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Hydrologic and Water Quality Assessment of Miller Run

A Study of Bucknell University's Impact

by

Alison C. Schaffer

An Honors Thesis Submitted to the Honors Council

For Honors in Environmental Studies

April 25, 2008

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Abstract

Human development causes degradation of stream ecosystems due to impacts on channel morphology, hydrology, and water quality. Urbanization, the second leading cause of stream impairment, increases the amount of impervious surface cover, thus reducing infiltration and increasing surface runoff of precipitation, which ultimately affects stream hydrologic process and aquatic biodiversity. The main objective of this study was to assess the overall health of Miller Run, a small tributary of the Bull Run and Susquehanna River watersheds, through an integrative hydrologic and water quality approach in order to determine the degree of Bucknell University's impact on the stream. Hydrologic conditions, including stage and discharge, and water quality conditions, including total suspended solids, ion, nutrient, and dissolved metal concentrations, specific conductivity, pH, and temperature, were measured and evaluated at two sampling sites (upstream and downstream of Bucknell's main campus) during various rain events from September 2007 to March 2008. The primary focus of the stream analysis was based on one main rain event on 26 February 2008. The results provided evidence that Miller Run is impacted by Bucknell's campus. From a hydrologic perspective, the stream's hydrograph showed the exact opposite pattern of what would be expected from a 'normal' stream. Miller run had a flashier downstream hydrograph and a broader upstream hydrograph, which was more than likely due to the increased amount of impervious surface cover throughout the downstream half of the watershed. From a water quality perspective, sediment loads increased at a faster rate and were significantly higher downstream compared to upstream. These elevated sediment concentrations were probably the combined result of sediment runoff from upstream and downstream construction sites that were being developed over the course of the study. Sodium, chloride, and potassium concentrations, in addition to specific conductivity, also significantly increased downstream of Bucknell's campus due to the runoff of road salts. Calcium and magnesium concentrations did not appear to be impacted by urbanization, although they did demonstrate a significant dilution effect downstream. The downstream site was not directly affected by elevated nitrate concentrations; however, soluble reactive phosphorus concentrations tended to increase downstream and ammonium concentrations significantly peaked partway through the rain event downstream. These patterns suggest that Miller Run may be impacted by nutrient runoff from the golf course, athletic fields, and/or fertilizers applications on the main campus. Dissolved manganese and iron concentrations also appeared to slightly increase downstream, demonstrating the affect of urban runoff from roads and parking lots. pH and temperature both decreased farther downstream, but neither showed a significant impact of urbanization. More studies are necessary to determine how Miller Run responds to changes in season, climate, precipitation intensity, and land-use. This study represents the base-line analysis of Miller Run's current hydrologic and water quality conditions; based on these initial findings, Bucknell should strongly consider modifications to improve storm water management practices and to reduce the campus's overall impact on the stream in order to enhance and preserve the integrity of its natural water resources.

Introduction

Human development causes degradation of stream ecosystems due to impacts on channel morphology, hydrology, and water quality. In some situations, streams in close proximity to human developments are physically altered in order to better suit the desired 'human' environment, including stream channelization, engineered in-stream hydrologic modifications, and installment of storm water pipe lines (EPA(e) 2008). In other cases, the stream channel itself is not physically altered, but human modifications to the surrounding landscape have a significant indirect impact on the stream, including the removal of vegetation and riparian buffers, increased impervious surfaces, and the application of fertilizers and pesticides on agricultural fields and/or manicured lawns. As human development and urbanization continue to increase now and into the future, streams will inevitably feel the amplified impact of our actions unless we willingly take the necessary precautions to maintain and preserve the overall health of our streams. From a watershed perspective, this entails managing all streams within a given watershed as one cohesive ecosystem unit, with just as much emphasis placed on small streams as is placed on larger streams. Thus, local communities, watershed groups, and universities can play an important role in the preservation of their watershed by promoting the appropriate regulations and practices to minimize localized human impacts on surrounding streams.

A Watershed Approach

A watershed is defined as the region of land from which surface and subsurface water drains into a stream (Finlayson et al. 1992). The understanding of watersheds and watershed processes is important because of their hierarchical nature. The Miller Run watershed, which is the focus of my research, is a relatively small watershed located within the Limestone Run (locally known as Bull Run) watershed and part of the West Branch Susquehanna River watershed. Therefore, processes in small watersheds, such as the Miller Run watershed, affect much larger systems, such as Chesapeake Bay watershed, which drains 166,760 square km of land (CBF 2006) because they are linked as one interconnected hydrologic system.

Since the creation of the Clean Water Act in 1972, government agencies, along with private organizations and local citizen groups, have come together to assess, protect, and restore river and stream health using a watershed approach (EPA(b) 2007). Ideally, by working at a watershed level, hydrology and water quality issues downstream can be mitigated by addressing the root of problems upstream.

Stream Health: An Integrative Approach

The overall “health”, or integrity of a stream, is influenced by hydrologic conditions, chemical variables, biotic factors, habitat structure, and energy sources, all of which interact with one another to create a tremendously complex ecosystem (USDA 1998). If one stream characteristic or process is altered, then the entire ecosystem may be affected.

Scientists study stream ecosystems and health by conducting hydrology and water quality assessments. Stream hydrology focuses on the "interrelationships and interactions between water and its environment in the hydrological cycle" using predictive and analytical methodologies (Finlayson et al. 1992). It pertains to the physical aspects of water movement within a stream including channel morphology, discharge, velocity, sediment load, and flooding (Finlayson et al. 1992). Hydrologic conditions vary among streams depending on a number of watershed variables including topography, soil type, climate, biotic community, human disturbances, and time. On the other hand, water quality focuses on the ecological conditions of a stream, which examine "interrelationships between organisms and their environment and with each other" using descriptive and experimental methodologies (Finlayson et al. 1992). Water quality assessment consists of five main categories of data including biological integrity, chemical properties, physical properties, habitat, and toxicity (EPA(a) 2006). Both perspectives provide valuable insights to stream integrity; however, neither approach tells the entire story. An integrated, interdisciplinary approach combining both perspectives is critical to understand a stream's complex interactions with its biotic and abiotic elements as well as to assess its overall health (Finlayson et al. 1992).

The Built Environment and its Effect on Streams

As of 2000, over 130,000 km of streams and rivers in the United States were designated “impaired” due to urbanization, which is the second leading cause of impairment, with agriculture being the first (Paul & Meyer 2001). Land development significantly affects hydrologic processes. Urban environments have more impervious surface cover and, therefore, lower infiltration and increased surface runoff of precipitation. This affects stream hydrology by reducing time from the start of storm to peak discharge, increasing peak discharge, increasing the frequency of flash floods, reducing groundwater recharge capacity, and reducing base flow in urban streams (see review by Paul & Meyer 2001). From a water quality perspective, urbanization may result in altered sediment loads; increased water temperature, oxygen demand, and specific conductivity; increased chemical substance concentrations including dissolved ions, nutrients, metals, and pesticides; increased degradation of aquatic habitats; and decreased aquatic biodiversity and density of organisms (see review by Paul & Meyer 2001).

Management

Until recently, local governments, scientists, and engineers have primarily managed stream systems in the built environment for either human purposes (e.g., to transport storm water runoff) or to prevent catastrophic damages (e.g., loss of infrastructure or property through erosion). Both of these stream management goals focus almost entirely on the physical hydrologic processes in stream channels, affording little consideration for stability and overall ecological health of the stream as an ecosystem. In order to create a more suitable environment for biota and maintain ecological services of a stream (e.g., flood mitigation, surface runoff filtration, improved water quality), an integrated ecological and hydrologic approach must be taken for storm water management and stream restoration plans. The first step towards taking this interdisciplinary approach is to assess current hydrologic and water quality conditions of the stream, which was the primary objective of my research.

Objectives

Miller Run is a relatively small stream that flows through Bucknell University's campus in Lewisburg, Pennsylvania. Viewing Miller Run as both a 'natural' stream ecosystem and as a part of Bucknell University's campus, I was interested in exploring the effect of the built environment ('urbanization') on the stream. Institutions of higher education, such as Bucknell, have the responsibility and opportunity to manage their own campuses in order to promote environmental stewardship and sustainability by minimizing their ecological footprints and setting positive examples for outside communities. Thus, the main objective of this thesis research was to assess the overall health of Miller Run through an integrative hydrologic and ecological approach in order to determine the degree of Bucknell's impact on the stream. More specifically, the stream's hydrologic and water quality conditions were analyzed at two sites during various rain events in order to compare conditions upstream and downstream of Bucknell's campus. Miller Run was predicted to exhibit hydrologic and water quality conditions typical of urban streams, particularly downstream of Bucknell's campus, due to the highly modified nature of the stream itself and its surrounding landscape. Furthermore, the downstream section of the stream was predicted to demonstrate characteristics of a 'flashy' stream system, with narrow, peaked hydrographs rising and falling quickly during rain events. Significant increases in ion, nutrient, and dissolved metal concentrations, as well as increases in temperature and specific conductivity were also predicted between the upstream and downstream reaches of the stream during rain events. The broader goal of this initial assessment of Miller Run is to collect hydrologic and water quality data as a baseline for future studies and to inform future stream restoration and storm water management practices.

Miller Run Sub-watershed

This study focused on the Miller Run sub-watershed located in the south-eastern portion of Union County in Lewisburg, Pennsylvania (UCPC 2002) (Figure 1). This

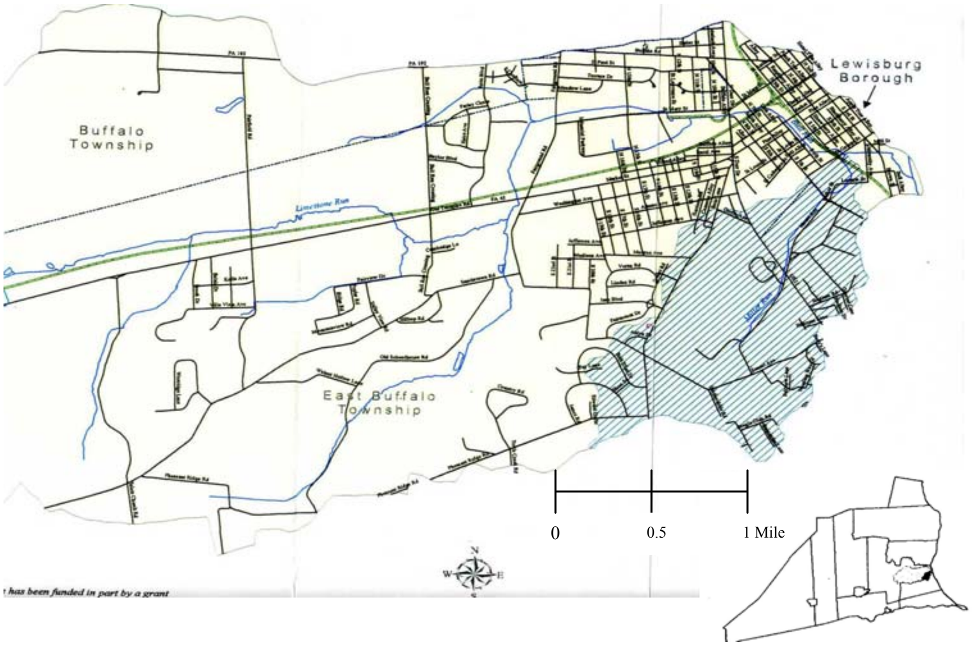

Figure 1: Map of the Bull Run and Miller Run watersheds in Union County, Lewisburg, Pennsylvania (UCPC 2002). The Miller Run watershed is represented by crosshatching.

small watershed is part of the larger Limestone Run watershed, which drains approximately 21.76 square km of land, and the West Branch Susquehanna River watershed, which drains approximately 18,109 square km in Pennsylvania (SRBC 2006).

The underlying geology of the Miller Run watershed is primarily the Silurian formation, including the Wills Creek and Bloomsburg formations; the Limestone Run watershed includes the Tonoloway and Keyser formations as well (BU Geology 2008, UCPC 2002) (Figure 2). The Wills Creek formation, characterized by "gray calcareous shale with interbedded light gray, calcareous, fine grained sandstone, limestone and red silty claystone", underlies the northern half of the watershed; the Bloomsburg formation, characterized as "red claystone shale with fine grained, argillaceous, hematitic sandstone at base and near top", underlies the southern half of the watershed that is non-limestone based (BU Geology 2008). The soils within the watershed are separated into two distinct hydrologic soil groups, which influence the volume and rate of storm water runoff (UCPC 2002). Soils in the northern half of the watershed are defined as having "moderate rate of infiltration when wetted and consisting chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse texture" (UCPC 2002). The soils in the lower portion of the watershed, including the headwaters of Miller Run, are defined as "soils having a slow rate of infiltration when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water or soils with moderately fine to fine textures" (UCPC 2002). The underlying geology and hydrologic features of the soil are likely to affect surface runoff rates, vegetation types, streambed materials, and water chemistry (Finlayson et al. 1992).

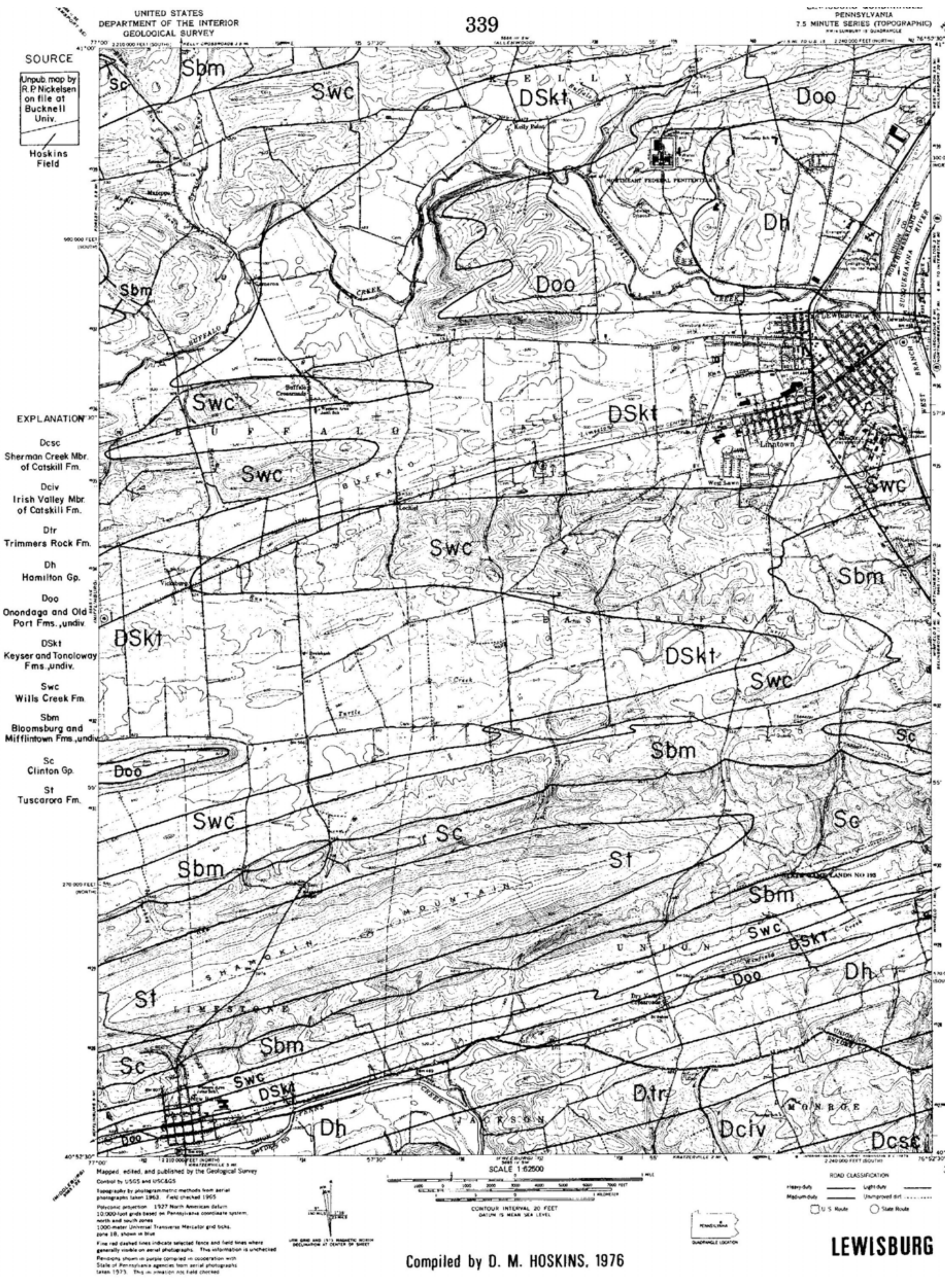

Figure 2: Geologic map of Lewisburg, Pennsylvania (USGS 1976).

By understanding these various features, it is possible to trace specific sediments in the water column (total suspended solids) to their source, thus providing a clearer picture of the sediment composition in runoff and where erosion takes place within the watershed. In addition, understanding the hydrologic features of these particular soils may be useful when developing a revised storm water management plan in the future. For example, soils with a slow to moderately slow infiltration rate will produce a moderately high rate of storm water runoff; therefore, creating retention ponds around the stream may be more beneficial for slowing storm water than relying on increased infiltration strategies.

According to the Union County Planning Commission, the majority of land within the Miller Run watershed is characterized as open space or institutional land (owned by Bucknell University), with a few residential and forested areas (Figure 3). It is important

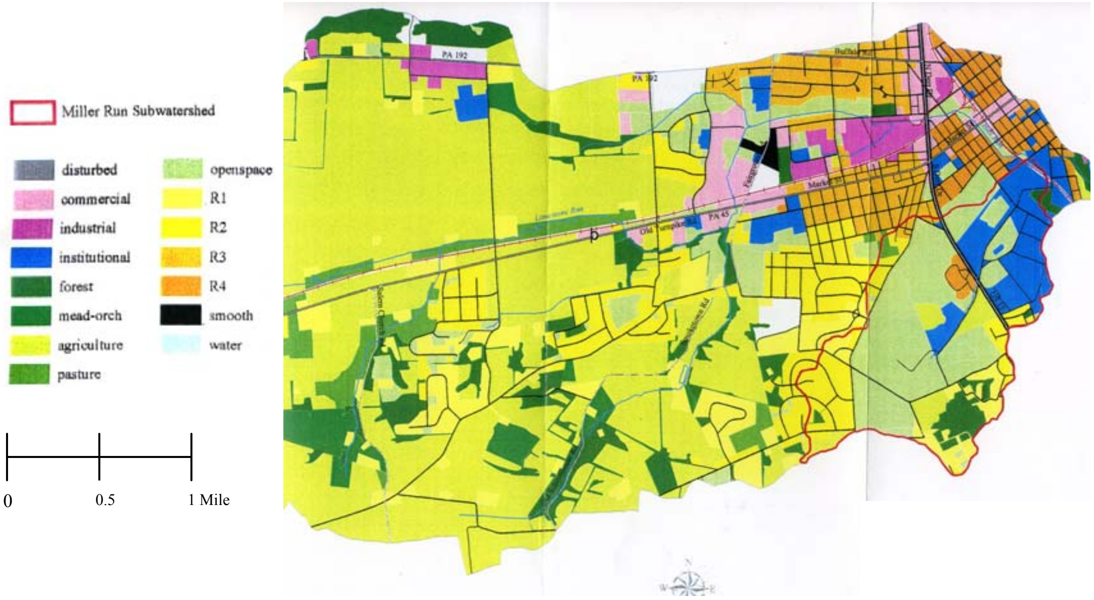

Figure 3: Current land uses within the Bull Run and Miller Run watersheds (UCPC 2002).

to note that during my study, from late November 2007 to March 2008, a large area of open space in the southern portion of the Miller Run watershed was being developed by Herbert, Rowland & Grubic Inc. (HRG) for residential homes. This development site had a noticeable impact on the stream's water quality conditions.

Miller Run: The Stream

Miller Run's headwaters originate from an underground aquifer underlying the upper half of the watershed on Bucknell property (specifically within the Bucknell Golf Course). The stream flows in a general north-east direction, passing through the Bucknell Golf Course, under U.S. Highway 15, through Bucknell's main campus, and into a culvert where it converges with Limestone Run before emptying into the West Branch of the Susquehanna River. The total length of the perennial surface stream is approximately 1.2 km. Miller Run also has a small tributary, which flows through the northern portion of the golf course and connects to the main branch just east of U.S. Highway 15. This tributary drains a portion of the golf course and Bucknell athletic fields during runoff events.

The stream currently demonstrates characteristics of an 'intermittent' stream, meaning that it flows during certain times of the year when it receives water from its spring sources and/or runoff. Miller Run can either be influent (a 'losing' stream that feeds the groundwater, and therefore decreases in surface discharge as it flows downstream) or effluent (a 'gaining' stream that receives water from groundwater), depending on the season (Finlayson et al. 1992). There is some evidence (as seen on older U.S. Geological Survey topographic maps that represent Miller Run by solid blue lines to symbolize perennial streams) that Miller Run may have at one time been a perennial stream or predominantly effluent, flowing year-round; however, this has not been the case over the last several very dry years (personal communication with Craig Kochel).

Miller Run’s stream channel is characterized as an ‘alluvial channel’ because its dimensions, shape, and gradient are predominately controlled by stream flow (Finlayson et al. 1992). Furthermore, the stream channel does not appear to be stable; rather, it is degrading into the bed materials and many of its banks are vertical to steep shaped, providing evidence of bank erosion (Finlayson et al. 1992). Over time, the stream channel has been physically modified by Bucknell University. Such changes include bank mobilization with the use of rip-rap (most of which has been transported to the streambed) along some of the stream’s highly erodable banks, stream channelization along the Sojka lawns, flow redirection through culverts under U.S. Highway 15, and the use of storm water pipe lines, which collect storm water from all over campus and transfer it directly

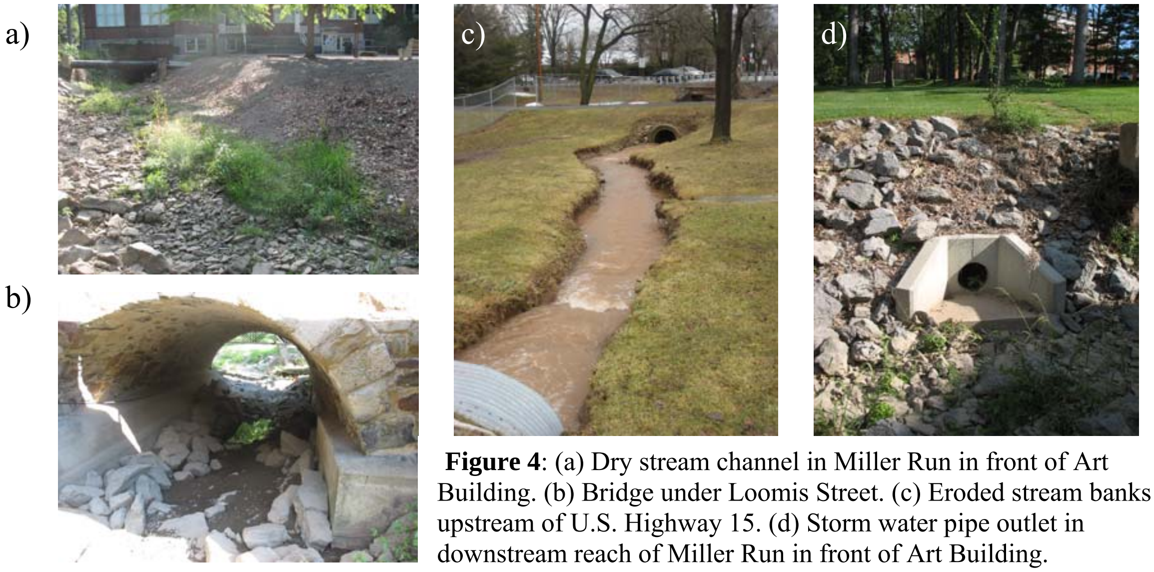

Figure 4: (a) Dry stream channel in Miller Run in front of Art Building. (b) Bridge under Loomis Street. (c) Eroded stream banks upstream of U.S. Highway 15. (d) Storm water pipe outlet in downstream reach of Miller Run in front of Art Building.

into the channel (Figure 4). Upstream, the stream's bed materials consist of transported, unconsolidated sediments; downstream, the bed materials consist of 'non-native' rocks, most of which have been transported from the rip rap along the banks to the stream bed floor (personal communication with Craig Kochel).

There is limited natural vegetation immediately surrounding the stream; rather it is mainly bordered by grassy fields, including the golf course, Sojka lawn, and the Grove; roads and side walks, including U.S. Highway 15, Moore Avenue, 7th Street, and Loomis Street; and parking lots, including those for the Fieldhouse, Langone Center, Smith Hall, and Hunt Hall.

For this study, two sampling sites were selected—one located upstream and the

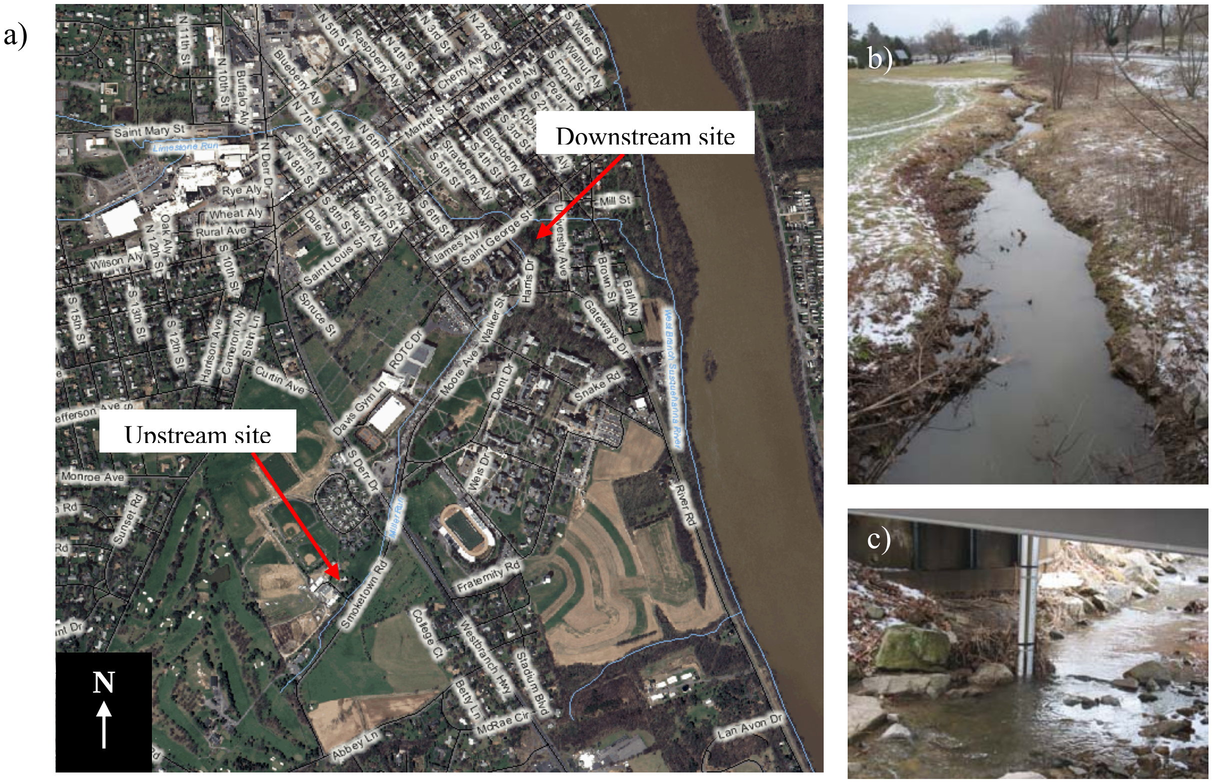

Figure 5: (a) Map of Miller Run and sampling site locations. (b) Upstream sampling site by Art Barn. (c) Stage marker and gauge at downstream sampling site behind Hunt Hall parking lot.

other downstream of Bucknell's main campus (Figure 5). The upstream site was located west of U.S. Highway 15, immediately downstream of the bridge leading to the Art Barn. This particular site was chosen because it is upstream of the University's main campus, and therefore, was not expected to be impacted by the main campus. However, this site is positioned downstream of the Bucknell Golf Course; therefore, I expected it to have some impact by the golf course and its few surrounding roads (mainly Smoketown Road).

The downstream site was located adjacent to Hunt Hall parking lot, downstream of Loomis Street, immediately downstream of the footbridge to Bucknell Hall. This particular site was selected because it is located along the last few meters of the stream before it converges with Limestone Run and empties into the Susquehanna River; therefore, it was expected to be impacted by Bucknell University's entire campus, particularly during runoff events.

Methodology

Hydrologic and water quality conditions of Miller Run were studied from late September 2007 to mid-March 2008. Prior to this period, the stream channel was dry due to unusually dry summer conditions and the stream's ephemeral nature. There were only about 4.31 inches of rain from June 1 to September 26 (27 September 2007 was the first rain event included in the study). Meteorological information for the Miller Run watershed was monitored using the Bucknell weather station (BUWX) located in the center of the watershed, between the golf course and Art Barn.

Sampling began on 27 September 2007 with the onset of a large rain event, prior to the installment of a stage monitoring station at the downstream site (installed 26 October 2007). Although this rain event supplied enough water to the stream for sampling purposes, it did not provide sufficient ground saturation to produce a constant, steady base flow. The stream remained dry until 9 December 2007; from that day forward, the stream maintained a continual base flow until the end of my study in late March 2008.

Assessment of Miller Run's stream conditions was broken down into two major components: hydrologic conditions and water quality conditions. For the purpose of this study, a single rain event on 26 February 2008 was the main focus. A "rain event" referred to any time rain produced a visual increase in stage. The "duration" of a rain event was time from when rain began to when stream stage returned to base flow. During the 26 Feb 2008 rain event, two teams of people, one located at each sampling site, simultaneously collected water samples and stage measurements every fifteen minutes from the start of the rain event (at 10:00 AM) to the time the rain stopped (at 5:30 PM). In addition, both teams measured discharge every thirty minutes. After seven hours and thirty minutes of systematic sampling, samples were collected and stage measurements were recorded about every thirty minutes until 11 PM. This particular sampling methodology was selected in order to more precisely capture the patterns of total suspended solid, ion, nutrient, and dissolved metal concentrations with time, site location, and stage during a rain event.

In addition to sampling the 26 February 2008 rain event, various other rain events were sampled from September 2007 to March 2008, primarily to obtain a wide range of discharge measurements at both sites for the creation of rating curves. Furthermore, base flow measurements were collected as a basis of comparison in order to determine how the hydrologic and water quality conditions were affected by runoff from rain events.

Hydrologic Conditions

The hydrologic conditions of Miller Run were assessed by measuring stage and discharge during base flow and rain events. Stage was measured using stage markers attached to the culvert under the entrance to the Art Barn at the upstream site, and anchored in the streambed at the downstream site. Stage was manually recorded each time a water sample was collected. At the downstream sampling site, an automated stage data logger recorded stage measurements every fifteen minutes throughout the entire study period. Manual stage recordings and results from the gauge were used to create detailed hydrographs of the upstream and downstream sites.

Discharge was measured using a sectional approach in which the sum of the discharge of ‘blocks’ of water was calculated (Finlayson et al. 1992). The discharge of ‘blocks’ of water were determined using a constant width, measured depth, and velocity from the center of each block (see equation below and Figure 6). Each block was approximately 0.2 m in width. Velocity was measured using a Marsh-McBirney digital flow meter at constant relative depth (0.6 x total depth). Discharge measurements were much easier to obtain, and therefore much more accurate, during base flow conditions as compared to rain events because stream depth, velocity, and total width may change while taking measurements due to rain. Thus, discharge measurements made during rain events, particularly at high flow, may exhibit a high degree of variability.

Equation for discharge:

$Q_{\text{total}} = \sum Q_{\text{block}}$, where Q_{total} = total discharge in m^3/s

$Q_{\text{block}} = d*w*v$, where Q_{block} = discharge of a block of water in m^3/s; d= depth of the water block in meters, w= width of the water block in meters, and v= velocity measured from the center of the water block in m/s.

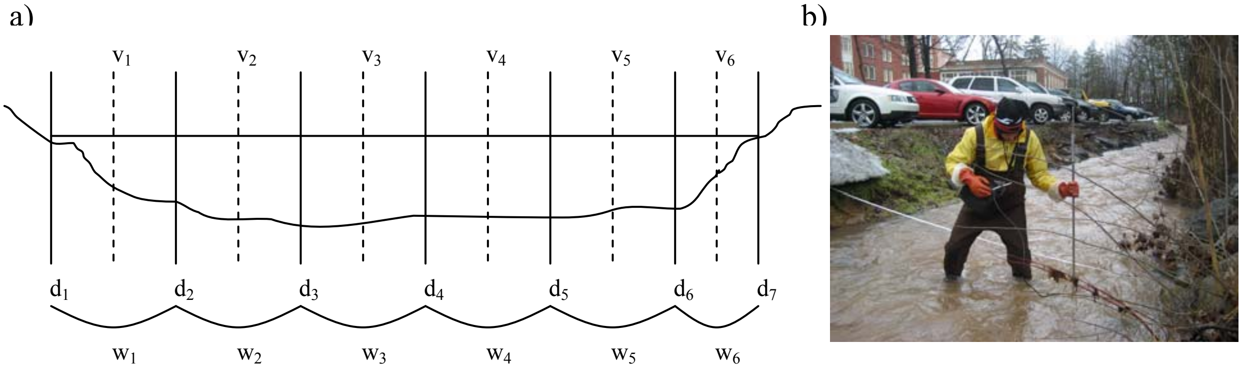

Figure 6: (a) Diagram of stream discharge measurement using sectional approach (d = depth in m, v = velocity in m^3/s, w = width in m). (b) Picture of Alison taking discharge measurements at downstream site.

Stage and discharge measurements were used to generate rating curves of stage vs. discharge for both the upstream and downstream sites. Once these graphs were fully developed, they were used to determine discharge measurements from stage readings alone (Finlayson et al. 1992).

Water Quality Conditions

Total Suspended Solids

Total suspended solids (TSS) were measured by collecting water samples from mid-channel in the thalweg, sampling throughout the entire water column. Once collected, samples were filtered using pre-weighed 47 mm glass filters (1.0 µm mesh size), dried for 48 hours in a desiccator, and weighed. TSS (in ppm) was calculated using the following equation:

$$TSS = \left(\frac{(filter1 - filter2)}{(bottle1 - bottle2)} \right) \times 1000000$$

, where $filter1$ = mass of filter with sediment (g), $filter2$ = mass of clean filter without sediment (g), $bottle1$ = mass of sampling bottle with water (g), and $bottle2$ = mass of dry sampling bottle without water (Johnson 1997).

Water Chemistry

Water chemistry analysis involved measuring ion, phosphorus, and dissolved metal concentrations from water samples in addition to measuring specific conductivity, pH, and temperature. Samples were collected from mid-channel in the thalweg. Once collected, all samples were initially filtered using 25 mm glass microfiber filters (0.7 µm mesh size). Ion chromatography was used to measure cation (sodium, potassium, magnesium, calcium, and ammonium) and anion (chloride, nitrate, and sulfate) concentrations. Metals samples were collected the same way but were acidified to pH ~ 2 with concentrated nitric acid. Dissolved manganese and iron were measured using ion-coupled plasma spectrometry (ICP). Five standards were run at the start of the analysis and several were repeated throughout the sample batch in order to assess instrument drift. Due to the large number of samples run in a single batch using the ICP, dissolved metal concentrations tended to drift from the beginning of the batch to the end; therefore, adjustments were made to concentrations to account for this drift, which were used in the final analysis. Additionally, upstream samples from 3-4:30 PM during the 26 Feb 2008 rain event were removed from the results due to possible contamination. Soluble reactive phosphorus (SRP) concentrations were analyzed using a spectrophotometric assay (APHA 1998).

These particular water chemistry components were selected as the focus for this study because of their relative importance to stream ecosystem health and their direct link to urban impact on aquatic ecosystems. Although all of these substances are found naturally in river systems, urbanization can elevate concentrations to unhealthy levels that may harm aquatic life and degrade stream ecosystems (Allan 1995). For example, sodium, chloride, potassium, calcium, magnesium, and sulfate are all naturally occurring ions associated with the weathering of rock and rain water; however, inputs of road salts, fertilizers, domestic sewage, and other pollutants from urban landscapes can also contribute to elevated concentrations that may be detrimental to stream health (Allan 1995). Similarly, nitrogen (as nitrate and ammonium) and phosphorus are important potentially limiting nutrients in aquatic ecosystems that are essential for plant and algal growth; however, excess nutrients from agricultural or urban runoff can have a negative impact on stream ecosystems by accelerating eutrophication and depleting dissolved oxygen concentrations. The presence of several heavy metals in the water column and stream sediments, including lead, zinc, chromium, copper, manganese, nickel, cadmium, arsenic, iron, boron, and cobalt, has also been linked to the impacts of urbanization (Paul & Meyer 2001). In this study, dissolved manganese and iron concentrations were specifically selected for analysis because of their connection to urban pollutants found on roads and parking lots primarily from cars.

Temperature, specific conductivity, and pH were monitored continuously at each sampling site during the 26 February 2008 rain event using YSI 600XML data loggers programmed to record variables every 15 minutes. Data loggers were anchored to the stream bed and recorded these parameters for eight days (specifically from 21-28 February 2008) to cover the 26 Feb 2008 event and base flow conditions.

Results

Downstream and Upstream Rain Events

Over the course the study, 23.20 inches of rain fell over the Miller Run watershed (from 27 Sept 07 to 30 Mar 08), but the monthly amount varied from 2.31 inches in January to 5.57 inches in March (Figure 7, Table 1). Seven rain events were sampled at the downstream site starting in late October, and five rain events were sampled at the

Table 1: Sampling dates, amount of monthly rainfall, and average monthly stage of Miller Run from 2007-2008.

Month	Sampling Date(s)	Monthly Rainfall (inches)	Average Monthly Stage (ft)
October* (1-3s1 Oct)	26-28 Oct	3.96	0.22
November (1-30 Nov)	13-15 Nov	3.39	0.32
December (1-31 Dec)	**2 Dec**	2.97	0.52
January (1-31 Jan)	**24-28 Jan****	2.31	0.52
February (1-29 Feb)	**1-6 Feb; 19-26 Feb**	4.95	0.67
March (1- 30 Mar)	**4-5 Mar;7-11 Mar**	5.57	0.69

*The stage gauge was installed at the downstream site behind the Hunt Hall parking lot on 26 October 2007.

**Samples taken during base flow (non-rain event)

Bold indicates sampling at both the upstream and downstream sites.

upstream site starting in early December (Table 1). Peaks in the hydrograph represent high flows during rain events (Figure 8). A stage of 0 ft indicates that the stream was dry when there was no rain, suggesting that the downstream reach of the stream was not being continually fed by groundwater. Average stage during base flow conditions for the downstream site ranged from 0 ft in October to about 0.6 ft in February. The hydrograph for the 26 Feb 08 rain event at the upstream site had to be constructed manually since a stage gauge was not installed at this site. Unlike the downstream site, which was dry up until 9 Dec 07, the upstream site maintained visible flowing water from at least 2 Dec 07 to 30 March 08. The upstream site was not as affected by the dry climatic conditions as

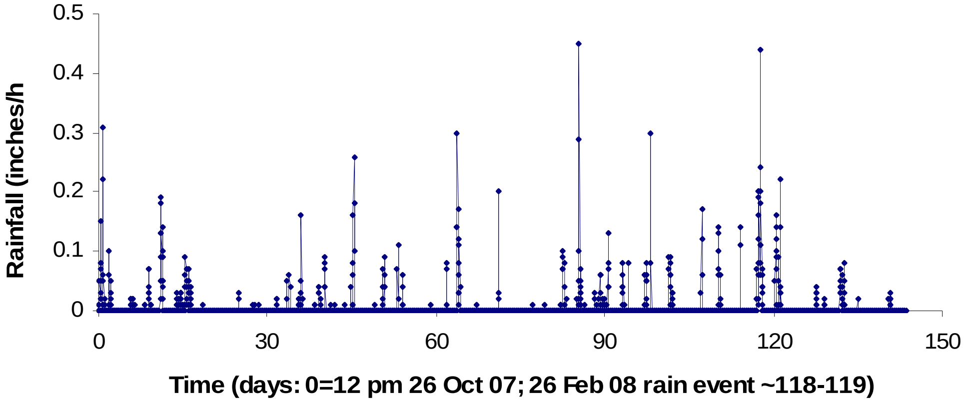

Figure 7: Rainfall in the Miller Run watershed (Lewisburg, Pennsylvania) from 26 Oct 2007 to 30 Mar 2008. The 26 Feb 2008 rain event is located at 118-119 days. Data collected by the BUWX.

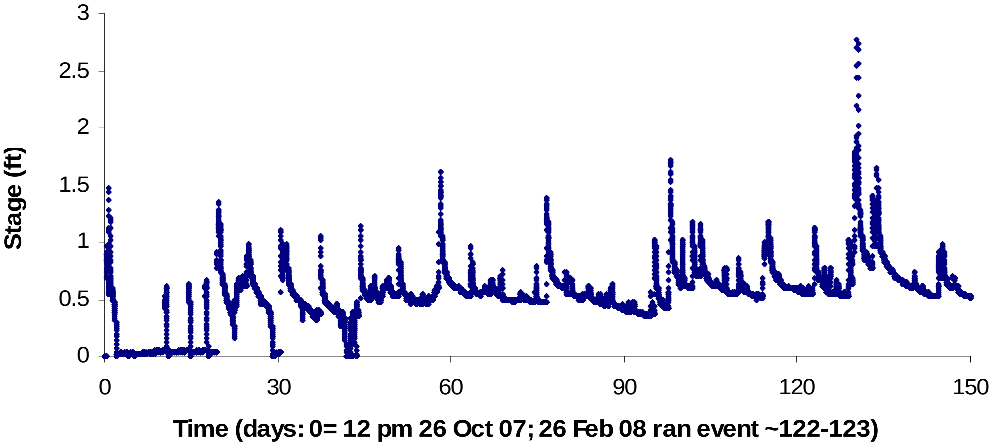

Figure 8: Hydrograph of the downstream site from 26 Oct 2007 to 30 Mar 2008 in days after the stage gauge installation on 26 Oct 2007. The 26 Feb 2008 rain event is located at 122-123 days.

the downstream site partly because of its close proximity to the stream's source. Average stage during base flow conditions for the upstream site in February and March was approximately 0.6 ft.

Hydrologic Conditions

Discharge

Discharge measurements collected during each rain event were used to construct rating curves and rating tables of stage vs. discharge for the upstream and downstream sites (Figure 9). As discharge increased, stage increased at a decreasing rate. By comparison, both stage and discharge reached higher maximum values downstream compared to upstream. Both rating curves started to level off when stage reached a certain height—approximately 1.25 ft upstream and 1.7 ft downstream. At this point, discharge increases more by increases in channel width (as water spills out of the original stream channel and onto the flood plain) with little to no change in stage height.

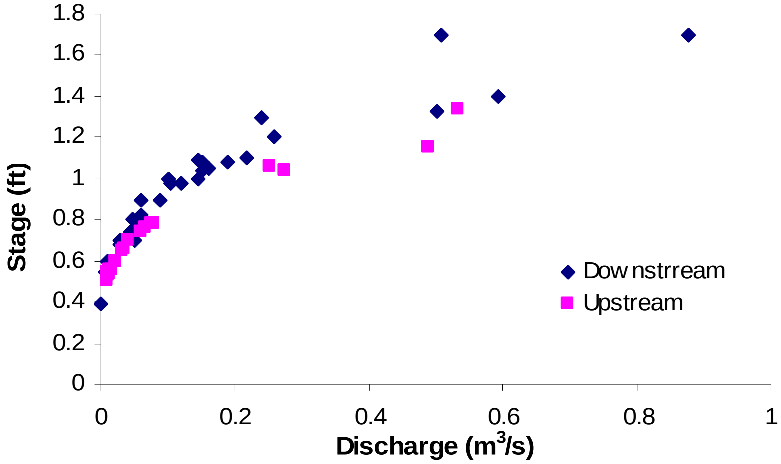

Figure 9: Rating curves for upstream and downstream sites.

Stage: 26 Feb 08 Rain Event

The start of the 26 Feb 08 rain event (at 10:00 AM) was characterized by light rain and sleet. Starting at 10:15 AM, a slow, steady rain persisted for 7.25 h (the rain ended at 5:30 PM), generating 0.59 inches of rain over this period. Stage increased at a faster rate and reached a higher maximum level at the downstream site (peak 1.09 ft, 1.42 ft/h) compared to the upstream site (peak 0.78 ft, 0.05 ft/h) (Figure 10). Comparatively, stage peaked earlier downstream than upstream (5 h and 6.25 h after the start of the rain event, respectively). At both sites, once stage peaked, it gradually decreased over the remainder of the sampling period, with water levels decreasing at a faster rate downstream compared to upstream.

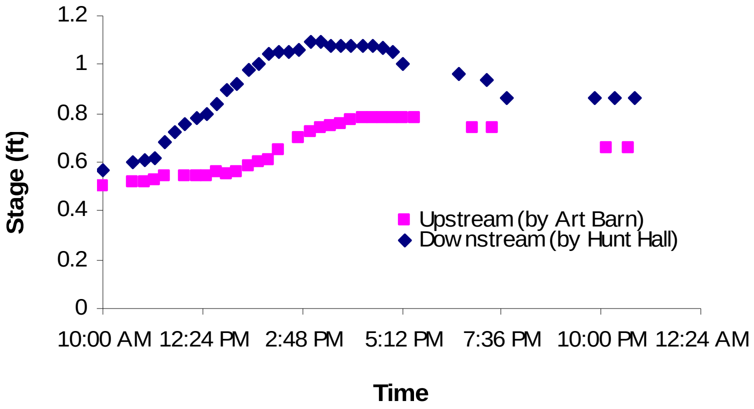

Figure 10: Upstream and downstream comparison of stage over time during 26 Feb 2008 rain event.

Water Quality Conditions: 26 Feb 08 Rain Event

Total Suspended Solids

Total suspended solid (TSS) concentrations were significantly higher at the downstream site compared to the upstream site (t = 6.19; p < 0.001) (Figure 11). In general, TSS concentrations increased during the first half of the rain event then subsequently decreased, at both sites. At the upstream site, concentrations peaked twice, whereas at the downstream site, they appear to have peaked three times. Overall, downstream TSS concentrations increased at a faster rate (88 ppm/h) and peaked earlier than upstream concentrations (18 ppm/h).

When plotted against stage, TSS concentrations peaked before stage reached its maximum height at both sites. Once TSS concentrations peaked, they gradually decreased as stage continued to increase and subsequently decrease. Shown as concentration-discharge hysteresis curves of TSS vs. discharge (Figure 12a), TSS in both upstream and downstream sites increased in concentration with discharge and peaked prior to peak flow. Once discharge started to decrease, TSS concentrations were already significantly lower than they were upon initial ascent, which results in clockwise loops. The hysteresis loop for the upstream site is much smaller than the hysteresis loop for the downstream site, suggesting that TSS concentrations and discharge were lower upstream compared to downstream.

Using data from all rain events (5 rain events at the upstream site and 7 at the

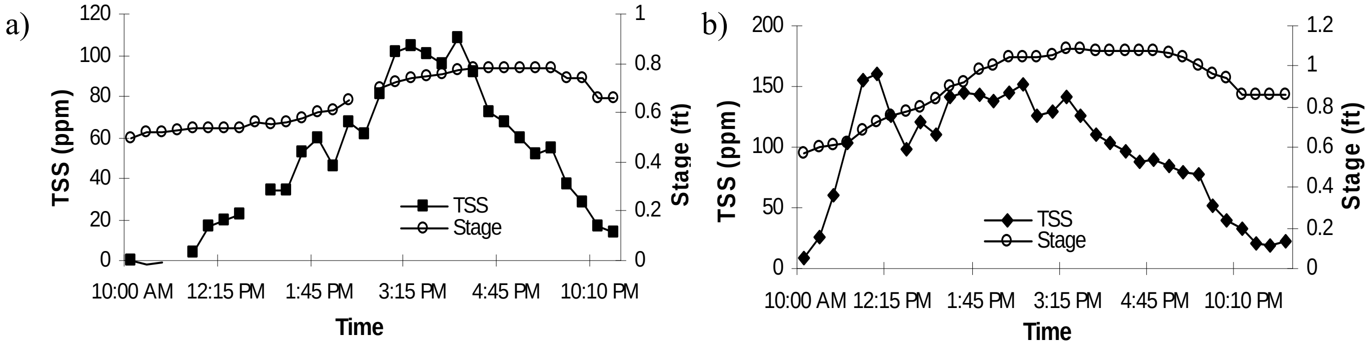

Figure 11: Comparison of stage and TSS concentrations at the (a) upstream site and (b) downstream site during the 26 Feb 2008 rain event.

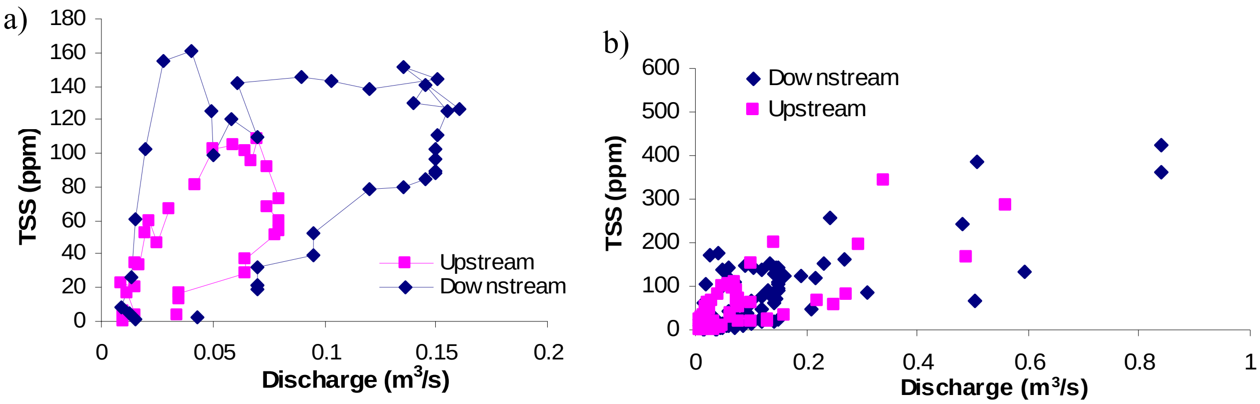

Figure 12: Upstream and downstream hysteresis loops of TSS concentrations vs. discharge for (a) the 26 Feb 2008 rain event and (b) all data (upstream: from 19 Feb – 11 Mar 2008; downstream: from 26 Oct 2007-11 Mar 2008).

downstream site), a graph of TSS vs. discharge was constructed to see if there was an overall relationship across all rain events from October to March. The TSS data formed clockwise positive hysteresis loops for both sites (Figure 12b). In general, the upstream loop appeared to be tighter and smaller than the downstream loop, with a few exceptions of points at high discharge.

Dissolved Ions and Nutrients

Sodium, Chloride, and Potassium

Sodium, chloride, and potassium ion concentrations behaved similarly to each other during the 26 Feb 08 rain event. All three ions had significantly higher concentrations at the downstream site than at the upstream site (paired t-test; sodium: $t = 5.26$, $p < 0.001$; chloride: $t = 4.33$, $p < 0.001$; potassium: $t = 8.65$, $p < 0.001$) (Figure 13). Additionally, all three ions reached peak concentrations at the downstream site before the upstream site.

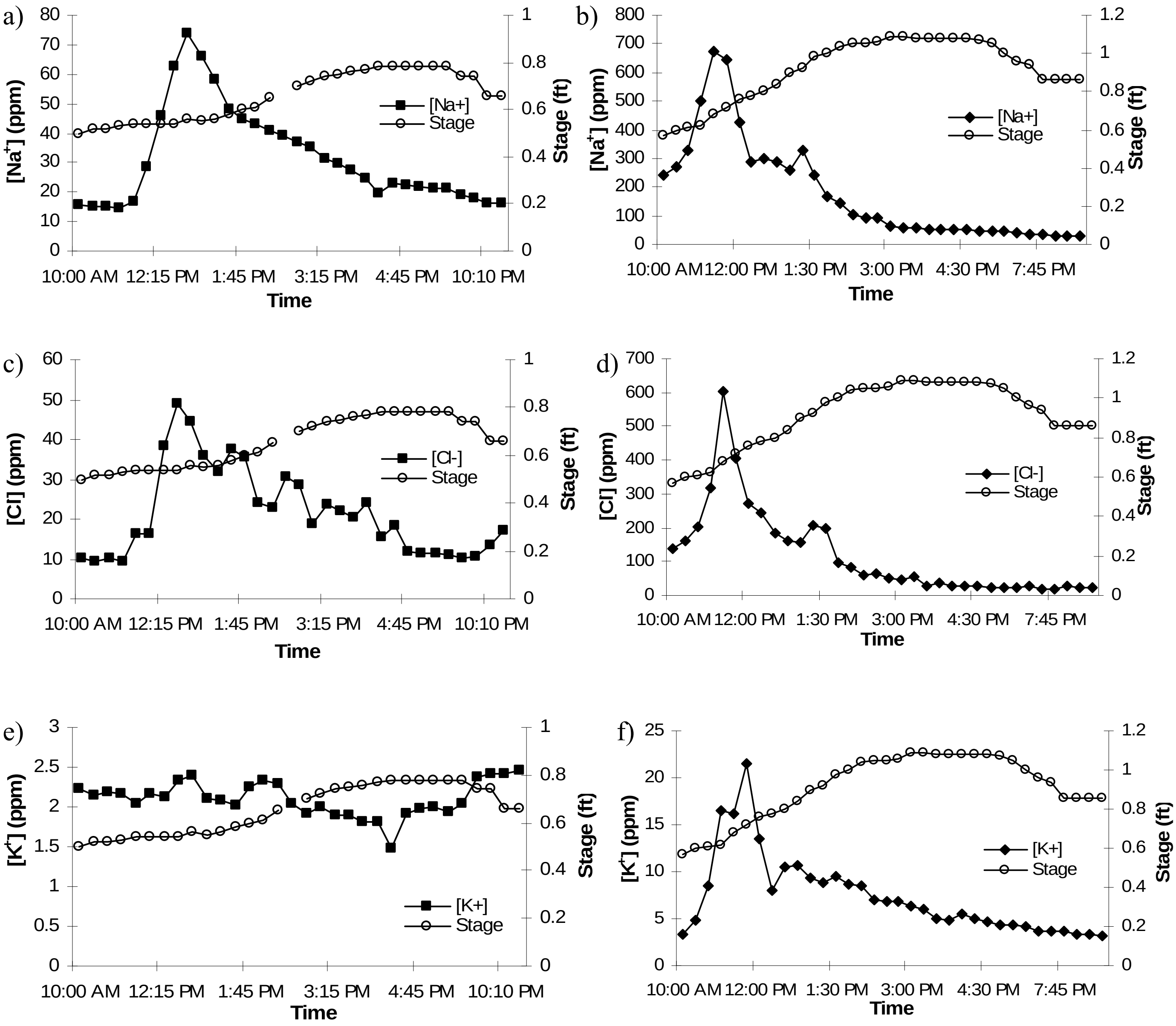

Figure 13: Comparison of stage and concentrations for (a) sodium at the upstream site, (b) sodium at the downstream site, (c) chloride at the upstream site, (d) chloride at the downstream site, (e) potassium at the upstream site, and (f) potassium at the downstream site during the 26 Feb 2008 rain event.

When plotted against stage, sodium, chloride, and potassium concentrations all peaked well before stage reached its maximum height at the upstream and downstream sites. Once these ion concentrations hit their peaks, concentrations decreased over time at both sites. By the end of the sampling period, about 5 h after the rain stopped, sodium and chloride concentrations returned to concentrations very similar to those measured at base flow at the upstream site. Conversely, at the downstream site, sodium and chloride concentrations fell below concentrations measured at base flow. Potassium concentrations remained slightly above base flow concentrations at the upstream site and returned to base flow concentrations at the downstream site.

Concentrations increased at 23.72 ppm/h for sodium, 15.53 ppm/h for chloride, and 0.06 ppm/h for potassium at the upstream site. Rates of increase at the downstream site were much higher (286.05 ppm/hr for sodium, 308.49 ppm/hr for chloride, and 12.61 ppm/hr for potassium). Hysteresis loops for sodium, chloride, and potassium (concentration vs. discharge) were all clockwise positive loops (Figure 14). For all three ions, the upstream loop is smaller and flatter as compared to the downstream loop, which shows a sharp spike in concentration in the rising limb of the loop.

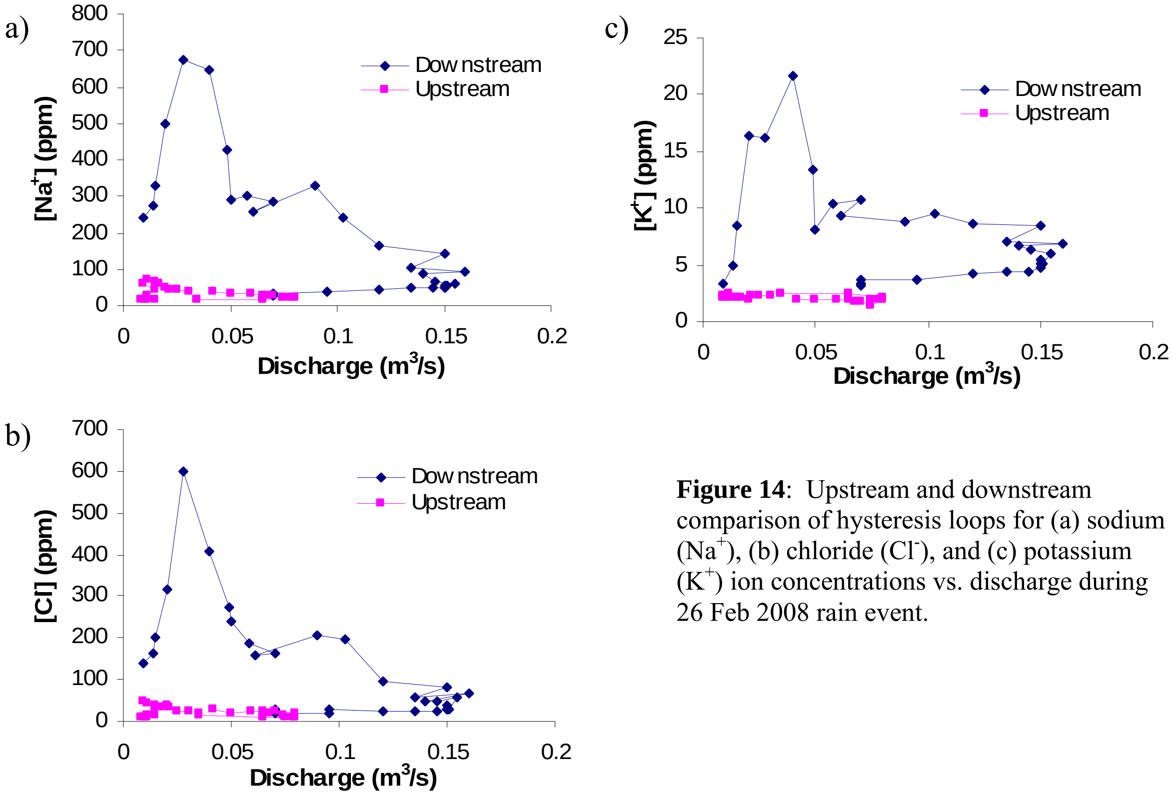

Figure 14: Upstream and downstream comparison of hysteresis loops for (a) sodium (Na^+), (b) chloride (Cl^-), and (c) potassium (K^+) ion concentrations vs. discharge during 26 Feb 2008 rain event.

Calcium and Magnesium

Calcium and magnesium ion concentrations behaved similarly during the 26 Feb 08 rain event. Both ions had significantly higher concentrations at the upstream site as compared to the downstream site (paired t-test; calcium: t = -9.53, p < 0.001; magnesium: t =-6.35, p< 0.001) (Figure 15). In general, calcium and magnesium concentrations decreased throughout the first half of the rain event, reaching minimum concentrations at the downstream site before the upstream site. Both ions decreased at a faster rate downstream (-35.09 ppm/h for Ca^{2+} and -8.70 ppm/h for Mg^{2+}) compared to upstream (-23.089 ppm/h for Ca^{2+} and -7.416 ppm/h for Mg^{2+}).

At the downstream site, calcium concentrations appear to have 'lingered' at fairly

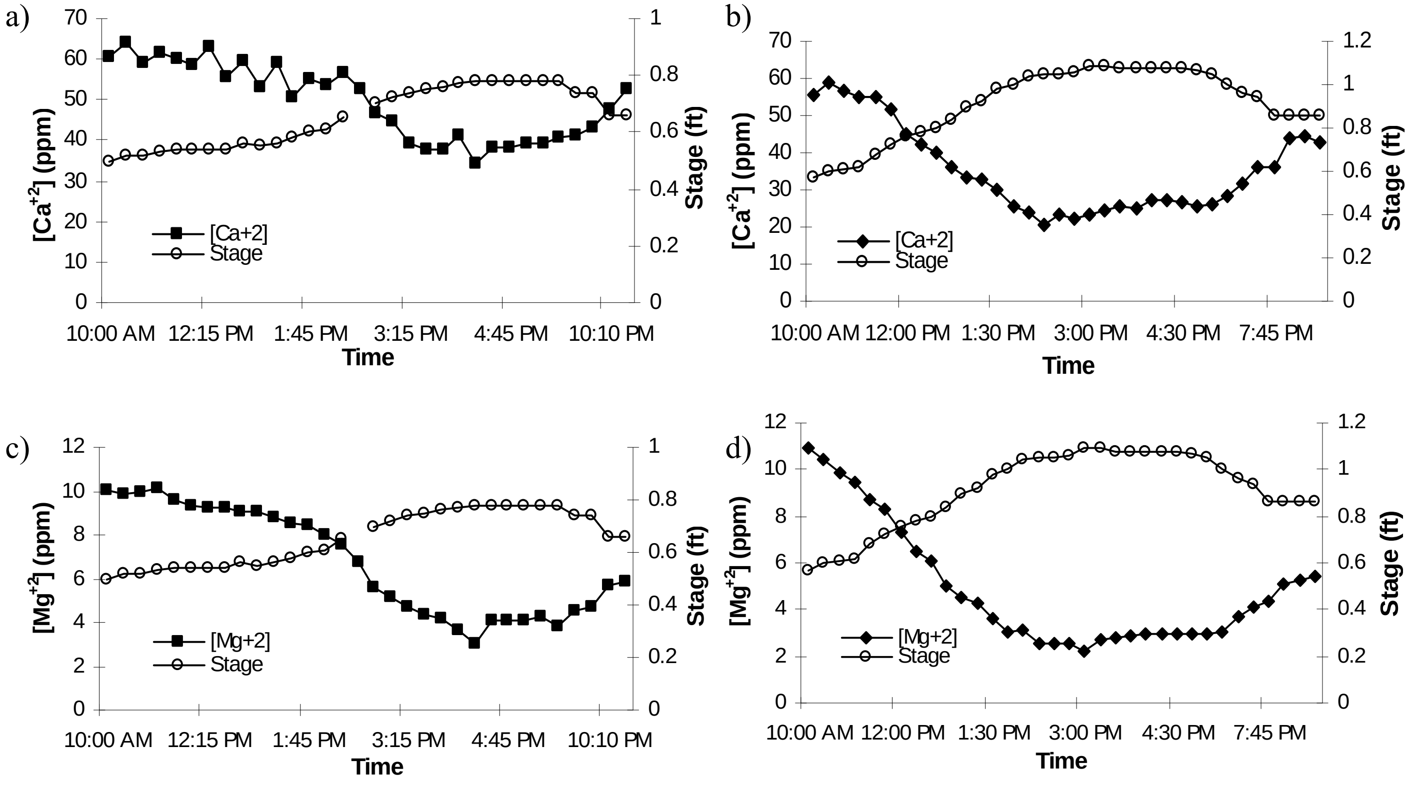

Figure 15: Comparison of stage and ion concentrations for (a) calcium at the upstream site, (b) calcium at the downstream site, (c) magnesium at the upstream site, and (d) magnesium at the downstream site during the 26 Feb 2008 rain event.

consistent concentrations during the first 1.5 h of the rain event before beginning to decline. This pattern was not observed (or at least was not as noticeable) at the upstream site or for magnesium concentrations. Instead, magnesium concentrations began dropping immediately at the start of the rain event. When plotted against stage, calcium reached its minimum concentration prior to stage reaching its peak at both sites. Magnesium reached its minimum concentration at the same time stage peaked at both sites. Once these ions hit their minimum concentrations, concentrations steadily increased at both sites on the falling limb of the hydrograph.

Unlike sodium, chloride, and potassium, hysteresis loops for calcium and magnesium do not show distinct clockwise loops; rather, they show elongated, fairly linear patterns of decreasing concentration with increasing discharge followed by increasing concentration with decreasing discharge (a negative association) (Figure 16). Upstream and downstream sites show similar patterns for both ions; however, upstream 'loops' are much smaller than downstream 'loops', indicating that discharge and ion concentrations did not change as much upstream as downstream.

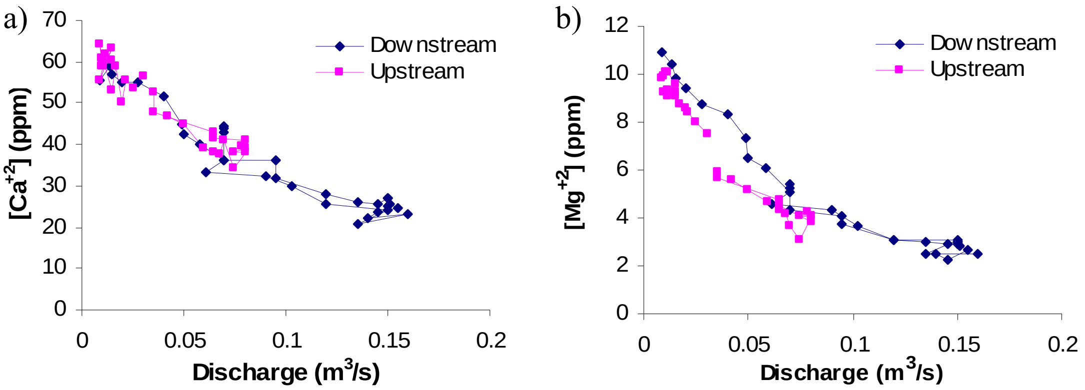

Figure 16: Upstream and downstream comparison of hysteresis loops for (a) calcium (Ca^{+2}) and (b) magnesium (Mg^{+2}) ion concentrations vs. discharge during 26 Feb 2008 rain event.

Nitrate and Sulfate

Nitrate and sulfate ion concentrations behaved similarly to each other during the 26 Feb 08 rain event. Both ion concentrations were significantly higher at the upstream site than at the downstream site (paired t-test; nitrate: $t = -8.03$, $p < 0.001$; sulfate: $t = -7.60$, $p < 0.001$) (Figure 17). In general, nitrate and sulfate concentrations decreased throughout the first half of the rain event, reaching minimum concentrations at the downstream site earlier than at the upstream site (similar to trends observed in calcium and magnesium concentrations). Both ions decreased at a faster rate downstream (-1.44 ppm/h for NO_3^- and -4.57 ppm/h for SO_4^{-2}) compared to upstream (-1.26 ppm/h for NO_3^- and -2.53 ppm/h for SO_4^{-2}).

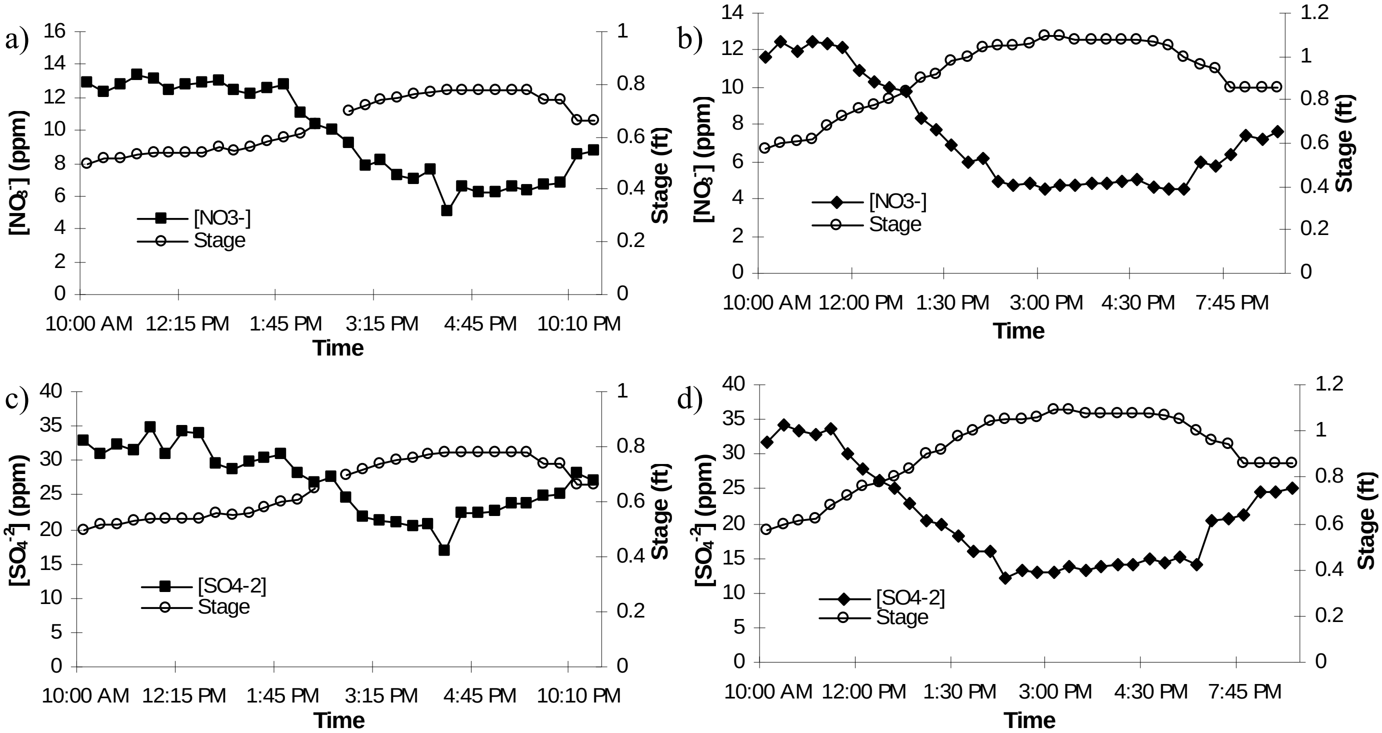

Figure 17: Comparison of stage and ion concentrations for (a) nitrate at the upstream site, (b) nitrate at the downstream site, (c) sulfate at the upstream site, and (d) sulfate at the downstream site during the 26 Feb 2008 rain event.

At the upstream and downstream sites, nitrate reached its minimum concentration at the same time stage reached its peak. Sulfate reached its minimum concentration at the same time stage reached its peak at the upstream site, and 45 min prior to the time stage reached its peak at the downstream site. Once the ions hit their minimum concentrations, concentrations increased at both sites on the falling limb of the hydrograph.

Nitrate and sulfate concentrations at both sites tended to 'linger' at fairly consistent and/or slightly elevated concentrations for the first few hours of the rain event before they started to rapidly decrease (similar to calcium). The concentration 'linger' persisted longer at upstream (3.75 h NO_3^- and 2.5 h SO_4^{-2} after the start of the rain event) than downstream (1.75 h NO_3^- and 1.5 h SO_4^{-2}).

Similar to calcium and magnesium, the hysteresis graphs do not show distinct circular loops; rather, they show elongated, almost linear patterns of decreasing concentration with increasing discharge followed by increasing concentration with decreasing discharge (Figure 18). The only data set that resembles an elongated, clockwise 'loop' shape is the downstream nitrate concentrations, which shows higher

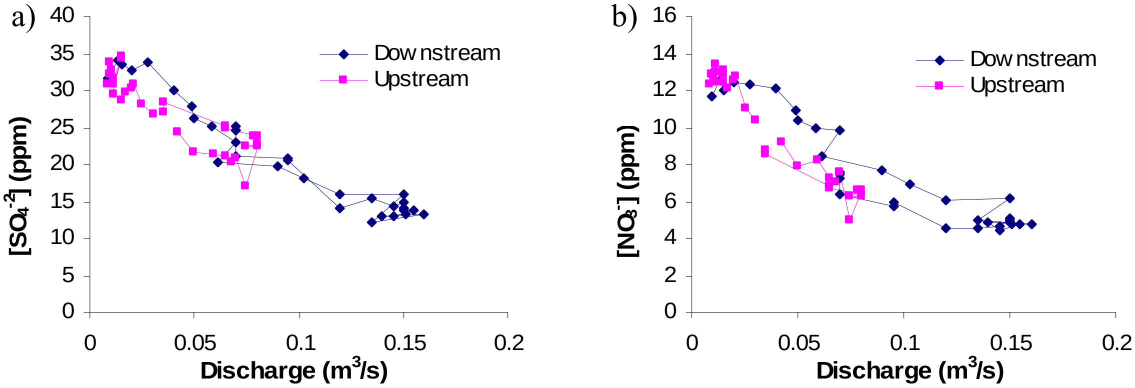

Figure 18: Upstream and downstream comparison of hysteresis loops for (a) nitrate (NO_3^-) and (b) sulfate (SO_4^{-2}) ion concentrations vs. discharge during 26 Feb 2008 rain event.

nitrate concentrations on the ascending discharge limb and lower nitrate concentrations on the descending discharge limb. As seen for calcium and magnesium, upstream ‘loops’ are much smaller than downstream ‘loops’, meaning that changes in discharge and concentration were not as high at the upstream site as at the downstream site.

Ammonium

Ammonium concentrations were significantly higher at the downstream site compared to the upstream site (paired t-test; $t = 5.56$, $p < 0.001$) (Figure 19). Ammonium was initially detected partway through the rain event, first appearing at downstream site 2.5 h after the start of the rain event (3.75 h after the start of the rain event upstream). Following initial detection, ammonium concentrations slightly increased at both sites, peaking earlier and at higher concentrations downstream compared to upstream.

When plotted against stage, ammonium concentrations peaked before stage reached its peak at both sites. Once ammonium peaked, concentrations decreased as stage peaked and subsequently decreased. Ammonium displayed distinct clockwise ‘half-loops’, which are missing the ascending limb of the loop, when plotted against

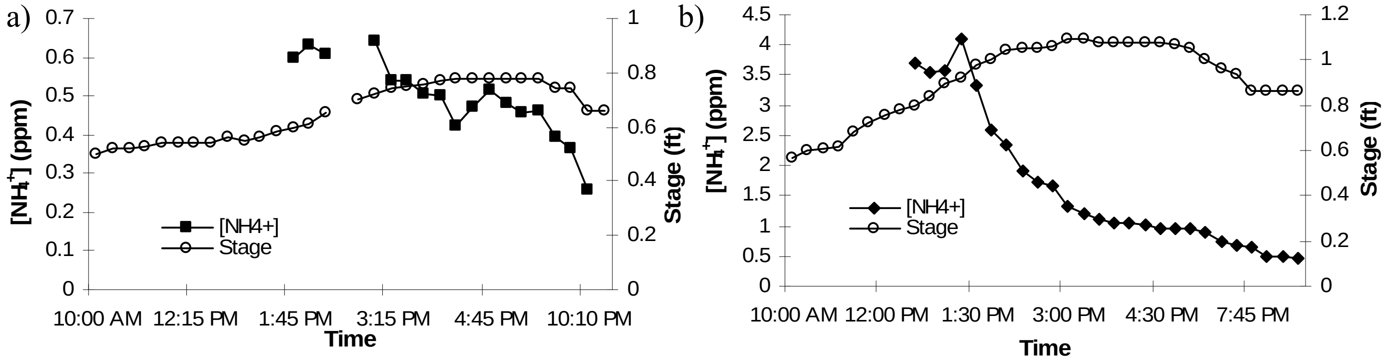

Figure 19: Comparison of stage and ion concentrations for (a) ammonium at the upstream site and (b) ammonium at the downstream site during the 26 Feb 2008 rain event.

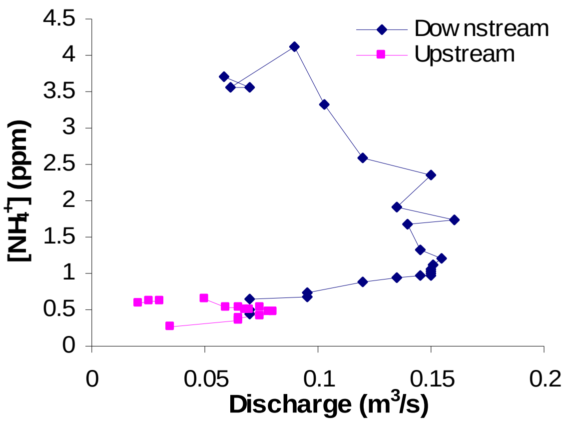

Figure 20: Upstream and downstream comparison of hysteresis loops for ammonium concentrations vs. discharge during 26 Feb 2008 rain event

discharge at both sites (Figure 20). The 'half-loop' shapes illustrate when ammonium concentrations were first detected in relation to discharge. Both loops show initial peaks in ammonium concentration with increasing discharge, followed by a decrease in concentration as discharge peaked and subsequently decreased. As seen in all the previous hysteresis graphs for ion concentrations, the upstream loop is much smaller than the downstream loop, showing that changes in discharge and ammonia concentration during the rain event at the downstream site exceeded those at the upstream site.

Soluble Reactive Phosphorus

Soluble reactive phosphorus (SRP) concentrations were not significantly higher at the downstream site as compared to the upstream site (paired t-test; $t = 0.48$, $p = 0.317$) (Figure 21). From the start of the rain event, SRP concentrations increased over time, with some degree of variability, peaking twice at both sites. Downstream SRP concentrations peaked earlier than upstream concentrations on both occasions; however, peak concentrations were higher upstream than downstream.

At both sites, when plotted against stage, the initial peaks in SRP concentrations occurred before stage reached its peak, but the second SRP peaks occurred after stage reached its peak. Following the second peak, SRP concentrations generally decreased at

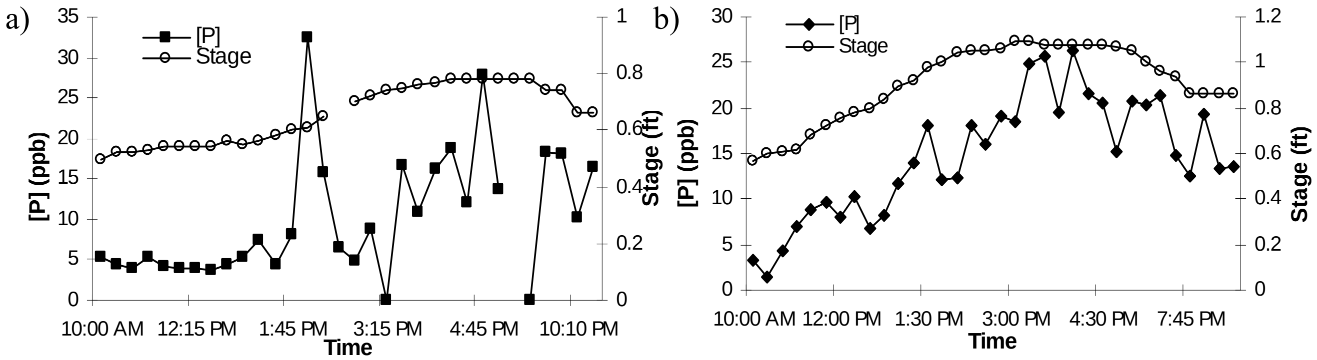

Figure 21: Comparison of stage and soluble reactive phosphorus concentrations at (a) upstream site and (b) downstream site during the 26 Feb 2008 rain event.

both sites, with some degree of variability. Neither site showed a distinct hysteresis pattern; however, upstream peaks in SRP are distinguishable (Figure 22). As a general pattern, the downstream 'loop' extended horizontally in an almost linear pattern, with a very slight increase in SRP concentration as discharge increased, followed by a slight decrease in SRP concentration as discharge decreased. The upstream 'loop' did not follow a consistent pattern, making trends difficult to detect. Additionally, the upstream 'loop' did not extend as far to the right as the downstream 'loop' due to its relatively low increase in discharge; however, the upstream peaks in SRP concentration exceeded concentrations measured downstream.

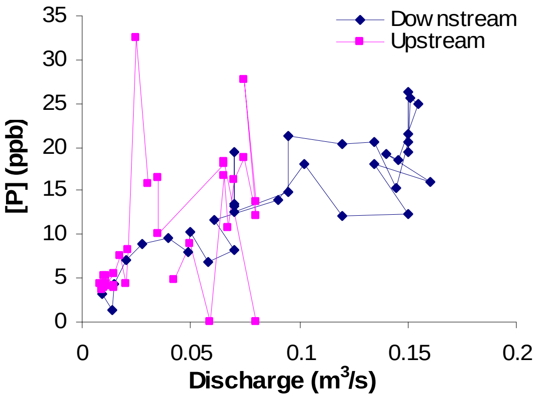

Figure 22: Upstream and downstream comparison of hysteresis loops for soluble reactive phosphorus concentrations during the 26 Feb 2008 rain event.

Dissolved Metals

Manganese

Dissolved manganese concentrations were significantly higher at the upstream site compared to the downstream site (paired t-test: $t = -12.08$, $p < 0.001$) (Figure 23). At the upstream site, concentrations decreased throughout the rain event, with a small peak 7.25 h after the start of the rain event. After the rain stopped, manganese concentrations began to increase. At the downstream site, concentrations slightly increased during the first 3.5 h of the rain event, then decreased for the remainder of the sampling period. There were two spikes in manganese concentrations—the first large peak occurred 5.25 h after the start of the rain event, and a second smaller peak occurred 8.5 h after the start of the rain event. Thus, downstream concentrations peaked before upstream concentrations, but at a significantly lower concentration. When plotted against stage, both upstream and downstream manganese concentrations peaked after stage reached its peak.

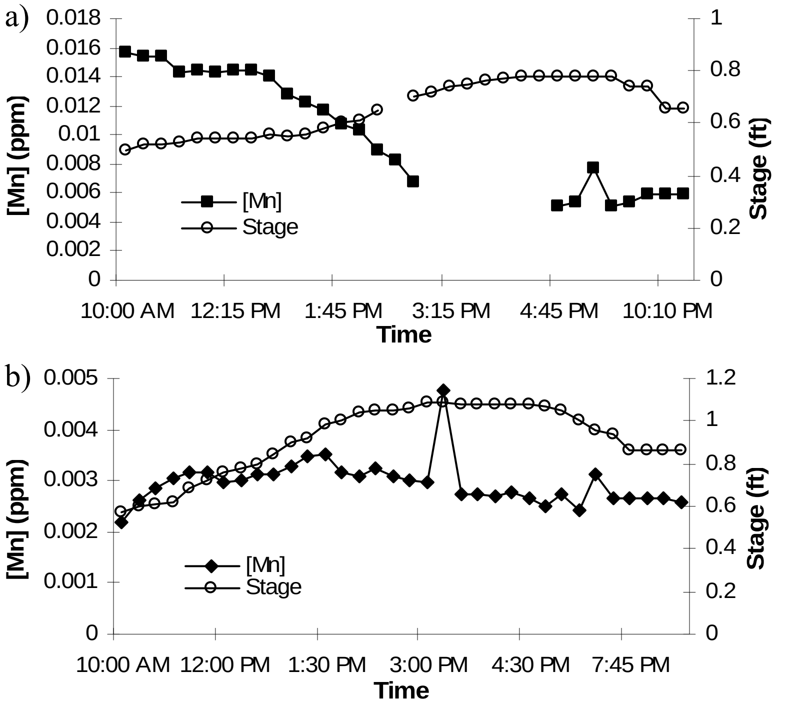

Figure 23: Comparison of stage and manganese concentrations at (a) upstream site and (b) downstream site during the 26 Feb 2008 rain event.

Neither upstream nor

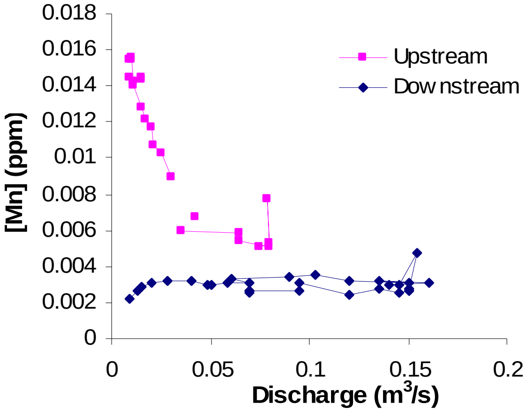

Figure 24: Upstream and downstream comparison of hysteresis loops for dissolved manganese during 26 Feb 2008 rain event.

downstream data showed a distinct hysteresis pattern for manganese; however, peaks in manganese concentrations are distinguishable at both sites (Figure 24). As a general pattern, manganese concentrations decreased with increasing discharge at the upstream site, creating a fairly linear pattern. On the other hand, at the downstream site concentrations appear to have remained relatively stable as discharge increased and subsequently decreased, creating a linear horizontal pattern.

Iron

Dissolved iron was significantly higher at the upstream site than at the downstream site (paired t-test: $t = -4.11$, $p < 0.001$) (Figure 25). At the upstream site, iron concentrations generally decreased throughout the rain event, with a high degree of variability. Seven hours after the start of the rain event there was one spike in iron concentrations. At the downstream site, concentrations initially decreased but then increased and remained fairly constant. Midway through the rain event, iron concentrations peaked 3 times, the largest two peaks occurring 5.25 h and 7 h after the start of the rain event. Thus, iron concentrations peaked earlier and at a higher concentration downstream than upstream.

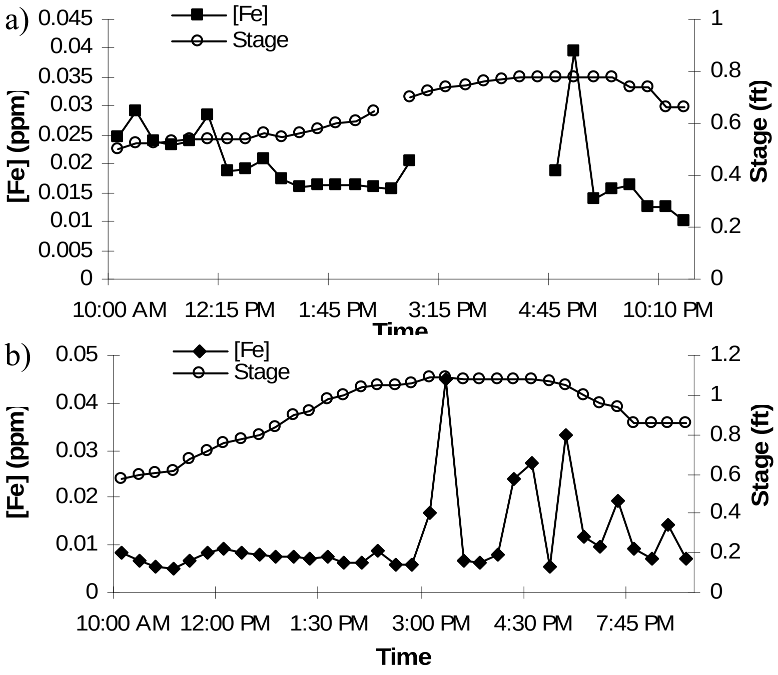

Figure 25: Comparison of stage and iron concentrations at (a) upstream site and (b) downstream site during the 26 Feb 2008 rain event.

When plotted against stage, iron concentrations at the upstream site peaked 1.25 h after stage reached its peak; concentrations initially peaked at the same time stage reached its peak downstream. At hey generally decreased on of the rain event, there was a high degree of variability in iron concentrations, primarily at the downstream site. Neither the upstream nor downstream data showed a distinct hysteresis; however, peaks in iron concentration were distinguishable at both sites (Figure 26).

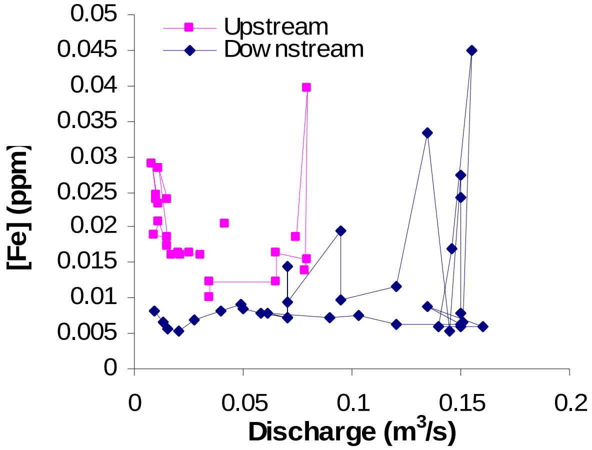

Figure 26: Upstream and downstream comparison of hysteresis loops for dissolved iron during 26 Feb 2008 rain event.

Other Water Properties

Specific Conductivity

Two days prior to the 26 Feb 08 rain event, from 24-25 Feb 08, average base flow specific conductivity at the upstream and downstream sites was similar. However, during the rain event, specific conductivity was significantly higher at the downstream site as compared to the upstream site (paired t-test: $t = 4.64$, $p < 0.001$) (Figure 27). Specific conductance, peaked downstream 1.25 h before peaking upstream, was significantly higher downstream, and increased faster downstream (upstream: 101.09 µS/cm/h; downstream: 1467.33 µS/cm/h). Specific conductivity peaked 3.5 h before stage reached its peak at both sites. After its peak, specific conductance decreased below initial measurements as stage continued to increase.

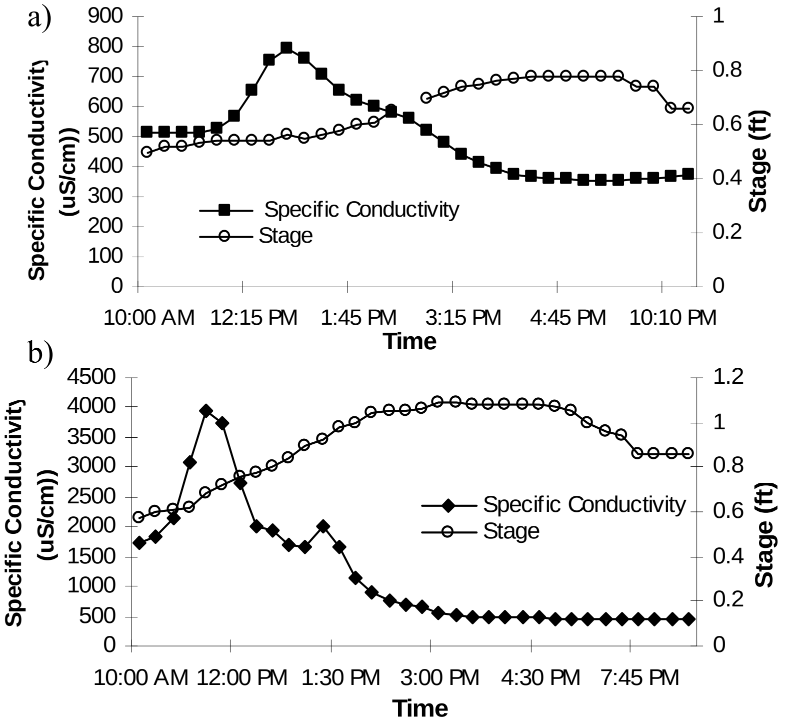

Figure 27: Comparison of stage and specific conductivity at (a) upstream site and (b) downstream site during the 26 Feb 2008 rain event.

pH

Prior to the 26 Feb 08 rain event (from 24-25 Feb 08), both sites experienced daily fluctuations in pH due to daily changes in temperature and biological activities (Figure 36). In general, average base flow pH was higher at the downstream site at 8.11 as compared to the upstream site at 7.01. During the 26 Feb 08 rain event, pH was significantly higher downstream compared to upstream (paired t-test: t = -5.83, $p < 0.001$) (Figure 28). pH generally decreased at both sites as stage increased. Comparatively, pH downstream dropped noticeably more and at a faster rate than pH upstream (upstream: -0.01 pH/h; downstream: -0.06 pH/h). When plotted against stage, pH at either site did not start to increase until after stage reached its peak.

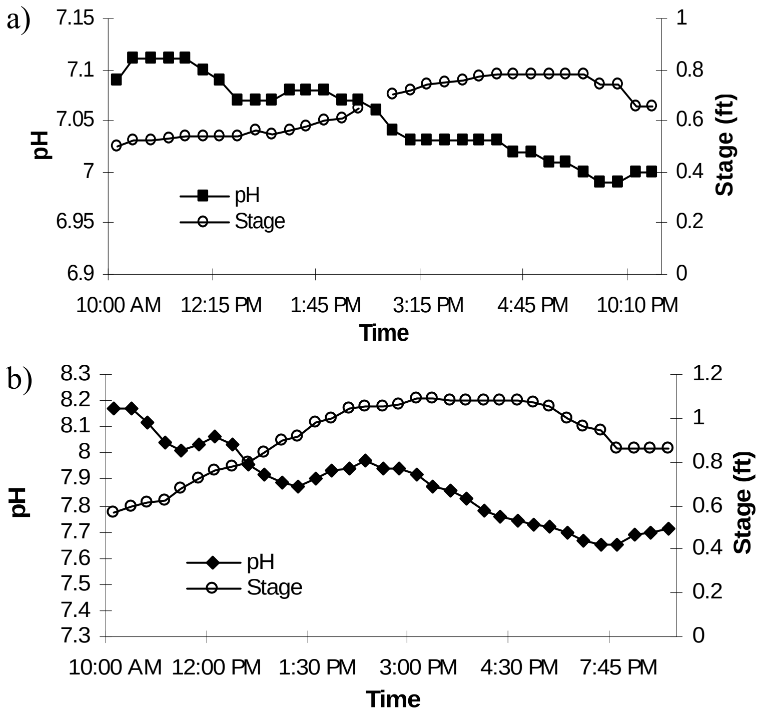

Figure 28: Comparison of stage and pH at (a) upstream site and (b) downstream site during the 26 Feb 2008 rain event.

Temperature

During base flow, both sites experienced daily fluctuations in temperature depending on the time of day. From 24-25 Feb 08, two days prior to the 26 Feb 08 rain event, average base flow temperatures upstream and downstream were approximately 4.67 °C and 3.13 °C, respectively. During the rain event, temperatures were significantly higher upstream as compared to downstream (paired t-test: $t = -5.83$, $p < 0.001$) (Figure 29). In general, temperatures decreased at both sites throughout the rain event, and then subsequently increased as stage started to descend. At the upstream site, temperature dropped at a faster rate and reached a lower minimum temperature than the downstream site (upstream: -0.35 °C/h; downstream: -0.09 °C/h). When plotted against stage, both upstream and downstream temperatures did not start to increase until after stage reached its peak.

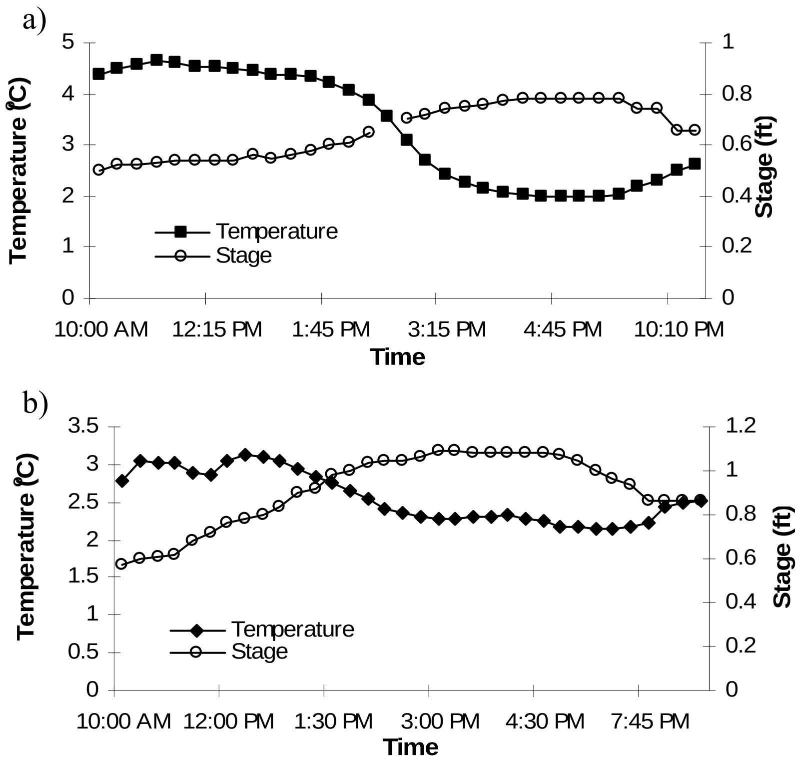

Figure 29: Comparison of stage and temperature at (a) upstream site and (b) downstream site during the 26 Feb 2008 rain event.

Both sites experienced a very slight increase in temperature at the beginning of the rain event before temperatures decreased**.** At the upstream site, temperatures increased 1.25 h after the start of the rain event; at the downstream site, temperatures increased twice within the first 2.25 h of the rain event.

Discussion

This study primarily focused on a 7.5 h rain event (from 10:00 AM to 5:30 PM) that took place on 26 Feb 08. Data gathered from this rain event allowed for analysis of how hydrologic conditions and water quality of Miller Run are affected by rain, infiltration, ground water, and surface runoff. Base flow measurements functioned as a basis for comparison, revealing how the hydrology and water quality conditions changed with the onset of a rain event. Repeated, systematic sampling throughout the duration of the rain event provided a detailed illustration of how these conditions changed over time, highlighting significant trends, some of which were predicted and others of which were unexpected. Additionally, sampling at two different locations—one upstream of Bucknell University's main campus and the other downstream of the main campus—allowed for interesting and significant comparisons between the two sites, thus exposing the effect of specific land-use practices on the hydrologic conditions and water quality of Miller Run.

Hydrologic Conditions

Stage and Discharge

Stream hydrographs are affected by the physical characteristics of the watershed (Finlayson et al. 1992). A narrow, peaked hydrograph is an indication that a stream is 'flashy'. In general, streams within smaller drainage basins tend to be 'flashier' than those streams within larger drainage basins, meaning that stage and discharge rise and fall at a faster rate in streams with smaller drainage basins. In addition, hydrographs are typically expected to be flashier upstream and become broader and less sharp downstream (Finlayson et al. 1992). During rain events, 'flood water' rapidly accumulates upstream, creating a relatively sharp increase in peak stage and discharge; but as water moves downstream it is temporarily stored in the channel and on the flood plains, resulting in an attenuation of peak stage and discharge downstream (Woltemade 1994) (Figure 30). However, Miller Run shows the exact opposite pattern of what we would expect from a 'normal' stream hydrologically. Miller Run shows a flashier downstream hydrograph and broader upstream hydrograph. Stage and discharge increased at a much faster rate downstream with higher peak

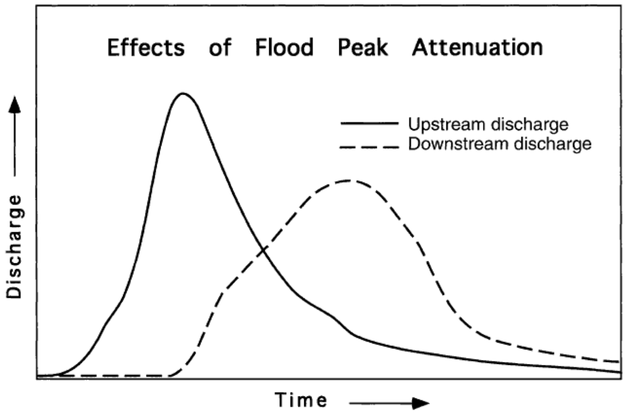

Figure 30: Generalized hydrographs illustrating the effects of flood-peak attenuation. In the process of flowing the upstream site to the downstream site, peak discharge is reduced while total flood volume is unchange (Woltemade 1994).

discharges compared to upstream; thus providing clear evidence that Miller is impacted by Bucknell's campus hydrologically.

The most probable explanation for this difference in hydrographs is differences in land use between the two sites. The removal of vegetation reduces infiltration rates, causing increased amounts of direct runoff and shaper-peaked hydrographs. Streams surrounded by grassland and agricultural lands within their watersheds tend to demonstrate more variable flows with faster rising hydrographs compared to forested lands. Urbanization leads to even more extreme changes in hydrology with increased total runoff, higher peak discharge, more frequent flooding and short lag times (Finlayson et al.1992). Storm water runoff in streams increases dramatically as the amount of impervious surface cover increases. For example, a 10-20% increase in impervious surface cover results in a two-fold increase in runoff, while streams with 75-100% impervious surface cover in their watersheds have five times more surface runoff than forested watersheds (Paul & Meyer 2001). The upstream reach of Miller Run is primarily surrounded by the golf course and grassy fields whereas the downstream reach

Figure 31: (a) Upstream reach of Miller Run at the Bucknell Gold Course. (b) Road and footbridge over downstream reach of Miller Run. Storm water is channeled directly into the stream off of Loomis Street.

is immediately surrounded by roads, sidewalks, and parking lots (Figure 31). In addition, most of the storm water from Bucknell's main campus is directly piped into the downstream reach of the stream. Therefore, the lack of vegetation, increased amount of impervious surfaces (including the compacted grassy fields), and engineered storm water practices had a direct effect on the amount of surface runoff flowing into the downstream reach of stream, creating the atypical patterns in hydrographs. Furthermore, the steep, hilly topography surrounding the downstream reach may have also contributed to the increased amount of surface runoff due to reduced infiltration.

The increased amount of impervious surface cover, and reduced infiltration, over Bucknell's main campus more than likely reduces groundwater recharge as well. This may partially explain why Miller Run was dry during the past summer and why the stream is less often perennial than in the past; however, further studies are necessary to determine the extent of Bucknell's impact on the stream's groundwater recharge capacity. Other factors, such as climatic conditions and irrigation may also affect base flow discharge in Miller Run. For example, Bucknell irrigates the golf course and all major athletic fields using water from Miller Run's source, which may reduce the stream's base flow during certain times of the year.

Hydrologic conditions are important for sustaining diverse aquatic life in stream ecosystems. Stream biota are affected by how rapidly a stream rises and falls and whether the stream maintains a constant base flow or is frequently dry (Finlayson et al. 1992). A stream's hydrologic conditions also affect the amount and rate at which materials (including debris, sediments, dissolved loads, and pollutants) are transported downstream during rain events. Miller Run's rapid increase in stage and discharge during rain events does affect material transport, especially at the downstream reach, as evidenced by the increased sediment and dissolved loads at the onset of a rain event. The increased, frequent movement of these materials may be potentially harmful to aquatic organisms downstream, particularly those that are sensitive to fluctuating water quality conditions. This study did not look into the different types and quantities of aquatic organisms living in Miller Run; however, in order to promote a biologically diverse and 'healthy' stream ecosystem, it is important to manage the stream's hydrologic conditions properly so that aquatic organisms are better able to survive and thrive (Finlayson et al. 1992). Proper hydrologic management may include reducing the amount of surface runoff and/or impervious surfaces on Bucknell's campus, increasing infiltration rates, slowing down surface runoff, and preventing surface runoff from flowing directly into the stream.

In addition to promoting the ecological integrity of Miller Run, proper management of the stream's hydrologic conditions may help to mitigate the negative impacts of flooding on the surrounding built environment. Although flooding is a natural stream process, it becomes a 'hazard' when people and property get in the way (Allan 1995). According to the *Bull Run Watershed Stormwater Management Plan Update* from 2002, the land immediately surrounding the downstream reach of Miller Run (from Loomis St. to the stream junction with Bull Run) is considered to be a flood zone (UCPC 2002) (Figure). Most of the flooding problems in this area are attributed to storm water runoff rates exceeding the channel and/or obstruction (any man-made structure located in, along, or across any stream channel) capacities (UCPC 2002). Therefore, improved storm water management techniques will ultimately help to improve the hydrologic conditions of Miller Run, thus reducing the amount of flooding and associated flood damages.

Water Quality Conditions

In general, urbanization alters sediment loads and consistently increases conductivity, ammonia, and dissolved metals in urban streams (Paul & Meyer 2001). Although Miller Run is not located in an 'urban' environment, based on the traditional sense of the word 'urban' meaning 'of the city' (Dictionary.com 2008), it does flow through a highly developed landscape, mainly consisting of Bucknell University's golf course and campus. Thus, predicted Miller Run was predicted to function as an 'urban' stream, experiencing similar water quality issues and impacts. Based on the results from the intensively sampled rain event on 26 Feb 08, significant differences were found between upstream and downstream TSS, ion, nutrient, and dissolved metal concentrations.

Total Suspended Solids

Sediment loads increased at a faster rate and were significantly higher at the downstream site as compared to the upstream site during the 26 Feb 08 rain event. During most of the study (from November to March) a rather large area of land upstream of the 'upstream' site was being developed for the construction of a residential community (between Smoketown Road and Beagle Club Road) (Figure 32). Despite efforts by the developer to control erosion and prevent sediment from reaching Miller

Figure 32: (a) Upstream construction site between Smoketown Road and Beagle Club Road. (b) Construction site with sediment guards.

Run, this development site had a noticeable impact on sediment loads at both the upstream and downstream sits based on a change in sediment color that occurred part way through a majority of the rain events. At the beginning of each rain event, sediments were generally a light tan color, indicative of loess sediments, which are the predominant sediments on campus (personal communication with Craig Kochel). However, the sediment color dramatically changed part way through most rain events from tannish-brown to dark red, indicating a change in sediment type. The source of the dark red sediments was traced to the Bloomsburg shale formation located at the construction site. Although the construction agency utilized sediment guards to reduce the amount of sediment runoff, there was a rather large section of the site that was not contained behind sediment guards. Therefore, during rain events these sediments were picked up by surface runoff and transported into the upstream reach of the stream. Furthermore, the excess sediments had a noticeable impact at the upstream site by creating a deep, unconsolidated layer of sediments on the stream bottom.

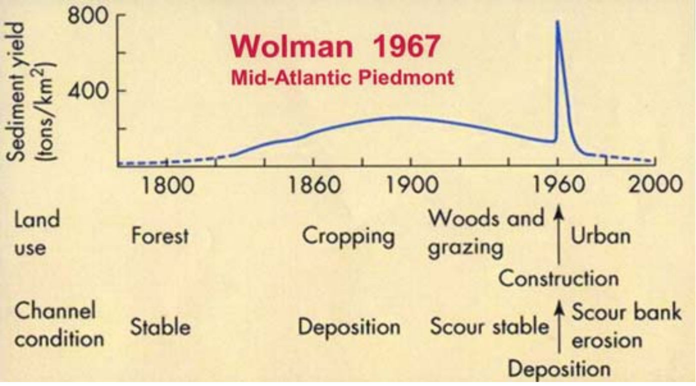

Figure 33: Land-use, sediment yield, and channel response in a watershed (Wolman 1967).

Based on the above evidence, the excess sediments from the construction site provided one major source of sediments in the stream. Typically, stream sediment loads dramatically increase during construction phases, leading to increased sediment deposition in the stream channel, as was seen in Miller Run (Wolman 1967) (Figure 33). However, once the construction is complete, the sediment dynamics will more than likely change once again, possibly reflecting sediment loads found in urbanized streams that are past the construction phase. Urbanized streams generally have very low sediment loads, elevated volumes of surface runoff, and increased frequency or volume of bankfull floods, thus leading to increased scour bank erosion (Wolman 1967, Paul & Meyer 2001). Bucknell's high percentage of impervious surfaces, elevated volumes of surface runoff, and Miller Run's steep, highly eroded banks are all indications that such erosion has already started taking place within the stream, probably before the upstream construction commenced (Figure 34).

Figure 34: Highly eroded banks along the upstream reach of Miller Run (west of U.S. Highway 15.

Although it is quite clear that the upstream construction site had a large impact on sediment loads in the stream at both sites, it was not the only major source of sediments during the 26 Feb 08 rain event. The significant difference in TSS concentrations between the upstream and downstream sites provides strong evidence that Bucknell's main campus has a direct affect on sediment loads during rain events; however, this second major sediment source is not as obvious. One possible source may have been excess sediments from the road construction on 7th Street, which began earlier that fall. Additionally, during the 26 Feb 08 rain event, there was a noticeable 'pulse' of sediments at the downstream site within the first two hours of the rain event. Based on first-hand observations, this pulse was the result of grayish runoff that was directly flowing into the stream from surrounding roads, parking lots, and storm water pipes. Thus, excess sediment from both construction sites and 'urban' runoff from Bucknell's campus more than likely contributed to the elevated sediment loads at the downstream site.

Future studies are critical to determine the exact source(s) of these high downstream sediment loads and to analyze how the overall sediment dynamics change when the upstream construction is completed. More specifically, it is important to determine whether the downstream sediment source(s) is(are) permanent or temporary, and whether or not sediment loads will significantly decrease downstream upon completion of all construction projects, as is to be expected in an urbanized stream.

Increased sedimentation can have a negative impact on aquatic diversity and abundance by increasing turbidity, degrading in-stream habitats, and either killing or removing those organisms that are intolerant of silty conditions (Allan 1995). Certain aquatic organisms are capable of surviving in silty and degraded habitat conditions; however, others are extremely intolerant of such conditions (Allan 1995). Diversity and abundance of aquatic species also vary depending on the type of substrate. Diversity and abundance are generally highest on organic substrates compared to mineral substrates, and least on sand (particle diameter 0.125-2 mm) (Allan 1995). Therefore, the inundation of sediments into Miller Run (especially from the construction site) may have a negative impact on the stream's ecological conditions, thus making it unsuitable for a diverse array aquatic life.

Sodium, Chloride, Potassium

Throughout the duration of the rain event, sodium, chloride, and potassium ion concentrations were significantly higher downstream as compared to upstream. Additionally, these ion concentrations increased at a much faster rate downstream, peaking earlier than ion concentrations upstream. This trend suggests that at some point between the upstream and downstream sites, relatively large amounts of sodium, chloride, and potassium ions were transported into the stream by surface runoff and/or infiltrating groundwater. Based on the time of year this event took place, the main source of these ions was salt from roads and walkways on Bucknell's campus. Almost all major roads and walking paths on the University's main campus had been generously salted over the previous few weeks in response to several snow events. We even directly observed a Bucknell employee spreading salt onto the footbridge above the downstream site during our sampling on 26 Feb 08 (around 10:25 AM). Three different types of road salt deicers are used on Bucknell's campus: sodium chloride is used on blacktop surfaces; potassium chloride is an ingredient of the product *Safe Step* mostly used for concrete, stone walks, brick, etc; and calcium chloride is used if temperatures are below 20 °F (personal communication with Bill Zimmerman). The fact that relatively large volumes of water flowed from blacktop roads and concrete sidewalks directly into the stream (primarily at the downstream site) provides strong evidence that road salts contributed to the rapid and significant increase in sodium, chloride, and potassium concentrations downstream, but not upstream. Although the upstream site was probably somewhat affected by sodium chloride from Smoketown Road, the impact was very minor compared to the downstream site, suggesting that the salt source upstream of Bucknell's main campus was limited and/or the surrounding grassy patches functioned as a buffer to remove excess ions. Unlike sodium and chloride, potassium barely increased during the storm upstream; therefore, it is likely that potassium chloride was not used upstream of Bucknell's main campus or that vegetation removed potassium selectively.

The clockwise hysteresis loops for sodium and chloride provide further evidence that the downstream site is impacted by urbanization. In one comparative study of solute-discharge hysteresis loops for urbanized and less-urbanized watersheds, sodium and chloride both demonstrated clockwise rotations in the urbanized watershed, which is consistent with my results at the downstream site (Rose 2003).

Average base flow concentrations of sodium, chloride, and potassium from January to February 08 also tended to be higher at the downstream site compared to the upstream site (although the differences were not significant). In addition, sodium, chloride, and potassium concentrations tended to be higher in Miller Run compared to average concentrations found in unimpacted (natural concentration values excluding pollution) and impacted (concentrations including inputs from human activities) rivers across North America (Table 2, from Allan 1995). This increase in base flow chloride concentrations, at the downstream site and for the entire stream in general, may have been partially due to the infiltration of chloride ions (from road deicers) into the ground water supply, which eventually reemerged into the stream system (Paul & Meyer 2001). Elevated ion concentrations are a general indication that a stream is affected by urbanization; therefore, my results provide evidence that Miller Run is impacted by Bucknell's campus (Paul & Meyer 2001). High salt concentrations can have detrimental effects on aquatic organisms; however, macroinvertebrates are generally not harmed unless chloride concentrations exceed 1 g/L (Allan 1995). Miller Run's maximum salt concentrations did not reach this extreme during this study, so the elevated salt concentrations observed likely have little impact on aquatic life.

Table 2: Average base flow ion concentrations for Miller Run from 24-28 Jan and 19-25 Feb 2008 and for river water in North America from 1987.

Ion	Upstream (ppm)	Downstream (ppm)	N. America Actual (ppm)	N. America Natural (ppm)
Na^+	13.19	22.45	8.4	6.5
Cl^-	10.46	13.65	9.2	7.0
K^+	2.21	2.45	1.5	1.5
Ca^{+2}	55.69	49.81	21.2	20.1
Mg^{+2}	10.78	11.18	4.9	4.9
NO_3^-	12.85	10.79	--	--
SO_4^{+2}	35.12	32.09	18.0	14.9
NH_4^-	0	0	--	--

*Actual concentrations include inputs from human activity. Natural values are corrected to exclude pollution (Allan 1995).

Calcium and Magnesium

Unlike sodium, chloride, and potassium, calcium and magnesium concentrations generally decreased throughout the rain event at both sites. These upstream and downstream patterns were the result of a dilution effect, which illustrates the close link between discharge and calcium and magnesium concentrations. At the downstream site, as discharge steeply increased early in the rain event, both calcium and magnesium concentrations steeply decreased (closely resembling a negative linear relationship). However, after stage peaked, discharge gradually decreased (at a much slower rate than it increased) accompanied by a gradual increase in calcium and magnesium concentrations. This suggests that the source of these ions was constant throughout the rain event but was simply diluted by rain water, which contained relatively little calcium or magnesium. At the upstream site, discharge increased at a much slower rate, resulting in a more gradual decrease in calcium and magnesium concentrations. However, once stage peaked, discharge steadily decreased accompanied by a gradual increase in calcium and magnesium ion concentrating. As the rating curves suggest, the downstream site receives a greater volume of water during rain events than the upstream site, thus the dilution effect is more pronounced in this part of the stream.

Dissolved calcium and magnesium ions are typically derived from below-ground mineral deposits including calcium carbonate (limestone or chalk), calcium sulfate, and dolomite (Government of Newfoundland & Labrador 2008). Since the northern half of the Miller Run watershed lies within a limestone region (UCPC 2002), the calcium ions more than likely originate from subsurface calcium carbonate deposits and are transported into the stream via groundwater.

In general, both calcium and magnesium showed the described pattern with changing discharge, but these ions behaved differently during the early portion of increasing discharge. Magnesium concentrations started to decrease immediately at the onset of the rain, but calcium concentrations appeared to ‘linger’ at fairly consistent and/or slightly elevated concentrations for approximately the first two hours of the rain event at both sites (upstream concentrations tended to ‘linger’ a little longer than downstream concentrations). This ‘lingering’ trend (or ‘dilution lag’) suggests that there may have been an additional source of calcium ions to Miller Run during the storm (in addition to relatively constant calcium inputs from ground water). Calcium chloride deicers are used by Bucknell University staff when temperatures are below 20 °F. Indeed, air temperatures were below 20 °F during the week prior to the 26 Feb 08 rain event (BUWX 2008). Calcium ions from these particular salts may have been transported to the stream via runoff, thus contributing to the slight ‘linger’ in calcium concentration followed by dilution. However, if this was the case, it is unclear why calcium concentrations ‘lingered’ longer upstream than downstream. Perhaps surface sources contributed calcium to downstream, while calcium was simply not diluted as rapidly upstream due to higher infiltration and therefore proportionally higher amounts of groundwater being measured in the upstream site.

Streams impacted by urbanization typically have elevated concentrations of calcium and magnesium, in addition to sodium, chloride, and potassium (Paul & Meyer

2001). The results from the 26 Feb 08 rain event do not permit strong conclusions linking elevated calcium and magnesium concentrations to the impact of urbanization on chemical properties of Miller Run; rather, they primarily demonstrate the exaggerated effect of dilution at the downstream site compared to the upstream site. Thus, changes in calcium and magnesium concentrations (during this particular rain event) provide further support for the impacted *hydrologic* conditions of the stream. Similarly, base flow concentrations do not reveal elevated calcium and/or magnesium concentrations downstream compared to upstream, verifying the claim that calcium and magnesium ions are primarily derived from the subsurface geology as opposed to the effects of urbanization. Furthermore, the hysteresis loops for calcium and magnesium did not demonstrate clockwise rotational patterns, as observed in other streams affected by urbanization (Rose 2003). However, in comparison to the chemical composition of unimpacted and impacted North American rivers, base flow calcium and magnesium concentrations tended to be higher in Miller Run (Table 2, from Allan 1995). Based on this comparison, Miller Run's elevated concentrations of calcium and magnesium *do* provide support of urban impact (Paul & Meyer 2001), possibly due to deicers and fertilizers. Yet, these elevated concentrations may be due simply to the limestone-rich geology in the watershed.

In general, species diversity is affected by the amount of calcium and magnesium concentrations in the water, commonly referred to as 'water hardness'. Certain aquatic species thrive in hard water environments, whereas others prefer soft water. Among invertebrates, mollusks, crustaceans, and leeches tend to be more sensitive to variations in ionic concentrations than aquatic insects (Allan 1995). However, based off initial personal observations during this study, none of these organisms appear to exist in Miller Run; therefore, calcium and magnesium concentrations probably have little effect on any aquatic organisms that might live in the stream. Nevertheless, different types of aquatic insects prefer different ionic concentrations (Allan 1995), possibly influencing the types of aquatic insects living in Miller Run.

Nitrate, Sulfate, Ammonium, and Phosphorus

Nitrate and sulfate ion concentrations followed a very similar trend to that of calcium and magnesium. As previously seen, changes in nitrate and sulfate concentrations inversely corresponded with changes in discharge at both sites, more strongly at the downstream site, again illustrating the effect of dilution. Similar to the subtle trend observed in calcium concentrations, nitrate and sulfate concentrations also tended to 'linger' at fairly consistent and/or slightly elevated concentrations for the first few hours of the rain event—generally longer at the upstream site. One of the major non-point sources of nitrate in stream ecosystems is fertilizers that are transported into streams through runoff (Appendix A Table 16). Although fertilizers were not actively being applied to the golf course or main campus at this time of year, some excess nitrates (from late fall fertilizer applications) may have been carried into Miller Run by runoff, leading to initially consistent nitrate concentrations at both sites. Sulfates demonstrated a very similar 'lingering' pattern at the beginning of the rain event as well, also suggesting that there was some initial input of sulfate that was eventually diluted both upstream and downstream. Possible sources of sulfate include the weathering of subsurface sedimentary rock and pollution from fertilizers and wastes (Allan 1995); however, elevated concentrations of sulfate are not generally connected to the impact of urbanization (Paul & Meyer 2001). The extended upstream concentration 'linger' for both nitrate and sulfate may have also been due to higher infiltration rates upstream that led to proportionally higher groundwater input, thus initially reducing the effect of dilution on nitrate and sulfate concentrations (as was seen for calcium).

Ammonium concentrations showed a very surprising trend. If anything, ammonium concentrations were expected to initially peak at the onset of the rain event followed by a dilution effect similar to that of nitrate; however, this was not the case. Ammonium was not detected at all until at least two hours into the rain event. Additionally, ammonium concentrations were expected to be higher upstream compared to downstream due to the proximity of the upstream site to the golf course and heavier fertilizer use. However, ammonium concentrations were first detected at the downstream site at extremely high concentrations compared to upstream concentrations. While the upstream site had significantly higher concentrations of nitrate compared to the downstream site, ammonium did not show this pattern. Four possible explanations for this discrepancy are 1) nitrate contamination of groundwater, 2) multiple drainage patterns for the golf course, 3) ammonium's tendency to bind to sediments, 4) a potential sewage leak. First, if fertilizers are regularly applied to the surrounding landscape within the upper catchment of the Miller Run watershed (especially on the golf course and athletic fields), then there is the potential for nitrates leaching into the groundwater supply, which may explain elevated nitrate concentrations at the upstream site. Secondly, while sampling upstream, it became apparent that not all runoff from the golf course drains directly into my designated ‘upstream’ site. Rather, a large percentage of runoff from the golf course and athletic fields flows into a tributary of the main stream, which joins the main stem downstream of my upstream site. This means that my upstream site was not receiving all runoff from the golf course; instead, the downstream site was picking up this runoff later into the rain event. The downstream spike in ammonium concentrations part way through the rain event may be evidence of the golf course and/or athletic field impact. Understanding the drainage patterns of Miller Run is important for future studies of the stream, including assessing the golf course’s impact on water quality. For future studies, adding an additional sampling site located immediately upstream of the junction between Miller Run’s tributary and the main branch is recommended, which could provide insight about whether ammonium concentrations are linked to runoff from the golf course and athletic fields. Thirdly, ammonium ions can adsorb to clays and humic materials, thus allowing them to be transported with sediments in runoff (Allan 1995). It is possible that ammonium concentrations peaked at significantly higher concentrations downstream due to the high influx of sediment concentrations around this time (TSS concentrations peaked approximately 45 min prior to the peak in ammonium downstream). Finally, the excess ammonium downstream may have come from a damaged subsurface sewage line. Over the summer, Bucknell Facilities had to repair a sewage pipe running from 7th Street Café under Miller Run; therefore, sewage may have continued to leak from this past damage.

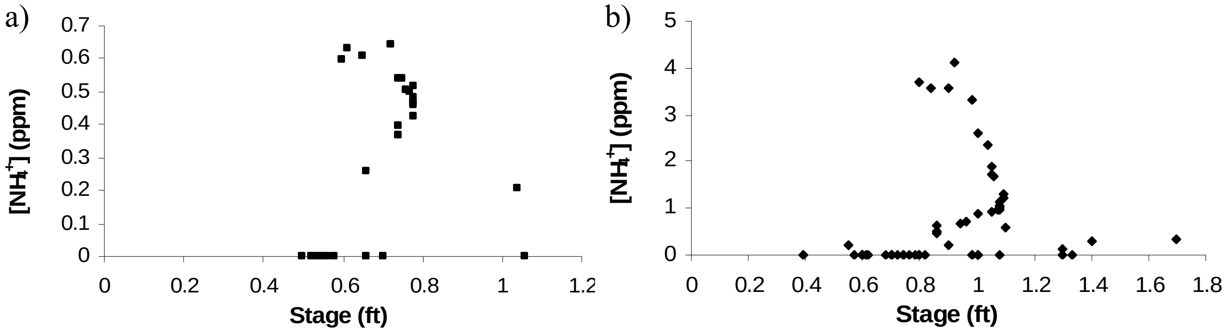

Figure 35: Ammonium concentrations vs. stage at the (a) upstream site for all data from 19 Feb to 5 Mar 2008 and (b) downstream site for all data from 26 Oct 2007 to 5 Mar 2008.

Ammonium concentrations also appeared to be directly related to stage. Using data from all rain events (Feb-March upstream, Oct-Mar downstream), ammonium concentration were plotted against stage to determine if there was a threshold stage above which ammonium ‘appeared’. Such a threshold seemed to exist at both sites—when stage reached approximately 0.6 ft upstream or 0.8 ft downstream, ammonium concentrations were generally detectable (Figure 35). Below 0.6 ft upstream or 0.8 ft downstream, ammonium concentrations were typically below detection limits of my analysis. This ‘ammonium-stage relationship may be due to something significant, such as a new source of ammonium being reached at a particular time into a rain event, or it may be coincident with timing of water delivery to the stream from all sources.

In general, SRP concentrations at both sites increased throughout the duration of the rain event and were higher at the downstream site, suggesting that Bucknell’s campus had some effect on SRP loads in Miller Run. The primary sources of phosphorus in stream ecosystems are wastewater and fertilizers (Paul & Meyer 2001). Fertilizers from campus lawns probably contributed to the increase in SRP concentrations at the downstream site, especially since most of the fertilizers used are rich in phosphorus (Appendix A Table 16). Additionally, the downstream site may have been impacted by fertilizers from the golf course and/or athletic fields (as explained above). The first peak in SRP concentrations at the downstream site was very close to the downstream peak in ammonium concentrations, suggesting that elevated ammonium and phosphorus concentrations may share a source (ammonium peaked 15 min before phosphorus peaked). Moreover, elevated SRP and ammonium concentrations were also observed upstream during the rain event, suggesting that bound-up SRP and ammonium may have been transported into the stream via sediment runoff (Allan 1995). Both of these nutrients commonly adsorb onto soil particles, thus allowing them to be retained in sediments until they are mobilized by soil runoff and erosion, resulting in a 'chemical time bomb' (Paul & Meyer 2001).

Ninety percent of small, relatively unpolluted streams in the United States have inorganic phosphorus concentrations less than 0.05 ppm; sevety-five percent of small agricultural streams have phosphorus concentrations between 0.05 and 0.1 ppm (Allan 1995). By comparison, base flow phosphorus concentrations in Miller Run were within the phosphorus range of relatively unpolluted streams; however, during the 26 Feb 08 rain event, concentrations at the upstream site peaked to levels comparable to those of agricultural streams. This suggests that Miller Run is impacted by elevated concentrations of phosphorus during rain events, but during base flow conditions, phosphorus concentrations were not abnormally high.

In summary, elevated concentrations of nitrogen, ammonium, and phosphorus are indicators of urban impact (Paul & Meyer 2001). During the 26 Feb 08 rain event, the downstream site did not appear to be directly impacted by nitrate runoff; however, it was noticeably impacted by ammonium and phosphorus runoff; therefore, Bucknell's main campus and/or golf course and athletic fields likely influence Miller Run's nutrient concentrations. Similarly, the upstream site appeared to be impacted by elevated nitrate and phosphorus concentrations flowing into the stream from the golf course and/or the upstream development site. Miller Run may also face problems of groundwater nitrate contamination.

It is difficult to determine whether the nutrient concentrations in Miller Run during my study were detrimental to the 'health' of the aquatic ecosystem. Excess nutrients in streams generally promote eutrophication, depleted dissolved oxygen concentrations, and decreased species diversity (Allan 1995). Future studies should assess the relationship between nutrient concentrations in Miller Run and the effects of eutrophication. In addition, nutrient concentrations vary depending on a number of factors including the time of year, the amount of precipitation, and the amount of fertilizers used; therefore, future studies should also conduct seasonal nutrient assessments of Miller Run to determine how concentrations change throughout the year. Even if these nutrients are not specifically affecting the ecological health of Miller Run, the excess nutrients (that are not used up by organisms in the stream) are flushed into the Susquehanna River, where they might have a negative, accumulative ecological impact.

Manganese and Iron

Elevated water column and sediment metal concentrations are another characteristic of urban streams (Paul & Meyer 2001). The most common metals found include lead, zinc, chromium, copper, manganese, nickel, and cadmium, most of which flow into streams from non-point sources (lawns, parking lots, roads). Other metals typically found in urban stream sediments, at elevated concentrations, include arsenic, iron, boron, cobalt, silver, strontium, rubidium, antimony, scandium, molybdenum, lithium, and tin. These metals are commonly derived from various aspects of human development, including urban infrastructure (bridges, pipes) and motor vehicles and may accumulate on paved roads and parking lots (Table 3). Manganese is primarily found in moving engine parts and gasoline (as a fuel additive), while iron sources include auto body rust, steel highway structures, and moving engine parts (ATSDR 2004, EPA(d) 2008). Small amounts of manganese and iron are also found in several of the fertilizers used on Bucknell's campus (Appendix A Table 16). Apart from urban runoff pollution, elevated concentrations of dissolved manganese and iron are naturally found in groundwater, derived from subsurface geologic sources (WSIS 2007). Since manganese and iron are typically found in non-point source runoff from roads, parking lots, sediments, etc., higher concentrations of these dissolved metals were expected to be found at the downstream site. However, this was not the case—for both metals, concentrations were significantly higher upstream compared to downstream throughout the 26 Feb 08 rain event. This suggests that dissolved manganese and iron generally come from groundwater sources. Nevertheless, there were some interesting trends in the

Table 3: Typical pollutants found in runoff from roads and highways (EPA 2008).

Sources of Pollution in Highway Runoff

	Pollutant	Source
Sedimentation	Particulates	Pavement wear, vehicles, the atmosphere and maintenance activities
Nutrients	Nitrogen & phosphorus	Atmosphere and fertilizer application
Heavy Metals	Lead	Leaded gasoline from auto exhausts and tire wear
	Zinc	Tire wear, motor oil and grease
	Iron	Auto body rust, steel highway structures such as bridges and guardrails, and moving engine parts
	Copper	Metal plating, bearing and brushing wear, moving engine parts, brake lining wear, fungicides & insecticides
	Cadmium	Tire wear and insecticide application
	Chromium	Metal plating, moving engine parts and brake lining wear
	Nickel	Diesel fuel and gasoline, lubricating oil, metal plating, bushing wear, brake lining wear and asphalt paving
	Manganese	Moving engine parts
	Cyanide	Anti-caking compounds used to keep deicing salt granular
	Sodium, calcium & chloride	Deicing salts
	Sulphates	Roadway beds, fuel and deicing salts
Hydrocarbons	Petroleum	Spills, leaks, antifreeze and hydraulic fluids and asphalt surface leachate

Adapted from Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters

data that suggest that non-point source metal runoff actually did have a greater impact on the downstream site, despite lower concentrations.

At the upstream site, both manganese and iron were diluted during the storm. Conversely, downstream manganese and iron concentrations did not decrease over time, as one would expect as a result of dilution. In fact, if dilution was the only factor affecting these metal concentrations at both sites, concentrations would have been expected to decrease at both sites, perhaps even more significantly at the downstream site.

However, dilution of metals was only observed at the upstream site, meaning that manganese and iron non-point source inputs must have been increasing proportional to increasing discharge at the downstream site over the course of the rain event. Large volumes of surface runoff were observed flowing directly into the downstream reach of the stream from Hunt Hall parking lot and Loomis Street; therefore, it seems reasonable to suggest that manganese and iron are transported to Miller Run during rain events. If this was indeed the case, Bucknell's campus directly affects concentrations of metals in Miller Run.

Slightly elevated concentrations of dissolved metals can be toxic to some aquatic organisms by causing developmental and growth defects, poor swimming performance, morphological changes in tissues, changes in circulation, enzyme activity, blood chemistry, behavior, and reproduction (Osmond et al. 1995). Many aquatic organisms, such as fish and crustaceans, are able to excrete excess metals including iron; however, aquatic plants and bivalves are not able to regulate metal concentrations in their tissues (Osmond et al. 1995). According to one study that assessed accumulation of manganese and iron in aquatic plants, manganese and iron are considered to be toxic to plants at 50-500 ppm and 40-500 ppm, respectively (Aksoy & Demierzen 2005). In another study, metal concentrations in water resulting in 25% mortality in 4 weeks of *Hyalella azteca* (a freshwater amphipod) was 10.82 ppm Mn (Borgmann et al. 2006). Dissolved manganese and iron concentrations measured in Miller Run were significantly lower than these 'toxicity-thresholds'; therefore, neither manganese nor iron pose a significant threat to aquatic organisms in Miller Run currently. However, metal accumulation in sediments over time could become a potential ecological problem in the future.

From a human health perspective, the Environmental Protection Agency's (EPA) recommended drinking water guidelines state that concentrations should not exceed 0.05 ppm for manganese and 0.3 ppm for iron (EPA(c) 2008). During the 26 Feb 08 rain event, neither manganese nor iron concentrations exceeded these levels at either site; therefore, neither substance poses a significant threat to human health.

Specific Conductivity, pH, and Temperature

Changes in conductivity during the 26 Feb 08 rain event very closely resembled changes in sodium, chloride, and potassium ion concentrations, as was expected since specific conductivity is caused by dissolved substances in the water column. In fact, the link between urbanization and increases in common dissolved ions (e.g. chloride) and conductivity has led some ecologists and hydrologists to suggest using chloride or conductivity as general indicators of urban impact (Paul & Meyer 2001). Using conductivity as an indicator of 'urban' impact for Miller Run, my data provide strong evidence that water quality of Miller Run is affected by runoff from Bucknell's campus. However, more studies need to be conducted year-round to determine if these trends are consistent throughout the year and how they vary due to seasonal land use changes.

At both sites, pH typically fluctuated daily due to daily changes CO_2 concentrations, which are affected by temperature and biological activity. At night, respiration produces CO_2 and water temperatures were generally colder, which increases dissolved CO_2 concentrations and decreases pH. Conversely, during the day, sunlight supports uptake of CO_2 by photosynthesis and increases water temperatures, which decreases dissolved CO_2 and increase pH. During the 26 Feb 08 rain event, pH decreased at both sites, with the downstream site experiencing a greater overall decrease than the upstream site. Furthermore, pH fell below the average 'low' at the downstream site; whereas this did not occur upstream. This decrease in pH was more than likely due to the influx of rain water, which had a pH lower than water in Miller Run during base flow. As the proportion of rain water increased during the rain event, pH decreased at the downstream site. In comparison, pH values remained relatively stable at the upstream site, maintaining a pH very similar to the upstream 'low'. pH values probably did not decrease as much at the upstream site because of the increased buffering capacity of the groundwater. Dissolved calcium carbonate from the bedrock functions as a buffer to prevent decreases in pH, thus holding pH relatively constant at the upstream site despite the influx of acidic rain. Overall, Bucknell's campus did not appear to have much of a direct affect on pH levels. In addition, Miller Run's pH values did not fall below 6.9, thus posing little threat to pH-sensitive aquatic organisms (a pH of 5.0 and below is considered to be harmful to aquatic organisms) (Allan 1995).

During winter, water emerging from the subsurface tends to be warmer and cools as it is exposed to colder air. As a result, Miller Run should be warmer at the upstream site than at the downstream site because a higher proportion of the flow is derived from groundwater that has had less exposure to cold air. Base flow temperatures were higher upstream compared to downstream from 24-25 February 08. During the 26 Feb 08 rain event, water temperatures generally decreased at both sites. The decrease in upstream and downstream water temperatures was likely caused by the influx of cold rain water, which resulted in larger decreases in water temperature at the upstream site. Studies focusing on the effects of urbanization on stream temperature have found that "removal of riparian vegetation, decreased groundwater recharge, and the 'heat island' effect associated with urbanization…all affect stream temperature, yet very little published data exists on temperature responses of streams to urbanization" (Paul & Meyer 2001). Considering this study was conducted in the midst of winter, it is difficult to draw any firm conclusions as to whether or not Bucknell's campus has an effect on Miller Run's water temperatures. However, studies conducted in the summer months, when impervious surface temperatures are substantially warmer than ground temperatures, may elucidate a seasonal effect on the stream's water temperature. Typically, during summer rain events, urban streams will receive temperature pulses 10-15% warmer than forested streams as a result of runoff flowing over heated impervious surfaces (Paul & Meyer 2001). Temperature can affect many different aspects of stream ecosystems including dissolved oxygen concentrations, species diversity, organismal life cycle patterns, growth rates, metabolic rates, and fecundity (Allan 1995).

Figure 36: Hot storm water being removed from a manhole and pumped into a storm drain that flows directly into Miller Run (10 March 2008).

Ultimately, temperature determines what organisms are able to survive in the current environmental conditions. Again, Bucknell's campus did not appear to have a significant impact on water temperature in Miller Run during the winter; however, studies during warmer months may reveal different results.

One important side note is that on 10 March 08, University facilities members were seen pumping hot water, approximately 52 °C, into the downstream reach of Miller Run (Figure 36). According to Dennis Hawley of Facilities, a steam manhole pump stopped working, thereby filling the manhole with water. The unwanted water was removed by pumping it into a storm drain, which leads directly into Miller Run, thus raising stream temperatures and specific conductivity dramatically (52 °C and 4150 μS/cm, respectively). Although not a frequent occurrence, this type of condition (i.e. extreme water chemistry fluctuation and temperature change) more than likely has a negative impact on aquatic organisms living in Miller Run.

Conclusions and Future Studies

This study primarily focused on Miller Run's hydrologic and water quality conditions during a single rain event in late February, which has never been done before. In order to determine the impact of Bucknell's campus on these stream conditions, stage, discharge, TSS, and water chemistry were analyzed and compared at two sites that experienced different degrees of 'urbanization'. The data showed that there were significant differences between the upstream and downstream reaches of the stream, providing strong evidence that Bucknell's campus did have an impact on the stream's hydrologic and water quality conditions.

Although this research provides a detailed examination of the stream's hydrologic conditions and water quality, stream conditions fluctuate in response to a number of factors, including time of day, climate, precipitation, vegetation, and land use. Therefore, more studies are required to determine how Miller Run responds to such factors, as well as to evaluate the consistency of these findings. Recommendations for future studies include using a similar methodology to study stream conditions during base flow and various rain events on a seasonal basis, and adding a third sampling site immediately upstream of the junction between the main branch of Miller Run and its small tributary that flows through the northern half of the golf course. Collecting samples every 15 min throughout the duration of the rain event and sampling every 30 min to 1 h from the time the rain stops to when stage returns to base flow is a good sampling methodology to use in future studies. Additionally, water samples should frequently be collected during base flow and high flow conditions throughout the entire study period. Several more discharge measurements during high flow rain events will contribute to the accuracy of the rating curve at high stage levels. Future studies may also include sampling a naturally forested, un-impacted stream within a similar geologic and hydrologic region as a basis for comparison. Using a reference stream would provide additional insight about the hydrologic and water quality conditions compared to a 'naturally' functioning ecosystem, thus providing further evidence of Bucknell's impact on conditions in Miller Run.

Although more studies are needed, it is clear from my research that Bucknell's campus does affect Miller Run's hydrologic and water quality conditions; therefore, the University should consider modifications to improve its storm water management practices and to reduce the campus's overall impact on the stream. Such measures could include redirecting surface runoff from the roads and sidewalks into grassy fields, creating storm water retention ponds along the floodplain of the stream, planting vegetated riparian buffers along the stream banks for bank stabilization and reduced surface runoff flow, elevating and planting vegetation around storm drains on campus to increase infiltration and groundwater recharge, and installing rain barrels to store rain water from roofs to be used for irrigation (See *Union County's Bull Run Watershed Stormwater Management Plan Update 2002* for further details and additional best management practices). Such measures should reduce chemical impacts of Bucknell's campus by 'filtering' nutrients and other ions and allow higher infiltration of water throughout the watershed, which would create more normal hydrologic conditions downstream (less flashy, more sustained base flow, etc.). As a leading national academic institution, member of the local community, and part of a broader watershed, Bucknell has the responsibility and opportunity to manage and preserve the hydrologic and ecologic integrity of its local stream. If the University chooses to protect its natural water resources and reduce its ecological footprint, Bucknell will set a positive example for other academic institutions and other communities in the region of how 'urbanized' human environments can successfully coexist with naturally functioning ecosystems.

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Appendix A: Tables

Table 1: Rating table for upstream (by Art Barn) and downstream sites (behind Hunt Hall parking lot).

Upstream Stage (ft)	Upstream Discharge (m^3/s)	Downstream Stage (ft)	Downstream Discharge (m^3/s)
--	--	0.4	0
0.5	0.01	0.5	0.01
0.6	0.02	0.6	0.015
0.7	0.045	0.7	0.035
0.8	0.09	0.8	0.06
0.9	0.15	0.9	0.085
1	0.22	1	0.12
1.1	0.3	1.1	0.16
1.2	0.4	1.2	0.21
1.25	0.52	1.3	0.27
--	--	1.4	0.35
--	--	1.5	0.48
--	--	1.6	0.63
--	--	1.7	0.84

Table 2: Amount of time to peaks in stage and total increase in stage at the upstream and downstream sites during 26 Feb 2008 rain event.

	Upstream	Downstream
Base flow stage (ft)	0.5 (10:00 AM)	0.57 (10:00 AM)
Peak Stage and Time of Peak (ft)	0.78 (4:15 PM)	1.09 (3:00 PM)
Time to Peak (h)	6.25	5
Total Increase in Stage (peak stage-base flow) (ft)	0.28	0.52
Rate Increase in Stage (ft/h)	0.05	0.104

Table 3: Amount of time to peaks in total suspended solid (TSS) concentrations and total increase in TSS concentrations at the upstream and downstream sites during 26 Feb 08 rain event.

	Upstream	**Downstream**
Time to peak in stage (h)	6.25 (4:15 PM)	5 (3:00 PM)
Base flow [TSS] (ppm)	0 (10:00 AM)	8 (10:00 AM)
1st Peak [TSS] (ppm) and Time of Peak	105 (3:15 PM)	161 (11:45 AM)
Time to 1st Peak (h)	5.25	1.75
2nd Peak [TSS] (ppm) and Time of Peak	108 (4:00 PM)	145 (1:15 PM)
Time to 2nd Peak (h)	6	3.25
3rd Peak [TSS] (ppm) and Time of Peak	--	152 (2:15 PM)
Time to 3rd Peak (h)	--	4.25
Total Increase in [TSS] ([highest]-[base flow]) (ppm)	108	153
Rate Increase (ppm/h)	18	88

Table 4: Upstream and downstream comparisons of ion and soluble reactive phosphorus (SRP) concentrations using paired t-tests from 10:00 AM to 5:15 PM during the 26 Feb 2008 rain event.

Ion/ Nutrient	**Mean difference (downstream-upstream)**	**Standard Deviation**	**T-value**	**p-value**
Na^+	183.3	181.1	5.26	0.000*
Cl^-	106.9	128.2	4.33	0.000*
K^+	5.639	3.389	8.65	0.000*
Ca^{+2}	-16.36	8.92	-9.53	0.000*
Mg^{+2}	-2.288	1.873	-6.35	0.000*
NO_3^-	-2.801	1.812	-8.03	0.000*
SO_4^{-2}	-7.140	4.883	-7.60	0.000*
NH_4^+	0.802	0.520	5.56	0.000*
SRP	1.41	14.95	0.43	0.317

*values are significant at 99% confidence ($\alpha<0.01$)

Table 5: Amount of time to peaks sodium, chloride, and potassium concentrations and total increase in ion concentrations for upstream and downstream sites during 26 Feb 2008 rain event.

	Upstream	**Downstream**
Time to peak in stage (h)	6.25 (4:15 PM)	5 (3:00 PM)
Base flow [Na^+] (ppm)	15.65	243.35
Peak [Na^+] (ppm) and Time of Peak	73.76 (12:45 AM)	672.42 (11:30 AM)
Total increase in [Na^+] ([highest peak]-[base flow]) (ppm)	58.11	429.07
Time to peak in [Na^+] (h)	2.75	1.5
Rate Increase [Na^+] (ppm/h)	23.72	286.05
Base flow [Cl^-] (ppm)	10.32	138.77
Peak [Cl^-] (ppm) and Time of Peak	49.15 (12:30 PM)	601.50 (11:30 AM)
Total increase in [Cl^-] ([highest peak]-[base flow]) (ppm)	38.83	462.73
Time to peak in [Cl^-] (h)	2.5	1.5
Rate Increase [Cl^-] (ppm/h)	15.53	308.49
Base flow [K^+] (ppm)	2.22	3.29
Peak [K^+] (ppm) and Time of Peak	2.40 (12:45 PM)	21.58 (11:45 AM)
Total increase in [K^+] ([highest peak]-[base flow]) (ppm)	0.18	18.29
Time to peak in [K^+] (h)	2.75	1.75
Rate Increase [K^+] (ppm/h)	0.06	12.61

Table 6: Amount of time to minimum calcium and magnesium concentrations and total decrease in ion concentrations for upstream and downstream sites during 26 Feb 2008 rain event.

	Upstream	**Downstream**
Time to peak in stage (h)	6.25 (4:15 PM)	5 (3:00 PM)
Base flow [Ca^{+2}] (ppm)	60.75	55.72
Minimum [Ca^{+2}] (ppm) and Time of Minimum	37.66 (3:45 PM)	20.63 (2:15 PM)
Total decrease in [Ca^{+2}] ([base flow]-[minimum]) (ppm)	-23.09	-35.09
Time to minimum in [Ca^{+2}] (h)	5.74	4.25
Rate Decrease [Ca^{+2}] (ppm/h)	-4.02	-8.26
Base flow [Mg^{+2}] (ppm)	10.05	10.94
Minimum [Mg^{+2}] (ppm) and Time of Minimum	3.05 (4:15 PM)	2.24 (3:00 PM)
Total decrease in [Mg^{+2}] ([base flow]-[minimum]) (ppm)	-7.42	-8.70
Time to minimum in [Mg^{+2}] (h)	6.25	5
Rate Decrease [Mg^{+2}] (ppm/h)	-1.19	-1.74

Table 7: Amount of time to minimum nitrate and sulfate concentrations; and total decrease in ion concentrations for upstream and downstream sites during 26 Feb 2008 rain event.

	Upstream	**Downstream**
Time to peak in stage (h)	6.25 (4:15 PM)	5 (3:00 PM)
Base flow [NO_3^-] (ppm)	12.89	11.67
Minimum [NO_3^-] (ppm) and Time of Minimum	5.03 (4:15 PM)	4.48 (3:00 PM)
Total decrease in [NO_3^-] ([base flow]-[minimum]) (ppm)	-7.86	-7.19
Time to minimum in [NO_3^-] (h)	6.25	5
Rate Decrease [NO_3^-] (ppm/h)	-1.26	-1.44
Base flow [SO_4^{-2}] (ppm)	32.76	31.64
Minimum [SO_4^{-2}] (ppm) and Time of Minimum	16.923 (4:15 PM)	12.24 (2:15 PM)
Total decrease in [SO_4^{-2}] ([base flow]-[minimum]) (ppm)	-15.84	-19.40
Time to minimum in [SO_4^{-2}] (h)	6.25	4.25
Rate Decrease [SO_4^{-2}] (ppm/h)	-2.53	-4.57

Table 8: Ammonium concentrations and detection times at the upstream and downstream sites during the 26 Feb 2008 rain event.

	Upstream	**Downstream**
Time to peak in stage (h)	6.25 (4:15 PM)	5 (3:00 PM)
Base flow [NH_4^+] (ppm)	0	0
Initial detection [NH_4^+] (ppm) and Detection Time	0.599 (1:45 PM)	3.714 (12:30 PM)
Peak [NH_4^+] (ppm) and Peak Time	0.641 (3:00 PM)	4.106 (1:15 PM)
Time to Initial Detection (h)	3.75	2.5
Time to Peak [NH_4^+] (h)	5	3.25
Total increase in [NH_4^+] ([peak]-[initial detection]) (ppm)	0.042	0.392
Rate Decrease from peak [NH_4^+] (ppm/h)	-0.053	-0.381

Table 9: Soluble reactive phosphorus (SRP) concentrations and amount of time to peak concentrations at the upstream and downstream sites during the 26 Feb 2008 rain event.

	Upstream	Downstream
Time to peak in stage (h)	6.25 (4:15 PM)	5 (3:00 PM)
Base flow [SPR] (ppb)	5	3
First Peak in [SPR] (ppb) and Peak Time	32 (2:00 PM)	18 (1:30 PM)
Second Peak [SPR] (ppb) and Peak Time	28 (4:45 PM)	26 (3:30 PM)
Time to First Peak (h)	4	3.5
Time to Second Peak (h)	6.75	5.5
Total increase in [SPR] ([highest peak]-[base flow]) (ppb)	27	23
Rate Increase in [SPR] to highest peak (ppb/h)	6.75	4.18

Table 10: Upstream and downstream comparisons of dissolved metal concentrations using paired t-tests from 10:00 AM to 5:15 PM during the 26 Feb 2008 rain event.

Dissolved Metal	Mean difference (downstream -upstream)	Standard Deviation	T-value	p-value
Mn	-0.008739	0.003758	-12.08	0.000*
Fe	-0.02367	0.02991	-4.11	0.000*

*values are significant at 99% confidence (0.01=α)

Table 11: Dissolved metal concentrations and amount of time to peak concentrations at the upstream and downstream sites during the 26 Feb 2008 rain event.

	Upstream	**Downstream**
Time to peak in stage (h)	6.25 (4:15 PM)	5 (3:00 PM)
Base flow [Mn] (ppm)	0.016	0.002
First Peak in [Mn] (ppm) and Peak Time	0.008 (5:15 PM)	0.005 (3:15 PM)
Second Peak [Mn] (ppm) and Peak Time	--	0.003 (6:35 PM)
Time to First Peak (h)	7.25	2.25
Time to Second Peak (h)	--	8 hrs 30 min
Total increase in [Mn] ([highest peak]-[base flow]) (ppm)	-0.008	0.003
Base flow [Fe] (ppm)	0.025	0.008
First Peak in [Fe] (ppm) and Peak Time	0.040 (5:00 PM)	0.045 (3:00 PM)
Second Peak [Fe] (ppm) and Peak Time	--	0.033 (5:00 PM)
Time to First Peak (h)	7	5
Time to Second Peak (h)	--	7
Total increase in [Fe] ([highest peak]-[base flow]) (ppm)	0.015	0.037

Table 12: Upstream and downstream comparisons of specific conductivity, pH, and temperature using paired t-tests from 10:00 AM to 5:15 PM during the 26 Feb 2008 rain event.

	Mean difference (downstream -upstream)	**Standard Deviation**	**T-value**	**p-value**
Specific Conductivity (µS/cm)	786	883	4.64	0.000*
pH	0.8563	0.1028	43.29	0.000*
Temperature (°C)	-0.887	0.791	-5.83	0.000*

*values are significant at 99% confidence (0.01=α)

Table 13: Amount of time to peaks in specific conductivity and total increase of specific conductivity for upstream and downstream sites during 26 Feb 2008 rain event.

	Upstream	**Downstream**
Time to peak in stage (h)	6.25 (4:15 PM)	5 (3:00 PM)
Avg Base Flow Sp. Conductivity (µS/cm) (24-25 Feb 08)	524	608
Base flow Sp. Conductivity (µS/cm)	516 (10:00 AM)	1740 (10:00 AM)
Peak Sp. Conductivity (µS/cm) and Time of Peak	794 (12:45 PM)	3941 (11:30 AM)
Time to Peak (h)	2.75	1.5
Total increase in Sp. Conductivity (highest peak-base flow) (µS/cm)	278	2201
Rate Increase (µS/cm/h)	101.09	1467.33

Table 14: Amount of time to minimum pH and total decrease in pH for upstream and downstream sites during 26 Feb 2008 rain event.

	Upstream	**Downstream**
Time to peak in stage (h)	6.25 (4:15 PM)	5 (3:00 PM)
Avg Base Flow pH (24-25 Feb 08)	7.01	8.11
Base flow pH (26 Feb 08)	7.09 (10:00 AM)	8.17 (10:00 AM)
Minimum pH and Time of Minimum	6.99 (6:55 PM)	7.65 (7:15 PM)
Time to Minimum (h)	8.92	9.25
Total decrease in pH (Minimum-base flow)	-0.1	-0.52
Rate Decrease (pH /h)	-0.01	-0.06

Table 15: Amount of time to minimum temperature and total decrease in temperature for upstream and downstream sites during 26 Feb 2008 rain event.

	Upstream	**Downstream**
Time to peak in stage (h)	6.25 (4:15 PM)	5 (3:00 PM)
Avg Base Flow Temperature (°C) (24-25 Feb 08)	4.66	3.13
Base flow Temperature (°C)	4.39 (10:00 AM)	2.79 (10:00 AM)
Minimum Temperature (°C) and Time of Minimum	2 (4:45 PM)	2.15 (5:15 PM)
Time to Minimum (h)	6.75	7.25
Total decrease in Temperature (Minimum-base flow) (°C)	-2.39	-0.64
Rate Decrease (°C /h)	-0.35	-0.09

Table 16: Breakdown of types, application times, amount applied, and chemical composition of fertilizers used at Bucknell University.

Fertilizer	Application Timing	Amount applied	Analysis Breakdown
12-3-12 Liquid Fert.	Greens: May-Sept every 7-21 days	22/100 of a pound N	Nitrogen-12% -6% urea -6% Slow Available N Phosphorus- 3%
	All Tees: May-Sept every 14-28 days	22/100 lb N	Potassium - 12% Sulfur 1.5% Iron .1% Boron -.05% Copper .05% Manganese .05% Zinc .05%
18-9-18 Granular Fert.	Greens 2 apps. early Aug	1/2 lb. N per app.	Nitrogen - 18% -1.9% Ammonical N -6.9% urea -5.4% Sol. N (Methy. Ur.)
	Bentgrass Tees: 1 app in May 1 app in Sept.	1/2 lb. N per app.	-3.8% Insol N Phosphorus- 9% Potassium- 18% Sulfur 6%
	Range Tee monthly June-Sept	1/2 lb. N per app.	Iron .28 % Mn .14%
20-5-20 Granular Fert.	Greens 1 fall app.	1 lb. N	Nitrogen - 20% -12% Methylene Urea -5.8% Urea
	Bentgrass Tees 1 fall app.	1 lb. N	-2.2% Ammonical N Phosphorus - 5% Potassium - 20% Sulfur 8.1% Iron 1%
20-4-10 granular fert. w/.13% Dimension Dimension (ai is dithiopyr)	All tees Green surrounds Fairways Rough (high play) 1 spring application	.88 lb N /1000 sqft.	Nitrogen - 20% -11% ammonical N -4.8% Insol. N -1.2% Urea -3% Sol. N (Meth. Urea) Phosphorus - 4% Potassium - 10% Iron .05%

25-5-15 Granular fert.	Fairways 1 late spring app	Controlled release N releases appx. 1/10 lb N per week until mid Sept.	Nitrogen - 25% -Methylene urea - 23% -Ammonical N - 2% Phosphorus - 5% Potassium - 15%
19-26-5 Granular fert. Seed starting fert	Fairways Ryegrass tees 1 early fall application any newly seeded area	1lb N /1000 sqft.	Nitrogen -19% -Urea 3.2% -Trikote urea 5.7% -Ammonical N 10.1% Phosphorus - 26% Potassium - 5% Sulfur - 2.6% Iron - 1%

Appendix B: Figures

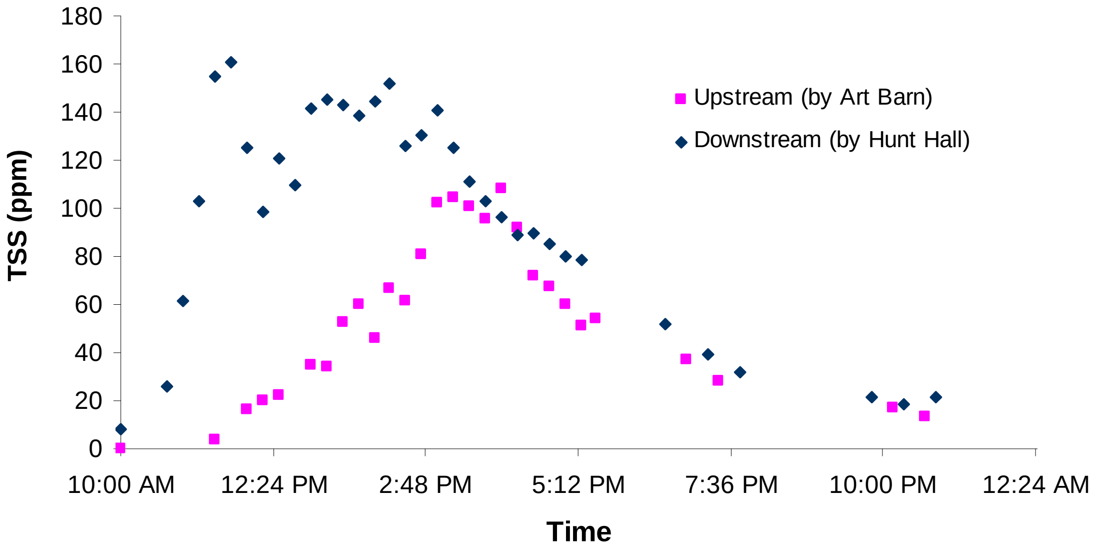

Figure 1: Upstream and downstream comparison of TSS concentrations over time during 26 Feb 2008 rain event.

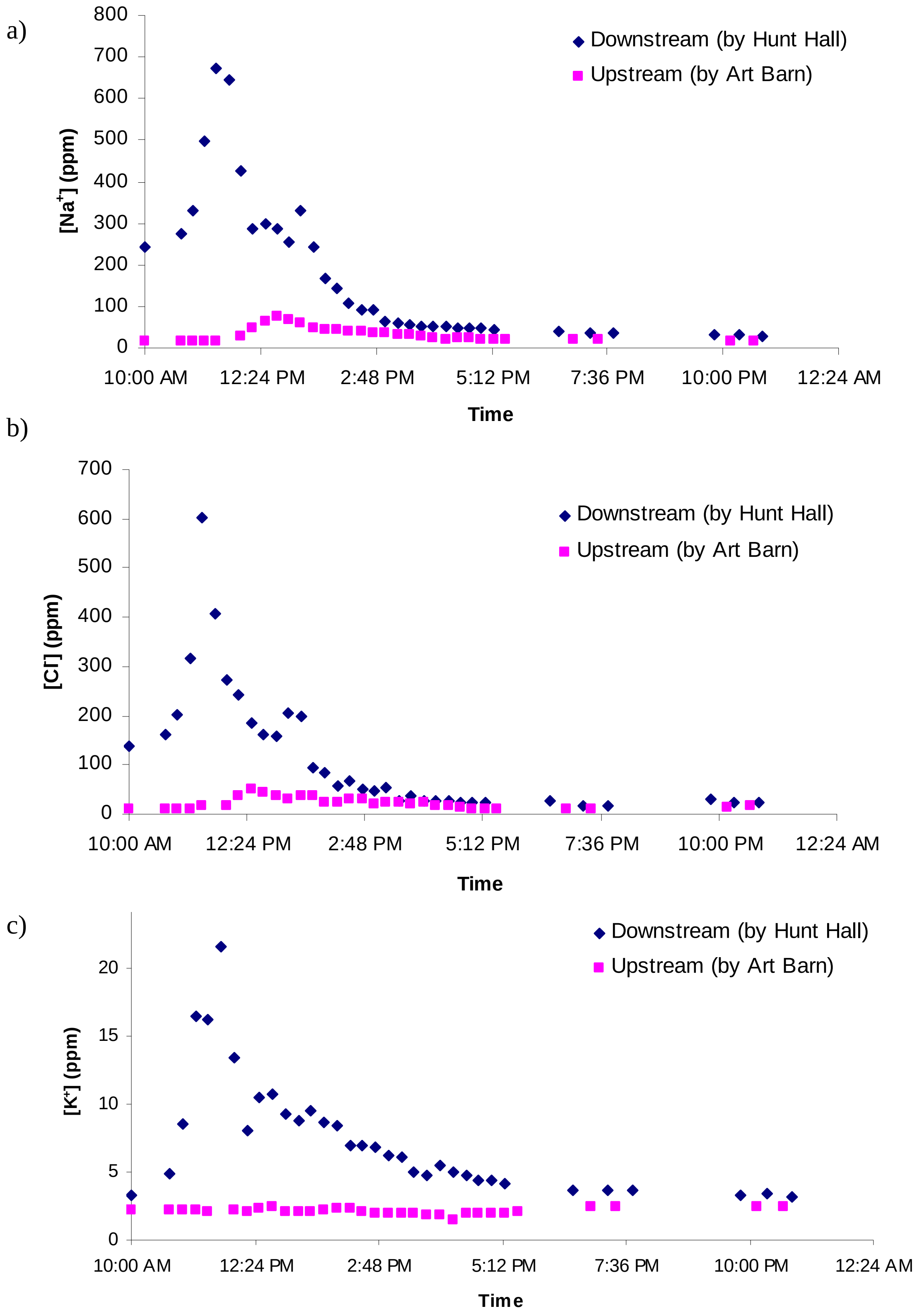

Figure 2: Upstream and downstream comparison of (a) sodium, (b) chloride, and (c) potassium concentrations over time during 26 Feb 2008 rain event.

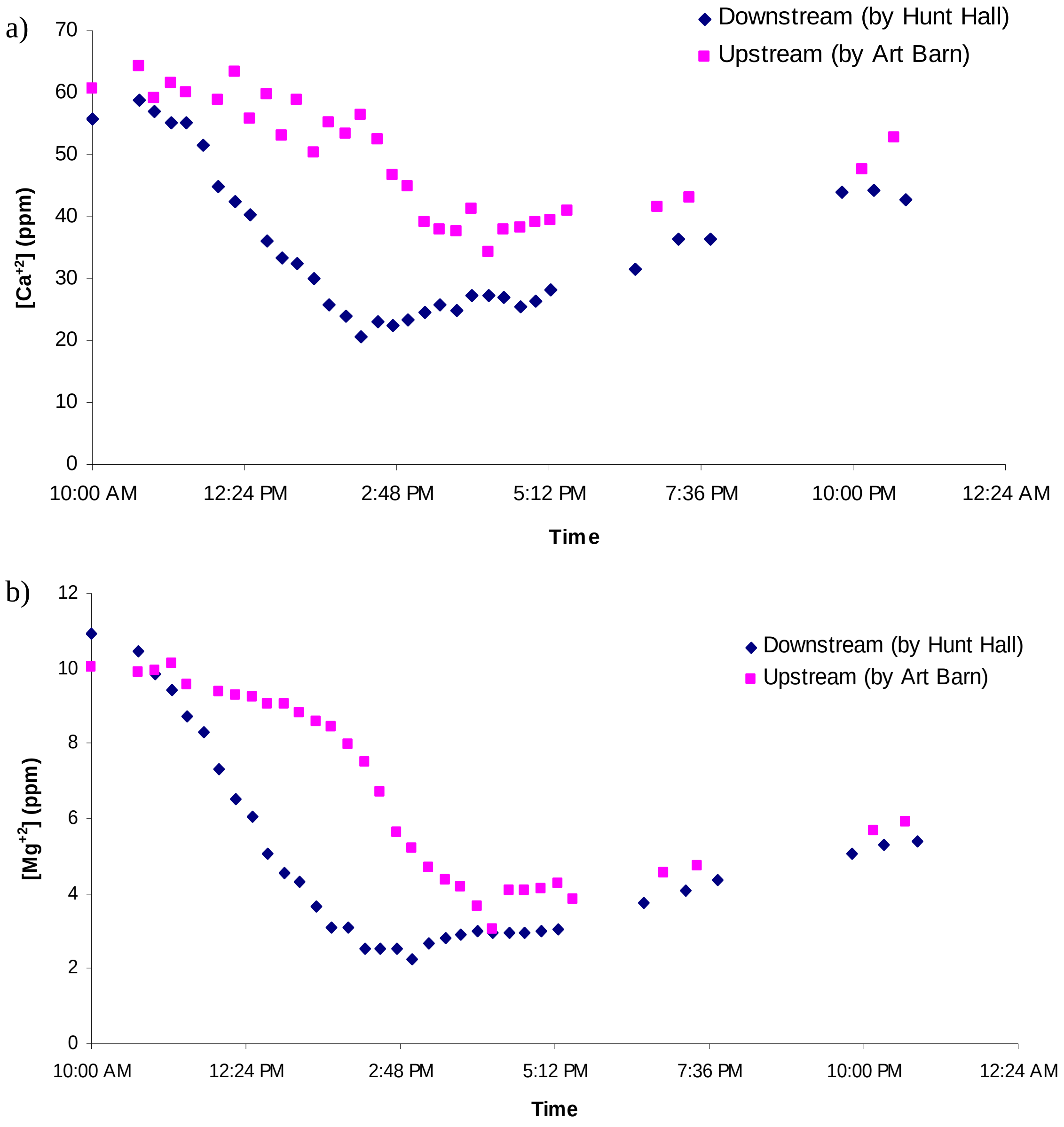

Figure 3: Upstream and downstream comparison of (a) calcium and (b) magnesium concentrations over time during 26 Feb 2008 rain event.

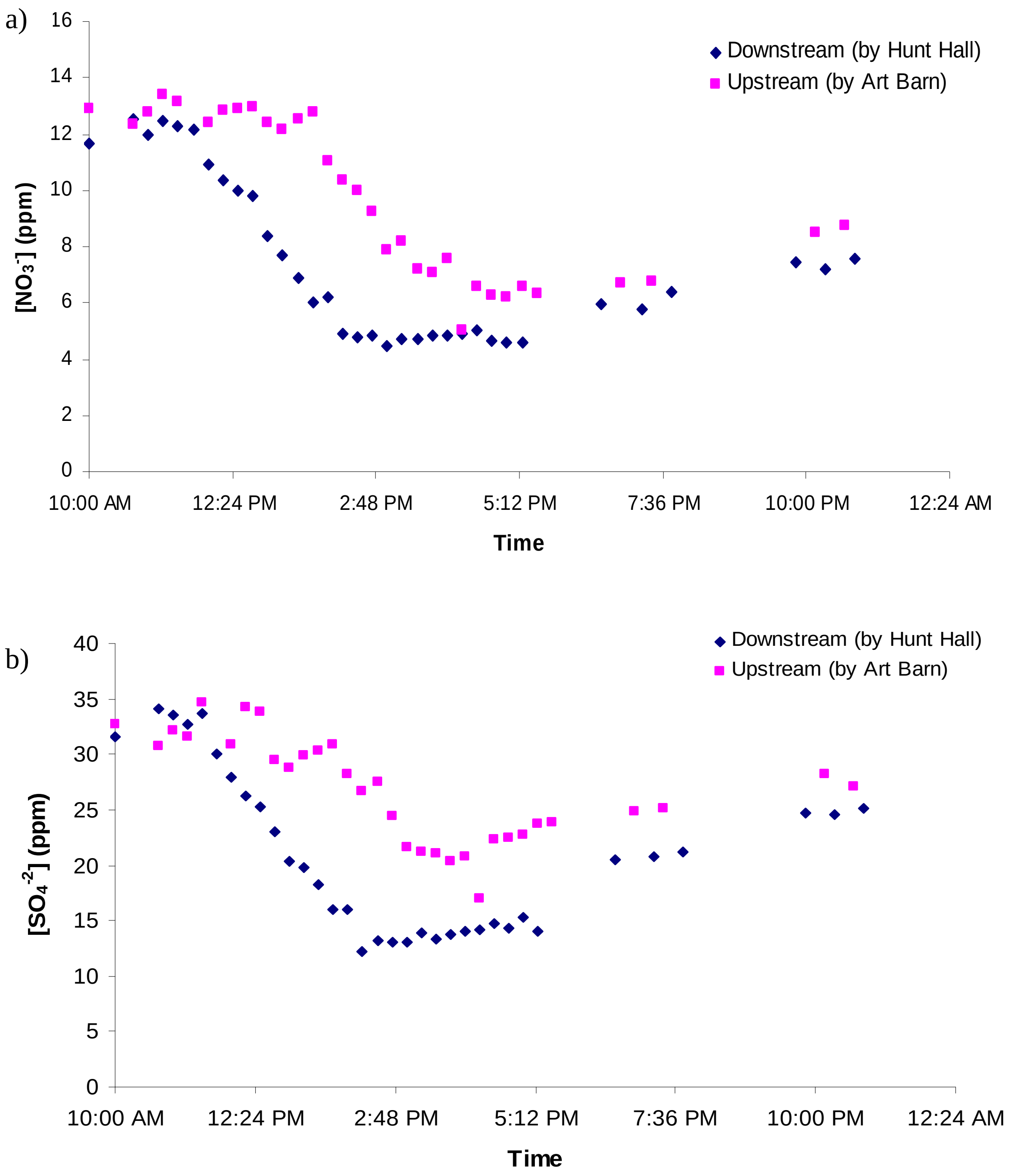

Figure 4: Upstream and downstream comparison of (a) nitrate and (b) sulfate concentrations over time during 26 Feb 2008 rain event.

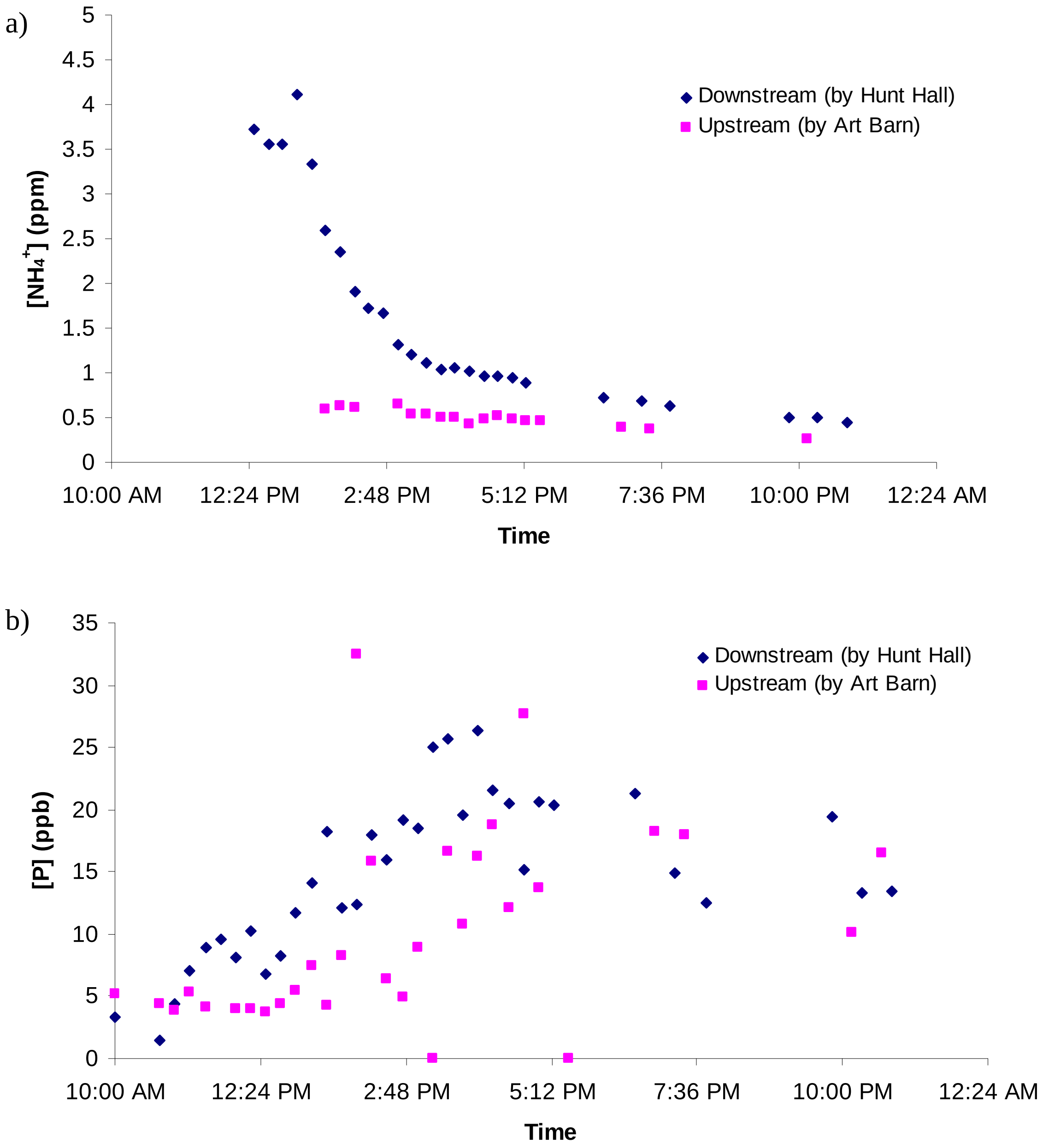

Figure 5: Upstream and downstream comparison of (a) ammonium and (b) soluble reactive phosphorus concentrations over time during 26 Feb 2008 rain event.

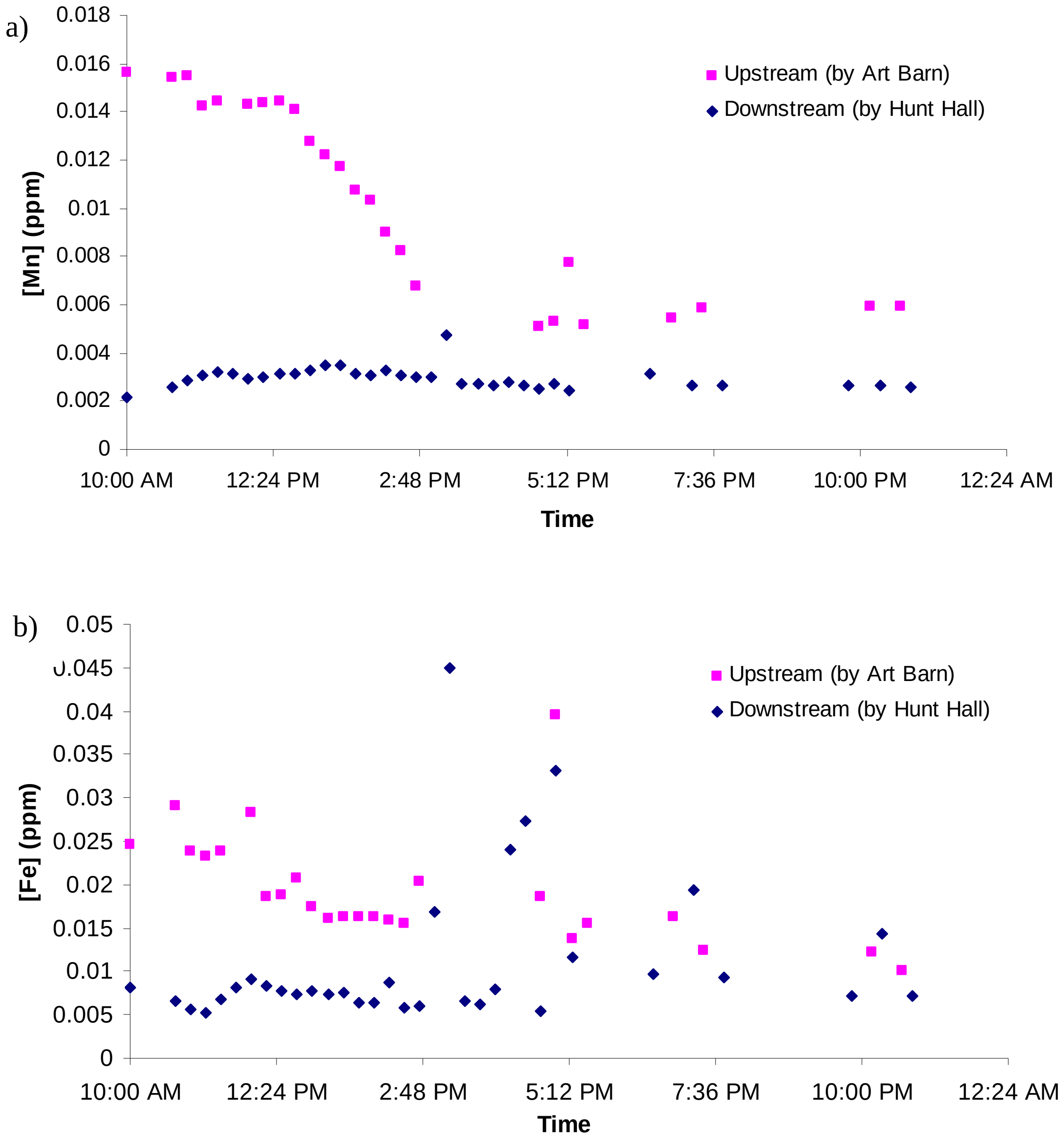

Figure 6: Upstream and downstream comparison of (a) manganese and (b) iron concentrations over time during 26 Feb 2008 rain event.

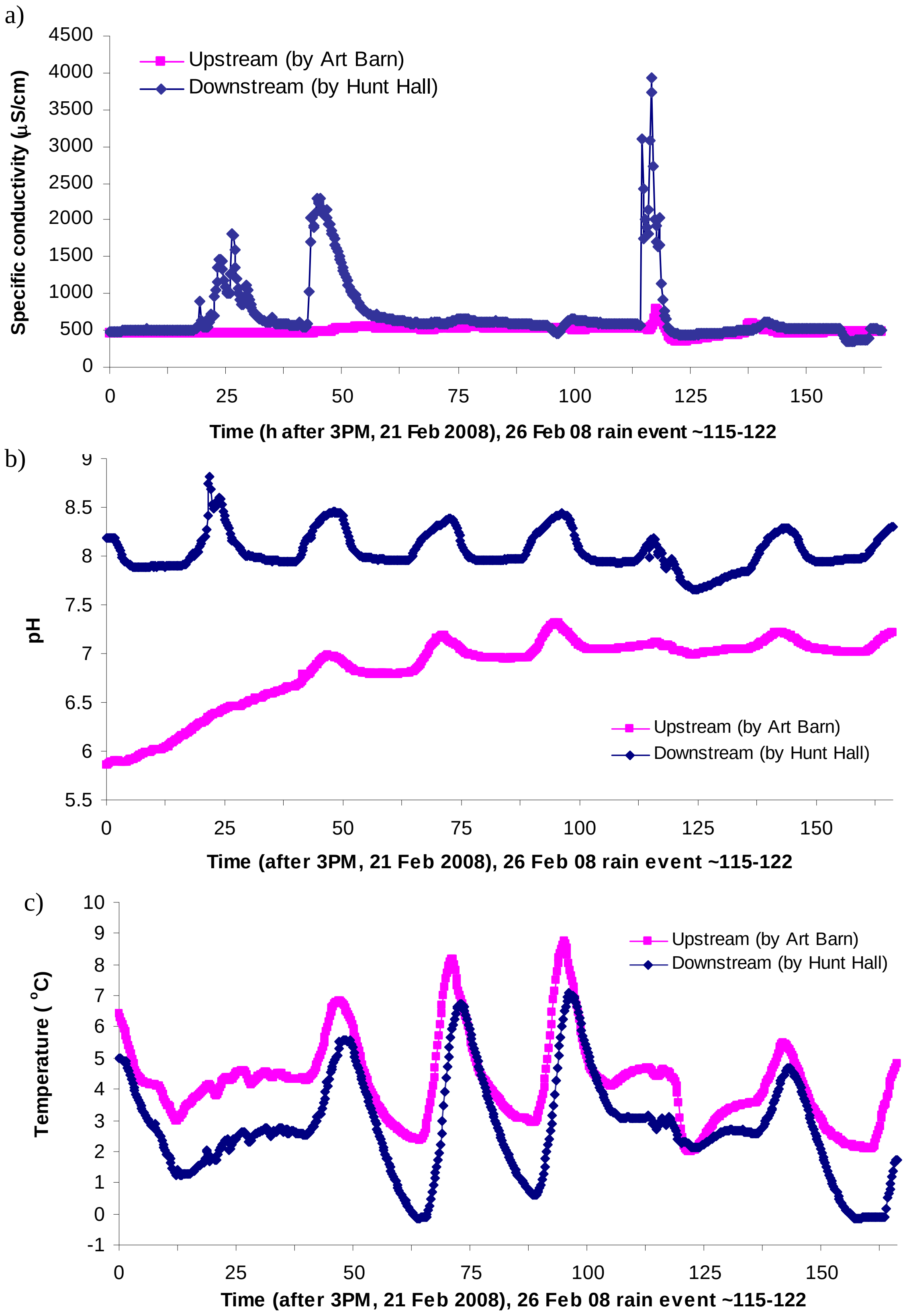

Figure 7: Comparison of upstream and downstream (a) specific conductivity, (b) pH, and (c) temperature from 21-27 Feb 2008. The 26 Feb 2008 rain event is represented by time = 115-122.

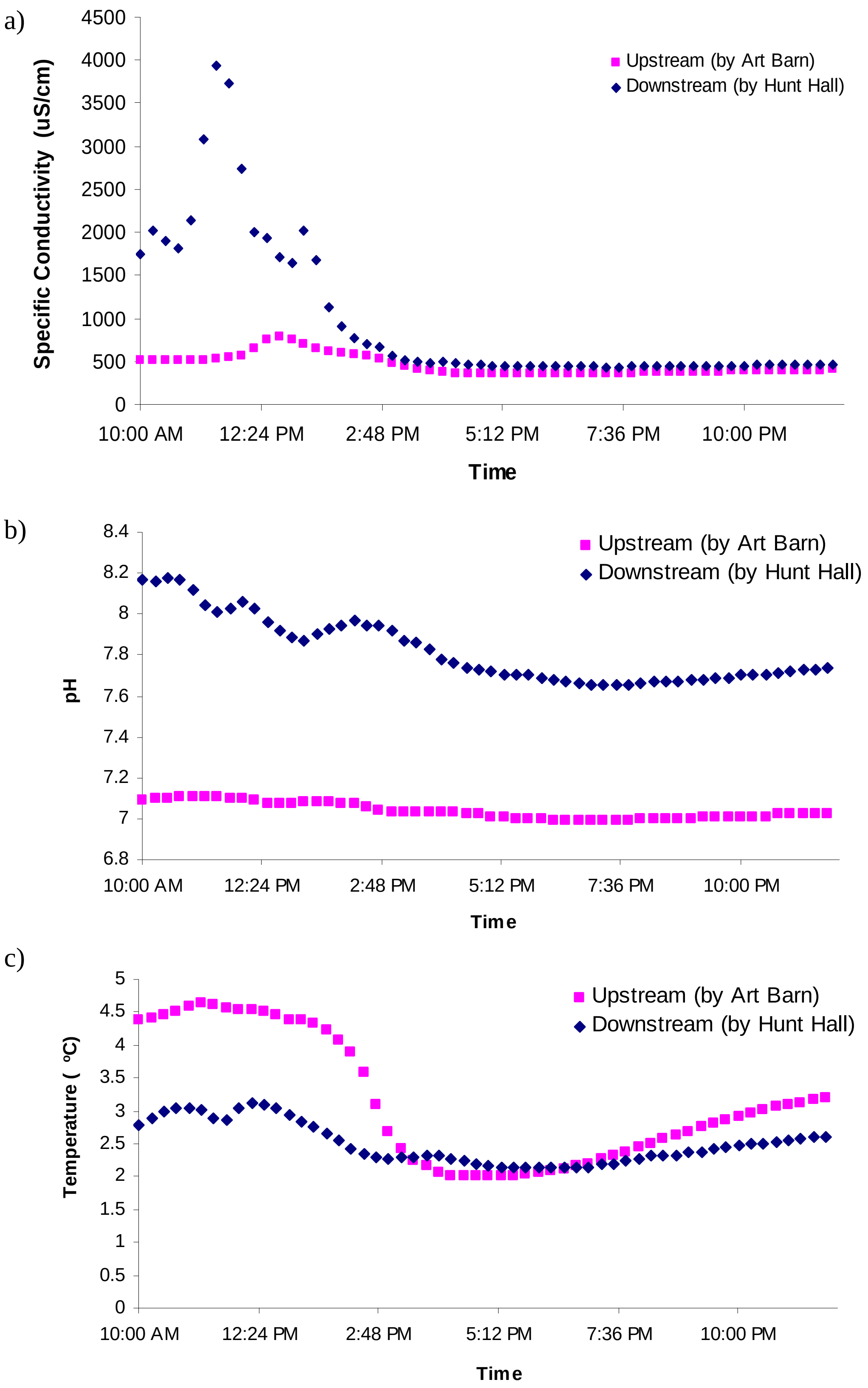

Figure 8: Upstream and downstream comparison of (a) specific conductivity, (b) pH, and (c) temperature during 26 Feb 2008 rain event.

Appendix C: Pictures

A

B

C D E

F

13 September 2007

A: Storm water drain on Loomis Street directly above Miller Run.
B: Bridge under Art Building.
C, D, E: Storm water pipes located in the downstream reach of Miller Run.
F: Storm water drain next to Art Building.

Upstream Reach

A

B

C

D

E

F

Upstream Reach

A, B: Upstream at the Bucknell Golf Course.
C: 7-8 Mar 2008 rain event. Upstream reach of the stream (by Art Barn) reached bankfull and spilled over onto the flood plain.
D: Drainage pipes in the stream at the golf course.
E: Upstream reach of Miller Run, between the Art Barn and U.S. Highway 15, during a rain event.
F: Upstream at the Bucknell Golf Course.

Downstream Reach

A

B

C

D

E

13 September 2007 (no base flow)

A: Covert under railroad where Miller Run joins Limestone Run.
B: Downstream reach of the stream behind Hunt Hall parking lot.
C: The footbridge at the downstream sampling site.
D: Downstream reach of Miller Run adjacent to Loomis Street. Example of rip rap and bank erosion along stream banks.
E: Downstream reach of the stream in front of the Art Building.

Downstream Reach (cont.)

A

B

C

D

E

A: Downstream reach of Miller Run in front of Bucknell Hall. Example of bank erosion.
B: Miller Run at bankfull between Loomis Street and Hunt Hall parking lot footbridge. 5 March 2008
C: Alison collecting water samples during 5 March 2008 rain event.
D: Downstream reach of the stream several days following a large rain event.
E: Dr. Matt McTammany setting up tape measure for discharge measurements during 5 March 2008 rain event.

Upstream Construction Site and Sediment Loads

A, B: Downstream (A) and upstream (B) reach of the stream impacted by high sediment loads during 7-8 Mar 2008 rain event.

C, D: Downstream reach impacted by sediment runoff from construction site during 11 Nov 2007 rain event.

E, F: Upstream construction site along Smoketown Road. 23 Jan 2008

G: Confluence between small tributary (right) and main stem (left) of Miller Run. The tributary drains the northern half of the golf course and athletic fields. The main stem received direct runoff from the construction site (8 Mar 2008)

Water Removal

10 March 2008

Hot storm water being removed from a manhole and pumped into a storm drain that flows directly into Miller Run.