East Chapel Hill High School, 500 Weaver Dairy Rd, Chapel Hill, NC, 27514, USA; yasmine.ackall@gmail.com

ABSTRACT: Bolin Creek, located in Chapel Hill, North Carolina, a highly urbanized town, has been listed on the NC 303 (d) list of impaired waters since 2003. The objective of this study was to investigate potential connections between urbanization and the declining water quality of Bolin Creek. Data were collected on the water chemistry and benthic macroinvertebrates of Bolin Creek and two reference streams. A strong negative correlation was found between the percentage of developed land around the stream sites and stream water quality. Correlational data on conductivity, turbidity, and nutrient concentration indicated that urban runoff, associated with the high percentage of impervious surface cover in Chapel Hill, largely contributed to the degradation of the water quality of Bolin Creek. The results suggest the need for further action to improve the water quality of the stream. The researchers of the present paper suggest the following actions to help restore the water quality of Bolin Creek and create a more resilient watershed plan for the community: restoration of the riparian buffer along Bolin Creek, policy and educational changes in Chapel Hill, street cleaning, green roofs, the use of the Clean Water State Revolving Fund (CWSRF) revenue, and relevant public engagement.

KEYWORDS: Environmental Effects on Ecosystems; Ecology; Urban Runoff; Impervious Surfaces; Benthic Macroinvertebrates.

Introduction

Significance of Water Quality:

The present study concerns water quality and how urbanization affects it. Freshwater is essential for life and scarce, as freshwater constitutes only 2.5% of the surface water of the Earth and is predominantly found in ice.[1] Presently, agricultural and urban development threatens the health of freshwater bodies, and population growth is decreasing freshwater accessibility.[1] In 2020, 26% of the world's population lacked clean drinking water and water services, and 2.3 billion people currently live in "water-stressed" environments.[2] Lower water quality increases the resources necessary to treat drinking water.[3] Studies reviewed by Carpenter *et al*. (2011) highlight that water quality is a major indicator of human health, and that decreased habitat biodiversity is associated with increased diseases in humans.[1]

Streams purify water, control flooding, decompose waste,[4] and remove contaminants and added nutrients.[5] Studying streams such as Bolin Creek is also important because streams and other water bodies are part of a complex, connected network of ecosystems. Ecosystems are fragile and more sensitive to stressors than individual organisms.[6] Currently, anthropogenic factors such as agriculture, urbanization, climate change, and invasive species synergistically threaten ecosystems globally.[1] Ecosystem services form the foundation of human life and the basis of human economic activity.[7,8] They provide ecosystem goods, such as timber and biomass fuels; support the life humans depend on; purify air and water; stabilize climates; and provide support and regulation services such as pollination, the dispersal of seeds, and control of pests.[7] Predicting the extent of the effects of anthropogenic stressors on ecosystems is complicated in that human impacts on ecosystems can affect societies elsewhere.[8]

Urbanization:

Currently, more than 4 billion people live in urban areas, and global urbanization is projected to further increase.[9] High probability estimates show an increase of 1.2 million km^2 in urban land cover by 2030.[10] The effects of urbanization remain complex and our knowledge of its effects remains limited.[11] There are benefits to urbanization; for example, the high-density development in urban areas could decrease total energy use and greenhouse gas emissions compared to suburban areas.[10] However, urbanization affects water quality, as well as ecosystem services derived from water bodies.[12] Below, two specific ways by which urbanization affects water quality are described: contaminated runoff and thermal pollution.

Runoff:

Urbanization increases the amount of impervious surface cover (ISC) in a watershed, which decreases infiltration rates.[13-16] Impervious surfaces are made of impermeable materials such as asphalt and concrete, and they are found in rooftops, parking lots, roads, and other works of infrastructure.[17] Increased ISC can increase stream channel erosion because impervious surfaces are hydrologically active, meaning that they can generate runoff that flows directly into the stream channel.[17] Together with increased artificial drainage systems (e.g., pipe drains and ditches), urbanization and ISC have large effects on the amount and intensity of runoff.[11,18-20] Sun and Caldwell (2015) have demonstrated the existence of a strong exponential correlation between imperviousness and runoff (R^2= 0.92).[12]

Stormwater runoff can directly contribute to the pollution of water bodies, and if stormwater drains into treatment facilities through pipes, overloads wastewater treatment facilities and impair sewer systems.[21] In addition, the increased intensity of the flowing water of runoff entering streams increases erosion in the stream channels, which degrades stream water quality[22] and increases sedimentation.[20] While runoff has physical effects on water bodies and streams, the most important way that runoff harms aquatic life is the toxins that runoff carries into freshwater ecosystems.[23] Runoff can contain contaminants washed off cars and from roads, chemicals used by industry and by the public, and chemicals deposited from the atmosphere. Atmospheric inputs of pollution (e.g., from industry or automobiles) also affect water bodies through direct transfer to water bodies, even without runoff.[1, 21] Runoff and municipal waste can contain organic compounds; heavy metals; acids; alkalis; pesticides such as insecticides, herbicides, fungicides; DDT and other banned substances; polychlorinated biphenyls (PCBs), even though their use has been outlawed; petroleum-based organic compounds; phosphorus and nitrogen from fertilizers; and chlorides; all entering water bodies and potentially poisoning aquatic organisms.[1,5] Water in urban areas can also contain human medication, including antibiotics, narcotics, psychotherapeutic drugs, and chemotherapeutic drugs.[12,5] Instead of infiltrating into the ground, the pollutants and solids accumulate in water bodies and the severity of this process are further accelerated as ISC increases the flow of runoff, leaving less time for the pollutants to infiltrate into the ground.[15, 20] When the runoff does infiltrate, urban pollutants then pollute groundwater. One indication of increased dissolved chemicals in water bodies is electrical conductivity (EC).[5] EC is measured by the ability of an electric charge to pass through a water sample.[24] EC is an indicator of human disturbances to water.[25] Another indicator, turbidity, is a measure of the solids suspended in water and is measured by the amount of light absorbed and scattered by a water sample.[26,27] Measurements of EC and Turbidity were used in this study.

Urbanization, ISC, runoff, and the resulting pollution have impacts on aquatic ecosystems, which include fish, macrophytes, and macroinvertebrates.[15,5] Ephemeroptera, Plecoptera, and Trichoptera (EPT) are examples of orders of aquatic insects sensitive to change in water quality and are useful as bioindicators because they are easily negatively affected by water pollution.[23,28,29] Gresens *et al*. (2006) found that EPT taxa numbers were lower in urban sites than rural sites.[23]

Benefits of Macroinvertebrate Use:

Pollution is broadly defined in Britannica as "the addition of any substance (solid, liquid, or gas) or any form of energy (such as heat, sound, or radioactivity) to the environment at a rate faster than it can be dispersed, diluted, decomposed, recycled, or stored in some harmless form." Pollution "can have negative effects on the environment and wildlife and often impacts human health and well-being." The extent of pollution can be assessed by examining damage to aquatic organisms.[30]

Monitoring organisms in aquatic ecosystems is essential in evaluating the effects of pollution on water quality. One way to notice how the changes in water quality affect aquatic organisms is to monitor and identify the benthic macroinvertebrates (BMI) populations in waterways.

Monitoring BMI survival has many benefits; they can be found in most aquatic habitats, they are affected by the physical and chemical conditions of the waterway, and they are generally sedentary in nature due to limited mobility, so they cannot escape acute water pollution events,[31] and thus they can be used to indicate changes in water quality over the course of months and years.[32]

Thermal Pollution and the Urban Heat Island Effect :

Urbanization is associated with thermal pollution. The Urban Heat Island Effect (UHI) is the process of urban areas heating up more rapidly than the surrounding areas due to decreased vegetation, increased heat-absorbing infrastructure, and increased heat-generating infrastructure.[11,33] Bornstein (1968) found an average UHI intensity of 1.6 °C in his studies of New York City.[33] Magee *et al*. (1999)[34] studied two areas in Alaska from 1949 to 1997: Fairbanks, which underwent urbanization and population growth, and Eilson, which had similar geographic features but less urbanization and a steady population. The authors found a substantial difference between the heating of Fairbanks and Eilson, and that ⅕ of the heating of Fairbanks was attributed to the UHI. Thermal inversions, typical in the winter, cause heat and pollution to be trapped in urban areas,[34] and previously mentioned atmospheric pollution can enter stormwater runoff.[1] Furthermore, layers of anthropogenic chemicals and air pollutantss, such as sulfur dioxide, water vapor, and smoke, also further re-radiate heat back to urban surfaces exacerbating the UHI.[33]

Stormwater runoff can heat up significantly due to the heat conducted into the runoff by ISC,[17] thereby transferring the heat into receiving water bodies.[18] According to the United States Environmental Protection Agency (EPA; 2020),[18] thermal pollution stresses aquatic life in a variety of ways. Fish increase their metabolism in proportion to temperature, and large temperature increases can have fatal effects when the thermal tolerances of aquatic organisms are exceeded.6 Additionally, warm water holds less DO than cold water due to entropy, reducing oxygen available to aquatic organisms and further degrading water quality.[35] Because fish are important members of, and even regulators of, aquatic ecosystems,[1] harm to fish can be inferred to affect many other organisms, including benthic macroinvertebrates.

Channelization :

Channelization is an example of anthropomorphic changes in aquatic ecosystems. The deepening and widening of streams by channelization destroy benthic habitats; straightening streams increases flow rates, affecting species and habitat quality.[36] Other species may decrease as channelization removes needed turbulent and rocky areas in streams with high oxygen contents.[37] Studies reviewed by Brooker (1985) show that bankside trees and stable soils are often decreased due to channelization.[38] The removal of riparian buffer zones can increase the sunlight entering headwaters which can increase water temperature and alter the normal tenets of the River Continuum Concept described by Vannote *et al*. (1980).[37, 39]

History of Bolin Creek:

This study analyzed the water quality of Bolin Creek, which is located in Orange County, North Carolina, in the Cape Fear

DOI: 10.36838/v4i5.22

river basin. It runs for 14½ km (9mi) through the cities of Carrboro and Chapel Hill and has an area of about 31 km^2 (11.98 mi^2).[40,41] The land cover of the Bolin Creek watershed is 16.9% impervious.[20] Bolin Creek converges with Booker Creek to form Little Creek.[41] Little Creek eventually flows into B. Everett Jordan Lake,[40] a source of water for hundreds of thousands of people.[42]

Bolin Creek has had a history of troubled water quality. It is listed on the state of North Carolina's 303 (d) list as a result of the excess sedimentation found in the creek.[40,41,43] This indicates that the creek has been unable to sustain the normal amount of biodiversity of a healthy stream.[40] The investigations by Beggs *et al*. (2012) of the North Carolina Department of Environmental Quality (NCDEQ) concluded that the water quality of Bolin Creek worsened as it traveled downstream into a denser urban environment, starting at Carrboro and flowing into Chapel Hill.[40] As seen on the NCDEQ Benthic Monitoring Data website, the site nearest to the headwaters of Bolin Creek near Homestead Road had a bioclassification of "Good-Fair" while the site furthest downstream was classified as "Poor".[44]

Recently, multiple developments have accelerated the degradation of Bolin Creek. In 2009, the Town of Carrboro, as part of its Bicycle Plan, proposed the replacement of the nature trail along Bolin Creek with a 10-foot wide paved path, eliciting a negative response from the community.[42,45] Similarly, according to a report done by the North Carolina Department of Environmental and Natural Resources (NCDENR), both Bolin Creek and its neighboring Booker Creek were channelized downstream of East Franklin Street to allow for straighter roads, railroads, and sewer and water lines.[41]

Broader Purpose:

The present study focused on the effects of urbanization and ISC on water quality in Bolin Creek, to aid organizations in removing Bolin Creek from the 303(d) list and mitigate the impacts of urbanization. We hypothesized that increased development around Bolin Creek would be correlated with a decrease in the water quality of the creek as determined by biological analyses on BMI assemblages, and measurements of physical and chemical parameters.

■ Materials and Methods

Overview:

This study researched the water quality of three sites at Bolin Creek as well as of two reference streams. The five sites were found using the NCDEQ Benthic Monitoring Data online interactive website.[44] Each site was chosen to represent a different bioclassification rank ranging from excellent to poor based on previous work (Figure 1). The "Excellent" reference site was at Pokeberry Creek (35.7742°, –79.1200°; Site ID: BB320). The "Good" site was at Morgan Creek (35.92361°, –79.11556°; ID: BB146). The "Good-Fair" site was located near State Road and Homestead Road (35.9436°, –79.08833°; ID: BB330). The "Fair" site was located at Bolin Creek near Village Road (35.92278°, –79.06667°; ID: BB449). The "Poor" site was located at Bolin Creek near East Franklin Street (35.92778°, –79.035°; ID: BB071). The research team tested riffles, areas of fast-moving shallow water passing over rock or sand that are optimal environments for aquatic organisms and BMI to inhabit.[46]

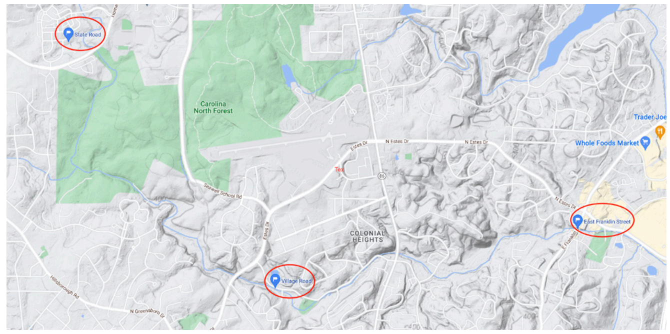

Figure 1: A Google Maps depiction of Bolin Creek. The three tested sites (upstream to downstream) are marked with red circles: State Road, Village Road, and East Franklin Street.

Macroinvertebrate Collection:

In order to collect the BMI, the team followed the 2016 NCDEQ Standard Operating Protocol (SOP) for the Collection and Analysis of Benthic Macroinvertebrates, specifically, the Qual-4 method.[32] The Qual-4 method involved four steps: a riffle-kick, sweep, leaf pack, and visual search. The riffle kick involved kicking the benthos (3m2) for 2min and letting BMI flow into a 1m wide net (with 1000μm mesh) downstream. A D-Net was used to sweep BMI from roots and undercut banks. All BMI were removed from leaf packs, and the visual searches involved BMI collection from riffle rocks, woody debris, and other features not previously sampled. Approximately 10–15 minutes were allocated to each step. All collected BMI were preserved in >70% ethanol solutions and stored in glass vials. After collection, the BMI were morphotyped using handheld magnifying glasses and identified to family using the Atlas of Common Freshwater Macroinvertebrates of Eastern North America as a reference.[47] In addition, previous NCDEQ BMI collection data were provided to the team by Mr. Eric Fleek from the NCDEQ as a reference to the taxa collected by the state of North Carolina.[48] Knowledge of previous BMI collections allowed the researchers to deduce the type of BMI, sometimes even identifying species.

North Carolina Biotic Index:

After identification (to family-level taxonomic group) and enumeration of each taxon, the BMI assemblages were used to determine the NCBI values of the stream sites. The NCBI score (equation 1) uses the abundance values and family-level tolerance values (mean of all reported NC species in the family) of BMI taxa to determine a quantitative value of water quality, the mean tolerance value of the sample. The outputs range from 0.0–10.0, where the lower values indicate less tolerance for pollution and higher water quality. An abundance of pollution-intolerant species (e.g., EPT taxa) would indicate better water quality, whereas an abundance of pollution-tolerant species would indicate poorer water quality. The following equation for calculating a mean (e.g., from the NCDEQ SOP) was used to determine the NCBI:[32]

$$B = \frac{\Sigma(Ti)(ni)}{N} \quad (1)$$

The North Carolina Biotic Index where:
B = the Biotic Index
T_i = the Tolerance Value (TV) for the i^{th} taxon
n_i = the abundance category value (1, 3, or 10) for the i^{th} taxon
N = the sum of all abundance category values

A lower value of the Biotic Index (B) signifies greater water quality with lower mean tolerance values. The resulting NCBI scores were compared to the bioclassification criteria according to the NCDEQ SOP Table 8 and ranked based on the scale from "Excellent" to "Poor" using the Piedmont area classifications.

Biodiversity Indices:

To prevent solely relying on the Biotic Index to determine the water quality of the stream sites, biodiversity was also quantified using two indices: Simpson's Diversity Index (equation 2) and Shannon-Wiener Diversity Index (equation 3), which produced results in ranges of 0–1 and 0–5, respectively. These indices indicate the level of biodiversity and evenness within a sample. For the Simpson's Diversity Index, which takes into account the dominance of species, numbers nearing the lower limit of the range represent relatively lower biodiversity and evenness whereas numbers nearing the upper limit represent relatively higher biodiversity and evenness. For the Shannon-Weiner Diversity Index, numbers nearing the lower limit of the range represent lower biodiversity while numbers nearing the upper limit of the range represent higher biodiversity. The formulas are displayed below:

$$DI = 1 - \Sigma(\frac{n}{N})^2$$ [redacted]

(2)

Simpson's Diversity Index where
n = total actual abundance of organisms of a certain species
N = the total actual abundance of organisms of all the species

$$H = -\Sigma[(\frac{n_i}{N}) \cdot ln(\frac{n_i}{N})]$$
$$E = \frac{H}{H_{max}}$$

(3)

Shannon-Wiener Diversity Index where
n_i= actual abundance of individual species
N= total actual abundance
H_{max}= maximum diversity possible

Water Chemistry and Physical Water Properties:

Eight measurements of water chemistry and physical water properties were collected at the five sites. The Vernier LabQuest® 2 probes and monitors were used to measure turbidity in Nephelometric Turbidity units (NTU), dissolved oxygen (DO, mg/L), conductivity in microsiemens per centimeter (μS/cm), pH, and water temperature (°C). All probes were "plug-and-play" with the exceptions of the turbidity probe, which required calibration before each use, and the DO probe, which also required occasional calibration. A LaMotte Earth Force® Low-Cost Water Monitoring Kit was used to test approximate nitrate (NO_3, ppm) and phosphate (PO_4, ppm) concentrations, as well as the presence or absence of mammalian fecal coliform (*Escherichia coli*).

BEHI:

A modified Bank Erosion Hazard Index (BEHI) was used to assess the extent of bank erosion at each site. The specific BEHI procedure used, developed by Dave Rosgen of Wildland Hydrology, Inc., was written and explained by Rathbun (2008). Factors that affected BEHI scores49 included root depth, root density, surface protection, bank angle, and the presence of various types of rock/soil and stratification.

Discharge:

Baseline discharge, or the amount of water usually flowing through a river at any given point and measured in ft3/s, was determined and recorded at each of the five sites. The team followed the protocol created by the National Great Rivers Research and Education Center for the calculations.[50] Briefly, this entaileds determining the cross-sectional area of the stream site in ft^2 multiplied by the water flow rate in ft/s.

Land Coverage Data:

Land coverage data for each of the areas around the watersheds that drained into their respective stream sites were collected through QGIS software with data retrieved from the USGS National Map as well as the National Land Cover Database (NLCD).[51] The NLCD is a product of the Multi-Resolution Land Characteristics (MRLC) Consortium, a federal collaboration.[52] The MRLC consortium uses Landsat satellite imagery as part of their data collection procedure. These data allowed for the categorization of urbanized land cover. The authors categorized the land use upstream to sampling sites into "low", "medium", and "high" groups based on the percentage of ISC in each watershed.[51] "Low" entails 20–49% ISC, "medium" entails 50–79% ISC, and "high" entails 80–100% ISC. For the purposes of the study, low, medium, and high land uses were combined into one measurement of "developed land coverage". In addition, the same methods were used to determine the percentage of agricultural and forested land cover. However, these data were not used in correlation calculations.

Results

North Carolina Biotic Index (NCBI) values ranged from 4 to 7 and increased as Bolin Creek flowed further downstream, indicating decreasing water quality (Figure 2). State Road is upstream from Village Road, and Village Road is upstream from East Franklin Street. Developed land cover increased from State Road to East Franklin Street, but Village Road had a lower percentage of developed land cover than State Road (Table 1). Notice that the percentage of developed (impervious) land cover at the "Poor" site at E. Franklin Street was approximately six times greater than that of the "Excellent" site at Pokeberry Creek. Strong positive correlations were found between developed land cover and NCBI (Figure 3) as well as developed land cover and conductivity (Figure 4). Conductivity was moderately positively correlated with NCBI values (Figure 5). Turbidity was strongly positively correlated with NCBI (Figure 6). Nitrate and phosphate concentrations strongly positively correlated with developed land cover (Figure 7) and with NCBI values (Figures 8–9). In comparing

DOI: 10.36838/v4i5.22

biodiversity scores determined using the Simpson's Diversity Index (SDI) and the Shannon-Wiener Index, it was found that Pokeberry Creek had the highest level of biodiversity and Morgan Creek had the lowest level of biodiversity (Figure 10). From furthest upstream (State Road) to furthest downstream (East Franklin Street), Bolin Creek's biodiversity decreased. Both biodiversity indices agreed on the relative biodiversity scores. It may appear that the SDI detected no difference between the biodiversity of Bolin Creek at State Road and Village Road (Figure 10), but closer analysis of the values indicated that it did. A moderately strong, positive correlation was found between SDI and dissolved oxygen (DO; Figure 11).

A moderate negative correlation was found between nitrate concentration and DO (R^2= 0.60; not shown). A weak–moderate positive correlation was found between DO and the number of EPT found at the sites (R^2= 0.39; not shown). A strong but chemically unexpected correlation was found between DO and temperature (R^2= 0.84; not shown).

Correlations with R^2 values below 0.40 were not considered meaningful. However, a correlation approaching R^2> 0.40 was found between temperature and SDI (R^2= 0.38). No meaningful correlations (not shown) were found between discharge and DO; turbidity and SDI; turbidity and the abundance of EPT; discharge and NCBI values; discharge and SDI; pH and NCBI values; temperature and NCBI; nitrates, phosphates, and SDI; or pH and SDI. No correlation was found between temperature and developed land cover (not shown).

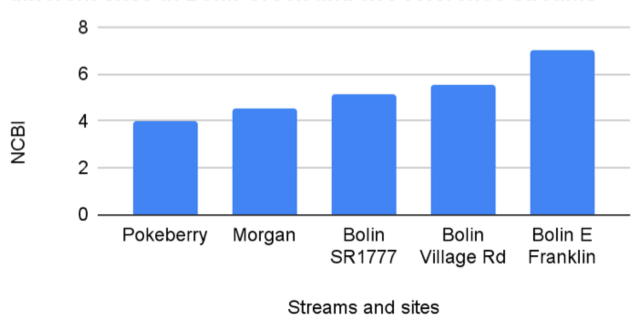

Figure 2: North Carolina Biotic Index values for three different sites at Bolin Creek and two reference streams (Pokeberry and Morgan Creeks).

Table 1: Percentage of developed, forested, and agricultural land in the area that drains into each of the five study sites. Notice that the percentage of developed (impervious) land cover at the "Poor" site at E. Franklin Street was approximately six times greater than that of the "Excellent" site at Pokeberry Creek.

Site name	% Developed land	% Forested land	% Agricultural land
Pokeberry Creek	3.08	70.06	12.09
Morgan Creek	0.76	69.39	18.79
Bolin Creek—SR1777	7.61	64.17	5.22
Bolin Creek—Village Rd	4.67	38.80	3.21
Bolin Creek—E. Franklin	18.10	45.84	4.02

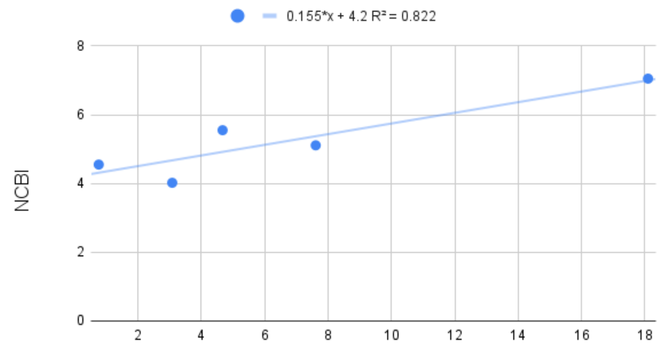

Figure 3: The relationship between the percentage of developed land cover and the North Carolina Biotic Index value.

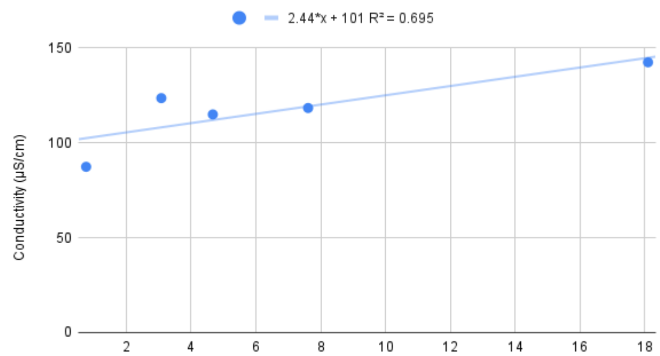

Figure 4: The relationship between the percentage of developed land and conductivity.

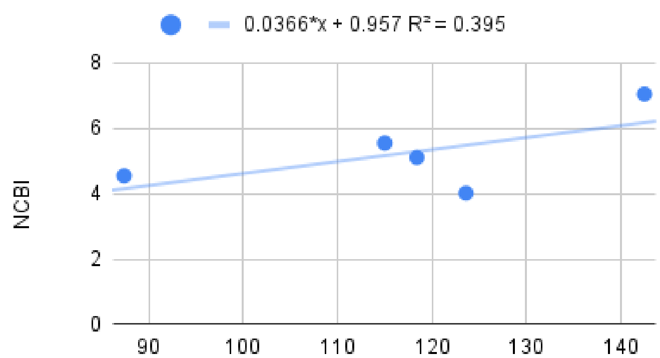

Figure 5: The relationship between conductivity and North Carolina Biotic Index scores.

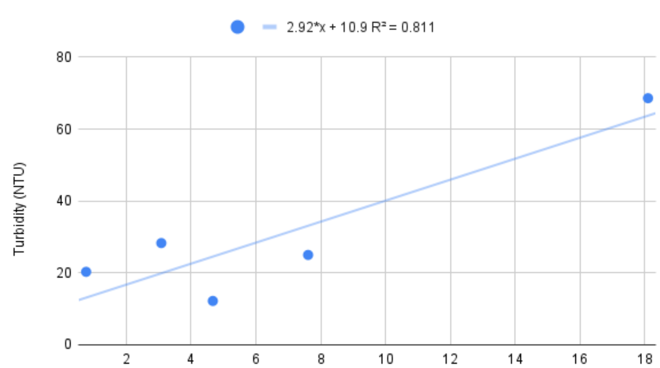

Figure 6: The relationship between the percentage of developed land cover and turbidity. Turbidity was measured in Nephelometric Turbidity Units, NTUs.

Water Chemistry and Physical Water Properties:

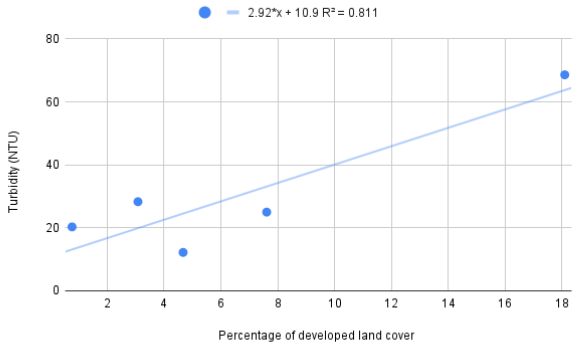

Figure 7: The relationship between the percentage of developed land cover and nitrate and phosphate concentrations. The red data points and red line-of-best-fit correspond to the correlation between the percentage of developed land and nitrate concentrations. The blue data points and line-of-best-fit correspond to the correlation between the percentage of developed land and phosphate concentrations.

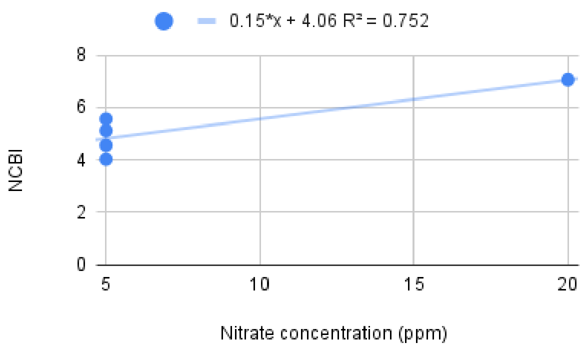

Figure 8: The relationship between nitrate concentration and North Carolina Biotic Index (NCBI) value.

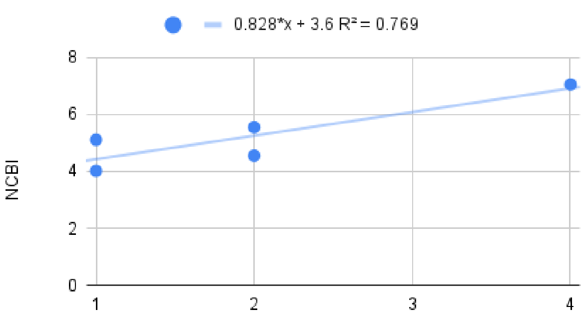

Figure 9: The relationship between phosphate concentration and North Carolina Biotic Index (NCBI) value.

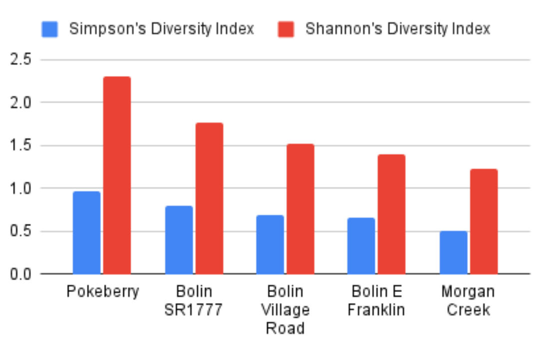

Figure 10: Biodiversity scores for the five tested sites as measured by both the Simpson's Diversity Index (blue bars) and the Shannon-Wiener Diversity Index (red bars).

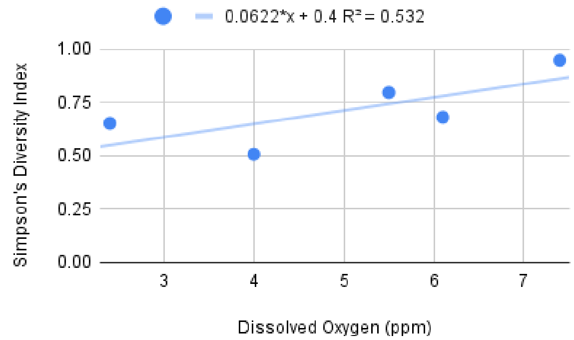

Figure 11: The relationship between Simpson's Diversity Index scores and dissolved oxygen (ppm).

Temporal Changes:

Figures 12–14 show changes in the water quality of the Bolin Creek sites at State Road, Village Road, and East Franklin Street over time, respectively. The water sites and graphs thereof are ordered from best to worst quality in terms of NCBI score. In each graph, the red bar indicates the data recorded by this study. The remaining data is taken from Lenat Consulting Services (2015) as well as data from the North Carolina Department of Water Resources (NCDWR), retrieved from the report by Lenat Consulting Services (2015).53 This study's data were calculated using the "Qual-4" method. Lenat Consulting Services (2015) mentioned other methods as well, such as the Standard Qualitative Method, so the comparisons may not be exact. However, since the NCBI takes the total abundance of species into account, the comparisons are nonetheless valuable. Compared to 2015, the water quality of the site of Bolin Creek at State Road has increased (Figure 12). Since 2002, the water quality of Village Road has increased, but the water quality is still lower than in 1998 (Figure 13). From March 2001 to July 2001, the water quality of Bolin Creek at East Franklin Street improved, but since July 2001 it worsened and remains at the same level as in March 2001 (Figure 14).

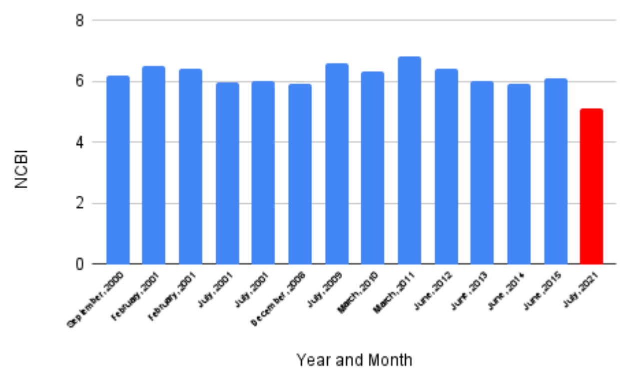

Figure 12: The change in the Biotic Index values of Bolin Creek at State Road 1777 over time.

DOI: 10.36838/v4i5.22

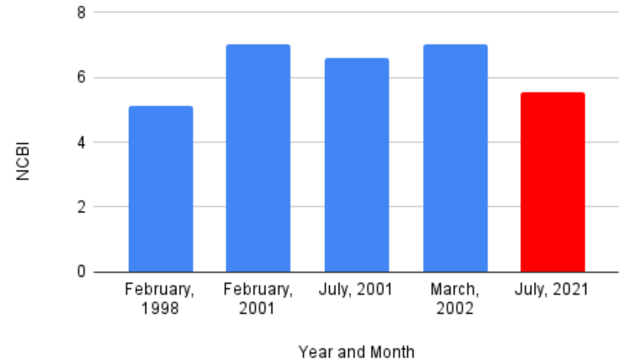

Figure 13: The change in Biotic Index values of Bolin Creek at Village Road over time.

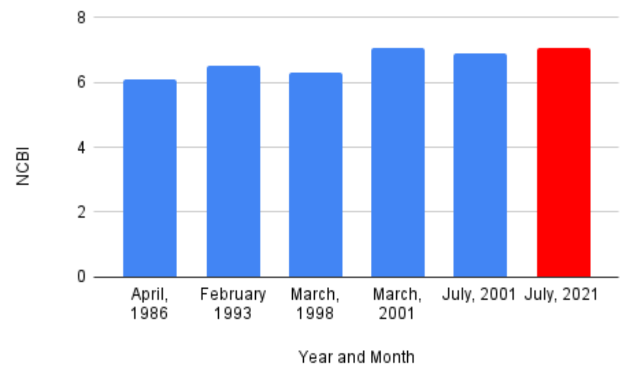

Figure 14: The change in Biotic Index values of Bolin Creek at East Franklin Street over time.

Discussion

Previous Studies and Observations:

Observations of NCDEQ data and previous studies show that the water quality of Bolin Creek does not decline uniformly, and upstream sites may be improving in water quality over time (Figures 12–13). However, as the creek flowed further into Chapel Hill, the bioclassifications changed into "Fair" near Estes Drive and Village Road; then, it flowed to a "Poor" rating at Bolinwood Drive and East Franklin Street.[44] The Watershed Assessment Restoration Project (WARP) determined urbanization and its effects as causes for the impairment, linking "habitat degradation, riparian degradation, [...], and toxicity" as primary stressors of the Bolin Creek watershed,40 as well as the possible stressors of extreme temperatures, high oxygen demand, and high nutrient levels.[40] The Bolin Creek Greenway, built in 1992, contributed to habitat and riparian degradation, as well as increased erosion along the banks of the river because of reduced vegetation to maintain bank stability, resulting in increased sedimentation in the stream substrate.[41] The installation of paved paths creates impervious surface cover (ISC) by which stormwater runoff can flow directly into the river.[54] Unpaved paths also create problems for the river as most unpaved paths are created in a "dip" shape which can erode and drain into the stream adjacent to the greenway, increasing sedimentation in the water.[55]

Bolin Creek has also had multiple sewage failures. The North Carolina Department of Water Quality (NCDWQ) non-discharge compliance unit data and the Orange Water and Sewage Authority (OWASA) recorded 4 sewage spills in the span of January 2000 to December 2002.[41]

Some efforts have been made to restore Bolin Creek. As a result of being on the 303 (d) list of impaired creeks, it qualified for an EPA 319 grant as part of the Clean Water Act.[56] The grant allowed the Bolin Creek Restoration Project (BCRP) to focus on repairing and controlling stream bank erosion, improving the overall water quality, and eliminating invasive species.[57] The BCRP included bank reshaping to reduce further erosion; removing and replacing invasive species; creating "step-pools" to reduce erosion and create riffles for aquatic life; and building multiple bioretention cells to redirect stormwater drainage, reduce erosion, recharge groundwater, and filter pollution.[57,58]

The Findings of this Study:

The findings of this study supported the conclusion made by the NCDWQ Watershed Assessment Report that the water quality of Bolin Creek declines as it flows further downstream (Figure 2).[40] The site of Bolin Creek at East Franklin Street, furthest downstream of the sites tested, has more urban development than the site of Bolin Creek at State Road, the site of Bolin Creek furthest upstream of the tested sites (Table 1). The site at East Franklin Street also had the poorest water quality in the study (Figure 2). In comparison, the site at State Road had the best water quality among the tested sites of Bolin Creek (Figure 2). Before the data collection, a decline in the water quality of Bolin Creek further downstream, as well as an increase in urbanized surroundings further downstream were observed, suggesting a correlation between urbanization and the declining water quality of Bolin Creek. The site of Bolin Creek at Village Road lies between State Road and East Franklin Street. According to the hypothesis that urbanization and poor water quality co-occur, Village Road's water quality would measure between those of State Road and East Franklin Street. This study showed that this is indeed the case (Figure 2). However, the site of Bolin Creek at Village Road had lower levels of development (ISC) than State Road (Table 1). This may be because Village Road has a lower percentage of forest land (Table 1).

The strong correlations found between developed land cover and declining water quality support the hypothesis that urbanization co-occurs with the declining water quality of Bolin Creek (Figure 3). The differences in development between the reference sites and the Bolin Creek sites in terms of ISC and development were associated with the decreased water quality of Bolin Creek. BMI populations were adversely affected in successive downstream sites on Bolin Creek (Figure 2). Sensitive BMI species' population densities decreased, while densities of tolerant species increased.

It was seen that electrical conductivity (EC) is an important effect of urbanization influencing water quality (Figures 4–5). EC was positively correlated with development (Figure 4) and declining water quality (Figure 5). Urban runoff can pick up pollutants,[17,23] as well as total dissolved solids (TDS).21 For example, Sartor et al. (1974) measured a weighted mean of 1,400 pounds of TDS per curb mile in their study of 12 cities.[21] Through urban and agricultural runoff, as well as sewage, TDS can accumulate in water bodies.[59] TDS, which also measures ions,[24] increases the EC of water. While the relation ship between EC and TDS is more complex in wastewater, the correlations between TDS and EC in natural water are significant,[24] further explaining the associations found between developed land cover, EC, and declining water quality.

Turbidity was shown to be a factor of development associated with declining water quality, ISC, and runoff (Figure 6). Sedimentation is correlated with turbidity,[27] and sediments and nutrients can harm habitats and benthic aquatic organisms.[60] Higher turbidity levels lead to decreases in photosynthesis levels and resulting dissolved oxygen concentrations, and vegetation density.[60] This may explain the decrease in biodiversity as Bolin Creek flowed further downstream into more developed land (Figure 10) as DO was correlated with biodiversity (SDI; Figure 11). Algal growth increases turbidity,[61] and in the events of algal blooms, turbidity measurements can inversely correlate with DO because of increased algal metabolic activity at night and increased aerobic bacterial decomposition of dead algae.[62]

Nitrate and phosphate levels were correlated with development and ISC (Figure 7). Increased nitrate and phosphate levels may cause higher turbidity and EC levels, as the nutrients cloud water. Urban areas are sources of nitrogen (N), found in nitrate ions, and phosphorus (P), found in phosphate ions, to aquatic ecosystems, for example from fertilized laws.[63] When runoff is insufficiently slowed, increased amounts of N and P can enter streams, providing essential nutrients for algal growth.[64] Growing human populations increase runoff and discharges of pollutants and sewage (including pet sewage), leading to cultural eutrophication, which entails pollution of water bodies by nutrients and toxic algal blooms.[63,65] Algal populations increase in proportion to the amount of N and P, essential nutrients, in water bodies. A study of the Belgian Coastal Zone found a meaningful relationship between nitrate concentration in water and the growth of *Phaeocystis globosa*, a harmful algal bloom species, and an indicator of eutrophication.[66] Algae blooms can increase turbidity and algal toxin concentrations, and cause deoxygenation due to the decay and cellular respiration of excesses of algae.[62] While nutrient pollution may lead to eutrophication, it is also important to consider that metals, toxins, and turbidity increases due to urban development can negatively affect algae biodiversity and biomass, as shown by studies reviewed by Paul and Meyer (2001).[5] It is clear, however, that nutrient pollution, similar to increased sediment and suspended matter, was associated with development, runoff, and declining water quality.

Similar to the correlations found between development and nutrient pollution (Figure 7), Kim et al. (2016),[67] in their studies of 47 sub-watersheds over 5 years in the Han River Basin in Korea found a strong correlation between ISC and P levels. Ballasiotes *et al*. (2015) showed that in Bolin Creek, there was a higher level of N at East Franklin Street, which has 15.58% ISC, than at a site they tested with 14.23% ISC.[20] The site with 14.23% ISC had higher levels of N than another site they tested with an even lower ISC percentage of 9.23%. They found that N was "generally increasing" further downstream in Bolin Creek.

Bolin Creek at East Franklin Street, the most developed site tested, has continually proved to have the poorest water quality of the three sampled sites at Bolin Creek (Figure 2). Comparisons between this study's data and those of the NCDWR show that the water quality at East Franklin Street has not improved since 2001 (Figure 14). Chapel Hill currently has dangerously high levels of ISC.[20]

The bioclassifcations determined by the NCBI scores calculated were relatively consistent with the data from the NCDEQ, but there were some differences. The NCDEQ rated Bolin Creek at State Road (BB330) and Village Road (BB449) "good-fair" in 2001 and "fair" in 2002, respectively. This study, however, rated them as "good" and "good-fair," respectively. These findings may indicate that the water quality of the two sites has improved.

The hypotheses that the UHI effect and that pH impact Bolin Creek were not supported. The correlation found between temperature and DO was the opposite of what would be expected chemically. The short time span of the data collection likely contributed to inconsistent findings on temperature. Further studies should be conducted to investigate the relationship between temperature and land cover at Bolin Creek. In addition, further research is needed to clarify the relationships between the pH of the water of Bolin Creek and development in its watershed.

Limitations:

Among the limitations encountered in this study, the most challenging was a lack of complex and precise equipment. The nitrate and phosphate tests provided a rounded measurement in ppm. The coliform (*E. coli*) test provided only qualitative results in the form of "positive" or "negative"; hence, there was a lack of precision in the density of coliform present in the streams. Another limitation encountered was the use of BMI to assess water quality. Although they are useful, BMI does not respond to all types of pollutants. The presence or absence of a species may be due to factors other than pollution, such as unfavorable water currents, type of substrate, or drought, and their abundance and distribution may vary seasonally. Our tools for BMI identification, such as handheld magnifying glasses, did not have enough magnifying power to allow specific morphotyping of all BMI into genera and species. Another limitation of this study was the researchers' general lack of experience and expertise in the collection and identification of BMI. However, the data collected in this study were considered sufficient enough to support this study's hypothesis and are consistent with NCDEQ findings. If this study were to be repeated with more sophisticated equipment, the results could be subject to small changes, but it is inferred that the overall conclusion would remain the same. Future research should be conducted to corroborate this study's conclusions over a longer time span, a larger number of samples, and in different weather conditions and seasons.

Broader Issues and an Orientation to the Future:

The continued study of urbanization, ISC, and water quality are crucial, both as it relates to Bolin Creek and water quality and ecosystems in general. Runoff is the third largest cause of water impairment in tested lakes, according to the National

DOI: 10.36838/v4i5.22

Water Quality Inventory.[68] Chapel Hill, where the worst water quality of Bolin Creek was reported, is undergoing further urbanization. This increased development will make the issue of declining water quality in the Bolin Creek watershed more relevant and apparent.[20] Biotic and abiotic components in ecosystems are complex and interconnected.[8] The impacts of urbanization (both present and future increased levels) on Bolin Creek could be threats to more complex networks of ecosystems.

The declining water quality of Bolin Creek falls under the broader development of urbanization. The process of urbanization has grown rapidly over a short amount of time. Urbanization mostly occurred over the past 200 years.[9] According to data from the Census Bureau, 40% of the US population lived in urban areas in 1900.9 In current times, in the US, 80% of the population lives in urban areas.[12] With increased technological power, and exponential improvements in technology and sciences,69 the rapid growth of urbanization does not appear to be slowing. By 2050 it is predicted that more than ⅔ of the world population will live in urban areas, amounting to 7 billion people.[9] The rapid growth of urbanization suggests that in addition to having to deal with the effects that urbanization has already had, the future effects of urbanization must be managed even more effectively.

Future Mitigation Strategies:

A major factor damaging the water quality of Bolin Creek was identified, both in previous studies and this study, as urban runoff linked to impervious surfaces. In areas with high urban development, it is important to develop conservation strategies to mitigate the impacts of urbanization.[10] Replanting native vegetation to restore the riparian buffer along Bolin Creek would retard runoff and erosion.[70]

Due to the ability of street contaminants to pollute streams in the form of runoff, Sartor *et al*. (1974) sought to explore the general efficacy of conventional street cleaning operations on the reduction of street contaminants.[21] The typical mechanical street cleaning operations conducted by U.S. cities were found to be unable to remove a majority of street contaminants. It was found that when the "effort" of mechanical street cleaning practices was increased, such as through conducting multiple "sweeps" of an area or operating at a slower speed, up to 90% of concentrations of dust and dirt could be removed from street surfaces. Ongoing research is exploring the efficacy of street cleaning as a best management tool.[71] However, the Town of Chapel Hill may still benefit from exploring street cleaning as an option to decrease the impact of urban runoff on aquatic ecosystems.

Green infrastructure (GI), such as green roofs, is also an option that the Town of Chapel Hill could explore. GI is defined by the Conservation Fund to describe the interconnected network of features, natural areas, semi-natural areas, and green spaces that maintain ecological processes in rural and urban areas.[72] GI has been identified as a sustainable method of managing stormwater.[73-75] Green roofs in partsicular contain vegetative layers that can slow and reduce stormwater runoff as well as filter pollution from rainfall.[76] Costs may discourage investment in green roofs; however, those costs may be offset by the environmental benefits green roofs can offer.76 Similarly, various types of permeable surfaces, surfaces that allow the infiltration of water, are effective at reducing runoff and the peak flow of floods.[77,78] Although the reduced durability of permeable surfaces serves as a challenge deterring their widespread adoption, the ability of permeable pavements to mitigate the aforementioned negative effects attributed to urbanization may still validate its consideration by the Town of Chapel Hill as a form of stormwater management.[77, 78] Additionally, future research should be conducted on the efficacy of other GI, such as the bioretention pools constructed as part of the BCRP, to prove if they are an effective solution to improve water quality.

A supplemental resource for the Town of Chapel Hill to consider is the Clean Water State Revolving Fund (CWSRF).[79] This government-sponsored program allows eligible recipients to receive low-interest loans for water infrastructure projects.[79] Chapel Hill could explore this program as a financing resource for water infrastructure projects aimed at improving the water quality of its aquatic ecosystems.

Lastly, it is important to raise the awareness of the community of Chapel Hill about the health of its aquatic ecosystems. Many adults and children live in urban areas; therefore, ecologists and education systems have a unique opportunity to educate the general public on ecological processes.[5] As specific outreach to reach many children, Bolin Creek could be used as an example in classrooms to demonstrate the negative effects of urbanization. Citizens with an increased awareness of the issues affecting their town may feel more inclined to support the mitigation of such issues. The implementation of some or all of the proposed solutions may lead to the improvement of the water quality of Bolin Creek as well as of other creeks affected by urbanization.

Conclusion

This study found meaningful correlations between metrics of developed land use and declining water quality. The sites at Bolin Creek declined further downstream as its immediate watershed became increasingly urbanized. The site at East Franklin Street consistently showed worse water quality than the other tested sites in terms of its conductivity, nitrates, phosphates, NCBI score, biodiversity, and DO levels. Biodiversity alone, however, was not found to meaningfully predict NCBI scores, and the UHI was not reflected by this study's data on temperature. Nonetheless, sensitive BMI such as EPT declined as ISC increased, and nutrient pollution due to developed land cover was reflected by the data of this study. Bolin Creek's site at East Franklin Street has not improved since 2001, and impervious surfaces in Chapel Hill are at high levels. Prior research as well as the data of this study prompted the researchers to determine runoff from impervious land cover to be the major probable cause of urbanization affecting Bolin Creek.

Due to the interconnected nature and sensitivity of ecosystems, and the ecosystem services provided by them, Bolin Creek's case cannot be viewed in isolation. The biological concerns of Bolin Creek are relevant both to the residents living near it, as well as to urban ecosystems in general. The findings of this study on the effects of urbanization are relevant and important because of the rapid growth of urbanization tak ing place in the US and globally. The authors hope that Bolin Creek's water quality will be restored to healthy levels and that further mitigation of the effects of urbanization will be a priority in the future.

Acknowledgements

The authors of this study wish to thank Mr. Scott Taylor, Mr. Kelly Ruff, and Mr. William McMahan for their instruction, help, and mentorship. Also, thanks are extended to Mr. Eric Fleek from the NCDEQ for providing previous data on benthic macroinvertebrates at the sites tested in this study. The authors would also like to thank Ms. Nina Johnson, Ms. Andromeda Crowell, and Ms. Megan Aeschleman for their comments and suggestions made during the process of writing and editing this paper. Furthermore, the authors extend their thanks to the peer reviewers for their time and effort in giving essential feedback that helped the authors publish this paper. Finally, the researchers wish to thank all of the Appalachian State faculty and especially the program director, Ms. Lori Tyler, who provided important logistical support, guidance, and mentorship through the Summer Ventures in Science and Mathematics program. Summer Ventures presented the researchers with incredible opportunities to develop themselves in science.

References

1. Carpenter, S. R., Stanley, E. H., and Vander Zanden, M. J. (2011) State of the World's Freshwater Ecosystems: Physical, Chemical, and Biological Changes. *Annual Review of Environment and Re sources* 36, 75–99.
2. UN-Water. (2021). *Summary Progress Update 2021: SDG 6 — Water and Sanitation for All*, pp 10–15. Rep. PDF Down load Link on Website: https://www.unwater.org/publications/summary-progress-update-2021-sdg-6-water-and-sanitation-for-all/
3. MPCA. (2020, November 10) Why You Should Care About Water Quality. *Minnesota Pollution Control Agency*.
4. (2018, September 17). United States Geological Survey. Stream Ecology. *USGS, Water Resources*.
5. Paul, M. J., and Meyer, J. L. (2001) Streams in the Urban Land scape. *Annual Review of Ecology and Systematics 32*, 333–365.
6. Clark, J. R. (1969) Thermal Pollution and Aquatic Life. *Scientific American 220*, 18–27.
7. Daily, G. C., and Mooney, H. (1997) Introduction: What Are Eco system Services?, *in Nature's Services: Societal Dependence on Natural Ecosystems*, pp 1–6. essayABBE Pub. Assoc.of Washing tonAnnandale.
8. Folke, C., Holling, C. S., and Perrings, C. (1996) Biological Diver sity, Ecosystems, and the Human Scale. *Ecological Applications 6*, 1018–1024.
9. Ritchie, H., and Roser, M. (2018, June 13) Urbanization. *Our World in Data*.
10. Seto, K. C., Guneralp, B., and Hutyra, L. R. (2012) Global forecasts of urban expansion to 2030 and direct impacts on biodi versity and carbon pools. *Proceedings of the National Academy of Sciences 109*, 16083–16088.
11. McGrane, S. J. (2016) Impacts of urbanization on hydrological and water quality dynamics, and Urban Water Management: A Review. *Hydrological Sciences Journal 61*, 2295–2311.
12. Sun, G., and Caldwell, P. (2015) Impacts of Urbanization on Stream Water Quantity and Quality in the United States. *Water Resources IMPACT 17,* 17–20.
13. Carter, R. W., and U.S. Geological Survey. (1961) Magnitude and Frequency of Floods in Suburban Areas, in Short Papers in the Geologic and Hydrologic Sciences: *Scientific Notes and Summaries of Investigations*, pp 9–12. essayU.S. Government Washington, D.C.
14. Chormanski, J., Van de Voorde, T., De Roeck, T., Batelaan, O., and Canters, F. (2008) Improving Distributed Runoff Prediction in Ur banized Catchments with Remote Sensing Based Estimates of Im pervious Surface Cover. *Sensors* 8, 910–932.
15. Chithra, S. V., Harindranathan Nair, M. V., Amarnath, A., and Anjana, N. S. (2015) Impacts of Impervious Surfaces on the Envi ronment. *International Journal of Engineering Science Invention ISSN (Online) 4*, 27–31.
16. Zhang, B., Xie, G., Zhang, C., and Zhang, J. (2012) The economic benefits of rainwater-runoff reduction by urban green spaces: A case study in Beijing, China. J*ournal of Environmental Manage ment 100*, 65–71.
17. Barnes, K. B., Morgan, J., and Roberge, M. (2000) Impervious Surfaces and the Quality of Natural and Built Environments. *Re searchgate*.
18. United States Environmental Protection Agency. (2020) Protect ing Water Quality from Urban Runoff. (PDF File).
19. Xu, Z., Xiong, L., Li, H., Liao, Z., Yin, H., Wu, J., Xu, J., and Chen, H. (2017) Influences of rainfall variables and antecedent discharge on urban effluent concentrations and loads in Wet Weather. *Water Science and Technology 75*, 1584–1598.
20. Ballasiotes, A., Farley, H., Rose, L., and Whitehead, A. (2015) Bolin Creek Watershed
21. Sartor, J. D. (1974) Water Pollution Aspects of Street Surface Contaminants. *Water Pollution Control Federation 46*, 458–467.
22. GW Solution Inc., and Vadgama, J. (2008) *Coalbed Methane and Salmon:* Assessing the Risks. rep. Pembina Institute.
23. Gresens, S. E., Belt, K. T., Tang, J. A., Gwinn, D. C., and Banks, P. A. (2006) Temporal and spatial responses of Chironomidae (Diptera) and other benthic invertebrates to urban stormwater run off. *Hydrobiologia* 575, 173–190.
24. Rusydi, A. F. (2018) Correlation between Conductivity and Total Dissolved Solid in Various Type of Water: A Review. *IOP Con ference Series:* Earth and Environmental Science 118, 012019.
25. (2021) Indicators: Conductivity. *EPA*. United States Environmen tal Protection Agency.
26. Meride, Y., and Ayenew, B. (2016) Drinking Water Quality As sessment and its Effects on Residents Health in Wondo Genet Campus, Ethiopia. *Environmental Systems Research 5*.
27. Ankcorn, P. D. (2003) Clarifying Turbidity—The Potential and Limitations of Turbidity as a Surrogate for Water-Quality Mon itoring. *Proceedings of the 2003 Georgia Water Resources Con ferences* .
28. Burton, G. A., and Pitt, R. (2002) Stormwater effects handbook: A Toolbox for Watershed Managers, Scientists, and Engineers. Lewis Boca Raton.
29. Lenat, D. R., and Eagleson, K. W. (1981, January) Ecological Ef fects of Urban Runoff on North Carolina Streams. *Researchgate*.
30. Nathanson, J. A. (2022, May 9) Pollution. Encyclopædia Britanni ca. Encyclopædia Britannica, inc.
31. Sallenave, R. (2015, November) Stream Biomonitoring using Ben thic Macroinvertebrates. *New Mexico State University*.
32. North Carolina Department of Environmental Quality Division of Water Resources Water Sciences Section Biological Assessment Branch. (2016, February) Standard Operating Procedures for the Collection and Analysis of Benthic Macroinvertebrates.
33. Bornstein, R. D. (1968) Observations of the Urban Heat Island Effect in New York City. *Journal of Applied Meteorology and Cli*

DOI: 10.36838/v4i5.22

Sponge City Construction. *Water, 10*, 172.
78. Zhu, H.; Yu, M.; Zhu, J.; Lu, H.; Cao, R. (2019) Simulation Study on Effect of Permeable Pavement on Reducing Flood Risk of Ur ban Runoff. *International Journal of Transportation Science and Technology, 8,* 373–382.
79. EPA. (2021, July) Learn about the Clean Water State Revolving Fund (CWSRF). *EPA*. United States Environmental Protection Agency.

Authors

Yasmine Ackall, of Brazilian and Palestinian descent, is a junior at East Chapel Hill High School. She is interested in fields of biology such as genetics/genomics, molecular biology, and biochemistry. She wishes to attend a 4-year research university. She enjoys music and can play the violin, piano, and guitar.

Katherine Lopez, an immigrant from El Salvador, is a junior at City of Medicine Academy. She has a passion for learning about the human body and healthcare accessibility within communities. In her spare time, she enjoys painting, reading, and writing. She aims to pursue a career in the medical field.

Pristine Onuoha is a junior at East Chapel Hill High School. She is a Nigerian immigrant and has a love for STEM. She also aspires to become a physician. One of her biggest goals as a physician is to work in underserved communities with high doctor-to-patient ratios.

Micah van Praag, a Senior at Orange High School and an immigrant from Holland, is passionate and curious about the human body and mind, writing, and expressing himself creatively through filmmaking. He is interested in pursuing a medical career—with a focus on psychiatry, psychology, neurology, and bridges between science and philosophy.

Dr. Shea Tuberty oversees the aquatic ecotoxicology lab at Appalachian State University and mentors high school students for Summer Ventures in Science and Math. He received his B.A. at Vanderbilt University, M.S. & Ph.D. at Tulane University, and Postdoctoral training at the University of West Florida/USEPA Gulf Ecology Division

.