THE EFFICACY OF URBAN STREAM RESTORATIONS TO IMPROVE WATER QUALITY ACROSS A SPECTRUM OF DESIGN APPROACHES

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at George Mason University

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Dedication

This is dedicated to my Mom for all her love and support.

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TABLE OF CONTENTS

LIST OF TABLES

List of Figures

Figure | Page

ABSTRACT

THE EFFICACY OF URBAN STREAM RESTORATIONS TO IMPROVE WATER QUALITY ACROSS A SPECTRUM OF DESIGN APPROACHES

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The most recent national water quality inventory lists more than one-third of assessed rivers in the United States as impaired or polluted (EPA 2002). Concerns over the impacts of urbanization – the second largest contributor of non-point source pollution to surface water (Veissman and Hammer 2005) – have resulted in the initiation of major investments in urban stream restoration in the United States. However, less than 10% of stream restorations are currently post-monitored for goal attainment (Bernhardt *et al.* 2005; Hassett 2007). This study strives to address the wide research gap in post-stream restoration monitoring; particularly those associated with urban, headwater streams, as they receive the largest share of river restoration dollars and effort in the United States (Bernhardt and Palmer 2007). More specifically, this study focuses on water quality monitoring, nationally one of the most commonly stated project goals of stream restoration (Bernhardt *et al.* 2005).

The general research design involved water quality and discharge monitoring of three restored stream reaches across a spectrum of design approaches ("hard" structural design, "soft" bioengineering design, and "seepage wetland" design) on a bimonthly basis between October 2007 and April 2008, primarily during baseflow conditions. Upstream and downstream water quality data for nitrogen (nitrate + nitrite and ammonium), total suspended solids, pH, dissolved oxygen, temperature, and specific conductivity were statistically evaluated with paired t-tests. Water quality improvement amongst the three design approaches was statistically evaluated by comparing the differences between upstream and downstream concentrations using an ANOVA test. All statistical analyses utilized a 95% confidence level and were conducted using SPSS statistical software. The efficacy of the three design approaches was further evaluated by calculating percent differences between upstream and downstream concentrations as well as by calculating nitrogen and sediment removal efficiencies.

This study's results suggests that (1) all restored urban streams have the potential to improve water quality, as demonstrated by statistically significant differences between upstream and downstream concentrations for nitrate-N and dissolved oxygen in all three streams in the paired t-tests; and (2) the "seepage wetland" approach exhibited a greater percent removal of nitrate-N than the other two approaches.

Chapter 1: Introduction

1.1 Study Purpose

The most recent national water quality inventory lists more than one-third of assessed rivers in the United States as impaired or polluted (EPA 2002). Concerns over the impacts of urbanization – the second largest contributor of non-point source pollution to surface water (Veissman and Hammer 2005) – have resulted in the initiation of major investments in urban stream restoration. In the United States alone, an exponential trend in stream restoration implementation and spending (in billions of dollars per year) has been documented over the past decade (Bernhardt *et al.* 2005). Still, less than 10% of stream restorations are currently post-monitored for goal attainment (Bernhardt *et al.* 2005; Hassett 2007). Of that 10%, monitoring occurs on a very infrequent basis and is limited to the stream's structural integrity (Palmer *et al.* 2007).

This study strives to address the wide research gap in post-stream restoration monitoring; particularly those associated with urban, headwater streams, as they receive the largest share of river restoration dollars and effort in the United States (Bernhardt and Palmer 2007). More specifically, this study focuses on assessing water quality improvement, nationally one of the most commonly stated project goals of stream restoration (Bernhardt *et al.* 2005) and *the* most commonly stated goal in the Chesapeake Bay (Hassett *et al.* 2007).

The lack of monitoring data of stream restorations has resulted in a minimal translation of scientific understanding of river ecosystems to practitioners and policy makers (Bernhardt *et al.* 2007). For example, "according to the Chesapeake Bay Program, stream restoration is one of the least effective measures in reducing nutrient and sediment loadings" (personal communications, Stack 2007), even though studies indicate that 50-90% of sediment loading to the Chesapeake Bay originates from streambank erosion (Simon 2007) and 50% of nitrogen entering streams may potentially be removed by natural processes before it reaches coastal waters (Galloway *et al.* 2004). Under this current CBP policy condition, the prospect of reducing streambank erosion and uptaking nitrogen via restored, urban streams is not yet considered an effective best management practice (BMP). In addition, while the scientific underpinnings and practical limitations of the most frequently used restoration design approach, the Rosgen Method (Rosgen 1994), have been heavily scrutinized by academic and practitioner communities, this design approach is often required by local-level policy makers. Thus, in an attempt to contribute to the debate within the stream restoration community on the efficacy of different restoration techniques or features, this study selected stream restorations across a spectrum of design approaches for their ability to improve water quality.

In summary, as urban landscapes and human activities have (1) altered stream flow regimes causing severe bank erosion and sediment supply to downstream water bodies (Simon 2007); (2) impacted streams so heavily that they cannot appreciably reduce in-stream nitrogen (Galloway *et al.* 2004); and (3) led to significant resources toward restoring urban streams (Bernhardt *et al.* 2005), it is imperative that the data gap on the efficacy of urban stream restorations to improve water quality be addressed. This is particularly important in light of mounting pressure for states to achieve total maximum daily loads (TMDLs) under Section 303d of the Clean Water Act (Beale and Sheldon 2003) and other water quality goals under the Chesapeake Bay Program's Tributary Strategies (CBP 2005). Only through the integration of scientific evidence, practical lessons, and policymaking can we more adequately address impaired streams and steer future restoration efforts.

1.2 Hypotheses

Based on the problem defined above in Section 1.1, this study strives to help answer the following questions:

1. Do urban stream restorations improve water quality (see Section 2.5)?
2. If so, which urban stream restoration design approach is most effective at improving water quality (i.e., causes the greatest change in water quality between upstream and downstream sample locations)?

The hypotheses associated with the above questions are as follows:

Hypothesis/Question 1:

H_o: There is no difference in water quality between locations upstream and downstream monitoring points of the restored segment.

H_A: There is a difference in water quality between upstream and downstream sampling locations. Downstream sampling locations will demonstrate improved water quality, as in-stream processing should occur (Craig *et al.* 2008; Bukaveckas 2007; Peterson *et al.* 2001).

Hypothesis /Question 2:

H_o: There is no difference in water quality means among the three stream restoration designs.

H_A: At least one difference in water quality means exists among the three stream restoration designs. The softer stream restoration designs, particularly the "seepage wetland" design approach, will improve water quality more than the "hard" stream restoration design because these design approaches increase residence time, provide for greater hyporheic zone interactions, and provide higher organic matter with which to uptake nitrogen (Craig *et al.* 2008; Groffman *et al.* 2003; Groffman *et al.* 2005; Kaushal *et al.* 2008; Bukaveckas 2007).

1.3 Study Design Overview

The general research design involved monitoring three restored stream reaches across a spectrum of design approaches (one representative of each of the three design approaches defined in Section 2.4.5) on a bimonthly basis between October 2007 and April 2008, primarily during baseflow conditions. It is noted that while it would be more statistically valid to have multiple streams representative of each restoration design approach, funding opportunities have limited the project to only one representative stream per design approach. Thus, generalizations about differences among the methods will be suggested, not proven.

Water samples were collected at the beginning of the stream restoration (or at the closest location downstream that does not have additional discharge inputs) and approximately 600 linear feet (or 183 meters or 183 m) downstream from the upstream sample location for general chemistry parameters (pH, dissolved oxygen, temperature and specific conductivity), nitrogen (nitrate + nitrite and ammonium) and total suspended solids (TSS). Nitrogen and TSS were the focus of the water quality monitoring program as they are the most frequently cited freshwater pollutants (Meyer *et al.* 2003; Groffman *et al.* 2003).

A transect at each stream was also selected for collecting cross-sectional area and velocity data in order to calculate stream discharge and pollutant loads in addition to concentrations. Staff gauges were installed and measurements recorded during each sampling event to create stream-rating curves. In addition, rapid stream assessments were conducted for each stream reach during the beginning and end of the sampling period to provide a more thorough description of the selected reference streams and any major changes they underwent during the study.

The following sections provide a literature review of the thesis topic, study methodology, study results, and conclusions.

CHAPTER 2: LITERATURE REVIEW

2.1 The Significance of Streams and Stream Degradation

The natural functions and ecosystem services that freshwater streams provide to humans are significant. Not only do rivers and streams offer aesthetic and recreational enjoyment, they are essential to human drinking water supply; they provide critical habitat to diverse flora and fauna; they supply natural flood and erosion control; and they can process pollutants before they reach sensitive receiving waterbodies, such as the Chesapeake Bay.

Despite these benefits and in spite of environmental policy efforts such as the Clean Water Act (CWA) and the Chesapeake Bay Agreement, decades of environmental degradation and land use changes have led to a nationwide and regional decline of our streams. Between 1973 and 1998, in large part to the CWA's emphasis on controlling point source pollution, U.S. freshwaters and rivers greatly improved (Palmer and Allan 2006). However, that trend has since reversed. Experts suggest that if the reverse continues U.S. streams will return to previous conditions as soon as 2016 (Palmer and Allan 2006). This is likely a result of the logical progression of federal water quality programs, which, rather successfully, addressed point source pollution before focusing on non-point source pollution (Riley 2008).

Many watersheds, particularly those in urbanized areas, have been irrevocably altered (e.g. deforestation, increased impervious cover, etc.), and quite simply, there is not enough money to restore all of the impacted streams. “The goal of river restoration scientists, practitioners and water resource managers should be to increase the ecological and cost-effectiveness of restoration strategies, enabling us to improve the environmental conditions for the highest possible number of degraded stream miles in the United States” (Bernhardt *et al.* 2007, p. 490).

“Second only to agriculture, urban activities that disturb the natural environment are the greatest contributors to surface water pollution in the United States” (Veissman and Hammer 2005, p. 233). An overwhelming majority of the US population (218 million or 72%) lives within 10 miles of waters officially listed as impaired or polluted by the EPA (EPA 2007). By 2025, almost two-thirds of the world’s population – 5 billion – will live in cities (Botkin and Keller 2007), most of which lie near streams or coastal waters. As world and U.S. populations increase, urbanization trends continue, and water sources are continually threatened, water quality and water shortages problems will only exacerbate.

2.2 The Impact of Urbanization

The most obvious and consistent result of urbanization to the landscape is vegetation clearing and addition of impervious surfaces such as asphalt, concrete, and rooftops. Impervious surfaces restrict the ability of precipitation to infiltrate soil, reduce evapotranspiration rates, and significantly increase the rate of stormwater runoff entering local streams. This process fundamentally alters the hydrology and geomorphology of receiving streams (Wolman 1967).

The impact of catchment urbanization on urban streams (increase in impervious surface area and resultant increase in runoff to receiving streams) has been established in a number of journal articles (e.g. Bernhardt and Palmer 2007; Wang *et al.* 2000) and is often referred to as the "urban stream syndrome". Essentially, the shift in hydrogeomorphic patterns causes higher peak discharges, greater water export from the watershed, reduced floodplain-stream interaction and diminished groundwater-surface water exchange (Delleur 2003; Bernhardt and Palmer 2007). Despite important differences in catchment geology, climate, and vegetation, the altered timing and volume of water, sediment, and pollutants overwhelmingly control the generic condition of urban streams (Bernhardt and Palmer 2007).

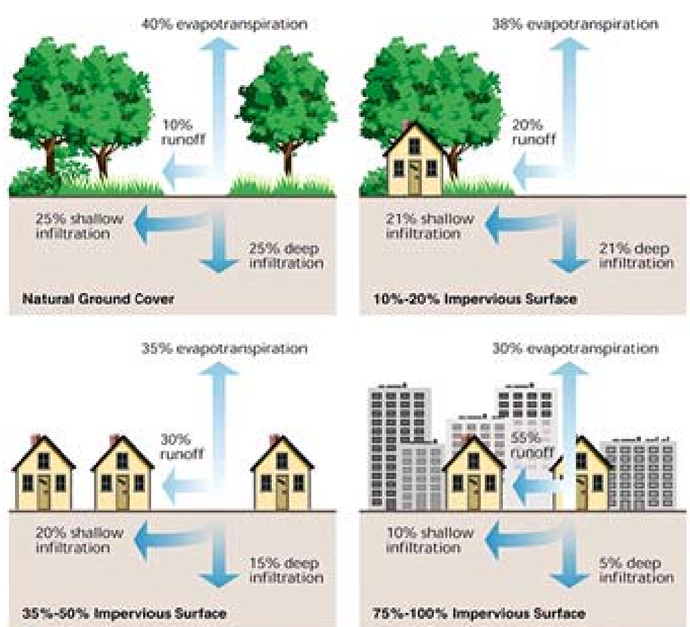


Figure 2-1 Relationship between Impervious Cover and Surface Runoff
(Source: FISRWG, 1998)

Studies show that the disconnect of urban streams from an effective floodplain and riparian buffer, exacerbated by piped stormwater drainage systems, can significantly reduce in-stream nutrient removal efficiencies (Craig *et al.* 2008; Groffman *et al.* 2002; Groffman *et al.* 2003; Kaushal *et al.* 2008). Further, studies indicate that impervious surface coverage as low as 10% can destabilize a stream channel, raise water temperature, and reduce water quality and biodiversity (Schueler 1995). Streams that possess a watershed impervious cover ranging from 11 to 25% show clear signs of degradation (Walsh *et al.* 2005). Once impervious cover exceeds 25%, streams are essentially conduits for stormwater flows and demonstrate qualities associated with the "urban stream syndrome" of severe streambank erosion, substrate elimination, fair to poor water quality and resultant loss of a diverse (or any) stream community (Walsh *et al.* 2005). Under these conditions, sediment delivery and deposition from the upper watershed shifts to dramatic channel incision and erosion (Simon *et al.* 2007), delivering nutrient and sediment loads to downstream receiving waters even if effective urban BMPs are installed and maintained (CWP 2008).

2.3 New Strategies to Address Impact Urban Streams

Common strategies to manage non-point source pollution include environmentally sensitive land use, the implementation of BMPs such as planting riparian buffers and developing stormwater catchment, detention and filtering systems (Riley 2008). The latest trend in managing non-point source pollution is stream restoration.

In response to a growing awareness of stream degradation in the U.S., freshwater managers are increasingly employing stream restoration applications (Bernhardt *et al.* 2007). Indeed, river restoration efforts have grown exponentially in every region in the United States with a price tag in excess of 1 billion dollars per year (Bernhardt *et al.* 2005). Following national trends, the number of restoration projects in the Chesapeake Bay Watershed (CBW) is second only to the Pacific Northwest and boasts the highest density of stream restoration projects in the nation (Hassett *et al.* 2005).

According to a recent synthesis of river restoration project information for the United States, the National River Restoration Science Synthesis (NRRSS), the majority of stream restoration resources are spent on urban streams (Berhnardt and Palmer 2007). In Maryland, for example, approximately 50% of all reported stream restoration funds were spent in four (of 23) most densely populated counties (Hassett *et al.* 2005). This concentration is likely an appropriate response to the more intense degradation in these systems.

Future spending trends point toward headwater and small streams, which make up at least 80% of the nation's total stream network (Meyer *et al.* 2003) and constitute more than two-thirds of total channel length in many watersheds, playing disproportionately large ecological roles, such as nutrient cycling (Meyer *et al.* 2007). Further, a recent study on stream restoration strategies for reducing nitrogen, reported that "small streams (1^{st} to 3^{rd} order) with considerable nitrogen loads delivered during low to moderate flows offer the greatest opportunities for nitrogen removal" (Craig *et al.* 2008). In summary, urban headwater streams offer strategic locations to "treat" urban stormwater effluent.

Another study suggested that the "most rapid uptake and transformation of inorganic nitrogen occurred in the smallest streams" (Peterson *et al.* 2001, p. 86).

2.4 The Hopes and Fears of Stream Restoration

2.4.1 Stream Restoration Defined

The term "stream restoration" often produces erroneous connotations of returning a degraded stream to its natural state, some ideal of its natural state, or to pre-impacted conditions. In practice, however, "stream restoration" refers to the return of a degraded stream to "a close approximation of its remaining natural potential" (Shields Jr. *et al.* 2003, p. 1). While this potential is subjective in nature and at times a moving target due to changing watershed conditions, in its broadest sense and in following popular convention, "stream restoration" involves "the application of any combination of restoration practices that improve stream health, as measured by physical, chemical, ecological or social indicators of stream quality" (Schuler 2005, p. 4). Alternative terms such as "recovery", "repair", "rehabilitation" or "enhancement" exist (Schuler 2005 p.4), but are not as widely used within the stream restoration community.

2.4.2 The Promise

Studies indicate that the "restoration of degraded streams and riparian buffers lead to species recovery, improved inland and coastal water quality and the creation of habitat for wildlife and recreational activities" (Hassett *et al.* 2005, p. 260). Groffman *et al.* (2003) conducted a study that demonstrated strong positive relationships between soil moisture and organic matter content and denitrification, the microbial conversion of nitrate to nitrogen and nitrous oxide. Groffman states "if we manage the vegetation and soil carbon levels in stormwater control structures, we may be able to restore and/or create important nitrate sinks in urban watersheds" (2003, p. 1148). Another study led by Groffman added that in-stream structures with high organic matter content showed higher levels of denitrification potential than others (Groffman *et al.* 2005), supporting the claims of the latest stream restoration design approach of "seepage wetlands" (Underwood *et al.* 2005).

Further, in practice, restored urban streams have demonstrated higher rates of nutrient uptake than non-restored urban streams (Baldwin 2005). A recent study of Minebank Run in Baltimore, MD – a second order stream with a watershed of 30-35% imperviousness – demonstrated significantly greater mean rates of denitrification in a restored stream reach as compared to an unrestored reach (Kaushal *et al.* 2008). Denitrification rates were also higher at low-bank sites (sites where the stream is connected to the floodplain) compared to sites where the stream was disconnected from the floodplain (Kaushal *et al.* 2008). Concentrations of nitrate-N were also significantly lower for both in-stream water and groundwater within the hyporheic zone within the restored reach compared to the unrestored reach (Kaushal *et al.* 2008). "Mass removal of nitrate-N appeared to be strongly influenced by hydrologic residence time in unrestored and restored reaches" (Kaushal *et al.* 2008, p. 789). Another study of a first order stream in Kentucky reported higher median travel times (50% higher) and nitrogen and phosphorus uptake 30- and 3-fold higher, respectively, within a restored reach channel relative to an unrestored reach (Bukaveckas 2007).

In response, practitioners and policy makers have turned to stream restoration as a means to repair our broken streams and regain the ecosystem services and broader community benefits streams have to offer, as demonstrated by the exponential expenditure and application of stream restoration in the United States (Bernhardt *et al.* 2007).

2.4.3 The Challenge

First and foremost, there is not enough money to restore all impacted streams, particularly those in urbanized areas where many watersheds have been irrevocably altered. This is compounded by the limited guidelines for prioritizing and funding stream restoration projects (Bernhardt *et al.* 2007). Second, controversial restoration design approaches, with significant theoretical and practical limitations remain ubiquitous in practice, particularly the popular Rosgen Method (Simon *et al.* 2007; Juracek and Fitzpatrick 2003). The majority of criticisms stem from Rosgen's reliance on form-based systems (Simon *et al.* 2007; Shields *et al.* 2003) versus the use of active processes such as erosion, transport and deposition (Simon *et al.* 2007; Juracek and Fitzpatrick 2003).

Finally, and most importantly, there has been little to no monitoring of stream restoration projects to demonstrate the efficacy of design approaches (Bernhardt *et al.* 2005). This limits the ability to determine which restoration practices perform best and under what conditions (i.e., most effective), as well as the capacity of practitioners and decision makers to make scientifically sound restoration choices.

2.4.4 The Evolution

Similar to the focal shift in national surface water pollution laws and policy from point source to non-point source pollution (Veissman and Hammer 2005) – the stream restoration field is undergoing an evolution. It is broadening its scope from conventional, hard-structural design approaches motivated by flood control and channel stabilization to more holistic, ecologically based design approaches motivated by habitat creation and water quality improvement.

Historically, stream restoration in the United States focused on physical stabilization of channel beds and stream banks to allow for maximum conveyance of stream flow while minimizing erosive forces (Haltiner *et al.* 2005; Palmer and Bernhardt 2006). This approach to stream restoration is often termed “hard bank channel stabilization” (Schueler and Brown 2004, p. 17), and “generally involve the use of rock, logs, or manufactured materials that are not deformable, and are intended to remain in place for decades” (Schueler and Brown 2004, p. 17). As the roots of stream “restoration” efforts grew out of the engineering field (Palmer and Bernhardt 2006) with an emphasis on “flood conveyance, stability, minimal right of way, maintenance and minimal cost” (Haltiner, *et al.* 2005), it is no surprise that hard design approaches are most widely used by practitioners (Shields *et al.* 2003) and most “widely adopted by governmental agencies, particularly those funding restoration projects” (Simon *et al.* 2007, p. 1).

However, river managers are shifting away from hard engineering restoration approaches to more holistic, ecologically-based restoration approaches to stream restoration (Palmer *et al.* 2005). Often termed "soft channel stabilization" (Schueler and Brown 2004, p. 17) or bioengineering, this more holistic approach to stream restoration attempts "to stabilize eroding streambanks through a combination of slope control, vegetation and biodegradable fabrics that establish a stable but deformable bank over time" (Schueler and Brown, 2004, p. 18).

The next step in the evolution of stream restoration attempts to take soft channel stabilization/bioengineering one-step further along the stream restoration design spectrum by creating quasi-wetland habitats within a stream reach. Not only does this approach have the potential to sustain ecological diversity and an environment conducive to retaining nutrients and other pollutants (Kaushal *et al.* 2008, Craig *et al.* 2008; Bukavekas *et al.* 2008), it offers the added value of wetland acres and freshwater storage.

2.4.5 Stream Restoration Approaches

For the purposes of this study, a "hard" stream restoration design approach is a stream restoration using various rock vanes in the development of step-pool sequences, the placement of substantial amounts of riprap for bank stabilization, and is likely based on Rosgen Method concepts (see Figure 2-2).

Figure 2-2 “Hard” Stream Restoration Design Approach

A “soft” bioengineering design approach utilizes conventional, rigid features such as weirs to create step-pool sequences, but typically incorporate more riffle features with varied particle size substrate. It also reconnects the stream to its floodplain and a more fully developed riparian buffer by re-grading the streambed (see Figure 2-3).

Figure 2-3 “Soft” Stream Restoration Design Approach

The most recently developed “seepage wetland” design approach to stream restoration offers amenities associated with “soft” channel design, such as a connected floodplain and step-pools, but it also employs the use of permeable berms or levees to create seepage reservoirs that interact with the main stream channel and the addition of significant wetland plant communities (see Figure 2-4).

Figure 2-4 “Seepage Wetland” Stream Restoration Design Approach

2.5 Water Quality: Background Levels and Restoration Goals

2.5.1 Non-Point Source Pollution and Background Levels

Typical pollutant levels found in urban stormwater for total nitrogen and TSS are 2.0 mg/L and 80 mg/L, respectively (MDE 1999). [This discussion is limited to nitrogen and TSS as they are relevant to the proposed study.]

There are several non-point sources of nutrients in urban areas, mainly fertilizers in runoff from lawns, pet wastes, failing septic systems, and atmospheric deposition from industry and automobile emissions (EPA 2005). Excessive nitrogen levels in receiving waters can lead to exceedances of drinking water criteria (10 mg/L for nitrate-N, the most common drinking water pollutant in U.S. waters) and eutrophication of sensitive receiving waterbodies (Groffman *et al.* 2003). Eutrophication can lead to changes in periphyton, benthic and fish communities (Kalff 2002); extreme eutrophication can cause hypoxia or anoxia, resulting in fish kills (EPA 2005).

Scholars increasingly recognize that streambank erosion in urban watersheds is the major culprit of sediment pollution in receiving waters (e.g. Simon *et al.* 2007). Suspended sediments can cause the following detrimental problems to stream systems: abrasion of and damage to fish gills, increasing risk of infection and disease; scouring of periphyton from streams; loss of sensitive or threatened fish species; shifts in fish communities toward less-diverse, more sediment-tolerant species; reduction in light penetration, resulting in a reduction in plankton and aquatic plant growth; reduction in filtering efficiency of zooplankton in lakes and estuaries; adverse impacts on aquatic insects; increases in stream temperature in summer; and decreased submerged aquatic vegetation (SAV) populations (EPA 2005).

2.5.2 Stream Restoration as a Tool for In-Stream Nitrogen and Sediment Removal

Stream restoration scientists and managers increasingly acknowledge the importance and potential of streams to transform or remove nutrients from surface water (e.g., Peterson *et al.* 2001; Ensign and Doyle 2006; Bernhardt and Palmer 2007). More recently, several papers have been published on the nutrient-processing capacity of restored urban streams (e.g. Craig *et al.* 2008; Kaushal *et al.* 2008; Groffman *et al.* 2005;

Bukaveckas 2007). However, comparatively few data on the efficacy of different stream restorations to improve water quality exist. Indeed, research of stream restoration as a tool to enhance in-stream nitrogen removal has only begun (Bukaveckas 2007).

Factors affecting the uptake of nitrogen can be classified as either biochemical (uptake by bacteria, fungi and algae) or geomorphic (control of hydrologic variables such as residence time, transient storage, and interaction of water with stream biota and substrates responsible for nutrient processing) (Ensign and Doyle 2006). The primary soluble and bioavailable forms of nitrogen dissolved in surface waters are nitrate (NO^-_3), nitrite (NO^-_2) and ammonium (NH_4^+). Particulate organic nitrogen also occurs in the form of plant and animal detritus. These organic forms are converted to ammonium and nitrate in the stream via proteolysis and nitrification, respectively (Kalff 2002).

The removal efficiencies for urban stream restoration BMPs used in the Chesapeake Bay watershed model are currently 0.02 pounds per foot per year (lbs/ft/yr) and 2.55 lbs/ft/yr for nitrogen and sediment, respectively (Baldwin 2005). The units correspond to load reduction per linear foot of stream, and therefore do not take into account the width of the stream. In an attempt to better account for stream width (3-30 ft or approximately 1-9 m), a recent study performed by the University of Maryland recommended the following efficiencies for urban stream restorations: 0.02 lb/ft/yr and 2.00 lb/ft/yr for nitrogen and sediment, respectively (Baldwin 2005). Results of the study also suggested that restored urban streams have higher rates of nutrient uptake than non-restored urban streams for both nitrate-N and ammonium (Baldwin 2005). Other studies have demonstrated much higher stream restoration removal efficiencies for nitrogen (e.g. Bukaveckas *et al.* 2007; Kaushal *et al.* 2008).

2.6 Discussion of Hypotheses

As a result of the literature review provided in the preceding sections, the following research questions and hypotheses arose:

1. Do urban stream restorations improve water quality?
2. If so, which urban stream restoration design approach is most effective at improving water quality (i.e., causes the greatest change in water quality between upstream and downstream sample locations)?

The hypotheses associated with the above questions are as follows:

Hypothesis/Question 1:

H_o: There is no difference in water quality between locations upstream and downstream monitoring points of the restored segment.

H_A: There is a difference in water quality between upstream and downstream sampling locations. Downstream sampling locations will demonstrate improved water quality, as in-stream nitrogen processing and sediment uptake should occur.

As touched on in Sections 2.4.2 and 2.5, recent studies of restored urban streams have demonstrated higher rates of nutrient uptake than non-restored urban streams. More specifically, Baldwin (2005) conducted a literature review and meta-analysis that restored streams were more effective in processing nitrate, ammonium, and phosphate than non-restored streams. Kaushal *et al.* (2008) conducted a study on a second order stream in

Baltimore, MD, and observed significantly greater mean rates of denitrification in restored stream segments than non-restored segments of the same stream. Finally, Bukaveckas (2007) found higher median travel times (50% higher) in a restored stream reach in Kentucky than a nearby non-restored reach. Bukaveckas suggested that the reduced velocity resulting from the restoration increased water residence time and hyporheic exchange leading greater nitrate and phosphate uptake than the non-restored reach.

Hypothesis /Question 2:

H_o: There is no difference in water quality means among the three stream restoration designs.

H_A: At least one difference in water quality means exists among the three stream restoration designs. The softer stream restoration designs, particularly the "seepage wetland" design approach, will improve water quality more than the "hard" stream restoration design because these design approaches increase residence time, provide for greater hyporheic zone interactions, and provide higher organic matter with which to uptake nitrogen.

As touched on in Sections 2.4.2 and 2.5, recent studies of restored urban streams have demonstrated greater water quality improvement under the presence of re-connected floodplains, adjacent riparian buffers, and in-stream features that reduce stream velocity and allow denitrification and sediment entrainment to occur. More specifically, Kaushal *et al.* (2008) observed greater denitrification rates in a restored segment that re-connected the stream to its floodplain than a restored segment more closely characterized by a "hard" stream restoration approach. Numerous studies (e.g., Mayer *et al.* 2005; Wenger 1999; Correll 1997) have further documented the denitrification potential of streams with adjacent riparian buffers ranging from 30-50 meters (~100-165 ft) in width. Both the "soft" (Kingstowne) and "seepage wetland" (Wilelinor) stream restoration designs are substantially more connected to their respective floodplains and adjacent riparian buffers than the "hard" (Stony Run) stream restoration.

Scholars (e.g., Groffman *et al*. 2003; Groffman *et al.* 2005; Roberts *et al.* 2007; Kasahara and Hill 2006) have also documented greater denitrification potential as a result of in-stream structures with high organic matter content and the use of coarse woody debris. Further, many studies of restored streams (e.g., Roberts *et al.* 2007; Kasahara and Hill 2006; Kaushal *et al.* 2008; Bukaveckas 2007; Peterson *et al.* 2001) have suggested that in-stream structures of greater topographic complexity can enhance nutrient uptake by slowing water velocity, and thus, improving organic material retention and increasing contact time with denitrifiers. Such structures are present at the "soft" (Kingstowne) stream restoration (diverse cobble substrate used in the cross vanes) and even more so at the "seepage wetland" (Wilelinor) stream restoration (seepage reservoirs, sand berms, off-line ponds, and prolific native plantings).

CHAPTER 3: METHODOLOGY

This section describes the research design and criteria for how stream restoration reaches were selected for this study as well as the methodology used to conduct a bimonthly water quality and discharge monitoring program and statistical analyses.

Because the study is restricted to only one stream representative of each design approach, it is noted the ability to generalize information to other restorations is limited. However, in order to better compare in-stream processing (presumably provided by the stream restoration) among the three stream reaches, watershed "profiles" were created to establish upstream catchment characteristics (i.e., land use, percent imperviousness, topography, watershed area, etc.) that may vary from one watershed to another and thus influence the water quality conditions and in-stream processing capabilities of the stream. In addition, the watershed "profiles" may provide useful information on the ability of stream restorations within similar watersheds to uptake sediments and nutrients.

3.1 Stream Selection

The Chesapeake Bay Watershed was selected because this watershed has "an extremely high density of restoration activities relative to other regions of the U.S." (Hassett *et al.* 2005) and it was geographically tangible as a study location. Second, "second only to agriculture, urban activities that disturb the natural environment are the greatest contributors to surface water pollution in the United States" (Veissman and Hammer 2005, p. 233). Urban, headwater streams also receive the largest share of river restoration dollars and effort in the United States (Bernhardt and Palmer 2007). As such, all three streams located in headwater stream restorations within urbanized watersheds, particularly those representative of the urban stream syndrome (or greater than 25% imperviousness).

Thirty-six streams were initially screened for inclusion in this study. Initially, research was conducted via the Internet and NRRSS database to find stream restorations in the Chesapeake Bay that used restoration elements within the "hard", "soft" or "seepage wetland" design approach. Recommendations by Dr. Margaret Palmer of the University of Maryland and Dr. Sean Smith of Maryland Department of Natural Resources narrowed the list to stream restorations that best fell into the three stream design categories. Finally, field trips to many of the streams provided a final screening process based on accessibility for bimonthly monitoring, urban stream criteria (percent imperviousness, primarily stormwater management reaches, etc.), project size (at least 500 linear feet), stream order (1^{st} order streams), and funding availability.

3.2 Watershed & Stream Profiling

A watershed "profile" was created for each selected stream restoration study site using GIS data provided by federal (EPA), state, and local stream-specific sources. Profiles include the following (next page):

- Subwatershed drainage area and map (entire watershed and that of the stream reach top and bottom);

- Percent imperviousness;
- Land use; and
- Topography (to determine slope and riparian buffer widths).

In addition to the above watershed criteria, the following information was included in the stream reach profiles for the selected study streams to better characterize and compare the restorations:

- Stream order (all selected study streams are first order);
- Total stream restoration length (linear feet and/or acres); and
- Restoration features utilized at the study site.

Further, the following information was included in the stream reach profiles as a policy contribution to this study to determine any major differences in funding resources and project motivation (government-mandate led, public request, voluntary or otherwise):

- Project intent;
- Project cost (total and per linear foot);
- Funding source; and
- Lead agency.

3.3 Stream Monitoring

3.3.1 Water Quality Monitoring

Water quality improvement is nationally one of the most commonly stated project goals of stream restoration (Bernhardt *et al.* 2005) and *the* most commonly stated goal in the Chesapeake Bay (Hassett *et al.* 2007). Despite these goals, as previously stated, minimal post-monitoring data is available. Because current research literature indicates that stream restorations have great potential at reducing sediment loading to streams (e.g. Simon 2007) and uptaking nitrogen (e.g. Craig *et al.* 2008; Galloway *et al.* 2004), suspended sediments and nitrogen are the focus of this study's water quality monitoring.

To determine the effectiveness of urban stream restoration approaches in improving water quality, stream water samples were collected at upstream and downstream transects, separated longitudinally by 600 ft (or 183 m), of restored stream length. Sample locations were selected as close as possible to the beginning of the stream restorations (where additional discharge inputs ceased) and 600 ft (or 183 m) downstream from the upstream sample. Water quality monitoring was conducted bimonthly primarily during baseflow conditions between mid-October 2007 and April 2008.

Basic water quality parameters (temperature, pH, dissolved oxygen and specific conductivity) were recorded in the field using a Hydrolab water quality probe (State of MD DNR # 0068208) and Hydrolab Scout 2 water quality data system (State of MD DNR #0068210), courtesy of Maryland Department of Natural Resources (MD DNR). The Hydrolab probe was calibrated for all parameters prior to each sampling event. Due to mandated probe maintenance by MD DNR, general chemistry parameters could not be collected during the February 14, 2008, monitoring event. In addition, general chemistry parameters could not be collected at the Kingstowne site on October 16, 2007, or the Wilelinor site on January 28, 2008, due to probe battery failure.

Water samples were collected for nitrate + nitrite-nitrogen (here shortened to nitrate-N), ammonium nitrogen (here shorted to ammonia-N), and total suspended solids (TSS) for laboratory analysis by Chesapeake Biological Laboratories (CBL) in Solomons

Island, Maryland. Water samples for nitrogen were filtered in the field using a 60-mL syringe adapted with a filter holder capable of holding 0.7-micron filter pads. The filtered water was dispensed to 60-mL poly bottles and stored on ice, and then a freezer, until delivery to CBL for nitrogen analyses. The filter pads were originally (through the January 2, 2008 sampling event) stored in aluminum "pockets" and frozen for TSS analysis at CBL. However, upon discovery of a discrepancy with the filter pads by CBL in January 2008, it was decided that unfiltered water would be collected in 500-mL to 1-L poly bottles and filtered at CBL for TSS analysis. One duplicate sample was collected on March 24, 2008, at each sampling location for nitrogen analyses for quality control/quality assurance.

3.3.2 Discharge Monitoring

Cross-sectional area and velocity measurements were collected in the field within each stream reach during the sample events in order to calculate pollutant loads in addition to pollutant concentrations. Discharge was measured using the United States Geological Survey (USGS) Method (Michaud 1991). Stream transect measurements were recorded with a taut measuring tape in feet. Each transect was subsequently divided into 10 intervals for which to measure depth and velocity. Working from left to right on the downstream side of the tape, depth was recorded at each measuring point and multiplied by 0.6 to determine the distance from the bottom for which to measure velocity. The velocity propeller was then set at the new depth and measurements were recorded for each interval. Depth measurements were recorded with a measured stick in inches and converted to feet (ft) for area calculations. Velocity measurements were recorded in feet per second (ft/sec) with a Marsh-McBirney, Inc. Flowmate portable flow meter (State of MD DNR # 0062615), courtesy of MD DNR.

3.3.3 Storm Event Monitoring

Flow events can have a major influence on how the streams respond to restoration (Roni 2005). Further, rather than sampling at only one point in time, it is often recommended to monitor under a range of conditions to capture temporal and seasonal heterogeneity (Roni 2005). Water quality monitoring was conducted during four rain and/or snow events that coincided with the normal sampling schedule (October 16, 2007, February 14, 2008, February 26, 2008 and April 7, 2008) to capture water quality conditions under varying flow conditions.

Staff gauges were installed at each stream reach and measured with each site visit, including storm events (stream conditions were never deemed unsafe, so velocity and area measurements were recorded during storm events), to create rating curves. Rating curves illustrate the relationship between stream stage (gage height) and stream flow (discharge).

3.3.4 Rapid Stream Assessment

In-field rapid stream assessments were performed during the beginning and end of the sampling period to provide a better description of the three stream reaches and to provide for comparisons of any in-stream/habitat changes during the study.

3.4 Discharge and Loading Calculations

The total amount of water moving through a stream is a product of the size of the stream (cross-sectional area) and the velocity. Using the depth, distance, and velocity measurements recorded in the field as described Section 3.3.2, the discharge, or total volume of water flowing through each stream interval was calculated. Total discharge was calculated as the summation of the discharge from each of the intervals measured (Michaud 1991).

To incorporate nutrient and pollutant flux along the stream reach with sample concentrations, discharge calculations were used to perform the following equation (Michaud 1991):

$L = f * c * d$, where L = load (pounds per day or lbs/day); f = units conversion factor (5.39; Michaud 1991); c = concentration of pollutant (milligrams per Liter or mg/L); and d = discharge (cubic feet per second or cfs). (3.1)

Although pollutant loads are often cited in lbs/day, particularly for total maximum daily loads (TMDLs) under the CWA's Section 303(d), the difference between upstream and downstream loads were converted to pounds per foot per year (lbs/ft/yr) to make comparisons to CBP removal efficiencies of 0.02 lbs/ft/yr for total nitrogen and 2.55 lbs/ft/yr for sediment (Baldwin 2005). All pollutant loads were subsequently converted to metric equivalents.

3.5 Statistical Analyses

Descriptive statistics were initially gathered to understand the basic features of the data in the study (distribution, central tendency, etc.). In addition, bar graphs were created to visually characterize any changes in concentration between upstream and downstream samples at each stream, and line graphs were created to inspect variability in water quality criteria amongst the three streams and over the duration of the study (i.e., seasonality). In addition, a combination of visual inspection (histograms; Q-Q plots) and statistical tests (skewness and kurtosis (± 2); Shapiro-Wilk test ($W \leq 1.0$), which is appropriate for samples with up to 50 observations) was used to determine the normality of the variables.

In order to test the first research question (Do urban stream restorations improve water quality?), a paired t-test was conducted to compare water quality data between upstream and downstream monitoring points. T-tests are appropriate for sample sizes less than thirty, such as the case with this study ($n \leq 30$ or approximately 15 data pairs/monitoring events with minor variability due to equipment failure), as the t-distribution adjusts for sample size (Berman 2007). The paired t-test tests the null hypothesis that the mean difference between the upstream and downstream water concentrations is zero (Berman 2007). For this study, the continuous variables were the water quality criteria (nitrate-N, ammonia-N, TSS, temperature, and DO) and the dichotomous variable was the sample location (upstream or downstream).

Whereas the t-test is used for testing differences between two groups on a continuous variable, ANOVA (analysis of variance) is used for testing means of a continuous variable across more than two groups (Berman 2007). Because this study's second research question (Which urban stream restoration design approach is most effective at improving water quality?) compares three restoration design approaches (i.e., "hard", "soft", and "seepage wetland"), the ANOVA test was most appropriate. In particular, the ANOVA test compared the mean concentration differences between upstream and downstream monitoring points across the three streams to demonstrate restoration efficacy to improve water quality.

The F-test statistic associated with the ANOVA method compares the variances within each group against those that exist between each group and the overall mean. When the between-group variances (stream restoration designs type) are enough larger than the within-group variances (upstream and downstream data for an individual stream) (i.e., large F-test statistic), it is possible to reject the null hypothesis. Conversely, when the within-group variances are larger than or even similar to the between-group variances (i.e., small F-test statistic), it is typically more difficult to reject the null hypothesis (Berman 2007). If the ANOVA tests resulted in statistically significant differences amongst the three streams, the Bonferroni post hoc test was conducted.

If water quality data for the three streams was not normally distributed, a nonparametric alternative to the paired t-test, namely the Wilcoxon test, was performed. The Wilcoxon nonparametric test assigns ranks to the testing variable. Then the sum of the ranks of each group is computed and a test is performed of the statistical significance of the difference between the sums (Berman 2007).

In addition, percent difference between upstream and downstream concentrations was calculated using the following equation (Mayer *et al.* 2005):

$$\% \text{ difference} = \frac{|A - B|}{A} * 100\% \qquad (3.2)$$

In general, any significant decreases between upstream and downstream concentrations of nitrate-N, ammonia-A, TSS, and temperature, as well as any significant increases in DO concentrations, were considered positive indicators for a stream restoration's ability to improve water quality. It is noted that while pH represents the logarithm of the reciprocal of hydrogen-ion concentration (i.e. not a linear variable), it was included in the statistical analyses because the data suggested trends in pH values between upstream and downstream monitoring points. Further, while some outliers were identified, none were removed prior to analysis because of the small sample size ($n \leq 30$). All statistical analyses utilized a 95% confidence level and were conducted using SPSS statistical software.

CHAPTER 4: DESCRIPTION OF CASES

Per methods discussed in Section 3.1, the following urban restored streams were selected for inclusion in the study:

1. "Hard" structural design approach: Middle Stony Run in Baltimore, Maryland (Stony Run);
2. "Soft" bioengineering design approach: Kingstowne Stream in Fairfax County, Virginia (Kingstowne); and
3. "Seepage wetland" design approach: Wilelinor Stream in Annapolis, Maryland (Wilelinor).

The following sections provide watershed and stream profiles for each of the three streams to better characterize and compare restoration features, settings (relief, land use, watershed size, etc.), and threshold for action/funding of the three restoration projects.

4.1 "Hard" Design Approach (Stony Run) Stream Restoration

Stony Run is a small urban stream in the north-central portion of Baltimore (see Figure 4-1, pg. 34 and Table 4-1, pg. 35). A tributary of Jones Falls, it ultimately empties into Baltimore City's Inner Harbor. The majority of Stony Run drainage is routed through pipes as part of the City's stormwater management system. In 2003, the watershed was systematically evaluated as part of a comprehensive watershed management plan to meet the City's Municipal National Pollution Discharge Elimination System (NPDES) permit requirement for stormwater. The plan identified the universe of restoration alternatives in a coordinated effort a local watershed association.

In 2006, the stream banks of Middle Stony Run (from Coldspring Lane to Wyndhurst Avenue) were subsequently improved and stabilized using excavation and fill placement in and along the stream channel, placement of boulders and imbricated riprap, and the installation of vegetative plantings and bioengineering measures along the channel bed using Rosgen concepts. The project is part of a greater Stony Run watershed restoration effort focused on minimizing impacts of the watershed's dominantly urban land uses.

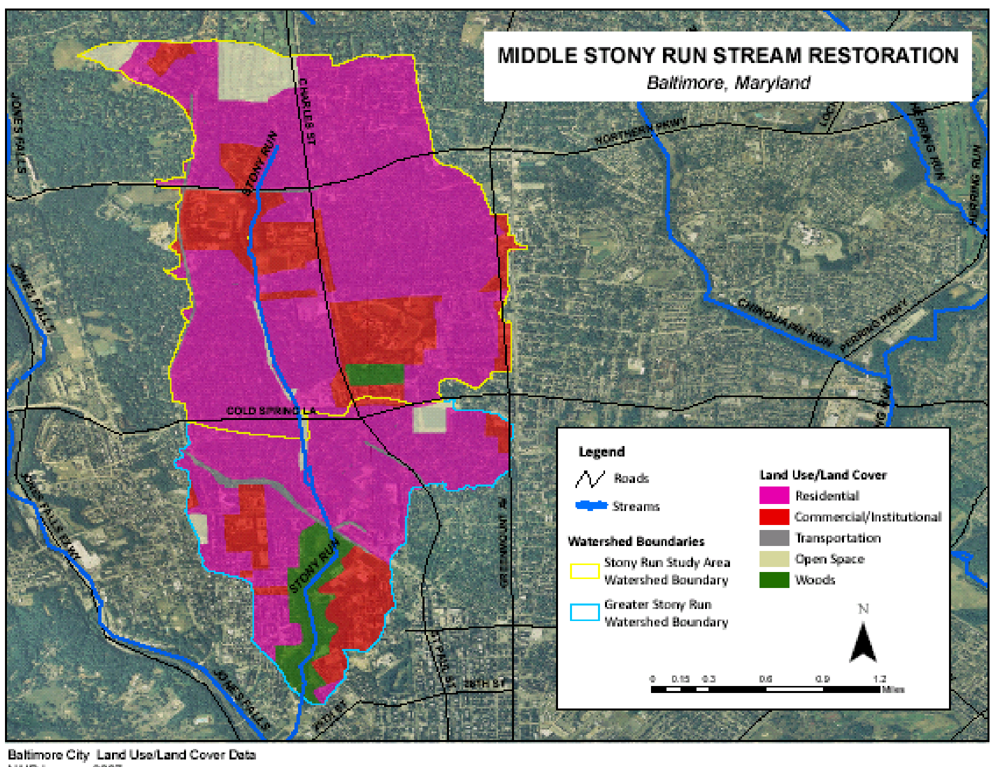


Figure 4-1 Middle Stony Run Site Location, Watershed Boundary and Land Use Map (Source: The Conservation Fund, to be printed)

Table 4-1 "Hard" Design Approach (Stony Run) Stream Restoration Profile
(Sources: Stack 2007; The Conservation Fund, to be printed)

RESTORATION SUMMARY	**Project Intent/Primary Restoration Goal(s):**	reduce streambank erosion; improve water quality; enhance in-channel and riparian areas associated with the free-flowing portion of the stream; alleviate further damages to public utilities and roads
	Restoration Length:	2,700 ft (823 m)
	Total Project Cost:	$2.5 million (adjusted from 2006 to 2008 dollars)
	Cost per linear foot:	$942/ft ($3,038/m)
	Source of Funding:	motor vehicle revenues
	Lead Agency:	Baltimore City Department of Public Works
WATERSHED SUMMARY	**Watershed Size:**	1,521 acres (6.16 square kilometers, km^2) (entire Stony Run watershed is 2,112 acres or 8.55 km^2)
	Percent Imperviousness:	30%
	Land Use:	73% residential; 20% commercial/institutional; 5% open space; 1% transportation; 1% woods
	Physiographic Province:	Piedmont
	Average Slope & Riparian Buffer Width:	0.022 river reach slope; 167 ft (51 m) average riparian buffer
DESIGN APPROACH	**On the Spectrum:**	"hard" approach; modified Rosgen Method
	Basic Channel Morphology:	step-pool sequences; mild stream meanders; hardened streambanks
	Average Baseflow Discharge:	0.490 cfs (0.014 cubic meters per second, m^3s)
	Bankfull Discharge/Maximum Design Discharge:	170 cfs (4.81 m^3s)
PRINCIPLE FEATURES	**Cross and J-Hook Vanes:**	grade control structures that reduce bank erosion by decreasing near-bank shear stress, velocity and stream power
	Imbricated Riprap:	overlapping large, durable materials used to protect a streambank from erosion
	Two-Stage Channels:	floodplain bench designed to accommodate baseflow and larger stormwater flows
	Step-Pool Sequences:	the construction of a series of steps (in this case via cross vanes) composed of natural materials longitudinally through a stream reach in which shallow to deep pools are created; offers grade and erosion control; creates habitat

PRINCIPLE RESTORATION FEATURES:

✓ ***Cross Vanes***

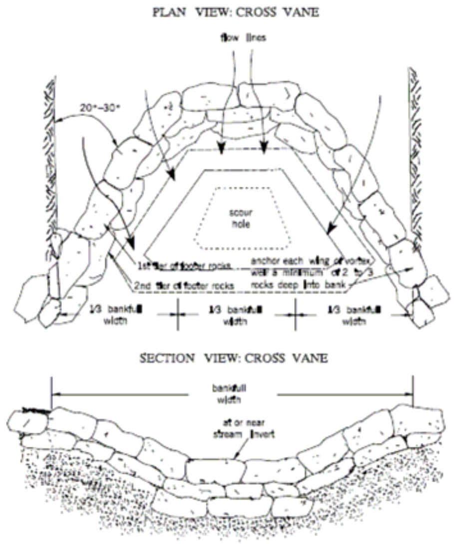


Figure 4-2a Photo of Cross Vane at Stony Run (during stream restoration);
Figure 4-2b Cross Vane Engineering Schematic (Source: MDE 2000)

✓ ***J-Hook Vanes***

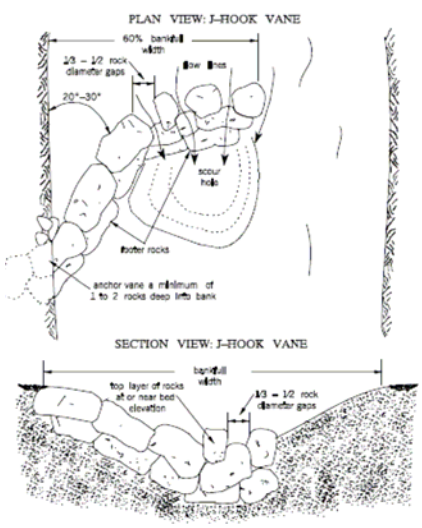


Figure 4-3 J-Hook Vane Engineering Schematic (Source: MDE 2000);
Figure 4-3b Photo of J-Hook Vane at Stony Run

✓ ***Imbricated Riprap and Two-Stage Channels***

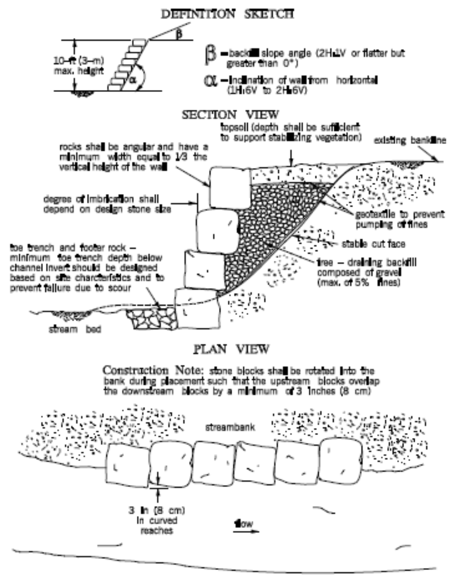


Figure 4-4a Photo of Imbricated Riprap and Two-Stage Channels at Stony Run;
Figure 4-4b Imbricated Riprap Engineering Schematic (Source: MDE 2000)

✓ ***Step-Pool Sequences***

Figure 4-5a Step Pool Engineering Schematic (Source: MDE 2000);
Figure 4-5b Photo of Step Pools at Stony Run

4.2 “Soft” Design Approach (Kingstowne) Stream Restoration

The Kingstowne Stream in the Alexandria portion of Fairfax County (see Figure 4-6 below; Table 4-2, pg. 49) suffered considerably from upstream development. The Kingstowne Stream is a main tributary of Dogue Creek, which feeds into the Potomac River six miles south of the confluence. Upstream development along the South Van Dorn Street corridor replaced natural vegetation with impervious surfaces, leading to less infiltration of stormwater and subsequent “flashy flows”. Streambank sediments and attached nutrients were subsequently being carried downstream to the wetlands of Huntley Meadows, the Potomac River and the Chesapeake Bay.

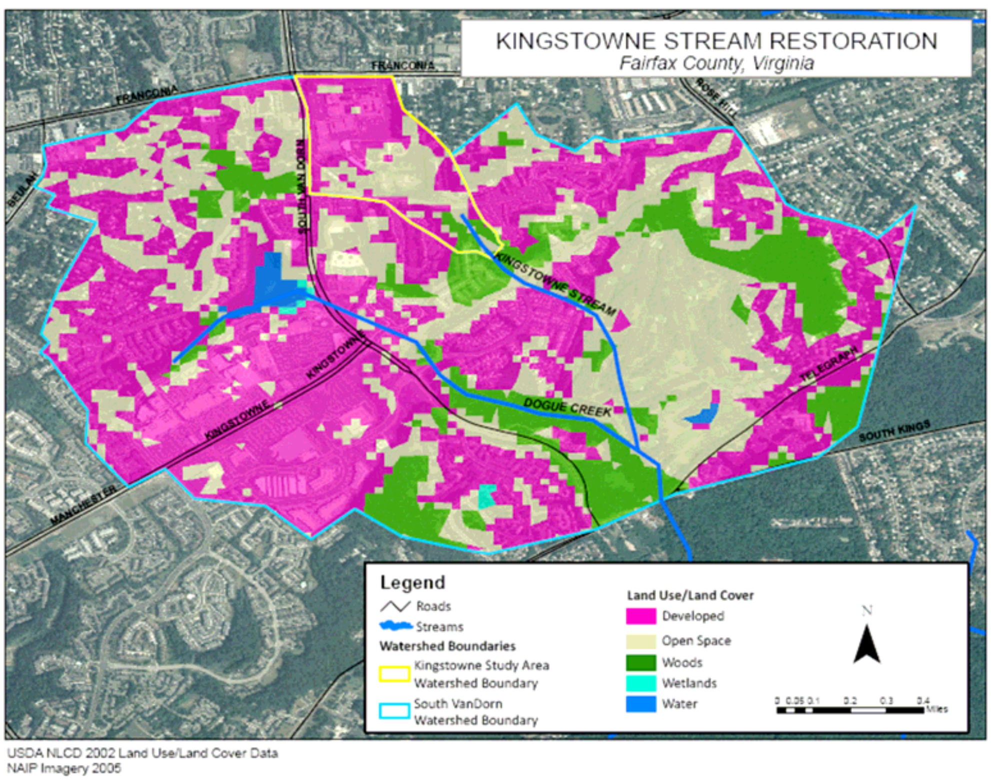


Figure 4-6 Kingstowne Site Location, Watershed Boundary and Land Use Map (The Conservation Fund, to be printed)

Table 4-2 "Soft" Design Approach (Kingstowne) Stream Restoration Profile (Source: Rouhi 2008; The Conservation Fund, to be printed)

RESTORATION SUMMARY	**Project Intent/Primary Restoration Goal(s):**	environmentally friendly approach to streambank erosion/sediment control
	Restoration Length:	1,000 ft (304.8 m)
	Total Project Cost:	$527K (adjusted from 1999 to 2008 dollars)
	Cost per linear foot:	$527/ft ($1,729/m)
	Source of Funding:	$150K grant from the Chesapeake Bay Water Quality Preservation Fund; Fairfax County match
	Lead Agency:	Northern Virginia Soil and Water Conservation District
WATERSHED SUMMARY	**Watershed Size:**	72 acres or 0.29 km^2 (South Van Dorn, 1,146 acres or 4.64 km^2)
	Percent Imperviousness:	54%
	Land Use:	58% developed; 35% open space; 6% woods
	Physiographic Province:	Coastal Plain
	Average Slope & Riparian Buffer Width:	0.026 river reach slope & 268 ft (82 m) average riparian buffer
DESIGN APPROACH	**On the Spectrum:**	"soft" bioengineering approach, yet still based on Rosgen Methods
	Basic Channel Morphology:	step-pool sequences; mild stream meanders; large riparian buffer; native plants used to stabilize streambank
	Average Baseflow Discharge:	0.109 cfs (0.003 m^3s) (bankfull/max discharge unknown)
PRINCIPLE FEATURES	**Dry Detention Pond:**	temporarily stores runoff and releases it slowly to stream following storms; designed to dry out between storm events
	Plunge Pool:	small, but deep pool used to dissipate energy as water enters the pool from its upland source.
	Soft Meanders:	snake-like appearance of the reach of a stream (length is 1.5 times or more the length of the valley through which it passes); reduces stream energy.
	Live Stakes:	sections of branches without twigs or leaves pounded directly into soft soil; reduces erosion
	Step-Pool Sequences:	the construction of a series of steps composed of natural materials (in this case cross vanes and various substrate); offers grade and erosion control; creates habitat
	Riparian Buffer:	swath of riparian vegetation along a channel bank; reduces erosion; may lower stream temperature and reduce sediment & nutrient transport

In 1998, the Northern Virginia Soil & Water Conservation District (NVSWCD) joined forces with Fairfax County, state and federal agencies, and two citizens groups to protect downstream resources, to maintain compliance with the county's various federal, state and local regulatory agencies and to implement a demonstration project that would serve as a model for the "soft," more environmentally-friendly approach to solving erosion problems. The site analysis and project design took nearly a year to complete. Construction began in October of 1999 and was finished within two months. This project restored gentle meanders to the stream and raised the level of the channel to reach the floodplain. The project used live plant materials native to the area to stabilize the stream banks as well as diverse, cobble substrate to create cross vanes and in-stream channel bars.

PRINCIPLE RESTORATION FEATURES:

- ✓ ***Dry Detention Pond & Plunge Pool***

Figure 4-7 Photo of Dry Detention Pond at Kingstowne (left)
Figure 4-8 Photo of Plunge Pool at Kingstowne (right)

- ✓ ***Soft Meanders***

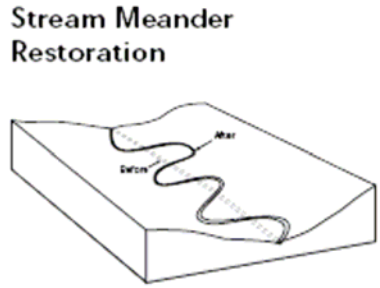


Figure 4-9a Photo of a Stream Meanders at Kingstowne (post-restoration)
Figure 4-9b Schematic of Stream Meander Restoration (FISRG 1998)

- ✓ ***Live Stakes***

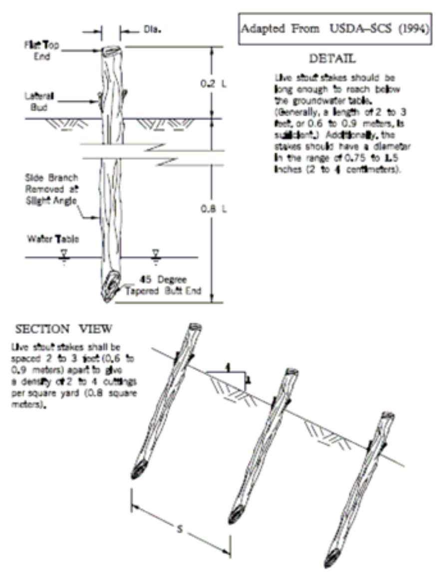


Figure 4-10a Photo of Live Stakes at Kingstowne (note erosion past live stakes)
Figure 4-10b Live Stake Engineering Drawing (MDE 2000)

✓ ***Step-Pool Sequences & Riparian Buffer***

Figure 4-11 Photo of Step-Pool Sequences at Kingstowne
(left; note various substrate material)

Figure 4-12 Photo of Riparian Buffer at Kingstowne (right)

4.3 "Seepage Wetland" Design Approach (Wilelinor) Stream Restoration

Anne Arundel County has approximately 1,500 miles of small streams (first- to third-order streams) with approximately 300 miles rated poor to very poor, requiring restoration (personal communications, Bowen 2008). The continuing degradation of these streams contributes significant sediment load to tidal waters in addition to the pollution generated from the rest of the County's watersheds. One of these degraded streams, the Wilelinor Stream, is located in the community of Wilelinor Estates below Maryland Route 2, just southwest of Annapolis (see Figure 4-13, next page; Table 4-3, pg. 44). It is the primary headwaters of the southern branch of Church Creek on the South River.

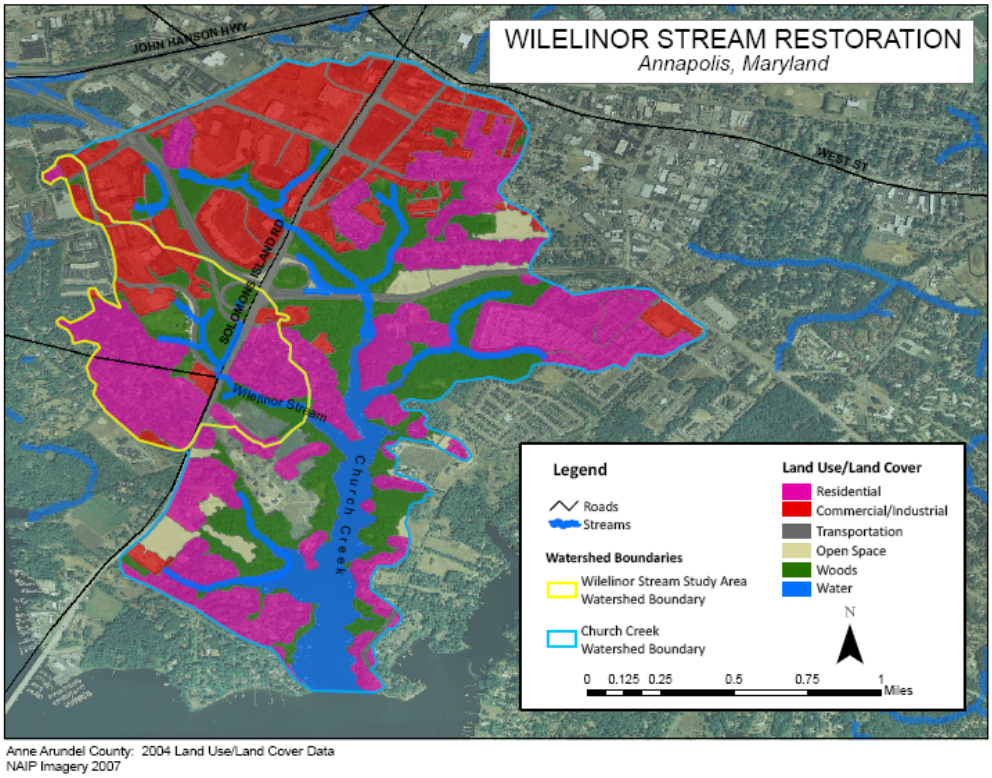


Figure 4-13 Wilelinor Site Location, Watershed Boundary and Land Use Map (Source: The Conservation Fund, to be printed)

This project was bolstered by the Wilelinor Community that mounted a significant campaign focused at local government to voice their dissatisfaction with the degradation of waterways within their communities. The Wilelinor Community was originally designed and constructed with in-stream recreational amenities (ponds) intended to provide fishing and canoeing (Bowen 2008). Over time, as the watershed was developed, the changed dynamics of greater runoff with less infiltration/evaporation as well as sediment influx from new, upstream development filled the ponds. The communities' amenities were lost, and they demanded they be restored (Bowen 2008).

Table 4-3 “Seepage Wetland” Design Approach (Wilelinor) Stream Restoration Profile (Source: Bowen 2008; The Conservation Fund, to be printed)

RESTORATION SUMMARY	**Project Intent/Primary Restoration Goal(s):**	reestablish stabile stream profile and planform; create capacity to convey peak discharges; enhance water quality, restore aquatic habitat and ecological function; return of Atlantic White Cedar
	Restoration Length:	1,311 ft (400 m)
	Total Project Cost:	$1.02 million (adjusted from 2005 to 2008 dollars)
	Cost per linear foot:	$776/ft ($2,553/m)
	Source of Funding:	Anne Arundel County-State share via capital improvement project
	Lead Agency:	Anne Arundel County Department of Public Works
WATERSHED SUMMARY	**Watershed Size:**	214 acres or 0.87 km^2
	Percent Imperviousness:	37%
	Land Use:	49% residential; 22% woods; 21% commercial/industrial; 7% transportation; 1% open space
	Physiographic Province:	Coastal Plain
	Average Slope & Riparian Buffer Width:	0.008 river reach slope; 166 ft (51 m) average riparian buffer
DESIGN APPROACH	**On the Spectrum:**	“seepage wetland” approach; holistic, stream ecosystem restoration
	Basic Channel Morphology:	reservoir seepage ponds; stream meanders; shallow step-pool sequences
	Average Baseflow Discharge & Maximum Design Discharge:	0.169 cfs (0.005 m^3s) 873 cfs (24.7 m^3s) (100-yr flood event)
PRINCIPLE FEATURES	**Sand Berms:**	sand bars used to create seepage reservoirs and separate off-line ponds from main stream channel; increases hyporheic zone and dissipates stormwater energy
	Seepage Reservoirs & Off-line Ponds:	temporary water containment area alongside streams; water exfiltrates from an area of higher elevation into the stream channel as baseflow
	Shallow Aquatic Step-Pool Sequences:	pools created with the placement of a riffle weir grade control structure
	Riffle Weirs:	weir used in a step-pool sequence that promotes shallow and turgid conveyance of water
	Regenerative Stormwater Conveyance:	conveys stormwater from drain outlets through a series of small plunge pools to the main stem of the receiving stream

This led to, among other things, a decision to address community concerns through the execution of a capital project to restore the stream. The community wanted their ponds returned to their original condition, but current regulation no longer allowed in-stream structures. In 2005, a year-long process of communication, education, and dialogue led to an agreement between various stakeholders on restoration of the flood plain after decades of stormwater degradation (Bowen 2008).

PRINCIPLE RESTORATION FEATURES:

- ✓ ***Sand Berm***

Figure 4-14 Photo of Sand Berm (center) and Off-line Pond (right) at Wilelinor (main stream channel to left)

✓ ***Seepage Reservoirs & Offline Ponds***

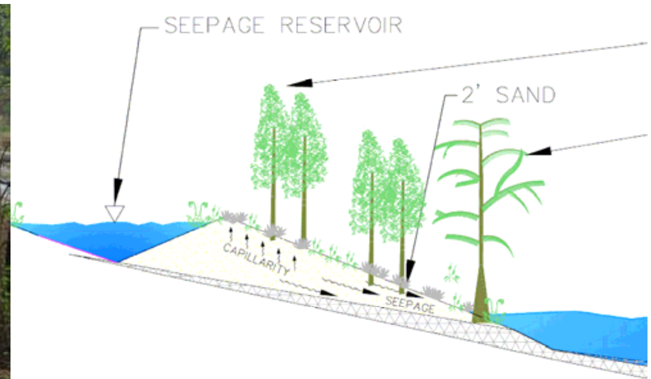


Figure 4-15a Photo of a Seepage Reservoir at Wilelinor

Figure 4-15b Seepage Reservoir Engineering Schematic
(Source: Underwood & Associates)

✓ ***Shallow, Aquatic Step-Pool Sequences***

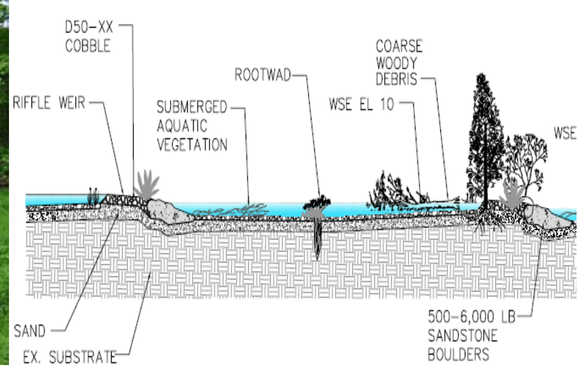


Figure 4-16a Photo of Shallow, Aquatic Step-Pools at Wilelinor

Figure 4-16b Shallow, Aquatic Step-Pool Engineering Schematic
(Source: Underwood & Associates)

✓ ***Riffle Weirs***

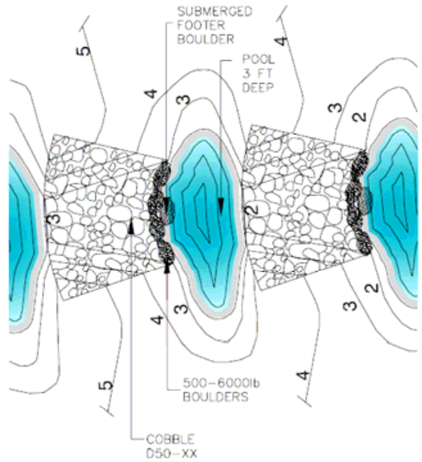


Figure 4-17a Photo of a Riffle Weir at Wilelinor

Figure 4-17b Riffle Weir and Step-Pool Engineering Schematic
(Source: Underwood & Associates)

✓ ***Regenerative Stormwater Convenyance***

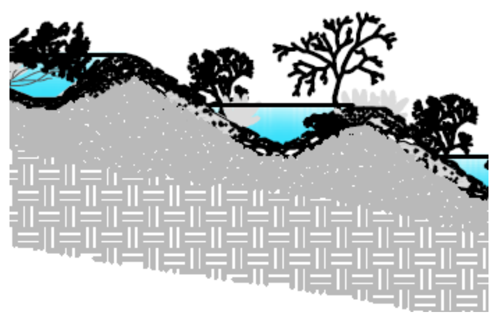


Figure 4-18a Photo of Riffle Weirs at Wilelinor
(from storm drain at Route 2 to stream valley)

Figures 4-18b Engineering Schematic of Riffle Weirs
(Source: Underwood & Associates)

CHAPTER 5: RESULTS

5.1 Water Quality Monitoring

Appendix A provides all water quality monitoring data observed and/or analyzed during this study. The following sections (Section 5.1.1-5.1.3) summarize water quality monitoring data for each individual stream and draws comparisons between upstream and downstream samples. Section 5.1.4 discusses differences between the three streams.

5.1.1 "Hard" Design Approach (Stony Run)

Table 5-1 provides the a summary of water quality results for Stony Run. Figures 5-1 through 5-6 illustrate the differences between upstream and downstream water concentrations over the duration of the study period.

Table 5-1 Descriptive Statistics for "Hard" Design Approach (Stony Run)

	nitrate-N (mg/L)	**ammonia -N (mg/L)**	**TSS (mg/L)**	**Temp. (°C)**	**DO (mg/L)**	**pH***	**Spec. Cond. (mS/cm)**
Mean	**2.93**	**0.05**	**4.19**	**9.14**	**12.60**	**7.76**	**0.53**
(min)	0.67	0.00	2.40	3.51	9.24	7.15	0.02
(max)	4.46	0.29	18.80	18.96	20.19	8.72	1.95
(N)	30	30	16	28	28	28	28
(std deviation)	1.21	0.07	4.60	4.48	2.53	0.48	0.38

*pH values are actually median values as pH data values are not linear

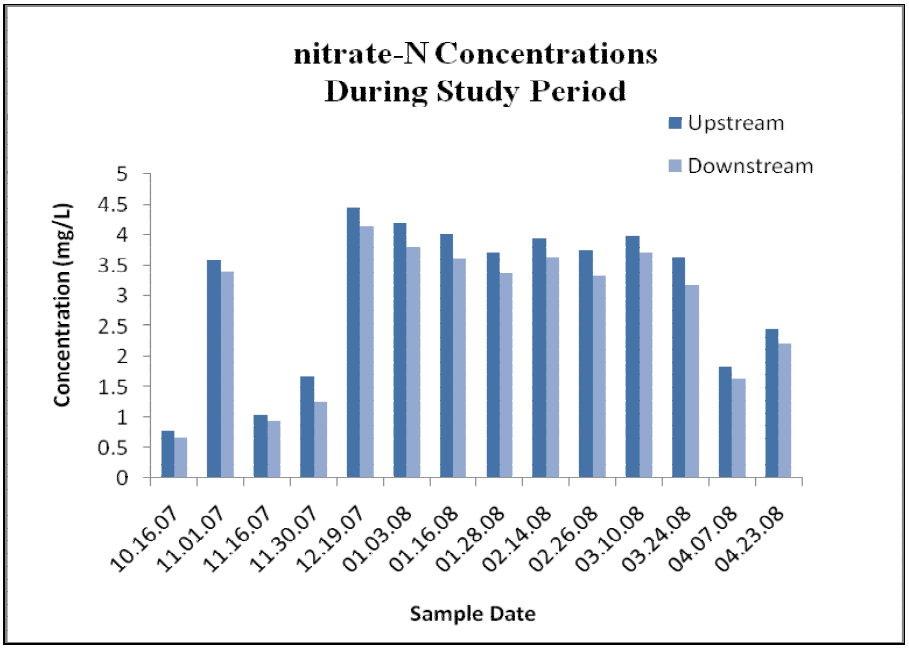


Figure 5-1 Upstream/Downstream Comparison of Nitrate-N, "Hard" Design Apprach (Stony Run)

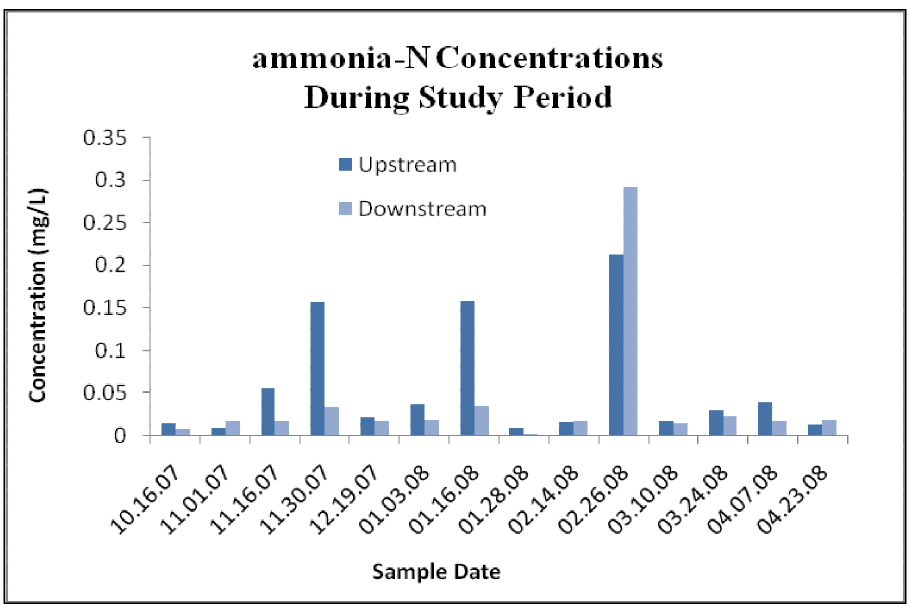


Figure 5-2 Upstream/Downstream Comparison of Ammonia-N, "Hard" Design Apprach (Stony Run)

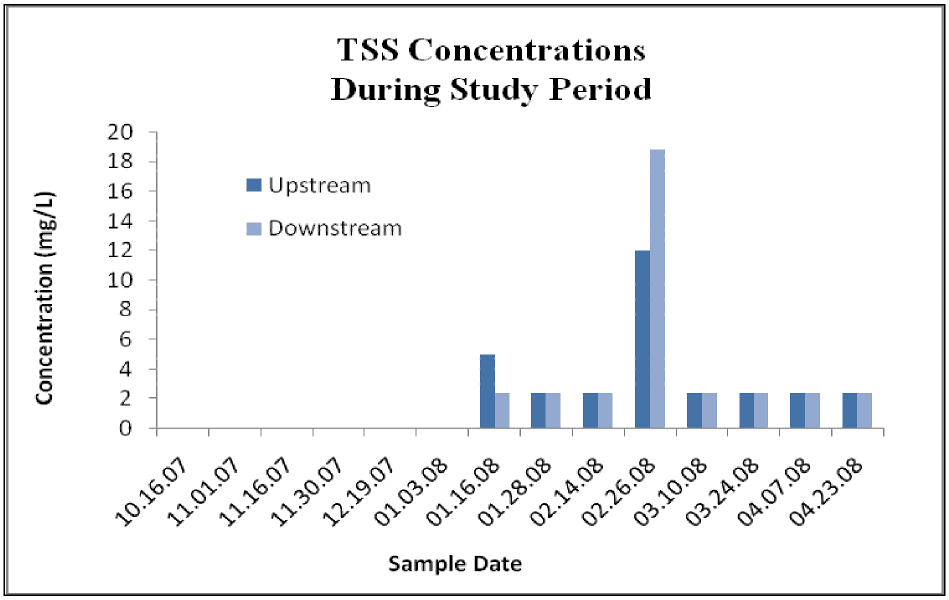


Figure 5-3 Upstream/Downstream Comparison of TSS,
“Hard” Design Apprach (Stony Run)

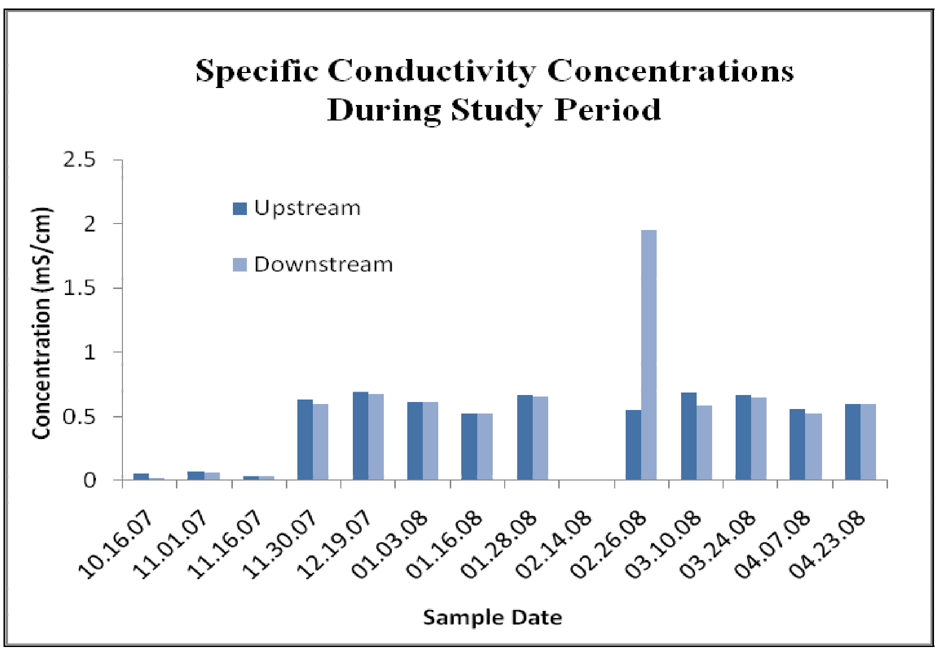


Figure 5-4 Upstream/Downstream Comparison of Specific Conductivity,
“Hard” Design Apprach (Stony Run)

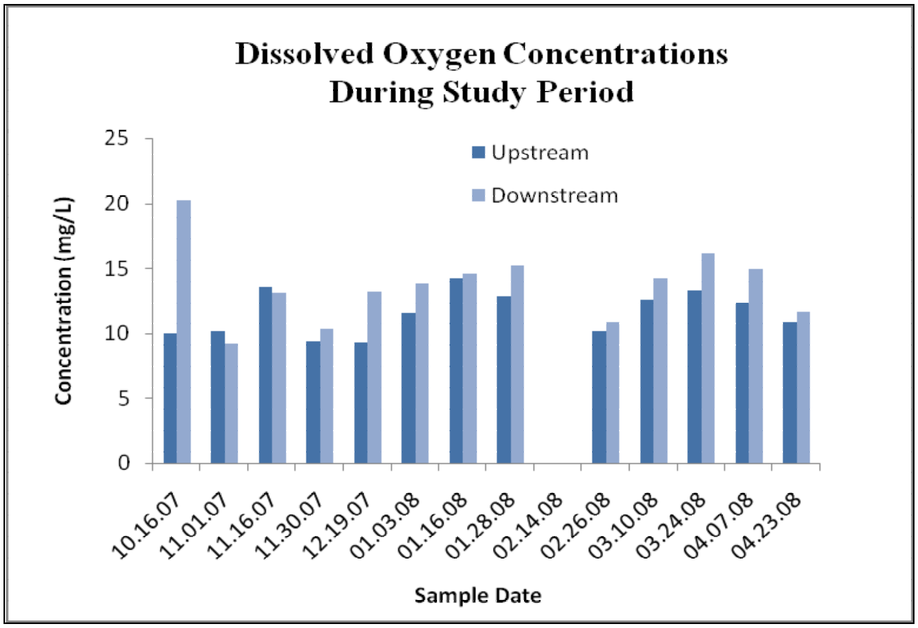


Figure 5-5 Upstream/Downstream Comparison of DO,
“Hard” Design Apprach (Stony Run)

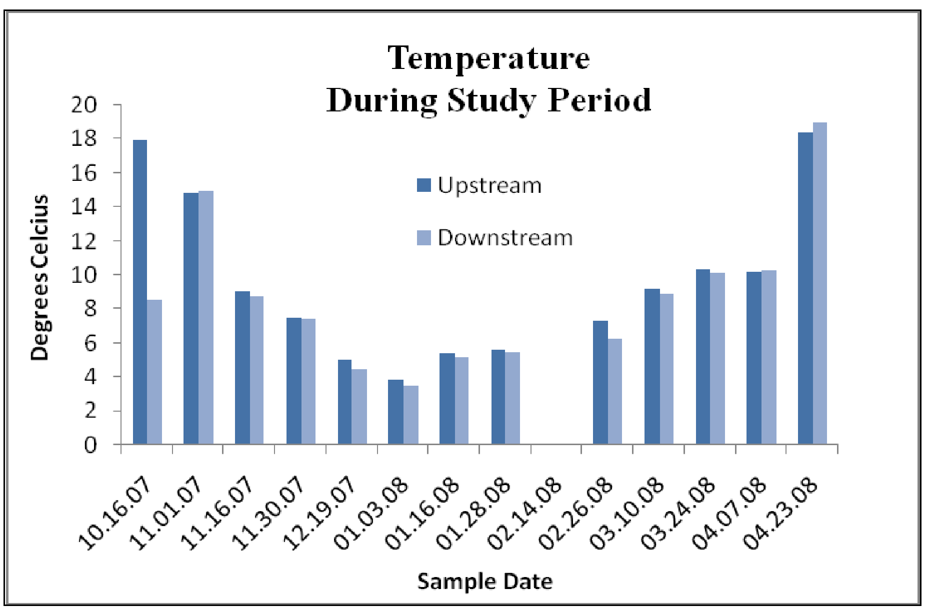


Figure 5-6 Upstream/Downstream Comparison of Temperature,
Hard” Design Apprach (Stony Run)

5.1.2 "Soft Design Approach (Kingstowne)

Table 5-2 provides the a summary of water quality results for Kingstowne, and Figures 5-7 through 5-12 illustrate the differences between upstream and downstream water concentrations over the duration of the monitoring period.

Table 5-2 Descriptive Statistics for "Soft" Design Approach (Kingstowne)

	Nitrate-N (mg/L)	Ammonia -N (mg/L)	TSS (mg/L)	Temp. (°C)	DO (mg/L)	pH*	Spec. Cond. (mS/cm)
Mean	**4.32**	**0.02**	**2.69**	**9.94**	**9.06**	**7.26**	**0.33**
(min)	2.76	0.00	2.40	2.59	7.60	6.86	0.20
(max)	5.58	0.12	7.00	19.78	11.77	8.36	0.54
(N)	30	30	16	26	26	26	26
(std deviation)	0.87	0.03	1.15	4.09	1.10	0.42	0.07

*pH values are actually median values as pH data values are not linear

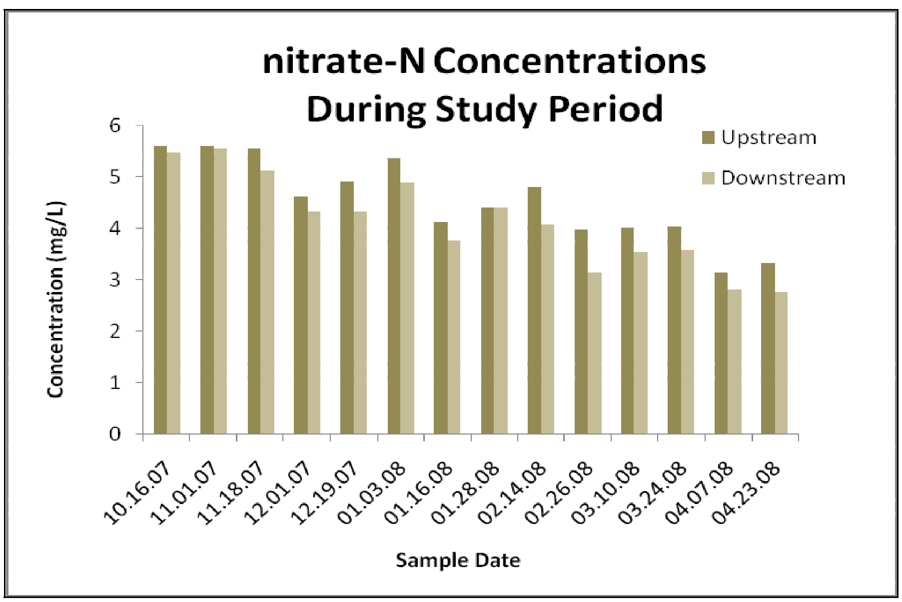


Figure 5-7 Upstream/Downstream Comparison of Nitrate-N, "Soft" Design Approach (Kingstowne)

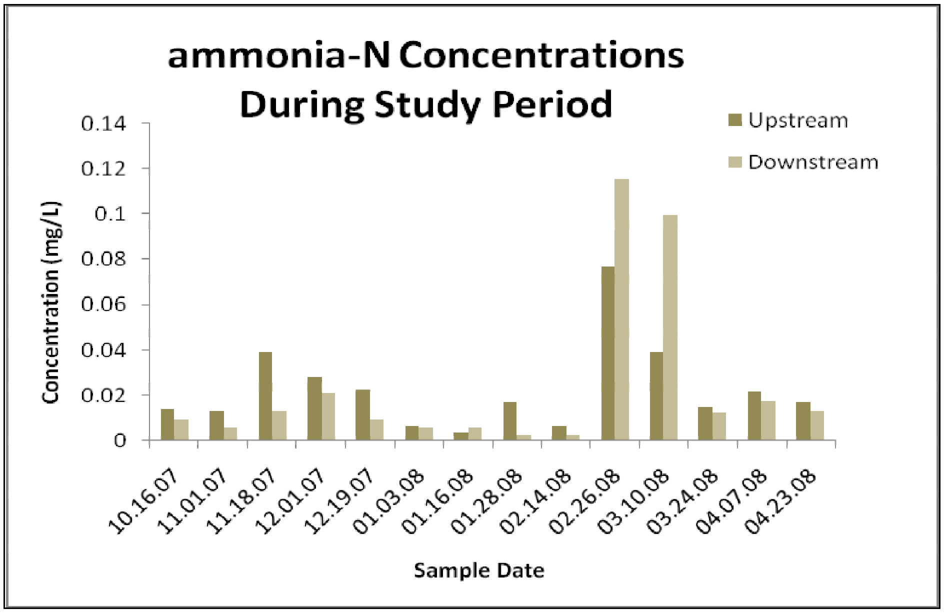


Figure 5-8 Upstream/Downstream Comparison of Ammonia-N,
“Soft” Design Approach (Kingstowne)

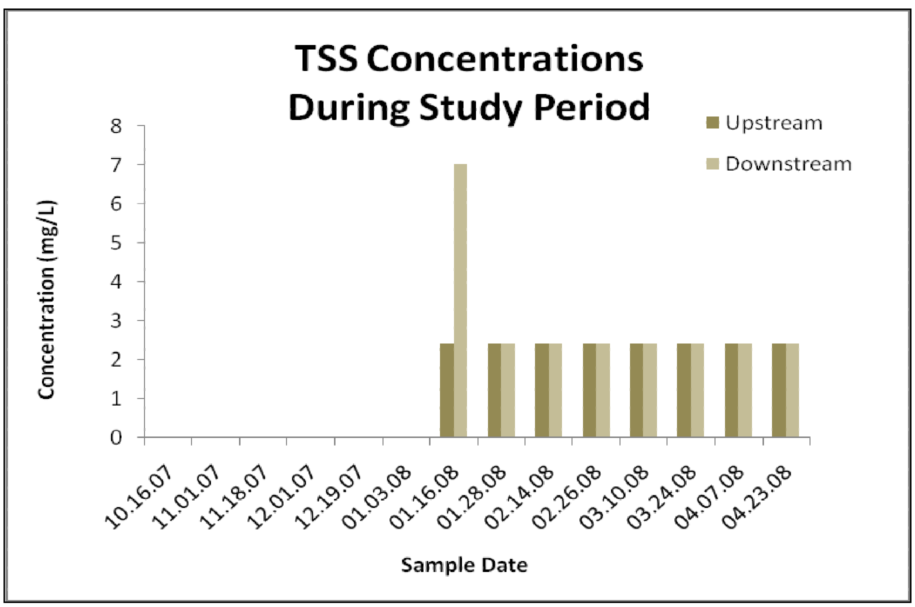


Figure 5-9 Upstream/Downstream Comparison of TSS,
“Soft” Design Approach (Kingstowne)

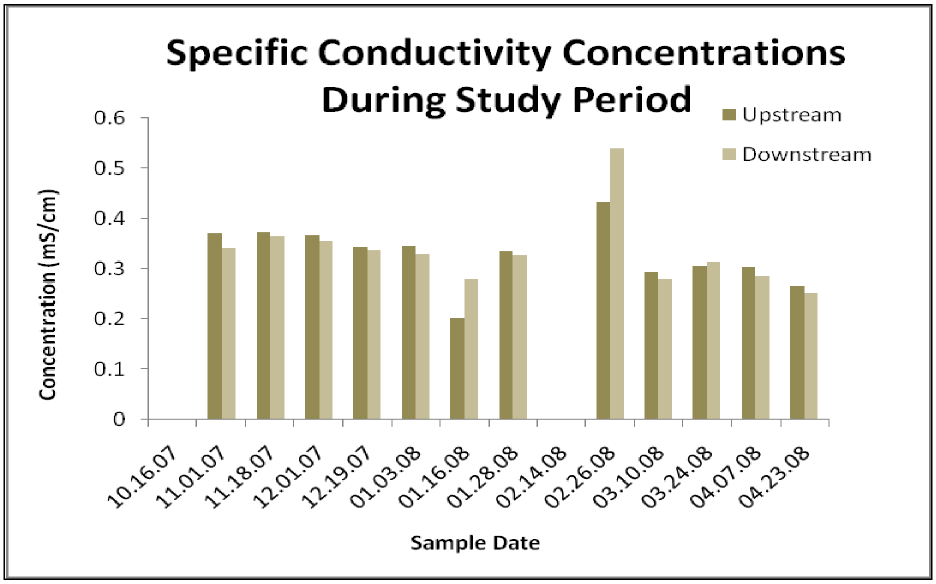


Figure 5-10 Upstream/Downstream Comparison of Specific Conductivity,
"Soft" Design Approach (Kingstowne)

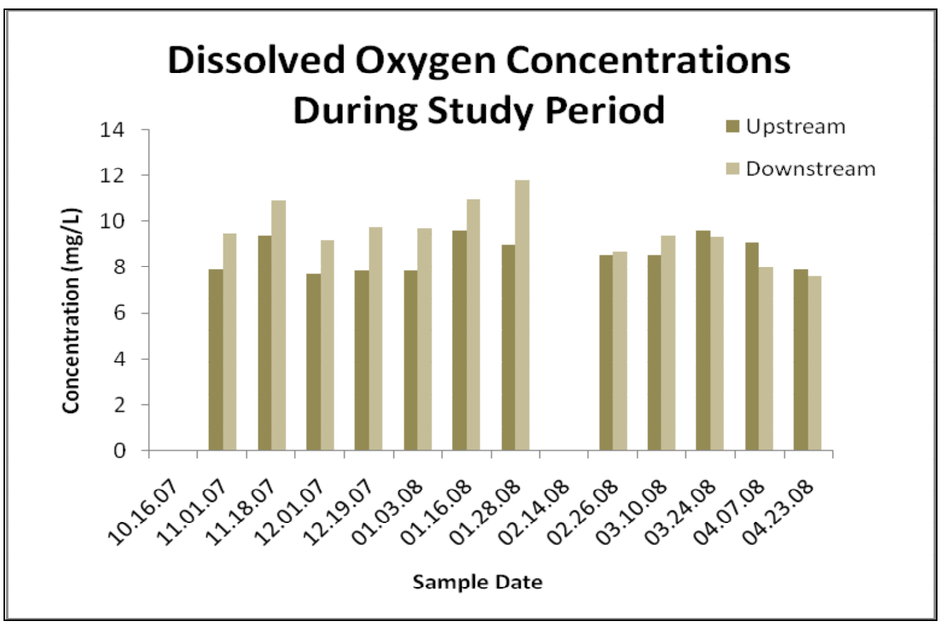


Figure 5-11 Upstream/Downstream Comparison of DO,
"Soft" Design Approach (Kingstowne)

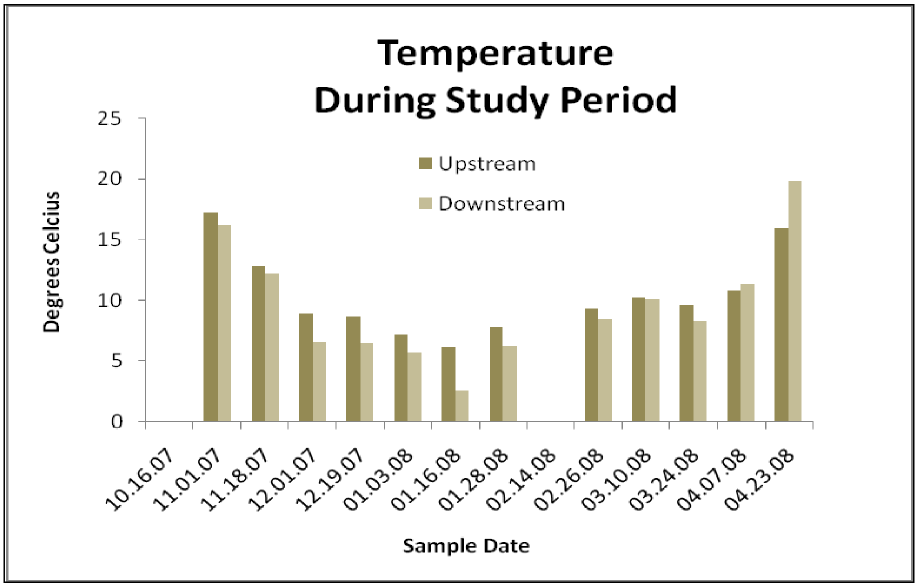


Figure 5-12 Upstream/Downstream Comparison of Temperature, "Soft" Design Approach (Kingstowne)

5.1.3 "Seepage Wetland" Design Approach (Wilelinor)

Table 5-3 provides the a summary of water quality results for Wilelinor, and Figures 5-13 through 5-18 illustrate the differences between upstream and downstream water concentrations during the monitoring period.

Table 5-3 Descriptive Statistics for "Seepage Wetland" Design Approach (Wilelinor)

	Nitrate-N (mg/L)	Ammonia -N (mg/L)	TSS (mg/L)	Temp. (°C)	DO (mg/L)	pH*	Spec. Cond. (mS/cm)
Mean	**0.40**	**0.14**	**11.42**	**9.19**	**8.06**	**6.90**	**0.50**
(min)	0.08	0.04	2.40	3.14	4.57	5.65	0.15
(max)	1.06	0.32	20.00	18.15	10.11	9.10	0.88
(N)	30	30	16	26	26	26	26
(std deviation)	0.23	0.07	4.83	4.78	1.60	0.70	0.20

*pH values are actually median values as pH data values are not linear

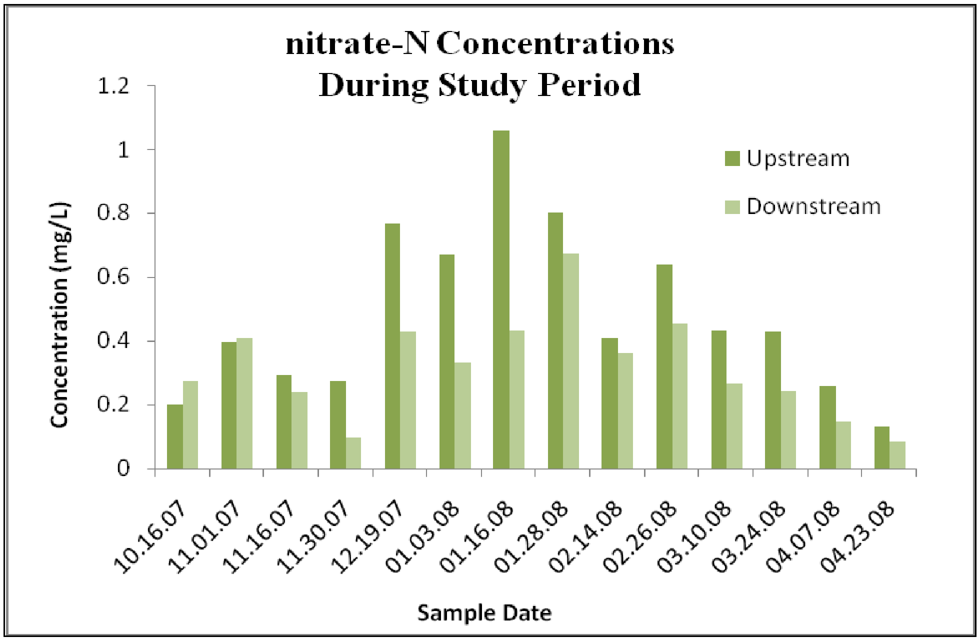


Figure 5-13 Upstream/Downstream Comparison of Nitrate-N, "Seepage Wetland" Design Approach (Wilelinor)

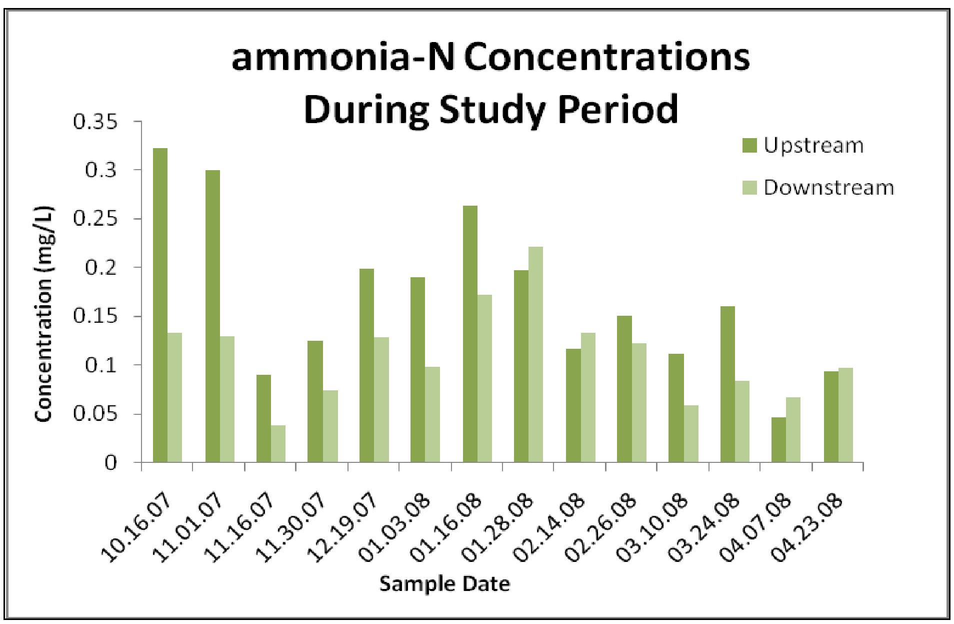


Figure 5-14 Upstream/Downstream Comparison of Ammonia-N, "Seepage Wetland" Design Approach (Wilelinor)

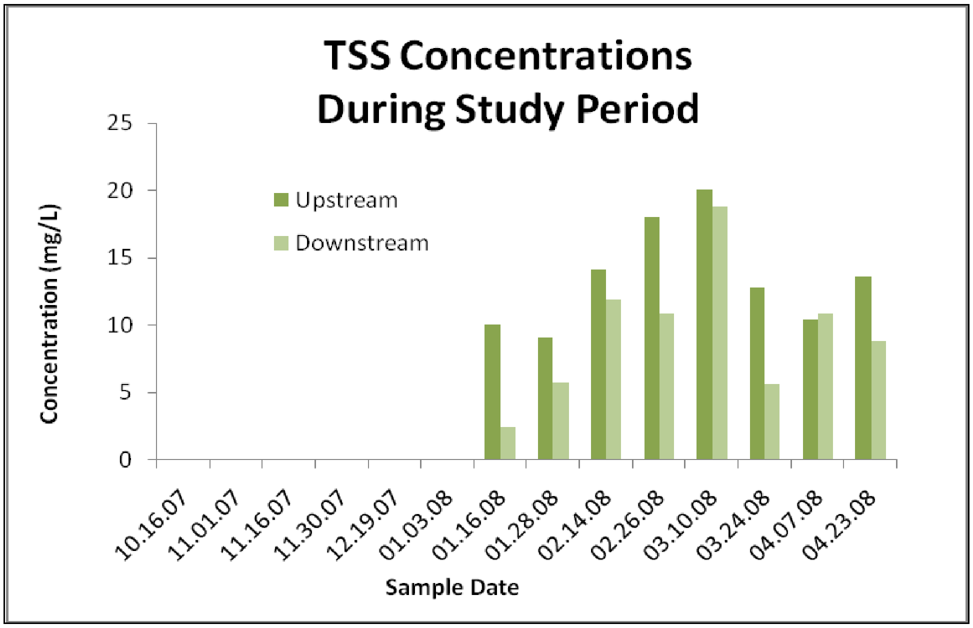


Figure 5-15 Upstream/Downstream Comparison of TSS,
“Seepage Wetland” Design Approach (Wilelinor)

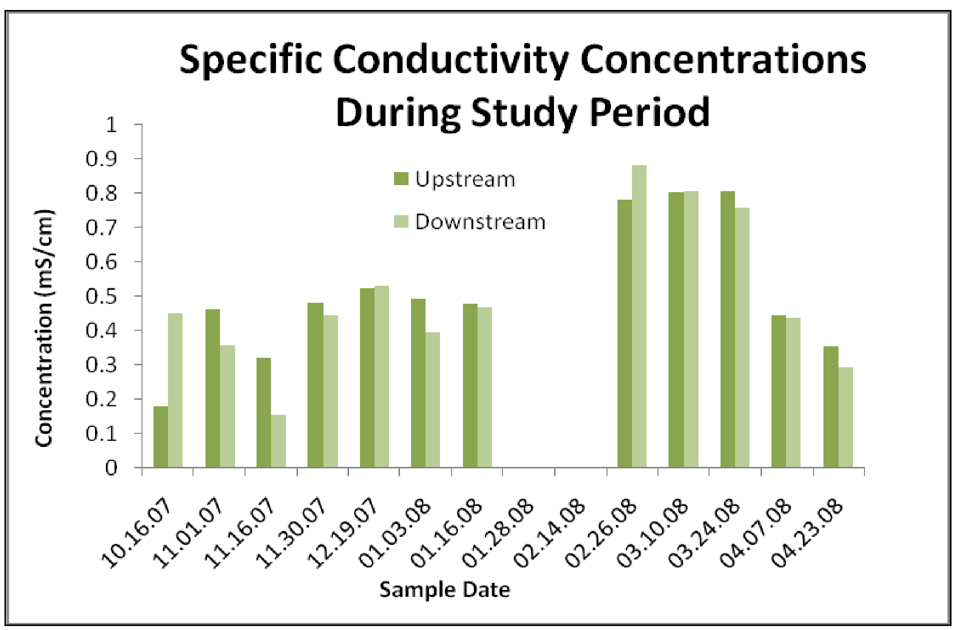


Figure 5-16 Upstream/Downstream Comparison of Specific Conductivity,
“Seepage Wetland” Design Approach (Wilelinor)

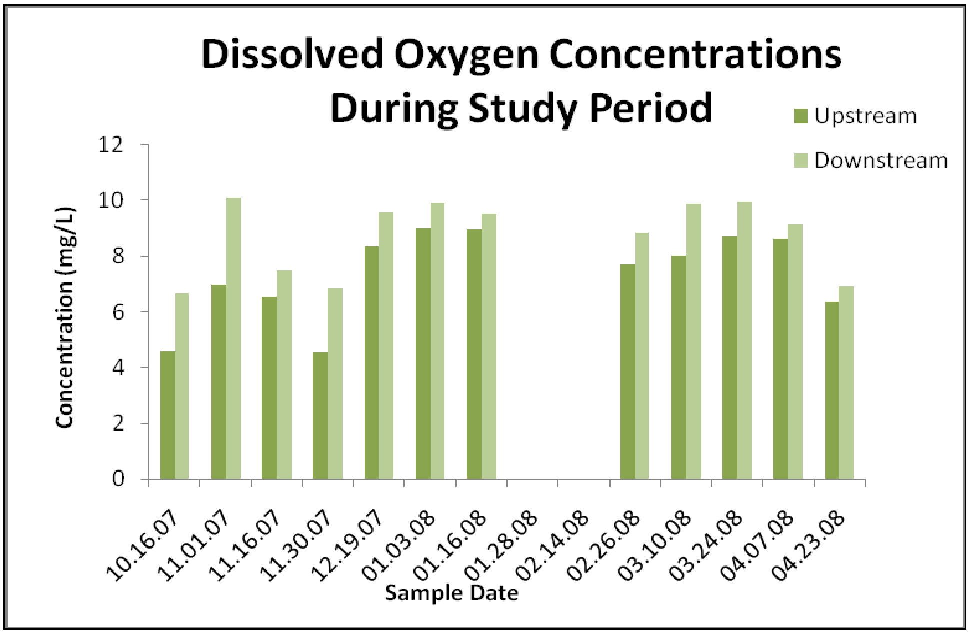


Figure 5-17 Upstream/Downstream Comparison of DO,
“Seepage Wetland” Design Approach (Wilelinor)

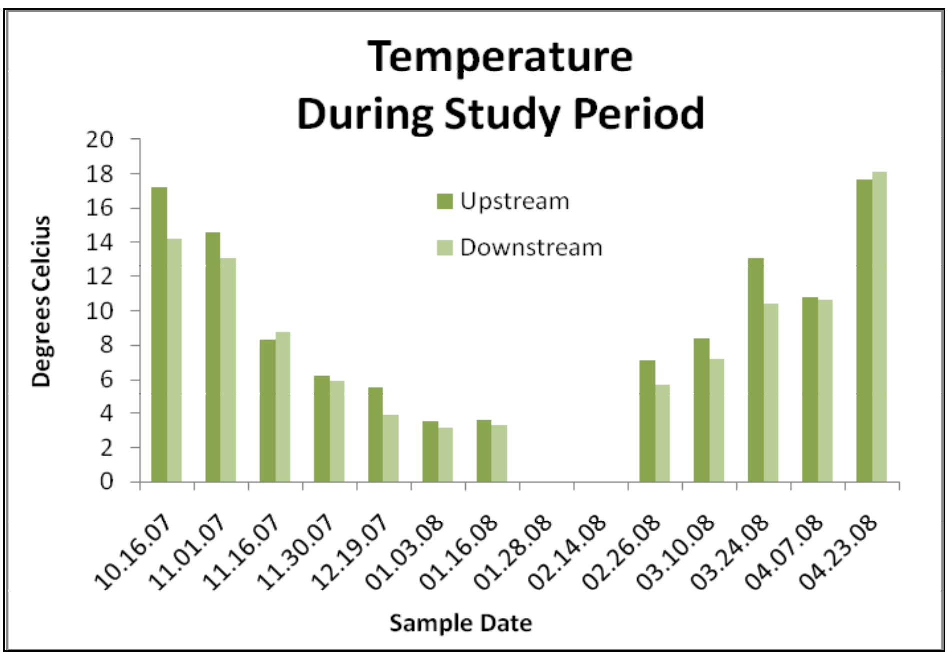


Figure 5-18 Upstream/Downstream Comparison of Temperature,
“Seepage Wetland” Design Approach (Wilelinor)

As illustrated in Figures 5-1 through 5-18, occassionally, parameters expected to decrease downstream (nitrate-N, ammonia-N, TSS, specific conductivity, and temperature) actually increased downstream; but overall, concentrations of these water quality criteria followed similar trends with lower concentrations in the downstream samples than the upstream samples. Overall, dissolved oxygen concentrations, which were expected to increase downstream within the restored reaches, did indeed increase downstream. It is noted that TSS concentrations decreased consistently only for samples collected at the "seepage wetland" (Wilelinor) stream restoration.

Nitrogen concentrations found at the study sites (0.13-5.58 mg/L) are comparable to typical pollutant levels found in urban stormwater, 2.0 mg/L (MDE 1999). TSS concentrations, on the other hand, were much lower for the study sites (2.4-20 mg/L) than concentrations typical of urban stormwater, 80 mg/L (MDE 1999).

5.1.4 Stream Comparison

Table 5-4 (next page) provides the mean differences and percent differences for the majority of water quality parameters. Overall, TSS concentratios increased between the upstream and downstream monitoring points for the "hard" (Stony Run) and "soft" (Kingstowne) stream restorations, so percent change was not calculated for these streams. Similarly, pH and specific conductivity values did not follow consistent trends among the three streams; no percent change was calculated.

Table 5-4 Mean Differences Between Upstream and Downstream Samples

		nitrate-N (mg/L)	ammonia-N (mg/L)	TSS (mg/L)	DO (mg/L)	Temp. (°C)	pH	Spec. Cond. (mS/cm)
Hard/ Stony Run	U Mean	3.111	0.056	3.925	11.551	9.601	7.770	0.487
	D Mean	2.807	0.041	4.450	13.644	8.687	7.978	0.575
	Mean Diff	**-0.303**	**-0.016**	**+0.525**	**+2.093**	**-0.914**	**+0.208**	**+0.087**
Soft/ Kingstowne	U Mean	4.487	0.024	2.400	8.565	10.396	7.493	0.328
	D Mean	4.087	0.024	2.975	9.493	9.545	7.353	0.333
	Mean Diff	**-0.401**	**0.000**	**+0.575**	**+0.928**	**-0.851**	**-0.140**	**+0.005**
Seepage Wetland/ Wilelinor	U Mean	0.478	0.167	13.488	7.372	9.673	7.218	0.510
	D Mean	0.310	0.109	9.350	8.698	8.739	7.173	0.497
	Mean Diff	**-0.168**	**-0.057**	**-4.138**	**+1.327**	**-0.934**	**-0.044**	**-0.012**

Of particular interest, as illustrated in Table 5-4, nitrate-N concentrations between upstream and downstream monitoring points were reduced at all three study sites, suggesting that restored urban streams can improve water quality. Similarly, DO concentrations increased and temperature decreased between upstream and downstream monitoring points at all three streams. Ammonia-N concentrations were reduced only at the “hard” (Stony Run) and “seepage wetland” (Wilelinor) study sites. Unlike the other restored streams, the “seepage wetland” (Wilelinor) restoration reported an appreciable decrease in TSS concentration between upstream and downstream monitoring points. Figures 5-19 through 5- 25 illustrate the seasonal trends for each water quality criteria as well as the overall concentration differences between the three streams.

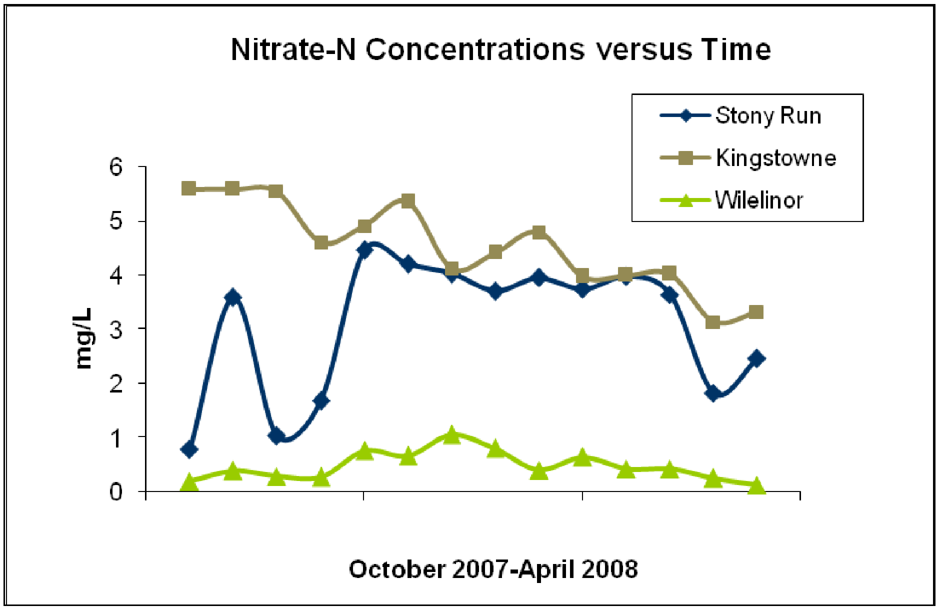


Figure 5-19 Nitrate-N versus Time, All Study Sites

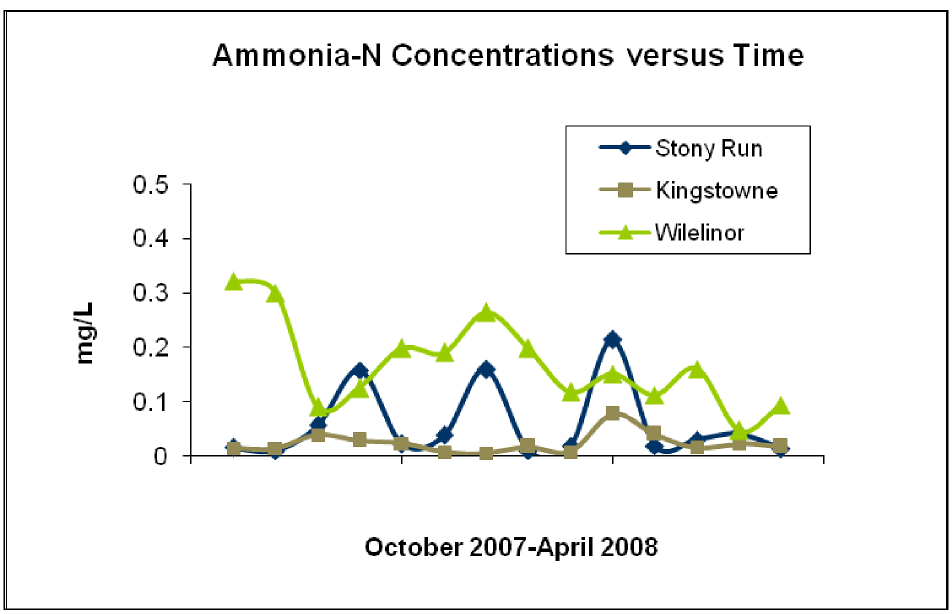


Figure 5-20 Ammonia-N versus Time, All Study Sites

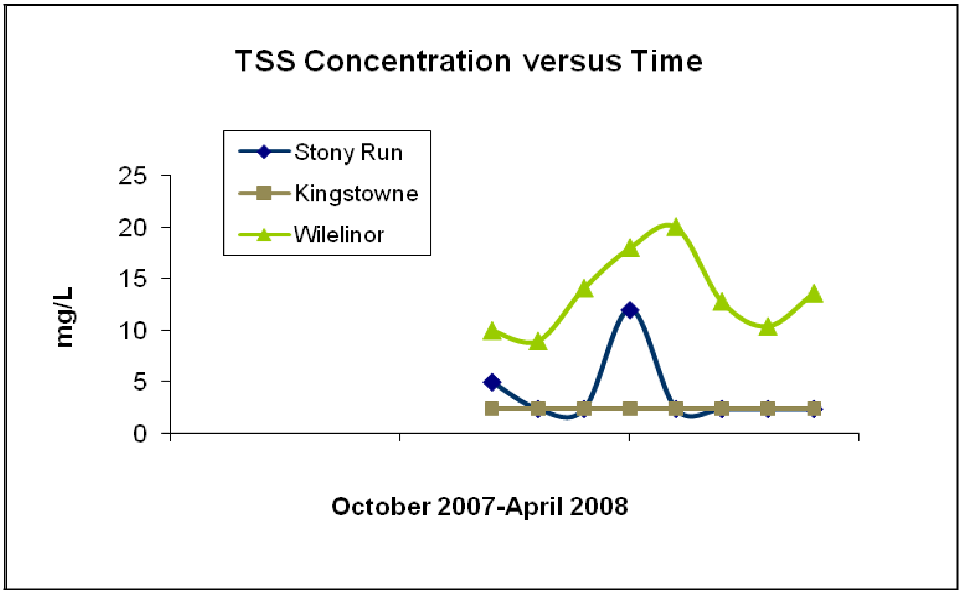


Figure 5-21 TSS versus Time, All Study Sites

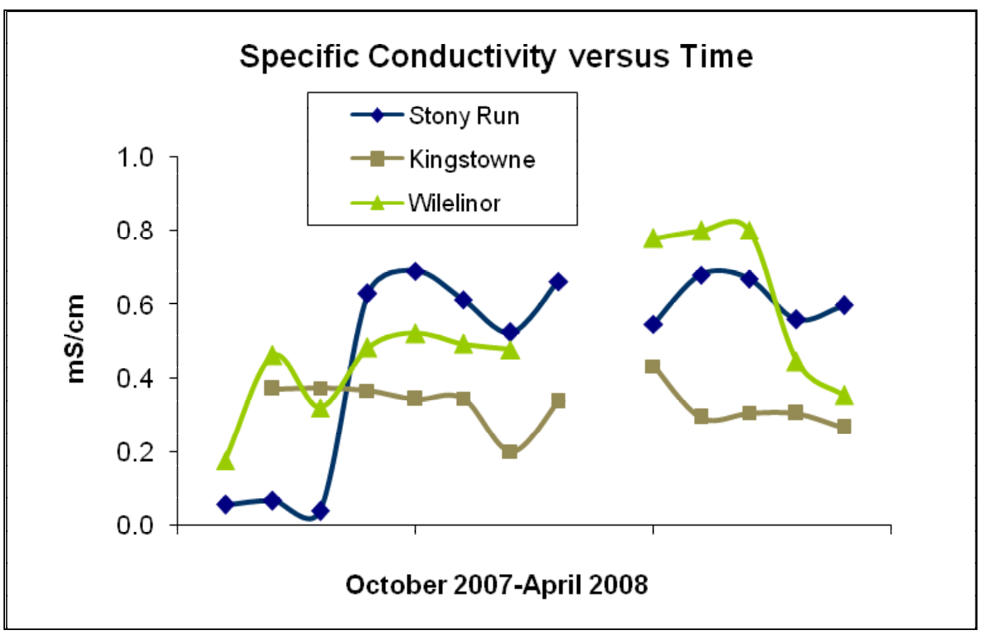


Figure 5-22 Specific Conductivity versus Time, All Study Sites

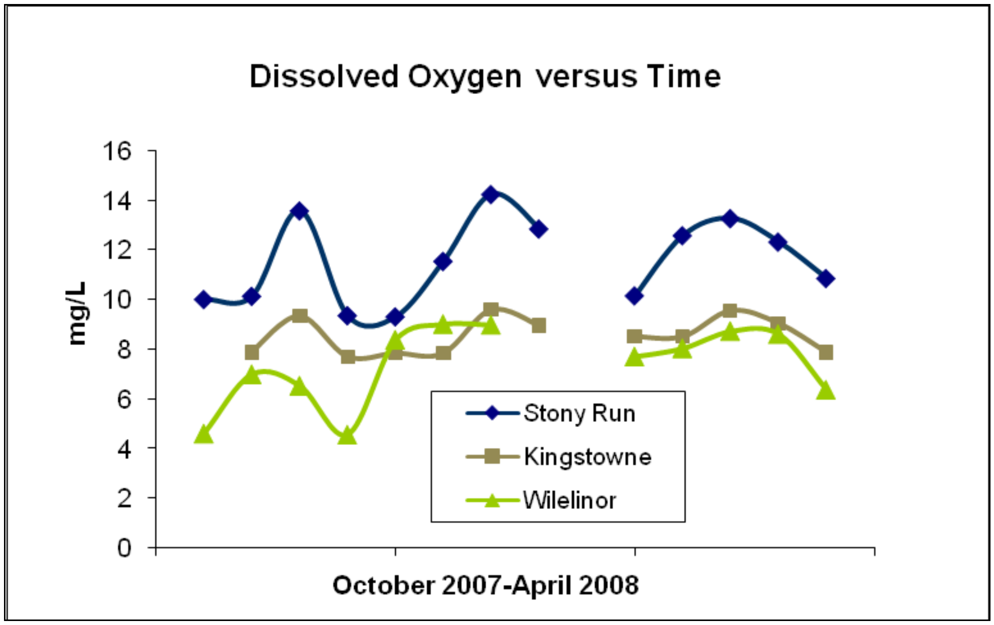


Figure 5-23 Dissolved Osygen versus Time, All Study Sites

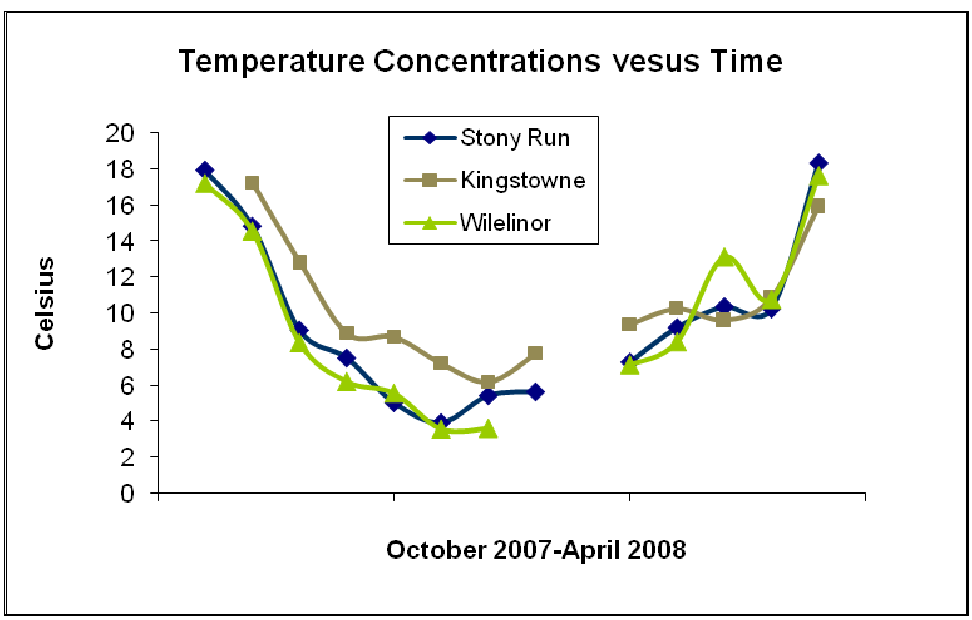


Figure 5-24 Temperature versus Time, All Study Sites

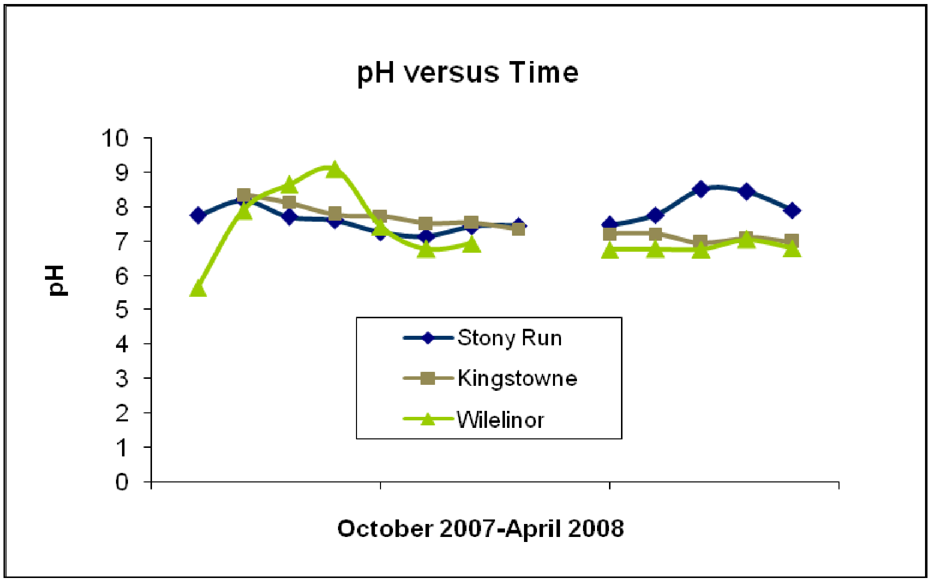


Figure 5-25 pH versus Time, All Study Sites

5.2 Discharge Monitoring Results

Average baseflow discharges for the three streams are as follows: "hard" (Stony Run), 0.490 cfs (0.014 m^3s); "soft" (Kingstowne), 0.109 cfs (0.003 m^3s); and "seepage wetland" (Wilelinor), 0.169 cfs (0.005 m^3s). The range of baseflow discharges for the "hard" (Stony Run) stream restoration was 0.048 -1.576 cfs (0.001-0.045 m^3s). These values are corroborated by baseflow discharges reported by Baltimore City Department of Public Works of 0.48 - 1.2 cfs (0.014-0.034 m^3s) (EA Engineering, Science, and Technology, Inc. 2001). The range of baseflow discharges for the "soft" (Kingstowne) stream restoration was 0.029 -0.545 cfs (0.001-0.015 m^3s) and 0.078-0.585 cfs (0.02-0.17 m^3s) for the "seepage wetland" (Wilelinor) stream restoration. In general, these discharge values make sense as they align with watershed acreage (Stony Run = 1,521 acres (6.16 sq km); Kingstowne = 72 acres (0.29 sq km); Wilelinor = 214 acres (0.87 sq km)). Appendix B provides all cross-sectional area and velocity field measurements as well as discharge calculations. Figure 5-26 illustrates rating curves developed from the calculated discharges and observed gage heights.

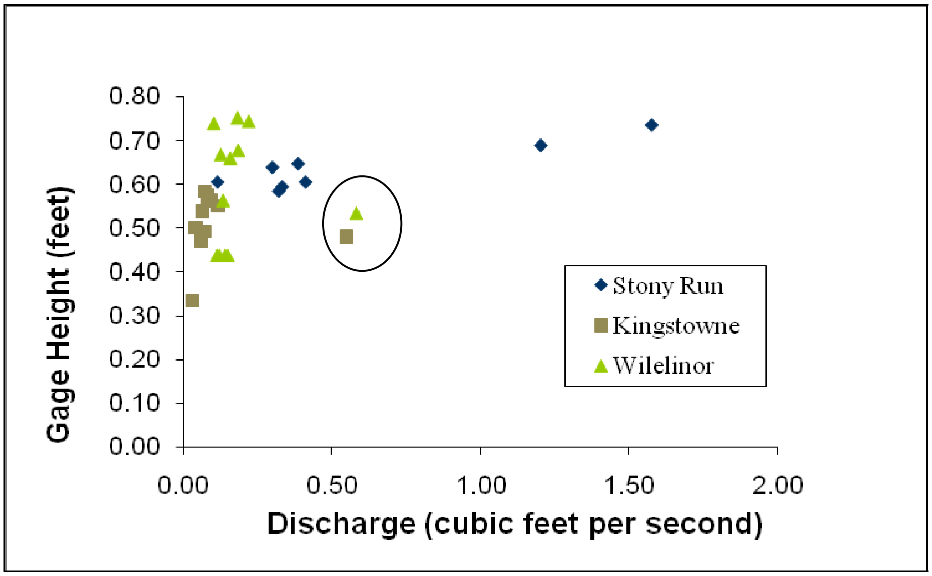


Figure 5-26 Rating Curves for Stony Run, Kingstowne, and Wilelinor

It is noted that Figure 5-26 illustrates two outliers (circled) that do not prescribe to the otherwise normal rating curves. One of the outliers (in green) was observed during a storm event at the “seepage wetland” (Wilelinor) stream restoration on February 14, 2008, and should have demonstrated both greater discharge and gage height. The other outlier was observed during baseflow conditions at the “soft” (Kingstowne) stream restoration on January 16, 2008. These outliers are likely observation errors.

5.3 Pollutant Load and Efficiency Results

Appendix C provides all pollutant load calculations. The most relevant average pollutant loads are those related to total nitrogen (total nitrogen calculated by adding nitrate-N and ammonia-N concentrations) and TSS. As such, average total nitrogen pollutant loads for the three streams are as follows: "hard" (Stony Run), 8.81 lbs/day (4.00 kg/day); "soft" (Kingstowne), 2.40 lbs/day (1.09 kg/day); and "seepage wetland" (Wilelinor), 0.46 lbs/day (0.21 kg/day). TSS average pollutant loads are: "hard" (Stony Run), 22.62 lbs/day (10.26 kg/day); "soft" (Kingstowne), 2.52 lbs/day (11.20 kg/day); and "seepage wetland" (Wilelinor), 13.67 lbs/day (6.20 kg/day).

Although pollutant loads are often cited in lbs/day, particularly for total maximum daily loads (TMDLs) under the CWA's Section 303(d), the difference between upstream and downstream loads were converted to pounds per foot per year (lbs/ft/yr) to make comparisons to CBP removal efficiencies of 0.02 lbs/ft/yr (0.03 kg/m/yr) for N and 2.55 lbs/ft/yr (3.79 kg/m/yr) for sediment (Baldwin 2005). As illustrated in Table 5-5 (next page), according to this study, average N load removal for the three restored streams far exceeds the Chesapeake Bay Program nitrogen removal efficiency allotted for urban stream restorations. This is not the case for sediment pollutant loads, which actually increased at Stony Run and Kingstowne.

Table 5-5 Pollutant Load Removal Comparisons

	"Hard" Design Approach (Stony Run)	"Soft" Design Approach (Kingstowne)	"Seepage Wetland" Design Approach (Wilelinor)	Chesapeake Bay Program Removal Efficiency
Total Nitrogen (lbs/ft/yr)	**0.50**	**0.13**	**0.10**	**0.02**
TSS (lbs/ft/yr)	↑	↑	2.37	**2.55**
Total Nitrogen (kg/m/yr)	**0.75**	**0.20**	**0.15**	**0.03**
TSS (kg/m/yr)	↑	↑	3.52	**3.79**

Another way to evaluate the pollutant removal efficiency of the streams and related restoration design approaches included in this study is through calculating percent differences between upstream and downstream concentrations. Percent differences for nitrate-N at the three streams were as follows: "hard" (Stony Run), 11%; "soft" (Kingstowne); 10%; and "seepage wetland" (Wilelinor), 39%. It is noted that although the mean difference of nitrate-N concentrations between upstream and downstream monitoring points was smallest at the "seepage wetland" restoration (-0.168 mg/L vs. -0.303 and -0.401 mg/L at the other restored streams), the percent difference was much higher. This supports the second alternate hypothesis that the "seepage wetland" design approach would demonstrate the greatest improvement in water quality.

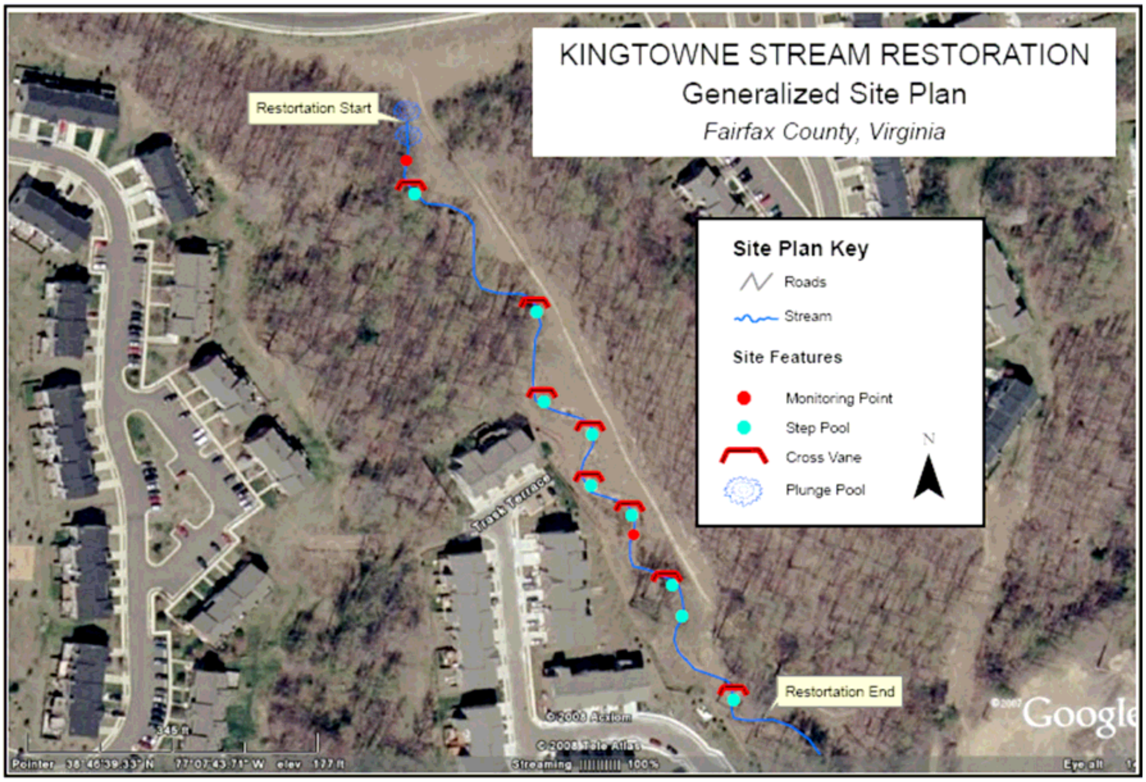
Similarly, while the other two restored streams demonstrated an increase in TSS concentrations between upstream and downstream monitoring points, the "seepage wetland" (Wilelinor) restoration reported an appreciable decrease in TSS concentration, resulting in a percent difference for TSS of 38%. Percent differences for ammonia-N were limited to the "hard" (Stony Run) stream restoration (49%) and the "seepage wetland" (Wilelinor) stream restoration (44%) (ammonia-N did not change between the upstream and downstream monitoring points at the "soft" (Kingstowne) stream restoration).

5.4 Rapid Stream Assessment Results

No major in-stream/habitat changes were observed over the duration of the study. This is particularly relevant at the "seepage wetland" (Wilelinor) stream restoration, where despite a 100-year flood event caused by a broken water main along MD Route 2, the restored stream maintained its structural integrity. Figures 5-27 through 5-29 illustrate major stream restoration features per field observations and engineering drawings provided by the lead agencies associated with each stream restoration project. It is noted that biological communities were observed at both the "seepage wetland" (Wilelinor) (abundant frogs and turtles) and "soft" (Kingstowne) stream restorations (crayfish and small homogenous fish population), but none were observed at the "hard" (Stony Run) study site.

Imagery: Google Earth 2007
Source: Adapted from graphic prepared by
Clear Creeks Consulting, Parsons Brinkerhoff, EBA Engineering Inc.

Figure 5-27 Stony Run Stream Restoration Generalized Site Plan
(Source: The Conservation Fund, to be printed)



Imagery: Google Earth 2007
Source: Adapted from graphic prepared by
Fairfax County Virginia Department of Public Works
and Environmental Service, Office of Capital Facilities

Figure 5-28 Kingstowne Stream Restoration Generalized Site Plan
(Source: The Conservation Fund, to be printed)

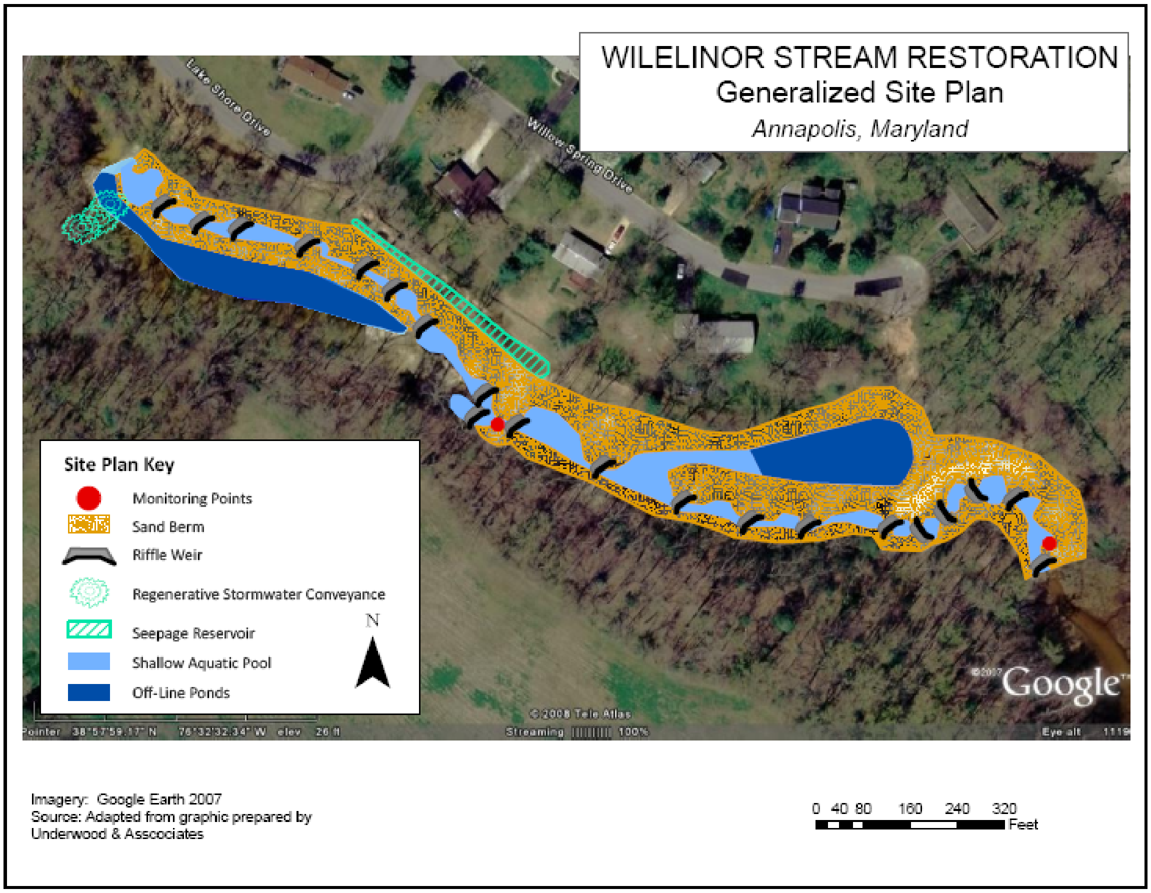


Figure 4-29 Wilelinor Stream Restoration Generalized Site Plan
(Source: The Conservation Fund, to be printed)

5.5 Statistical Results

Sections 5.5.1-5.5.3 summarize statistical results for the paired t-tests and nonparametric Wilcoxon tests conducted to answer the first hypothesis (Do urban stream restorations improve water quality?). Section 5.5.4 summarizes statistical results for the ANOVA tests conducted to answer the second hypothesis (Which urban stream restoration design approach is the most effective at improving water quality?).

5.5.1 "Hard" Design Approach (Stony Run) Results

Based on a combination of visual inspection (histograms; Q-Q plots) and statistical tests (skewness and kurtosis (±2); Shapiro-Wilk test ($W \leq 1.0$), the data distributions of water quality variables at the "hard" (Stony Run) stream restoration were determined. Dissolved oxygen and appeared to have normal distributions. Nitrate-N, ammonia-N, TSS, temperature, and specific conductivity were not normally distributed. A paired t-test was conducted to evaluate DO and pH, as these water quality criteria passed the assumptions associated with this test. The nonparametric Wilcoxon test was conducted to evaluate nitrate-N, ammonia-N, TSS, temperature, and specific conductivity.

Differences between upstream and downstream samples at the "hard" (Stony Run) stream restoration were statistically significant for DO ($t(12) = -2.703$, $p = 0.019$), pH ($t(12) = -3.406$, $p = 0.005$), nitrate-N ($Z = -3.408$, $p = 0.001$), temperature ($Z = -2.062$, $p = 0.039$), and specific conductivity ($Z = 2.271$, $p = 0.023$). Differences were not statistically significant for ammonia-A ($Z = -1.278$, $p = 0.201$) and TSS ($Z = -0.447$, $p = 0.655$).

5.5.2 "Soft" Design Approach (Kingstowne) Results

Based on a combination of visual inspection (histograms; Q-Q plots) and statistical tests (skewness and kurtosis (±2); Shapiro-Wilk test ($W \leq 1.0$), the data distributions of water quality variables at the "hard" (Stony Run) stream restoration were determined. Nitrate-N, temperature, DO, and pH appeared to have normal distributions and were evaluated with a paired t-test. The nonparametric Wilcoxon test was conducted to evaluate ammonia-N, TSS, and specific conductivity, as these criteria did not have normal data distributions.

Differences between upstream and downstream samples at the "soft" (Kingstowne) stream restoration were statistically significant for nitrate-N ($t(14) = 6.701$, $p = 0.000$), DO ($t(11) = -3.013$, $p = 0.012$), and pH ($t(11) = 4/690$, $p = 0.001$). Temperature ($t(11) = 1.711$, $p = 0.115$), ammonia-N ($Z = -1.621$, $p = 0.105$), TSS ($Z = -1.000$, $p = 0.317$), and specific conductivity ($Z= -1.099$, $p = 0.272$) differences between upstream and downstream monitoring points were not statistically significant. It is noted that ammonia-N concentrations could be considered statistically significant at the 90% confidence level (alpha level of $p = 0.1$).

5.5.3 "Seepage Wetland" Design Approach (Wilelinor) Results

Based on a combination of visual inspection (histograms; Q-Q plots) and statistical tests (skewness and kurtosis (±2); Shapiro-Wilk test ($W \leq 1.0$), the data distributions of water quality variables at the "hard" (Stony Run) stream restoration were determined. Nitrate-N, ammonia-N, TSS, temperature, and DO appeared to have normal distributions and were evaluated with a paired t-test. The nonparametric Wilcoxon test was conducted to evaluate pH and specific conductivity, as these criteria did not have normal data distributions.

Differences between upstream and downstream samples at the "seepage wetland" (Wilelinor) stream restoration were statistically significant for nitrate-N ($t(14) = 3.821$, p

= 0.002), ammonia-N (t(14) = 3.521, p = 0.003), TSS (t(7) = 3.845, p = 0.006), DO (t(11) = -5.938, p = 0.000) and temperature (t(11) = 2.911, p = 0.013). Specific conductivity (Z = -1.138, p = 0.255) and pH (Z = -0.392, p = 0.695) differences were not statistically significant.

5.5.4 Restored Stream Comparison

A new variable was created representative of the differences observed between upstream and downstream sample concentrations, and an ANOVA test was subsequently conducted to compare water quality criteria that were statistically significant in all three restored streams: nitrate-N and dissolved oxygen. An ANOVA test was also conducted for those variables that were statistically significant in at least two of the three restored streams (i.e., temperature and pH).

Mean DO concentration differences (F = 1.755, p = 0.187) and mean temperature differences (F = 0.060, p = 0.942) were not statistically significant. Mean pH concentrations (F = 13.706, p = 0.000) and mean nitrate-N concentrations, however, were statistically significant (F = 6.369, p = 0.004). A Bonferroni post hoc test for pH suggested that the "soft" (Kingstowne) stream restoration approach changed pH values to a greater extent than the "hard" (Stony Run) stream restoration approach (mean difference = -0.359, p = 0.036), while the pH differences between the "soft" and "seepage wetland" approaches (mean difference = 0.096, p = 1.000) and between the "hard" and "seepage wetland" approaches (mean difference = -0.260, p = 0.189) were not statistically significant.

Most interestingly, the Bonferroni post hoc test suggested that the "soft" (Kingstowne) stream restoration approach was better at uptaking nitrate-N than the "seepage wetland" (Wilelinor) restoration approach (mean difference = 0.232 mg/L; $p = 0.003$). While this makes sense upon looking at the mean differences between upstream and downstream nitrate-N concentrations (-0.168 mg/L at Wilelinor vs.-0.421 mg/L at Kingstowne), the percent differences paint another picture (39% at Wilelinor vs. 10% at Kingstowne). Thus, a second ANOVA test was conducted comparing nitrate-N percent differences amongst the three restored streams. Mean nitrate-N percent differences showed a greater statistical significance ($F = 27.948$, $p = 0.000$) than the mean nitrate-N concentration differences. The subsequent Bonferroni post hoc test indicated that indeed the "seepage wetland" (Wilelinor) approach had greater uptake of nitrate-N than the "hard" (Stony Run) restoration approach (mean difference = 25.411, $p = 0.000$) and the "soft" (Kingstowne) stream restoration approach (mean difference = 26.608, $p = 0.000$).

5.6 Conclusions

5.6.1 Summary of Findings

Table 5-6 (next page) provides a summary of findings based on watershed and stream characteristics and statistical analyses as well as other factors of importance, such as project cost and threshold of action.

Table 5-6 Summary of Findings

	"Hard" Design Approach (Stony Run)	**"Soft" Design Approach (Kingstowne)**	**"Seepage Wetland" Design Approach (Wilelinor)**
Watershed and Stream Reach Summary:	• Piedmont • 1,521 acres (6.16 km^2) • 30 % imperviousness • 167 ft average buffer • 0.022 river slope • 0.490 cfs (0.014 m^3s) baseflow	• Coastal Plain • 72 acres (0.29 km^2) • 54 % imperviousness • 268 ft average buffer • 0.026 river slope • 0.109 cfs 0.004 m^3s) baseflow	• Coastal Plain • 214 acres(0.87 km^2) • 37 % imperviousness • 166 ft average buffer • 0.008 river slope • 0.169 cfs 0.005 m^3s) baseflow
Major Restoration Features:	• Cross vanes • J-hook vanes • Imbricated riprap • Two-stage channels • Step-pools • Rootwad revetments	• Dry detention pond • Plunge pools • Soft meanders • Live stakes • Riparian buffer • Step-pools (diverse cobble substrate)	• Sand berms • Seepage reservoirs • Off-line ponds • Riffle weirs • Shallow, aquatic step pools • Regenerative stormwater conveyance
Mean Difference Between Upstream and Downstream:	• -0.30 mg/L nitrate-N • -0.02 mg/L ammonia- N • +0.53 mg/L TSS • +2.09 mg/L DO • -0.914 °C	• -0.40 mg/L nitrate-N • -0.00 mg/L ammonia- N • +0.58 mg/L TSS • +0.93 mg/L DO • -0.851 °C	• -0.12 mg/L nitrate-N • -0.06 mg/L ammonia- N • -4.12 mg/L TSS • +1.33 mg/L DO • -0.934 °C
% Removal Efficiency:	• 11% nitrate-N • 49% ammonia-N • --% TSS	• 10% nitrate-N • --% ammonia-N • --% TSS	• 39% nitrate-N • 44% ammonia-N • 38% TSS
Average Pollutant Loads:	• 8.81 lbs/day (4.00 kg/day) Total-N • 22.62 lbs/day (10.26 kg/day) TSS	• 2.40 lbs/day (1.09 kg/day) Total-N • 2.65 lbs/day (1.20 lbs/day) TSS	• 0.46 lbs/day (0.21 kg/day) Total-N • 8.32 lbs/day (6.20 lbs/day) TSS
Average Pollutant Removal:	• 0.50 lbs/ft/yr (0.75 kg/m/yr) Total-N • TSS ↑	• 0.13 lbs/ft/yr (0.20 kg/m/yr) Total-N • TSS ↑	• 0.10 lbs/ft/yr (0.15 kg/m/yr) Total-N • 2.37 lbs/ft/yr (3.52 kg/m/yr) TSS
Statistically Significant Results:	• *paired t-test*: nitrate-N, DO, pH, temperature and specific cond.	• *paired t-test*: nitrate-N, DO and pH • *ANOVA test*: pH difference greater than "hard" design; nitrate-N difference greater than "seepage wetland" design	• *paired t-test*: nitrate-N, ammonia-N, TSS, DO, and temperature • *ANOVA test*: nitrate-N percent difference greater than "hard" and "seepage wetland" designs
Cost (adjusted to 2008):	• \$942/ft (\$3,038/m)	• \$527/ft (\$1,729/m)	• \$776/ft (\$2,553/m)
Lead Agency:	• Baltimore DPW	• NVSWCD	• Anne Arundel County DPW
Threshold for Action:	• NPDES/MS4	• NPDES/MS4	• Community action

5.6.2 Summary of Statistical Analyses

Based on the statistical analyses described in Section 5.5, the first null hypothesis that there is no difference in water quality between upstream and downstream sample locations was rejected. Partial support for the first alternate hypothesis that urban stream restorations can improve water quality is the statistically significant difference between upstream and downstream concentrations for nitrate-N and DO in all three streams; for ammonia-N and TSS at Wilelinor; for pH at Stony Run and Kingstowne; and for temperature at Stony Run and Wilelinor in the paired t-tests. While the processes responsible for these improvements were not examined in this study, uptake by the biofilm on the streambed surface and denitrification (the microbial conversion of nitrate to gaseous forms of N) are likely the primary processes (Kaushal *et al.* 2008; Craig *et al.* 2008) responsible for the observed nitrogen depletion at the three restored streams. Other water quality criteria improvements, such as the reduction in temperature and the increase of DO towards the bottom of the restored reaches, are likely a result of the adjacent riparian buffers that offer shade to the restored streams.

The second hypothesis that there is no difference in water quality means among the three stream restoration designs was also rejected. Partial evidence of the second alternate hypothesis that the “seepage wetland” design approach would improve water quality to a greater extent than the other restorations as this design exhibited a greater percent removal of nitrate-N than the other two approaches in the second ANOVA test. Based on the Bonferroni post hoc test for nitrate-N percent difference, the “seepage wetland” stream restoration design approach associated with the Wilelinor stream improved water quality more than the other stream restoration designs (39% at Wilelinor versus 9-11% in the other restored streams). In addition, the "seepage wetland" design approach was the only observed stream to entrain sediment as demonstrated by the high removal efficiency of TSS (38%). These observations are likely the result of this design approach's ability to lower stream velocity and to enhance nitrogen processing through greater hyporheic exchanges with more denitrifiers (i.e., higher organic matter and carbon sources) (Craig *et al.* 2008; Kaushal *et al.* 2008).

5.6.3 Project Constraints

It is important to point out project constraints that limit the ability to generalize this study's results to other stream restorations. More specifically, these case studies can only suggest, not prove, which restoration design approach is more effective than other approaches. Project constraints that contribute to these limitations include: (1) the lack of a non-restored urban stream for use as a control; (2) only one stream representative of each restoration design approach was monitored; (3) small sample size ($n \leq 30$); (4) exclusion of the summer growing season when nitrogen uptake is likely highest; and (5) the majority of monitoring was conducted primarily during baseflow conditions so the amount and timing of pollutant delivery to the streams, and thus processing, during storm events is reduced.

Despite these project constraints, several peer-reviewed studies (e.g., Groffman *et al.* 2003; Baldwin 2005; Kaushal *et al.* 2008; Peterson *et al.* 2001; Roberts *et al.* 2007; Kasahara and Hill 2006) have demonstrated that restored urban streams have greater denitrification potential than non-restored urban streams. This study's results support those findings despite the fact that the majority of the study was conducted outside of the summer growing season when nitrogen uptake should be greatest. With regard to baseflow monitoring, while it is widely known that large amounts of nitrogen and sediment can be exported during high flows (i.e., storm events), substantial export can also occur through baseflow (Craig *et al.* 2008). In fact, Phillips *et al.* (1999) estimate that approximately 50% of nitrate loading to the Chesapeake Bay occurs during baseflow conditions. While this study did observe noticeably higher concentrations of TSS, ammonia-N, and specific conductivity at the "hard" (Stony Run) stream restoration and higher concentrations of ammonia-A and specific conductivity at the "soft" (Kingstowne) stream restoration during the February 26, 2008, storm event, concentration increases were not observed at the "seepage wetland" (Wilelinor) restoration. As Craig *et al.* (2008) finds, pollutant delivery varies from stream to stream, and stream restorations should be targeted towards small order streams that receive the largest amount of nutrient loading during low to moderate flows, as may be the case with the Kingstowne and Wilelinor restorations.

5.6.4 Policy Implications

Policy implications from this study can be applicable to stream restoration mangers and practitioners as well as research scientists. First, upon comparison of the data presented here and the restoration costs amongst the three restored streams ("hard" design, $942 per/ft; "soft" design, $527 per/ft; and "seepage wetland" design, $776 per/ft – all adjusted to 2008 dollars), it appears the "seepage wetland" design approach restores the most ecosystem services for a reasonable cost per linear foot, relatively speaking. As policy makers grapple with the "substantial variability in the efficacy of stream restoration designs" (Kaushal *et al.* 2008, p. 789), this study suggests that (1) all restored urban streams have the potential to improve water quality, as demonstrated by the paired t-tests associated with the first hypothesis; and (2) the "seepage wetland" approach, or at least features associated with this approach, may offer more bang for the buck than other design approaches. Not only did this restoration maintain its structural integrity through a 100-year flood event, it also demonstrated the greatest nitrogen and sediment removal efficiencies, as demonstrated by the ANOVA test associated with the second hypothesis.

These findings are of particular importance, as many agencies, including the CBP, do not heed stream restoration as an effective BMP for reducing nitrogen and sediment export from urban watersheds (Stack 2007; Simon 2007). Further, many municipalities require the use of the Rosgen Method during the design of a restoration (Simon 2007), as used and modified at the Stony Run and Kingstowne restorations. This study suggests that restored urban streams *can* be effective, value-added BMPs and that alternate approaches to urban stream restoration design should be considered.

In summary, these findings should persuade management agencies to reevaluate guidelines and funding availability for urban stream restoration in better recognition of the efficacy of restored urban streams to reduce sediment and nutrient export, to lower stream velocities and increase water residence time (thus increasing freshwater storage and groundwater recharge), and to provide recreational and aesthetic benefits to local communities. In addition, this study should encourage additional funding for post-restoration monitoring so we can continue learning what works and why and better steer future efforts. In addition, over the duration of this study, it became apparent that an open-dialogue amongst managers, practitioners, and stream restoration research scientists is necessary. This dialogue could facilitate manager awareness of the benefits offered by restored urban streams as well as knowledge about the most effective watershed and stream restoration strategies; practitioner awareness of the developing science so they may adopt the use of in-stream features or designs that offer the greatest benefits; and more effective and approachable scientific communication of technical findings while researchers continue perfecting the science. Finally, common removal rates that include a pollutant concentration, distance, and duration (time interval) should be adopted to increase the comparability of future monitoring and research.

On that note, it is recognized that this thesis serves as a pilot study for further research. This study could be expanded to include several restorations within each design approach as well as the inclusion of a non-restored stream to broaden the generalizability of the findings. It would also be of value to conduct the study over a longer duration to better identify seasonal trends, particularly for nitrogen. For example, the "seepage wetland" stream restoration was largely ammonia-N dominated compared to the other streams. This is likely a result of the greater amount of organic material available for decay during the winter months (nitrogen mineralization, or the conversion of organic matter to ammonium) and higher suspended solids (positively charged ammonium sorbs to clay particles and soil organic material) found at this study site. It is also possible that this stream would have demonstrated even higher nitrogen removal efficiencies had the study extended into the summer growing period, when nitrification, and subsequently denitrification, would be greatest. Of other interest is the efficacy of the specific restoration features to improve water quality so that they may be applied independently of the broader design.

APPENDIX A: WATER QUALITY MONITORING RESULTS

Sample Identification	Sample Date	Location	nitrate-N (mg/L)	ammonia-N (mg/L)	TSS (mg/L)	Temp. (Celsius)	DO (mg/L)	pH	Spec. Cond. (mS/cm)
SRU101607	10.16.07	U	0.784	0.015	--	17.97	10	7.75	0.0555
SRD101607	10.16.07	D	0.671	0.008	--	8.54	20.19	8.06	0.019
SRU110107	11.01.07	U	3.585	0.009	--	14.85	10.13	8.2	0.0676
SRD110107	11.01.07	D	3.405	0.018	--	14.94	9.24	8.14	0.0661
SRU111607	11.16.07	U	1.035	0.056	--	9.06	13.58	7.72	0.039
SRD111607	11.16.07	D	0.938	0.018	--	8.73	13.11	7.61	0.037
SRU113007	11.30.07	U	1.678	0.157	--	7.51	9.35	7.62	0.63
SRD113007	11.30.07	D	1.254	0.034	--	7.47	10.35	7.7	0.595
SRU121907	12.19.07	U	4.46	0.022	--	5.02	9.3	7.27	0.691
SRD121907	12.19.07	D	4.141	0.018	--	4.44	13.2	7.59	0.676
SRU010208	01.03.08	U	4.204	0.037	--	3.9	11.54	7.15	0.613
SRD010208	01.03.08	D	3.797	0.019	--	3.51	13.77	7.3	0.608
SRU011608	01.16.08	U	4.027	0.159	5.0	5.42	14.24	7.44	0.524
SRD011608	01.16.08	D	3.626	0.035	2.4	5.2	14.54	7.66	0.518
SRU012808	01.28.08	U	3.706	0.009	2.4	5.63	12.85	7.46	0.662
SRD012808	01.28.08	D	3.361	0.003	2.4	5.49	15.16	7.98	0.659
SRU021408	02.14.08	U	3.950	0.017	2.4	--	--	--	--
SRD021408	02.14.08	D	3.645	0.018	2.4	--	--	--	--
SRU022608	02.26.08	U	3.740	0.213	12.0	7.28	10.15	7.48	0.548
SRD022608	02.26.08	D	3.320	0.293	18.8	6.27	10.83	7.53	1.95
SRU031008	03.10.08	U	3.980	0.018	2.4	9.2	12.58	7.77	0.68
SRD031008	03.10.08	D	3.710	0.015	2.4	8.93	14.25	8.37	0.581
SRU032408	03.24.08	U	3.640	0.030	2.4	10.36	13.27	8.52	0.669
SRD032408	03.24.08	D	3.180	0.024	2.4	10.15	16.14	8.72	0.645
SRU032408X	03.24.08	U	3.580	0.052	--	10.36	13.27	8.52	0.669
SRD032408X	03.24.08	D	3.210	0.068	--	10.15	16.14	8.72	0.645
SRU040708	04.07.08	U	1.830	0.040	2.4	10.25	12.32	8.45	0.559
SRD040708	04.07.08	D	1.630	0.018	2.4	10.3	14.96	8.72	0.523
SRU042308	04.23.08	U	2.460	0.013	2.4	18.36	10.85	7.91	0.597
SRD042308	04.23.08	D	2.220	0.020	2.4	18.96	11.63	8.33	0.593
KU101607	10.16.07	U	5.582	0.014	--	--	--	--	--
KD101607	10.16.07	D	5.464	0.009	--	--	--	--	--

Sample Identification	Sample Date	Location	nitrate-N (mg/L)	ammonia-N (mg/L)	TSS (mg/L)	Temp. (Celsius)	DO (mg/L)	pH	Spec. Cond. (mS/cm)
KU101607	10.16.07	U	5.582	0.014	--	--	--	--	--
KD101607	10.16.07	D	5.464	0.009	--	--	--	--	--
KU110107	11.01.07	U	5.582	0.013	--	17.21	7.89	8.36	0.37
KD110107	11.01.07	D	5.547	0.006	--	16.17	9.43	8.08	0.34
KU111807	11.18.07	U	5.54	0.039	--	12.82	9.35	8.14	0.372
KD111807	11.18.07	D	5.116	0.013	--	12.24	10.9	7.96	0.363
KU120107	12.01.07	U	4.601	0.028	--	8.87	7.72	7.79	0.365
KD120107	12.01.07	D	4.311	0.021	--	6.54	9.14	7.61	0.355
KU121907	12.19.07	U	4.902	0.023	--	8.68	7.85	7.73	0.343
KD121907	12.19.07	D	4.317	0.009	--	6.49	9.75	7.54	0.336
KU010208	01.03.08	U	5.349	0.007	--	7.2	7.85	7.53	0.345
KD010208	01.03.08	D	4.873	0.006	--	5.69	9.68	7.47	0.327
KU011608	01.16.08	U	4.121	0.004	2.4	6.18	9.6	7.55	0.201
KD011608	01.16.08	D	3.763	0.006	7.0	2.59	10.95	7.25	0.279
KU012808	01.28.08	U	4.405	0.017	2.4	7.76	8.96	7.35	0.335
KD012808	01.28.08	D	4.392	0.003	2.4	6.23	11.77	7.14	0.326
KU021408	02.14.08	U	4.790	0.007	2.4	--	--	--	--
KD021408	02.14.08	D	4.059	0.003	2.4	--	--	--	--
KU022608	02.26.08	U	3.970	0.077	2.4	9.37	8.53	7.22	0.431
KD022608	02.26.08	D	3.140	0.115	2.4	8.46	8.68	7.13	0.538
KU031008	03.10.08	U	4.000	0.039	2.4	10.25	8.52	7.21	0.293
KD031008	03.10.08	D	3.530	0.099	2.4	10.13	9.35	7.27	0.279
KU032408	03.24.08	U	4.020	0.015	2.4	9.61	9.57	6.95	0.305
KD032408	03.24.08	D	3.580	0.013	2.4	8.3	9.32	6.91	0.313
KU032408X	03.24.08	U	3.990	0.039	--	9.61	9.57	6.95	0.305
KD032408X	03.24.08	D	3.650	0.032	--	8.3	9.32	6.91	0.313
KU040708	04.07.08	U	3.140	0.022	2.4	10.85	9.05	7.1	0.304
KD040708	04.07.08	D	2.800	0.017	2.4	11.29	7.97	7.01	0.285
KU042308	04.23.08	U	3.320	0.017	2.4	15.95	7.89	6.98	0.266
KD042308	04.23.08	D	2.760	0.013	2.4	19.78	7.6	6.86	0.251
WU101607	10.16.07	U	0.201	0.322	--	17.23	4.61	5.65	0.177
WD101607	10.16.07	D	0.272	0.133	--	14.26	6.65	7.09	0.451
WU110107	11.01.07	U	0.395	0.299	--	14.57	6.99	7.9	0.461
WD110107	11.01.07	D	0.407	0.13	--	13.09	10.11	7.79	0.359
WU111607	11.16.07	U	0.292	0.09	--	8.35	6.53	8.65	0.32
WD111607	11.16.07	D	0.237	0.038	--	8.79	7.5	7.81	0.154
WU113007	11.30.07	U	0.274	0.125	--	6.19	4.57	9.1	0.482
WD113007	11.30.07	D	0.096	0.074	--	5.89	6.84	8.07	0.444
WU121907	12.19.07	U	0.764	0.198	--	5.54	8.37	7.42	0.522
WD121907	12.19.07	D	0.427	0.129	--	3.87	9.56	7.25	0.529
WU010208	01.03.08	U	0.671	0.19	--	3.53	9	6.78	0.493
WD010208	01.03.08	D	0.329	0.099	--	3.14	9.92	6.77	0.395
WU011608	01.16.08	U	1.059	0.263	10.0	3.58	8.97	6.94	0.477

Sample Identification	Sample Date	Location	nitrate-N (mg/L)	ammonia-N (mg/L)	TSS (mg/L)	Temp. (Celsius)	DO (mg/L)	pH	Spec. Cond. (mS/cm)
WD011608	01.16.08	D	0.432	0.172	2.4	3.27	9.55	6.79	0.469
WU012808	01.28.08	U	0.802	0.197	9.0	--	--	--	--
WD012808	01.28.08	D	0.673	0.221	5.7	--	--	--	--
WU021408	02.14.08	U	0.408	0.117	14.1	--	--	--	--
WD021408	02.14.08	D	0.361	0.133	11.9	--	--	--	--
WU022608	02.26.08	U	0.640	0.151	18.0	7.12	7.7	6.77	0.779
WD022608	02.26.08	D	0.453	0.123	10.8	5.71	8.85	6.8	0.881
WU031008	03.10.08	U	0.429	0.112	20.0	8.4	8.03	6.78	0.801
WD031008	03.10.08	D	0.266	0.059	18.8	7.21	9.88	6.82	0.803
WU032408	03.24.08	U	0.428	0.160	12.8	13.14	8.72	6.77	0.803
WD032408	03.24.08	D	0.241	0.084	5.6	10.39	9.95	6.86	0.756
WU032408X	03.24.08	U	0.425	0.135	--	13.14	8.72	6.77	0.803
WD032408X	03.24.08	D	0.229	0.083	--	10.39	9.95	6.86	0.756
WU040708	04.07.08	U	0.257	0.046	10.4	10.77	8.6	7.05	0.445
WD040708	04.07.08	D	0.146	0.067	10.8	10.61	9.15	7.07	0.435
WU042308	04.23.08	U	0.131	0.094	13.6	17.66	6.37	6.8	0.354
WD042308	04.23.08	D	0.083	0.097	8.8	18.15	6.91	6.96	0.292

Notes:

1. *Sample identification numbers that begin with SRU = Stony Run Upstream; SRD = Stony Run Downstream; KU = Kingstowne Upstream; KD = Kingstowne Downstream; WU = Wilelinor Upstream; WD = Wilelinor Downstream.*
2. *Sample identification numbers with an 'X' on the end are duplicate samples, collected for quality control/quality assurance.*

APPENDIX B: CROSS-SECTIONAL AREA AND VELOCITY FIELD MEASUREMENTS &DISCHARGE CALCULATIONS

	Date	*Cross-Sectional Area and Velocity Field Measurements Middle Stony Run*										*Total Q*
	10.16.07											
Distance from Left Bank (ft)		0.60	1.20	1.80	2.40	3.00	3.60	4.20	4.80	5.40	6.00	
Depth (ft)		0.08	0.16	0.15	0.17	0.20	0.19	0.21	0.20	0.16	0.08	
Depth of Avg. Velocity (ft)		0.05	0.09	0.09	0.10	0.12	0.11	0.13	0.12	0.09	0.05	
Velocity (ft/sec)		0.01	0.05	0.10	0.02	0.02	0.03	0.10	0.10	0.01	0.01	
Discharge (cfs)		0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	**0.048**
	11.01.07											
Distance from Left Bank (ft)		1.22	2.44	3.66	4.88	6.10	7.32	8.54	9.76	10.98	12.20	
Depth (ft)		0.22	0.43	0.47	0.51	0.58	0.69	0.60	0.48	0.50	0.25	
Depth of Avg. Velocity (ft)		0.13	0.26	0.28	0.31	0.35	0.41	0.36	0.29	0.30	0.15	
Velocity (ft/sec)		0.08	0.15	0.17	0.18	0.21	0.25	0.22	0.17	0.18	0.09	
Discharge (cfs)		0.01	0.04	0.02	0.02	0.14	0.03	0.04	0.02	0.02	0.00	**0.351**
	11.18.07											
Distance from Left Bank (ft)		0.66	1.32	1.98	2.64	3.30	3.96	4.62	5.28	5.94	6.60	
Depth (ft)		0.09	0.18	0.16	0.10	0.18	0.31	0.34	0.28	0.18	0.08	
Depth of Avg. Velocity (ft)		0.06	0.11	0.09	0.06	0.11	0.19	0.21	0.17	0.11	0.05	
Velocity (ft/sec)		0.10	0.03	0.05	0.10	0.43	0.30	0.46	0.41	0.04	0.01	
Discharge (cfs)		0.01	0.00	0.01	0.01	0.05	0.06	0.10	0.08	0.00	0.00	**0.320**
	12.01.07											
Distance from Left Bank (ft)		0.30	0.60	0.90	1.20	1.50	1.80	2.10	2.40	2.70	3.00	
Depth (ft)		0.21	0.21	0.21	0.21	0.21	0.20	0.18	0.17	0.13	0.08	
Depth of Avg. Velocity (ft)		0.13	0.13	0.13	0.13	0.13	0.12	0.11	0.10	0.08	0.05	
Velocity (ft/sec)		0.01	0.27	0.28	0.28	0.29	0.14	0.28	0.27	0.10	0.10	
Discharge (cfs)		0.00	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.00	0.00	**0.114**
	12.19.07											
Distance from Left Bank (ft)		0.66	1.32	1.98	2.64	3.30	3.96	4.62	5.28	5.94	6.60	
Depth (ft)		0.26	0.36	0.19	0.17	0.23	0.27	0.33	0.31	0.24	0.16	
Depth of Avg. Velocity (ft)		0.16	0.22	0.11	0.10	0.14	0.16	0.20	0.19	0.14	0.09	
Velocity (ft/sec)		0.15	0.14	0.22	0.19	0.06	0.27	0.46	0.54	0.18	0.04	
Discharge (cfs)		0.03	0.03	0.03	0.02	0.01	0.05	0.10	0.11	0.03	0.00	**0.410**

	Date	Cross-Sectional Area and Velocity Field Measurements Middle Stony Run										Total Q
	01.02.08											
Distance from Left Bank (ft)		0.70	1.40	2.10	2.80	3.50	4.20	4.90	5.60	6.30	7.00	
Depth (ft)		0.23	0.23	0.19	0.16	0.18	0.15	0.18	0.16	0.10	0.10	
Depth of Avg. Velocity (ft)		0.14	0.14	0.11	0.09	0.11	0.09	0.11	0.10	0.06	0.06	
Velocity (ft/sec)		0.08	0.25	0.21	0.29	0.66	0.35	0.41	0.07	0.01	0.10	
Discharge (cfs)		0.01	0.04	0.03	0.03	0.08	0.04	0.05	0.01	0.00	0.01	**0.298**
	01.16.08											
Distance from Left Bank (ft)		0.54	1.08	1.62	2.16	2.70	3.24	3.78	4.32	4.86	5.40	
Depth (ft)		0.35	0.32	0.26	0.32	0.35	0.31	0.31	0.26	0.26	0.23	
Depth of Avg. Velocity (ft)		0.21	0.19	0.16	0.19	0.21	0.19	0.19	0.16	0.16	0.14	
Velocity (ft/sec)		0.03	0.21	0.11	0.11	0.16	0.33	0.53	0.23	0.30	0.03	
Discharge (cfs)		0.01	0.04	0.02	0.02	0.03	0.06	0.09	0.03	0.04	0.00	**0.331**
	01.28.08											
Distance from Left Bank (ft)		0.55	1.10	1.65	2.20	2.75	3.30	3.85	4.40	4.95	5.50	
Depth (ft)		0.26	0.22	0.15	0.13	0.17	0.16	0.14	0.17	0.19	0.10	
Depth of Avg. Velocity (ft)		0.16	0.13	0.09	0.08	0.10	0.10	0.08	0.10	0.11	0.06	
Velocity (ft/sec)		0.60	0.46	0.39	0.31	0.38	0.60	0.30	0.28	0.46	0.12	
Discharge (cfs)		0.09	0.06	0.03	0.02	0.03	0.05	0.02	0.03	0.05	0.01	**0.385**
	2.14.08											
Distance from Left Bank (ft)		0.77	1.54	2.31	3.08	3.85	4.62	5.39	6.16	6.93	7.70	
Depth (ft)		0.13	0.13	0.16	0.28	0.35	0.32	0.33	0.34	0.25	0.18	
Depth of Avg. Velocity (ft)		0.08	0.08	0.10	0.17	0.21	0.19	0.20	0.21	0.15	0.11	
Velocity (ft/sec)		0.10	0.47	0.52	0.53	0.40	0.81	1.13	1.27	0.06	0.15	
Discharge (cfs)		0.01	0.05	0.06	0.11	0.11	0.20	0.29	0.34	0.01	0.02	**1.202**
	2.26.08											
Distance from Left Bank (ft)		0.75	1.50	2.25	3.00	3.75	4.50	5.25	6.00	6.75	7.50	
Depth (ft)		0.16	0.18	0.23	0.35	0.42	0.36	0.39	0.35	0.26	0.14	
Depth of Avg. Velocity (ft)		0.09	0.11	0.14	0.21	0.25	0.22	0.23	0.21	0.16	0.08	
Velocity (ft/sec)		0.16	0.55	0.49	0.99	0.32	0.71	1.28	1.36	0.30	0.52	
Discharge (cfs)		0.02	0.07	0.08	0.26	0.10	0.19	0.37	0.36	0.06	0.05	**1.576**
	3.10.08											
Distance from Left Bank (ft)		0.81	1.62	2.43	3.24	4.05	4.86	5.67	6.48	7.29	8.10	
Depth (ft)		0.06	0.10	0.22	0.32	0.36	0.33	0.29	0.33	0.33	0.17	
Depth of Avg. Velocity (ft)		0.04	0.06	0.13	0.19	0.22	0.20	0.18	0.20	0.20	0.10	
Velocity (ft/sec)		0.03	0.01	0.35	0.39	0.39	0.27	0.46	0.21	0.01	0.07	
Discharge (cfs)		0.00	0.00	0.06	0.10	0.12	0.07	0.11	0.06	0.00	0.01	**0.530**
	3.24.08											
Distance from Left Bank (ft)		0.58	1.16	1.74	2.32	2.90	3.48	4.06	4.64	5.22	5.80	
Depth (ft)		0.32	0.26	0.17	0.15	0.13	0.29	0.33	0.20	0.17	0.14	
Depth of Avg. Velocity (ft)		0.19	0.16	0.10	0.09	0.08	0.18	0.20	0.12	0.10	0.08	
Velocity (ft/sec)		0.31	0.79	0.46	0.27	0.26	0.25	0.19	0.15	0.29	0.12	
Discharge (cfs)		0.06	0.12	0.05	0.02	0.02	0.04	0.04	0.02	0.03	0.01	**0.402**

	Date	***Cross-Sectional Area and Velocity Field Measurements Middle Stony Run***										***Total Q***
	4.07.08											
Distance from Left Bank (ft)		0.72	1.43	2.15	2.86	3.58	4.29	5.01	5.72	6.44	7.15	
Depth (ft)		0.15	0.21	0.25	0.24	0.24	0.30	0.38	0.30	0.22	0.18	
Depth of Avg. Velocity (ft)		0.09	0.13	0.15	0.14	0.14	0.18	0.23	0.18	0.13	0.11	
Velocity (ft/sec)		0.13	0.06	0.50	0.15	0.28	0.23	0.09	0.47	0.35	0.07	
Discharge (cfs)		0.01	0.01	0.09	0.03	0.05	0.05	0.02	0.10	0.05	0.01	**0.424**
	4.23.08											
Distance from Left Bank (ft)		0.69	1.38	2.07	2.76	3.45	4.14	4.83	5.52	6.21	6.90	
Depth (ft)		0.22	0.26	0.14	0.15	0.29	0.30	0.25	0.29	0.27	0.13	
Depth of Avg. Velocity (ft)		0.13	0.16	0.08	0.09	0.17	0.18	0.15	0.18	0.16	0.08	
Velocity (ft/sec)		0.14	0.31	0.15	0.17	0.28	0.62	0.40	0.26	0.26	0.08	
Discharge (cfs)		0.02	0.06	0.01	0.02	0.06	0.13	0.07	0.05	0.05	0.01	**0.471**

Average Discharge (cfs), Stony Run: **0.490**

Average Discharge (m^3s), Stony Run: **0.014**

	Date	***Cross-Sectional Area and Velocity Field Measurements Kingstowne***										***Total Q***
	10.16.07											
Distance from Left Bank (ft)		0.35	0.70	1.05	1.40	1.75	2.10	2.45	2.80	3.15	3.50	
Depth (ft)		0.09	0.24	0.25	0.16	0.08	0.15	0.29	0.23	0.19	0.13	
Depth of Avg. Velocity (ft)		0.06	0.14	0.15	0.09	0.05	0.09	0.18	0.14	0.12	0.08	
Velocity (ft/sec)		0.02	0.01	0.18	0.10	0.22	0.10	0.35	0.02	0.06	0.13	
Discharge (cfs)		0.00	0.00	0.02	0.01	0.01	0.01	0.04	0.00	0.00	0.01	**0.081**
	11.01.07											
Distance from Left Bank (ft)		0.35	0.70	1.05	1.40	1.75	2.10	2.45	2.80	3.15	3.50	
Depth (ft)		0.09	0.24	0.25	0.16	0.08	0.15	0.29	0.23	0.19	0.13	
Depth of Avg. Velocity (ft)		0.06	0.14	0.15	0.09	0.05	0.09	0.18	0.14	0.12	0.08	
Velocity (ft/sec)		0.02	0.01	0.18	0.10	0.22	0.10	0.35	0.02	0.06	0.13	
Discharge (cfs)		0.00	0.00	0.02	0.01	0.01	0.01	0.04	0.00	0.00	0.01	**0.081**
	11.18.07											
Distance from Left Bank (ft)		0.47	0.94	1.41	1.88	2.35	2.82	3.29	3.76	4.23	4.70	
Depth (ft)		0.02	0.13	0.28	0.34	0.35	0.31	0.18	0.14	0.19	0.10	
Depth of Avg. Velocity (ft)		0.01	0.08	0.17	0.21	0.21	0.19	0.11	0.08	0.11	0.06	
Velocity (ft/sec)		0.01	0.17	0.10	0.08	0.15	0.22	0.02	0.12	0.08	0.10	
Discharge (cfs)		0.00	0.01	0.01	0.01	0.02	0.03	0.00	0.01	0.01	0.00	**0.115**
	12.01.07											
Distance from Left Bank (ft)		0.36	0.72	1.08	1.44	1.80	2.16	2.52	2.88	3.24	3.60	
Depth (ft)		0.23	0.31	0.23	0.08	0.23	0.22	0.01	0.10	0.13	0.06	
Depth of Avg. Velocity (ft)		0.14	0.19	0.14	0.05	0.14	0.13	0.01	0.06	0.08	0.04	
Velocity (ft/sec)		0.10	0.15	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
Discharge (cfs)		0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.029**

	Date	Cross-Sectional Area and Velocity Field Measurements Kingstowne										Total Q
	12.19.07											
Distance from Left Bank (ft)		0.43	0.86	1.29	1.72	2.15	2.58	3.01	3.44	3.87	4.30	
Depth (ft)		0.17	0.17	0.20	0.16	0.19	0.17	0.08	0.01	0.05	0.04	
Depth of Avg. Velocity (ft)		0.10	0.10	0.12	0.09	0.11	0.10	0.05	0.01	0.03	0.03	
Velocity (ft/sec)		0.26	0.24	0.01	0.18	0.03	0.06	0.02	0.01	0.10	0.01	
Discharge (cfs)		0.02	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	**0.059**
	01.02.08											
Distance from Left Bank (ft)		0.43	0.86	1.29	1.72	2.15	2.58	3.01	3.44	3.87	4.30	
Depth (ft)		0.09	0.05	0.02	0.04	0.10	0.15	0.08	0.02	0.04	0.02	
Depth of Avg. Velocity (ft)		0.06	0.03	0.01	0.03	0.06	0.09	0.05	0.01	0.03	0.01	
Velocity (ft/sec)		0.10	0.10	0.28	0.16	0.01	0.30	0.20	0.01	0.07	0.02	
Discharge (cfs)		0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.00	**0.040**
	01.16.08											
Distance from Left Bank (ft)		0.47	0.94	1.41	1.88	2.35	2.82	3.29	3.76	4.23	4.70	
Depth (ft)		0.60	0.55	0.49	0.45	0.29	0.06	0.10	0.13	0.06	0.04	
Depth of Avg. Velocity (ft)		0.36	0.33	0.29	0.27	0.18	0.04	0.06	0.08	0.04	0.03	
Velocity (ft/sec)		0.30	0.90	0.40	0.30	0.30	0.20	0.01	0.30	0.20	0.01	
Discharge (cfs)		0.09	0.23	0.09	0.06	0.04	0.01	0.00	0.02	0.01	0.00	**0.545**
	01.28.08											
Distance from Left Bank (ft)		0.40	0.80	1.20	1.60	2.00	2.40	2.80	3.20	3.60	4.00	
Depth (ft)		0.60	0.57	0.56	0.45	0.41	0.41	0.30	0.15	0.02	0.02	
Depth of Avg. Velocity (ft)		0.36	0.34	0.34	0.27	0.24	0.24	0.18	0.09	0.01	0.01	
Velocity (ft/sec)		0.08	0.10	0.04	0.03	0.03	0.03	0.02	0.02	0.10	0.01	
Discharge (cfs)		0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	**0.071**
	2.14.08											
Distance from Left Bank (ft)		0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00	
Depth (ft)		0.13	0.27	0.23	0.17	0.24	0.34	0.19	0.15	0.25	0.17	
Depth of Avg. Velocity (ft)		0.08	0.16	0.14	0.10	0.14	0.20	0.11	0.09	0.15	0.10	
Velocity (ft/sec)		0.01	0.11	0.08	0.05	0.04	0.06	0.07	0.09	0.10	0.02	
Discharge (cfs)		0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.00	**0.071**
	2.26.08											
Distance from Left Bank (ft)		0.37	0.74	1.11	1.48	1.85	2.22	2.59	2.96	3.33	3.70	
Depth (ft)		0.38	0.34	0.25	0.27	0.19	0.07	0.05	0.21	0.33	0.21	
Depth of Avg. Velocity (ft)		0.23	0.21	0.15	0.16	0.11	0.04	0.03	0.13	0.20	0.13	
Velocity (ft/sec)		0.02	0.08	0.18	0.01	0.22	0.08	0.02	0.05	0.07	0.02	
Discharge (cfs)		0.00	0.01	0.02	0.00	0.02	0.00	0.00	0.00	0.01	0.00	**0.062**
	3.10.08											
Distance from Left Bank (ft)		0.48	0.96	1.44	1.92	2.40	2.88	3.36	3.84	4.32	4.80	
Depth (ft)		0.04	0.08	0.13	0.25	0.26	0.22	0.19	0.11	0.14	0.17	
Depth of Avg. Velocity (ft)		0.03	0.05	0.08	0.15	0.16	0.13	0.11	0.07	0.08	0.10	
Velocity (ft/sec)		0.10	0.01	0.00	0.10	0.19	0.23	0.07	0.28	0.07	0.02	
Discharge (cfs)		0.00	0.00	0.00	0.01	0.02	0.02	0.01	0.02	0.00	0.00	**0.091**

	Date	Cross-Sectional Area and Velocity Field Measurements Kingstowne										Total Q
	3.24.08											
Distance from Left Bank (ft)		0.35	0.70	1.05	1.40	1.75	2.10	2.45	2.80	3.15	3.50	
Depth (ft)		0.09	0.24	0.25	0.16	0.08	0.15	0.29	0.23	0.19	0.13	
Depth of Avg. Velocity (ft)		0.06	0.14	0.15	0.09	0.05	0.09	0.18	0.14	0.12	0.08	
Velocity (ft/sec)		0.02	0.01	0.18	0.10	0.22	0.10	0.35	0.02	0.06	0.13	
Discharge (cfs)		0.00	0.00	0.02	0.01	0.01	0.01	0.04	0.00	0.00	0.01	**0.081**
	4.07.08											
Distance from Left Bank (ft)		0.36	0.72	1.08	1.44	1.80	2.16	2.52	2.88	3.24	3.60	
Depth (ft)		0.06	0.10	0.13	0.27	0.51	0.52	0.55	0.54	0.48	0.31	
Depth of Avg. Velocity (ft)		0.04	0.06	0.08	0.16	0.31	0.31	0.33	0.33	0.29	0.19	
Velocity (ft/sec)		0.01	0.01	0.01	0.02	0.05	0.20	0.17	0.11	0.05	0.01	
Discharge (cfs)		0.00	0.00	0.00	0.00	0.01	0.04	0.03	0.02	0.01	0.00	**0.115**
	4.23.08											
Distance from Left Bank (ft)		0.47	0.94	1.41	1.88	2.35	2.82	3.29	3.76	4.23	4.70	
Depth (ft)		0.23	0.29	0.23	0.24	0.32	0.29	0.04	0.17	0.25	0.13	
Depth of Avg. Velocity (ft)		0.14	0.18	0.14	0.14	0.19	0.18	0.03	0.10	0.15	0.08	
Velocity (ft/sec)		0.03	0.09	0.21	0.00	0.04	0.06	0.01	0.24	0.07	0.01	
Discharge (cfs)		0.00	0.01	0.02	0.00	0.01	0.01	0.00	0.02	0.01	0.00	**0.080**

Average Discharge (cfs), Kingstowne Stream: **0.109**

Average Discharge (m^3s), Kingstowne Stream: **0.003**

	Date	Cross-Sectional Area and Velocity Field Measurements Wilelinor										Total Q
	10.16.07											
Distance from Left Bank (ft)		0.60	1.20	1.80	2.40	3.00	3.60	4.20	4.80	5.40	6.00	
Depth (ft)		0.15	0.21	0.22	0.27	0.27	0.28	0.30	0.31	0.28	0.13	
Depth of Avg. Velocity (ft)		0.09	0.13	0.13	0.16	0.16	0.17	0.18	0.19	0.17	0.08	
Velocity (ft/sec)		0.10	0.05	0.05	0.07	0.04	0.04	0.07	0.06	0.04	0.01	
Discharge (cfs)		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	**0.078**
	11.01.07											
Distance from Left Bank (ft)		0.40	0.80	1.20	1.60	2.00	2.40	2.80	3.20	4.60	4.00	
Depth (ft)		0.07	0.17	0.21	0.18	0.16	0.22	0.15	0.15	0.23	0.15	
Depth of Avg. Velocity (ft)		0.04	0.10	0.13	0.11	0.09	0.13	0.09	0.09	0.14	0.09	
Velocity (ft/sec)		0.10	0.04	0.04	0.55	0.03	0.19	0.13	0.39	0.14	0.10	
Discharge (cfs)		0.00	0.00	0.00	0.04	0.00	0.02	0.01	0.02	0.01	0.01	**0.116**
	11.18.07											
Distance from Left Bank (ft)		0.41	0.82	1.23	1.64	2.05	2.46	2.87	3.28	3.69	4.10	
Depth (ft)		0.06	0.07	0.14	0.15	0.18	0.14	0.15	0.24	0.13	0.02	
Depth of Avg. Velocity (ft)		0.04	0.04	0.08	0.09	0.11	0.08	0.09	0.14	0.08	0.01	
Velocity (ft/sec)		0.10	0.01	0.01	0.03	0.07	0.47	0.60	0.42	0.15	0.12	
Discharge (cfs)		0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.04	0.01	0.00	**0.122**

	Date	Cross-Sectional Area and Velocity Field Measurements Wilelinor										Total Q
	12.01.07											
Distance from Left Bank (ft)		0.33	0.65	0.98	1.30	1.63	1.95	2.28	2.60	2.93	3.25	
Depth (ft)		0.21	0.15	0.11	0.15	0.23	0.16	0.16	0.25	0.19	0.15	
Depth of Avg. Velocity (ft)		0.13	0.09	0.07	0.09	0.14	0.09	0.09	0.15	0.11	0.09	
Velocity (ft/sec)		0.10	0.10	0.10	0.16	0.03	0.32	0.35	0.33	0.09	0.15	
Discharge (cfs)		0.01	0.00	0.00	0.01	0.00	0.02	0.02	0.03	0.01	0.01	**0.098**
	12.19.07											
Distance from Left Bank (ft)		0.37	0.74	1.11	1.48	1.85	2.22	2.59	2.96	3.33	3.70	
Depth (ft)		0.04	0.04	0.08	0.16	0.23	0.16	0.17	0.26	0.16	0.10	
Depth of Avg. Velocity (ft)		0.03	0.03	0.05	0.09	0.14	0.09	0.10	0.16	0.09	0.06	
Velocity (ft/sec)		0.01	0.01	0.15	0.04	0.57	0.24	0.01	0.51	0.16	0.04	
Discharge (cfs)		0.00	0.00	0.00	0.00	0.05	0.01	0.00	0.05	0.01	0.00	**0.130**
	01.02.08											
Distance from Left Bank (ft)		0.42	0.84	1.26	1.68	2.10	2.52	2.94	3.36	3.78	4.20	
Depth (ft)		0.04	0.08	0.13	0.19	0.21	0.18	0.13	0.13	0.10	0.04	
Depth of Avg. Velocity (ft)		0.03	0.05	0.08	0.11	0.13	0.11	0.08	0.08	0.06	0.03	
Velocity (ft/sec)		0.10	0.06	0.13	0.37	0.45	0.25	0.74	0.10	0.05	0.10	
Discharge (cfs)		0.00	0.00	0.01	0.03	0.04	0.02	0.04	0.01	0.00	0.00	**0.146**
	01.16.08											
Distance from Left Bank (ft)		0.25	0.49	0.74	0.98	1.23	1.47	1.72	1.96	2.21	2.45	
Depth (ft)		0.18	0.10	0.14	0.28	0.32	0.33	0.19	0.18	0.27	0.11	
Depth of Avg. Velocity (ft)		0.11	0.06	0.08	0.17	0.19	0.20	0.11	0.11	0.16	0.07	
Velocity (ft/sec)		0.10	0.01	0.04	0.04	0.08	0.23	0.35	0.68	0.40	0.08	
Discharge (cfs)		0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.03	0.03	0.00	**0.109**
	01.28.08											
Distance from Left Bank (ft)		0.25	0.49	0.74	0.98	1.23	1.47	1.72	1.96	2.21	2.45	
Depth (ft)		0.19	0.07	0.15	0.26	0.29	0.32	0.18	0.17	0.25	0.23	
Depth of Avg. Velocity (ft)		0.11	0.04	0.09	0.16	0.18	0.19	0.11	0.10	0.15	0.14	
Velocity (ft/sec)		0.10	0.10	0.01	0.03	0.15	0.22	0.53	0.58	0.41	0.15	
Discharge (cfs)		0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.02	0.03	0.01	**0.118**
	2.14.08											
Distance from Left Bank (ft)		0.51	1.01	1.52	2.02	2.53	3.03	3.54	4.04	4.55	5.05	
Depth (ft)		0.13	0.09	0.10	0.16	0.19	0.24	0.29	0.23	0.13	0.06	
Depth of Avg. Velocity (ft)		0.08	0.06	0.06	0.10	0.11	0.14	0.18	0.14	0.08	0.04	
Velocity (ft/sec)		0.17	0.15	0.20	0.12	0.85	1.09	0.94	1.58	0.15	0.01	
Discharge (cfs)		0.01	0.01	0.01	0.01	0.08	0.13	0.14	0.18	0.01	0.00	**0.580**
	2.26.08											
Distance from Left Bank (ft)		0.22	0.44	0.66	0.88	1.10	1.32	1.54	1.76	1.98	2.20	
Depth (ft)		0.35	0.35	0.39	0.35	0.32	0.27	0.19	0.15	0.08	0.03	
Depth of Avg. Velocity (ft)		0.21	0.21	0.23	0.21	0.19	0.16	0.11	0.09	0.05	0.02	
Velocity (ft/sec)		0.02	0.11	0.27	0.20	0.23	0.20	0.95	0.52	0.19	0.10	
Discharge (cfs)		0.00	0.01	0.02	0.02	0.02	0.01	0.04	0.02	0.00	0.00	**0.137**

	Date	Cross-Sectional Area and Velocity Field Measurements Wilelinor										Total Q
	3.10.08											
Distance from Left Bank (ft)		0.38	0.75	1.13	1.50	1.88	2.25	2.63	3.00	3.38	3.75	
Depth (ft)		0.13	0.14	0.20	0.13	0.04	0.08	0.18	0.19	0.16	0.11	
Depth of Avg. Velocity (ft)		0.08	0.09	0.12	0.08	0.03	0.05	0.11	0.11	0.09	0.07	
Velocity (ft/sec)		0.10	0.02	0.45	0.94	0.10	0.79	0.63	0.24	0.10	0.10	
Discharge (cfs)		0.00	0.00	0.03	0.04	0.00	0.02	0.04	0.02	0.01	0.00	**0.181**
	3.24.08											
Distance from Left Bank (ft)		0.27	0.54	0.81	1.08	1.35	1.62	1.89	2.16	2.43	2.70	
Depth (ft)		0.22	0.20	0.17	0.22	0.30	0.34	0.23	0.23	0.25	0.10	
Depth of Avg. Velocity (ft)		0.13	0.12	0.10	0.13	0.18	0.20	0.14	0.14	0.15	0.06	
Velocity (ft/sec)		0.12	0.04	0.02	0.18	0.56	0.72	0.08	0.04	0.19	0.07	
Discharge (cfs)		0.01	0.00	0.00	0.01	0.05	0.07	0.01	0.00	0.01	0.00	**0.154**
	4.07.08											
Distance from Left Bank (ft)		0.44	0.88	1.32	1.76	2.21	2.65	3.09	3.53	3.97	4.41	
Depth (ft)		0.11	0.10	0.15	0.20	0.15	0.09	0.09	0.21	0.25	0.11	
Depth of Avg. Velocity (ft)		0.07	0.06	0.09	0.12	0.09	0.06	0.06	0.13	0.15	0.07	
Velocity (ft/sec)		0.02	0.09	0.47	0.06	1.08	0.49	0.60	0.21	0.02	0.03	
Discharge (cfs)		0.00	0.00	0.03	0.01	0.07	0.02	0.02	0.02	0.00	0.00	**0.179**
	4.23.08											
Distance from Left Bank (ft)		0.42	0.84	1.26	1.68	2.10	2.52	2.94	3.36	3.78	4.20	
Depth (ft)		0.14	0.15	0.17	0.16	0.16	0.15	0.11	0.07	0.13	0.08	
Depth of Avg. Velocity (ft)		0.08	0.09	0.10	0.09	0.09	0.09	0.07	0.04	0.08	0.05	
Velocity (ft/sec)		0.09	0.51	0.47	0.62	0.93	0.25	0.10	0.68	0.02	0.10	
Discharge (cfs)		0.01	0.03	0.03	0.04	0.06	0.02	0.00	0.02	0.00	0.00	**0.216**

Average Discharge (cfs), Wilelinor Stream: **0.169**

Average Discharge (m^3s), Wilelinor Run: **0.005**

Notes:

1. *The total amount of water moving through a stream is a product of the size of the stream (cross-sectional area) and the velocity. Using the depth, distance, and velocity measurements recorded in the field, the discharge (q) , or total volume of water flowing through each stream interval was calculated. Total discharge (Q) was calculated as the summation of the discharge from each of the intervals measured (Michaud 1991).*
2. *Average discharge was then converted to the metric equivalent of m^3s (1 cfs = 0.0283 m^3s).*

Appendix C: Pollutant Loads

Sample Number	Sample Date	Loc.	Q (cfs)	NO3+2 (mg/L)	nitrate-N Load (lbs/day)	nitrate-N Load (kg/day)	NH_4 (mg/L)	ammonia-N Load (lbs/day)	ammonia-N Load (kg/day)	TSS (mg/L)	TSS Load (lbs/day)	TSS Load (kg/day)
SRU101607	10.16.07	U	0.05	0.78	0.20	0.09	0.02	0.00	0.00	--	--	--
SRD101607	10.16.07	D	0.05	0.67	0.17	0.08	0.01	0.00	0.00	--	--	--
SRU110107	11.01.07	U	0.35	3.59	6.79	3.08	0.01	0.02	0.01	--	--	--
SRD110107	11.01.07	D	0.35	3.41	6.45	2.93	0.02	0.03	0.02	--	--	--
SRU111607	11.16.07	U	0.32	1.04	1.78	0.81	0.06	0.10	0.04	--	--	--
SRD111607	11.16.07	D	0.32	0.94	1.62	0.73	0.02	0.03	0.01	--	--	--
SRU113007	11.30.07	U	0.11	1.68	1.03	0.47	0.16	0.10	0.04	--	--	--
SRD113007	11.30.07	D	0.11	1.25	0.77	0.35	0.03	0.02	0.01	--	--	--
SRU121907	12.19.07	U	0.41	4.46	9.86	4.47	0.02	0.05	0.02	--	--	--
SRD121907	12.19.07	D	0.41	4.14	9.15	4.15	0.02	0.04	0.02	--	--	--
SRU010208	01.03.08	U	0.30	4.20	6.76	3.07	0.04	0.06	0.03	--	--	--
SRD010208	01.03.08	D	0.30	3.80	6.11	2.77	0.02	0.03	0.01	--	--	--
SRU011608	01.16.08	U	0.33	4.03	7.19	3.26	0.16	0.28	0.13	5.00	8.93	4.05
SRD011608	01.16.08	D	0.33	3.63	6.47	2.94	0.04	0.06	0.03	2.40	4.28	1.94
SRU012808	01.28.08	U	0.38	3.71	7.69	3.49	0.01	0.02	0.01	2.40	4.98	2.26
SRD012808	01.28.08	D	0.38	3.36	6.97	3.16	0.00	0.01	0.00	2.40	4.98	2.26
SRU021408	02.14.08	U	1.20	3.95	25.60	11.61	0.02	0.11	0.05	2.40	15.55	7.05
SRD021408	02.14.08	D	1.20	3.65	23.62	10.71	0.02	0.12	0.05	2.40	15.55	7.05
SRU022608	02.26.08	U	1.58	3.74	31.77	14.41	0.21	1.81	0.82	12.00	101.92	46.23
SRD022608	02.26.08	D	1.58	3.32	28.20	12.79	0.29	2.49	1.13	18.80	159.68	72.43
SRU031008	03.10.08	U	0.53	3.98	11.37	5.16	0.02	0.05	0.02	2.40	6.85	3.11
SRD031008	03.10.08	D	0.53	3.71	10.60	4.81	0.02	0.04	0.02	2.40	6.85	3.11
SRU032408	03.24.08	U	0.40	3.64	7.88	3.58	0.03	0.06	0.03	2.40	5.20	2.36
SRD032408	03.24.08	D	0.40	3.18	6.89	3.12	0.02	0.05	0.02	2.40	5.20	2.36
SRU032408X	03.24.08	U	0.40	3.58	7.75	3.52	0.05	0.11	0.05	--	--	--
SRD032408X	03.24.08	D	0.40	3.21	6.95	3.15	0.07	0.15	0.07	--	--	--
SRU040708	04.07.08	U	0.42	1.83	4.19	1.90	0.04	0.09	0.04	2.40	5.49	2.49
SRD040708	04.07.08	D	0.42	1.63	3.73	1.69	0.02	0.04	0.02	2.40	5.49	2.49
SRU042308	04.23.08	U	0.42	2.46	5.63	2.55	0.01	0.03	0.01	2.40	5.49	2.49
SRD042308	04.23.08	D	0.42	2.22	5.08	2.30	0.02	0.04	0.02	2.40	5.49	2.49
KU101607	10.16.07	U	0.08	5.58	2.45	1.11	0.01	0.01	0.00	--	--	--
KD101607	10.16.07	D	0.08	5.46	2.40	1.09	0.01	0.00	0.00	--	--	--
KU110107	11.01.07	U	0.08	5.58	2.45	1.11	0.01	0.01	0.00	--	--	--
KD110107	11.01.07	D	0.08	5.55	2.44	1.11	0.01	0.00	0.00	--	--	--
KU111807	11.18.07	U	0.11	5.54	3.43	1.55	0.04	0.02	0.01	--	--	--
KD111807	11.18.07	D	0.11	5.12	3.17	1.44	0.01	0.01	0.00	--	--	--
KU120107	12.01.07	U	0.03	4.60	0.71	0.32	0.03	0.00	0.00	--	--	--
KD120107	12.01.07	D	0.03	4.31	0.67	0.30	0.02	0.00	0.00	--	--	--
KU121907	12.19.07	U	0.06	4.90	1.55	0.70	0.02	0.01	0.00	--	--	--
KD121907	12.19.07	D	0.06	4.32	1.37	0.62	0.01	0.00	0.00	--	--	--
KU010208	01.03.08	U	0.04	5.35	1.15	0.52	0.01	0.00	0.00	--	--	--
KD010208	01.03.08	D	0.04	4.87	1.05	0.47	0.01	0.00	0.00	--	--	--
KU011608	01.16.08	U	0.55	4.12	12.11	5.49	0.00	0.01	0.01	2.40	7.05	3.20
KD011608	01.16.08	D	0.55	3.76	11.05	5.01	0.01	0.02	0.01	7.00	20.56	9.33
KU012808	01.28.08	U	0.07	4.40	1.68	0.76	0.02	0.01	0.00	2.40	0.92	0.42
KD012808	01.28.08	D	0.07	4.39	1.68	0.76	0.00	0.00	0.00	2.40	0.92	0.42
KU021408	02.14.08	U	0.07	4.79	1.83	0.83	0.01	0.00	0.00	2.40	0.92	0.42
KD021408	02.14.08	D	0.07	4.06	1.55	0.70	0.00	0.00	0.00	2.40	0.92	0.42
KU022608	02.26.08	U	0.06	3.97	1.34	0.61	0.08	0.03	0.01	2.40	0.81	0.37
KD022608	02.26.08	D	0.06	3.14	1.06	0.48	0.12	0.04	0.02	2.40	0.81	0.37
KU031008	03.10.08	U	0.09	4.00	1.95	0.89	0.04	0.02	0.01	2.40	1.17	0.53
KD031008	03.10.08	D	0.09	3.53	1.72	0.78	0.10	0.05	0.02	2.40	1.17	0.53
KU032408	03.24.08	U	0.08	4.02	1.77	0.80	0.02	0.01	0.00	2.40	1.05	0.48

Sample Number	Sample Date	Loc.	Q (cfs)	NO3+2 (mg/L)	nitrate-N Load (lbs/day)	nitrate-N Load (kg/day)	NH_4 (mg/L)	ammonia-N Load (lbs/day)	ammonia-N Load (kg/day)	TSS (mg/L)	TSS Load (lbs/day)	TSS Load (kg/d)
KD032408	03.24.08	D	0.08	3.58	1.57	0.71	0.01	0.01	0.00	2.40	1.05	0.48
KU032408X	03.24.08	U	0.08	3.99	1.75	0.79	0.04	0.02	0.01	--	--	--
KD032408X	03.24.08	D	0.08	3.65	1.60	0.73	0.03	0.01	0.01	--	--	--
KU040708	04.07.08	U	0.11	3.14	1.94	0.88	0.02	0.01	0.01	2.40	1.48	0.67
KD040708	04.07.08	D	0.11	2.80	1.73	0.79	0.02	0.01	0.00	2.40	1.48	0.67
KU042308	04.23.08	U	0.08	3.32	1.44	0.65	0.02	0.01	0.00	2.40	1.04	0.47
KD042308	04.23.08	D	0.08	2.76	1.19	0.54	0.01	0.01	0.00	2.40	1.04	0.47
WU101607	10.16.07	U	0.08	0.20	0.08	0.04	0.32	0.13	0.06	--	--	--
WD101607	10.16.07	D	0.08	0.27	0.11	0.05	0.13	0.06	0.03	--	--	--
WU110107	11.01.07	U	0.12	0.40	0.25	0.11	0.30	0.19	0.08	--	--	--
WD110107	11.01.07	D	0.12	0.41	0.25	0.12	0.13	0.08	0.04	--	--	--
WU111607	11.16.07	U	0.12	0.29	0.19	0.09	0.09	0.06	0.03	--	--	--
WD111607	11.16.07	D	0.12	0.24	0.16	0.07	0.04	0.03	0.01	--	--	--
WU113007	11.30.07	U	0.10	0.27	0.15	0.07	0.13	0.07	0.03	--	--	--
WD113007	11.30.07	D	0.10	0.10	0.05	0.02	0.07	0.04	0.02	--	--	--
WU121907	12.19.07	U	0.13	0.76	0.54	0.24	0.20	0.14	0.06	--	--	--
WD121907	12.19.07	D	0.13	0.43	0.30	0.14	0.13	0.09	0.04	--	--	--
WU010208	01.03.08	U	0.15	0.67	0.53	0.24	0.19	0.15	0.07	--	--	--
WD010208	01.03.08	D	0.15	0.33	0.26	0.12	0.10	0.08	0.04	--	--	--
WU011608	01.16.08	U	0.11	1.06	0.62	0.28	0.26	0.15	0.07	10.00	5.86	2.66
WD011608	01.16.08	D	0.11	0.43	0.25	0.11	0.17	0.10	0.05	2.40	1.41	0.64
WU012808	01.28.08	U	0.12	0.80	0.51	0.23	0.20	0.12	0.06	9.00	5.70	2.59
WD012808	01.28.08	D	0.12	0.67	0.43	0.19	0.22	0.14	0.06	5.70	3.61	1.64
WU021408	02.14.08	U	0.58	0.41	1.27	0.58	0.12	0.37	0.17	14.10	44.10	20.00
WD021408	02.14.08	D	0.58	0.36	1.13	0.51	0.13	0.42	0.19	11.90	37.22	16.88
WU022608	02.26.08	U	0.14	0.64	0.47	0.21	0.15	0.11	0.05	18.00	13.26	6.01
WD022608	02.26.08	D	0.14	0.45	0.33	0.15	0.12	0.09	0.04	10.80	7.95	3.61
WU031008	03.10.08	U	0.18	0.43	0.42	0.19	0.11	0.11	0.05	20.00	19.50	8.84
WD031008	03.10.08	D	0.18	0.27	0.26	0.12	0.06	0.06	0.03	18.80	18.33	8.31
WU032408	03.24.08	U	0.15	0.43	0.36	0.16	0.16	0.13	0.06	12.80	10.65	4.83
WD032408	03.24.08	D	0.15	0.24	0.20	0.09	0.08	0.07	0.03	5.60	4.66	2.11
WU032408X	03.24.08	U	0.15	0.43	0.35	0.16	0.13	0.11	0.05	--	--	--
WD032408X	03.24.08	D	0.15	0.23	0.19	0.09	0.08	0.07	0.03	--	--	--
WU040708	04.07.08	U	0.18	0.26	0.25	0.11	0.05	0.04	0.02	10.40	10.01	4.54
WD040708	04.07.08	D	0.18	0.15	0.14	0.06	0.07	0.06	0.03	10.80	10.40	4.72
WU042308	04.23.08	U	0.22	0.13	0.15	0.07	0.09	0.11	0.05	13.60	15.87	7.20
WD042308	04.23.08	D	0.22	0.08	0.10	0.04	0.10	0.11	0.05	8.80	10.27	4.66
				NO3+2 (mg/L)	**nitrate-N Load (lbs/day)**	**nitrate-N Load (kg/day)**	**NH_4 (mg/L)**	**ammonia-N Load (lbs/day)**	**ammonia-N Load (kg/day)**	**TSS (mg/L)**	**TSS Load (lbs/day)**	**TSS Load (kg/day)**
Average Concentration/Pollutant Loads (Stony Run):				**2.96**	**8.61**	**3.90**	**0.05**	**0.20**	**0.09**	**4.19**	**22.62**	**10.26**
Average Concentration/Pollutant Loads (Kingstowne):				**4.29**	**2.39**	**1.09**	**0.02**	**0.01**	**0.00**	**2.69**	**2.65**	**1.20**
Average Concentration/Pollutant Loads (Wilelinor):				**0.39**	**0.34**	**0.16**	**0.14**	**0.12**	**0.05**	**11.42**	**13.67**	**6.20**

Notes:

1. *Sample identification numbers that begin with SRU = Stony Run Upstream; SRD = Stony Run Downstream; KU = Kingstowne Upstream; KD = Kingstowne Downstream; WU = Wilelinor Upstream; WD = Wilelinor Downstream.*
2. *Sample identification numbers with an 'X' on the end are duplicate samples, collected for quality control/quality assurance.*
3. *Pollutant loads calculated using the following equation: L (load in lbs/day) = concentration (mg/L) * discharge (cfs) * conversion factor (5.39, Michaud 1991).*
4. *Pollutant loads were then converted from lbs/day to the metric equivalent of kg/day (1 pound = 0.45359237 kilogram).*

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