2-2007

Basin-Scale Methodology for Evaluating Relative Impacts of Pollution Source Abatement

James T. Mangarillo

University of Massachusetts - Amherst

Follow this and additional works at: https://scholarworks.umass.edu/cee_ewre

Part of the [Environmental Engineering Commons](#)

Mangarillo, James T., "Basin-Scale Methodology for Evaluating Relative Impacts of Pollution Source Abatement" (2007).
Environmental & Water Resources Engineering Masters Projects. 29.
<https://doi.org/10.7275/H9HP-8310>

This Article is brought to you for free and open access by the Civil and Environmental Engineering at ScholarWorks@UMass Amherst. It has been accepted for inclusion in Environmental & Water Resources Engineering Masters Projects by an authorized administrator of ScholarWorks@UMass Amherst. For more information, please contact scholarworks@library.umass.edu.

**BASIN-SCALE METHODOLOGY FOR EVALUATING RELATIVE IMPACTS
OF POLLUTION SOURCE ABATEMENT**

A Masters Project Presented by

James T. Mangarillo

Submitted to the Department of Civil and Environmental Engineering

of the University of Massachusetts at Amherst

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Environmental Engineering

February, 2007

Department of Civil and Environmental Engineering

University of Massachusetts, Amherst

**BASIN-SCALE METHODOLOGY FOR EVALUATING RELATIVE IMPACTS
OF POLLUTION SOURCE ABATEMENT**

A Masters Project Presented by

James T. Mangarillo

Approved as to style and content by:

Paula L. Sturdevant Rees, Chairperson

David A. Reckhow, Member

John E. Tobiason
Graduate Program Director
Environmental Engineering Program

Acknowledgements

I would like to thank my academic advisor, Dr. Paula L. S. Rees of the Civil and Environmental Engineering Department at the University of Massachusetts, Amherst for her input and guidance during the course of this project. I would also like to thank Dr. David Reckhow for serving as a member of my committee.

My thanks are also due to Tom Walsh and the Upper Blackstone Water Pollution Abatement District for their financial support.

I would also like to thank the faculty and students at UMass, especially 318 Cold Storage, for their help with the project and their continued support.

Finally I would like to thank my family and friends. Without their support, I could never have achieved so much.

Abstract

The Blackstone River watershed covers an area of 475 mi² in central Massachusetts and northern Rhode Island. The Blackstone flows from its headwaters in the hills above Worcester, MA, through Woonsocket, RI and finally joins the Seekonk River in Pawtucket, RI. The Seekonk then flows into the Providence River on its way into Narragansett Bay. The historical significance of the Blackstone River has been recognized at the federal, state and local levels. Furthermore, the Blackstone is known to play a significant role on the hydrology and ecology of Narragansett Bay.

This study is part of a larger study designed to evaluate the cost-benefit effectiveness of past remediation efforts and, in a modeling framework, potential future, traditional and progressive abatement strategies at the local and watershed scales. A driving theme of this portion of the study is the development of a detailed understanding of point and nonpoint source contributions within both the headwaters of the Blackstone and the watershed as a whole. Understanding the source, fate and transport of contaminants along the mainstem of the Blackstone River is essential for setting reasonable management strategies in order to achieve the desired water quality goals in both the river and the bay.

Initial investigations into the relative magnitudes of point source and nonpoint source nutrient loadings under current and future loading regimes were conducted to allow a better understanding of the impacts of current regulations and the need if any for future regulatory action. Relationships between water quality and surrounding land use characteristics were analyzed to determine if correlations between the two exist and to predict the impact on water quality that may be caused by future changes in land use in the basin. Analyses on monthly and annual point and nonpoint source loadings dynamics between the Blackstone and Narragansett Bay were conducted as well. The relative nutrient loadings under wet and dry weather loading regimes were determined, with

particular attention being placed on the impacts of the numerous impoundments along the mainstem of the Blackstone River.

Based on the work contained herein, it has been concluded that there is a positive correlation between the amount of urbanized area and the amount of water quality degradation in the Blackstone watershed and its sub-basins. Furthermore, increasing amounts of urbanization will lead to increased peak flow values seen in the river, allowing for increased resuspension of pollutant laden sediment from behind the impoundments along the mainstem of the river, especially during wet weather events. Also, due to the complex hydraulics and loading dynamics of the Blackstone River, its tributaries and the bay as a whole, further regulation of point source pollution alone may not be an adequate or cost effective method for reducing nutrient loadings into the Blackstone River and Narragansett Bay. The loading dynamics have been shown to be highly variable on a monthly timescale, a variability that is likely to increase if more refined water quality and quantity data is collected for the river. Finally, the lack of available wet weather data also points to the need for additional, more refined data collection to be undertaken in order to better assess the loadings into the Blackstone River and their propagation downstream into Narragansett Bay. The need for additional data is supported by the highly variable loadings seen in the river as well as the changes in both the land use and the hydrology in the watershed that have occurred since the BRI was conducted.

Table of Contents

Acknowledgements	i
Abstract	ii
1.0 - Introduction	1
2.0 - Literature Review.....	11
2.1 - Blackstone River Watershed	11
2.2 - Narragansett Bay Watershed	15
2.3 - Regulatory Focus.....	20
2.3.1 - Point Source Based Regulation	20
2.3.2 - Nonpoint Source/Watershed Based Regulation	24
2.3.3 - Regulatory Focus in the Blackstone.....	26
2.3.4 - Regulatory Focus in Narragansett Bay.....	29
2.4 - Nutrient Impacts, Sources and Cycling.....	32
2.5 - Urbanization, Land Use Change and Population Growth	37
2.6 - Percent Imperviousness.....	39
2.7 - Watershed Modeling	40
2.8 - Summary	41
3.0 – Spatial Water Quality and Pollutant Loading Analysis.....	43
3.1 - Available Data.....	44
3.2 - Methodology	46
3.2.1 - Land Use and Percent Imperviousness Analysis.....	46
3.2.2 - Water Quality Analysis - Upper Blackstone Watershed	50
3.2.3 - Comparison between Water Quality Impairment Metrics	51
3.2.4 - Point Source vs. Nonpoint Source Loading Analysis	51
3.2.5 - Major River Annual Pollutant Load Estimation to Narragansett Bay.....	56
3.2.6 - Total Loading into Narragansett Bay	61
3.3 - Results & Discussion.....	62
3.3.1 - Land Use and Percent Imperviousness Analysis.....	62
3.3.2 - Water Quality Analysis - Upper Blackstone Watershed	67
3.3.3 - Comparison between Water Quality Impairment Metrics	69
3.3.4 - Point Source vs. Nonpoint Source Loading Analysis	70
3.3.5 - Major River Annual Pollutant Load Estimation to Narragansett Bay.....	84
3.3.6 - Total Loading into Narragansett Bay	87
3.4 - Conclusions & Discussion.....	99
4.0 – Along Stream Processes	102
4.1 - Methodology	105
4.1.1 - Dry Weather Loading Analysis.....	107
4.1.2 - Wet Weather Loading Analysis	108
4.1.3 - Source/Sink Identification Analysis.....	109
4.1.4 - Assimilative Capacity Analysis.....	109
4.2 - Results and Discussion.....	111
4.2.1 - Dry and Wet Weather Loading Analysis	111
4.2.2 - Gain/Loss Analysis.....	116
4.2.3 - Assimilative Capacity Analysis.....	120
4.3 - Conclusions	123

5.0 - Temporal Analysis.....	125
5.1 - Methodology	126
5.1.1 - Trends in Water Quality	126
5.1.2 - Population Trends.....	127
5.1.3 - Land Use Changes over Time	128
5.1.4 - Changes in Percent Impervious Values over Time	128
5.1.5 - Temporal Changes in PS vs. NPS Loading Estimates	129
5.1.6 - Hydrological Changes over Time.....	130
5.2 - Results & Discussion.....	131
5.2.1 - Trends in Water Quality	131
5.2.2 - Population Trends.....	132
5.2.3 - Land Use Changes over Time	133
5.2.4 - Changes in Percent Impervious Values over Time	135
5.2.5 - Temporal Changes in PS vs. NPS Loading Estimates	137
5.2.6 - Hydrological Changes over Time.....	143
5.3 - Conclusions	148
6.0 - Summary and Conclusions.....	150
6.1 - Summary of Results	150
6.2 - Conclusions	156
7.0 - Future Work	159
7.1 - Data Collection.....	159
7.2 - Watershed Modeling	160
8.0 - References	162

List of Figures

Figure 1 – Blackstone River Watershed	1
Figure 2 - Urban Centers along the Blackstone River	3
Figure 3 - Narragansett Bay Watershed.....	6
Figure 4 – Facility Construction and Upgrade Timeline for the Blackstone River and Select Narragansett Bay Facilities	27
Figure 5 - Blackstone Watershed and its Sub-Watersheds	49
Figure 6 - Upper Blackstone Watershed and its Sub-Watersheds	49
Figure 7 - Blackstone River Watershed Sub-Basins and Land Use Classifications.....	62
Figure 8 - Percent Imperviousness of the Blackstone Watershed and its Sub-Basins.....	64
Figure 9 - UBS Sub-Watershed Percent Imperviousness Classifications	65
Figure 10 – Blackstone Basin Estimated Annual Nonpoint Source Total Nitrogen Loading	71
Figure 11 – Blackstone Basin Estimated Annual Point Source Total Nitrogen Loading..	71
Figure 12 – Blackstone Basin Estimated Annual Nonpoint Source Total Phosphorus Loading	73
Figure 13 – Blackstone Basin Estimated Annual Point Source Total Phosphorus Loading	73
Figure 14 - Blackstone Basin Estimated Monthly Point Source Total Nitrogen Loading	74
Figure 15 - Blackstone Basin Estimated Monthly Nonpoint Source Total Nitrogen Loading.....	74
Figure 16 - Blackstone Basin Estimated Monthly Point Source Total Phosphorus Loading	76
Figure 17 - Blackstone Basin Estimated Monthly Nonpoint Source Total Phosphorus Loading	76
Figure 18 – Upper Blackstone Basin Estimated Annual Nonpoint Source Total Nitrogen Loading.....	78
Figure 19 – Upper Blackstone Basin Estimated Annual Point Source Total Nitrogen Loading.....	78
Figure 20 – Upper Blackstone Basin Estimated Annual Nonpoint Source Total Phosphorus Loading	79
Figure 21 – Upper Blackstone Basin Estimated Annual Point Source Total Phosphorus Loading	79
Figure 22 – Upper Blackstone Basin Estimated Monthly Point Source Total Nitrogen Loading.....	80
Figure 23 – Upper Blackstone Basin Estimated Monthly Nonpoint Source Total Nitrogen Loading.....	80
Figure 24 – Upper Blackstone Basin Estimated Monthly Point Source Total Phosphorus Loading.....	82
Figure 25 – Upper Blackstone Basin Estimated Monthly Nonpoint Source Total Phosphorus Loading	82
Figure 26 - Q vs. N Plot for the Blackstone River.....	84
Figure 27 - Q vs. P Plot for the Blackstone River	85
Figure 28 - Narragansett Bay NPS Total Nitrogen Loading	88
Figure 29 - Narragansett Bay PS Total Nitrogen Loading	88

Figure 30 - Narragansett Bay NPS Total Phosphorus Loading.....	89
Figure 31 - Narragansett Bay PS Total Phosphorus Loading.....	89
Figure 32 - Narragansett Bay Monthly NPS Total Nitrogen Loading.....	91
Figure 33 - Narragansett Bay Monthly PS Total Nitrogen Loading	91
Figure 34 - Narragansett Bay Monthly NPS Total Phosphorus Loading	93
Figure 35 - Narragansett Bay Monthly PS Total Phosphorus Loading	93
Figure 36 - BRI Wet and Dry Weather Survey Monitoring Locations	104
Figure 37 - WWTP and Tributary Identifications and Locations.....	112
Figure 38 - BRI Dry Weather PO ₄ Loading	113
Figure 39 - BRI Wet Weather PO ₄ Loading	113
Figure 40 - BRI Dry Weather NO ₃ Loading.....	114
Figure 41 - BRI Wet Weather NO ₂ /NO ₃ Loading	114
Figure 42 - BRI Dry Weather NH ₃ Loading.....	115
Figure 43 - BRI Wet Weather NH ₃ Loading.....	115
Figure 44 - Flow Regimes of the BRI Sampling Events	122
Figure 45 - Historical Trends of NO ₂ + NO ₃ Loading at the USGS gauge at Millville (01111230).....	131
Figure 46 - Historical Trends of Phosphorus at the USGS gauge at Millville (01111230)	132
Figure 47 - Current Land Use and Sub-Basin Delineation in the Blackstone River Watershed	134
Figure 48 - Current and Future PS Loading Estimates of Total Phosphorus in the Blackstone River Watershed.....	138
Figure 49 - Current and Future NPS Loading Estimates of Total Phosphorus in the Blackstone River Watershed.....	138
Figure 50 - Current and Future PS Loading Estimates of Total Nitrogen in the Blackstone River Watershed	139
Figure 51 - Current and Future NPS Loading Estimates of Total Nitrogen in the Blackstone River Watershed.....	139
Figure 52 - Current and Future PS Loading Estimates of Total Phosphorus in the Upper Blackstone River Watershed.....	141
Figure 53 - Current and Future NPS Loading Estimates of Total Phosphorus in the Upper Blackstone River Watershed.....	141
Figure 54 - Current and Future PS Loading Estimates of Total Nitrogen in the Upper Blackstone River Watershed.....	142
Figure 55 - Current and Future NPS Loading Estimates of Total Nitrogen in the Upper Blackstone River Watershed.....	142
Figure 56 - Q vs. Time Plot for the Blackstone River at Woonsocket, RI	144
Figure 57 - Q vs. Time Plot for the Branch River	145
Figure 58 - Q vs. Time Plot for the Quinsigamond River	145
Figure 59 - Q vs. Time Plot for the Blackstone River at Woonsocket, RI.....	146
Figure 60 - Q vs. Time Plot for the Branch River	147
Figure 61 - Q vs. Time Plot for the Quinsigamond River	147

List of Tables

Table 1 -List of Dams, Impoundments, Hydroelectric Plants and WWTPs on the mainstem Blackstone River (Source: Adapted from Wright <i>et al.</i> , 2001).....	4
Table 2 – Water Quality Data Collection in the Blackstone River Watershed	13
Table 3 – River Nitrogen Mass Balance in Narragansett Bay (Source: Adapted from Nixon <i>et al.</i> , 1995) Units are in 10^6 moles/yr	16
Table 4 – WWTP Nitrogen Mass Balance in Narragansett Bay (Source: Adapted from Nixon <i>et al.</i> , 1995) Units are in 10^6 moles/yr	17
Table 5 – Total Nitrogen Mass Balance in Narragansett Bay (Source: Adapted from Nixon <i>et al.</i> , 1995) Units are in 10^6 moles/yr	17
Table 6 – River Phosphorus Mass Balance in Narragansett Bay (Source: Adapted from Nixon <i>et al.</i> , 1995) Units are in 10^6 moles/yr	18
Table 7 – WWTP Phosphorus Mass Balance in Narragansett Bay (Source: Adapted from Nixon <i>et al.</i> , 1995) Units are in 10^6 moles/yr	18
Table 8 – Total Phosphorus Mass Balance in Narragansett Bay (Source: Adapted from Nixon <i>et al.</i> , 1995) Units are in 10^6 moles/yr	18
Table 9 – Cost Estimation for TMDL Implementation (Adapted from EPA 2001b).....	25
Table 10 – Water Quality Degradation Thresholds	39
Table 11 – HSPF Modeling Efforts and Scales	41
Table 12 – Water Quality Data Collection in the Blackstone River Watershed	45
Table 13 – Water Quality Degradation Thresholds	46
Table 14 - Land Use Categories and Associated Percent Imperviousness Values.....	47
Table 15 - Land Use Classifications.....	48
Table 16 - Phosphorus and Nitrogen Impairment Criteria used by the BRC	51
Table 17 - Impairment Metric Breakdown	51
Table 18 - Nutrient Export Coefficients for MA Land Use Categories	53
Table 19 - Average Monthly Rainfall Totals (Source - NWS Web Page)	54
Table 20 - Period of Record Available for WWTPs Load Estimation	55
Table 21 - Fraction of the Year that is Occupied by Each Month (F)	56
Table 22 - Major Rivers Flowing into Narragansett Bay	57
Table 23 - Adjusted Long Term Average Flow into Narragansett Bay	58
Table 24 - Available Data for the Development of Q-C Relationship Equations	59
Table 25 - Load Adjustment Factors for Q-C Loading Analysis	60
Table 26 – Areas and Land Use Percentages for the Blackstone Watershed and its Sub-Basins.....	63
Table 27 - Percent Imperviousness Values for the Blackstone Watershed and its Sub-Basins.....	64
Table 28 - UBS Sub-Watershed Percent Imperviousness Values	66
Table 29 - Overall Average Nutrient Concentrations for the BRC	68
Table 30 - Impairment Metric Comparison: Water Quality vs. Percent Imperviousness	69
Table 31 – Percent of Total Estimated Total Nitrogen Loading in the Blackstone Basin.....	75
Table 32 – Percent of Total Estimated Total Phosphorus Loading in the Blackstone Basin	77
Table 33 – Percent of Total Estimated Total Nitrogen Loading in the Upper Blackstone Basin	81

Table 34 – Percent of Total Estimated Total Phosphorus Loading in the Upper Blackstone Basin	83
Table 35 - Q vs. C Equations used in River Loading Estimations	85
Table 36 - Estimated Annual Nutrient River Loadings	86
Table 37 - Estimated Monthly Percentages of Nutrient River Loadings.....	87
Table 38 - PS vs. NPS Total Nitrogen Loading Monthly Breakdown - Narragansett Bay	92
Table 39 - PS vs. NPS Total Phosphorus Loading Monthly Breakdown - Narragansett Bay.....	94
Table 40 - Annual Total Nitrogen Loading into Narragansett Bay	95
Table 41 - Annual Total Phosphorus Loading into Narragansett Bay.....	97
Table 42 - Monthly Breakdown of Nitrogen Loadings into Narragansett Bay	98
Table 43 - Monthly Breakdown of Total Phosphorus Loadings into Narragansett Bay ...	99
Table 44 - BRI Wet and Dry Weather Survey Monitoring Location Site Descriptions..	105
Table 45 - Locations of WWTPs, Dams and Tributary Confluences along the Mainstem of the Blackstone River	107
Table 46 - Gain/Loss Matrix for Wet and Dry Weather Loading	117
Table 47 - Wet Weather Storm I Loading Summary.....	120
Table 48 - Wet Weather Storm II Loading Summary	120
Table 49 - Wet Weather Storm III Loading Summary	120
Table 50 - Dry Weather I Loading Summary	121
Table 51 – Dry Weather II Loading Summary	121
Table 52 – Dry Weather III Loading Summary.....	121
Table 53 - USGS Gauges used in the Q_{peak} and 7Q Analyses	130
Table 54 - Population Trends in the Blackstone Watershed (Source: USCB)	133
Table 55 - Estimated Water Demands and Wastewater Returns in the Blackstone Watershed	133
Table 56 - Historical, Current and Projected Land Use Percentages	134
Table 57 - Percent Impervious Area of the Blackstone River Watershed and its Sub-basins	135
Table 58 - Percent Imperviousness Values for the UBS Watershed Sub-basins.....	137

1.0 - Introduction

The Blackstone River watershed, Figure 1, encompasses an area of approximately 475 mi² in central Massachusetts and northern Rhode Island. The Blackstone flows from its headwaters in the hills above Worcester, MA, through Woonsocket, RI and finally joins the Seekonk River in Pawtucket, RI. The Seekonk then flows into the Providence River on its way into Narragansett Bay.

Figure 1 – Blackstone River Watershed

The Blackstone is known as the “Birthplace of the American Industrial Revolution” (BRNHC, 2006). During its 46 mile run toward Narragansett Bay, the river drops 438 ft (Shanahan, 1994; BRNHC, 2006), a steeper gradient than the Colorado River (Arizona Humanities Council, 2006). Recognizing the hydraulic potential of the river, Samuel Slater built the first mill in America at the outlet of the Blackstone in 1793. Others followed suit, and at one point the river had almost one dam for every mile of river along its run. The historical and future significance of the Blackstone River has been recognized at the federal level. In 1986, the John H. Chafee Blackstone River Valley National Heritage Corridor was established by an Act of Congress. This designation provides the region an organizational framework with the ability to preserve the unique and significant value of the Blackstone Valley and to celebrate the role it played in the development of the nation (BRNHC, 2006). In 1998, the Blackstone received American

Heritage River status, opening up the potential for making more efficient and effective use of existing federal resources and cutting red-tape, without any new regulations on private property owners or state and local governments (USEPA, 2006b). In 2002, the Blackstone was one of eight rivers named to the Urban Rivers Restoration Pilot Study conducted by the United States Environmental Protection Agency (EPA) and the United States Army Corps of Engineers (ACOE). This study is aimed at promoting collaboration among the EPA, ACOE, local businesses and the non-profit community within the watershed. Its ultimate function will be to advance pollution prevention, water quality improvements and restoration of wildlife habitat within the watershed while understanding that the goal of restoring the Blackstone by 2015 will require urban rivers cleanups beyond stormwater and CSO improvement (EPA and ACOE, 2006).

The river provides aesthetic and recreational opportunities such as hiking and canoeing in addition to attractions for those seeking to learn more about the industrialization history of the region. Non-government, volunteer driven organizations have spear-headed various campaigns to improve river and ecosystem health including volunteer monitoring, river cleanups, green development projects, sewer stenciling and education outreach activities. These organizations are also actively seeking government support, both regulatory and monetary, to further improve water quality throughout the basin.

Among the industrialized watersheds of the East Coast, the Blackstone is demographically unique. The hydraulic power of the river and resulting industry, coupled with the construction of the Blackstone Canal and the Worcester-Providence Railroad (Eckilson, 2006) facilitated the growth of major population centers in the headwaters of the Blackstone as well as along its run and at its outlet. The locations of the major urban areas within the Blackstone watershed are shown in Figure 2.

Figure 2 - Urban Centers along the Blackstone River

Based on the 2000 census data obtained for communities lying within the watershed, the population density within the Blackstone River watershed is approximately 1,000 people/mi², classifying the watershed as an urbanized area (USCB, 2006). The high population density of the region combined with its industrial history has resulted in a legacy of complex water quality issues, including significant urban runoff in the headwaters; an abundance of remnant and functioning dams that influence contaminant transport and flow patterns along the river; and known or suspected deposits of nutrients, toxics, heavy metals and other pollutants that remain trapped in impoundment sediments. The locations and descriptions of the remaining dams as well as the wastewater treatment plants (WWTPs) along the mainstem of the Blackstone are shown in Table 1. The outlet of the Blackstone River in Pawtucket, RI is denoted as river mile zero, with river mile increasing in the upstream direction.

Table 1 -List of Dams, Impoundments, Hydroelectric Plants and WWTPs on the mainstem Blackstone River (Source: Adapted from Wright *et al.*, 2001)

Rivermile	Description	Rivermile	Description
44.4	UBWPAD	22	Uxbridge WWTP
43.9	McCracken Rd Dam	17.8	Tupperware Dam
41	Millbury Electric Dam	16.5	Blackstone Dam
39.8	Singing Dam	15.5	Thundermist Hydro Dam
39.2	Wilkinsonville Dam	12.8	Hamlet Ave Dam
38.7	Saundersville Dam	12.4	Woonsocket WWTP
36.5	Fisherville Dam	9.9	Manville Dam
35.6	Farnumsville Hydro Dam	8.2	Albion Dam
35.4	Grafton WWTP	6.8	Ashton Dam
31.9	Riverdale Hydro Dam	4.1	Lonsdale Dam
29.2	Northbridge WWTP	2	Central Falls Dam
27.8	Rice City Pond Dam	0.8	Pawtucket Hydro Dam
		0	Slater's Mill Dam

Five waste water treatment plants (WWTPs) discharge effluent directly to the mainstem of the Blackstone River. Most notable in terms of volume are the Upper Blackstone Water Pollution Abatement District (UBWPAD) and the Woonsocket WWTP, Table 1. The UBWPAD is located in the highly urbanized headwaters of the Blackstone, defined here as the area above the United States Geologic Survey (USGS) stream gauging station at Millbury. The UBWPAD discharge accounts for a large percentage of the flow that exits the headwaters of the watershed. Additional waste water treatment plants in Rhode

Island discharge to the Seekonk and Providence Rivers which, as previously noted, the Blackstone River flows into. Anthropogenic influences such as WWTP discharges and urban runoff have resulted in water quality degradation along the entire mainstem of the Blackstone and its tributaries. Based on data collected for the 2002 303(d) list in the Blackstone Watershed, the entire mainstem of the Blackstone as well as the majority of its tributaries are deemed impaired for at least one use. Approximately 64 percent of the river miles in the basin were assessed, with 68 percent classified as impaired. Eighty-three percent of the watershed lakes were assessed, with 65 percent classified as impaired (MADEP, 2003; RIDEM, 2003b; EPA 2006c).

The Blackstone River plays an important role in the health of Narragansett Bay. The Narragansett Bay watershed, Figure 3, encompasses approximately 1850 mi² including the 475 mi² Blackstone watershed. The Blackstone is one of the largest contributors of freshwater to Narragansett Bay, providing on average almost one quarter of the estimated 2.4 billion gallons per day (gpd) of freshwater flow to the bay (Ries, 1990; Ely, 2002; Save the Bay, 2006). The bay itself has an area of 147 mi², and an approximate volume of 706 billion gallons (Ely, 2002; Save the Bay, 2006).

Figure 3 - Narragansett Bay Watershed
(Source: NBEP, 2006)

Currently over two million people reside within the Narragansett Bay watershed with higher population densities occurring during the summer tourism season (Nixon *et al*, 2005). Over half the people in the watershed are serviced by the 33 WWTPs within the watershed (Greene and Deacutis, 2000). In addition to the WWTPs noted above which lie

within the Blackstone River watershed, major plants in the Rhode Island portion of the Narragansett Bay watershed include the Fields Point and Bucklin Point WWTPs. Fields Point and Bucklin Point are operated by the Narragansett Bay Commission (NBC) and discharge into the Providence and Seekonk Rivers respectively. Excess nutrients from the WWTPs, inland and on the shores of the bay, along with large amounts of urban runoff input directly to the bay and its tributaries are identified as the leading causes of water quality issues in the bay (Wright *et al*, 2001; Ely, 2002; Bergondo *et al*, 2005). Septic systems along the shores of the bay have also been identified as potential pollution sources, prompting a strong push to replace these typically older systems with sewer connections to WWTPs in the area (RIDEM, 2003; Nixon *et al*, 2005).

Like the Blackstone, Narragansett Bay was also significantly impacted by the Industrial Revolution. As industry replaced maritime commerce and the population of the area began to increase, the health of the bay deteriorated. Raw sewage and industrial wastes were dumped into the bay and its tributaries, creating many water quality issues and prompting closures of shellfish beds throughout the bay (Save the Bay, 2006). Over the last decade, problems with hypoxia and fish kills have occurred nearly every summer (RIDEM, 2003).

In 2003, a large fish kill was reported in Greenwich Bay. Scientists believe that a long period of rain prior to the event resulted in significant urban runoff and combined sewer overflows and the delivery of large nutrient loads to the bay. This episodic eutrophication resulted in a large algal bloom. Subsequent decomposition of the algal bloom depleted oxygen in the water column and resulted in the death of over one million fish and other aquatic organisms including eels and soft shell clams (RIDEM, 2003).

The fish kill of 2003 prompted a renewed interest in water quality of the bay and its watershed through both volunteer efforts and regulatory action. In October 2003, Rhode Island governor Donald L. Carcieri established the Governor's Narragansett Bay and Watershed Planning Commission (GNBAWPC) to unite the efforts of the various groups working in the bay under a common goal of restoration within the bay and its watershed

(GNBAWPC, 2004). In the Blackstone River watershed, prior to the Greenwich Bay fishkill, volunteer groups have formed the Blackstone River Coalition (BRC) with the goal of achieving fishable/swimmable water quality status along the entire Blackstone River by 2015 (BRC, 2006).

Current regulatory focus in the Blackstone River is aimed at reducing phosphorus concentrations (EPA, 2006); while in Narragansett Bay reduction of nitrogen and bacteria loads are the priority (GNBAWPC, 2004; RIDEM, 2005). Further point source effluent controls have been identified as a plausible means of achieving the desired water quality improvements for both the Blackstone River and Narragansett Bay.

This study is part of a larger study designed to evaluate the cost-benefit effectiveness of past remediation efforts and, in a modeling framework, potential future, traditional and progressive abatement strategies at the local and watershed scales. A driving theme of this portion of the study is the development of a detailed understanding of point and nonpoint source contributions within both the headwaters of the Blackstone and the watershed as a whole. Understanding the source, fate and transport of contaminants along the mainstem of the Blackstone River is essential for setting reasonable management strategies in order to achieve the desired water quality goals in both the river and the bay.

The following research hypotheses were developed for this project to focus on the study of the nutrient loading patterns in the Blackstone, both spatially and temporally, as well as the relative loading of the Blackstone compared to other sources discharging into Narragansett Bay:

- Due to complex hydraulics and chemistry along the river, further regulation of point source dischargers may not result in a commensurate improvement in downstream water quality, particularly when evaluated in a cost-benefit framework.
- Implementation of nonpoint source pollution abatement strategies may be critical for cost-effectively achieving water quality goals.

- As the amount of urbanization in a watershed increases, water quality degradation increases in a parallel manner.
- Accurate determination of monthly and annual nutrient loads from the Blackstone River to Narragansett Bay, particularly in relation to the magnitude of other load sources to the bay, is critical for the development of effective management schemes for improving water quality in the bay.
- For some contaminants, wet weather loadings in the river may be more significant than dry weather loadings, particularly when taking into account the deposition and resuspension of sediments behind dams. The dams may act as sources and/or sinks under different weather regimes.
- In order to better assess inter-annual variability in pollutant loads due to varying hydrologic conditions, more accurate information is necessary.
- Population increases and changes in land use may put additional pressure on an already pressured ecosystem including changes in the hydraulics of the water balance.
- The effect of upstream water quality improvements and their propagation to downstream reaches needs to be understood in order to implement the proper water quality improvement strategies.
- A dynamic modeling tool is needed to model current and future loading and abatement regimes in order to best utilize the limited resources available for restoration of the river and the bay.

In order to study the above hypotheses, the following research objectives were created:

- Develop a simple watershed model to estimate the magnitude of point source (PS) versus nonpoint source (NPS) pollution under current and future loading regimes.
- Qualitatively evaluate spatial trends in water quality and correlate trends with the surrounding land use characteristics.
- Analyze PS and NPS loadings from the Blackstone on an annual and monthly basis to compare with direct PS pollution and peak loadings in Narragansett Bay.
- Analyze dry weather and wet weather nutrient loading to determine the relative magnitudes of each to annual and monthly loading estimates.

- Spatially analyze loading along the Blackstone Mainstem to determine the effects of the numerous impoundments on loading patterns in the river.
- Determine the magnitude of population and land use change in the near future and surmise what net effects may have on loading patterns and water quality.
- Analyze changes in the largest peak flows observed over the water year (Qpeaks) and the 7-day, low flow averages observed over the water year (7Q's) to determine if any changes have occurred to the hydraulics of the system over time.

The remainder of this report is organized as follows. First a review of the available literature on the Blackstone River, Narragansett Bay and water quality degradation and remediation as they apply to this study is presented in Chapter 2. A series of analyses pertaining to the current state of the Blackstone and Narragansett Bay watershed are presented in Chapter 3. Emphasis of these analyses was placed on the impairment status and PS vs. NPS loading dynamics of the watersheds and their respective sub-basins. Chapter 4 contains an analysis of the loading dynamics along the mainstem of the Blackstone using data from the Blackstone River Initiative (BRI) conducted in the early 1990's. An analysis of the impact of increasing population and changing land use on the Blackstone watershed and its sub-watersheds is presented in Chapter 5. The report concludes with a list of conclusions drawn from the analyses contained herein followed by a plan outlining future work to be conducted on the project.

2.0 - Literature Review

2.1 - Blackstone River Watershed

The Blackstone River watershed covers 475 mi² in central Massachusetts and northern Rhode Island. Along its 46 mile run from the hills above Worcester to its outlet in Pawtucket, RI, the Blackstone drops 438 ft (Shanahan, 1994; BRNHC, 2006), a steeper gradient than the Colorado River (Arizona Humanities Council, 2006). Recognizing the hydraulic potential of the river, Samuel Slater constructed the first mill in America at the outlet of the Blackstone in 1793. According to Shanahan (1994), others followed suit, constructing over 100 mills throughout the region, initiating the industrialization of the nation. By 1830, there was an average of one dam per river mile.

The rapid industrialization of the area was accompanied by large increases in population and the growth of three major cities within the watershed, Worcester, Woonsocket and Pawtucket. Studies have shown that the construction of the Blackstone Canal and its associated industrial increase led to the doubling of the population of Worcester between 1825 and 1835 (Shanahan, 1994). Additional increases in both manufacturing and population were seen after the construction of the Worcester-Providence Railroad. Historical records show that as populations grew, so did the amounts of wastes transported to the river. Raw sewage and garbage were either dumped directly into the waterways transported there by urban runoff, resulting in a multitude of water quality issues. Industrial discharges into the river further degraded the water quality of the Blackstone.

Like many rivers that powered the Industrial Revolution, contamination of both the water column and sediments occurred. Shanahan (1994) reports that by 1870, the former Blackstone Canal had become an open sewer, caused most notably by the newly constructed sewer system that transported 11,000 m³/day of raw sewage into Mill Brook. Based on work by Tarr and McCurley (1984), as of 1925, there were 44 metal working plants, 130 textile mills, 3 paper mills and 21 other plants along the banks of the

Blackstone. Based on the types of industries and their associated processes, potential contaminants in the stream bed and behind dams include arsenic, both from metal working and pesticide deposition, and other toxic metals such as cadmium, silver and lead. Additional likely sediment contaminants include chromium and mercury from textile dyes and other metals from wire manufacturing, plating and machining (Shanahan, 1994). Other potential contaminants include fossil fuel combustion byproducts such as trace metals and oxides (SO_x and NO_x) (Tarr and Ayers, 1990). There are no known estimates of the potential mass of these contaminants still stored in river sediments.

Volunteer groups have been active in protecting and restoring the Blackstone. In 1972, approximately 10,000 volunteers removed over 10,000 tons of garbage from the Blackstone River and its tributaries (BRNHC, 2006; BRC, 2006b). Volunteer groups active in the Blackstone watershed, including the Blackstone River Watershed Association (BRWA), the Blackstone Headwaters Commission (BHC) and the Blackstone River Watershed Council (BRWC), have recently combined their efforts under the Blackstone River Coalition (BRC). Their goal is to restore the Blackstone to Class B status (fishable/swimmable) by 2015. Their efforts include river cleanups, volunteer water quality monitoring, public outreach programs and educational activities. The BRC is lobbying both state and federal regulatory agencies for monetary and regulatory assistance in attaining their goal.

As previously stated, the federal government has also been active in the Blackstone watershed. In 1986, the John H. Chafee Blackstone River National Heritage Corridor was established under the control of the National Park Service (BRNHC, 2006). In 1998, the Blackstone River was one of 14 rivers to receive American Heritage River (AHR) status (EPA, 2006b). The Blackstone was one of eight rivers named to the Urban Rivers Restoration Pilot Study in 2002 (EPA and ACOE, 2006).

As part of their restoration efforts, both volunteer and government organizations have been collecting water quality and quantity data in the watershed to identify problem areas, Table 2. Numerous studies have been conducted over separate areas of the

watershed, but few have collected data over the length of time necessary to understand the long term effects of changes within the watershed. Wet weather data in the watershed is scarce, limited to that collected by the Blackstone River Initiative (BRI) and select MADEP studies.

Table 2 – Water Quality Data Collection in the Blackstone River Watershed

Organization	Parameters	Frequency	No. of Sites	Comments
BHC/BRC	Stage (discharge) Dissolved Oxygen Temperature (water and air) pH Turbidity Nitrate Orthophosphate	Monthly (Apr – Nov)	20+ – Upper Blackstone, additional sites added in major tributaries as well as along the mainstem of the Blackstone	Some data exists since 1999; the majority of data is since 2003. Data collection expected to continue for multiple years.
RIDEM	Fecal coliform Enterococci Dissolved Metals (Pb,Cu) TSS, VSS Hardness Nutrients (TP, TKN, NH3, NOx) Chlorophyll Dissolved oxygen Temperature Specific conductance Turbidity, pH Chlorides	Monthly (Nov-Apr) at primary stations or intermittent at remaining	5 primary and 15 intermittent.	Not all parameters are measured at intermittent sites. Wet-weather data collection also planned. Collection focused in 2005 only. Possible insitu monitoring of temp and DO at 4 primary sites. Data collection possible at impoundments (6 sites) as well.
MA DEP	Various DEP - SMART Data	Various	Various DEP – Rivers	Dependent on identified problem areas.
MADPH	DPH - Bacterial Sampling	Various	DPH – Beaches	Dependent on identified problem areas.
USGS	Various	Monthly	USGS gauge at Millville and others	Conducting monthly data collection during 2005.
URI/EPA – BRI Study	Dissolved Oxygen BOD (BOD/NBOD) Total and Dissolved Metals (Cd, Pb, Zn others) Nutrients (TP, ,OrthoP, TKN, NH3, NOx) pH, TSS, VSS, Others	3 Wet and 3 Dry Weather Events	21 Sites along mainstem of Blackstone and its Tribs.	Sampling occurred from 1991-1993 over Summer and Fall
USACOE MADEP	Same as BRI = NOM, BOD and tP	5 Dry Weather Events	24 sites along Blackstone in MA	Follow up to BRI Study Conducted by Wright 2000-03

Another suspected source of downstream water quality degradation is the Upper Blackstone Water Pollution Abatement District (UBWPAD). The UBWPAD is a 56 million gallon per day (MGD) activated sludge treatment plant that serves the city of Worcester and the surrounding communities. Constructed in 1975, the plant replaced several failed attempts at treating the sewage from Worcester as described by Shanahan (1994). According to values reported by the plant, on average, the facility treats approximately 38.5MGD of wastewater with average biological oxygen demand (BOD) and suspended solids (SS) removals of 97 and 96% respectively (UBWPAD, 2006). Average reported effluent concentrations are 5.0 mg/L of BOD and 7.2 mg/L SS.

Prior to the construction of UBWPAD, work by Shanahan (1994) reports that as late as 1940, the flow coming from the Upper Blackstone River (flow exiting Worcester) was comprised of virtually all untreated wastewater. Work by Chaudhury *et al* (1998) estimates that the UBWPAD effluent accounts for over 75% of the flow from the Upper Blackstone during July and August. Ji *et al* (2002) reports that the UBWPAD effluent accounts for 80 percent of the flow leaving the Upper Blackstone during the summer months. A more in depth analysis of the magnitude of the UBWPAD effluent and the waters leaving the Upper Blackstone watershed are presented in Chapter 4 of this thesis.

Despite the significant manpower and monetary investments in the Blackstone River watershed over the past three decades, the Blackstone is still considered to be impaired by the Environmental Protection Agency (EPA). According to the 2002 303(d) list published by the EPA, the entire mainstem of the Blackstone and its major tributaries do not meet their designated use requirements (MADEP, 2003; RIDEM, 2003b; EPA 2006c). Leading causes of impairment identified by the EPA include noxious aquatic plants, pathogens and turbidity. Work by the EPA and others indicate that runoff generated in the highly urbanized headwaters negatively affects downstream water quality.

2.2 - Narragansett Bay Watershed

The Blackstone River plays a significant role in the health of Narragansett Bay. The freshwater source of Narragansett Bay is an 1850 mi² watershed located in Massachusetts (60%) and Rhode Island (40%), which includes the Blackstone watershed.

Approximately 2.4 billion gpd of freshwater enter the bay (Ries 1990; Ely, 2002). Based upon work by Ries (1990), freshwater from the inland rivers accounts for 74 percent of the freshwater inputs to the bay. Eighty-six percent of the inland river flows are delivered by the Taunton (39%), the Blackstone (32%) and the Pawtuxet Rivers (15%). Additional sources of freshwater include precipitation (13%), coastal rivers and drainage (11%) and water diversions (2%). The Blackstone accounts for approximately 23 percent of the total freshwater flow into the bay.

The Narragansett Bay Estuary has an area of 147mi² with a mean depth of 26 ft and a volume of 7.6 billion gallons at mid-tide. Pilson (1985) hydrodynamically modeled the flushing of the bay and concluded that the flushing time ranged from 10-40 days with an average of 26 days. He also surmised that the flushing behavior of the bay was largely dependent on the freshwater input from the surrounding watershed.

RIDEM reports that of the 156.3 mi² of estuarine waters in Rhode Island, 156.2 of them were assessed for designated use impairment in 2004. Since the Narragansett Bay comprises the majority of the total estuarine waters in Rhode Island, subsequent analyses are applicable to describe the use impairment of Narragansett Bay. It should be noted that the majority of the assessed waters are monitored solely for pathogens by the RIDEM Shellfishing Monitoring Program. Therefore, the majority of the waters have enough data to assess swimming and shellfishing support but limited data for assessment of aquatic life support (RIDEM, 2004).

RIDEM reports that 69 percent of the assessed waters fully support all designated uses while 30 percent fail to meet at least one use. Ninety percent of the waters assessed

support swimming use with non-support typically caused by fecal coliform contamination. Seventy-five percent of the estuarine waters were assessed for aquatic life support with 64 percent of them meeting their designated use. Greene and Deacutis (2000) report that the major causes of impairment to Rhode Island's coastal waters include pathogens, nutrients, low dissolved oxygen, metals contamination and thermal modification.

RIDEM (2004) states that approximately 20 percent of Narragansett Bay is permanently or conditionally closed to shell fishing. Ely (2002) reports that the closed areas are located near marinas, WWTPs or urban regions such as Providence and Mt. Hope Bay. The major causes of the impacts on aquatic life support are bacterial contamination, low dissolved oxygen and nutrient enrichment with combined sewer overflows (CSO's), urban runoff and point source discharges being the respective sources (RIDEM, 2004).

In order to develop a better understanding of the relative magnitudes of various sources of the aforementioned nutrient enrichment, Nixon *et al* (1995) developed a mass balance of nitrogen and phosphorus into Narragansett Bay. A summary of their findings for the Nitrogen Mass Balance are shown in Table 3, Table 4 and Table 5. DON is dissolved organic nitrogen, PN is particulate nitrogen.

Table 3 – River Nitrogen Mass Balance in Narragansett Bay (Source: Adapted from Nixon *et al*, 1995) Units are in 10^6 moles/yr

	NO ₂ +NO ₃	NH ₄	DON	PN	Total N	Percent of Total N into Bay	Percent of River N into Bay
Blackstone River	61.4	35.0	30.0	5.0	131.4	20.3	33.0
All Rivers	177.9	112.5	96.3	12.1	398.8	61.5	100.0

Table 4 – WWTP Nitrogen Mass Balance in Narragansett Bay (Source: Adapted from Nixon *et al*, 1995) Units are in 10⁶ moles/yr

	NO ₂ +NO ₃	NH ₄	DON	PN	Total N	Percent of Total N into Bay	Percent of WWTP Load into Bay
FP BP EP WWTPs	4.1	90.0	20.3	6.7	121.1	18.7	66.3
All WWTPs	6.2	136.0	30.3	10.1	182.6	28.2	100.0

Table 5 -- Total Nitrogen Mass Balance in Narragansett Bay (Source: Adapted from Nixon *et al*, 1995) Units are in 10⁶ moles/yr

	NO ₂ +NO ₃	NH ₄	DON	PN	Total N	Percent of Total N into Bay
All Rivers	177.9	112.5	96.3	12.1	398.8	61.5
All WWTPs	6.2	136.0	30.3	10.1	182.6	28.2
Direct Runoff	4.0	13.0	18.0	2.0	37.0	5.7
Atm. Dep.	19.0	5.6	5.6	0.0	30.2	4.7
Total	207.1	267.1	150.2	24.2	648.6	100.0

Based on their calculations, the Blackstone contributed approximately 33 percent of the TN from all of the rivers that flow into the bay and 20 percent of the total TN load transported to Narragansett Bay. It should be noted that the river inputs **do include** loadings contributed by inland WWTPs that discharge into the rivers. Three of the WWTPs that discharge into the bay itself (Bucklin Point (BP), Fields Point (FP) and East Providence (EP)) account for 66 percent of the WWTP load input directly into the bay while accounting for 19 percent of the total TN loading into the bay. Estimated contributions to the TN loading into Narragansett Bay were as follows: river loadings (62%), WWTP loadings (28%), runoff (6%) and atmospheric deposition (5%).

Subsequent loading analysis conducted by RIDEM estimates that approximately 66 percent of the TN loading into the bay is due to WWTPs, both inland and on the shore of the bay (Ely, 2002; RIDEM, 2003; GNBAWPC, 2004). Nixon *et al* (2005) published additional work on TN loading estimates to Narragansett Bay. They estimated that the four larger rivers that flow into the Providence and Seekonk Rivers (Blackstone, Pawtuxet, Woonasquatucket and Moshassuck) contributed 1.5 times more TN than the three WWTPs that directly discharge to them (Bucklin Point, Fields Point and East

Providence). The Blackstone was estimated to contribute 53 percent of the total tributary TN loading.

The results of the phosphorus mass balance conducted by Nixon *et al* in 1995 are shown in Table 6, Table 7 and Table 8. Similar procedures for allocating TN loads were used to estimate TP loads as well. DIP is dissolved inorganic phosphorus, DOP is dissolved organic phosphorus and PP is particulate phosphorus.

Table 6 – River Phosphorus Mass Balance in Narragansett Bay (Source: Adapted from Nixon *et al*, 1995) Units are in 10^6 moles/yr

	DIP	DOP	PP	Total P	Percent of Total P into Bay	Percent of River P into Bay
Blackstone River	2.7	1.0	1.6	5.3	13.3	25.1
All Rivers	13.1	3.2	4.8	21.1	42.2	100.0

Table 7 – WWTP Phosphorus Mass Balance in Narragansett Bay (Source: Adapted from Nixon *et al*, 1995) Units are in 10^6 moles/yr

	DIP	DOP	PP	Total P	Percent of Total P into Bay	Percent of WWTP Load into Bay
FP BP EP WWTPs	4.6	1.4	1.1	7.0	17.6	50.8
All WWTPs	9.1	2.8	2.0	13.8	34.7	100.0

Table 8 – Total Phosphorus Mass Balance in Narragansett Bay (Source: Adapted from Nixon *et al*, 1995) Units are in 10^6 moles/yr

	DIP	DOP	PP	Total P	Percent of Total P into Bay
All Rivers	13.1	3.2	4.8	21.1	53.1
All WWTPs	9.1	2.8	2.0	13.8	34.7
Direct Runoff	2.0	0.8	1.9	4.7	11.8
Atm. Dep.	0.0	0.0	0.0	0.1	0.3
Total	24.2	6.8	8.6	39.8	100.0

According to their report, the Blackstone accounted for an estimated 25 percent of the TP loads from the tributaries that flow into Narragansett bay and 13 percent of the total TP load into the bay. The three treatment plants contributed approximately 18 percent of

the total TP load into the bay. Estimated contributions to the TP loading into Narragansett Bay were as follows: river loadings (53%), WWTP loadings (35%), runoff (12%) and atmospheric deposition (<1%). The subsequent TP analysis published by Nixon *et al* in 2005 estimated that the four rivers brought 2.7 times more TP into the bay than the three WWTPs that directly discharge into it. The Blackstone River accounted for 45 percent of the tributary TP loading.

Anthropogenic eutrophication caused by the aforementioned influx of nutrients has resulted in large algal blooms within the bay. Nixon (1997) estimates that human activity in the region has increased dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) by five and two times respectively over predevelopment conditions. It is widely accepted that the sources of the excess nutrients are WWTP effluent and runoff transported to the bay via rivers and/or sewer systems.

The growth and subsequent decomposition of the algal blooms deplete oxygen concentrations in the water, threatening the aquatic life in the area (Nixon, 1998; Carey *et al*, 2005; Bergondo *et al*, 2005; others). While excess nutrients contribute to the occurrence of eutrophication in the bay, work by Bergondo *et al* (2005) suggests that additional factors need to be taken into consideration. Their work concludes that the hypoxic events which occurred in the summer of 2001 were due to several factors including: availability of nutrients, water column stratification and weak tidal amplitude or so called “neap” tides. According to their research, water column stratification is caused by increased freshwater inputs (storm effects), surface heating and low wind speeds. These factors in conjunction with a neap tide decrease the mixing ability of the water column. This allows for depleted oxygen levels on the bottom of the bay to remain there for extended periods of time. They also found that the input of freshwater into the bay was highly dependent on the flow from the Blackstone River.

Utilizing the hypoxia inducing criteria they developed, Bergondo *et al* (2005) were able to predict the episodic hypoxic events in the bay in previous years as well as the future, including the Greenwich Bay fishkill of 2003. Their criteria consist of neap tidal events

(less than 0.9m tidal change) in the bay during the summer months. The increased stratification of the water due to temperature differences and weak tidal and wind induced mixing (indicative of summer winds on Narragansett Bay) in conjunction with increased microbial activity in the warmer months are sufficient to cause the hypoxic events seen in the bay.

2.3 - Regulatory Focus

2.3.1 - Point Source Based Regulation

The rampant industrialization of the region led to a rapid decrease in the water quality of the Blackstone River. Despite complaints by the population and mill owners alike, state legislatures refused to pass laws controlling pollution from the mills (Shanahan, 1994). Industrial development was favored over environmental health, a precedent that would continue for over a century.

In 1867, the Massachusetts legislature authorized the city of Worcester to construct a sewer system in an effort to control the wastes generated by its citizens. The sewers dumped into the Blackstone and Mill Brook, resulting in Mill Brook (part of the Blackstone Canal) becoming an open sewer by 1870 (Shanahan, 1994). Ely (2002) reports that similar issues occurred in Providence, RI where after the construction of their sewer system in 1871 (Nixon, 1998), there were reports of people fainting because of the smell. In 1886, a law was passed requiring Worcester to institute waste water treatment. By 1891, the first such system was in operation. In 1917, Worcester had constructed their second WWTP that utilized secondary treatment as a way to reduce pollutant loading in the river. Despite the attempts at waste water treatment, in 1937, the State Planning Board described the Blackstone as an “industrial river”, stating that industrial uses were more important than cleaning up the pollution (Shanahan, 1994). It wasn’t until 1966 that the Massachusetts Clean Waters Act was passed, but it did not have enough power behind it to clean up the state’s waters.

On the national level, public awareness of water quality issues related to pollution resulted in the passing of the Federal Water Pollution Control Act in 1948. Due to the poor management strategies entailed in them, subsequent amendments to the act in 1961, 1965, 1966 and 1970 had little or no impact on the cleanliness of the nation's waters. These issues were exemplified in the work by Wolman (1971). His research showed that despite large amounts of money being spent on reducing loads to the Potomac River, the dissolved oxygen situation in the river was getting worse. According to the EPA (2000a), amendments in 1972 and beyond (1977, 1981, 1989), commonly known as the Clean Water Act (CWA), shifted control of cleaning up the nation's waters from state legislatures to the federal government.

Recognizing that site specific pollutant reduction, as called for by legislation prior to the CWA was unmanageable, the CWA sought to implement nationally consistent pollution controls on municipal and industrial waste streams. These limits were initially based on best available technology for reducing biological oxygen demand (BOD) into the nation's waterways. The law also called for pretreatment of industrial effluent prior to discharge. This goal was accomplished by requiring secondary treatment (usually activated sludge processes) in all WWTPs across the nation. Permits were issued to dischargers under the National Pollutant Discharge Elimination System (NPDES) program. The permits required utilities to meet effluent limits set by legislatures or face penalties, usually monetary in nature. The 1972 amendment also called for controls on urban runoff and nonpoint source (NPS) pollution.

The strength of the CWA in its ability to clean up our nation's waters lay in its monetary provisions to help fund water quality improvement plans. Figures compiled by the EPA (2000a) estimate that from 1970 to 1995, the EPA distributed \$61.1 billion in grants for WWTP upgrades to secondary treatment or higher. This accounts for a large percentage of the \$541 billion we as a nation have spent on water pollution control since 1972 (Knopman and Smith, 1993; Puckett, 1995), the majority of which was spent on end of pipe controls of point source (PS) discharges (Knopman and Smith, 1993).

The benefits of these expenditures are shown through the work compiled by EPA (2000a). According to their research, by 1996, the number of WWTPs offering less than secondary treatment decreased from 4,278 in 1978 to fewer than 200. BOD loading into rivers from WWTPs decreased 45 percent from 6,932 metric tons per day in 1968 to 3,812 metric tons per day in 1996. This decrease in loading was observed despite an increase in the population served by WWTPs from 140 million to 190 million. Several researchers suggest that further increases in the population served by WWTPs will cause increases in BOD effluent levels (Carlin *et al*, 1992; EPA, 2000a; Knopman and Smith, 1993, others). While initial expenditures in WWTPs decreased BOD loadings drastically, current and future expenditures on pollution control will be required to maintain current levels of water quality, with additional expenditures required for improvements.

The dissolved oxygen (DO) levels in our rivers and lakes are testaments to the effects of the BOD reduction program. Initially, Knopman and Smith (1993) hypothesized that one could only detect DO improvements immediately downstream of recently reduced effluent sources. However, the EPA (2000a) developed a methodology for determining the effect of BOD reduction on worst case DO levels in the water column. They showed that of the 311 reaches that qualified for their analysis (see paper for qualifications), 69 percent of them showed improvement after the CWA. On the watershed scale, 11 of 18 watersheds qualified for their analysis with 8 showing statistically significant improvement in the worst case DO levels and the remaining three showing no signs of decrease in worst case DO levels.

Subsequent amendments expanded the scope and regulatory authority of the 1972 amendment. The 1977 amendment strengthened the water quality regulations of the act, including control over toxic discharges. In 1987, control over NPS pollution was increased via section 319. Section 319 set up a federal grant program to help states develop NPS pollution management strategies. The 1987 amendment also expanded control over stormwater runoff from major cities. According to Lee and Jones-Lee (1993), the 1987 amendment required all cities with populations greater than 100,000 people to apply for Phase I stormwater permits under the NPDES program. Another

large part of the NPDES Phase I program is the abatement of CSO discharges into rivers and streams. Industrial sources and site specific sources were required to apply for and subsequently comply with the NPDES Phase I program as well. Subsequent storm water control for smaller cities is required under the NPDES Phase II program. Since 1988, \$16.1 billion has been loaned to states to deal with water quality improvements through the state revolving loan fund (EPA, 2000a). Lee and Jones-Lee (1993) estimate that the cost of controlling contaminants from urban runoff to be several hundred billion dollars for Phase I cities, roughly \$1000 per capita per annum, with increases in per capita cost for Phase II cities.

The mechanism for pollution reduction provided by the NPDES program is seen as beneficial to some and unfair to others. As previously stated, initial efforts required implementation of uniform pollution controls to increase water quality across the nation. States then adopted water quality standards and assigned water bodies a designated use (drinking water source, recreation, fishery etc.). If the water body does not meet that designated use, the NPDES permits that discharge into that water body are identified. While initially under national limits, permits are currently adjusted on a site specific basis to ensure non impairment via ever decreasing effluent limits to continue to meet water quality standards. While many impairments are eliminated using these water quality based point source effluent limits, water quality issues still exist, most notably due to nonpoint source pollution.

According to the National Water Quality Index (NWQI) of 2000, much of the remaining use impairment to US surface waters is due to nonpoint source pollution (NPS). NPS pollution is classified as any pollution that enters a water body from a diffuse source. Sources of NPS pollution include agricultural runoff, urban runoff, combined sewer overflow discharges and septic system inputs that travel via groundwater flows. The National Water Quality Index summarized use impairment findings for rivers, lakes and ponds, and estuaries based on data collected by state agencies. Findings from the study are summarized as follows. Only 19 percent of the total US river miles have been assessed in terms of designated use attainment. Of the assessed river miles, 39 percent

were considered impaired. Agricultural and urban runoff accounted for 48 and 13 percent respectively of the identified use impairments. Forty-three percent of the nation's lakes and ponds have been assessed for use impairment. Of those assessed, 45 percent were impaired with agricultural and urban runoff among the top causes of impairment. Of the 36 percent of the nation's estuaries that have been assessed, 51 percent were found to be impaired. Municipal point sources (WWTPs) and urban runoff/storm sewer discharge were listed as the leading causes of impairment.

2.3.2 - Nonpoint Source/Watershed Based Regulation

While the practice of simply decreasing point source effluents to meet water quality standards worked in the past, it is evident in the results of the NWQI that this is no longer the case. Remaining water quality issues are both point source and nonpoint source in nature, typically defined by local conditions impacted by various sources. Research by Puckett (1995) has shown that in some instances, nonpoint sources dominate water quality impacts and in all cases, atmospheric deposition of pollutants must be taken into account. Work by the EPA (2001b) warns that simply using NPDES as a way to improve water quality can be expensive and may not be enough to resolve some water quality issues. This is why the EPA supports a watershed based total maximum daily load (TMDL) approach to pollution reduction.

According to the EPA (2001b), the TMDL program allows for the assessment of water quality problems on a larger scale. Pollutant loads are allocated to a number of point source and nonpoint source polluters based on an assessment of a water body's pollutant receiving capacity. This mechanism allows for flexibility in the methods utilized in elimination of designated use impairments.

Based on the 1998 303(d) list, the EPA (2001b) estimated that 36,000 TMDLs need to be developed across the U.S. In determining the cost of developing TMDLs, the EPA looked at three scenarios: least flexible, moderately cost effective and more cost

effective. The least flexible scenario called for an increase in both point and nonpoint source controls with no regard to which sources contribute the majority of the load. Typically, the majority of the cost under this scenario would be set upon point source controls, due mainly to the NPDES program which applies federal laws to point source pollution while no such law exists for nonpoint source pollution. The moderately cost effective scenario calculates which sources of pollution will need to reduce their loading to achieve designated uses and by how much. Under this methodology, some of the many sources of pollution will not have to reduce their loading at all. This is the scenario that the EPA feels will apply to the majority of TMDL development. This scenario results in fewer total sources having to be reduced than in the least flexible scenario. The more cost effective program models a scenario in which the state attempts to reduce costs by assigning the responsibility for achieving the bulk of the load reduction to the sources with the lowest per unit cost for achieving load reduction. Additionally, the EPA feels that similar results can be achieved if trading of pollutant reductions between sources is allowed. Caton (2002) proposes such a trading program for use in Narragansett Bay and reported that several others have been implemented across the nation.

Cost estimates for the three scenarios were developed by the EPA on an annualized basis, starting in the year 2000 and continuing forever. Costs are reported in billions of 2000 dollars per year, Table 9.

Table 9 – Cost Estimation for TMDL Implementation (Adapted from EPA 2001b)

Program	Cost	Notes
Least Flexible	\$1.9-4.3	PS based
Moderately Flexible	\$1.0-3.4	PS and NPS based, most likely to be implemented
Most Flexible	\$0.9-3.2	PS and NPS based, effluent trading programs

2.3.3 - Regulatory Focus in the Blackstone

As previously stated, current regulatory focus in the Blackstone is on phosphorus reduction. Like the majority of freshwater systems, biological activity in the Blackstone is believed to be a phosphorus limited system. Previous regulatory efforts in the Blackstone have been focused on point source reduction strategies for all pollutants. Construction of WWTPs and systematic decreases in NPDES permit limits have substantially increased the health of the river. As late as 1994, Shanahan reported that the water quality of the Blackstone was “considerably improved.” He surmised that the improvement was due to continual WWTP investment to meet increasingly stringent federal laws (NPDES program) as well as the control of industrial dischargers. Work by Nixon *et al* (2005) estimates that there has been a 20 percent decrease in total nitrogen (TN) loading and 50 percent decrease in total phosphorus (TP) from the Blackstone since the 1970’s. Nixon *et al* (2005) attributes the majority of the load reduction to a decrease in WWTP effluent concentrations. Additional reduction from atmospheric sources is also cited a cause of TN reduction to the river and subsequently the bay.

A facility construction and treatment upgrade timeline focusing on the UBWPAD facility is shown in Figure 4. Improvements shown in the timeline typically represent responses to regulatory action such as the lowering of NPDES permit levels.

Figure 4 – Facility Construction and Upgrade Timeline for the Blackstone River and Select Narragansett Bay Facilities

The UBWPAD facility was built in 1975 in response to the CWA. In 1989, the Worcester CSO facility was built in order to bring the city of Worcester into compliance with the NPDES Phase I program. Dechlorination requirements were added to both UBWPAD (1993) and the CSO facility (1998) in response to permit limit changes. Currently, the UBWPAD is undergoing a \$130 million upgrade to reduce the amount of nutrients being discharged into the river. These upgrades are in response to more stringent effluent limits placed on the facility when their permit was renewed in 2001 (Walsh, 2006).

Despite the continual reduction in PS effluent concentrations, the Blackstone and its tributaries are still classified as impaired. In Massachusetts, there is no numerical nutrient criterion that classifies a stream as being impaired or meeting its designated use. According to the Massachusetts Surface Water Quality Standards, nutrient concentrations in lakes and streams “shall not exceed the site-specific limits necessary to control accelerated or cultural eutrophication.” Numerical criterion in the form of TMDLs are being developed for the Blackstone to eliminate designated use impairment. Currently phosphorus (TMDLs) are under development for several lakes in the Blackstone watershed. As part of these TMDLs, target concentrations and attainment strategies are

proposed. TMDLs are developed for lakes prior to their development for rivers due to the publicly perceived aesthetic issues associated with eutrophication in lakes. As mandated by the EPA, TMDLs will eventually be developed for all identified use impaired ponds, lakes, and river reaches along the Blackstone.

Target concentrations for nitrogen and phosphorus are based upon estimates of ambient concentrations for the region. In 1994, the EPA determined ambient phosphorus concentrations in lakes and rivers across Massachusetts as part of the Massachusetts Ecoregions Project (Griffith *et al*, 2004). Data on more than 10 pristine lakes in the Blackstone watershed, considered to be relatively unaffected by human influence, were included in the study. However, due to its extensive urbanization, only one riverine station for the study was situated within the Blackstone River watershed. It was determined that lakes in the upper region of the watershed had ambient phosphorus concentrations of 15-19 ug/L, while those in the lower section of the basin were characterized by ambient phosphorus concentrations of 10-14 ug/L. Subsequent work by Rohm *et al* (1995) also reported phosphorus concentrations in the lakes of the Blackstone watershed ranged between 15-19 ug/L. Ambient phosphorus concentrations in the Blackstone River were estimated to be in the range of 71-100 ug/L. Values for ambient N concentrations were not provided in Griffith *et al* or Rohm *et al*.

Using the findings of reports such as Griffith *et al* and Rohm *et al*, the EPA has adapted an ecoregion based approach for developing ambient water quality criteria recommendations for streams and rivers, lakes and reservoirs, estuarine systems and wetlands (EPA, 2000b). The EPA has chosen to use the 25th percentile value (P25) of all of the water quality data available to develop its ambient nutrient criteria. P25 values were developed for Ecoregion 14 as a whole as well as each sub-ecoregion within it. They justify the use of P25 through the results of previous studies which have shown that the P25 of an entire population of water quality data adequately represents the 75th percentile (P75) of the reference data population. P75 is used whenever possible because it represents minimally impacted stream conditions, provides protection of designated uses and also allows for flexibility in reduction management strategies (EPA, 2000b).

In Ecoregion 14, TP concentrations ranged from 1.25 to 1525 ug/L with a P25 of 31.25 ug/L. TN concentrations ranged from 0.07 to 10.68 mg/L with a P25 of 0.44 mg/L. In Ecoregion 14-59, where the Blackstone watershed is located, TP concentrations ranged from 2.5 to 907.5 ug/L with a P25 of 23.75 ug/L. TN concentrations ranged from 0.15 to 5.57 mg/L with a P25 of 0.61 mg/L. Differences between ambient water quality concentrations between this study and previous studies lie within their analyzed data sets. Previous studies (Rohm *et al* and Griffith *et al*) utilized all data for the region, as far back as the 1970's. The EPA (2000b) study however only took data from 1990 to 1998 into consideration when developing their water quality recommendations.

2.3.4 - Regulatory Focus in Narragansett Bay

Similar to the efforts to improve water quality in the Blackstone, efforts in Narragansett Bay also initially focused on point source controls for pollution reduction, mainly BOD. Initially, funds were used to construct new WWTPs or upgrade existing facilities and reductions were controlled by decreasing NPDES permit limits on effluents. According to Greene and Deacutis (2000), almost \$500 million was spent on WWTP improvements from 1975-1995.

The program worked fairly well, reducing BOD loading to the bay from 4,000 metric tons per year in 1953 to 14,000 metric tons per year in the 1970's to under 2,000 in 1997 (Greene and Deacutis, 2000). Decreases were observed despite increases in population from 1.4 million in 1950 to approximately 2 million in the 1990's (Nixon *et al*, 2005). Nutrient loadings into the bay decreased during this time period as well. Work by Nixon *et al* (2005) estimated that between the 1970's and now, phosphorus inputs into the bay have declined significantly. They also report that even though the amount of TN input into the bay remained unchanged, the form in which it enters the bay has. In an effort to reduce the organic loading into the bay, NPDES permits began requiring ammonification and later nitrification of the wastewater. Nixon *et al* (2005) reports that from the 1970's to today, the organic portion of the nitrogen loading has decreased from 60 to 20 percent.

While helping to eliminate the DO issues seen in the providence and Seekonk Rivers, the shift to inorganic nitrogen provides algae with more readily available nitrogen, increasing the potential for algal blooms.

The industrial pre-treatment program in Narragansett Bay was also affective. Both Greene and Deacutis (2005) and Nixon *et al* (1995) report significant decreases in metal transported to the bay. Work by Ely (2002) states that Cd, Cu, Cr, Hg, Ag, Pb and Zn concentrations have decreased over the last 20 years. She also states that there has been a 94.4 percent reduction in total metals and a 95.6 percent reduction in total cyanide loading coming from the Fields Point facility over the same period.

As previously stated, water quality issues in the bay still remain, most notable bacterial contamination and episodic hypoxic events due to algal blooms. These issues were highlighted in the Greenwich Bay fishkill, making the public and regulators alike realize that current efforts and strategies were not enough to keep Narragansett Bay healthy (RIDEM, 2003). Subsequent work by Bergondo *et al* (2005) emphasized the fragile balance of life in the bay and how easily it can be disrupted, especially in the upper bay region. In the wake of the fishkill, the GNBAWPC was formed to unite the previously disparate improvement efforts, including regulatory efforts under a common goal (Coastal Institute at URI, 2006).

Many feel that efforts in restoring Narragansett Bay should focus on a watershed based approach. Work by the Narragansett Bay Estuary Program (Ardito, 1999) calls for watershed wide cooperation in reducing pollutants to the bay. The GNBAWPC has called for a watershed wide monitoring and response program which would allow information sharing across the bay for decision and policy making purposes. Greene and Deacutis (2000) feel that the sheer size of the watershed and the fact that it encompasses over 100 cities and town creates additional difficulty in controlling the pollutants transported to the bay.

Current regulatory focus in Narragansett Bay is on nitrogen and bacterial pollution reduction (GNBAWPC, 2004; RIDEM, 2005). RIDEM states that their number one priority for remediation is restoring waters with bacteria levels that impact shellfish harvesting. While the systematic upgrading of WWTPs has caused them to become minor sources of bacterial loads into the bay, CSOs, especially those on the shores of the bay are still a major problem (Greene and Deacutis, 2000; GNBAWPC, 2004).

According to Greene and Deacutis, there are over 120 CSO outputs along the border of the bay that contribute approximately 92 percent of the bacterial load into the bay. Ely (2002) reports that as of 2002, an effort to alleviate the CSO problem began with the construction of large underground holding tanks to store the CSO effluents during storm events. Over time, the CSO waste will be pumped out of the tanks and treated at WWTPs, resulting in a significant decrease in bacterial loading into the bay. Work by the NBEP (Ardito, 1999), estimates that the CSO abatement in the upper bay region will cost approximately \$300 million

Nitrogen reduction, specifically in the upper bay (Providence and Seekonk Rivers) has been identified by RIDEM as the second remediation priority. Despite the importance of NPS pollution documented at the national and local levels, current remediation efforts are focused on point source pollution reduction. Analyses by Greene and Deacutis (2000), Carey *et al* (2005) and RIDEM (2005) have estimated that WWTPs account for two thirds of the total nitrogen input into the bay. Their analyses include the inland WWTPs, accounted for differently than the study conducted by Nixon *et al* (1995). Greene and Deacutis state that the WWTP effluents are the most treatable part of the nutrient load being input into the bay, at least currently. They do state however that future pollution efforts must also take into consideration current development trends that create additional NPS pollution.

The current plan by RIDEM (2005) is to reduce the nitrogen inputs of the 11 WWTPs that discharge directly into the bay by 50 percent by 2008. They reason that these WWTP discharge to the shallow, poorly flushed areas of the bay where most water quality issues in the bay occur. They have developed a cost-benefit analysis as well as a

plan to achieve the 50 percent nitrogen reduction from the WWTPs. Based on the consensus that the nitrogen impacts in the bay are not a major issue during the remainder of the year, RIDEM's focus is on nitrogen reduction in the summer (RIDEM, 2005). As of 2004, four WWTPs were upgraded. They estimate that an additional 80 million will be needed for upgrades to be implemented on the remaining WWTPs. Furthermore, they estimate that these efforts will reduce nitrogen loading to the bay from 15,000 pounds per day to approximately 4,000 pounds per day.

Additional remediation efforts will likely be necessary to meet RIDEM's goals for designated use attainment within the bay. Work by URI at the Marine Ecosystems Research Laboratory (MERL) estimates that even if the WWTP nitrogen loading is reduced to the best available technology level of 3 mg/L, far below the specified seasonal limits of 5-8 mg/L in the current strategy, the Seekonk and portions of the Providence River would still not fully comply with existing water quality standards.

Other sources of nitrogen reduction have been identified as potential future nitrogen reduction mechanisms. RIDEM (2005) identifies the elimination of septic systems along the shores of the bay and near other sensitive area as future reductions in both nitrogen and bacterial loading into the bay. Additional WWTP effluent treatment at inland WWTPs has also been identified as a possible reduction mechanism. Nixon *et al* (1995) has identified watershed wide urban and to a lesser extent, agricultural runoff as a major component of the nutrient loading (6% of TN). The remediation of such runoff has been suggested as a potential future nutrient reduction option (RIDEM, 2003; Carey *et al* 2005; RIDEM 2005).

2.4 - Nutrient Impacts, Sources and Cycling

The importance of nutrient inputs and their effects on aquatic systems has been well documented. Nutrients are vital to all living things and the ecosystems which they inhabit. However, in excess, nutrients can disrupt the balance of aquatic systems resulting in detrimental effects on water quality, impacting flora and fauna alike.

Excess nutrient inputs can lead to large algal blooms in lakes, estuaries and riverine systems (Bergondo *et al*, 2005; RIDEM 2005). The blooms prevent incoming light from penetrating the water column, threatening the survival of bottom dwelling aquatic plants. The loss of habitat results in the emigration of the aquatic life that relied on the plants for habitat, altering the ecosystem of the region. As the nutrient supply in the water is exhausted and/or the algae itself grows too deep into the water column, algal die off occurs. The microbial activity that breaks down the algae, as well as the dead aquatic plant material creates a large oxygen demand in the water column. The hypoxic zone can cause the death of both aquatic plants and animals that are unable to escape the affected region.

Algal bloom growth is dependent on a number of factors including a multitude of nutrients and minerals, the most important of which are nitrogen and phosphorus. It is commonly accepted that in temperate coastal waters such as Narragansett Bay, nitrogen is the limiting nutrient (Nixon, 1997; Carey *et al*, 2005; Nixon *et al*, 2005). In freshwaters such as the Blackstone River however, phosphorus is the limiting nutrient.

As previously stated, nitrogen is derived from numerous sources, both anthropogenic and natural. Nitrogen is transported into aquatic systems via urban and agricultural runoff. Fertilization of lawns and crops followed by rain events contribute a significant amount of NPS pollution into rivers, lakes and estuaries. Nixon (1995) estimates that runoff directly into Narragansett Bay accounts of 5 percent of the total nitrogen (TN) load into the bay. As detailed in previous sections, WWTP effluent contributes significant amounts of nitrogen as well, accounting for 60-70 percent of the TN load into Narragansett Bay (Nixon, 1995). Atmospheric deposition is also a significant contributor to the TN load into aquatic systems. Fossil fuel combustion, as detailed by Tarr and Ayers (1990), results in the formation of NO_x compounds. These noxious compounds are then directly deposited into the system via precipitation. According to Nixon (1995), 5 percent of the TN load into Narragansett Bay is from atmospheric deposition.

Similar to nitrogen, the major sources of phosphorus to aquatic systems are urban and agricultural runoff as well as WWTP effluent. In his 1995 study, Nixon estimated that 10 percent of the total phosphorus (TP) load into Narragansett Bay was from runoff. Thirty-six percent of the TP load entered the bay through direct WWTP effluent. Inland WWTP effluent enters the bay through river inputs which contribute 54 percent of the TP load into the bay. Unlike nitrogen, atmospheric deposition of phosphorus is not a major nutrient import into aquatic systems, accounting for less than 1 percent of the TP load into Narragansett Bay (Nixon, 1995). Phosphorus also results from the treatment of human and animal wastes. Other significant sources of phosphorus include urban and agricultural runoff.

TN and TP are comprised of several species in both natural and anthropogenically impacted environments. For algal growth to occur, certain forms of each nutrient need to be biologically available. It is commonly accepted that soluble inorganic phosphorus or orthophosphate is the only readily available form of phosphorus that can be utilized by algae (Chapra, 1997; Correll *et al*, 1999). Correll adds that in estuaries and to a lesser extent freshwaters, the majority of the particulate organic phosphorus can be mineralized to dissolved inorganic phosphorus through microbial activity (diagenesis). Chapra notes that ammonia and nitrate are the nitrogen species readily available for algal growth, with ammonia being the preferred form.

Phosphorus is typically not readily available in the water column due to its tendency to adhere to soils and organics in both the water column and in runoff. Studies have shown that the majority of the phosphorus that enters a water body via runoff is in particulate form (Heathwaite *et al*, 1996; Evans and Johnes, 2004). Work by Correll *et al* (1999) estimated that up to 83 percent of the TP load into the Rhode River, MD was particulate phosphorus. He attributed the high amounts of particulate phosphorus to erosion from the steep slopes of the watershed. Work by Nixon *et al* in 1995 estimated that 20 percent of the annual TP load into Narragansett Bay was particulate. More recent work by Nixon *et al* (2005) estimates that between 30-50 percent of the TP load to Narragansett Bay is particulate. This study however, estimates nutrient fluxes from April-May of 2004, not

the entire year like the previous study. Differences in estimates between the two studies can be attributed to differences in precipitation between the two studies and its resultant effect on the magnitude of flow in the river. Reasons as to why differences in flow regime may cause differences in particulate loading estimates are detailed later in this section. Namely, flow regimes directly affect sediment transport within an aquatic system, which in turn affect phosphorus loading due to the strong adsorption characteristics of phosphorus.

Particulate phosphorus is not completely unavailable for use in algal growth however. Studies cited in Correll *et al* state that up to 50 percent of the particulate inorganic phosphorus is biologically available to algae, mostly due to equilibrium kinetics in the system.

Nitrogen is more readily available for algal growth than phosphorus. The necessary forms of nitrogen (ammonia and nitrate) are more abundant in the environment than orthophosphate and other forms of nitrogen can be readily transformed to the required forms via natural processes. Also, nitrogen sorption onto particles is not as strong as phosphorus sorption, leaving more nitrogen in the water column. Particulate nitrogen accounts for 3 to 4 percent of the annual nitrogen input to Narragansett Bay Nixon *et al*, 1995; Nixon *et al*, 2005). Despite the possible differences in flow regimes between the two studies, the particulate nitrogen loadings to the bay are similar. This behavior is likely due to the aforementioned weak sorption characteristics of nitrogen, allowing nitrogen loading behaviors to be independent of sediment transport and therefore flow regimes in the watershed.

When considering a riverine system, there are several transformation and transport mechanisms which may increase or decrease the readily available forms of nitrogen and phosphorus in the water column. Algal uptake can remove significant amounts of nutrients from the water column. Algal blooms typically tend to occur in the slow moving waters behind impoundments, absorbing the necessary materials to grow and photosynthesize, thus sequestering nutrients into their biomass. Subsequent algal die off

transports the biomass to the riverbed, removing the nutrients from the water column. Similarly, nutrients adhered to particulates tend to settle out in these slow moving reaches behind impoundments.

However, large storm events may resuspend the sediments stored behind impoundments, releasing available nitrogen and to a lesser extent phosphorus back into the water column. Correll *et al* (1999) reports that during their study, large intense storms discharged higher concentrations of particulate nutrients than smaller storms. This increase was partly attributed to the resuspension of sediments and the associated release of nutrients back into the water column. These resuspended nutrients have been shown to act as a significant source of loading in the river, along with the aforementioned runoff, atmospheric deposition, near water septic systems and WWTP effluent contributions.

Wetlands can be an important nutrient sink in both riverine and estuary systems. Similar to what occurs behind impoundments, slow moving waters in the wetlands allows for particulate settling as well as plant uptake, resulting in decreases in soluble and particulate phosphorus and nitrogen. Similar to WWTP operations described previously, nitrogen can be converted to free nitrogen ($N_{2(g)}$) via denitrification by microbes in the wetlands. Another benefit of wetlands is that they do not typically exhibit the die off behavior seen with algal blooms, allowing for oxygen depletion concerns to be mitigated.

Natural attenuation as described above was examined in a study conducted by Nixon *et al* (2005) in the Rhode Island section of the Blackstone River. Their work investigated potential natural attenuation of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) from the MA/RI state line to the outlet of the Blackstone. Their results showed that the DIN (ammonia, nitrite, nitrate) increased by 39 percent. Thirty-two percent of the DIN increase was attributed to WWTP inputs along the reach. They concluded that there is no evidence of natural attenuation of dissolved inorganic nitrogen in this section of the river. When analyzing potential DIP attenuation, their results showed that despite a 25 percent increase in DIP from the state line to the outlet, natural attenuation of DIP had occurred between Manville, RI and the outlet of the

Blackstone. Increases were observed between the state line and Manville, attributed mainly to WWTP inputs. When examining loads between Manville and the outlet in Pawtucket, RI, a 12 percent decrease in DIP load was observed. Nixon *et al* (2005) attributed this decrease to sorption onto sediment in the river as well as biological uptake by algae.

The ability of the river to naturally attenuate nutrient loading as described above is vital to developing a basin wide loading program such as a total maximum daily load (TMDL). Loadings that can be attenuated by the river itself decrease expenditures needed to reduce the loading from other sources.

2.5 - Urbanization, Land Use Change and Population Growth

The rapid urbanization of the United States began with the Industrial Revolution and continues today at an alarming rate. During the post World War II era (1950's-present), the amount of urbanized area in the United States has quadrupled (EPA, 2001). Nearly half of the world's population currently resides in urban areas and projections suggest that by 2030, this will reach 60 percent (Burns *et al*, 2005). Once fueled by the construction of mill villages and then factories (Shanahan 1994), urbanization today is driven by the construction of the interstate highway system, the rise in the popularity of the automobile and the associated decreases in both private and commercial transportation costs (EPA, 2001). While the increasing trend of urbanization has its benefits, specifically increased revenues, more personal space and cleaner living, urbanization also negatively affects both water resources and water quality in urbanized areas. Water quality degradation from urbanization impacts has been noted to propagate to downstream stream reaches (Peters and Meybeck, 2000).

Urbanization consists of transforming forested, agricultural and/or wetlands into suburban and urban areas. Between the 1700's and 1980's, half of the wetlands in the United States were lost to urbanization and other land transformations (Dahl, 1990). The

EPA (2001) estimates that urbanization has also claimed almost one third of the nation's most fertile farmland. Work by Hasse and Lathrop (2003) suggests that between 1982 and 1997, over half of the newly developed land in the United States was farmland and another third was from forested areas. Urban sprawl is typically associated with increases in population. However, from 1950-1990, urban land areas grew, on average, almost twice as fast as their respective populations (EPA, 2001). Work by Elvidge shows that the impervious surface area in the contiguous 48 states is equal to the area of Ohio (AGU, 2004). The conversion of natural areas to urbanized areas causes not only the loss of habitat for local flora and fauna, but decreases the assimilative capacity of the river and alters its ability to control high flow events. It is widely accepted that increases in impervious areas associated with urbanization can cause significant changes to the water balance (Schueler 1994; Arnold and Gibbons, 1996; Booth and Jackson, 1997; Konrad and Booth, 2005; Burns *et al*, 2005). Both the magnitude of runoff and channel form can be altered. Increased surface runoff and channelization of streams often results in increased peak storm flows and flood occurrence. High peak flows lead to increased stream bank erosion and also have adverse effects on biota within the stream (Booth *et al*, 2004). The decrease in infiltration associated with urbanization may also lead to increased periods of drought conditions due to a decrease in baseflow contributions to streams in urbanized areas (Tang *et al*, 2005).

Urban and storm sewer runoff tend to contain elevated amounts of pesticides, fertilizers, heavy metals, other toxics, sediment, debris and pathogens (Arnold and Gibbons, 1996; EPA, 2001; Tang *et al*, 2005). When these contaminants are washed from impervious areas into streams and lakes, they cause aquatic degradation (Lee and Jones-Lee, 1993). Contaminants tend to build up on impervious surfaces between rain events, causing the highest concentrations of pollution in the stormwater to occur after long periods of no rain. Studies have shown that streets tend to contribute the largest amount of pollution in urban runoff including heavy metals and pathogens. Lawns have been shown to contribute the majority of the nutrient pollution (Arnold and Gibbons, 1996). Additionally, increased atmospheric deposition of pollutants has been observed in urban areas, largely due to increased amounts of vehicular traffic (EPA, 2001).

2.6 - Percent Imperviousness

A widely used indicator of the extent of urbanization in a watershed is the percent imperviousness of the watershed. While the percent imperviousness does not account for the complex interactions and diverse environmental stressors that are associated with urbanization (Booth *et al*, 2004), it has been shown in numerous studies that the percent imperviousness of a watershed has a direct impact on the water quality of the streams within the watershed (Schueler 1994; Arnold and Gibbons, 1996; Booth and Jackson, 1997, Booth *et al* 2004). It has been consistently shown that water quality degradation tends to occur at a 10% imperviousness level (Schueler 1994; Booth and Jackson, 1997; AGU, 2004). Several researchers have suggested that the following categories, Table 10, can be used to describe water quality impairment in urbanized watersheds.

Table 10 – Water Quality Degradation Thresholds
(Source: Adapted from Arnold and Gibbons, 1996, Schueler, 1994).

Percent Imperviousness	Degradation Status	Potential for Restoration
<10 %	Protected	High
10-30%	Impaired	Improvement and Partial Restoration Possible
>30%	Degraded	Full Restoration Impossible Some Improvement Possible

The probability of restoration for each category is also listed in Table 10. It is unlikely that highly urbanized streams, those with imperviousness levels greater than 30 percent, can be fully restored. Mitigating flow regime changes as well as water quality degradation may be difficult to achieve when other needs such as housing and transportation are considered (Booth *et al*, 2002). Biotic improvement of impacted streams can be achieved, but full restoration is still unlikely. Complete restoration of protected streams should be possible under the correct set of circumstances. However, some studies have shown that degradation can occur in watersheds that are classified as protected (Booth and Jackson, 1997; Booth *et al*, 2004). Such instances are usually found in sensitive watersheds or areas with poor riparian protection.

2.7 - Watershed Modeling

As previously stated, this study is part of a larger study designed to evaluate the cost-benefit effectiveness of past remediation efforts and, in a modeling framework, potential future, traditional and progressive abatement strategies at the local and watershed scales. The Hydrologic Simulation Program in Fortran (HSPF) program has been chosen as the framework of our modeling analysis.

HSPF is one of EPA's suggested models for developing watershed based total maximum daily loads (TMDLs). The program has been used by the USGS and the ACOE as well. HSPF is a lumped parameter model able to simulate hydrology, sediment cycles and chemicals in a stream and its surrounding watershed. HSPF also has the ability to model specific coupled kinetics, including: BOD-DO, nutrients (P and N) and phytoplankton interactions in the water column, and pesticides (Ward and Benaman 1999). HSPF is commonly used to assess the effects of land use changes and point and nonpoint source treatment alternatives on watersheds (Filoso 2004). The model is able to simulate short (storm based) events as well as long continuous time periods.

HSPF models have been used throughout the nation on a variety of scales and watershed types as described in Table 11. CDM used an HSPF to model water quality and hydraulic regimes in the mainstem Merrimack River in Massachusetts. HSPF was also used in the Chesapeake Bay watershed to investigate the impact of anthropogenic influences and land use change on average sediment and nutrient loadings transported to the bay (Shenk and Linker, 2002). Work by Socolofsky (1997) and then Munson (1998) modeled hydrologic trends and bacterial loads in the Upper Charles River and Charles River Basins respectively. Booth *et al* (2002) used HSPF to simulate changes in runoff volumes due to land use change from sites as small as 100 acres. In 2005, ENSR developed TMDLs for the Assabet River using HSPF.

Table 11 – HSPF Modeling Efforts and Scales

Watershed	Area (mi ²)	Year	Researcher/Agency
Upper Charles River	84	1997	Socolofsky
Charles River	311	1998	Munson
Kings County Oregon Simulation	0.16	2002	Booth <i>et al</i>
Chesapeake Bay	64000	2002	Shenk and Linker
Ipswich	156	2004	CDM
Merrimack	5000	2004	CDM
Assabet	144	2005	ENSR

Several groups have called on the need for a basin wide model to simulate nutrient loadings and determine the most cost effective course of action regarding nutrient reduction in the watershed. The Blackstone River Watershed River Five Year Action Plan (2004) called on state agencies and universities to create a bi-state water quality and quantity model to be used as a watershed tool. Also plans for a Narragansett Bay watershed modeling effort have been called for by RIDEM (2005).

2.8 - Summary

As stated previously, this study is part of a larger study designed to evaluate the cost-benefit effectiveness of past remediation efforts. Evaluation of future, traditional and progressive abatement strategies at the local and watershed scales in a modeling framework will also be conducted.

The initial work conducted in this report is aimed at gaining a more in-depth understanding of the Blackstone River and its link to Narragansett Bay, including point and nonpoint source contributions within the headwaters of the Blackstone, the Blackstone itself and Narragansett Bay watershed as a whole. Based on the review of the available literature, it was determined that the behavior of the river was constantly variable, changing based on a myriad of factors. It was determined that prior to modeling

the river and the various abatement scenarios it would be subjected to, understanding the source, fate and transport of contaminants along the mainstem of the Blackstone River is essential.

Complete understanding of the watershed dynamics prior to modeling, will result in a more rigorous and representative the model. Furthermore, the understanding of the actual loading dynamics of the river will allow for setting reasonable management strategies in order to achieve the desired water quality goals in both the Blackstone River and Narragansett Bay.

3.0 – Spatial Water Quality and Pollutant Loading Analysis

The current rehabilitation efforts in the Blackstone watershed have resulted in significant water quality improvements throughout the basin. While the water quality improvements are celebrated by all who have a vested interest in the watershed, volunteer and government agencies recognize that additional, more focused efforts are needed to achieve a fishable/swimmable status for the Blackstone by 2015. The most effective use of the limited resources available for achieving this goal is to focus on areas and issues identified as “hot spots”. In the context of water quality monitoring, a “hot spot”, or problem area, refers to an area and/or a phenomenon that is a known source of water quality degradation. These problem areas can include runoff that contains significant amounts of contaminants or CSO discharges. In the city of Worcester, several projects are underway focusing on eliminating “hot spots” in the city’s waterways. One such project focuses on the elimination of illicit sewer connections, often a cause of site specific water quality degradation in urban streams. Additionally, a plan for daylighting the majority of Beaver Brook in northern Worcester has been proposed to alleviate another water quality “hot spot” in the city’s waterways.

The focus of this chapter is to identify additional potential water quality “hot spots” in the Blackstone River watershed and the Narragansett Bay watershed as a whole. Two issues are of interest. First are relative load contributions within the Blackstone River, i.e. the loading from the headwaters (UBS) versus the loading from the mainstem and its other tributaries. Second is the relative loading to Narragansett Bay, i.e., from the Blackstone River compared to the other contributing rivers and direct runoff. Contributions to the aforementioned loading analyses from both point source and nonpoint sources are considered, including their relative magnitude and delivery timing throughout the year.

The chapter is organized as follows. First, the available water quality data in the Blackstone watershed is presented and discussed as a reference point for water quality analyses. Next, the procedures used to analyze the watersheds and their sub-sheds are described in detail. The first analysis consists of land use and percent impervious area

calculations for both the Blackstone watershed as a whole and the headwaters of the Blackstone, referred to henceforth as the Upper Blackstone watershed (UBS). Following the percent imperviousness analysis, a water quality analysis of the UBS is presented, culminated by a comparison of the impairment metrics (percent imperviousness versus water quality criterion). After the impairment metric comparison, an estimation of the relative magnitudes of point source and nonpoint source loadings in the Blackstone watershed and the Upper Blackstone watershed are presented. Next an estimation of the annual flow and nutrient loading contributions into Narragansett Bay from the Blackstone, the Taunton and the Pawtuxet rivers are shown. These loadings are then utilized in the following section, an analysis of the total nutrient loading, both phosphorus and nitrogen, into the bay from all of the major sources.

Following the methodology section, the results of each analysis are presented in the same order. The chapter ends with a Conclusion section, summarizing the main information drawn from the analyses conducted herein.

3.1 - Available Data

As previously stated, both volunteer and government organizations have been collecting water quality and quantity data in the watershed in order to identify problem areas (“hot spots”), Table 12, enabling focus of the limited available resources on essential water quality remediation efforts. Wet weather data in the watershed is scarce, limited to that collected by the Blackstone River Initiative (BRI) and select MADEP studies.

Table 12 – Water Quality Data Collection in the Blackstone River Watershed

Organization	Parameters	Frequency	No. of Sites	Comments
BHC/BRC	Stage (discharge) Dissolved Oxygen Temperature (water and air) pH Turbidity Nitrate Orthophosphate	Monthly (Apr – Nov)	20+ – Upper Blackstone, additional sites added in major tributaries as well as along the mainstem of the Blackstone	Some data exists since 1999; the majority of data is since 2003. Data collection expected to continue for multiple years.
RIDEM	Fecal coliform Enterococci Dissolved Metals (Pb,Cu) TSS, VSS Hardness Nutrients (TP, TKN, NH3, NOx) Chlorophyll Dissolved oxygen Temperature Specific conductance Turbidity pH Chlorides	Monthly (Nov-Apr) at primary stations or intermittent at remaining	5 primary and 15 intermittent.	Not all parameters are measured at intermittent sites. Wet-weather data collection also planned. Collection focused in 2005 only Possible insitu monitoring of temperature and DO at 4 primary sites. Data collection possible at impoundments (6 sites) as well.
MA DEP	Various DEP - SMART Data	Various	Various DEP – Rivers	Dependent on identified problem areas.
MADPH	DPH - Bacterial Sampling	Various	DPH – Beaches	Dependent on identified problem areas.
USGS	Various	Monthly	USGS gauge at Millville and others	Conducting monthly data collection during 2005.
URI/EPA – BRI Study	Dissolved Oxygen BOD (BOD/NBOD) Total and Dissolved Metals (Cd, Pb, Zn others) Nutrients (TP, ,OrthoP, TKN, NH3, NOx) pH, TSS, VSS Others	3 Wet and 3 Dry Weather Events	21 Sites along mainstem of Blackstone and its Tribs.	Sampling occurred from 1991-1993 over Summer and Fall
USACOE MADEP	Same as BRI + NOM, BOD and tP	5 Dry Weather Events	24 sites along Blackstone in MA	Follow up to BRI Study Conducted by Wright 2000-03

3.2 - Methodology

3.2.1 - Land Use and Percent Imperviousness Analysis

One method for determining the locations of potential problem areas is to examine the percent imperviousness of the watershed and its sub watersheds. As stated previously, studies have shown that the water quality in a watershed can be correlated to the amount of impervious surface area in a watershed (Schueler 1994; Arnold and Gibbons, 1996; Booth and Jackson, 1997, Booth *et al* 2004). Degradation thresholds and their associated percent imperviousness values adapted from Arnold and Gibbons (1996) and Schuler (1994) are shown in Table 13.

Table 13 – Water Quality Degradation Thresholds
(Source: Adapted from Arnold and Gibbons, 1996, Schueler, 1994).

Percent Imperviousness	Degradation Status
<10 %	Protected
10-30%	Impaired
>30%	Degraded

In order to determine the percent imperviousness of the watershed and its sub-watersheds, land use breakdowns were tabulated for each watershed based on data obtained from MassGIS and RIGIS. To facilitate the basin wide analysis of land use classification and determination, the MA and RI land use data had to be merged into a common theme. The consolidation matrix between the two data sets is presented in Table 14. The percent impervious area values for each land use classification are also included in Table 14. The percent impervious values were derived by the MADEP based on imperviousness value assessments in Massachusetts (Brodeur, 2005). It should be noted that RI land use categories 150 and 161 are listed twice. Land use classification 150 is listed under both Commercial and Industrial categories while land use classification 161 is listed under Commercial and Open. The initial classification of the land use fit both of their respective merged categories, therefore the land use areas were split evenly between the combined land use categories they are listed under.

Table 14 - Land Use Categories and Associated Percent Imperviousness Values

LU Classification	MA - 1999	RI - 1995	Percent Imperviousness
Cropland	1	220	0.03
Pasture	2	210	0.02
Forest	3	310-340, 400	0.02
Wetland	4	600	0.00
Mining	5	740	0.02
Open Land	6	146, 250, 730, 760	0.06
Part Rec	7	161	0.10
Spec Rec	8	161	0.20
Water Rec	9	710	0.17
Res Multi	10	111	0.46
Res High Den	11	112	0.35
Res Med Den	12	113	0.19
Res Low Den	13	113-115	0.15
Salt Wetland	14		0.01
Commercial	15	120, 150	0.77
Industrial	16	130, 150	0.65
Urban Open	17	162, 163, 170, 720, 750	0.21
Transport	18	141-43, 147	0.66
Waste Disp	19	144-45	0.03
Water	20	500, 550	0.02
Woody Perrenial	21	230	0.02

Once calculated, the MA and RI land use categories were merged into the land use categories shown in Table 15 to enable the estimation of nonpoint source loadings in the watershed. The unmerged land use categories were too refined to match available literature export loading coefficient values.

Table 15 - Land Use Classifications

MA	RI 1 - 1995, 88	Land Use Category
1,2	210, 220	Agriculture
3	310, 320, 330, 340, 400	Forested
4,14	600	Wetlands
20	500, 550	Water
10,11,12,13	111, 112, 113, 114, 115	Residential
8,15	120, 150, 161	Commercial
5,16,19	130, 144, 145, 150, 740	Industrial
18	141, 142, 143, 147	Transportation
6,7,9,17,21	146, 161, 162, 163, 170, 230, 250, 710, 720, 730, 750, 760	Open

The imperviousness values, along with the land use tabulations, were used to calculate the percent imperviousness of the Blackstone watershed and its sub-watersheds, Figure 5. The percent imperviousness values were then used to determine if there was a potential water quality issue based on the degradation thresholds in Table 13. A similar analysis was conducted on the sub-watersheds of the Upper Blackstone watershed (UBS) to determine the locations of potential hot spots in the highly urbanized headwaters of the Blackstone River, Figure 6. Although visual inspection of the waterways and collection of water quality data is perhaps the best way to identify problem areas and their exact nature, the methodology described above provides an adequate screening tool that is cost effective, systematic and can be applied throughout the basin.

Figure 5 - Blackstone Watershed and its Sub-Watersheds

Figure 6 - Upper Blackstone Watershed and its Sub-Watersheds

3.2.2 - Water Quality Analysis - Upper Blackstone Watershed

Several volunteer organizations under the BRC have been monitoring the water quality of the Blackstone and its tributaries since 1999, although the majority of the data has been collected since 2003. The current monitoring network stretches from the headwaters to the outlet of the watershed and includes 70 monitoring locations (BRC, 2006).

A detailed list of the current BRC monitoring site locations as well as their associated period of record can be found in Appendix A. No loading estimates could be made with the data collected by the volunteer groups due to lack of adequate flow data. Instead, average concentrations of water quality parameters collected by the group were used to identify problem areas.

Of the available water quality databases, the most extensive data collected for the upper watershed have been collected by the Blackstone Headwaters Coalition (BHC), which has since joined the BRC. In this section, these data are used to determine, on a water quality basis, problem areas in the Upper Blackstone watershed and its sub-watersheds. In addition to the BRC data, MADEP collected data in the upper watershed under the SMART program in 2003. While this data was useful in identifying site specific problems, the data was not comprehensive enough, in spatial or temporal scales, to be useful in this analysis.

BRC data collection was conducted on a monthly basis from April to November, eliminating the ability to determine an annually averaged concentration. Instead, monthly average concentrations were calculated to determine when and where water quality issues arise in the watershed. Currently, Massachusetts has no numerical criterion for water quality impairment, so the criterion developed by the BRC were used to determine the impairment status of the waters in question.

The BRC criterion, based on guidance from the MADEP, for phosphorus and nitrogen impairment is shown in Table 16. Impairment criteria, based on guidance from the

MADEP, for the entire suite of parameters monitored by the BRC are located in Appendix A.

Table 16 - Phosphorus and Nitrogen Impairment Criteria used by the BRC

Nitrate as N		OrthoPhos as P	
Concentration (mg/L)	Classification	Concentration (mg/L)	Classification
<0.31	Standard	<0.025	Standard
<.3	Excellent	<0.025	Excellent
0.3 - 0.599	Good	0.025 - 0.049	Good
0.6 - 0.9	Fair	0.05 - 0.1	Fair
> 0.9	Poor	> 0.1	Poor

3.2.3 - Comparison between Water Quality Impairment Metrics

A comparison between the two impairment metrics detailed above (percent imperviousness and concentration based) was conducted to determine any similarities between them. For ease of analysis, each metric was broken into three categories: unaffected, impaired and degraded. The resulting classifications for each methodology are outlined in Table 17.

Table 17 - Impairment Metric Breakdown

Water Quality Status	Percent Imperviousness	NO3 as N Conc. (mg/L)	PO4 as P Conc. (mg/L)
Unaffected	<10 %	<.3	<0.025
Impaired	10-30%	0.3 - 0.9	0.025 - 0.1
Degraded	>30%	> 0.9	> 0.1

3.2.4 - Point Source vs. Nonpoint Source Loading Analysis

As previously described, traditional regulatory action for the improving water quality has consisted of reducing point source pollution. While this strategy has resulted in

significant improvements, future improvement strategies should include nonpoint pollution reduction strategies as well.

It is hypothesized that implementing nonpoint source abatement strategies may be equally or more effective than creating more stringent point source discharge regulations. Additionally, it may not be cost effective to assign all of the WWTPs in the watershed the same numerical standards due to their relative distance from Narragansett Bay. According to Greene and Deacutis, (2000), a cumulative total of 500 million dollars has been spent on WWTP upgrades in the Narragansett Bay watershed since 1975. While cost estimates are not readily available on reducing nonpoint source pollution, it remains one of the leading causes to water quality impairment in the US (EPA, 2006c).

Estimates of yearly and monthly point source (PS) and nonpoint source (NPS) loadings for total phosphorus (TP) and total nitrogen (TN) were calculated in order to compare their relative load magnitude and variability under current land use and WWTP operation regimes. The previously tabulated land use values were used to estimate a range of NPS loading values based the basic export coefficient model:

$$W=\epsilon A \quad (1)$$

where ϵ is the export coefficient (kg/ha/yr), A is the area of the land use in question (ha) and W is the resulting load (kg/yr). Load estimates were calculated with high, medium and low export coefficient values for each land use derived from export coefficients reported by Reckhow et al (1980) and export coefficients used by MADEP for NPS loading estimates provided by Brian Brodeur (2005). A detailed description of the process used by Dr. Brodeur to develop the export coefficients can be found in Appendix B. The resulting range of export coefficients for each land use is shown in Table 18.

Table 18 - Nutrient Export Coefficients for MA Land Use Categories
(Source: Adapted from Brodeur, 2005 and Reckhow, 1980)

TP High	TP Med	TP Low	TN High	TN Med	TN Low	MA 21 LU ID	Land Use Classification
kg/ha/yr	kg/ha/yr	kg/ha/yr	kg/ha/yr	kg/ha/yr	kg/ha/yr		
1.35	0.73	0.47	22.21	14.31	3.75	1	Agriculture
1.35	0.73	0.47	22.21	14.31	3.75	2	Agriculture
0.32	0.21	0.10	3.06	2.46	1.87	3	Forested
1.00	0.46	0.20	23.51	13.71	4.47	4	Atmospheric
2.14	1.10	0.06	9.19	5.50	1.28	5	Urban
1.00	0.46	0.06	23.51	13.71	1.28	6	Barren
1.00	0.46	0.20	23.51	13.71	5.01	7	Barren
2.14	1.10	0.19	18.05	5.50	1.82	8	Urban
1.00	0.46	0.06	23.51	13.71	1.28	9	Barren
3.46	1.10	0.19	17.26	5.50	1.82	10	Urban
2.70	1.10	0.19	13.56	5.50	1.82	11	Urban
2.14	1.10	0.19	11.03	5.50	1.82	12	Urban
2.14	1.10	0.19	9.19	5.50	1.82	13	Urban
1.00	0.46	0.20	23.51	13.71	4.48	14	Atmospheric
2.14	1.10	0.19	10.10	5.50	1.82	15	Urban
2.14	1.10	0.19	12.33	5.50	1.82	16	Urban
1.00	0.46	0.20	23.51	13.71	6.27	17	Barren
3.05	1.10	0.19	12.33	5.50	1.82	18	Urban
2.14	1.00	0.19	9.19	5.01	1.82	19	Urban
1.00	0.46	0.00	23.51	13.71	0.00	20	Atmospheric
1.00	0.46	0.20	23.51	13.71	2.90	21	Barren

To determine the variability in NPS loads in the watershed, monthly loading estimates were also calculated. The NPS export coefficients are based on a yearly rainfall of 42 inches (Brodeur, 2005), about average for the region. To determine a monthly loading estimate, the yearly NPS loading estimate was divided among the months based on the fraction of the average annual rainfall that fell each month, resulting in an estimated monthly load in kg. Monthly rainfall averages were taken from the National Weather Service (NWS) weather stations located in Worcester, MA and Providence, RI, Table 19. The rainfall averages recorded at the weather station in Worcester, MA were used in the monthly NPS estimations for both the Blackstone River and Upper Blackstone watersheds. The averages recorded in Providence, RI were used in estimating the monthly NPS estimations for the Narragansett Bay watershed.

Table 19 - Average Monthly Rainfall Totals (Source - NWS Web Page)

Month	Average Rainfall (in.)		Fraction of Total (in.)	
	Worcester	Providence	Worcester	Providence
January	4.07	4.37	0.08	0.09
February	3.1	3.45	0.06	0.07
March	4.23	4.43	0.09	0.10
April	3.92	4.16	0.08	0.09
May	4.35	3.66	0.09	0.08
June	4.02	3.38	0.08	0.07
July	4.19	3.17	0.09	0.07
August	4.09	3.9	0.08	0.08
September	4.27	3.7	0.09	0.08
October	4.67	3.69	0.10	0.08
November	4.34	4.4	0.09	0.09
December	3.8	4.14	0.08	0.09

Point source loadings of TP and TN were estimated based on the Permit Compliance System (PCS) database, part of the NPDES (National Pollutant Discharge Elimination System) program. Under the NPDES program, utilities, industry and other businesses that discharge to the nation's waterways are required to comply with the discharge limits set by their NPDES permit. Typically, the limits are enforced on a monthly time scale, i.e. average BOD concentration needs to be below X mg/L on a monthly average basis. The discharger is required to report effluent concentrations of the parameters listed on their permit, as well as other parameters of interest as defined by the permit. These reported values are stored in a database of effluent flows and concentrations for each discharger.

This analysis utilized the monthly averaged flow and concentration values reported over the period of record to estimate average monthly and annual loads from each plant. As shown in Table 20, the periods of record available for load estimation vary among plants. Only data through the year 2004 were available.

Table 20 - Period of Record Available for WWTPs Load Estimation
(Source: EPA PCS Database)

Facility	POR	Facility	POR
Hopedale WWTP	5/01 - 8/04	Douglas WWTP	4/03 - 8/04
UBWPAD	11/99 - 9/04	Uxbridge WWTP	11/99 - 9/04
Millbury WWTP	11/99 - 8/04	Woonsocket WWTP	7/00 - 10/04
Grafton WWTP	11/99 - 9/04	Burrillville Sewer Commission	3/00 - 10/04
Upton WWTP	9/02 - 9/04	NBC Bucklin Point	2/02 - 10/04
Northbridge WWTP	11/99 - 9/04	NBC Fields Point	2/02 - 10/04

The process for estimating the average annual point source loads from each plant are outlined in Equations 2 and 3. L_i is the annual load for an individual year based on a set of reported values (1 to n) available for that year, with n varying from year to year. Q_i is the reported flow in MGD, C_i is the reported concentration in mg/L, x is the number of years of data over the period of record and L_{annual} is the average annual load for a given plant over the period of record in kg/yr. Note that 1381.7 is the conversion factor from MGD*mg/L to kg/yr.

$$L_i = 1381.7 \frac{\sum_{i=1}^n Q_i C_i}{n} \quad (2)$$

$$L_{\text{annual}} = \frac{\sum_{i=1}^x [L_i]}{x} \quad (3)$$

The annual point source loadings were calculated for the Narragansett Bay Watershed, the Blackstone River Watershed and the UBS Watershed, the location of the UBWPAD.

To determine variability in PS loads throughout the year, monthly PS loading estimates were also calculated. The monthly PS loading estimates were calculated in a similar manner to the yearly loading estimates, outlined in Equations 4 and 5 below. L_{mi} is equal to the average monthly load in kg/yr for month m in year i, Q_{mi} is the reported average monthly flow in MGD, C_{mi} is the reported average monthly concentration in mg/L, n is the number of monthly values for month m over the period of record and L_m is the average monthly load in kg/yr for month m over the period of record. The variable m

varies from 1 to 12, representing the month of the year. Note that 1381.7 is the conversion factor from MGD*mg/L to kg/yr.

The monthly point source loading estimates were multiplied by the factor F, the length of time over the course of the year that each of the months represents. The resulting average monthly load, L_m is in kg. The values for F are outlined in Table 21 below.

$$L_{mi} = 1381.7 \sum_{i=1}^n Q_{mi} C_{mi} \quad (4)$$

$$L_m = F \left[\frac{\sum_{i=1}^n L_{mi}}{n_m} \right] \quad (5)$$

Table 21 - Fraction of the Year that is Occupied by Each Month (F)

Month	Days	Fraction of the Year	Month	Days	Fraction of the Year
January	31	0.085	July	31	0.085
February	28	0.077	August	31	0.085
March	31	0.085	September	30	0.082
April	30	0.082	October	31	0.085
May	31	0.085	November	30	0.082
June	30	0.082	December	31	0.085

3.2.5 - Major River Annual Pollutant Load Estimation to Narragansett Bay

Equations two through five, NPDES data, and land use based export coefficients were used to resolve *within basin* relative source contributions (point source versus non-point source) and temporal variability (monthly versus annual). Such estimates, however, do not account for along-stream sources and sinks. Available in-stream data were used to estimate annual load by river basin as described in this section. Point and nonpoint sources within each watershed, as well as along-stream sources and sinks, are assumed to be captured by the in-stream data. Thus in-stream based estimates of load are considered

to be more representative of true load. Analyses in this section were used mainly to estimate major river contributions to Narragansett Bay.

Along with the Taunton and Pawtuxet Rivers, the Blackstone River is one of the largest contributors of freshwater to Narragansett Bay (Ries, 1990; Ely, 2002; Bergondo *et al*, 2005). The average flow from each of the rivers into the bay was calculated using flow data collected by the USGS using stream gauges with significant periods of record located nearest to the outlet of each river, Table 22. The long term, daily average stream flow values were used to calculate the long term annual stream flow for each station. The contributing areas to the utilized stream flow gauges as well as the area of the entire watershed were tabulated for each river. USGS gauges are placed where flow can be accurately monitored, which rarely corresponds to the true basin outlet. Thus there is a need to inflate the estimated flow to account for discharge from the entire watershed area.

Table 22 - Major Rivers Flowing into Narragansett Bay

River	Stream Gauge	USGS ID	POR	Drainage Area to Gauge	Average Flow	Drainage Area of Entire Basin
				(mi ²)	(cfs)	(mi ²)
Blackstone	Blackstone River at Woonsocket	1112500	1929-2004	416	775	475
Pawtuxet	Pawtuxet River at Cranston	1116500	1929-2004	200	478	234
Taunton	Taunton River nr Bridgewater	1108000	1939-2004	261	348	562

Sources: USGS MA/RI Water Science Center
RIDEM - Pawtuxet River Watershed Page
MassEOEA - Taunton River Watershed Page

Using Equation 6, the size of the entire watershed for each river was used to linearly adjust the long term average flow at the stream gauges to the estimated flow from their respective watersheds into Narragansett Bay, Table 23.

$$Q_{adjusted} = Q_{Str} \left(\frac{A_w}{A_{Str}} \right) \quad (6)$$

Q_{adjusted} is the estimated average flow from each river into Narragansett Bay, Q_{str} is the long term average flow recorded at the stream gauge, A_{str} is the area that contributes to the flow at the stream gauge and A_w is the area of the entire watershed.

Table 23 - Adjusted Long Term Average Flow into Narragansett Bay

River	Stream Gauge	USGS ID	Adjusted Average Flow to Narr. Bay
			(cfs)
Blackstone	Blackstone River at Woonsocket	1112500	885
Pawtuxet	Pawtuxet River at Cranston	1116500	559
Taunton	Taunton River nr Bridgewater	1108000	750

As shown Table 23, the three rivers contribute 1.42 billion gallons/day of freshwater into Narragansett Bay, approximately 60 percent of the daily freshwater inputs into the bay. This value corresponds to the flow values reported by Ries (1990). The remaining flow into the Bay comes from smaller tributaries and direct runoff.

The amount of flow delivered to the bay from the Blackstone, the Taunton and the Pawtuxet causes the rivers to play a significant role in the health of the bay. The annual loading of phosphorus and nitrogen from the rivers have been shown in previous studies (Nixon *et al*, 1995; Nixon *et al*, 2005) to be a large component of the overall nutrient loading into the bay. For this work, USGS flow data (described above) and water quality data were combined to estimate the annual total phosphorus and total nitrogen loading as described below.

Mean daily values of flow (Q_{mdv}) data were plotted against total phosphorus and total nitrogen concentrations in each river as measured by the USGS. The Q_{mdv} data are published for every day except for periods when the gauge has malfunctioned. Estimates are often available on these days. Table 24 shows the period of record (POR) which data were available for both concentration and Q_{mdv} for the three rivers. It was hypothesized that changing land use in the area would affect the flow-concentration (Q-C) relationships

in the rivers. Therefore, only flow and concentration data collected from 1990 onward was used in the development of the Q-C correlation equations. The resulting number of concentration data points that were available for the development of the Q-C equations are also provided in Table 24.

While both flow and concentration data were available at the same USGS gauge for the Pawtuxet and Taunton Rivers, that was not the case for the Blackstone River. To account for the fact that the USGS water quality sampling location (Manville) is located downstream of the Woonsocket stream flow gauge, the flows at the Woonsocket gauge were multiplied by the flow adjustment factor prior to the development of the Blackstone River Q-C relationship equations.

Table 24 - Available Data for the Development of Q-C Relationship Equations

River	Stream Gauge	USGS ID	Drainage Area	POR - WQ	POR - Used	Number of Data Points	Stream Gauge used for Flow Values	Flow Adjustment Factor
Blackstone	Blackstone River at Manville	1112900	430.6	1970-2002	1992-2003	77	Blackstone River at Woonsocket	1.04
Pawtuxet	Pawtuxet River at Cranston	1116500	200	1901-2002	1993-2002	69	Pawtuxet River at Cranston	1
Taunton	Taunton River nr Bridgewater	1108000	261	1952-2002	1996-2002	24	Taunton River nr Bridgewater	1

As shown in the table above, both the Blackstone and Pawtuxet Rivers have a large number of data points available from which Q-C correlation equations may be developed. While the Taunton River has significantly fewer data points on which an equation may be based, it was deemed adequate for the analyses conducted herein.

Once the data were plotted, a natural log (ln) based, best fit line was fit to the data, resulting in the Q-C equations for each river. Available Q_{mdv} values were combined with

the regression equation to simulate daily concentration values of both total phosphorus and total nitrogen. The recorded Q_{mdv} values and the simulated concentration values were used to calculate daily loads based on Equation 7. Where Q_{mdv} is the mean daily value of flow as reported by the USGS in cfs, C_{sim} is the simulated concentration value based on the previously developed equations and L is the estimated daily load in kg/yr. Note that 893 is the conversion factor from cfs*mg/L to kg/yr.

$$893Q_{mdv}C_{sim}=L_{sim} \quad (7)$$

The estimated daily loads were then combined appropriately to calculate average monthly and annual loads for each river over the period of record available at each stream gauge, Table 24. Similar to the flow adjustments outlined previously in this section, the loading values estimated at the inland stream gauges were adjusted to be representative of the loading from the entire watershed using Equation 8.

$$L_{adjusted} = L_{sim} \left(\frac{A_w}{A_{Str}} \right) \quad (8)$$

$L_{adjusted}$ is the adjusted average load from each river into Narragansett Bay, L_{sim} is the simulated average loads estimated at the stream gauge, A_{str} is the area that contributes to the flow at the stream gauge, A_w is the area of the entire watershed and A_w/A_{str} is listed as the load adjustment factor, Table 25.

Table 25 - Load Adjustment Factors for Q-C Loading Analysis

River	Stream Gauge	USGS ID	Load Adjustment Factor
Blackstone	Blackstone River at Manville	1112900	1.11
Pawtuxet	Pawtuxet River at Cranston	1116500	1.17
Taunton	Taunton River nr Bridgewater	1108000	2.15

These loads were used in conjunction with the calculated PS and NPS loading into Narragansett Bay to determine the relative magnitude of loads into the bay on a monthly and annual basis, detailed in the next section.

3.2.6 - Total Loading into Narragansett Bay

Similar to the loading analyses conducted for the Blackstone Watershed, point source and nonpoint source loading estimates were calculated on a monthly and annual basis for the Narragansett Bay watershed as well. The PS loading estimates were calculated for the Fields Point and Bucklin Point WWTPs. They are the two largest WWTPs that discharge into Narragansett Bay and both are operated by the Narragansett Bay Commission.

In order to determine the NPS loading to the bay, only the area that drains directly into the bay was analyzed to ensure that the inland areas that contribute to the loading in the bay via river inputs were not double counted. Unlike the monthly NPS analysis for the Blackstone, average monthly rainfalls used in the NPS loading estimates for Narragansett Bay were calculated using data from the NWS weather station in Providence, RI.

3.3 - Results & Discussion

3.3.1 - Land Use and Percent Imperviousness Analysis

The sub-basin delineation and land use classifications for the Blackstone River watershed are shown in Figure 7 below. The areas and land use percentages for the watersheds and their respective sub-watersheds are presented in Table 26. The sub-watersheds are listed in an upstream to downstream order, with the watershed that drains directly to the mainstem of the Blackstone River (BSMS) listed last.

Figure 7 - Blackstone River Watershed Sub-Basins and Land Use Classifications

Table 26 – Areas and Land Use Percentages for the Blackstone Watershed and its Sub-Basins

Basin	Area (mi2)	Agri.	Forest	Wetlands	Water	Res.	Comm.	Ind.	Trans.	Open
Blackstone	474.0	4.9	53.4	4.1	3.5	22.4	1.8	2.5	1.5	5.9
UBS	72.1	3.5	41.5	0.8	4.0	29.9	3.6	4.4	3.6	8.7
Quinsigamond	37.7	4.1	37.8	2.0	4.2	32.5	3.1	3.4	2.3	10.5
Mumford	56.1	6.3	64.4	1.1	4.8	16.5	0.5	1.2	1.1	4.2
West	37.4	6.6	66.5	2.5	1.2	18.0	0.5	0.7	0.2	3.8
Nipmuck	15.6	2.7	77.0	4.1	0.5	11.5	0.1	0.7	0.0	3.5
Mill	33.0	6.1	55.5	1.8	2.7	25.4	0.8	2.8	0.6	4.5
Branch	56.3	2.9	64.3	8.4	4.3	14.1	0.9	1.7	0.2	3.1
Chepachet	19.2	5.4	65.1	10.1	4.1	11.1	0.7	1.6	0.0	1.9
Peters	12.3	8.3	50.8	4.5	1.3	24.2	1.8	1.6	0.0	7.5
Abbot	28.6	8.0	44.6	6.1	5.2	26.1	0.8	1.6	0.9	6.7
BSMS	105.3	4.5	47.1	6.0	3.0	24.3	2.8	3.5	2.0	6.8

As shown in the figure and table above, the Blackstone watershed contains a significant amount of urban and suburban area, defined here as the following land uses: Residential, Commercial, Industrial and Transportation. This is especially evident along the mainstem of the river (BSMS), which contains 32.6% urban/sub-urban areas and in its headwaters (UBS) which contain 41.5% urban/sub-urban areas.

The percent imperviousness of the Blackstone River Watershed and its sub-basins are presented in Figure 8 and Table 27. Figure 8 also depicts the impairment status of each of the sub-watersheds based on the impairment classifications listed in Table 13.

Figure 8 - Percent Imperviousness of the Blackstone Watershed and its Sub-Basins

Table 27 - Percent Imperviousness Values for the Blackstone Watershed and its Sub-Basins

Basin	Area (mi ²)	Percent Impervious Area
Blackstone	474.0	10.4
UBS	72.1	18.5
Quinsigamond	37.7	16.4
Mumford	56.1	6.3
West	37.4	5.5
Nipmuck	15.6	3.9
Mill	33.0	7.8
Branch	56.3	5.9
Chepachet	19.2	4.6
Peters	12.3	8.5
Abbot	28.6	9.0
BSMS	105.3	12.5

As shown in Table 27, the Blackstone Watershed, as a whole has greater than 10% impervious area, classifying it as being impaired. However, it is apparent from the figure and table above that only the two headwaters sub-basins: UBS (18.5%) and

Quinsigamond (16.4%) and the watershed draining to the mainstem of the river, BSMS (12.5%) are classified as impaired. The data also shows that despite their current status as protected, both the Abbot and Peters River sub-basins are very close to exceeding the 10% imperviousness threshold at 9.0 and 8.5% respectively.

Due to the large amount of urbanized area found in the UBS watershed, a more in depth percent impervious analysis of the UBS sub-watersheds was conducted. The UBS watershed was split into nine (9) sub-basins to determine the spatial variability of the imperviousness in and around the city of Worcester. The results of this more refined percent imperviousness analysis are detailed in Figure 9 and Table 28.

Figure 9 - UBS Sub-Watershed Percent Imperviousness Classifications

Table 28 - UBS Sub-Watershed Percent Imperviousness Values

Sub Basin	% Impervious Area
Blackstone River North	31.6
Blackstone River South	14.5
Dark Brook	11.6
Kettle Brook North	7.6
Kettle Brook Central	10.2
Kettle Brook South	16.3
Mill Brook and Middle River	34.3
Tatnuck Brook North	3.1
Tatnuck Brook South	23.1

The order in which the major tributaries in the UBS watershed flow from upstream to downstream is as follows: Kettle Brook, Tatnuck Brook, Middle River, Mill Brook and finally the mainstem of the Blackstone. The tributaries themselves flow from north to south, except for Kettle Brook. Half of Kettle Brook flows from south to north, referred to here as Kettle Brook South and the northern section of the Kettle Brook Center sub-basin, while the other half of the brook flows from north to south Kettle Brook North and the southern half of the Kettle Brook Center sub-basin.

As shown above, only Kettle Brook North and Tatnuck Brook North sub-basins are classified as protected areas. This is likely due to urbanization restrictions in the area, implemented to protect the drinking water supply for the city of Worcester. Both the Mill Brook and Blackstone North sub-basins are classified as degraded. The remaining sub-basins are considered impaired, with Tatnuck Brook South bordering on being classified as degraded. Subsequent analysis of Beaver Brook, which makes up the eastern half of Tatnuck Brook South, has an impervious area of about 27%, bordering on degraded. Analysis for the area around St Johns Cemetery, located on the Middle River, part of the Mill Brook/Middle River sub-basin, shows that there is an impervious area percentage of greater than 40% in this area.

Even though several sub-watersheds of UBS and mainstem Blackstone River are classified as protected, they may be susceptible to water quality degradation. Work by Booth *et al.* (2004) suggests that the >10% threshold used to classify a water body as

impaired may be the upper bound to the threshold; water quality can be negatively impacted by urbanization that results in less than 10% impervious area.

3.3.2 - Water Quality Analysis - Upper Blackstone Watershed

The resulting overall averages of NO_3 and PO_4 concentrations from the BRC volunteer monitoring data collected in the UBS watershed are presented in Table 29. The tributaries are listed from upstream to downstream as are the sampling locations listed under each tributary. For example, on Kettle Brook, the James St. sampling location is upstream of the Dark Brook sampling location and so on. In general, all of the tributaries flow toward the city of Worcester as they flow downstream. Therefore, it is expected that the upstream sites will show less degradation than the downstream sites. A table with all of the water quality concentrations for each site by month, year and overall average concentrations can be found in Appendix A. In general, most sites have either no change or become more degraded on an annual basis. The exceptions are the sites located on Mill Brook which tend to show improvements in water quality on an annual basis.

**Table 29 - Overall Average Nutrient Concentrations for the BRC
Sampling Locations in the UBS Watershed**

Tributary	Sampling Location	Overall NO ₃ as N Conc. (mg/L)	Impairment Status - N	Overall PO ₄ as P Conc. (mg/L)	Impairment Status - P
Kettle Brook	James St	0.06	Excellent	0.054	Fair
	Dark Brook	0.13	Excellent	0.042	Good
	Leesville Pond In	0.06	Excellent	0.097	Fair
	Leesville Pond Out	0.06	Excellent	0.049	Good
Tatnuck Brook	Dawson Rd	0.05	Excellent	0.034	Good
	Mill St/Am Leg.	0.01	Excellent	0.027	Good
	Park Ave	0.27	Excellent	0.037	Good
Beaver Brook	JCC	0.08	Excellent	0.024	Excellent
	Flagg St	0.06	Excellent	0.042	Good
	Maywood St	0.29	Excellent	0.064	Fair
	Park Ave	0.19	Excellent	0.049	Good
Middle River	St Johns Cem.	0.11	Excellent	0.065	Fair
	Millbury St	-	-	0.051	Fair
Mill Brook	Salisbury Pond East	0.29	Excellent	0.099	Fair
	Salisbury Pond West	0.32	Good	0.081	Fair

All but one of the sampling locations are classified as excellent according to the NO₃ concentration metric utilized by the BRC. The only site not classified as excellent is Salisbury Pond West in the Mill Brook sub-watershed. The location is classified as good, with an average NO₃ concentration of 0.32 mg/L, just above the excellent threshold.

The opposite is true for the phosphorus based impairment classification. Only one site is classified as excellent, the Jewish Community Center (JCC) sampling site located in the headwaters of Beaver Brook. The remaining sites are all classified as good or fair with none being classified as poor.

The classifications shown for the Beaver Brook sampling locations signify the effects of increasing urbanization on the water quality of a stream. As Beaver Brook flows from its headwaters to the center of Worcester, the impairment classifications change from excellent to good to fair. Similar patterns are shown in Kettle Brook and Tatnuck Brook,

with PO₄ concentrations generally increasing as the streams flow through increasing amounts of impervious area toward the center of the city.

3.3.3 - Comparison between Water Quality Impairment Metrics

Table 30 shows the comparison matrix between the two impairment metrics outlined above. The impairment classifications for the monitoring locations of the BRC, based on the nutrient concentration and percent imperviousness ranges that were outlined in Table 17.

Table 30 - Impairment Metric Comparison: Water Quality vs. Percent Imperviousness

	Concentration Based			Imperviousness Based	
Tributary	BRC Sampling Location	Impairment Status - N	Impairment Status - P	Sub-Basin	Impairment Status - Percent Impervious
Kettle Brook					
	Dark Brook	Unimpaired	Impaired	KBS	Impaired
	Leesville Pond In	Unimpaired	Impaired	KBS	Impaired
	Leesville Pond Out	Unimpaired	Impaired	KBS	Impaired
	James St	Unimpaired	Impaired	KBC	Impaired
Tatnuck Brook	Dawson Rd	Unimpaired	Impaired	TBS	Impaired
	Mill St/Am Leg.	Unimpaired	Impaired	TBS	Impaired
	Park Ave	Unimpaired	Impaired	TBS	Impaired
Beaver Brook	JCC	Unimpaired	Unimpaired	TBS (BB)	Unimpaired
	Flagg St	Unimpaired	Impaired	TBS (BB)	Impaired
	Maywood St	Unimpaired	Impaired	TBS (BB)	Impaired
	Park Ave	Unimpaired	Impaired	TBS (BB)	Impaired
Middle River	St Johns Cem.	Unimpaired	Impaired	MB (MR)	Degraded
	Millbury St	-	Impaired	MB (MR)	Degraded
Mill Brook	Salisbury Pond East	Unimpaired	Impaired	Mill Brook	Degraded
	Salisbury Pond West	Impaired	Impaired	Mill Brook	Degraded

Based on the values seen in the table above, the impairment metrics for nitrate concentration and percent imperviousness do not correspond well to one another. However, the NO₃ concentrations for Salisbury Pond East, Tatnuck Brook - Park Ave and Beaver Brook – Maywood St. are all very close to the impairment threshold, suggesting at least some correlation between the two metrics.

The phosphate concentration metric correlates well with the percent imperviousness metric in Table 30, with all but the Mill Brook/Middle River sites matching exactly. When looking at the concentrations listed in Table 29, it can be seen that Salisbury Pond East, the uppermost monitoring location on Mill Brook, has a PO₄ concentration just below the degradation threshold, suggesting that the two metrics are correlated at all levels of impairment status.

3.3.4 - Point Source vs. Nonpoint Source Loading Analysis

The estimated annual NPS and PS loading of total nitrogen in the Blackstone River watershed are presented in Figure 10 and Figure 11 respectively. As shown in the two figures, the point source loading of total nitrogen (960,000 kg/yr) is within the estimated range of NPS total nitrogen loading (257,000 – 1,120,000 kg/yr). As stated previously, the point source loadings are based on reported monthly concentration and flow values for each WWTP from approximately 2000 to 2004. The NPS loading estimate ranges were calculated using published NPS pollution loading export coefficients. Further inspection of Figure 11 shows that UBWPAD and Woonsocket WWTP make up the majority (80%) of the current total nitrogen loading from point sources in the watershed.

Figure 10 – Blackstone Basin Estimated Annual Nonpoint Source Total Nitrogen Loading

Figure 11 – Blackstone Basin Estimated Annual Point Source Total Nitrogen Loading

Figure 12 and Figure 13 show the estimated annual NPS and PS loading of total phosphorus in the Blackstone River watershed. As with the nitrogen loading estimates, the point source loadings are based on reported monthly concentration and flow values for each WWTP from approximately 2000 to 2004. The NPS loading estimate ranges were calculated using published NPS pollution loading export coefficients. Similar to the nitrogen loading estimates, UBWPAD and Woonsocket WWTP comprise 80% of the total current PS total phosphorus loading in the basin (215,000kg/yr). Unlike the N loading estimates, the PS total phosphorus loadings exceed the NPS total phosphorus range of 18,000 to 127,000 kg/yr. The UBWPAD total phosphorus loading alone exceeds the high end of the NPS total phosphorus loading at 136,000 kg/yr.

Figure 12 – Blackstone Basin Estimated Annual Nonpoint Source Total Phosphorus Loading

Figure 13 – Blackstone Basin Estimated Annual Point Source Total Phosphorus Loading

The estimated monthly PS and NPS loadings of total nitrogen into the Blackstone watershed are presented in Figure 14 and Figure 15. Tabulated monthly values of PS and medium NPS total nitrogen loadings are outlined in Table 31.

Figure 14 - Blackstone Basin Estimated Monthly Point Source Total Nitrogen Loading

Figure 15 - Blackstone Basin Estimated Monthly Nonpoint Source Total Nitrogen Loading

Table 31 – Percent of Total Estimated Total Nitrogen Loading in the Blackstone Basin

Total N Loading	PS	NPS	PS+NPS	Percent of Total	
	(kg)	(kg)	(kg)	PS	NPS
Jan	89000	55000	144000	61.6	38.4
Feb	89000	42000	131000	67.9	32.1
Mar	96000	58000	154000	62.6	37.4
Apr	105000	53000	158000	66.3	33.7
May	92000	59000	151000	60.8	39.2
Jun	79000	55000	133000	59.0	41.0
Jul	61000	57000	118000	51.9	48.1
Aug	67000	56000	123000	54.6	45.4
Sept	64000	58000	122000	52.5	47.5
Oct	82000	64000	146000	56.4	43.6
Nov	69000	59000	128000	54.0	46.0
Dec	83000	52000	135000	61.7	38.3
Annual	977000	667000	1644000	59.4	40.6

The dynamic between the NPS and PS loading of total nitrogen is listed in Table 31 on a monthly basis. The percent of the total nitrogen loading values listed in Table 31 are calculated using the medium or average estimated values of NPS total nitrogen loading. The monthly variability in the PS loading of TN is quite dramatic. April has the largest TN loading at 105,000 kg, while July has the smallest at 61,000kg. The NPS total nitrogen loading is less variable with the highest average TN loading in October at 63,000kg and the lowest in February at 42, 000 kg. As previously discussed, the NPS loading is driven by monthly rainfall accumulation variability. On an annual basis, it is estimated that the NPS loading makes up 40% of the total nitrogen loading, ranging from 32% in February to 48% in July.

The estimated monthly PS and NPS loadings of total phosphorus into the Blackstone watershed are presented in Figure 16 and Figure 17. Tabulated monthly values of PS and medium NPS total phosphorus loading are shown in Table 32.

Figure 16 - Blackstone Basin Estimated Monthly Point Source Total Phosphorus Loading

Figure 17 - Blackstone Basin Estimated Monthly Nonpoint Source Total Phosphorus Loading

Table 32 – Percent of Total Estimated Total Phosphorus Loading in the Blackstone Basin

Total P Loading	PS	NPS	PS+NPS	Percent of Total	
	(kg)	(kg)	(kg)	PS	NPS
Jan	16000	5300	21000	75.3	24.7
Feb	22000	4000	26000	84.7	15.3
Mar	19000	5500	25000	78.0	22.0
Apr	18000	5100	23000	77.8	22.2
May	14000	5600	20000	71.4	28.6
Jun	15000	5200	20000	74.0	26.0
Jul	21000	5400	27000	79.8	20.2
Aug	16000	5300	21000	75.1	24.9
Sept	18000	5500	23000	76.0	24.0
Oct	20000	6000	26000	76.9	23.1
Nov	15000	5600	21000	73.3	26.7
Dec	21000	4900	26000	80.9	19.1
Annual	215000	63500	279000	77.2	22.8

The relative loading of PS vs. NPS is outlined in Table 32 on a monthly and an annual basis. Similar to the monthly TN loading, the PS loading of total phosphorus varies significantly from month to month. The highest monthly point source TP loading is found in February at 22,000kg with the lowest found in May at 14,000 kg. The NPS total phosphorus loading is less variable, ranging from 6,000kg in October to 4,000kg in February. Annually, NPS loading makes up 23% of the total phosphorus loading. On a monthly basis, NPS makes up to 29% of the total loading in May dropping to as low as 15% in February.

The estimated annual NPS and PS loads of total nitrogen into the UBS watershed are shown in Figure 18 and Figure 19. As shown in the figures, UBWPAD, the only PS in the UBS watershed, contributes almost six times the amount of TN compared to the average NPS loading estimate.

Figure 18 – Upper Blackstone Basin Estimated Annual Nonpoint Source Total Nitrogen Loading

Figure 19 – Upper Blackstone Basin Estimated Annual Point Source Total Nitrogen Loading

A similar trend is shown in the NPS and PS total phosphorus loading estimates, Figure 20 and Figure 21. UBWPAD contributes more than ten times the amount of TP into the UBS watershed than the average NPS loading estimate.

Figure 20 – Upper Blackstone Basin Estimated Annual Nonpoint Source Total Phosphorus Loading

Figure 21 – Upper Blackstone Basin Estimated Annual Point Source Total Phosphorus Loading

The monthly dynamics of the PS and NPS total nitrogen loadings are presented in Figure 22 and Figure 23. The monthly PS loadings as well as the average monthly NPS nitrogen loading estimates are shown in Table 33. Monthly PS total nitrogen loading in the UBS watershed ranges from 66,000kg in April to 31,000 in July. The lower numbers in the summer months represent the nitrogen reduction achieved at UBWPAD via summer

nitrification. The NPS total nitrogen estimates are not as variable, ranging from 6,700kg in February to 10,000kg in October.

Figure 22 – Upper Blackstone Basin Estimated Monthly Point Source Total Nitrogen Loading

Figure 23 – Upper Blackstone Basin Estimated Monthly Nonpoint Source Total Nitrogen Loading

Table 33 – Percent of Total Estimated Total Nitrogen Loading in the Upper Blackstone Basin

Total N Loading	PS	NPS	PS+NPS	Percent of Total	
	(kg)	(kg)	(kg)	PS	NPS
Jan	59000	8800	68000	87.0	13.0
Feb	60000	6700	67000	90.0	10.0
Mar	60000	9100	69000	86.8	13.2
Apr	66000	8400	75000	88.7	11.3
May	60000	9400	69000	86.4	13.6
Jun	46000	8700	55000	84.1	15.9
Jul	31000	9000	40000	77.5	22.5
Aug	36000	8800	45000	80.3	19.7
Sept	39000	9200	49000	81.0	19.0
Oct	46000	10000	57000	82.2	17.8
Nov	42000	9400	52000	82.0	18.0
Dec	45000	8200	53000	84.7	15.3
Annual	591000	106000	697000	84.8	15.2

The loading dynamics between the NPS and PS total nitrogen estimates result in NPS loading constituting 15% of the annual nitrogen load. The NPS load ranges from 10% in February to 22% in July.

The PS and NPS total phosphorus loading into the UBS watershed are presented in Figure 24 and Figure 25. The monthly and annual values of the PS and average NPS total phosphorus loading estimates are tabulated in Table 34.

The monthly PS total phosphorus loading for the UBS ranges from 9,200kg in January to 15,000kg in October. The NPS estimates vary less, ranging from 700kg in February to 1,100kg in October. The NPS loading makes up only 8% of the annual total phosphorus loading in the watershed, ranging from 5% in February to 10% in May.

Figure 24 – Upper Blackstone Basin Estimated Monthly Point Source Total Phosphorus Loading

Figure 25 – Upper Blackstone Basin Estimated Monthly Nonpoint Source Total Phosphorus Loading

Table 34 – Percent of Total Estimated Total Phosphorus Loading in the Upper Blackstone Basin

Total P Loading	PS	NPS	PS+NPS	Percent of Total	
	(kg)	(kg)	(kg)	PS	NPS
Jan	9200	1000	10000	90.4	9.6
Feb	14000	700	15000	95.0	5.0
Mar	9400	1000	10000	90.3	9.7
Apr	11000	900	12000	92.2	7.8
May	9600	1000	11000	90.2	9.8
Jun	10000	1000	11000	91.2	8.8
Jul	14000	1000	15000	93.2	6.8
Aug	9500	1000	11000	90.7	9.3
Sept	12000	1000	13000	91.9	8.1
Oct	15000	1100	16000	92.9	7.1
Nov	10000	1000	11000	90.8	9.2
Dec	13000	900	14000	93.3	6.7
Annual	136000	12000	148000	92.0	8.0

It is illustrated in the section above that the PS and NPS loading estimates vary throughout the year in both the Blackstone Basin as a whole and the UBS watershed. The UBS watershed loading is dominated on an annual and monthly basis, by the discharge from the UBWPAD for both phosphorus and nitrogen. PS loadings on an annual basis constitute approximately 85% of the total nitrogen loading and 92% of the total phosphorus loading in the UBS watershed.

The Blackstone Basin as whole is also dominated by PS loading of total nitrogen and total phosphorus. PS loadings constitute approximately 59% of the annual total nitrogen loading and 77% of the annual total phosphorus loading into the Blackstone watershed.

While the analyses conducted herein shed additional light on the variability of the PS and NPS loading in both the UBS and the Blackstone watersheds, there are still many unknowns in the loading behavior of the system. In order to better understand the nutrient loadings that the system is subjected to, the true variability of the PS and NPS loading must be assessed, perhaps on a daily time scale. Furthermore, the potential for in stream losses and/or gains in pollutant loading are not accounted for in this analysis. Additional analysis of the gain/loss loading behavior along the stream need to be

conducted in order to better understand the impact of the gains and losses on pollutant propagation to downstream reaches and ultimately Narragansett Bay.

3.3.5 - Major River Annual Pollutant Load Estimation to Narragansett Bay

The Q vs. TN and the Q vs. TP plots used to develop the Q-C relationship equations for the Blackstone River are shown in Figure 26 and Figure 27. The plots for the Pawtuxet and Taunton Rivers are located in Appendix C.

Figure 26 - Q vs. N Plot for the Blackstone River

Figure 27 - Q vs. P Plot for the Blackstone River

A best fit line was used to produce a concentration estimation equation for each river and constituent, dependent on Qmdv. The resulting equations are presented in Table 35. It should be noted that any data point, concentration or flow that was more than 2 standard deviations from the average flow or concentration was excluded from the regression fit, resulting in the “Final” plots as designated above.

Table 35 - Q vs. C Equations used in River Loading Estimations

River	Stream Gauge	USGS ID	Q vs. TP Relationship	R ² Value	Q vs. TN Relationship	R ² Value
Blackstone	Blackstone River at Manville	1112900	C = -.1657ln(Qmdv) + 1.3633	0.3757	C = -.8631ln(Qmdv) + 7.798	0.7234
Pawtuxet	Pawtuxet River at Cranston	1116500	C = -.1435ln(Qmdv) + 1.0146	0.5919	C = -.9332ln(Qmdv) + 7.1336	0.6265
Taunton	Taunton River nr Bridgewater	1108000	C = -.0185ln(Qmdv) + .2317	0.2012	C = -.823ln(Qmdv) + 6.5652	0.8459

The relatively high R² values for the total nitrogen estimation equations show that the relationship between TN and flow is quite strong, allowing for accurate estimation of total nitrogen concentrations based on flow values. The R² values for total phosphorus are much lower than those for the Q-TN correlation equations. This is likely due to the

strong influence of sediment transport on total phosphorus concentrations, a phenomenon that is not as prevalent in the nutrient cycle.

The estimated annual nutrient loadings to Narragansett Bay from each river, based on the equations in Table 35 and observed mdvs, are shown in Table 36. As shown in the table, the Blackstone contributes the majority of the riverine load to Narragansett Bay, followed by the Taunton River and the Pawtuxet River. This finding corresponds to the findings of Nixon *et al* (1995), who based his estimates on bi-weekly concentration measurements from 1982-1983 for the majority of the rivers, and monthly concentration and flow measurements from 1988-1989 for the Taunton River. The similarity between the findings lends validity to the procedure used in this study for the estimation of the river loads into Narragansett Bay.

Table 36 - Estimated Annual Nutrient River Loadings

	Blackstone	Pawtuxet	Taunton	Total
Annual Loading	(kg/yr)	(kg/yr)	(kg/yr)	(kg/yr)
TP	159000	51000	127000	336000
TN	1376000	517000	1204000	3097000
Percent of Total				
TP	47.2	15.2	37.6	100
TN	44.4	16.7	38.9	100

The monthly loading estimates for the three rivers are shown in Table 37. It is shown that while the Blackstone dominates both the total nitrogen and total phosphorus loadings on an annual basis, the Taunton River is the dominant riverine source of total phosphorus during the months of March and April and of total nitrogen during June and July.

Table 37 - Estimated Monthly Percentages of Nutrient River Loadings

Percent of Total	Blackstone		Pawtuxet		Taunton		Total	
	TP	TN	TP	TN	TP	TN	TP	TN
January	48.6	46.3	14.2	16.5	37.2	37.3	100	100
February	47.4	45.7	13.6	16.1	39.0	38.2	100	100
March	42.7	46.4	12.0	15.4	45.3	38.3	100	100
April	42.3	47.4	11.3	15.8	46.4	36.8	100	100
May	46.1	43.0	14.0	15.3	39.9	41.7	100	100
June	45.4	39.7	15.7	15.6	38.9	44.7	100	100
July	46.5	37.6	19.1	18.5	34.3	43.9	100	100
August	52.7	40.9	22.2	21.0	25.1	38.1	100	100
September	54.8	40.9	23.2	21.1	22.0	37.9	100	100
October	50.1	45.9	17.2	17.7	32.7	36.4	100	100
November	52.6	44.8	17.3	17.4	30.0	37.7	100	100
December	48.8	47.7	14.9	16.5	36.2	35.8	100	100

The loading analysis described in the above section is used to estimate both the magnitude and timing of the riverine nutrient loading into Narragansett Bay.

3.3.6 - Total Loading into Narragansett Bay

Overall loading into Narragansett Bay was estimated using three components: inland watershed loading, referred to here as riverine loading, point source loadings directly into the bay and finally NPS loading directly into the bay. Riverine loading consists of the loading from inland sources, both PS and NPS, transported to the bay via river flows. The riverine loadings into the bay were calculated in the previous section. The point source loadings consist of loading from the Fields Point and Bucklin Point WWTPs, both of which discharge directly into the bay. NPS loading consists of direct runoff into the bay that is not delivered as part of the rivers loading component. Both the PS and NPS loadings into Narragansett Bay were calculated using the same procedures used in the PS vs. NPS analysis conducted for the UBS watershed and the Blackstone Watershed as a whole. The PS and NPS loadings into Narragansett Bay are outlined below.

Figure 28 and Figure 29 show the NPS and PS total nitrogen loading into Narragansett Bay. When examining the two figures, it is apparent that the NPS pollution is almost two times larger than the PS total nitrogen pollution. Similarly, the NPS total phosphorus

pollution to the bay, shown in Figure 30, is almost one and a half times larger than the PS total phosphorus pollution shown in Figure 31.

Figure 28 - Narragansett Bay NPS Total Nitrogen Loading

Figure 29 - Narragansett Bay PS Total Nitrogen Loading

Figure 30 - Narragansett Bay NPS Total Phosphorus Loading

Figure 31 - Narragansett Bay PS Total Phosphorus Loading

The monthly estimates for NPS and PS total nitrogen loadings into Narragansett Bay are presented in Figure 32 and Figure 33. The monthly PS loading estimates as well as the monthly average NPS total nitrogen loads are presented in Table 38. The NPS total nitrogen loading varies from 260,000kg in July to 363,000kg in March. The PS TN loading however is far less variable, ranging from 146,000kg in August to 182,000kg in December.

Unlike the Blackstone Watershed, the NPS total nitrogen loading dominates the PS vs. NPS dynamic in the Narragansett Bay watershed. NPS total nitrogen loading accounts for 66% of the average annual PS vs. NPS dynamic, ranging from 62% in July to 71% in November.

Figure 32 - Narragansett Bay Monthly NPS Total Nitrogen Loading

Figure 33 - Narragansett Bay Monthly PS Total Nitrogen Loading

Table 38 - PS vs. NPS Total Nitrogen Loading Monthly Breakdown - Narragansett Bay

Total N Loading	PS	NPS	PS+NPS	Percent of Total	
	(kg)	(kg)	(kg)	PS	NPS
Jan	180000	359000	539000	33.4	66.6
Feb	152000	283000	436000	35.0	65.0
Mar	168000	364000	532000	31.6	68.4
Apr	152000	341000	493000	30.8	69.2
May	182000	300000	482000	37.7	62.3
Jun	168000	277000	445000	37.7	62.3
Jul	161000	260000	422000	38.3	61.7
Aug	146000	320000	466000	31.3	68.7
Sept	151000	304000	455000	33.2	66.8
Oct	173000	303000	475000	36.3	63.7
Nov	151000	361000	513000	29.5	70.5
Dec	182000	340000	522000	34.9	65.1
Annual	1966000	3812000	5779000	34.0	66.0

Monthly NPS and PS total phosphorus loadings into Narragansett Bay are shown in Figure 34 and Figure 35. The monthly PS and average NPS total phosphorus loads are tabulated in Table 39. The monthly NPS TP loadings range from 23,000kg in July to 33,000 in March. Unlike the monthly PS loading of total nitrogen into the bay, the PS loading of total phosphorus is quite variable, ranging from 10,000kg in June to 20,000kg in March. The resulting PS vs. NPS total phosphorus loading dynamic results in an annual average of 66%NPS loading, ranging from 62% in March to 72% in January, October and December.

Figure 34 - Narragansett Bay Monthly NPS Total Phosphorus Loading

Figure 35 - Narragansett Bay Monthly PS Total Phosphorus Loading

Table 39 - PS vs. NPS Total Phosphorus Loading Monthly Breakdown - Narragansett Bay

Total P Loading	PS	NPS	PS+NPS	Percent of Total	
	(kg)	(kg)	(kg)	PS	NPS
Jan	13000	32000	45000	28.0	72.0
Feb	15000	25000	41000	37.4	62.6
Mar	20000	33000	53000	38.1	61.9
Apr	13000	31000	44000	30.2	69.8
May	15000	27000	42000	35.2	64.8
Jun	10000	25000	35000	29.0	71.0
Jul	17000	23000	41000	42.5	57.5
Aug	15000	29000	44000	34.5	65.5
Sept	13000	27000	41000	32.9	67.1
Oct	11000	27000	38000	27.9	72.1
Nov	19000	32000	51000	36.3	63.7
Dec	12000	30000	42000	28.1	71.9
Annual	173000	342000	515000	33.5	66.5

The results of the previously described analyses were used to estimate an annual nutrient load into the bay as well as to determine the timing and relative magnitudes of pollutant loads.

Table 40 illustrates the annual TN loading estimates (kg/yr) from all three sources, riverine, direct NPS loading and direct PS loading into Narragansett Bay as well as their relative percentage of the total into the bay on an individual and a group basis.

Table 40 - Annual Total Nitrogen Loading into Narragansett Bay

Total Nitrogen				
Annual Loading		(kg/yr)	Percent of Sub Total	Percent of Total
WWTP's	NBC Bucklin Pt	730000	36.9	8.2
	NBC Fields Pt	1250000	63.1	14.1
	Total WWTP	1980000	100.0	22.3
Rivers	Blackstone	1376000	44.4	15.5
	Pawtuxet	517000	16.7	5.8
	Taunton	1204000	38.9	13.5
	Total Rivers	3097000	100.0	34.8
NPS		3812000	100.0	42.9
	Total NPS	3812000	100.0	42.9
Total	(kg/yr)	8890000	0	100

On an annual basis, WWTPs discharging directly to the Bay contribute 22%, river loadings contribute 35% and NPS contribute 43% of the annual total nitrogen loads into the bay. These values are similar to those reported by Nixon *et al* in 1995. They reported that 9.1E6 kg/yr of TN enter Narragansett Bay, which corresponds well with the value of 8.9E6 kg/yr estimated in this study. They reported that the WWTPs input 28% of the total nitrogen load into the bay, rivers contributed 61.5% and NPS contributed 10% of the load into the bay.

Differences between the river loadings between the two studies are likely due to the methodologies used here to estimate the loadings vs. the methodologies used during their study. Another potential difference in the loadings is the reduction of PS effluents into the inland waters as well as the bay itself since the 1980's when the data used in that study was collected. This phenomenon is apparent when looking at the loadings of total nitrogen from the Blackstone River. In this analysis, the Blackstone is estimated to contribute 16% of the total nitrogen loading into the bay, down from 20% in the 1995 study. The reduction in PS loadings coupled with the development around the bay could have caused a significant shift in the PS vs. NPS dynamic of the loading into the bay.

The annual total phosphorus loading values into the bay are detailed in Table 41. On an annual basis, WWTPs discharging directly into the bay are estimated to account for 27% of the total phosphorus load into the bay, while rivers and NPS sources accounting for 36% and 37% respectively.

When comparing the values estimated by Nixon *et al* (1995), the values estimated in this study are very reasonable. They reported that 1.2E6 kg/yr of phosphorus were delivered to the bay by the various sources, while during this study it was estimated that 9.2E5 kg/yr were delivered to the bay. Nixon *et al* estimated that the rivers contribute 53% of the total phosphorus load while WWTPs contributed 35% and direct runoff contributed 12% (add comparison values). Similar to the nitrogen loading analysis, differences between the two total phosphorus loading values estimated during the two studies can be attributed to increased PS control, both inland and on the shores of the bay. This would cause both the rivers and the WWTP portions of the overall loading to decrease from 1995 to now, causing an increase in the influence of NPS pollution on the overall loading into Narragansett Bay.

Table 41 - Annual Total Phosphorus Loading into Narragansett Bay

Total Phosphorus				
Annual Loading		(kg/yr)	Percent of Sub Total	Percent of Total
WWTP's	NBC Bucklin Pt	113000	46.1	12.2
	NBC Fields Pt	132000	53.9	14.3
	Total WWTP	245000	100.0	26.5
Rivers	Blackstone	159000	47.2	17.2
	Pawtuxet	51000	15.2	5.5
	Taunton	127000	37.6	13.7
	Total Rivers	336000	100.0	36.4
NPS		342000	100.0	37.1
	Total NPS	342000	100.0	37.1
Total	(kg/yr)	923000	0	100

Based upon the similarities between the results of this study and those conducted previously, it was determined that the annual loading estimates presented in this study adequately represent the overall loading into Narragansett Bay. The strength of the annual loading estimates allowed for a monthly loading estimate to be conducted as well.

The monthly estimates for total nitrogen loading into the bay are presented in Table 42. As shown in the table, monthly TN loading to the watershed varies from 600,000kg in July and August to 900,000kg in March. The dynamics of the loading also change from month to month, with rivers loadings and direct NPS loadings becoming the largest component of the total nitrogen loading depending on the month and direct WWTP loading into the bay consistently being the smallest loading component.

Table 42 - Monthly Breakdown of Nitrogen Loadings into Narragansett Bay

Total N Loading	Total	WWTPS	Percent of Total	Rivers	Percent of Total	NPS	Percent of Total
Month	(kg)	(kg)		(kg)		(kg)	
January	857000	180000	21.0	319000	37.2	359000	41.8
February	729000	152000	20.9	294000	40.3	283000	38.8
March	879000	168000	19.1	348000	39.5	364000	41.4
April	828000	152000	18.3	335000	40.4	341000	41.3
May	805000	182000	22.6	323000	40.1	300000	37.3
June	701000	168000	23.9	256000	36.5	277000	39.6
July	599000	161000	27.0	177000	29.6	260000	43.4
August	616000	146000	23.7	150000	24.4	320000	51.9
September	597000	151000	25.3	142000	23.8	304000	50.9
October	673000	173000	25.6	198000	29.4	303000	45.0
November	760000	151000	19.9	248000	32.6	361000	47.5
December	816000	182000	22.4	294000	36.0	340000	41.6

The monthly loading estimates for total phosphorus loading into Narragansett Bay are found in Table 43. Monthly loading varies from 55,000kg in September to 92,000kg in March. As with total nitrogen loading, rivers and direct NPS loadings compete to be the largest component of the total phosphorus loading depending on the month, with direct WWTP loading into the bay consistently being the smallest loading component. The variation in the monthly dynamic of nutrient loadings into Narragansett Bay supports the argument that future abatement strategies need to include NPS load reduction as well as PS reduction.

Table 43 - Monthly Breakdown of Total Phosphorus Loadings into Narragansett Bay

Total P Loading	Total	WWTPS	Percent of Total	Rivers	Percent of Total	NPS	Percent of Total
Month	(kg)	(kg)	0	(kg)	0	(kg)	0
January	78000	13000	16.1	33000	42.5	32000	41.4
February	72000	15000	21.1	32000	43.7	25000	35.2
March	92000	20000	21.8	39000	42.8	33000	35.4
April	82000	13000	16.2	38000	46.2	31000	37.6
May	76000	15000	19.2	35000	45.6	27000	35.2
June	62000	10000	16.4	27000	43.2	25000	40.3
July	61000	17000	28.4	20000	33.1	23000	38.5
August	60000	15000	25.2	16000	27.0	29000	47.8
September	56000	13000	24.0	15000	26.9	27000	49.1
October	60000	11000	17.4	23000	37.4	27000	45.1
November	77000	19000	24.0	26000	34.0	32000	42.0
December	74000	12000	16.2	31000	42.4	30000	41.4

3.4 - Conclusions & Discussion

The analyses contained in this chapter helped to provide some insight into the loading dynamics of the Blackstone Watershed as well as the Narragansett Bay Watershed. It was shown in the work conducted herein, on both local and regional scales, that as the amount of urbanization (percent imperviousness) in a watershed increases, water quality degradation in those watersheds increases as well. This finding is important when determining future abatement strategies for the Blackstone and Narragansett Bay watersheds. Continued urbanization in these areas may result in water quality degradation that is irreversible despite increasing limits placed on PS of pollution. Furthermore, under current loading estimates, NPS loads of total nitrogen are of the same order of magnitude as point source loadings in the Blackstone watershed. When considering future abatement strategies for total nitrogen reduction in the Blackstone and ultimately Narragansett Bay, NPS reductions of total nitrogen should be considered as important as PS reductions. However, there is evidence that PS reductions should still be considered as potential sources of pollutant reduction. Under current conditions, PS total phosphorus loading dominates the NPS phosphorus loadings in the Blackstone watershed. A large amount of total phosphorus PS loading is due to the UBWPAD facility located in the UBS watershed. The UBWPAD dominates the nutrient loading of

the UBS watershed, contributing six times the amount of total nitrogen and over ten times the amount of total phosphorus than NPS loadings.

While phosphorus reductions are the main focus of regulatory action in the Blackstone watershed, nitrogen reductions in the Blackstone watershed and the Narragansett Bay watershed as a whole are being driven by the regulatory focus in Narragansett Bay itself. As shown in the results above, when considering potential sources of nutrient reduction into the bay, three main sources of loading need to be considered, riverine loadings, direct NPS loadings and direct WWTP discharges into the bay.

The loading dynamics between Narragansett Bay and its watershed, especially the Blackstone, are complex and continually varying. On an annual basis, nonpoint sources of nutrients dominate the nutrient loading into Narragansett Bay. On a monthly basis however, nonpoint source loadings as well as rivers loadings dominate the nutrient loading into the bay. The loadings from the three main rivers into Narragansett Bay are also dynamic with the Blackstone or the Taunton becoming the dominant nutrient loading source depending on the month. Based on these findings, it is important to consider all sources of pollution into the bay when developing future abatement strategies.

The complex dynamics of the system, including the constantly varying loading and flow dynamics of the river creates the need for a dynamic modeling tool to adequately model the Blackstone River watershed. Based upon the estimates above, the loading dynamics in the watershed are highly variable on a monthly timescale, a variability that is likely to increase if more refined water quality and quantity data is collected for the river.

The above conclusions helped to outline several broad based project conclusions outlined below.

- Due to the complex hydraulics and loading dynamics of both the individual rivers and the bay as a whole, further regulation of point source pollution alone may not be an adequate or cost effective method for reducing nutrient loadings into the Blackstone River and Narragansett Bay.

- In order to develop an adequate management strategy for reducing nutrient loadings into the Blackstone and subsequently Narragansett Bay, accurate monthly and annual loads for each must be determined. Accurate annual and monthly loading estimates may be achieved through additional water quality monitoring throughout the year. Based on the variability in flows and behaviors of the river, it may be necessary to monitor water quality and quantity on a daily basis.
- In order to adequately model the Blackstone River watershed, a dynamic modeling tool is needed due to the constantly varying loading and flow dynamics of the river.

The above analysis is important in understanding the overall loading that enters into the river and ultimately Narragansett Bay. However, it does not illuminate any of the uncertainties that are associated with how the pollution is distributed along the mainstem of the river. Furthermore, the dynamics of the river in terms of gains and losses in nutrient loadings is also not very clear. To better understand the dynamics of the river and how the spatial loading of the river is impacted by those dynamics must be undertaken.

4.0 – Along Stream Processes

This section focuses on the analysis of along stream water quality trends in the Blackstone River mainstem. As previously stated, the remnant and functioning dams on the mainstem Blackstone create a complex hydrologic system. The effects of the impoundments on flows, pollutant transport and ultimately downstream loadings should be taken into account when determining future management strategies.

While numerous water quality studies have been conducted on the Blackstone, only the Blackstone River Initiative (BRI) is inclusive enough to conduct a comprehensive along stream water quality analysis. The BRI is a multi-state, multi-agency project aimed at modeling the water and sediment quality of the Blackstone River. Conducted beginning in 1991 and published in 2001, the BRI consisted of three dry weather water quality surveys as well as three wet weather water quality surveys. Each survey monitored the water quality along the mainstem of the Blackstone River, its major tributaries and the major point source dischargers to the river.

Subsequent work conducted for the Army Corps of Engineers consisted of additional water quality monitoring along the mainstem of the Blackstone. The overall aim of the project was to refine the previously developed QUAL2E model that was based on the BRI data. Phase I of the project focused on increasing the number of data collection locations along the mainstem of the river, enabling more refined river segments to be used in the model. Phase II of the project involved the development of monthly impoundment profiles on both Fisherville Pond and Rice City Pond, focusing on nutrient levels and dissolved oxygen profile characteristics.

At the time of this report, the data for the subsequent 2004 work on the Blackstone was not yet finalized. Furthermore, no new wet weather data was collected, nor did the 2004 study collect data for the entire mainstem of the Blackstone. These limitations prompted the exclusion of the data from the 2004 report in conducting the along stream river process analysis conducted herein.

The dry weather water quality characterization of the Blackstone River conducted for the BRI consisted of three 48hr surveys conducted on 10-11 July 1991, 14-15 August 1991 and 2-3 October 1991. The locations of the monitoring stations within the Blackstone watershed are shown on Figure 36. During the dry weather surveys, there were fifteen monitoring stations along the mainstem of the Blackstone and six monitoring stations at the outlets of the major tributaries to the river. The wet weather water quality characterization of the Blackstone River consisted of three storm oriented surveys referred to here as Storm I, Storm II and Storm III. The survey for Storm I was conducted from September 22-24, 1992, the survey for Storm II was conducted from November 2-5, 1992 and the survey for Storm III was conducted from October 12-14, 1993. The locations of the monitoring stations within the Blackstone watershed are also shown in Figure 36. During the wet weather surveys, there were thirteen monitoring stations along the mainstem of the Blackstone and six monitoring stations located at the outlets of the major tributaries to the river. The site description and associated river mile for each monitoring location as well as their site designation during both the dry and wet weather surveys are shown in Table 44.

Figure 36 - BRI Wet and Dry Weather Survey Monitoring Locations

**Table 44 - BRI Wet and Dry Weather Survey Monitoring Location Site Descriptions
and Associated River miles**

Dry Weather	Wet Weather	Rivermile	Description
	BWW00	46.0	Greenwood St, Worcester
BLK01	BWW01	45.8	Millbury St, Worcester
BLK02	BWW02	44.0	McCracken Rd, Millbury
BLK03		41.4	Riverlin St, Millbury
BLK04	BWW04	39.8	Blackstone St (Singing Dam), Sutton
BLK05	BWW05S	36.6	Millbury St, Grafton
BLK06	BWW06	35.7	Route 122A, Grafton
BLK07	BWW07	32.0	Riverdale St, Northbridge
BLK08	BWW08	27.8	Hartford St (Rice City pond Dam), Uxbridge
BLK09	BWW09	25.6	Mendon St (Rt 16), Uxbridge
BLK10	BWW10S	25.0	Centerville (Off Rt 16), Uxbridge
BLK11	BWW11	23.2	Rt 122 Bridge, Uxbridge
BLK12		20.5	Route 122 (nr USGS gauge), Millville
BLK14	BWW14	17.4	Route 146A, Slatersville
BLK13	BWW13	16.6	Bridge St (State Line), Blackstone
BLK15	BWW15S	13.4	Winter St, Woonsocket
BLK16	BWW16	13.3	Route 114, Woonsocket
BLK17	BWW17	12.8	Hamlet Ave Dam (Rt 122 & 126), Woonsocket
BLK18	BWW18	10.0	Manville Hill Rd, Cumberland
BLK19		9.4	School St/Albion Rd, Cumberland
BLK20	BWW20	3.8	Lonsdale Ave, Pawtucket
BLK21	BWW21	0.1	Main St (Slater's Mill), Pawtucket

4.1 - Methodology

The water quality data collected during the BRI was initially used to produce a comprehensive profile of water quality within the Blackstone River during wet and dry flow regimes using concentrations of pollutants as a basis (Wright *et al*, 2001). While the analysis of the water quality profiles has proven useful, the data can be analyzed on a pollutant loading basis as well. Preliminary loading estimates were conducted during the BRI, but not to the scale or methodology presented here. By analyzing the contaminants on a loading basis, one can not only identify sources and sinks of pollutants within the river system, but also estimate the assimilative capacity of the river under various flow regimes.

In order to identify sources and sinks of pollutants along the Blackstone River, pollutant loading for each monitoring station was calculated based on the BRI dry and wet weather data and compared to the loading calculated for the next station downstream. The BRI monitoring scheme was designed to isolate all known potential sources/sinks of pollution. Potential sources and sinks of pollution in the Blackstone include, but are not limited to, wastewater treatment plants (WWTPs), impoundments, stormwater runoff and along stream degradation. WWTP discharges to the Blackstone have long been held accountable for the water quality problems within the river (Shanahan, 1994; Wright *et al*, 2001) and were therefore monitored during the BRI as potential point sources of pollution. Sedimentation and resuspension of materials behind river impoundments have been previously identified as a potential sink (source) for several pollutants (Wright *et al*, 2001; Zi *et al*, 2002). Monitoring locations were thus established upstream and downstream of major impoundments along the mainstem. Stormwater runoff was only directly monitored from the Worcester CSO facility during the BRI; no sampling of flowing storm sewers in the watershed was conducted. It should be noted that stormwater runoff can be a major pollutant source to a river during heavy rainfalls (Lee and Lee, 1993). Another potential source of pollution to the mainstem of the Blackstone River are the tributaries, which were monitored during the BRI (Table 44).

Table 45 below presents the locations of known WWTPs, dams and the confluences of the major tributaries and the Blackstone River. River mile zero is defined as the outlet of the Blackstone at Slater's Mill Dam, located in RI, with river miles increasing in the upstream direction.

Table 45 - Locations of WWTPs, Dams and Tributary Confluences along the Mainstem of the Blackstone River

River mile	Description	River mile	Description
44.4	UBWPAD	22.0	Uxbridge WWTP
43.9	McCracken Rd Dam	17.8	Tupperware Dam
41.0	Millbury Electric Dam	17.4	Confl. of Branch Riv.
40.6	Millbury WWTP*	16.5	Blackstone Dam
39.8	Singing Dam	15.5	Thundermist Hydro Dam
39.2	Wilkinsonville Dam	13.4	Confl. of Mill Riv.
38.7	Saundersville Dam	13.3	Confl. of Peters Riv.
36.6	Confl. of Quinsigamond Riv.	12.8	Hamlet Ave Dam
36.5	Fisherville Dam	12.4	Woonsocket WWTP
35.6	Farnumsville Hydro Dam	9.9	Manville Dam
35.4	Grafton WWTP	8.2	Albion Dam
31.9	Riverdale Hydro Dam	6.8	Ashton Dam
29.2	Northbridge WWTP	4.1	Lonsdale Dam
27.8	Rice City Pond Dam	2.0	Central Falls Dam
25.6	Confl. of Mumford Riv.	0.8	Pawtucket Hydro Dam
25.0	Confl. of West Riv.	0.0	Slater's Mill Dam
*-As of Jan 2005, Millbury WWTP has been connected to the UBWPAD discharge			

4.1.1 - Dry Weather Loading Analysis

The loads for each station monitored during the dry weather surveys were calculated using Equation 9 where Q is average daily flow (cfs) estimated for the monitoring location, C_{ave} is the pollutant concentration (mg/L) as described below, and L is the resulting load (kg/day). Typically, that average concentration was calculated using 4 samples taken over the course of the day. However any sample taken during the day falling more than one standard deviation away from the initial average concentration was removed and the average was recalculated. Note that the 2.45 is a conversion factor from cfs*mg/L to kg/day.

$$L = 2.45QC_{ave} \quad (9)$$

The estimated flows and concentrations were assumed to be constant over the day thus facilitating an estimation of a daily load. The estimation of a daily load provides a snapshot of water quality in the river on the day of sampling.

4.1.2 - Wet Weather Loading Analysis

The loads for each station monitored during the wet weather surveys were calculated using Equations 10 and 11. Note that the 2.45 is a conversion factor from cfs*mg/L to kg/day.

$$L = 2.45 \sum_{i=1}^n \left[C_{fwmc} (T_{i+1} - T_i) \left(\frac{Q_{i+1} + Q_i}{2} \right) \right] \quad (10)$$

$$C_{fwmc} = \frac{\sum_{i=1}^n (Q_i C_i)}{\sum_{i=1}^n Q_i} \quad (11)$$

where C_i is the concentration observed for a given sample (mg/L), Q_i is the flow observed while the sample is being collected (cfs), $(T_{i+1} - T_i)$ is the duration between that sample and the next (in days), C_{fwmc} is the flow weighted mean concentration observed at the station over the course of the event (mg/L) and L is the total load observed at the monitoring location for that storm event (kg). Comparison of the total event load observed at each station during an event with an adjacent station is an acceptable way to compare the loads due to similar event durations among the stations. Inter-storm loading comparisons however, need to be adjusted due to storm duration differences.

4.1.3 - Source/Sink Identification Analysis

A loading comparison between consecutive stations was conducted using Equation 12 to determine the locations of pollutant sources and sinks along the mainstem of the river.

$$L_d = L_2 - L_1 \quad (12)$$

L_1 is the load observed at the upstream location (kg or kg/day), L_2 is the load observed at the downstream location (kg or kg/day) and L_d is the difference between them (kg or kg/day). A positive value of L_d is representative of a gain in contaminant in the water column between the two stations. A negative value is representative of a loss of contaminant from the water column between the two stations, indicating a sink in that reach of the river. It should be noted that due to a smaller number of monitoring stations, the pollutant source/sink analysis is less refined for wet weather events than dry weather events.

4.1.4 - Assimilative Capacity Analysis

The assimilative capacity of the river was calculated using Equation 13. The assimilative capacity reported here is on a percentage basis, unlike typical assimilative capacities.

$$AC = 100 \left(1 - \frac{L_{out} - L_{up}}{\sum L_{Gains}} \right) \quad (13)$$

L_{out} is the load that is observed at the outlet of the river, L_{up} is the load observed at the uppermost monitoring station and L_{Gains} are the gains in loading seen between stations (positive values of L_d as described above). The summation of all of the gains in loadings represents the total amount of pollutant that the river is subject to, while the difference in load between the headwaters and the outlet represents how much of the total pollutant loading the river could not assimilate. The lower the percentage of the total loadings that

leave the river, the more assimilative capacity the river is considered to have. In the case where no assimilation occurs, the difference between the loads seen at the top of the watershed and the load seen at the outlet ($L_{out}-L_{up}$), would be equivalent to the summation of the gains seen along the river, resulting in an assimilative capacity of 0%.

4.2 - Results and Discussion

4.2.1 - Dry and Wet Weather Loading Analysis

Nutrient loading trends from Storm II (Nov, 1992) of the BRI as well as the dry weather survey conducted in July 1991 are presented in Figure 38 through Figure 43. A detailed loading analysis of the remaining wet weather and dry weather surveys is provided in Appendix D.

The vertical bars represent the load difference, L_d , between that station and the station immediately upstream. A positive bar value thus indicates a source between the two stations, while a negative vertical bar value indicates a sink between the two stations. The locations and loads of the tributaries and the WWTPs are marked by the diamonds while the dam locations are denoted by a triangle and a vertical dashed line. It should be noted that for all wet and dry weather loading analyses, only the loadings of the major WWTPs (UBWPAD and Woonsocket) were calculated. The minor WWTPs were not monitored during the surveyed events and are represented as having a value of zero. They are included in the following charts to indicate their position along the river as well as identify any effects the WWTPs might have on the downstream water quality and loadings. The locations of the tributaries and the WWTPs are outlined in Figure 37. This figure is used solely to denote the locations of the tributaries and WWTPs as they enter the mainstem of the river, this figure is not used for any of the subsequent analyses in this chapter.

Figure 37 - WWTP and Tributary Identifications and Locations

Figure 38 - BRI Dry Weather PO₄ Loading

Figure 39 - BRI Wet Weather PO₄ Loading

Figure 40 – BRI Dry Weather NO₃ Loading

Figure 41 – BRI Wet Weather NO₂/NO₃ Loading

Figure 42 – BRI Dry Weather NH₃ Loading

Figure 43 – BRI Wet Weather NH₃ Loading

As expected, the UBWPAD and Woonsocket WWTPs contributed significant loads to the river during wet and dry weather events. UBWPAD was the largest known PS of PO₄ during both wet and dry weather events. While the UBWPAD contributed the highest NH₃-N load during wet weather event, the NH₃-N loading from the Woonsocket WWTP

was greater during the dry weather. However, the opposite was true for the NO_2/NO_3 loading behaviors. Woonsocket had the highest NO_3 load during the wet weather event and UBWPAD had the highest NO_2/NO_3 load during the dry weather event.

It should be noted that during the wet weather event shown (event II), there was no nitrification at the UBWPAD (Wright et al, 2001), which accounts for the large ammonia load seen in Figure 43 after the UBWPAD. The other wet weather events monitored by Wright et al (2001) occurred during the nitrification period for the plant. Based on the data gathered from these events, if nitrification had been in operation, the UBWPAD NH_3 load in event II would have been approximately $1/10^{\text{th}}$ of what is shown in Figure 43.

Along the mainstem of the Blackstone, wet weather loads of $\text{PO}_4\text{-P}$ are typically more than double dry weather loads along the river (data not shown but may be inferred from these plots). This suggests that runoff carries additional $\text{PO}_4\text{-P}$ to the river as NPS pollution. Similarly, dry weather $\text{NH}_3\text{-N}$ and NO_2/NO_3 loadings are significantly smaller than wet weather loading. NPS runoff is the suspected cause of these increases as well. It should be noted that for both the wet and dry weather events, the tributary loads are much smaller than those observed in the mainstem of the Blackstone.

4.2.2 - Gain/Loss Analysis

The resulting gain/loss matrix for each parameter under wet and dry weather regimes is shown in Table 46.

Table 46 - Gain/Loss Matrix for Wet and Dry Weather Loading

	RiverMile	45.8	44.0	41.4	39.8	35.7	32.0	27.8	23.2	20.5	16.6	12.8	10.0	9.4	3.8	0.1
Dry Weather																
July	PO4	NA	+	+	-	-	+	-	-	+	+	-	+	-	-	+
	NO3	NA	+	+	+	-	+	-	-	+	+	-	+	+	+	+
	NH3	NA	+	-	+	-	-	-	-	-	+	-	+	-	-	-
Wet Weather	PO4	-	+	NA	+	-	+	+	-	NA	-	+	+	NA	+	-
Storm II	NO2/NO3	+	+	NA	+	+	+	+	+	NA	+	+	-	NA	+	+
	NH3	+	+	NA	-	+	-	+	-	NA	-	-	+	NA	-	+
	# of Dams		0	1	2*	3	1	2*	0	0	1	3*	0	1	3	2
	# of WWTP's		1	0	1	0	1	1	0	1	0	0	1	0	0	0
	Ponds					Fisherville		Rice City								Slater Mill
	Tribs					Quin			Mum and West		Branch	Mill and Peters				
						* site located on dam which is included in number of dams between										
					+	represents a gain in loading from the upstream station to the station in question										
					-	represents a loss in loading from the upstream station to the station in question										

The Gain/Load matrix analysis was conducted with the following syntax. Gains and losses are referred to the mile marker of the downstream location, i.e. a gain at mile marker 44.4 refers to a gain between the site at mile marker 44.4 and the site immediately upstream of it. Similarly, the number of dams and the number of WWTPs refers to the number of dams or WWTPs between the site at that particular mile marker and the site immediately upstream of it. The same syntax is used when identifying the tributary confluences and locations of the major ponds along the mainstem of the Blackstone River.

During the dry weather event, losses in PO_4 were observed at the following mile markers: 39.8, 35.7, 27.8, 23.2, 12.8, 9.4 and 3.8. These losses were typically seen downstream of at least one impoundment and/or pond. PO_4 gains during the dry weather event were seen at mile markers 44, 41.4, 32, 20.5, 16.6, 10 and 0.1. These gains are typically seen after WWTPs such as UBWPAD (44) and Woonsocket (10). During wet weather, losses were seen at 45.8, 35.7, 23.2, 16.6 and 0.1, significantly less sites than during the dry weather loading. These losses were typically seen after reaches with multiple impoundments in them. Gains in PO_4 however, were seen at mile markers 44, 39.8, 32, 27.8, 12.8, 10 and 3.8. These gains usually occurred in reaches with impoundments in them as well as in reaches with WWTPs and tributary confluences in them. When comparing the dry and wet weather loading, it is evident that the majority of sites with impoundments in the reach above them experienced gains during wet weather and losses during dry weather conditions. This suggests that resuspension is an important source of water column phosphorus during wet weather while settling and algal uptake in the slow moving waters behind impoundments are important phosphate sinks during dry weather.

During the dry weather event, gains in NH_3 loading were seen at mile markers 44, 39.8, 16.6 and 10. All but one of these sites correspond with reaches containing WWTPs, (UBWPAD, Millbury WWTP and Woonsocket WWTP). Losses were observed over the majority of the sites, albeit the major losses are seen at mile marker 9.4, 3.8 and 0.1, most likely due to the numerous dams in that reach providing potential for algal uptake. Gains in NH_3 during wet weather were seen at mile markers 45.8, 44, 35.7, 27.8, 10 and 0.1.

These include Fisherville Pond and Rice City Pond. Losses during wet weather occurred less frequently than during the dry weather event but were typically to a larger magnitude.

As expected, the loading behavior of NO_2/NO_3 was typically the opposite of NH_3 . During the dry weather event, gains in NO_3 were seen at mile markers 44, 41.4, 39.8, 32, 20.5, 16.6, 10, 9.4, 3.8 and 0.1. The majority of the gains could be attributed, at least in part to WWTP inputs or tributary inputs. Losses were seen at 35.7, 27.8, 23.2 and 12.8. These losses all occurred in reaches with multiple dams or impoundments such as Rice City Pond and Fisherville Pond. The slow moving waters behind the impoundments, especially in the ponds allows for increased algal uptake of nitrogen, resulting in the losses seen in the loading analysis. During wet weather event however, gains in NO_2/NO_3 were seen throughout the mainstem of the river, except for mile marker 10.0. These gains are attributed to runoff carrying N to the river as well as potential flushing of impoundment sediment bound N back into the water column during increased flow regimes. The sole loss of nitrogen observed during the wet weather event was very small compared to the gains in loads seen during analysis.

The data suggest that while point sources are an important source of contamination, additional sources exist, particularly during wet weather. This is shown by the fact that the loads seen after UBWPAD and Woonsocket are often higher than the loads input to the river by those WWTPs, especially during wet weather events. In addition, sinks along the river exist, most notably the numerous impoundments along the mainstem of the river. These sinks affect the loading behavior seen along the river and must be accounted for in any modeling effort.

4.2.3 - Assimilative Capacity Analysis

The nutrient loading analyses for all wet and dry weather events are presented in Table 47 through Table 52. Included in each table are the summation of the positive differences in loads (gains), a summation of the negative differences (losses), total loading contributed to the river from WWTPs (PS), the difference between loading at the headwaters and loading at the outlet and finally the assimilative capacity of the river on a percent basis.

Table 47 - Wet Weather Storm I Loading Summary

	NH3 (kg)	NO2+NO3 (kg)	PO4-P (kg)
Positive Differences	3689.6	2961.8	666.5
Negative Differences	-3249.4	-776.3	-445.0
Post+ Neg	440.2	2185.5	221.5
WWTP Total	1794.3	1147.4	603.1
Outlet - Headwaters	440.2	2185.5	221.5
Assimilative Capacity	88.1%	26.2%	66.8%

Table 48 - Wet Weather Storm II Loading Summary

	NH3 (kg)	NO2+NO3 (kg)	PO4-P (kg)
Positive Differences	9226.7	7777.7	1384.3
Negative Differences	-5557.7	-31.6	-335.7
Post+ Neg	3669.0	7746.1	1048.6
WWTP Total	6796.3	139.3	774.0
Outlet - Headwaters	3669.0	7746.1	1048.6
Assimilative Capacity	60.2%	0.4%	24.2%

Table 49 - Wet Weather Storm III Loading Summary

	NH3 (kg)	NO2+NO3 (kg)	PO4-P (kg)
Positive Differences	2806.4	8354.4	1942.1
Negative Differences	-2609.9	-3446.1	-1043.4
Post+ Neg	196.5	4908.4	898.7
WWTP Total	238.5	1979.4	610.9
Outlet - Headwaters	196.5	4908.4	898.7
Assimilative Capacity	93.0%	41.2%	53.7%

Table 50 - Dry Weather I Loading Summary

	NH3 (kg/day)	NO3 (kg/day)	PO4 (kg/day)
Positive Differences	431.5	1129.3	202.0
Negative Differences	-318.4	-426.9	-142.0
Post+ Neg	113.1	702.4	60.0
WWTP Total	612.6	627.9	282.6
Outlet - Headwaters	113.1	702.4	60.0
Assimilative Capacity	73.8%	37.8%	70.3%

Table 51 – Dry Weather II Loading Summary

	NH3 (kg/day)	NO3 (kg/day)	PO4 (kg/day)
Positive Differences	446.8	1308.7	254.3
Negative Differences	-291.4	-611.5	-192.8
Post+ Neg	155.4	697.1	61.6
WWTP Total	395.9	2899.3	351.8
Outlet - Headwaters	155.4	697.1	61.6
Assimilative Capacity	65.2%	46.7%	75.8%

Table 52 – Dry Weather III Loading Summary

	NH3 (kg/day)	NO3 (kg/day)	PO4 (kg/day)
Positive Differences	546.6	4790.8	851.7
Negative Differences	-226.0	-1872.5	-592.4
Post+ Neg	320.7	2918.2	259.3
WWTP Total	407.2	1943.7	610.8
Outlet - Headwaters	320.7	2918.2	259.3
Assimilative Capacity	41.3%	39.1%	69.6%

When examining the tables above, it is important to note that the wet weather loads are in units of kg, while the dry weather loads are in units of kg/day. If comparisons are made between the wet and dry weather scenarios, you must divide the wet weather loadings by 3 to adjust for the fact that the wet weather storms were measured over a period of three days.

It is apparent when looking at the tables above that the amount of loading that the river is subject to under wet and dry weather conditions is highly variable. In order to truly get an annual load value for the river, useful for TMDL development, more rigorous data collection needs to be undertaken.

The ability of the river to assimilate the loadings it is subjected to is also highly variable. Assimilative capacities range from 0.4% for the Storm III NO₂/NO₃ loadings to 93% for the Storm III NH₃ loadings. In general, the river was able to assimilate more of both the PO₄ and NO₃ loadings under dry weather conditions. This is most likely due to the previously mentioned algal uptake potential in the slow moving waters behind impoundments as well as the settling potential for phosphorus in the same locales. The river was able to assimilate more of the wet weather NH₃ loading than the dry weather loadings, despite the higher amounts of NH₃ the river was subjected to during the wet weather events.

The variation among the assimilative capacities of the river could be attributed to the variation in the flow regimes of the river during the different events.

Figure 44 below shows the flow regimes for the three wet weather and the three dry weather events.

Figure 44 - Flow Regimes of the BRI Sampling Events

From the figure above, it is apparent that even dry weather events can have as high a flow regime as a storm event depending on the time of year the event is conducted in. Based on the flow regimes, it seems as though the river would behave similarly, in terms of assimilative capacity, during Dry Weather events I and II and Storm I.

The average assimilation capacities for NH_3 , NO_3 and PO_4 across the three events (Dry Weather I and II and Storm I) were calculated to be 76%, 37% and 71% for NH_3 , NO_3 and PO_4 respectively. While the assimilation values are similar between the three events, they are no better matched than splitting the events into wet and dry weather events as before. This suggests that more than simple flow dynamics are affecting the assimilation capacity of the rivers. This furthers the argument that more rigorous data collection over the course of the entire year needs to be conducted to truly develop an understanding of the annual loading of the river.

4.3 - Conclusions

The analyses contained in this chapter provided significant insight as to the loading propagation and sources along the mainstem of the Blackstone River. Based on the above analyses, the following was determined:

- Wet weather loading of nutrients were greater than dry weather loading over the same period of time.
- Impoundments typically act as pollutant sources during wet weather, while acting as pollutant sinks during dry weather
- The loading behavior of the river was variable among the storms, likely due to variations in rainfall amounts, durations and intensities.
- Tributaries don't contribute significant amounts of nutrient pollution to the mainstem river
- UBWPAD and Woonsocket are largest known point sources of nutrient pollution along the mainstem of the river.

- The assimilative capacity of the river (as measured here) is greater during dry weather periods than during wet weather periods. It is likely that the increased travel time during the low-flow dry weather events allows for more in stream degradation and loss due to sedimentation and algal uptake along the length of the river.
- There is no clear correlation between flow and assimilative capacity of the river

The above conclusions helped to outline several broad based project conclusions outlined below.

- The impoundments along the mainstem of the river add a great deal of complexity to both the flow and loading dynamics of the river.
- Due to the complex hydrology and loading dynamics of the river, the expected propagation of upstream water quality improvements to downstream reaches must be better understood in order to cost-effectively reduce the loading from the Blackstone into Narragansett Bay.
- The overall dynamics of the river require more rigorous sampling of water quality in order to truly develop an annual nutrient loading estimate.

The analyses contained in this chapter are vital to understanding the dynamics of the river; however the data used here is 15 years old. New data may be needed to correctly model the current processes that occur in the river today. It is not certain if the hydrologic dynamics of the system have changed since 1991 or if increases in population and urbanization have caused significant increases in NPS pollution to enter the river. Furthermore, a dynamic model will be needed to account for the ongoing changes in the watershed to make informed decisions regarding watershed management and future regulatory decisions.

5.0 - Temporal Analysis

Data collected during the BRI was very useful in helping to better understand nutrient, metals, and bacteria dynamics in the Blackstone River under wet and dry weather conditions. The data were ultimately used to develop TMDL guidelines for improving water quality in the river. Similar to the national trend during the same period, remediation efforts in the Blackstone focused on point source controls and, more recently, CSO improvements (particularly in Worcester). Water quality improvements directly resulting from CSO improvements in Worcester have been documented through the monitoring efforts by the City of Worcester.

While millions of dollars and countless man hours have been spent on restoring the river, limited focus has been placed on demonstrating the effectiveness of these efforts. Furthermore, the BRI data is currently 15 years old and possibly no longer suited to adequately represent the current loading dynamics and transportation behavior of the river.

This section focuses on temporal water quality changes in the Blackstone and the impact such trends may have on the development and success of future abatement strategies. Of particular interest is population growth in the area, including the impacts on water and wastewater demands. The impact of associated land use change on water quality was also investigated. Land use changes, specifically urbanization, typically lead to increased imperviousness and associated increased nonpoint source loadings to the river. These changes are due both to alteration of the hydrologic cycle and a change in source. Work by Konrad and Booth (2005) and others suggests that increased imperviousness can cause significant changes to the water balance. Increased surface runoff and channelization of streams often results in increased peak storm flows and flood occurrence. The decrease in infiltration associated with urbanization may also lead to a decrease in base flow contributions to streams in urbanized areas, resulting in increased periods of drought conditions (Tang *et al*, 2005).

The chapter is organized as follows. First, a historical record of water quality in the Blackstone is presented to determine if the current remediation efforts in the watershed are an effective means of improving the quality of the Blackstone River. Next, analyses of current and projected population values are presented. The impact of population change on the distribution of land use type is investigated next, with particular attention focused on changes in the percent impervious areas of the watershed. Current and future point source and nonpoint source estimates for both the Blackstone River and the UBS watershed are presented, followed by an analysis of the hydrology in the watershed to determine if any hydrological changes have occurred due to increased urbanization.

5.1 - Methodology

5.1.1 - Trends in Water Quality

In order to determine the impacts of the current remediation efforts on water quality in the Blackstone, water quality and flow data collected by the USGS were used. The USGS gauge at Millville (01111230) was chosen for the analysis due to its long period of record for water quality monitoring as well as its location in the center of the Blackstone watershed.

Instantaneous loading values were calculated for the available data collection points using equation 14 below. Q_{inst} is the instantaneous flow (cfs) calculated during the sampling event, C is the pollutant concentration (mg/L), and L is the resulting instantaneous load (kg/day). It is assumed that the Q_{inst} value is representative of the flow at the site throughout the day. Note that the 2.45 is a conversion factor from $cfs \cdot mg/L$ to kg/day .

$$L = 2.45Q_{inst}C \quad (14)$$

To illustrate the changing loading behavior over time, a sliding 12-month average was plotted along with the instantaneous loading data. The sliding scale calculates an average load of +/- six months from the date in question, reducing the impacts of monthly and seasonal variability on the long term loading analysis.

5.1.2 - Population Trends

Population values for each town in the Blackstone Basin were gathered from the USCB for 1980, 1990 and 2000. To estimate the population growth from 2000-2010, a high, medium and low estimate of population change were calculated for each town. The high estimates of population change were calculated using the maximum value of percent change shown between 1980-1990 and 1990-2000. The low estimates of population change were calculated using the minimum value of percent change between 1980-1990 and 1990-2000. The medium or average estimates of population change were calculated using the average between the minimum and maximum values of percent change between 1980-1990 and 1990-2000. The three resulting population values were tabulated for each town and then used to estimate the high, medium and low population values in 2010. The estimated populations for each town were summed together to estimate the range of population and percent change for the entire watershed.

The impact on population growth on water demands and wastewater returns was also investigated. According to the USEPA, the average water demand for the United States is 100gal/day per capita water use (USEPA, 2006d). The average wastewater return rate for the average American is 75 gal/day per capita (Metcalf and Eddy, 2003). Using these values and the estimated ranges of population change, an estimate of the increase in water demand and wastewater returns for the Blackstone was calculated.

5.1.3 - Land Use Changes over Time

Also associated with the expected increase in population of the watershed is an increase in the amount of urbanized land cover. In order to investigate the land use trends in the Blackstone, historical and current land use data were obtained from MassGIS and RIGIS.

The land uses were tabulated using the same procedures outlined in Chapter 1. Land use breakdowns were calculated based on the land use data for the 1970's, 1980's and the 1990's. Similar to the future population estimates procedure, estimates for each land use category were calculated over a range with high, average and low values. The high value was estimated by summing the 1990's land use percentage with the maximum change in land use percentages between the 1970's-80's, the 1980's-90's and the 1970's-90's. The low estimate of the 2010 land use percentages was calculated by summing the 1990's land use percentage value with the minimum change between the three land use change calculations. The average 2010 land use percentage estimate was calculated by summing the 1990's land use percentages with the average of the three changes in percentage between the decades. High, medium and low estimates of the percent of the total area for each land use classification were calculated for the Blackstone River watershed and its sub-basins.

5.1.4 - Changes in Percent Impervious Values over Time

Anticipated changes in impervious area extent were also estimated. Unlike the land use change estimates, only percent imperviousness values for the 1980's and the 1990's were calculated. Estimates for the percent imperviousness of the Blackstone watershed, its sub-basins and the sub-basins of the UBS watershed were calculated using a linear adjustment method. The adjustment was conducted using a linear extension of the available imperviousness data. This was done by summing the 1990's percent imperviousness value with the difference between the percent impervious values from each decade.

5.1.5 - Temporal Changes in PS vs. NPS Loading Estimates

The expected changes in land use were hypothesized to impact the future PS vs. NPS loading dynamic in the Blackstone watershed. Future NPS load estimates were calculated based on individual land use types, not broad classifications such as forested or agricultural. Using the area values tabulated for each land use type during the 1980's and the 1990's, estimates for the aerial coverage of each category in 2010 were calculated via linear adjustment. The tabulated values were then multiplied by the export coefficients outlined in Chapter 1 to create a range of loading values for each land use category. Results for the individual land use areas were summed across the basin based on their aerial extent in order to develop a future estimate of NPS loads for the entire watershed. Estimates of future point source loadings accounted for current improvements underway at the UBWPAD. Similar to the previous PS loading calculations, average monthly values of flow and concentration were used to estimate an annual load from all of the PS dischargers in the watershed. Estimates for the 2010 PS loadings were conducted as follows. All of the WWTPs in the watershed except for the UBWPAD and Woonsocket WWTP were assumed to have the same flows and concentrations in 2010 as they have currently, essentially assuming that the contribution to the overall loading of the lesser PS dischargers remains the same. The two main sources of PS pollution however, were assumed to have effluent concentrations of phosphorus and nitrogen of 0.75mg/L and 10 mg/L respectively. This methodology assumes that both the UBWPAD and the Woonsocket WWTP have to meet the current effluent limits on the UBWPAD NPDES permit. The flows from the two plants were adjusted to account for the expected increases in the populations that they serve by 2010.

Similar to the previously conducted PS vs. NPS analysis, the present and future loading dynamics were estimated for the Blackstone River watershed as well as the UBS watershed, the location of the UBWPAD.

5.1.6 - Hydrological Changes over Time

Increasing amounts of urbanized area impact the hydrologic cycle of a watershed, often resulting in increased flood frequency and magnitude. Increased imperviousness can also decrease infiltration resulting in lower base flow and increased frequency and duration of drought events.

For this study, potential changes in watershed hydraulics due to changes in land use were conducted using two methodologies. First, to determine the effect, if any, of increased urbanization on the magnitude of peak storm flows, an analysis of the annual peak flows in the Blackstone and its tributaries was conducted. The annual peak flows (Q_{peak}) were plotted over time. To determine the effect of increasing urbanization on base flow in the river, the annual seven day low flow values (7Q's) were tabulated for each monitoring location and plotted over time. The presence or absence of a temporal trend and associated magnitude were determined through regression.

The flow gauges used for both the Q_{peak} and the 7Q analyses are listed in Table 53. Also included in the table are the periods of record (POR) of data available for each of the analyses. Additional gauges in the watershed had significant periods of record for additional Q_{peak} and 7Q analyses; however, they were impacted by flow regulations, likely skewing the trends seen in the aforementioned analyses, and thus were not used.

Table 53 - USGS Gauges used in the Q_{peak} and 7Q Analyses

Stream Gauge	USGS ID	POR	
		Q_{peak}	7Q
Quinsigamond River	1110000	1940-2004	1939-2004
Blackstone River at Woonsocket	1112500	1929-2004	1929-2004
Branch River	1111500	1936-2004	1940-2004

5.2 - Results & Discussion

5.2.1 - Trends in Water Quality

The time series of historical phosphorus and nitrogen loads at the USGS gauge at Millville are shown in Figure 45 and Figure 46 respectively. Also included in each plot is a sliding 12 month average loading line, calculated +/- six months on either side of a given loading value.

Figure 45 - Historical Trends of NO₂ + NO₃ Loading at the USGS gauge at Millville (01111230)

Figure 46 - Historical Trends of Phosphorus at the USGS gauge at Millville (01111230)

The decrease in the loadings seen in the river during the 1990's appears to be leveling off in recent years, suggesting a decrease in the effectiveness of current abatement strategies (i.e. implementing ever decreasing PS effluent limits). While current plans for additional WWTP upgrades will likely reduce river loadings, they will require significant monetary investments in advanced WWTP design and construction. Among these anticipated WWTP upgrades is the \$130 million dollar upgrade to the UBWPAD facility as described in Section 2.2.3. Alternative future abatement strategies, particularly those addressing nonpoint source pollution, may be necessary to realize future improvements in a cost-effective manner.

5.2.2 - Population Trends

The population values for the watershed based on the U.S. Census data are presented in Table 54. A range of estimates for the watershed population in 2010 are also listed. The percent change values listed in the table represent the percent change in population from the previous decade to the decade the value is listed under. As shown in the table, it is estimated that the population in the Blackstone watershed in 2010 could increase between 5 and 12 percent, resulting in a population of 864,000 to 919,000 people.

Table 54 - Population Trends in the Blackstone Watershed (Source: USCB)

Year	1980	1990	2000	2010 High	2010 Low	2010 Average
Total Population	709,132	763,892	822,884	919,000	864,00	892,000
Percent Change		7.7	7.7	11.7	4.9	7.8

The resulting estimated increase in water demand and wastewater returns are presented in Table 55. By 2010, water demands are estimated to increase by 4.1% to 9.6 MGD while wastewater returns are estimated to increase by 3.1% to 7.2 MGD. These increases will put additional pressure on the already stressed Blackstone watershed, making the goal of a Class B river by 2015 that much harder to achieve.

Table 55 - Estimated Water Demands and Wastewater Returns in the Blackstone Watershed

Year	1980	1990	2000	2010 High	2010 Low	2010 Average
Water Demand	7.09E+07	7.64E+07	8.23E+07	9.19E+07	8.64E+07	8.92E+07
Wastewater Returns	5.32E+07	5.73E+07	6.17E+07	6.89E+07	6.48E+07	6.69E+07

5.2.3 - Land Use Changes over Time

Additional pressure on the Blackstone will come from the changes in land use that are associated with increasing populations. The most current land use breakdown (1999 for MA, 1995 for RI) is provided in Figure 47 as a visual reference. Land use breakdown by type are provided for the current land use delineations (1990's), the past land use delineations (1970's and 1980's) and the estimated future land use delineations (2010) in Table 56.

Figure 47 - Current Land Use and Sub-Basin Delineation in the Blackstone River Watershed

Table 56 - Historical, Current and Projected Land Use Percentages
in the Blackstone River Watershed

	Percent of Total Area			Estimated 2010 Land Use Values		
	70's	80's	90's	2010 High	2010 Low	2010 Average
Agriculture	6.3	6.2	4.9	4.8	3.5	4.0
Forested	65.3	57.1	53.4	49.7	41.4	45.4
Wetlands	1.4	4.1	4.1	6.8	4.1	5.9
Water	3.2	3.5	3.5	3.8	3.5	3.7
Residential	15.0	18.1	22.4	29.8	25.5	27.3
Commercial	1.6	1.7	1.8	2.0	1.9	2.0
Industrial	1.7	2.5	2.5	3.4	2.6	3.1
Transportation	1.1	1.3	1.5	1.8	1.6	1.7
Open	4.4	5.6	5.9	7.4	6.3	6.9

As expected, the category with the largest percentage of growth since the 1970's is the Residential classification. The largest decreases since the 1970's are seen in the Forested and Agricultural land uses, similar to the national trends in land use changes described by Hasse and Lathrop (2003).

The estimates of the average land uses in 2010 result in residential areas increasing from 22 to 27 percent of the watershed area while forested areas decrease from 53 to 45 percent. Other urban areas such as commercial, industrial and transportation are expected to rise as well, with agricultural areas continuing to decrease.

5.2.4 - Changes in Percent Impervious Values over Time

The increasing amounts of urban and suburban areas traditionally result in increasing amounts of percent impervious area in the watershed. The percent of impervious area for the Blackstone River and its sub-basins are shown in Table 57. Values for 2010 are estimated as outlined above.

Table 57 - Percent Impervious Area of the Blackstone River Watershed and its Sub-basins

Sub Basin	% Impervious Area		
	1980's	1990's	2010's
Blackstone	9.4	10.4	11.7
UBS	17.3	18.5	19.6
Quinsigamond	14.4	16.4	18.4
Mumford	5.4	6.3	7.2
West	4.4	5.5	6.5
Nipmuck	2.9	3.9	4.9
Mill	6.3	7.8	9.4
Branch	5.6	5.9	6.1
Chepachet	4.5	4.6	4.7
Peters	7.2	8.5	9.7
Abbot	7.8	9.0	10.2
BSMS	11.4	12.5	13.7

The percent imperviousness for the entire watershed is expected to increase to 12 percent from 10.4 percent by 2010, classifying the watershed as impaired according to the metrics used during the imperviousness analyses conducted in Chapter 1. The UBS, the Quinsigamond and the BSMS sub-watersheds are expected to still be classified as impaired in 2010. Both the Mill River and the Peters River watersheds are estimated to approach the 10% imperviousness threshold by 2010, which would result in a re-classification as “impaired”. The remaining sub-watersheds are estimated to still be considered “protected” in 2010 despite increased levels of impervious cover. Of these sub-basins, the Mumford River is anticipated to have the greatest extent of impervious cover, at a value of 7%.

The increases in impervious area will likely lead to increased pollutant loads in runoff entering the river and its tributaries. These additional demands on the system may create localized hot spots and larger scale water quality issues. This additional pressure on the watershed will lead to an increase in the difficulty in restoring the Blackstone to a Class B river by 2015.

As shown in Table 57, the percent impervious area of the UBS watershed is expected to increase to almost 20 percent. To determine the changes this increase may have on the spatial distribution of imperviousness in the watershed, a smaller scale imperviousness analysis was conducted, similar to the UBS watershed analyses in Chapter 1. The resulting past, present and future values of percent impervious area for the sub-watersheds in the UBS watershed are shown in Table 58.

Table 58 - Percent Imperviousness Values for the UBS Watershed Sub-basins

UBS Sub-Basin	% Impervious Area		
	1980's	1990's	2010's
Blackstone River North	23.8	31.6	39.4
Blackstone River South	12.2	14.5	16.8
Dark Brook	10.4	11.6	12.8
Kettle Brook North	7.3	7.6	7.9
Kettle Brook Central	9.7	10.2	10.7
Kettle Brook South	15.3	16.3	17.3
Mill Brook and Middle River	33.5	34.3	35.1
Tatnuck Brook North	2.8	3.1	3.4
Tatnuck Brook South	22.1	23.1	24.1

The percent impervious area values for each sub-basin are expected to increase from the 1990's to 2010. Most notable is the estimated increase of the Blackstone North to 39 percent impervious area. Despite the increases in imperviousness seen throughout the watershed, all of the basins are expected to be classified with the same impairment status in 2010 as they are currently. The basin nearest to a change in impairment classification is Kettle Brook North with an estimated 8 percent imperviousness in 2010.

5.2.5 - Temporal Changes in PS vs. NPS Loading Estimates

The impacts of the expected changes in land use as well as the expected changes in PS control strategies on the PS vs. NPS loading dynamics of the Blackstone River watershed are illustrated in Figure 48 through Figure 51. The resulting population increases resulted in an increase of 0.72MGD in the average UBWPAD discharge and an increase of 0.04 MGD increase in the discharge of the Woonsocket WWTP. For ease of comparison, the current PS and NPS loads were plotted along with the expected future loading estimates.

Figure 48 – Current and Future PS Loading Estimates of Total Phosphorus in the Blackstone River Watershed

Figure 49 - Current and Future NPS Loading Estimates of Total Phosphorus in the Blackstone River Watershed

Figure 50 - Current and Future PS Loading Estimates of Total Nitrogen in the Blackstone River Watershed

Figure 51 - Current and Future NPS Loading Estimates of Total Nitrogen in the Blackstone River Watershed

When examining the PS total phosphorus loadings in Figure 48, it can be seen that the decrease in the Woonsocket WWTP and the UBWPAD effluent concentrations combined

with the expected increase in the population served at each plant decrease the PS total phosphorus loading in the watershed from 215,000kg to 65,000kg. By 2010, the average NPS total phosphorus loadings are estimated to increase from 64,000kg to 69,000kg with lower and upper estimate bounds from 18,000kg to 139,000kg. When comparing the estimated values of PS and NPS total phosphorus loading, it is apparent that the two sources of loading are estimated to be of the same order of magnitude by 2010. This finding supports the hypothesis that NPS loading reductions should be considered as important as PS loading reductions in future abatements strategies.

Similar results are seen when comparing the 2010 PS and NPS total nitrogen loading estimates. The PS reductions combined with the increases in served populations at the Woonsocket WWTP and the UBWPAD result in a decrease of the PS total nitrogen loading from 963,000kg to 756,000kg. Estimated changes in land use by 2010 have increased the average NPS total nitrogen loading from 667,000kg to 672,000 with lower and upper estimate bounds from 255,000 to 1,146,000kg. The results of the comparison of future PS and NPS total nitrogen loadings further support the call for including NPS reduction in future abatement scenarios.

The impacts of the estimated changes in land use and point source controls in the UBS watershed are shown in Figure 52 through Figure 55. The current annual loads from the UBWPAD are estimated to be 594,000 kg of TN and 136,000kg kg of TP. Upon the completion of the upgrades at the plant, year round nitrification and biological phosphorus removal are anticipated to reduce the average effluent concentrations to 10 mg/L of N and 0.75 mg/L of P. Based on the estimated increases in population, resulting in the average daily flow from the plant increases by 0.72 MGD, it is estimated that annual load of TN and TP will be reduced to 505,000kg and 38,000kg a decrease of 15 % and 72 % respectively.

Figure 52 - Current and Future PS Loading Estimates of Total Phosphorus in the Upper Blackstone River Watershed

Figure 53 - Current and Future NPS Loading Estimates of Total Phosphorus in the Upper Blackstone River Watershed

Figure 54 - Current and Future PS Loading Estimates of Total Nitrogen in the Upper Blackstone River Watershed

Figure 55 - Current and Future NPS Loading Estimates of Total Nitrogen in the Upper Blackstone River Watershed

NPS total phosphorus loads are expected to increase to an average of 12,000kg with lower and upper estimate bounds from 2,800kg to 26,000kg. NPS total nitrogen loads in the UBS are expected to increase to an average of 106,000kg, with an estimated range of 39,000kg to 194,000kg.

The expected PS total nitrogen loading in 2010 is far larger than the 2010 NPS total nitrogen loads, by almost five times. However, when comparing the future estimates of total phosphorus loading, it can be seen that they are closer in magnitude, proof that NPS reductions should be considered in future remediation strategies.

As shown in the above analyses for both the Blackstone watershed and the UBS watershed, the future estimates of PS and NPS loadings are of the same order of magnitude across the Blackstone, but in the UBS, PS loadings dominate. The conclusion could be drawn that in sub-basins other than the UBS watershed, NPS loading could in fact be larger than PS loadings. While the dominance by the UBWPAD of the PS loading in both the UBS watershed and the Blackstone as a whole will likely continue, other, more cost effective loading reduction could achieve the same load reductions as additional PS controls that are expected to be more costly.

5.2.6 - Hydrological Changes over Time

The plots of 7Q vs. time for the Blackstone River at Woonsocket, the Branch River and the Quinsigamond River are shown in Figure 56 through Figure 58 respectively. The R^2 value for each of the best fit lines is quite low, a maximum of 0.05 among the three plots. The purpose of the lines were not to estimate future values of 7Q, but rather to determine if there were any trends to be seen in the 7Q data over time. While there are more sophisticated methods for determining a trend in the data, this methodology was deemed satisfactory for use in this study.

For all three plots, a slightly decreasing trend is seen over time. The downward trends are especially evident in the 7Q values from the 1990's onward. These downward trends indicate a decrease in the base flow of the rivers over time. This decrease is thought to be caused by the increases in urbanization of the region over the same time period.

Figure 56 – Q vs. Time Plot for the Blackstone River at Woonsocket, RI

Figure 57 - Q vs. Time Plot for the Branch River

Figure 58 - Q vs. Time Plot for the Quinsigamond River

The plots of Q_{peak} vs. time for the Blackstone River at Woonsocket, the Branch River and the Quinsigamond River are shown in Figure 59 through Figure 61 respectively. All three plots show slight increases in the peak flow values over time. This finding suggests that increased amounts of urbanized area over time have resulted in higher peak flow values in the watershed, similar to the behavior reported in the literature review section.

Figure 59 - Q vs. Time Plot for the Blackstone River at Woonsocket, RI

Figure 60 - Q vs. Time Plot for the Branch River

Figure 61 - Q vs. Time Plot for the Quinsigamond River

Based upon the results of the 7Q and Q_{peak} analyses, the hydrology of the watershed has been impacted, at least in part by increased amounts of urbanization in the watershed. As reported in the literature, the increased amounts of urbanization resulted in lower base flow values as well as higher storm peak values.

5.3 - Conclusions

The analyses conducted in this chapter illustrate the potential changes that may occur as increasing amounts of the watershed are urbanized. The expected increases in water demands and wastewater returns that accompany the increase in urbanization will place additional pressure on an already stressed environment. Furthermore, the ongoing urbanization suggests that further decreases in base flow of the river may occur, reducing the ability of the river to assimilate the additional pollutants that are being discharged to it. It is expected that the majority of the additional loading into the rivers will be from NPS loading caused by the changes in land use associated with urbanization. Furthermore, additional Blackstone River sub-basins are expected to be impaired (>10% imperviousness) by 2010, creating additional sources of water quality degradation throughout the basin. Based on the above analyses, the following conclusions have been drawn for the analyses conducted in this chapter:

- Expected population increases in the watershed will cause further urbanization and an increase in the extent of impervious areas. These changes will subject the river and its tributaries to additional NPS loadings.
- Current upgrades at the WWTPs in the watershed, in conjunction with the expected changes in land use, will likely shift the relative importance of PS and NPS loading. The majority of the change in the dynamic is due to decreases in PS loadings rather than increases in NPS loadings.
- Estimated future NPS loads will be of the same order of magnitude as expected PS loading values, largely due to the expected decreases in PS loading into the watershed.

- Land use changes in the watershed have altered the hydrology of the river. Expected increases in urbanization will likely effect further alterations and possibly change the loading dynamics of the river. Decreases in base flow would reduce dilution under dry weather conditions. Increases in storm peaks could cause additional resuspension of sediment bound contaminants from behind the impoundments.
- The UBWPAD dominates the nutrient loading of the UBS watershed under current and future loading scenarios.

The above conclusions helped to outline several broad based project conclusions outlined below.

- The relative magnitude of NPS loading under future loading conditions supports the need to include NPS loading reductions in future abatement strategies.
- In order to adequately model the effect of land use changes on water quality and loading dynamics in the Blackstone River watershed, a dynamic modeling tool is required.

6.0 - Summary and Conclusions

6.1 - Summary of Results

As previously stated, this study is part of a larger study designed to evaluate the cost-benefit effectiveness of past remediation efforts and, in a modeling framework, potential future, traditional and progressive abatement strategies at the local and watershed scales. A driving theme of this portion of the study is the development of a detailed understanding of point and nonpoint source contributions within both the headwaters of the Blackstone and the watershed as a whole. Understanding the sources, fate and transport of contaminants along the mainstem of the Blackstone River is essential for setting reasonable management strategies in order to achieve the desired water quality goals in both the river and the bay. A secondary purpose of this work was to determine the previous and current efforts underway in the watershed to examine the aforementioned processes in the Blackstone River and its watershed as well as Narragansett Bay and its watershed.

The analyses contained in Chapter 3 helped to provide some insight into the loading dynamics of the Blackstone Watershed as well as the Narragansett Bay Watershed. It was shown in the work conducted in Chapter 3, on both local and regional scale, that as the amount of urbanization (percent imperviousness) in a watershed increases, water quality degradation in those watersheds increases as well. Continued urbanization in these areas may result in water quality degradation that is irreversible despite increasing limits placed on PS of pollution.

Furthermore, under current loading estimates, non-point source loads of total nitrogen (257,000 – 1,120,000 kg/yr, average of 667,000kg/yr) are of the same order of magnitude as point source loadings of total nitrogen (960,000 kg/yr) in the Blackstone watershed. On a monthly timescale, the NPS component of total nitrogen loading ranges from 32% in February to 48% in July and September.

Under current conditions, PS total phosphorus loading (215,000kg/yr) dominates the NPS total phosphorus loadings (18,000 to 127,000 kg/yr, average of 63,000 kg/yr)) in the Blackstone watershed. On a monthly timescale, the NPS component of phosphorus loading ranges from 15% in February to 29% in May. A large amount of the PS loading is in the Blackstone watershed is due to the UBWPAD facility located in the UBS watershed. The UBWPAD dominates the nutrient loading of the UBS watershed, contributing six times the amount of total nitrogen (594,000 kg/yr) and over ten times the amount of total phosphorus (136,000 kg/yr) than NPS loadings into the UBS watershed.

When examining the loading into Narragansett Bay, it was determined that on an annual basis, WWTPs discharging directly to the Bay contribute 22%, river loadings contribute 35% and NPS contribute 43% of the total nitrogen loads into the bay. On an annual basis, WWTPs discharging directly into the bay are estimated to account for 27% of the total phosphorus load into the bay, while rivers and NPS sources accounting for 36% and 37% respectively.

When examining total nitrogen loading into Narragansett Bay on a monthly scale, WWTP loadings range from 18% to 27%, riverine loadings range from 24% to 40% and NPS loadings range from 37% to 52%. The loading is always dominated by either riverine loadings or NPS loadings with WWTP loadings always being the smallest component. When examining total phosphorus loading into Narragansett Bay on a monthly scale, WWTP loadings range from 16% to 28%, riverine loadings range from 27% to 46% and NPS loadings range from 35% to 49%. The loading is always dominated by either riverine loadings or NPS loadings with WWTP loadings always being the smallest component.

While the results in Chapter 3 helped to estimate the loadings into the Blackstone River, and Narragansett Bay, the analyses conducted in Chapter 4 helped to quantify the nutrient gains and losses occurring in the Blackstone itself.

Along the mainstem of the Blackstone, wet weather loads of $\text{PO}_4\text{-P}$ are typically more than double dry weather loads along the river (data not shown but may be inferred from these plots). Similarly, dry weather $\text{NH}_3\text{-N}$ and NO_2/NO_3 loadings are significantly smaller than wet weather loadings. NPS runoff is the suspected cause of these increases in PO_4 and NO_2/NO_3 as well. It should be noted that for both the wet and dry weather events, the tributary loads are much smaller than those observed in the mainstem of the Blackstone.

When comparing the dry and wet weather phosphorus loading, it is evident that the majority of sites with impoundments in the reach above them experienced gains during wet weather and losses during dry weather conditions. This suggests that resuspension is an important source of water column phosphorus during wet weather while settling and algal uptake in the slow moving waters behind impoundments are important phosphate sinks during dry weather.

During the dry weather event, the majority of the gains in nitrite/nitrate could be attributed, at least in part to WWTP inputs or tributary inputs. Losses typically occurred in reaches with multiple dams or impoundments such as Rice City Pond and Fisherville Pond. The slow moving waters behind the impoundments, especially in the ponds allows for increased algal uptake of nitrogen, resulting in the losses seen in the loading analysis. During wet weather event however, gains in NO_2/NO_3 were seen throughout the mainstem of the river, except for mile marker 10.0. These gains are attributed to runoff carrying N to the river as well as potential flushing of impoundment sediment bound N back into the water column during increased flow regimes. The sole loss of nitrogen observed during the wet weather event was very small compared to the gains in loads seen during analysis.

For all pollutants, the amount of loading (the total positive gains that the river is subjected to) varies not only between wet and dry weather events but among events under the same weather regime as well. The wet weather NH_3 loading varies from 2800kg to 9200kg while the dry weather NH_3 loading varies from 400 kg/day to 500 kg/day. The

wet weather NO_2/NO_3 loading ranges from 2700kg to 8400kg while the dry weather NO_3 loading varies from 1100 kg/day to 5000 kg/day. When examining the phosphorus loading, the wet weather loadings vary from 700 kg to 1900 kg while the dry weather loadings vary from 200 kg/day to 850 kg/day.

The results in Chapter 4 suggest that while point sources are an important source of pollution, additional sources exist, particularly during wet weather. This is supported by the fact that the loads seen after UBWPAD and Woonsocket are often higher than the loads input to the river by those WWTPs, especially during wet weather events. In addition, sources and sinks of pollution along the river exist, most notably the numerous impoundments along the mainstem of the river. Typically the impoundments were shown to act as sources during wet weather events and sinks during dry weather events. The impoundments affect the loading behavior seen along the river and must be accounted for in any modeling effort.

The varying conditions in the river were also shown to impact the assimilative capacity of the river. When looking at the assimilative capacity of the Blackstone River, NH_3 assimilative capacity ranged from 41% to 74% during dry weather events and 60% to 93% during wet weather events. NO_2/NO_3 assimilative capacity ranged from 38% to 47% during dry weather events and 0.4% to 41% during wet weather events. PO_4 assimilative capacity was shown to range from 70% to 76% during dry weather events and 24% to 67% during wet weather events.

The analyses contained in Chapter 4 were vital to understanding the loading dynamics of the river; however the data used there is 15 years old possibly no longer suited to adequately represent the current loading dynamics and transportation behavior of the river. Chapter 5 focused on temporal water quality changes in the Blackstone and the impact such trends may have on the development and success of future abatement strategies. Of particular interest was population growth in the area, including the impacts on water and wastewater demands. The impact of the associated land use change on water quality was also investigated.

The analyses in Chapter 5 showed that despite continuing efforts in PS reduction strategies, pollutant loadings in the river seem to be increasing in recent years. Several factors were investigated as potential causes for this increase in pollutant loads into the river. It was estimated that the population in the watershed would increase from 823,000 in 2000 to a range of 864,000 to 919,000 by 2010. The expected increase in population was estimated to increase water demands by 4.1% to 9.6 MGD and wastewater demands by 3.1% to 7.2 MGD.

The estimated changes in land use over time were also calculated for the Blackstone watershed. As expected, the category with the largest percentage of growth since the 1970's was the Residential classification. The largest decreases since the 1970's are seen in the Forested and Agricultural land uses, similar to the national trends in land use changes described by Hasse and Lathrop (2003). The estimates of the average land uses in 2010 result in residential areas increasing from 22 to 27 percent of the watershed area while forested areas decrease from 53 to 45 percent. Other urban areas such as commercial, industrial and transportation are expected to rise as well, with agricultural areas continuing to decrease.

The associated changes in the percent imperviousness of the Blackstone and its sub-watersheds were also calculated. It was estimated that the Blackstone watershed as a whole would increase from 10.4% to 12% imperviousness. Increases were seen in all sub-basins of the Blackstone with the largest increase seen in the Quinsigamond sub-basin which increased from 16% to 18% impervious area by 2010. The sub-basins of the UBS watershed also showed increases in their percent imperviousness values. The UBS watershed increased from 18.5% to 19.6% impervious area by 2010. The largest increase in imperviousness was seen in the Blackstone North sub-basin with an increase from 32% to 39% imperviousness by 2010.

The affects of the expected changes in land use as well as expected future PS reductions were utilized in estimating future PS and NPS loading dynamics in the Blackstone

Watershed. The expected decreases in PS effluent concentrations combined with the expected increase in the population served by each plant decreased the PS total phosphorus loading in the watershed from 215,000kg to 65,000kg. By 2010, the average NPS total phosphorus loadings were estimated to increase from 64,000kg to 69,000kg with lower and upper estimate bounds from 18,000kg to 139,000kg. The expected PS reductions combined with the increases in served populations the WWTPs resulted in a decrease of the PS total nitrogen loading from 963,000kg to 756,000kg. Estimated changes in land use by 2010 increased the average NPS total nitrogen loading from 667,000kg to 672,000 with lower and upper estimate bounds from 255,000 to 1,146,000kg. For both total nitrogen and total phosphorus loading on a the scale of the Blackstone watershed, future estimates of NPS loadings were estimated to be greater than or equal to estimates of PS loadings.

A similar analysis was conducted on the estimated future PS and NPS loading dynamic in the UBS watershed. Based on the estimated increases in population, resulting in the average daily flow from the UBWPAD to increase by 0.72 MGD, it was estimated that annual load of TN and TP will be reduced to 505,000kg and 38,000kg a decrease of 15 % and 72 % respectively. Based on the changes in land use in the UBS watershed, NPS total phosphorus loads are expected to increase to an average of 12,000kg with lower and upper estimate bounds from 2,800kg to 26,000kg. NPS total nitrogen loads in the UBS are expected to increase to an average of 106,000kg, with an estimated range of 39,000kg to 194,000kg. The expected PS total nitrogen loading in 2010 is far larger than the 2010 NPS total nitrogen loads, by almost five times. However, when comparing the future estimates of total phosphorus loading, it can be seen that they are closer in magnitude for the UBS watershed.

Impacts of the urbanization over time in the Blackstone were also investigated. As shown in the analysis conducted using the low flow values, at all three stations, a slightly decreasing trend is seen over time. The downward trends are especially evident in the 7Q values from the 1990's onward. These downward trends indicate a decrease in the base flow of the rivers over time. When examining the effects of urbanization on the peak

flows seen in the Blackstone and its tributaries, slight increases in the peak flow values are seen over time.

6.2 - Conclusions

Based on the findings summarized above and throughout the work contained herein, several conclusions have been drawn about the Blackstone Watershed, its impact on Narragansett Bay and the status of the current data collection and remediation efforts in the region.

It has been shown that there is a positive correlation between the amount of urbanized area and the amount of water quality degradation in the Blackstone watershed and its sub-basins. Continued urbanization will result in additional pressures being placed on the Blackstone River including increased amounts of NPS pollution. Furthermore, increasing amounts of urbanization will lead to increased peak flow values seen in the river, allowing for increased resuspension of pollutant laden sediment from behind the impoundments along the mainstem of the river, especially during wet weather events. Additionally, the impoundments along the mainstem of the river add great deal of complexity to both the flow and loading dynamics of the river.

Due to the complex hydraulics and loading dynamics of the Blackstone River, its tributaries and the bay as a whole, further regulation of point source pollution alone may not be an adequate or cost effective method for reducing nutrient loadings into the Blackstone River and Narragansett Bay. The results of the comparison of future PS and NPS nitrogen loadings further support the call for including NPS reduction in future abatement scenarios.

Based upon the estimates above, the loading dynamics in the watershed are highly variable on a monthly timescale, a variability that is likely to increase if more refined water quality and quantity data is collected for the river. The loadings from the Blackstone River and the rest of the Narragansett Bay watershed into the bay are also

complex and vary monthly. It has been shown in the above that NPS loadings are expected to be of the same order of magnitude as point source loadings in the near future. Furthermore, NPS pollution into Narragansett Bay dominates the majority of the loadings into Narragansett Bay throughout the year. On an annual basis, nonpoint sources of nutrients dominate the nutrient loading into Narragansett Bay. On a monthly basis however, nonpoint source loadings as well as rivers loadings dominate the nutrient loading into the bay. Finally, the loadings from the tributaries into Narragansett Bay are also quite important to the overall nutrient loading into the bay.

The riverine loadings however, as shown herein, are highly variable. The loadings from the three main rivers into Narragansett Bay are dynamic with the Blackstone or the Taunton becoming the dominant nutrient loading source depending on the month. Nonpoint source loadings are considered highly variable from month to month and event to event as well. In order to develop an adequate management strategy for reducing nutrient loadings into the Blackstone and subsequently Narragansett Bay, more accurate monthly and annual loads for each must be determined. More rigorous sampling of water quality is required, perhaps on a daily time scale, over an extended period of time, in order to truly develop an annual nutrient loading estimate in both the Blackstone and Narragansett Bay.

The lack of available wet weather data also points to the need for additional, more refined data collection to be undertaken in order to better assess the loadings into the Blackstone River and their propagation downstream into Narragansett Bay. It has been shown in this work that wet weather loadings of pollutants are typically much larger than dry weather loadings, resulting in sporadic periods of increased loadings that may not be adequately captured by monthly or even weekly sampling schedules.

While the analyses contained herein are vital to understanding the dynamics of the river, some of the data used here is 15 years old. New data is needed to correctly model the current processes that occur in the river today and in the future. Based upon the results of the $7Q$ and Q_{peak} analyses, the hydrology of the watershed has been impacted over time,

especially since the early 1990's, at least in part by increased amounts of urbanization in the watershed. These changes in the flow dynamics are likely to have affected the loading dynamics of the river itself, prompting even more need for new data to be collected in order to adequately estimate the pollutant and flow dynamics in the Blackstone.

As previously stated, this study is part of a larger study designed to evaluate the cost-benefit effectiveness of past remediation efforts and, in a modeling framework, potential future, traditional and progressive abatement strategies at the local and watershed scales. In order to adequately model the loading behaviors of the Blackstone River, a dynamic modeling tool is needed.

The large amount of variability in both the sources and timing of nutrient loadings into the Blackstone River call for in order to adequately model the Blackstone River watershed. The need for a dynamic model is supported by the complex dynamics of the system, including the constantly varying loading and flow dynamics of the river. Furthermore, the effects and variability of the dynamics between the NPS and PS loadings call for a watershed wide model, not just an in-stream model.

7.0 - Future Work

As previously stated, this study is part of a larger study designed to evaluate the cost-benefit effectiveness of past remediation efforts and, in a modeling framework, potential future, traditional and progressive abatement strategies at the local and watershed scales. While the work conducted in this report has accomplished a great deal toward the overall goals for the project more remains to be completed. A watershed wide water quantity and quality model of the Blackstone watershed still needs to be developed. Prior to its completion, additional data collection needs to be undertaken for reasons outlined below.

7.1 - Data Collection

Additional data is needed to adequately model the flow and loading dynamics of the Blackstone River. A multitude of factors contributes to the need for more data. More accurate monthly and annual loads for the Blackstone must be determined. The lack of available wet weather data also points to the need for additional, more refined data collection to be undertaken in order to better assess the loadings into the Blackstone River and their propagation downstream into Narragansett Bay. Based upon the results of the 7Q and Q_{peak} analyses, the hydrology of the watershed has been impacted over time. These changes in the flow dynamics are likely to have affected the loading dynamics of the river itself, prompting the need for new data to be collected in order to adequately estimate the pollutant and flow dynamics in the Blackstone.

More rigorous sampling of water quality is required, perhaps on a daily time scale, over an extended period of time, in order to truly develop an annual nutrient loading estimate in the Blackstone River and its sub-basins. Continuous flow data is also necessary for the development of more accurate flow and loading estimates in the river and its tributaries.

The tasks for the data collection portion of the project are listed below. Their completion status is also listed.

- Develop a monitoring network to support the modeling effort as well as add to the temporal and spatial analysis of water quality in the Upper Blackstone watershed.
 - Completed
- Record flow measurements throughout the water year in conjunction with the water quality monitoring network in order to better estimate annual loads from the UBS basin as a whole as well as its sub-watersheds.
 - Completed
- Develop a similar water quality and quantity monitoring network for the entire Blackstone watershed to develop a better understanding of relative flows and loading values from the watershed as a whole and its tributaries.
 - Underway
- Acquire additional wet weather data for both the UBS watershed and the Blackstone River watershed as a whole.
 - Former completed, later underway

The additional data will also be used as validation data for the watershed model that is being developed in conjunction with the rest of the project.

7.2 - Watershed Modeling

As previously stated, this study is part of a larger study designed to evaluate the cost-benefit effectiveness of past remediation efforts and, in a modeling framework, potential future, traditional and progressive abatement strategies at the local and watershed scales. In order to adequately model the loading behaviors of the Blackstone River, a dynamic modeling tool is needed.

The model must be able to analyze the effectiveness of abatement strategies including best management practices and future land use changes. The model will also be used to investigate the propagation of water quality improvements to downstream reaches of the Blackstone. Due to the importance of the surrounding watershed on the Blackstone River and its tributaries, the model must be a watershed wide model, not just an in-stream

model. The more accurate annual loadings are then available, along with the model, to develop more accurate and reasonable TMDLs for the watershed.

The model chosen for use in this project is the Hydrologic Simulation Program in Fortran (HSPF). HSPF is a lumped parameter model able to simulate hydrology, sediment cycles and chemicals in a stream and its surrounding watershed. HSPF also has the ability to model specific coupled kinetics, including: BOD-DO, nutrients (P and N) and phytoplankton interactions in the water column, and pesticides (Ward and Benaman 1999). HSPF is one of EPA's suggested models for developing watershed based total maximum daily loads (TMDLs). The program has been used by the USGS and the ACOE as well. HSPF is commonly used to assess the effects of land use changes and point and nonpoint source treatment alternatives on watersheds (Filoso 2004). The model is able to simulate short (storm based) events as well as long continuous time periods.

During the model development for this project, the model will be calibrated based on the water quantity and quality data available from 1996 through 2005. The data being collected during the course of this project, for both the UBS watershed and the Blackstone River watershed as a whole, will then be used in model validation to ensure the model performs up to the standards outlined in the goals of the project. Once calibrated and validated, the model will be used to simulate various pollutant abatement strategies in an effort to achieve pollution reduction in the river in a cost effective manner.

The development of the HSPF model of the Blackstone River watershed is currently underway. The model is expanding on the water quantity model that was developed for the basin by the USGS. Our efforts include expanding the water quantity component to include up to 2005 as well as activating the water quality components to the model over the entire calibration period. A more detailed description of the modeling effort, including its calibration and validation results as well as the results of the abatement scenario analyses will be provided in future reports.

8.0 - References

- Alexander, R.B., Murdoch, P.S. and Smith, R.A. (1996). "Stream flow-Induced variations in Nitrate Flux in Tributaries to the Atlantic Coastal Zone". *Biogeochemistry* (33) p149-177.
- American Geophysical Union (AGU) (2004). "AGU Release No. 04-23: U.S.A.'s Built-up Surfaces Equal Ohio in Area". *American Geophysical Union and National Oceanic and Atmospheric Administration Joint Release*. Sent by Liefert, H. (June 14, 2004). 2p.
- Ardito, T. (1999). "Working Across the Watershed: 1998 Report". *Narragansett Bay Estuary Program (NBEP)* June 29, 1999
<http://www.nbep.org/pubs/pdf/watw98.pdf>
- Arizona Humanities Council Web Page (2001). "Moving Waters: The Colorado River and the West" <http://www.azhumanities.org/movingwaters/index.html> (January 24, 2006).
- Arnold, C.A. and Gibbons, C.J. (1996). "Impervious Surface Coverage: The Emergence of a Key Environmental Indicator". *Journal of the American Planning Association* (62-2) Spring 1996. p243-258
- Bergondo, D.L., Kester, D.R., Stoffel, H.E. and Woods, W.L. (2005). "Time-series observations during the low sub-surface oxygen events in Narragansett Bay during summer 2001". *Marine Chemistry*. (97) p90-103.
- Blackstone River Coalition (BRC) Web Page. "Why We're Here" *Blackstone River Coalition* <http://www.zaptheblackstone.org/inner/whywehere/whywehere.htm> (January 25, 2006).
- Blackstone River Coalition (BRC) Web Page (b). "Who We Are" *Blackstone River Coalition* http://www.zaptheblackstone.org/inner/whoweare/who_history.htm (April 10, 2006).
- Blackstone River National Heritage Corridor (BRNHC) Web Page. "The John H. Chafee Blackstone River Valley National Heritage Corridor Commission" <http://www.nps.gov/blac> (January 24, 2006).
- Booth D.B., and Jackson, C.R. (1997). "Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection and the Limits of Mitigation". *Journal of the American Water Resources Association* (33-5) October 1997. p1077-1090.
- Booth D.B., Hartley, D. and Jackson, R. (2002). "Forest Cover, Impervious-Surface Area and the Mitigation of Stormwater Impacts". *Journal of the American Water Resources Association* (38-3) June 2002. p835-845.

- Booth D.B., Karr, J.R., Schauman, S., Konrad, C.P., Morley, S.A., Larsong, M.G. and Burges, S.J. (2004). "Reviving Urban Streams: Land Use, Hydrology Biology and Human Behavior". *Journal of the American Water Resources Association* (40-5) October 2004. p1351-1364.
- Brodeur, Br. MADEP GIS Division. Personal communication 6-16-2005. See Appendix B for additional details.
- Burns, D., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J. and Kendall, C. (2005). "Effects of Suburban Development on Runoff Generation in the Croton River Basin, New York, USA". *Journal of Hydrology* (311) p266-281.
- Camp Dresser and McKee (CDM) et al (2004). "Blackstone Watershed Simulation Modeling Plan (Draft)"
- Caton, P.A. (2002). "Developing an Effluent Trading Program to Address Nutrient Pollution in the Providence and Seekonk Rivers". *Masters Thesis*. Brown University, Center for Environmental Studies
<http://envstudies.brown.edu/Thesis/2002/caton/index.htm>
- Carcieri, D.L., (2003) "Executive Order 03-16: Establishing the Governor's Narragansett Bay and Watershed Planning Commission". State of Rhode Island and Providence Plantations October 22, 2003 3p.
- Carey, D., Desbonnet, A., Colt, A.B., Costa-Pierce, B.A. (2005). "State of Science on Nutrients in Narragansett Bay: Findings and Recommendations from the Rhode Island Sea Grant 2004 Science Symposium". *Rhode Island Sea Grant* July 2005 43p.
- Carlin, A. and The Environmental Law institute (1990). "Environmental investments: the Cost of a Clean Environment-A Summary". *EPA Report 230-11-90-083* December 1990 305p.
- Carlin, A., Scodari, P.F. and Garner, D.H. (1992). "Environmental Investments: The Cost of Cleaning Up," *Environment* (34-2) March 1992 p12-20, 38-44.
- Chapra, S. C. (1997). *Surface Water-Quality Modeling*. McGraw-Hill Companies Inc. Boston, MA
- Chaudhury, R.R., Sobrino, J.A.H., Wright, R.M. and Sreenivas, M. (1998) "Dissolved Oxygen Modeling of the Blackstone River (Northeastern United States)". *Water Resources* (32-8) p2400-2412.

- Coastal Institute at URI (CIURI) Web Page. "The Governor's Narragansett Bay and Watershed Planning Commission". <http://www.ci.uri.edu/GovComm/Default.htm> (May 31, 2006)
- Correll, D.L. (1998). "The Role of Phosphorus in the Eutrophication of Receiving Waters: A Review". *Journal of Environmental Quality* (27-2) March-April, 1998 p261-266.
- Correll, D.L., Jordan, T.E., Weller, D.E. (1999). "Transport of Nitrogen and Phosphorus from Rhode River Watersheds during Storm Events". *Water Resources Research* (35-8) p2513-2521.
- Dahl, T. E. (1990). "Wetlands losses in the United States 1780's to 1980's". U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. Jamestown, ND: Northern Prairie Wildlife Research Center Home Page. <http://www.npwrc.usgs.gov/resource/othrdata/wetloss/wetloss.htm> (Version 16JUL97).
- Daisey, J.M. and Harwell M.A. (1998) "U.S. Environmental Protection Agency Science Advisory Board Ecological Processes and Effects Committee: Review of the Blackstone River Initiative". EPA-SAB-EPEC-98-011 September 1998 61p.
- Duda, A.M. (1993) "Addressing Nonpoint Sources of Water Pollution Must Become an International Priority". *Water Science and Technology* (28-3-5) p1-11.
- Eckilson, E. (1999-2005). "Blackstone Canal" *Woonsocket: My Home Town on the Web* <http://www.woonsocket.org/canal.html> (January 24, 2006).
- Ely, E. (2002). "An Overview of Narragansett Bay". Rhode Island Sea Grant, Narragansett, RI. 8p.
- Evans, D.J. and Johnes, P.J. (2004). "Physio-Chemical Controls on phosphorus Cycling in Two Lowland Streams: Part 1-The Water Column" *Science of the Total Environment* (329) p145-163.
- Geosyntech (2004). "Blackstone River Watershed River Five Year Action Plan". September 2004 40p.
- Greene, R. and Deacutis, C. (2000). "Narragansett Bay Water Quality: Status and Trends 2000". RIDEM, Narragansett Bay Estuary Program and Narragansett Bay Estuarine Research Reserve April 2000 35p.
- Griffith, G.E., Omernik, J.M., Pierson, S.M. and Kiilsgaard, C.W. (1994). "Massachusetts Ecological Regions Project". Publication No. 17587-74-70-6/94-DEP June 30, 1994 67p.

- Governor's Narragansett Bay and Watershed Planning Commission (GNBAWPC) (2004). "Phase I Strategic Work Plan: Short Term Recommendation". March 2004 27p.
- Hasse, J.E., Lathrop, R.G. (2003). "Land Resource Indicators of Urban Sprawl". *Applied Geography* (23) p159-175.
- Harrison, J., Wetherbee, P., Quezner, A. and Beduhn, B. (1999) "Developing Tools to Tackle Non-Point Source Pollution". *Pollution Engineering* May 1999 p54-57.
- Heathwaite, A.L., Johnes, P.J. and Peters N.E. (1996). "Trends in Nutrients". *Hydrological Processes* (10) p263-293.
- Howarth, R.W., Sharpley, A. and Walker, D. (2002). "Sources of Nutrient Pollution to Coastal Waters in the United States: Implications for Achieving Water Quality Goals". *Estuaries* (25-4) August 2002 p656-676.
- Ji, Z.G., Hamrick J.H. and Pagenkopf, J. (2002). "Sediment and Metals Modeling in a Shallow River". *Journal of Environmental Engineering* (128-2) p105-119.
- Johnes, P.J. and Burt, T.P. (1991). "Water Quality Trends in the Windrush Catchment: Nitrogen Speciation and Sediment Interactions". *Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation Proceedings of the Vienna Symposium* August 1991 IAHS Publ no. 203 p349-357.
- Knopman, D.S. and Smith, R.A. (1993). "20 years of the Clean Water Act" *Environment* (35-1) January-February 1993 p16-20, 34-41.
- Konrad, C.P. and Booth, D.B. (2005). "Hydrologic Changes in Urban Streams and their Ecological Significance". *American Fisheries Symposium* (47) p157-177.
- Lee, G.F. and Jones Lee, A. (1993). "Water Quality Impacts of Stormwater-Associated Contaminants: Focus on Real Problems". *Water Science and Technology* (28-3-5) p231-240.
- Massachusetts Department of Environmental Protection (MADEP) (2006). "Massachusetts Surface Water Quality Standards". MADEP Web Page May 8, 2006. <http://www.mass.gov/dep/water/laws/314cmr4.htm>
- Massachusetts Department of Environmental Protection (MADEP) (2004). "Massachusetts Year 2002 Integrated List of Waters". MADEP Division of Watershed Management September 2003 123p.
- Massachusetts Geographical Information System (MassGIS) (2006). MassGIS Web Page September 1, 2006. <http://www.mass.gov/mgis/>

- Massachusetts Executive Office of Environmental Affairs (EOEA) (2006). "Taunton River Watershed Page" EOEA Web Page August 13, 2006.
<http://www.mass.gov/envir/water/taunton/taunton.htm>
- Metcalf and Eddy (2003). Wastewater Engineering: Treatment and Reuse 4th edition. McGraw-Hill Companies Inc. Boston, MA
- Narragansett Bay Estuary Program (NBEP) Web Page. "Maps". *Narragansett Bay Estuary Program* <http://www.nbep.org/maps/index.html> (January 24, 2006).
- National Park Service Web Page. "Blackstone River Valley National Heritage Corridor." <http://www.nps.gov/blac/>. (Jan 28, 2005)
- National Weather Service Web Page (September 14, 2006)
- Worcester weather station <http://www.weather.com/weather/local/USMA0502>
 - Providence weather station <http://www.weather.com/weather/local/USRI0050>
- Nixon, S.W., Granger, S.L. and Nowicki, B.L. (1995). "An Assessment of the Annual Mass Balance of Carbon, Nitrogen and Phosphorus in Narragansett Bay". *Biogeochemistry*. (31-1) October 1995. p15-61.
- Nixon, S.W. (1997). "Prehistoric Nutrient Inputs and Productivity in Narragansett Bay". *Estuaries* (20-2) June 1997. p253-261
- Nixon, S.W. (1998). "Enriching the Sea to Death". *Scientific American* Special Issue August 1998 p48-53.
- Nixon, S., Buckley, B., Granger, S., Harris, L., Oczkowski, A., Cole, L. and Fulweiler, R. (2005). "Anthropogenic Nutrient Inputs to Narragansett Bay: A 25 year Perspective". A report to the Narragansett Bay Commission and Rhode Island Sea Grant Feb 2005. 50p.
- Peters, N.E. and Meybeck, M. (2000). "Water Quality Degradation Effects on Freshwater Availability: Impacts of Human Activities". *Water International* (25-2) June 2000. p185-193.
- Pilson, M.E.Q. (1985). "On the Residence Time of Narragansett Bay". *Estuaries*. (8-1) March 1985. p2-14.
- Puckett, L.J. (1995). "Identifying the Major Sources of Nutrient Water Pollution". *Environmental Science and Technology* (29-9) p408-414.
- Reckhow, K.H., Beaulac, M. N., and Simpson, J. T. (1980). "Modeling Phosphorus Loading and Lake Response Under Uncertainty: A Manual and Compilation of Export Coefficients". USEPA 440/5-80-011. Washington, DC: Office of Water Regulations and Standards, USEPA. Washington, DC, USA.

- Rhode Island Department of Environmental Management (RIDEM) (2003). "The Greenwich Bay Fish Kill – August 2003: Causes, Impacts and Responses". RIDEM, Sept 2003 31p.
- Rhode Island Department of Environmental Management (RIDEM) (2003b). "State of Rhode Island 2002 303(d) List: List of Impaired Waters". RIDEM, March 2003 51p.
- Rhode Island Department of Environmental Management (RIDEM) (2004). "State of Rhode Island and Providence Plantations 2004 Section 305(b): State of the States Waters". *Chapter IIIF: Estuary and Coastal Assessment* RIDEM, 2004 25p.
- Rhode Island Department of Environmental Management (RIDEM) (2005). "Plan for Managing Nutrient Loadings to Rhode Island Waters". February 1, 2005 17p.
- Rhode Island Department of Environmental Management (RIDEM) (2005). "Pawtuxet River Watershed" RIDEM Web Page. August 13, 2006.
<http://www.dem.ri.gov/programs/bpoladm/stratpp/partnership/pawtuxet/>
- Rhode Island Geographic Information System (RIGIS) (2006) RIGIS Web Page September 1, 2006 <http://www.edc.uri.edu/rigis/>
- Rhode Island Department of Environmental Management (RIDEM) (2006) "Rhode Island Water Quality Standards" Web Page. August 11, 2006.
<http://www.dem.ri.gov/pubs/regs/regs/water/h20q06.pdf>
- Ries, K.G. (1990). "Estimating Surface-Water Runoff to Narragansett Bay, Rhode Island and Massachusetts". *USGS Water-Resources Investigations Report, 89-4164* 44p.
- Robinson, K.W., Campbell, J.P. and Jaworski, N.A. (2003). "Water Quality Trends in New England Rivers During the 20th Century". *USGS Water Resources Investigations Report 03-4012* 20p.
- Rohm, C.M., Omernik, J.M. and Kiilsgaard, C.W. (1995). "Regional patterns of Total Phosphorus in Lakes of the Northeastern United States". *Lake and Reservoir Management* (11-1) p1-14
- Save the Bay Inc Web Page. "About Narragansett Bay" *Save the Bay: Narragansett Bay*
http://www.savebay.org/about_aboutthebay.asp (January 24, 2006).
- Schueler, T. (1994). "The Importance of Imperviousness". *Watershed Protection Techniques*. (1-3) Fall 1994. p100-111.

- Shanahan, P. (1994). "A Water-Quality History of the Blackstone River, Massachusetts, USA: Implications for Central and Eastern European Rivers". *Water Science and Technology*. (30-5), p59-68.
- Shenk, G.W. and Linker, L.C. (2002). "Simulating the Chesapeake bay Watershed with Time-Varying Land Use and Management Actions". *Watershed 2002, February 24-27, 2002*. Fort Lauderdale, FL. WEF-2002.
- Smith, R.A., Alexander, R.B. and Wolman, M.G. (1987). "Water Quality Trends in Our Nation's Rivers". *Science* (235) p1607-1615.
- Smith, R.A., Schwarz, G.E. and Alexander, R.B (1997). "Regional Interpretation of Water Quality Monitoring Data". *Water Resources Research* (33-12) December 1997 p2781-2798.
- Smith, R.A., Alexander, R.B and Schwarz, G.E. (2003). "Natural Background Concentrations of Nutrients in Streams and Rivers of the Conterminous United States". *Environmental Science and Technology* (37-14) p3039-3047.
- Tang, Z., Engel, B.A., Pijanowski, B.C. and Lim, K.J. (2005). "Forecasting Land Use Change and Its Environmental Impact at a Watershed Scale". *Journal of Environmental Management* (76) p35-45.
- Tarr, J.A. and Ayers, R.U. (1990), "Chapter 38: The Hudson-Raritan Basin." *The Earth as Transformed by Human Action*, Cambridge University Press p624-639.
- Tarr, J.A. and McCurley, J. (1984), "Pollution Trends in Five Estuaries: the Potomac, the Delaware, the Hudson-Raritan, the Connecticut, the Narragansett." Carnegie-Melon University.
- United States Census Bureau (USCB) Information and Resources Internet Staff (2002) "Your Gateway to Census 2000" *United States Census 2000* <http://www.census.gov/main/www/cen2000.html> (January 24, 2006).
- United States Environmental protection Agency (EPA) (2000a). "Progress in Water Quality: An Evaluation of the National Investment in Municipal Wastewater Treatment". *EPA Report 832-R-00-008* June, 2000 452p.
- United States Environmental protection Agency (EPA) (2000b). "Ambient Water Quality Criteria Recommendations: Rivers and Streams in Nutrient Ecoregion XIV". *EPA Report 822-B-00-022* December, 2000 31p.
- United States Environmental protection Agency (EPA) (2001a). "Our Built and Natural Environments". *EPA Report 231-R-01-002* January 2001 93p.

- United States Environmental protection Agency (EPA) (2001b). "The National Costs of the Total Maximum Daily Load Program (Draft Report)". *EPA Report 841-D-01-003* August 1, 2001 51p.
- United States Environmental Protection Agency (EPA) Web Page (2006a) "Surf Your Watershed: Blackstone" *USEPA* http://cfpub.epa.gov/surf/huc.cfm?huc_code=01090003 (January 25, 2006).
- United States Environmental Protection Agency (EPA) Web Page (2006b) "American Heritage Rivers" *USEPA* <http://www.epa.gov/rivers/> (April 10, 2006).
- United States Environmental Protection Agency (EPA) Web Page (2006c) "2002 National Assessment Database" *USEPA* <http://www.epa.gov/waters/305b/index.html> (April 10, 2006).
- United States Environmental Protection Agency (EPA) Web Page (2006d) "Chapter 3 Sustainable Urban Water Management" <http://www.epa.gov/nrmrl/pubs/600r99029/600R99029chap3.pdf#search=%22Water%20Demand%20100%20gpcd%20EPA%22>
- United States Environmental Protection Agency (EPA) and United States Army Corps of Engineers (ACOE) (2006) "Urban Rivers Restoration Pilot Fact Sheet: Blackstone-Woonasquatucket Rivers and Communities, Massachusetts and Rhode Island" 2p http://www.epa.gov/oswer/landrevitalization/download/factsheet_blackstone.pdf (March 27, 2006).
- United States Geological Survey (USGS) Web Page (2006) "MA-RI Water Science Center" <http://ma.water.usgs.gov/> (January 24, 2006).
- Upper Blackstone Water Pollution Abatement District (UBWPAD) Web Page (2006) *UBWPAD* <http://www.ubwpad.org/> (April 11, 2006).
- Wolman, M.G. (1971). "The Nation's Rivers" *Science* (174) p905-918
- Walsh, Tom (2006). Director of UBWPAD facility. Personal Communication. August 21, 2006.
- Wright, R.M., Nolan, P.M., Pincumbe D., Hartman, E. and Viator, O.J. (2001). "Blackstone River Initiative: Water Quality Analysis of the Blackstone River Under Wet and Dry Conditions", USEPA New England.
- Wright, R.M., Viator, O.J and Michaelis, B. (2004). "Dry Weather Water Quality Sampling and Modeling Blackstone River Feasibility Study Phase 1: Water Quality Evaluation and Modeling of the MA Blackstone River" Submitted to the ACOE 174p.

Appendices for

**BASIN-SCALE METHODOLOGY FOR EVALUATIONG RELATIVE IMPACTS
OF POLLUTION SOURCE ABATEMENT**

A Masters Project Presented by

James T. Mangarillo

**Appendix A: BRC Water Quality Monitoring Background, Impairment Criterion
and Data Analysis**

Table 1 - BRC Water Quality Monitoring Locations and Periods of Record

BRC ID	Site Number	Watershed Subwatershed	WaterBody	Site Location	Period of Record Start
A-01-01-01	BB010	Beaver Brook	Beaver Brook	Jewish Comm. Ctr.	Oct-99
A-01-01-02	BB020	Beaver Brook	Beaver Brook	Maywood	Jun-01
A-01-01-03	BB030	Beaver Brook	Beaver Brook	Park Ave. Carwash	Sep-99
A-02-01-01	BMB010	Broad Meadow Brook	Broad Meadow Brook	Dunkirk	Sep-99
A-02-01-02	BMB020	Broad Meadow Brook	Broad Meadow Brook	Dupuis Ave	Jul-03
A-02-01-03	BMB030	Broad Meadow Brook	Broad Meadow Brook	Sprague Lane	Oct-99
A-02-01-04	BMB040	Broad Meadow Brook	Broad Meadow Brook	Holdridge	Jun-02
A-02-01-05	BMB050	Broad Meadow Brook	Broad Meadow Brook	Dosco	Apr-04
A-03-01-01	CSB010	Cold Spring Brook	Cold Spring Brook ^{*cwf}	Hatchery Rd	Apr-04
A-04-01-01	KB010	Kettle Brook	Kettle Brook	Stafford Street	Sep-99
A-04-01-02	KB020	Kettle Brook	Kettle Brook	James St	Oct-99
A-04-02-01	KDB010	Kettle Brook	Dark Brook	Auburn High	Apr-04
A-04-03-01	LP010	Kettle Brook	Leesville Pond	Leesville inflow	Jun-01
A-04-03-02	LP020	Kettle Brook	Leesville Pond	Leesville outflow	Oct-99
A-05-01-01	MDR010	Middle River	Middle River	St. John's Cemetery	Jun-01
A-06-01-01	AB010	Mill Brook	Ararat Brook ^{*cwf}	Esta Brook - Footbridge	Apr-04
A-06-01-02	AB020	Mill Brook	Ararat Brook ^{*cwf}	Shore Drive	Mar-03
A-06-02-01	KNB010	Mill Brook	Kendrick Brook	Ararat Street	Jul-03
A-06-03-01	WB010	Mill Brook	Weasel Brook	Heald Mfg.	Jun-01
A-06-03-02	WB020	Mill Brook	Weasel Brook	Norton	May-01
A-06-04-01	SP010	Mill Brook	Salisbury Pond	Salisbury Pond East	Sep-99
A-06-04-02	SP020	Mill Brook	Salisbury Pond	Salisbury Pond West	Sep-99
A-07-01-01	CMB010	Quinsigamond River	Coal Mine Brook	Plantation St	Sep-99
A-07-02-01	PFB010	Quinsigamond River	Poor Farm Brook ^{*cwf}	Clark St	Sep-02
A-07-02-02	PFB020	Quinsigamond River	Poor Farm Brook ^{*cwf}	Roberto Clemente	Nov-01
A-07-03-01	SB010	Quinsigamond River	Sewall Brook ^{*cwf}	School St.	Apr-04
A-07-03-02	SB020	Quinsigamond River	Sewall Brook ^{*cwf}	Holden St	Jul-01
A-07-04-01	TLB010	Quinsigamond River	Tilly Brook	Vinny Testa's	Apr-03
A-07-05-01	WSB010	Quinsigamond River	West Brook ^{*cwf}	Main St. Shrewsbury	Apr-04
A-07-06-01	QRMB010	Quinsigamond River	Meadow Brook	385 S. Quinsig Rd.	May-04
A-07-07-01	QR010	Quinsigamond River	Quinsigamond River	rte 140	Apr-03
A-07-07-02	QR020	Quinsigamond River	Quinsigamond River	Wheeler Rd.	May-01
A-07-07-03	QR030	Quinsigamond River	Quinsigamond River	Pleasant St	May-01
A-07-08-01	QRBB010	Quinsigamond River	Bummitt Brook	Pratts Pond	Jun-01
A-08-01-01	SGB010	Singletary Brook	Singletary Brook	Sycamore Circle	Apr-03
A-09-01-01	TB010	Tatnuck Brook	Tatnuck Brook ^{*cwf}	VFW-north	May-04
A-09-01-02	TB020	Tatnuck Brook	Tatnuck Brook ^{*cwf}	VFW-south	Apr-04
B-01-01-01	BCB010	Bacon Brook	Bacon Brook ^{*cwf}	East of Bridge, South Street	Apr-04
B-02-01-01	BR010	Blackstone River	Blackstone River	outlet of Fisherville Pond @ Rt. 122A	Apr-04
B-02-01-02	.BR020	Blackstone River	Blackstone River	Sutton St. USGS flow station	Apr-04

B-02-01-03	BR030	Blackstone River	Blackstone River	Plummer's Landing	Apr-04
B-02-01-04	BR040	Blackstone River	Blackstone River	Tow path north of Stanley Woolen	Apr-04
B-02-01-05	BR050	Blackstone River	Blackstone River	Upstream at Gorge off Staples Lane	Apr-04
B-02-01-06	BR060	Blackstone River	Blackstone River	downstream @ St. Paul St.	Apr-04
B-03-01-01	CB010	Cold Spring Brook	Casey Brook	Putnam Hill Road	Apr-04
B-04-01-01	EB010	Emerson Brook	Emerson Brook ^{*cwf}	bridge @ Mill Street - before pond St.	Jun-04
B-04-01-02	EB020	Emerson Brook	Emerson Brook ^{*cwf}	Above Quaker Highway, access from northern shore	May-04
B-05-01-01	MLR010	Mill River	Mill River	Upstream of Deer Run Drive	Apr-04
B-06-01-01	MR010	Mumford River	Mumford River	Inlet L. Manchaug	Jun-04
B-06-01-02	MR020	Mumford River	Mumford River	outlet of L. Manchaug near Parker Road	Apr-04
B-06-01-03	MR030	Mumford River	Mumford River	Potter Road	Apr-04
B-06-01-04	MR040	Mumford River	Mumford River	Gilboa Street	Apr-04
B-06-01-05	MR050	Mumford River	Mumford River	below WWTP	Apr-04
B-06-01-06	MR060	Mumford River	Mumford River	downstream @ Depot St.	Apr-04
B-06-02-01	MRDB010	Mumford River	Dark Brook	Putnam Hill Road	Apr-04
B-06-03-01	MRUT010	Mumford River	unnamed tributary	outlet of Whitin Reservoir	Apr-04
B-06-04-01	CTVB010	Mumford River	Centerville Brook ^{*cwf}	West Street in Douglas	Apr-04
B-06-05-01	CAB010	Mumford River	Cook Allen Brook ^{*cwf}	off Mendon Road, west of 146	Apr-04
B-06-06-01	PB010	Mumford River	Purgatory Brook	upstr of bridge on Johnson Road	Apr-04
B-07-01-01	WR010	West River	West River ^{*cwf}	Glen Ave. Wells	Apr-04
B-07-01-02	WR020	West River	West River ^{*cwf}	Hartford Avenue	Apr-04
B-07-01-03	WR030	West River	West River ^{*cwf}	Pleasant and Glen	May-04
B-07-01-04	WR040	West River	West River ^{*cwf}	Mendon Road	Apr-04
B-07-01-05	WR050	West River	West River ^{*cwf}	upstream @ Harrington Pool	Apr-04
B-07-01-06	WR060	West River	West River ^{*cwf}	under Rte. 16 bridge	Apr-04
B-07-02-01	WRB010	West River	Warren Brook ^{*cwf}	Fowler Road Bridge	Apr-04
B-07-03-01	CTB010	West River	Center Brook ^{*cwf}	Hopkinton Road, 1/8 mile east of church at culvert west side of road	Apr-04
B-07-03-02	CTB020	West River	Center Brook ^{*cwf}	at Mendon Street	Apr-04
B-07-04-01	WRMB010	West River	Meadow Brook	upstream at Blackstone St. bridge	Apr-04
C-01-01-01	SLB010	Abbott Run	Sylvys Brook	Grants Mill Road	Apr-04
C-01-02-01	RHP010	Abbott Run	Robin Hollow Pond	Dexter Street, Cumberland	Apr-04
C-02-01-01	MB010	Blackstone River	Mussey Brook	New River Road	Apr-04
C-02-02-01	SNB010	Blackstone River	Sneech Brook	Albion Rd., Cumberland	Apr-04

C-02-03-01	BRUB010	Blackstone River	unnamed brook	Flat Street	May-04
C-02-03-02	BRUB020	Blackstone River	unnamed brook	1/2 mile from Manville Dam, east side	Apr-04
C-02-03-03	BRUB030	Blackstone River	unnamed brook	Midway Albion & Manville Dam	Apr-04
C-02-03-04	BR070	Blackstone River	Blackstone River	Albion Dam	Apr-04
C-02-03-05	RIHS010	Blackstone River	RIPDES discharge	Martin Street	Apr-04
C-02-03-06	RIHS020	Blackstone River	Stormwater outfall	Behind Royal Panda , Cumberland	Apr-04
C-02-04-01	BRUT010	Blackstone River	unnamed trib	Behind Highland Falls Condos	May-04
C-03-01-01	BRR010	Branch River	Branch River	Branch River Rte. 146 (Great Road) North Smithfield	Apr-04
C-04-01-01	MLR020	Mill River	Mill River	Privelege Street	Apr-04
C-05-01-01	PR010	Peters River	Peters River*cwf	Paine Street	Apr-04
	TB05	Tatnuck Brook	Tatnuck Brook*cwf	Dawson Road	May-02

4

Table 2 - BRC Water Quality Monitoring Parameters and Impairment Criterion
(Source: BRC, 2006)

Rating Categories by Parameter									
Temperature									
Warm water					Cold water				
<24° C (75.2° F) =green					<15°C (59°F) =green				
24° C (75.2° F) - <27° C (80.6° F) = yellow					15°C (59°F) - <20°C (68°F) = yellow				
27°C (80.6°F) - 28.6°C (83°F) = orange					20°C (68°F) - 24°C (75.2°F) = orange				
> 28.6° C (83° F) = red					> 24°C (75.2°F) = red				
no data = gray					no data = gray				
Turbidity (standard 0 - 10 NTU)									
>1 = green									
>1 - <5 = yellow									
5 - 50 = orange									
> 50 = red									
no data = gray									
pH (standard 6.5 - 8.3)									
6.5 - 8.5 = green									
6.0 - 9.0 = yellow									
5.5 - 6 = orange									
< 5.5 = red									
no data = gray									
Dissolved Oxygen (standard > 5 mg/L for warm water fisheries, > 6 mg/L for coldwater fisheries)									
Warm water					Cold water				
> 6.5 = green					> 9 = green				
>5 - 6.5 = yellow					>6 - 9 = yellow				
4 - 5 = orange					5 - 6 = orange				
< 4 = red					< 5 = red				
no data = gray					no data = gray				
Nitrate (standard < 0.31 mg/L)									
< 0.3 = green									
0.3 - <.6 mg/L = yellow									
.6 - .9 = orange									
> .9 mg/L = red									
no data = gray									
Orthophosphate (reported as P) (standard <.025 mg/L)									
< .025 = green									
.025 - <.05 = yellow									
.05 - .1 = orange									
> .1 = red									
no data = gray									

Table 3 – BRC Data Analysis Values for the UBS Watershed – Tatnuck Brook

Tatnuck Brook	Dawson Rd						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	0.04	0.01	Excellent	April	0.08	0.02608	Good
May	-	-	-	May	0.02	0.00652	Excellent
June	0.02	0.00	Excellent	June	0.23	0.07498	Fair
July	0.15	0.03	Excellent	July	0.11	0.034773	Good
August	0.30	0.07	Excellent	August	0.12	0.03912	Good
September	0.40	0.09	Excellent	September	0.09	0.02934	Good
October	0.30	0.07	Excellent	October	0.07	0.02282	Excellent
November	0.50	0.11	Excellent	November	0.09	0.02934	Good
1999	-	-	-	1999	-	-	-
2000	-	-	-	2000	-	-	-
2001	-	-	-	2001	-	-	-
2002	-	-	-	2002	0.14	0.046944	Good
2003	0.02	0.00	Excellent	2003	0.02	0.00652	Excellent
2004	0.36	0.08	Excellent	2004	0.14	0.044336	Good
Overall	0.23	0.05	Excellent	Overall	0.11	0.034463	Good
Site							
Tatnuck Brook	Mill St/ Amer Legion						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	0.16	0.04	Excellent	April	0.20	0.0652	Fair
May	0.02	0.00	Excellent	May	0.01	0.004347	Excellent
June	0.02	0.00	Excellent	June	0.05	0.015213	Excellent
July	0.04	0.01	Excellent	July	0.21	0.069547	Fair
August	-	-	-	August	0.12	0.03912	Good
September	0.06	0.01	Excellent	September	0.04	0.011953	Excellent
October	0.08	0.02	Excellent	October	0.07	0.02282	Excellent
November	-	-	-	November	0.03	0.008693	Excellent
1999	-	-	-	1999	0.09	0.028253	Good
2000	-	-	-	2000	-	-	-
2001	-	-	-	2001	0.15	0.0489	Good
2002	-	-	-	2002	0.06	0.020864	Excellent
2003	0.06	0.01	Excellent	2003	0.07	0.022277	Excellent
2004	-	-	-	2004	-	-	-
Overall	0.06	0.01	Excellent	Overall	0.08	0.027092	Good
Site							
Tatnuck Brook	Park Avenue						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	0.92	0.21	Excellent	April	0.25	0.080783	Fair
May	2.09	0.47	Good	May	0.05	0.016689	Excellent
June	1.04	0.24	Excellent	June	0.06	0.019772	Excellent
July	1.00	0.23	Excellent	July	0.06	0.019152	Excellent
August	1.19	0.27	Excellent	August	0.07	0.023859	Excellent
September	1.68	0.38	Good	September	0.19	0.061558	Fair
October	-	-	-	October	0.23	0.076067	Fair
November	-	-	-	November	0.06	0.01956	Excellent
1999	-	-	-	1999	-	-	-
2000	-	-	-	2000	-	-	-
2001	-	-	-	2001	0.14	0.04401	Good
2002	-	-	-	2002	0.05	0.0163	Excellent
2003	1.00	0.23	Excellent	2003	0.16	0.051871	Fair
2004	1.48	0.33	Good	2004	0.05	0.016741	Excellent
Overall	1.21	0.27	Excellent	Overall	0.11	0.036786	Good

Table 4 – BRC Data Analysis Values for the UBS Watershed – Beaver Brook

Beaver Brook	JCC						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	0.38	0.09	Excellent	April	0.04	0.01304	Excellent
May	0.59	0.13	Excellent	May	0.06	0.018473	Excellent
June	0.38	0.08	Excellent	June	0.11	0.03586	Good
July	0.32	0.07	Excellent	July	0.18	0.05868	Fair
August	-	-	-	August	-	-	-
September	0.40	0.09	Excellent	September	0.00	0	Excellent
October	0.28	0.06	Excellent	October	0.04	0.01304	Excellent
November	0.09	0.02	Excellent	November	0.03	0.00978	Excellent
1999	0.23	0.05	Excellent	1999	0.10	0.0326	Good
2000	0.19	0.04	Excellent	2000	-	-	-
2001	0.44	0.10	Excellent	2001	0.03	0.00815	Excellent
2002	0.07	0.01	Excellent	2002	0.12	0.03912	Good
2003	0.32	0.07	Excellent	2003	0.03	0.009314	Excellent
2004	0.62	0.14	Excellent	2004	0.19	0.063027	Fair
Overall	0.33	0.08	Excellent	Overall	0.07	0.024269	Excellent
Site							
Beaver Brook	Flagg St						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	0.30	0.07	Excellent	April	0.00	0	Excellent
May	0.20	0.05	Excellent	May	0.00	0	Excellent
June	-	-	-	June	0.14	0.04564	Good
July	0.29	0.07	Excellent	July	0.26	0.08476	Fair
August	-	-	-	August	0.23	0.07498	Fair
September	-	-	-	September	-	-	Poor
October	-	-	-	October	0.16	0.05216	Fair
November	-	-	-	November	0.09	0.02934	Good
1999	-	-	-	1999	0.14	0.04564	Good
2000	-	-	-	2000	-	-	Poor
2001	-	-	-	2001	0.24	0.07824	Fair
2002	-	-	-	2002	0.07	0.02282	Excellent
2003	0.26	0.06	Excellent	2003	0.11	0.036947	Good
2004	-	-	-	2004	-	-	Poor
Overall	0.26	0.06	Excellent	Overall	0.13	0.041945	Good
Site							
Beaver Brook	Maywood						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	1.23	0.28	Excellent	April	0.25	0.082059	Fair
May	1.23	0.28	Excellent	May	0.46	0.148873	Poor
June	1.03	0.23	Excellent	June	0.07	0.022678	Excellent
July	1.68	0.38	Good	July	0.16	0.050919	Fair
August	0.53	0.12	Excellent	August	0.05	0.017007	Excellent
September	1.85	0.42	Good	September	0.06	0.020196	Excellent
October	-	-	-	October	0.13	0.04238	Good
November	-	-	-	November	0.04	0.01304	Excellent
1999	-	-	-	1999	-	-	-
2000	-	-	-	2000	-	-	-
2001	-	-	-	2001	0.10	0.0326	Good
2002	-	-	-	2002	0.34	0.11084	Poor
2003	1.10	0.25	Excellent	2003	0.27	0.086882	Fair
2004	1.52	0.34	Good	2004	0.13	0.04075	Good
Overall	1.27	0.29	Excellent	Overall	0.20	0.063781	Fair

Site							
Beaver Brook	Park Ave						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	0.92	0.21	Excellent	April	0.13	0.043293	Good
May	2.09	0.47	Good	May	0.13	0.04238	Good
June	1.04	0.24	Excellent	June	0.17	0.05542	Fair
July	0.68	0.15	Excellent	July	0.13	0.043467	Good
August	0.62	0.14	Excellent	August	0.13	0.04238	Good
September	0.07	0.01	Excellent	September	0.20	0.0652	Fair
October	1.15	0.26	Excellent	October	0.13	0.043339	Good
November	-	-	-	November	0.17	0.055886	Fair
1999	-	-	-	1999	0.14	0.04564	Good
2000	-	-	-	2000	-	-	-
2001	0.52	0.12	Excellent	2001	0.17	0.05379	Fair
2002	-	-	-	2002	-	-	-
2003	0.83	0.19	Excellent	2003	0.06	0.020016	Excellent
2004	1.48	0.33	Good	2004	0.16	0.05216	Fair
Overall	0.86	0.19	Excellent	Overall	0.15	0.048696	Good

Table 5 – BRC Data Analysis Values for the UBS Watershed – Kettle Brook

Kettle Brook	James St						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	1.15	0.26	Excellent	April	0.18	0.058028	Fair
May	0.10	0.02	Excellent	May	0.14	0.046455	Good
June	0.02	0.00	Excellent	June	0.19	0.060636	Fair
July	0.17	0.04	Excellent	July	0.18	0.057376	Fair
August	0.13	0.03	Excellent	August	0.06	0.01956	Excellent
September	1.20	0.27	Excellent	September	0.18	0.05868	Fair
October	-	-	-	October	0.12	0.039772	Good
November	-	-	-	November	0.27	0.08802	Fair
1999	-	-	-	1999	-	-	-
2000	-	-	-	2000	0.10	0.0326	Good
2001	-	-	-	2001	0.28	0.08965	Fair
2002	-	-	-	2002	0.3	0.08802	Fair
2003	0.09	0.02	Excellent	2003	0.11	0.036419	Good
2004	0.38	0.08	Excellent	2004	0.16	0.052975	Fair
Overall	0.25	0.06	Excellent	Overall	0.17	0.053855	Fair
Site							
Kettle Brook	Dark Brook/ Aubrun High						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	3.00	0.68	Fair	April	0.10	0.0326	Good
May	0.20	0.05	Excellent	May	0.08	0.02608	Good
June	0.20	0.05	Excellent	June	0.11	0.03586	Good
July	0.10	0.02	Excellent	July	0.12	0.03912	Good
August	0.00	0.00	Excellent	August	0.19	0.06194	Fair
September	0.23	0.05	Excellent	September	0.13	0.04238	Good
October	0.40	0.09	Excellent	October	0.09	0.02934	Good
November	0.30	0.07	Excellent	November	0.21	0.06846	Fair
1999	-	-	-	1999	-	-	-
2000	-	-	-	2000	-	-	-
2001	-	-	-	2001	-	-	-
2002	-	-	-	2002	-	-	-
2003	-	-	-	2003	-	-	-
2004	0.55	0.13	Excellent	2004	0.13	0.041973	Good
Overall	0.55	0.13	Excellent	Overall	0.13	0.041973	Good

Site							
Kettle Brook	Leesville In						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	2.70	0.61	Fair	April	0.25	0.0815	Fair
May	0.12	0.03	Excellent	May	0.16	0.05053	Fair
June	0.01	0.00	Excellent	June	0.18	0.05868	Fair
July	52.51	11.87	Poor	July	0.19	0.06194	Fair
August	0.00	0.00	Excellent	August	0.70	0.22657	Poor
September	0.02	0.00	Excellent	September	0.16	0.05216	Fair
October	0.01	0.00	Excellent	October	0.30	0.0978	Fair
November	-	-	-	November	-	-	-
1999	-	-	-	1999	-	-	-
2000	-	-	-	2000	-	-	-
2001	-	-	-	2001	0.47	0.152133	Poor
2002	-	-	-	2002	-	-	-
2003	0.02	0.01	Excellent	2003	0.16	0.05216	Fair
2004	0.48	0.11	Excellent	2004	0.33	0.10595	Poor
Overall	0.27	0.06	Excellent	Overall	0.30	0.096636	Fair
Site							
Kettle Brook	Leesville Out						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	2.70	0.61	Fair	April	0.21	0.06846	Fair
May	0.06	0.01	Excellent	May	0.12	0.03912	Good
June	0.01	0.00	Excellent	June	0.20	0.06357	Fair
July	0.01	0.00	Excellent	July	0.18	0.05868	Fair
August	0.00	0.00	Excellent	August	0.18	0.05705	Fair
September	0.02	0.00	Excellent	September	0.12	0.03912	Good
October	0.11	0.02	Excellent	October	0.09	0.029992	Good
November	-	-	-	November	-	-	-
1999	-	-	-	1999	0.07	0.023907	Excellent
2000	-	-	-	2000	-	-	-
2001	-	-	-	2001	0.26	0.083945	Fair
2002	-	-	-	2002	-	-	-
2003	0.02	0.00	Excellent	2003	0.12	0.037816	Good
2004	0.50	0.11	Excellent	2004	0.15	0.04727	Good
Overall	0.28	0.06	Excellent	Overall	0.15	0.0489	Good

Table 6 – BRC Data Analysis Values for the UBS Watershed – Middle River

Middle River	St Johns Cem						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	2.00	0.45	Good	April	0.24	0.07661	Fair
May	0.30	0.07	Excellent	May	0.11	0.03423	Good
June	0.20	0.05	Excellent	June	0.11	0.03423	Good
July	0.10	0.02	Excellent	July	0.26	0.08313	Fair
August	0.30	0.07	Excellent	August	0.06	0.01956	Excellent
September	0.10	0.02	Excellent	September	0.30	0.0978	Fair
October	0.40	0.09	Excellent	October	0.18	0.05868	Fair
November	0.40	0.09	Excellent	November	0.36	0.11736	Poor
1999	-	-	-	1999	-	-	-
2000	-	-	-	2000	-	-	-
2001	-	-	-	2001	0.11	0.03586	Good
2002	-	-	-	2002	0.03	0.00978	Excellent
2003	-	-	-	2003	-	-	-
2004	0.48	0.11	Excellent	2004	0.28	0.090058	Fair
Overall	0.48	0.11	Excellent	Overall	0.20	0.0652	Fair
Site							
Middle River	Millbury St						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	-	-	-	April	0.12	0.03912	Good
May	-	-	-	May	0.24	0.07824	Fair
June	-	-	-	June	-	-	-
July	-	-	-	July	0.16	0.05216	Fair
August	-	-	-	August	-	-	-
September	-	-	-	September	0.10	0.0326	Good
October	-	-	-	October	-	-	-
November	-	-	-	November	-	-	-
1999	-	-	-	1999	-	-	-
2000	-	-	-	2000	-	-	-
2001	-	-	-	2001	0.13	0.04238	Good
2002	-	-	-	2002	0.18	0.05868	Fair
2003	-	-	-	2003	-	-	-
2004	-	-	-	2004	-	-	-
Overall	-	-	-	Overall	0.16	0.05053	Fair

Table 7 – BRC Data Analysis Values for the UBS Watershed – Middle River

Mill Brook	Salisbury Pond East						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	2.00	0.45	Good	April	0.25	0.083087	Fair
May	1.47	0.33	Good	May	0.30	0.097177	Fair
June	0.66	0.15	Excellent	June	0.25	0.080632	Fair
July	1.13	0.26	Excellent	July	0.10	0.033911	Good
August	0.85	0.19	Excellent	August	0.46	0.14928	Poor
September	0.70	0.16	Excellent	September	0.26	0.083307	Fair
October	0.81	0.18	Excellent	October	0.44	0.14344	Poor
November	-	-	-	November	0.32	0.10432	Poor
1999	-	-	-	1999	0.51	0.166912	Poor
2000	-	-	-	2000	0.41	0.132573	Poor
2001	-	-	-	2001	0.26	0.08476	Fair
2002	-	-	-	2002	0.3	0.109536	Poor
2003	1.48	0.33	Good	2003	0.19	0.061532	Fair
2004	1.01	0.23	Excellent	2004	0.26	0.08476	Fair
Overall	1.28	0.29	Excellent	Overall	0.30	0.098555	Fair
Site							
Mill Brook	Salisbury Pond West						
Month	NO3	NO3 as N	Impairment Status - N	Month	PO4	PO4 as P	Impairment Status - P
	mg/L	mg/L			mg/L	mg/L	
April	1.70	0.38	Good	April	0.11	0.034299	Good
May	3.67	0.83	Fair	May	0.28	0.09265	Fair
June	0.61	0.14	Excellent	June	0.11	0.036923	Good
July	0.74	0.17	Excellent	July	0.19	0.063269	Fair
August	0.77	0.17	Excellent	August	0.34	0.1123	Poor
September	0.72	0.16	Excellent	September	0.18	0.058184	Fair
October	0.98	0.22	Excellent	October	0.48	0.157411	Poor
November	-	-	-	November	0.28	0.09128	Fair
1999	-	-	-	1999	0.43	0.14018	Poor
2000	-	-	-	2000	0.41	0.13366	Poor
2001	-	-	-	2001	0.22	0.071313	Fair
2002	-	-	-	2002	0.4	0.126488	Poor
2003	1.65	0.37	Good	2003	0.06	0.020786	Excellent
2004	1.09	0.25	Excellent	2004	0.13	0.043311	Good
Overall	1.40	0.32	Good	Overall	0.25	0.081372	Fair

**Appendix B: Details on the Nutrient Export Coefficients provided by Brian Brodeur
of the MADEP**

ArcView scripts were developed by Brian Brodeur of the MADEP in order to estimate NPS loadings and percent imperviousness values from watersheds with varying land use classifications.

The background for the NPS loading estimate script is provided below.

NPS Background

The model is based on the Watershed Management Model developed by Camp Dresser & McKee, who in turn draw very heavily on the EPA's Urban Runoff Program. The calculations are based on a "event mean concentration" for each contaminant multiplied by a volume of water to get yearly load. The EMCs come from the EPA and CDM. The volume of water is the depth of rain {assumed to be 42 inches} times the area of each land use, times a percentage of runoff calculated as $0.8 * \text{the impervious fraction of a land use} + 0.2 * \text{the pervious fraction of the land use}$. So basically runoff ranges from 20% for completely pervious areas to 80% for completely impervious. Of course there is a constant thrown in to make the units work out. That is the theoretical basis anyway.

If you look at the script however, rather than do all those calculations over and over the results were reduced to a loading in terms of pounds per acre per year which were more readily comparable with other studies. These loading rates are stored in data dictionaries with the land use code the dictionary key and the loading rate the corresponding value. So the calculation in the script is the loading rate times the area for that land use which is also stored in a dictionary keyed on land use code.

The background for the percent imperviousness estimations script is provided below.

A % imperviousness is assigned to each of the 21 land use codes used by MassGIS. Values were originally based on literature and revised by B. Brodeur based on interpretation of half meter ortho photos for the imperviousness of the area under landuse polygons. Further work with a larger number of polygons from diverse areas of the state would be a good means of refining these estimates.

Appendix C: Q-C Relationship Plots for the Blackstone River, the Quinsigamond River and the Branch River

The following plots were generated using the available data at each monitoring location to develop the Q-C relationship equations. The plots that are not labeled as final are the plots generated using all of the available data with no adjustments. The concentration values were plotted against both the mean daily value for flow at the stream gauge (Q_{mdv}) as well as being plotted against the instantaneous flow value recorded at the time of sampling. The plots labeled as final have been adjusted to remove flow or concentration values that were more than two standard deviations away from the average. The adjusted finalized plots were those used to develop the final Q-C relationship equations for each river.

Figure 2 - P vs. Q – Blackstone River at Manville

Figure 3 - N vs. Q - Blackstone River at Manville

Figure 4 – Adjusted P vs. Q - Blackstone River at Manville

Figure 5 – Adjusted N vs. Q - Blackstone River at Manville

Figure 6 – P vs. Q – Taunton River at Bridgewater

Figure 7 – N vs. Q – Taunton River at Bridgewater

Figure 8 – Adjusted P vs. Q – Taunton River at Bridgewater

Figure 9 – Adjusted N vs. Q – Taunton River at Bridgewater

Figure 10 – P vs. Q – Pawtuxet River at Cranston

Figure 11 – N vs. Q – Pawtuxet River at Cranston

Figure 12 – Adjusted P vs. Q – Pawtuxet River at Cranston

Figure 13 – Adjusted N vs. Q – Pawtuxet River at Cranston

It is seen in the plots above that the adjustment performed produces a better fitting best fit line. This is especially evident in the difference between the original and adjusted equations for the Taunton River.

Appendix D: BRI Background and Data Analysis

Table of Contents

Background (Wright et al, 2001)	1
Dry Weather Water Quality Surveys	2
Wet Weather Water Quality Surveys	4
Objectives	5
Procedure	5
Dry Weather Survey Loading Calculation	6
Wet Weather Loading Analysis	7
Source/Sink Identification Analysis	8
Assimilative Capacity Analysis	8
Results and Discussion - Dry Weather Loading Analysis	9
Dry Weather Flow Survey	9
Loading Profile Analysis	11
PO ₄ Dry Weather Loading Profiles	13
NO ₃ Dry Weather Loading Profiles	16
NH ₃ Dry Weather Loading Profiles	19
Dissolved Oxygen Dry Weather Concentration Profiles	22
Biological Oxygen Demand Dry Weather Concentration Profiles	24
Results and Discussion - Wet Weather Loading Analysis	26
Wet Weather Flow Survey	26
PO ₄ Wet Weather Loading Profiles	28
NO ₂ and NO ₃ Wet Weather Loading Profiles	31
NH ₃ Wet Weather Loading Profiles	35
Dissolved Oxygen Wet Weather Concentration Profiles	38
Biological Oxygen Demand Wet Weather Concentration Profiles	39
Fecal Coliform Wet Weather Concentration Profiles	42
E Coli Wet Weather Concentration Profiles	43
Results and Discussion – Dry Weather vs. Wet Weather	46
Flow Regimes	46
PO ₄ Loading	46
NO ₃ Loading	47
NH ₃ Loading	47
Dissolved Oxygen Concentrations	48
Biological Oxygen Demand Concentrations	48

List of Figures

Figure 1 - BRI Wet and Dry Weather Survey Monitoring Locations	3
Figure 2 - WWTP and Tributary Identifications and Locations	12
Figure 3 - BRI Dry Weather PO ₄ Loading July	13
Figure 4 - BRI Dry Weather PO ₄ Loading August	14
Figure 5 - BRI Dry Weather PO ₄ Loading October	14
Figure 6 - BRI Dry Weather NO ₃ Loading July	17

Figure 7 - BRI Dry Weather NO ₃ Loading August	17
Figure 8 - BRI Dry Weather NO ₃ Loading October.....	18
Figure 9 - BRI Dry Weather NH ₃ Loading July	20
Figure 10 - BRI Dry Weather NH ₃ Loading August	20
Figure 11 - BRI Dry Weather NH ₃ Loading October.....	21
Figure 12 - BRI Dry Weather DO Concentrations July	22
Figure 13 - BRI Dry Weather DO Concentrations August.....	23
Figure 14 - BRI Dry Weather DO Concentrations October	23
Figure 15 - BRI Dry Weather BOD Concentrations July.....	24
Figure 16 - BRI Dry Weather BOD Concentrations August.....	25
Figure 17 - BRI Dry Weather BOD Concentrations October.....	25
Figure 18 - BRI Wet Weather PO ₄ Loading Storm I.....	29
Figure 19 - BRI Wet Weather PO ₄ Loading Storm II	29
Figure 20 - BRI Wet Weather PO ₄ Loading Storm III	30
Figure 21 - BRI Wet Weather NO ₂ and NO ₃ Loading Storm I.....	32
Figure 22 - BRI Wet Weather NO ₂ and NO ₃ Loading Storm II.....	33
Figure 23 - BRI Wet Weather NO ₂ and NO ₃ Loading Storm III.....	33
Figure 24 - BRI Wet Weather NH ₃ Loading Storm I	35
Figure 25 - BRI Wet Weather NH ₃ Loading Storm II	35
Figure 26 - BRI Wet Weather NH ₃ Loading Storm III.....	36
Figure 27 - BRI Wet Weather DO Concentrations Storm I.....	38
Figure 28 - BRI Wet Weather DO Concentrations Storm II	39
Figure 29 - BRI Wet Weather DO Concentrations Storm III	39
Figure 30 - BRI Wet Weather BOD Concentrations Storm I	40
Figure 31 - BRI Wet Weather BOD Concentrations Storm II.....	40
Figure 32 - BRI Wet Weather BOD Concentrations Storm III.....	41
Figure 33 - BRI Wet Weather Fecal Coliform Concentrations Storm I	42
Figure 34 - BRI Wet Weather Fecal Coliform Concentrations Storm II.....	43
Figure 35 - BRI Wet Weather Fecal Coliform Concentrations Storm III.....	43
Figure 36 - BRI Wet Weather E Coli Concentrations Storm I	44
Figure 37 - BRI Wet Weather E Coli Concentrations Storm II.....	45
Figure 38 - BRI Wet Weather E Coli Concentrations Storm III.....	45

List of Tables

Table 1 - BRI Dry and Wet Weather Survey Monitoring Location Site Descriptions and Associated Rivermiles	4
Table 2 - Locations of WWTP's, Dams and Tributary Confluences along the Mainstem of the Blackstone River.....	6
Table 3 - Estimated Flows for the BRI Dry Weather Water Quality Surveys.....	10
Table 4 - Loading Matrix for the BRI Dry Weather PO ₄ Loading.....	15
Table 5 - BRI Dry Weather PO ₄ Loading Values.....	16
Table 6 - Loading Matrix for the BRI Dry Weather NO ₃ Loading	16
Table 7 - BRI Dry Weather NO ₃ Loading Values	18
Table 8 - Loading Matrix for the BRI Dry Weather NH ₃ Loading	19
Table 9 - BRI Dry Weather NH ₃ Loading Values.....	21

Table 10 – Time Weighted Average Flows for the BRI Wet Weather Water Quality Surveys	27
Table 11 - Loading Matrix for the BRI Wet Weather PO ₄ Loading	30
Table 12 - BRI Wet Weather PO ₄ Loading Values	31
Table 13 - Loading Matrix for the BRI Wet Weather NO ₂ and NO ₃ Loading.....	33
Table 14 - BRI Wet Weather NO ₂ and NO ₃ Loading Values.....	34
Table 11 - Loading Matrix for the BRI Wet Weather NH ₃ Loading.....	36
Table 15 - BRI Wet Weather NH ₃ Loading Values	37

Background (Wright et al, 2001)

The Blackstone River Initiative (BRI) was a multi-state, multi-agency project aimed at monitoring and modeling the water and sediment quality of the Blackstone River. Conducted in 1991 and published in 2001, the BRI consisted of three dry weather water quality surveys as well as three wet weather water quality surveys. Each survey monitored the water quality along the mainstem of the Blackstone River, its major tributaries and the major point source dischargers to the river.

While numerous water quality studies had been conducted on the Blackstone prior to the BRI, these earlier studies focused individually on particular questions and/or river segments within the watershed. In addition, because they occurred under varying conditions, including flows, seasons and times, inter-comparison between the studies was problematic. Recognizing the importance of the Blackstone River in terms of its cultural heritage, recreational potential and impacts on Narragansett Bay, the commissioners of the Massachusetts Department of Environmental Protection (DEP) and the Rhode Island Department of Environmental Management (DEM) asked the EPA to organize a comprehensive study of the river as an integrated system. The resulting study was the BRI monitoring and modeling effort.

The goals of the BRI were multi-fold. The study was aimed at quantifying the wet and dry weather loadings into the Blackstone, both PS and NPS. Additionally, they were examining the ecological health of the river from more than just a loading stand point. Investigations into the toxicology and the dissolved oxygen dynamics were also of importance. Ultimately the data from the model was used to develop a dissolved oxygen and trace metals model for the Blackstone River.

Prior to the publication of the report in 2001, the EPA Science Advisory Board (SAB) reviewed the efforts undertaken in the BRI. While the SAB commended the effort put forth by the BRI, especially the volunteer efforts utilized in the wet weather monitoring, they did site several limitations of the study. The authors of the report state that most of

the questions that were posed by the SAB have been addressed in the finalized report in 2001.

The current interest in the data is to examine the loading behaviors seen in the river, most notably the pollutant loadings and their propagation to downstream reaches. The BRI study is still considered to be state of the art, both in its collection techniques and modeling efforts. However, significant development has occurred in the 15 years since it was completed. One goal of the current study is to compare the loading behaviors demonstrated in the 1991 study to the loading behaviors determined during the current UMass study to determine the effect of the increased development. In addition, new water quality goals have been set for the river since the BRI as well as changes in PS and NPS loading dynamics, most notably significant decreases in point source loadings since 1991. It is expected that newer, more powerful and enable better comparisons of PS and NPS loadings under varying conditions and over longer periods of time.

Despite the age of the data collected during the BRI, the data is still of interest today. The data will be used not only for loading behavior analysis contained herein, but for calibrating and validation water quality model, examining potential sources and sinks of contaminants and investigating critical hydrologic and atmospheric hypotheses about the river and the watershed as a whole.

Dry Weather Water Quality Surveys

The dry weather water quality characterization of the Blackstone River consisted of three 48hr surveys conducted on July 10-11, 1991, August 14-15, 1991 and October 2-3, 1991. The locations of the monitoring stations within the Blackstone watershed can be seen on Figure 14 below. During the dry weather surveys, there were fifteen monitoring stations along the mainstem of the Blackstone and six monitoring stations at the outlets of the major tributaries to the river.

Table 8 includes site descriptions, the associated river mile for each and the labeling designation used during the dry and wet weather surveys.

Figure 14 - BRI Wet and Dry Weather Survey Monitoring Locations

Table 8 - BRI Dry and Wet Weather Survey Monitoring Location Site Descriptions and Associated Rivermiles

Dry Weather	Wet Weather	Rivermile	Description
	BWW00	46.0	Greenwood St, Worcester
BLK01	BWW01	45.8	Millbury St, Worcester
BLK02	BWW02	44.0	McCracken Rd, Millbury
BLK03		41.4	Riverlin St, Millbury
BLK04	BWW04	39.8	Blackstone St (Singing Dam), Sutton
BLK05	BWW05S	36.6	Millbury St, Grafton
BLK06	BWW06	35.7	Route 122A, Grafton
BLK07	BWW07	32.0	Riverdale St, Northbridge
BLK08	BWW08	27.8	Hartford St (Rice City pond Dam), Uxbridge
BLK09	BWW09	25.6	Mendon St (Rt 16), Uxbridge
BLK10	BWW10S	25.0	Centerville (Off Rt 16), Uxbridge
BLK11	BWW11	23.2	Rt 122 Bridge, Uxbridge
BLK12		20.5	Route 122 (nr USGS gauge), Millville
BLK14	BWW14	17.4	Route 146A, Slatersville
BLK13	BWW13	16.6	Bridge St (State Line), Blackstone
BLK15	BWW15S	13.4	Winter St, Woonsocket
BLK16	BWW16	13.3	Route 114, Woonsocket
BLK17	BWW17	12.8	Hamlet Ave Dam (Rt 122 & 126), Woonsocket
BLK18	BWW18	10.0	Manville Hill Rd, Cumberland
BLK19		9.4	School St/Albion Rd, Cumberland
BLK20	BWW20	3.8	Lonsdale Ave, Pawtucket
BLK21	BWW21	0.1	Main St (Slater's Mill), Pawtucket

Wet Weather Water Quality Surveys

The wet weather water quality characterization of the Blackstone River consisted of three storm oriented surveys referred to here as Storm I, Storm II and Storm III. The survey for Storm I was conducted from September 22-24, 1992; the survey for Storm II was conducted from November 2-5, 1992; and the survey for Storm III was conducted from October 12-14, 1993. The locations of the monitoring stations within the Blackstone watershed are shown on Figure 14. During the wet weather surveys there were thirteen monitoring stations along the mainstem of the Blackstone and six monitoring stations at the outlets of the major tributaries to the river. Site descriptions, the associated river mile and the labeling designation used during the wet and dry weather surveys are shown in Table 8.

Objectives

The water quality data collected during the BRI was initially used to produce a comprehensive profile of water quality within the Blackstone River during wet and dry flow regimes using concentrations of pollutants as a basis (Wright *et al*, 2001). While the analysis of the water quality profiles has proven useful, the data can be utilized differently than originally planned.

This study analyzes the data collected during the BRI on a pollutant loading basis. By analyzing the contaminants on a loading basis, one can not only identify sources and sinks of pollutants within the river system, but calculate the assimilative capacity of the river under various flow regimes as well.

Procedure

In order to identify sources and sinks of pollutants along the Blackstone River, pollutant loading for each monitoring station was calculated based on the BRI dry and wet weather data. The BRI monitoring scheme was designed to isolate known potential sources/sinks of pollution. Potential sources and sinks of pollution in the Blackstone include, but are not limited to, wastewater treatment plants (WWTPs), impoundments and stormwater runoff. WWTP discharges to the Blackstone have long been held accountable for the water quality problems within the river and were therefore monitored during the BRI as potential point sources of pollutants. Sedimentation and resuspension of materials behind river impoundments had been previously identified as a potential source and or sink for several pollutants (citation) and monitoring locations were established upstream and downstream of major impoundments along the mainstem of the river. Stormwater runoff was only directly monitored from the Worcester CSO facility during the BRI; no sampling of flowing storm sewers in the watershed was conducted. It should be noted that stormwater runoff can be a major pollutant source to a river during heavy rainfalls

(citation). Another potential source of pollution to the mainstem of the Blackstone River is the tributaries which were monitored during the BRI as described above. Table 9 shows the known WWTPs, dams and the confluences of the major tributaries along the Blackstone River by river mile. The outlet of the Blackstone is classified as river mile zero, increasing as you travel upstream.

Table 9 - Locations of WWTPs, Dams and Tributary Confluences along the Mainstem of the Blackstone River

River mile	Description	River mile	Description
44.4	UBWPAD	22.0	Uxbridge WWTP
43.9	McCracken Rd Dam	17.8	Tupperware Dam
41.0	Millbury Electric Dam	17.4	Confl. of Branch Riv.
40.6	Millbury WWTP*	16.5	Blackstone Dam
39.8	Singing Dam	15.5	Thundermist Hydro Dam
39.2	Wilkinsonville Dam	13.4	Confl. of Mill Riv.
38.7	Saundersville Dam	13.3	Confl. of Peters Riv.
36.6	Confl. of Quinsigamond Riv.	12.8	Hamlet Ave Dam
36.5	Fisherville Dam	12.4	Woonsocket WWTP
35.6	Farnumsville Hydro Dam	9.9	Manville Dam
35.4	Grafton WWTP	8.2	Albion Dam
31.9	Riverdale Hydro Dam	6.8	Ashton Dam
29.2	Northbridge WWTP	4.1	Lonsdale Dam
27.8	Rice City Pond Dam	2.0	Central Falls Dam
25.6	Confl. of Mumford Riv.	0.8	Pawtucket Hydro Dam
25.0	Confl. of West Riv.	0.0	Slater's Mill Dam

*-Millbury WWTP was connected to the UBWPAD discharge in 2004

Dry Weather Survey Loading Calculation

The loads for each station monitored during the dry weather surveys were calculated using Equation 1 where Q is average daily flow (cfs) estimated for the monitoring location, C_{ave} is the pollutant concentration (mg/L), and L is the resulting load (kg/day). Typically, that average concentration was calculated using 4 samples taken over the course of the day. If any of the samples taken during the day were more than one

standard deviation away from the initial calculated average they were removed from the final average concentration calculation.

$$L = 2.45QC_{ave} \quad (1)$$

The estimated flows and concentrations were assumed to be constant over the day thus facilitating an estimation of a daily load. The estimation of a daily load provides a snapshot of the water quality in time of the water quality in the river.

Wet Weather Loading Analysis

The loads for each station monitored during the wet weather surveys were calculated using Equations 2 and 3.

$$L = 2.45 \sum_{i=1}^n \left[C_{fwmc} (T_{i+1} - T_i) \left(\frac{Q_{i+1} + Q_i}{2} \right) \right] \quad (2)$$

$$C_{fwmc} = \frac{\sum_{i=1}^n (Q_i C_i)}{\sum_{i=1}^n Q_i} \quad (3)$$

where C_i is the concentration observed for a given sample (mg/L), Q_i is the flow observed while the sample is being collected (cfs), $(T_{i+1} - T_i)$ is the duration between that sample and the next (in days), C_{fwmc} is the flow weighted mean concentration observed at the station over the course of the event (mg/L) and L is the total load observed at the monitoring location for that storm event (kg). Comparison of the total event load observed at each station during an event with an adjacent station is an acceptable way to compare the loads due to similar event durations among the stations. Inter-storm loading comparisons however, need to be adjusted due to storm duration differences.

Source/Sink Identification Analysis

A loading comparison between consecutive stations was conducted using Equation 4 to determine the locations of pollutant sources and sinks along the mainstem of the river.

$$L_d = L_2 - L_1 \quad (4)$$

L_1 is the load observed at the upstream location (kg or kg/day), L_2 is the load observed at the downstream location (kg or kg/day) and L_d is the difference between them (kg or kg/day). A positive value of L_d is representative of a gain in loading between the two stations. A negative value is representative of a loss in loading between the two stations, indicating a sink in that reach of the river. It should be noted that due to a smaller number of monitoring stations, the pollutant source/sink analysis is less refined for wet weather events than dry weather events.

Assimilative Capacity Analysis

The assimilative capacity of the river was calculated using Equation 5. The assimilative capacity reported here is on a percentage basis, unlike typical assimilative capacities.

$$AC = 100 \left(1 - \frac{L_{out} - L_{up}}{\sum L_{Gains}} \right) \quad (5)$$

L_{out} is the load that is observed at the outlet of the river, L_{up} is the load observed at the uppermost monitoring station and L_{Gains} are the gains in loading seen between stations (positive values of L_d as described above). The summation of all of the gains in loadings represents the total amount of pollutant that the river is subject to, while the difference in load between the headwaters and the outlet represents how much of the total pollutant loading

the river could not assimilate. The lower the percentage of the total loadings that leave the river, the more assimilative capacity the river is considered to have. In the case where no assimilation occurs, the difference between the loads seen at the top of the watershed and the load seen at the outlet ($L_{out}-L_{up}$), would be equivalent to the summation of the gains seen along the river, resulting in an assimilative capacity of 0%.

Results and Discussion - Dry Weather Loading Analysis

Dry Weather Flow Survey

As previously stated, flows for the BRI dry weather survey stations were estimated based on observed flow at gauged stations within the watershed. These flow estimates, as well as the observed flows for the WWTPs that discharge to the mainstem of the Blackstone are provided in Table 10 below.

Table 10 – Estimated Flows for the BRI Dry Weather Water Quality Surveys

	7/10-11/91	8/14-15/91	10/2-3/91
Station	Flow (cfs)	Flow (cfs)	Flow (cfs)
BLK01	13.8	14.3	71.2
BLK02	53.4	60.2	145.0
BLK03	55.7	62.7	163.0
BLK04	57.4	64.7	173.0
BLK05	9.0	10.4	65.0
BLK06	69.3	78.2	260.0
BLK07	72.2	81.2	271.0
BLK08	75.1	83.5	281.0
BLK09	13.5	14.4	103.0
BLK10	7.4	7.9	56.5
BLK11	96.5	106.0	445.0
BLK12	102.0	112.0	460.0
BLK13	129.0	144.0	576.0
BLK14	26.4	30.9	107.0
BLK15	4.5	4.8	34.7
BLK16	2.3	2.4	17.5
BLK17	140.0	156.0	659.0
BLK18	151.0	170.0	691.0
BLK19	152.0	171.0	698.0
BLK20	154.0	172.0	711.0
BLK21	158.0	177.0	746.0
UBWPAD Final	38.4	44.6	64.7
Millbury WWTF	0.6	0.8	1.3
Grafton WWTF	1.6	1.6	1.6
Nbridge WWTF	1.8	1.2	1.8
Uxbridge WWTF	3.9	3.9	3.9
Woonsocket WWTF Final	8.3	11.5	13.4

Flows estimated for both the July and August dry weather BRI events are similar in magnitude while those estimated for the October event were approximately 2.5 times higher. While the difference in the flows observed at the WWTPs is not as significant as the differences in flows seen in the river, an increase in flows was observed during the October event over the July and August events. The increased rivers flows for October can be attributed to a number of factors including increased groundwater recharge during the fall when compared to the summer months or a decrease in the amount of water lost to evapotranspiration from summer to fall.

Loading Profile Analysis

When examining the figures in the subsequent analyses, the following methodologies should be followed. The vertical bars represent the load difference L_d between that station and the station immediately upstream. A positive bar value thus indicates a source between the two stations, while a negative vertical bar value indicates a sink between the two stations. The locations and loads of the tributaries and the WWTPs are marked by the diamonds while the dam locations are denoted by a triangle and a vertical dashed line. It should be noted that for all wet and dry weather loading analyses, only the loadings of the major WWTPs (UBWPAD and Woonsocket) were calculated. The minor WWTPs were not monitored during the survey events and are represented as having a value of zero. They are included in the following charts to indicate their position along the river as well as identify any effects the WWTPs might have on the downstream water quality and loadings. The locations of the tributaries and the WWTPs are outlined in Figure 15. This figure is used solely to denote the locations of the tributaries and WWTPs as they enter the mainstem of the river, this figure is not used for any of the subsequent analyses in this Appendix.

Figure 15 - WWTP and Tributary Identifications and Locations

PO₄ Dry Weather Loading Profiles

Figure 16 - Figure 18 show PO₄ loading profiles for the BRI dry weather water quality surveys conducted in July, August and October respectively. The UBWPAD was the largest point source of PO₄ discharging to the river during all three dry weather surveys. Losses in load between stations during all three dry weather events occurred at Singing Dam (mile 39.8), Rice City Pond (mile 27.8), after the confluence with the Mumford and West Rivers (mile 23.2) and between the Manville and Albion Dams (mile 9.4). Gains in loading were seen downstream of the UBWPAD, Woonsocket WWTP and Uxbridge WWTP. The majority of the losses observed during the three events occurred in Rice City Pond and behind the Riverdale Hydro Dam (mile 31.9), although not during all three events at the Riverdale Hydro Dam. These losses are hypothesized to be due to sedimentation and plant uptake within the slow moving waters behind the dams.

Figure 16 - BRI Dry Weather PO₄ Loading July

Figure 17 - BRI Dry Weather PO₄ Loading August

Figure 18 - BRI Dry Weather PO₄ Loading October

Table 11 shows the resulting loading matrices for the PO₄ loading from the dry weather BRI events. As shown in the table, loadings increased at mile markers 44, 20.5 and 10.0 for all three dry weather events. All of these sites correspond to monitoring locations downstream of UBWPAD, Uxbridge WWTP and Woonsocket WWTP respectively. Losses occurred during all three events at mile markers 39.8, 27.8, 23.2 and 9.4. All of

the sites where losses consistently occurred are located downstream of an impoundment, suggesting losses of PO₄ due to sedimentation.

Table 11 - Loading Matrix for the BRI Dry Weather PO₄ Loading

RiverMile	45.8	44.0	41.4	39.8	35.7	32.0	27.8	23.2	20.5	16.6	12.8	10.0	9.4	3.8	0.1
July	NA	+	+	-	-	+	-	-	+	+	-	+	-	-	+
August	NA	+	-	-	-	-	-	-	+	-	+	+	-	-	-
October	NA	+	+	-	+	-	-	-	+	-	+	+	-	+	-
# of Dams		0	1	2*	3	1	2*	0	0	1	3*	0	1	3	2
# of WWTP's		1	0	1	0	1	1	0	1	0	0	1	0	0	0
Ponds					Fisherville		Rice City								Slater Mill
Tribs					Quin			Mum and West		Branch	Mill and Peters				
					* site located on dam which is included in number of dams between										

Table 12 shows the summation of both the positive and negative loading differences as well as the total loading contributed to the Blackstone by the WWTPs. When comparing the three loading regimes, it can be seen that both the July and August surveys are very similar to one another in terms of gains, losses and WWTP inputs. This is likely due to the similar flow regimes that the river was subject to during these events. Loadings from the October event however are much greater than the other two events, likely due to the larger flow regime the river was subject to in October.

For the July and August events, the WWTP load exceeds the summation of positive differences suggesting that the river is assimilating the PO₄ in some way. In both the July and August surveys, the river assimilates approximately 70 percent of the total PO₄ loading it is subjected to, most likely through sedimentation in low velocity reaches. During the October event however, the summation of positive differences exceeds the WWTP loading to the river indicating other sources of PO₄ are contributing to the system loading. Since the survey was conducted during dry weather, there should be no runoff entering the system, leaving the additional loading to be attributed to resuspension of the sediments trapped behind the impoundments.

Table 12 - BRI Dry Weather PO₄ Loading Values

	July	August	October
	PO ₄ (kg/day)	PO ₄ (kg/day)	PO ₄ (kg/day)
Positive Differences	202.0	254.3	851.7
Negative Differences	-142.0	-192.8	-592.4
Pos+ Neg	60.0	61.6	259.3
WWTP Total	282.6	351.8	610.8
Outlet - Headwaters	60.0	61.6	259.3
Assimilative Capacity	70.3	75.8	69.6

NO₃ Dry Weather Loading Profiles

Table 13 shows the resulting loading matrices for the NO₃ loading from the dry weather BRI events. As shown in the table, loadings increased at mile markers 44, 41.4, 39.8, 32, 20.5, 10.0, 9.4 and 3.8 for all three dry weather events. Losses occurred during all three events at mile markers 23.2.

Table 13 - Loading Matrix for the BRI Dry Weather NO₃ Loading

RiverMile	45.8	44.0	41.4	39.8	35.7	32.0	27.8	23.2	20.5	16.6	12.8	10.0	9.4	3.8	0.1
July	NA	+	+	+	-	+	-	-	+	+	-	+	+	+	+
August	NA	+	+	+	-	+	+	-	+	-	-	+	+	+	-
October	NA	+	+	+	+	+	+	-	+	-	+	+	+	+	-
# of Dams		0	1	2*	3	1	2*	0	0	1	3*	0	1	3	2
# of WWTP's		1	0	1	0	1	1	0	1	0	0	1	0	0	0
Ponds					Fisherville		Rice City								Slater Mill
Tribs					Quin			Mum and West		Branch	Mill and Peters				
* site located on dam which is included in number of dams between															

Figure 19 through Figure 21 show the NO₃ loading profiles for the dry weather water quality surveys conducted in July, August and October respectively. As with the PO₄ loadings, UBWPAD is shown to be the largest point source contributor of NO₃ to the Blackstone River. The gain/loss loading patterns along the river are very similar for all three surveys. Gains in NO₃ are seen after each WWTP as well as after the majority of the dams. It is hypothesized that reaeration over the dams causes other forms of nitrogen in the river to transform into NO₃. A potential sink for the NO₃ loading is uptake by plants and algae.

Figure 19 - BRI Dry Weather NO₃ Loading July

Figure 20 - BRI Dry Weather NO₃ Loading August

Figure 21 - BRI Dry Weather NO₃ Loading October

Table 14 - BRI Dry Weather NO₃ Loading Values

	July	August	October
	NO3 (kg/day)	NO3 (kg/day)	NO3 (kg/day)
Positive Differences	1129.3	1308.7	4790.8
Negative Differences	-426.9	-611.5	-1872.5
Post- Neg	702.4	697.1	2918.2
WWTP Total	627.9	2899.3	1943.7
Outlet - Headwaters	702.4	697.1	2918.2
Assimilative Capacity	37.8	46.7	39.1

The summation of both the positive and negative loading differences as well as the total loading contributed to the Blackstone by the WWTPs is shown in Table 14. When comparing the three loading regimes one can see that in each case, the river assimilated approximately 40 percent of the NO₃ loading it is subjected to. It should also be noted that despite the large differences in WWTP loadings between the July and August events, they each resulted in similar gains over the length of the river as well as similar loads that are discharged by the river into the receiving body. The WWTP loads in the August and October events are exceeded by the summation of positive differences for each event, suggesting an additional source of NO₃ within the river. As shown in the figures above, there are several instances where the loading in the river downstream of a treatment plant is higher than the loading of the treatment plant, also suggesting additional sources of NO₃ in the river.

NH₃ Dry Weather Loading Profiles

Table 15 shows the resulting loading matrices for the NH₃ loading from the dry weather BRI events. Gains in loading are seen after UBWPAD (44), Millbury (39.8) and Woonsocket WWTPs(10) for all three surveys. Losses in NH₃ loading are seen after both Grafton and Northbridge WWTPs as well as between the confluences of the Mill and Peters Rivers and Hamlet Avenue Dam (mile 12.8)

Table 15 - Loading Matrix for the BRI Dry Weather NH₃ Loading

RiverMile	45.8	44.0	41.4	39.8	35.7	32.0	27.8	23.2	20.5	16.6	12.8	10.0	9.4	3.8	0.1
July	NA	+	-	+	-	-	-	-	-	+	-	+	-	-	-
August	NA	+	+	+	+	-	-	+	-	+	-	+	-	-	-
October	NA	+	-	+	+	-	-	-	+	+	-	+	+	-	+
# of Dams		0	1	2*	3	1	2*	0	0	1	3*	0	1	3	2
# of WWTP's		1	0	1	0	1	1	0	1	0	0	1	0	0	0
Ponds					FisherMile		Rice City								Slater Mill
Tribs					Quin			Mum and West		Branch	Mill and Peters				
					* site located on dam which is included in number of dams between										

Figure 22 through Figure 24 show the NH₃ loading profiles for the dry weather water quality surveys conducted in July, August and October respectively. As seen in the figures below, Woonsocket is the largest point source contributor of NH₃ to the Blackstone River. Losses in NH₃ are contributed to the aeration of the water transforming NH₃ to NO₃ over the dams located in the reach that showed a loss in loading.

Figure 22 - BRI Dry Weather NH₃ Loading July

Figure 23 - BRI Dry Weather NH₃ Loading August

Figure 24 - BRI Dry Weather NH₃ Loading October

Table 16 shows the summation of both the positive and negative loading differences as well as the total loading contributed to the Blackstone by the WWTPs. It can be seen that for all three dry weather surveys, positive loadings to the river were approximately the same. While the river assimilates approximately 70 percent of the NH₃ loading during both the July and August events, it can only assimilate approximately 40 percent during the October event. The loss in assimilative capacity between the summer and fall events is most likely caused by the decrease in time that the water spends in the river due to higher flows during the October event. Both the August and October surveys resulted in WWTP loads being less than the positive loads seen by the river suggesting additional sources of NH₃ are located within the basin that are not accounted for in this analysis.

Table 16 - BRI Dry Weather NH₃ Loading Values

	July	August	October
	NH ₃ (kg/day)	NH ₃ (kg/day)	NH ₃ (kg/day)
Positive Differences	432	447	547
Negative Differences	-318	-291	-226
Pos+ Neg	113	155	321
WWTP Total	613	396	407
Outlet - Headwaters	113	155	321
Assimilative Capacity	74	65	41

Dissolved Oxygen Dry Weather Concentration Profiles

The dissolved oxygen (DO) concentration profiles for the dry weather water quality surveys conducted in July, August and October are shown in Figure 25 - Figure 27 respectively. It should be noted that all shown DO values are the average concentrations of the five replicate samples collected at each site over the course of a day during each dry weather survey. The WWTPs do not have DO concentrations because they were not sampled for DO during the dry weather events. They are included in the following figured to show their relative location along the length of the Blackstone as well as to identify any effects the WWTPs may have on the downstream water quality.

Figure 25 - BRI Dry Weather DO Concentrations July

Figure 26 - BRI Dry Weather DO Concentrations August

Figure 27 - BRI Dry Weather DO Concentrations October

As expected, the DO concentrations within the river are generally higher after the water passes over a dam due to aeration. The figures above show that DO concentrations as a whole, were lower during the July and August surveys than in the October survey, likely due to higher water temperatures in the summer months. Also, the lower DO values in the tributaries do significantly affect the DO profile along the mainstem of the river as do the discharges of both UBWPAD and Woonsocket WWTP, for which data were available.

Biological Oxygen Demand Dry Weather Concentration Profiles

Figure 28 - Figure 30 shows the biological oxygen demand (BOD) concentration profiles for the dry weather water quality surveys conducted in July, August and October respectively. It should be noted that all shown BOD values are the average values of the five replicate samples collected over the course of a day during each dry weather survey. No BOD data was recorded for the smaller WWTPs, but they are included in the figures to show their location along the length of the river as well as determine any effects that the small WWTP discharges may have on downstream water quality. Woonsocket had the highest concentration of BOD in its effluent; the tributaries of the Blackstone generally had very low BOD concentrations. The higher concentrations seen in the July survey may be caused by algal bloom and die-off events taking place within the river during the time of the survey.

Figure 28 - BRI Dry Weather BOD Concentrations July

Figure 29 - BRI Dry Weather BOD Concentrations August

Figure 30 - BRI Dry Weather BOD Concentrations October

Results and Discussion - Wet Weather Loading Analysis

Wet Weather Flow Survey

The flow regimes resulting from the three storm surveys can be seen in Table 17 below. The values shown are the time weighted averages of the flow rates observed at each station over the course of the storm events. When comparing the three flow regimes, the influence of the storm characteristics on the resulting flow distributions is evident. Storm I was a short, light rainfall distributed evenly over the entire watershed. Storm II was a long, moderate rainfall that was evenly distributed across the watershed as well. Storm III however, was a short intense rainfall that was concentrated in the northern part of the watershed (Wright et al, 2001).

Table 17 – Time Weighted Average Flows for the BRI Wet Weather Water Quality Surveys

	Storm I	Storm II	Storm III
Station	Flow (cfs)	Flow (cfs)	Flow (cfs)
BWW00	37.7	115.3	151.1
BWW01	40.2	125.3	162.2
BWW02	95.4	175.2	270.1
BWW04	103.9	190.1	296.1
BWW05S	6.2	12.2	21.5
BWW06	110.4	199.9	225.8
BWW07	110.6	212.8	240.3
BWW08	124.5	257.8	274.6
BWW09	11.9	79.0	27.8
BWW10S	8.8	21.9	12.2
BWW11	155.3	362.3	272.0
BWW13	200.3	474.9	330.2
BWW14	41.5	109.3	48.3
BWW15S	12.0	18.5	-
BWW16	5.9	15.3	4.1
BWW17	211.5	498.5	349.4
BWW18	222.9	529.5	346.0
BWW20	244.7	594.1	370.5
BWW21	250.2	636.9	384.6
Worcester CSO	0.0	97.2	246.0
UBWPAD	50.1	51.9	45.0
Woonsocket WWTF	9.5	10.0	9.9

Due to the more intense and longer lasting rainfall distributed over the entire watershed, flows observed during Storm II are higher on all of the mainstem and tributary monitoring locations than those seen during Storm I. The flows observed during Storm III however, are only higher than the flows seen in Storm II upstream of Rice City Pond (BWW08). Downstream of Rice City Pond, flows seen during Storm III are less than those seen during Storm II. This behavior is caused by the intense, concentrated rainfall that fell in the headwaters of the basin during Storm III. The discrepancy in rainfall distributions between Storm III and the other storm events is further exemplified when comparing the flows observed at the Worcester combined sewer overflow facility (CSO). During the short, light rainfall of Storm I, the CSO did not discharge. Under the long, moderate rainfall of Storm II the CSO discharged at a rate of 97 cfs. The intense rainfall of Storm III which was concentrated in the Worcester area resulted in a CSO discharge that was approximately 2.5 times the discharge resulting from Storm II.

PO₄ Wet Weather Loading Profiles

Figure 31 - Figure 33 show the PO₄ loading profiles for the wet weather water quality surveys Storm I, Storm II and Storm III respectively. The vertical bars represent the load difference between that station and the station immediately upstream of it. A positive bar value indicates a source between the two stations, while a negative vertical bar value indicated a sink between the two stations. The locations and loads of the tributaries and the WWTPs are marked by diamonds while the dam locations are denoted by a triangle and a vertical dashed line. It should be noted that for all wet weather loading analyses, only the loadings of the major WWTPs (UBWPAD and Woonsocket) were monitored and calculated. The minor WWTPs were not monitored during the survey events and are represented as having a value of zero. They are included in the following charts to indicate their position along the river as well as identify and effects the WWTPs might have on the downstream water quality and loadings.

While the wet weather loading analysis was conducted in the same manor as the dry weather analysis, there are differences between the two. As shown in Table 17, there are fewer wet weather stations than dry weather monitoring stations. Station BWW00 was added to isolate the Worcester CSO discharge from other upstream sources. Monitoring stations corresponding to BLK03, BLK12 and BLK 19 were cut out of the wet weather monitoring for budgetary reasons. The loss of these three stations causes the segmentation of the river to be less defined than in the dry weather surveys, but an accurate loading analysis can still be conducted on the data.

As in the dry weather loading analyses, UBWPAD is the largest known point source contributor of PO₄ to the Blackstone River under wet weather conditions. The loads discharged to the Blackstone via its tributaries are minor when compared to the point source loadings of UBWPAD and Woonsocket WWTP. For all three storm events, losses were seen at Fisherville Pond, downstream of the confluences of the Mumford and West Rivers and upstream of the Slater Mill Dam (mile 0.1). It is thought that the losses are due to sedimentation of PO₄ in the slower waters caused by impoundments or

widening of the river channel. Gains in PO_4 loading were observed after UBWPAD, Millbury WWTP and Grafton WWTP. In several instances, the loading gained by the river after the aforementioned WWTPs is greater than the load contributed by the WWTP. In these instances it is thought that additional phosphorus loading is added to the river via resuspension of sediments behind impoundments within the reach that the WWTP is in.

Figure 31 - BRI Wet Weather PO_4 Loading Storm I

Figure 32 - BRI Wet Weather PO_4 Loading Storm II

Figure 33 - BRI Wet Weather PO₄ Loading Storm III

Table 18 shows the resulting loading matrices for the PO₄ loading from the wet weather BRI events. As shown in the table, loadings increased at mile markers 44, 39.8, 27.8 and 10.0 for all three wet weather events. These sites correspond to monitoring locations downstream of UBWPAD and Woonsocket WWTP among others. Losses occurred during all three events at mile markers 35.7, 23.2 and 0.1.

Table 18 - Loading Matrix for the BRI Wet Weather PO₄ Loading

RiverMile	45.8	44.0	41.4	39.8	35.7	32.0	27.8	23.2	20.5	16.6	12.8	10.0	9.4	3.8	0.1
July	-	+	NA	+	-	-	+	-	NA	-	-	+	NA	-	-
August	-	+	NA	+	-	+	+	-	NA	-	+	+	NA	+	-
October	+	+	NA	+	-	+	+	-	NA	+	-	+	NA	+	-
# of Dams		0	1	2*	3	1	2*	0	0	1	3*	0	1	3	2
# of WWTP's		1	0	1	0	1	1	0	1	0	0	1	0	0	0
Ponds					Fisherville		Rice City								Slater Mill
Tribs					Quin			Mum and West		Branch	Mill and Peters				

Table 19 shows the summation of both the positive and negative loading differences as well as the total loading contributed to the Blackstone by the WWTPs. It can be seen that the positive loadings in the river observed during Storm II and Storm III are much higher than the positive differences observed during Storm I. For all three wet weather surveys, the positive loadings observed during the events are larger than the loads discharged to the Blackstone by the WWTPs. This suggests that there are additional PO₄ sources present in the system. Some of the load increases are likely due to resuspension of PO₄

laden sediment from behind the impoundments. Additional PO₄ loading might come from stormwater runoff. This argument is supported by the fact that the storm events with the least amount of rainfall exceed the load discharged to the river by WWTPs the least and vice versa. The impact of stormwater inputs of PO₄ is most evident during the short intense rainfall that fell during Storm III. The large surge of stormwater is likely not only to flush any PO₄ on the surface into the sewers, but flush the sewers as well, resuspending anything that was in the sewers, including additional nutrients.

Table 19 - BRI Wet Weather PO₄ Loading Values

	Storm I	Storm II	Storm III
	PO₄-P (kg)	PO₄-P (kg)	PO₄-P (kg)
Positive Differences	667	1384	1942
Negative Differences	-445	-336	-1043
Post+ Neg	222	1049	899
WWTP Total	603	774	611
Outlet - Headwaters	222	1049	899
Assimilative Capacity	67	24	54

One can also see in the above table that at the highest flows in the river, the smaller the amount of PO₄ it can assimilate, on a percent basis. The river assimilated 67 percent of the PO₄ loading in Storm I, but only 24 percent in Storm II. The larger the flow in the river, the larger the velocity of the flow becomes. The increased velocities cause more potential of sediment scour while reducing the number of deposition zones along the river. Storm III loadings of PO₄ were assimilated by half despite the heavy rainfall. It is hypothesized that the difference in the assimilative capacities of the river between Storm II and Storm III reflects the changing hydrodynamics along the river. The lower velocities along the more southern reaches of the river seen in Storm II allow for increased opportunities for deposition which is reflected in the increased assimilation capacity of the river seen in Storm III.

NO₂ and NO₃ Wet Weather Loading Profiles

The NO_2 and NO_3 loading profiles for the wet weather water quality surveys Storm I, Storm II and Storm III are shown in Figure 34- Figure 36 below. Gains in NO_2 and NO_3 are generally attributed to the effluents of the WWTPs, but additional observed loadings may be due to stormwater runoff. This is especially evident in the loadings seen in the headwaters during Storm III and the loadings seen near Woonsocket WWTP in Storm II. The loading downstream of the UBWPAD discharge during Storm III is shown to be higher than the discharge itself, suggesting other sources of NO_2 and NO_3 . Losses in NO_3 loading may be attributed in part to plant and algal uptake that generally takes place behind impoundments.

Figure 34 - BRI Wet Weather NO_2 and NO_3 Loading Storm I

Figure 35 - BRI Wet Weather NO₂ and NO₃ Loading Storm II

Figure 36 - BRI Wet Weather NO₂ and NO₃ Loading Storm III

Table 20 shows the resulting loading matrices for the PO₄ loading from the wet weather BRI events. As shown in the table, loadings increased at mile markers 45.8, 44, 35.7, 12.8 and 3.8 for all three wet weather events. These sites correspond to monitoring locations downstream of UBWPAD and Woonsocket WWTP as well as several of the tributaries into the Blackstone. No uniform loss behaviors were observed across the three storm events.

Table 20 - Loading Matrix for the BRI Wet Weather NO₂ and NO₃ Loading

RiverMile	45.8	44.0	41.4	39.8	35.7	32.0	27.8	23.2	20.5	16.6	12.8	10.0	9.4	3.8	0.1
July	+	+	NA	+	+	-	-	-	NA	-	+	+	NA	+	-
August	+	+	NA	+	+	+	+	+	NA	+	+	-	NA	+	+
October	+	+	NA	-	+	+	-	+	NA	+	+	+	NA	+	+
# of Dams		0	1	2*	3	1	2*	0	0	1	3*	0	1	3	2
# of WWTP's		1	0	1	0	1	1	0	1	0	0	1	0	0	0
Ponds					Fisherville		Rice City								Slater Mill
Tribs					Quin			Mum and West		Branch	Mill and Peters				
* site located on dam which is included in number of dams between															

Table 21 shows the summation of both the positive and negative loading differences as well as the total loading contributed to the Blackstone by the WWTPs. The NO₂ and NO₃ loadings to the river are approximately the same for Storm II and Storm III, despite the fact that the WWTP inputs to the system are much smaller for Storm II. However, Storm I and Storm III have similar WWTP loadings but differ greatly in the total amount of NO₂ and NO₃ put into the river. The large amount of positive differences seen in Storm II might be the result of the intense rainfall that fell in the headwaters of the Blackstone washing a significant amount of NO₂ and NO₃ into the system through NPS loading.

Unlike the PO₄ assimilation capacity of the river, there seems to be no correlation between flow and the amount of NO₂ and NO₃ assimilated by the river. During Storm III, forty percent of the 8,000kg of NO₂ and NO₃ were assimilated while during Storm II, the river assimilated almost no NO₂ and NO₃.

Table 21 - BRI Wet Weather NO₂ and NO₃ Loading Values

	Storm I	Storm II	Storm III
	NO ₂ +NO ₃ (kg)	NO ₂ +NO ₃ (kg)	NO ₂ +NO ₃ (kg)
Positive Differences	2962	7778	8354
Negative Differences	-776	-32	-3446
Pos+ Neg	2185	7746	4908
WWTP Total	1147	139	1979
Outlet - Headwaters	2185	7746	4908
Assimilative Capacity	26	0	41

NH₃ Wet Weather Loading Profiles

The NH₃ loading profiles for the wet weather water quality surveys Storm I, Storm II and Storm III are shown in Figure 37 - Figure 39 below. With the exception of Storm II, Woonsocket WWTP is the biggest point of NH₃ in the system. It should be noted however, that during the Storm II survey, the nitrification system at UBWPAD was not functioning, causing the high levels of NH₃ seen in the plot.

Figure 37 - BRI Wet Weather NH₃ Loading Storm I

Figure 38 - BRI Wet Weather NH₃ Loading Storm II

Figure 39 - BRI Wet Weather NH₃ Loading Storm III

Table 22 shows the resulting loading matrices for the NH₃ loading from the wet weather BRI events. As shown in the table, loadings increased at mile markers 45.8, 44 and 10.0 for all three wet weather events. These sites correspond to monitoring locations downstream of the Worcester CSO facility, UBWPAD and Woonsocket WWTP. Losses occurred during all three events at mile markers 23.2 and 12.8. Losses in NH₃ loading were observed on the reach between the confluence of the Mumford and West Rivers and the confluence of the Mill and Peters Rivers.

Table 22 - Loading Matrix for the BRI Wet Weather NH₃ Loading

RiverMile	45.8	44.0	41.4	39.8	35.7	32.0	27.8	23.2	20.5	16.6	12.8	10.0	9.4	3.8	0.1
July	+	+	NA	-	-	+	+	-	NA	+	-	+	NA	-	-
August	+	+	NA	-	+	-	+	-	NA	-	-	+	NA	-	+
October	+	+	NA	+	-	+	-	-	NA	-	-	+	NA	+	-
# of Dams		0	1	2*	3	1	2*	0	0	1	3*	0	1	3	2
# of WWTP's		1	0	1	0	1	1	0	1	0	0	1	0	0	0
Ponds					Fisherville		Rice City								Slater Mill
Tribs					Quin			Mum and West		Branch	Mill and Peters				

* site located on dam which is included in number of dams between

Table 23 shows the summation of both the positive and negative loading differences as well as the total loading contributed to the Blackstone by the WWTPs. It can be seen that the large load discharged by UBWPAD during the Storm II event dominates both the total WWTP load for that storm event and the positive loadings as well. It can further be seen that the large NH₃ load from UBWPAD greatly diminished the assimilative capacity of the Blackstone. During Storm I and Storm III, the river was able to assimilate approximately 90 percent of the NH₃ load that it was exposed to. However, during Storm

II, the river was only able to assimilate approximately 60 percent of the total load, but a higher amount of loading on a mass basis. In all three events, the positive loading differences exceed the WWTP loads, suggesting additional NH₃ sources in the watershed, either from unmonitored WWTPs or NPS pollution.

Table 23 - BRI Wet Weather NH₃ Loading Values

	Storm I	Storm II	Storm III
	NH3 (kg)	NH3 (kg)	NH3 (kg)
Positive Differences	3690	9227	2806
Negative Differences	-3249	-5558	-2610
Post- Neg	440	3669	197
WWTP Total	1794	6796	238
Outlet - Headwaters	440	3669	197
Assimilative Capacity	88	60	93

Dissolved Oxygen Wet Weather Concentration Profiles

Figure 40 - Figure 42 show the flow weighted average concentrations of dissolved oxygen (DO) for each wet weather water quality survey. It can be seen in the figures that DO concentrations in the river are generally higher during high flow periods due to aeration as the water flows over dams. The DO concentration of both the UBWPAD and Woonsocket discharges was lower than the DO levels found in the river. The same can be said for the DO levels found in the tributaries of the Blackstone. In both cases, the water entering the system with lower DO levels causes DO depletion downstream of the inputs.

Figure 40 - BRI Wet Weather DO Concentrations Storm I

Figure 41 - BRI Wet Weather DO Concentrations Storm II

Figure 42 - BRI Wet Weather DO Concentrations Storm III

Biological Oxygen Demand Wet Weather Concentration Profiles

Figure 43 - Figure 45 show the flow weighted average concentrations of biological oxygen demand (BOD) for each wet weather water quality survey. The BOD concentrations in the Blackstone River do not go above 10mg/L in this analysis. Increases in BOD concentration are generally seen after WWTP discharges, with Woonsocket having the highest concentration of BOD for all three surveys. However,

increases in BOD concentration are also seen in the headwaters of the Blackstone River. This suggests that the stormwater being flushed from the highly urbanized headwaters is high in BOD. The BOD in the river tends to decrease as you travel downstream, most likely due to degradation processes and settling.

Figure 43 - BRI Wet Weather BOD Concentrations Storm I

Figure 44 - BRI Wet Weather BOD Concentrations Storm II

Figure 45 - BRI Wet Weather BOD Concentrations Storm III

Fecal Coliform Wet Weather Concentration Profiles

The flow weighted average concentrations of fecal coliform for each wet weather water quality survey are shown in Figure 46 - Figure 48 below. When comparing the three wet weather event profiles, it can be seen that for Storm I and Storm III, the headwaters above the UBWPAD have high concentrations of fecal coliform, while immediately downstream of the UBWPAD discharge, the concentrations of fecal coliform decrease significantly. One possible explanation for the decrease in the number of organisms is that the residual chlorine from the UBWPAD treatment process has killed off a significant amount of the organisms. A second hypothesis is that the flow from the UBWPAD diluted the flow from the headwaters, causing a decrease in the concentration. The high concentration of fecal coliform in the UBWPAD discharge in Storm II causes an elevated concentration of fecal coliform in the stream from the UBWPAD discharge to the confluence with the Mumford and West Rivers where the flow is diluted again. One should note that during all three wet weather events, the Peters River (mile marker 13.3) is shown to have elevated fecal coliform levels which need to be investigated.

Figure 46 - BRI Wet Weather Fecal Coliform Concentrations Storm I

Figure 47 - BRI Wet Weather Fecal Coliform Concentrations Storm II

Figure 48 - BRI Wet Weather Fecal Coliform Concentrations Storm III

E Coli Wet Weather Concentration Profiles

Figure 49 - Figure 51 show the flow weighted average concentrations of E Coli for each wet weather water quality survey. The E Coli concentrations follow the same basic behavior as the fecal coliform concentrations. There are elevated concentrations of E Coli in the headwaters of the Blackstone during Storm I and Storm III, but the concentrations drop significantly after the UBWPAD discharge. Again the drop in

concentrations in E coli is attributed to either residual chlorine in the UBWPAD effluent killing the organisms or dilution effects of the UBWPAD discharge. As seen with the fecal coliform concentrations, the elevated levels of E coli at the UBWPAD during Storm II cause elevated concentrations along the mainstem until the water is diluted with the flows from the Mumford and West Rivers. High concentrations of E Coli are also seen in the Peters River, which should be investigated, as well as in Slater's Mill Pond.

Figure 49 - BRI Wet Weather E Coli Concentrations Storm I

Figure 50 - BRI Wet Weather E Coli Concentrations Storm II

Figure 51 - BRI Wet Weather E Coli Concentrations Storm III

Results and Discussion – Dry Weather vs. Wet Weather

A comparison of the behaviors of the Blackstone River under wet and dry conditions provides insight into the effects that stormwater runoff and increased flows have on the behavior of pollutants in the river.

Flow Regimes

When comparing Table 10 and Table 17, one can see that the flows for the October dry weather survey are higher than the flows observed during Storm I as well as the flows observed downstream of the confluence of the Blackstone and Quinsigamond Rivers for Storm II and Storm III. For this reason, the dry weather survey conducted in October will not be used for comparison between the wet and dry weather water quality profiles.

PO₄ Loading

During dry weather events, the majority of the dams along the length of the Blackstone appear to act as PO₄ sinks, while during wet weather, the dams overall are apparent sources of PO₄. It is interesting to note however, that under both flow regimes, the river segment after the confluence with the Mumford and West Rivers and upstream of the Tupperware Dam (mile 17.8) acts as a PO₄ sink.

As expected, the dry weather loading of PO₄ to the Blackstone is much less than the wet weather loading. This suggests that a significant portion of the PO₄ loading to the river under wet weather conditions comes from nonpoint source pollution and/or resuspension of sediments behind dams. The assimilative capacity of the river also decreases under wet weather conditions, presumably due to less time for the PO₄ to settle out of the water column.

NO₃ Loading

Similarly to the PO₄ loading behaviors, the amount of NO₃ input into the Blackstone River is far greater during the wet weather events than during the dry weather events. A large amount of flushing and nonpoint source pollution seems to be contributing to the wet weather loadings of NO₃ to the Blackstone with virtually no NO₃ sinks during Storm II and Storm III of the wet weather surveys.

In terms of ability of the river to assimilate NO₃, the dry weather assimilative capacity of the river is approximately 40 percent of the load that the river is subject to. During the wet weather events however, Storm I and Storm II showed virtually no assimilative capacity what so ever, while Storm II showed an assimilative capacity of less than 40 percent.

NH₃ Loading

When comparing the NH₃ loading profiles under wet and dry scenarios, it can be seen that a significant amount of the NH₃ load contributed to the river comes from the Woonsocket WWTP. However, the loading seen downstream of both UBWPAD and Woonsocket is larger than the loads contributed to the river by the point sources. This behavior suggests that the river is being subjected to additional NH₃ loading.

As with PO₄, larger amounts of NH₃ are put into the river during wet weather events. However, the NH₃ assimilative capacity of Blackstone is shown to increase during wet weather events. The increase in the assimilative capacity is most likely due to the aeration that occurs over the dams transforming NH₃ to NO₃.

Dissolved Oxygen Concentrations

Under both wet and dry weather regimes, the dams along the length of the river serve as aerators to the water column. As previously stated, higher DO levels are seen in the river under wet weather conditions, due to increased aeration of the water as it flows over the dams. All of the tributaries act as DO depleters during the dry weather events while both the Mill and the Peters River are shown to act as DO depleters during wet weather events as well.

Biological Oxygen Demand Concentrations

BOD concentrations are, on the average, lower during the dry weather events. This is especially true in the headwaters of the Blackstone. While the BOD concentration decreases in the reach located between the confluence with the Quinsigamond and the Tupperware Dam during wet weather conditions, the concentrations increase in this reach during dry weather conditions. It is hypothesized that during wet weather, a decrease in the concentration of BOD is caused by dilution and flushing under increased flow conditions. Under dry weather conditions however, algal blooms can more readily form behind the impoundments and the associated die-off can cause significant increase in BOD concentration.

**BASIN-SCALE METHODOLOGY FOR EVALUATING RELATIVE IMPACTS
OF POLLUTION SOURCE ABATEMENT**

A Masters Project Presented by

James T. Mangarillo

Approved as to style and content by:

Paula L. Sturdevant Rees, Chairperson

David A. Reckhow, Member

John E. Tobiason
Graduate Program Director
Environmental Engineering Program

Acknowledgements

I would like to thank my academic advisor, Dr. Paula L. S. Rees of the Civil and Environmental Engineering Department at the University of Massachusetts, Amherst for her input and guidance during the course of this project. I would also like to thank Dr. David Reckhow for serving as a member of my committee.

My thanks are also due to Tom Walsh and the Upper Blackstone Water Pollution Abatement District for their financial support.

I would also like to thank the faculty and students at UMass, especially 318 Cold Storage, for their help with the project and their continued support.

Finally I would like to thank my family and friends. Without their support, I could never have achieved so much.

Abstract

The Blackstone River watershed covers an area of 475 mi² in central Massachusetts and northern Rhode Island. The Blackstone flows from its headwaters in the hills above Worcester, MA, through Woonsocket, RI and finally joins the Seekonk River in Pawtucket, RI. The Seekonk then flows into the Providence River on its way into Narragansett Bay. The historical significance of the Blackstone River has been recognized at the federal, state and local levels. Furthermore, the Blackstone is known to play a significant role on the hydrology and ecology of Narragansett Bay.

This study is part of a larger study designed to evaluate the cost-benefit effectiveness of past remediation efforts and, in a modeling framework, potential future, traditional and progressive abatement strategies at the local and watershed scales. A driving theme of this portion of the study is the development of a detailed understanding of point and nonpoint source contributions within both the headwaters of the Blackstone and the watershed as a whole. Understanding the source, fate and transport of contaminants along the mainstem of the Blackstone River is essential for setting reasonable management strategies in order to achieve the desired water quality goals in both the river and the bay.

Initial investigations into the relative magnitudes of point source and nonpoint source nutrient loadings under current and future loading regimes were conducted to allow a better understanding of the impacts of current regulations and the need if any for future regulatory action. Relationships between water quality and surrounding land use characteristics were analyzed to determine if correlations between the two exist and to predict the impact on water quality that may be caused by future changes in land use in the basin. Analyses on monthly and annual point and nonpoint source loadings dynamics between the Blackstone and Narragansett Bay were conducted as well. The relative nutrient loadings under wet and dry weather loading regimes were determined, with

particular attention being placed on the impacts of the numerous impoundments along the mainstem of the Blackstone River.

Based on the work contained herein, it has been concluded that there is a positive correlation between the amount of urbanized area and the amount of water quality degradation in the Blackstone watershed and its sub-basins. Furthermore, increasing amounts of urbanization will lead to increased peak flow values seen in the river, allowing for increased resuspension of pollutant laden sediment from behind the impoundments along the mainstem of the river, especially during wet weather events. Also, due to the complex hydraulics and loading dynamics of the Blackstone River, its tributaries and the bay as a whole, further regulation of point source pollution alone may not be an adequate or cost effective method for reducing nutrient loadings into the Blackstone River and Narragansett Bay. The loading dynamics have been shown to be highly variable on a monthly timescale, a variability that is likely to increase if more refined water quality and quantity data is collected for the river. Finally, the lack of available wet weather data also points to the need for additional, more refined data collection to be undertaken in order to better assess the loadings into the Blackstone River and their propagation downstream into Narragansett Bay. The need for additional data is supported by the highly variable loadings seen in the river as well as the changes in both the land use and the hydrology in the watershed that have occurred since the BRI was conducted.

Table of Contents

Acknowledgements	i
Abstract	ii
1.0 - Introduction	1
2.0 - Literature Review.....	11
2.1 - Blackstone River Watershed	11
2.2 - Narragansett Bay Watershed	15
2.3 - Regulatory Focus.....	20
2.3.1 - Point Source Based Regulation	20
2.3.2 - Nonpoint Source/Watershed Based Regulation	24
2.3.3 - Regulatory Focus in the Blackstone.....	26
2.3.4 - Regulatory Focus in Narragansett Bay.....	29
2.4 - Nutrient Impacts, Sources and Cycling.....	32
2.5 - Urbanization, Land Use Change and Population Growth	37
2.6 - Percent Imperviousness.....	39
2.7 - Watershed Modeling	40
2.8 - Summary	41
3.0 – Spatial Water Quality and Pollutant Loading Analysis.....	43
3.1 - Available Data.....	44
3.2 - Methodology	46
3.2.1 - Land Use and Percent Imperviousness Analysis.....	46
3.2.2 - Water Quality Analysis - Upper Blackstone Watershed	50
3.2.3 - Comparison between Water Quality Impairment Metrics	51
3.2.4 - Point Source vs. Nonpoint Source Loading Analysis	51
3.2.5 - Major River Annual Pollutant Load Estimation to Narragansett Bay.....	56
3.2.6 - Total Loading into Narragansett Bay	61
3.3 - Results & Discussion.....	62
3.3.1 - Land Use and Percent Imperviousness Analysis.....	62
3.3.2 - Water Quality Analysis - Upper Blackstone Watershed	67
3.3.3 - Comparison between Water Quality Impairment Metrics	69
3.3.4 - Point Source vs. Nonpoint Source Loading Analysis	70
3.3.5 - Major River Annual Pollutant Load Estimation to Narragansett Bay.....	84
3.3.6 - Total Loading into Narragansett Bay	87
3.4 - Conclusions & Discussion.....	99
4.0 – Along Stream Processes	102
4.1 - Methodology	105
4.1.1 - Dry Weather Loading Analysis.....	107
4.1.2 - Wet Weather Loading Analysis	108
4.1.3 - Source/Sink Identification Analysis.....	109
4.1.4 - Assimilative Capacity Analysis.....	109
4.2 - Results and Discussion.....	111
4.2.1 - Dry and Wet Weather Loading Analysis	111
4.2.2 - Gain/Loss Analysis.....	116
4.2.3 - Assimilative Capacity Analysis.....	120
4.3 - Conclusions	123