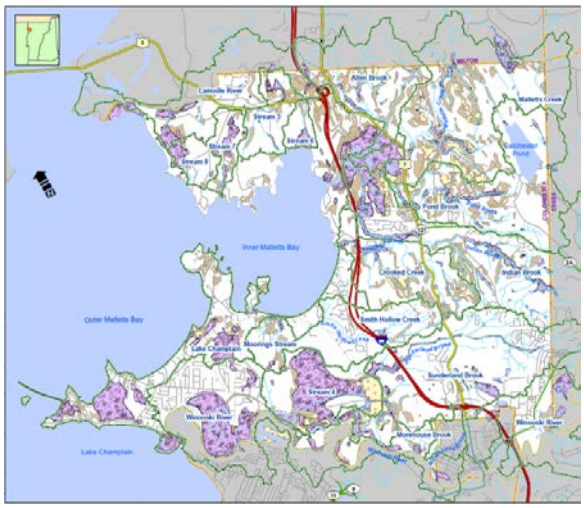

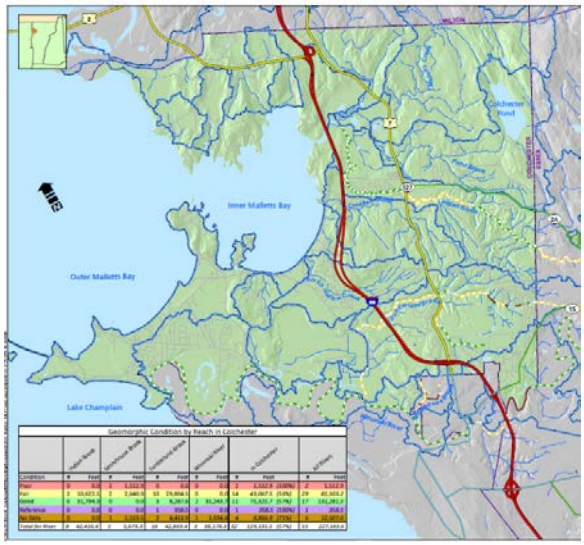

Synoptic Survey of Stream Phosphorus Concentrations in Colchester, Vermont

INTEGRATED WATER RESOURCES MANAGEMENT PROGRAM—TASK 2

VOLUME 2 OF 2

TOWN OF COLCHESTER, VERMONT

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EXECUTIVE SUMMARY

Nutrient enrichment is the leading cause of water quality impairment in Lake Champlain and phosphorus is the nutrient of greatest concern. Under most conditions, the supply of phosphorus limits the growth of suspended algae and higher aquatic plants – if the concentration of phosphorus is increased, the productivity of these organisms increases, occasionally forming undesirable algae blooms.

The Town of Colchester has a long-standing interest in water quality protection and improvement in Lake Champlain. The Town voluntarily initiated a survey of stream phosphorus concentrations to help inform its water resources management decisions. This survey of stream phosphorus is part of the Town's wider Integrated Water Resources Management Project.

Thirteen stream locations were monitored on three wet weather and two dry weather dates between March and October, 2010. The sampling locations were intended to represent the range of land uses in Colchester watersheds. The first conclusion to draw from these results is that major land uses are controlling stream phosphorus concentrations under most conditions. This conclusion is supported by the finding that streams draining watersheds with a greater percentage of agricultural land generally had higher phosphorus concentrations than streams draining primarily forested watersheds. Streams draining watersheds with higher population density generally had higher phosphorus concentrations than streams draining watersheds with lower population density. The watershed that was almost entirely forested (a headwater tributary of Malletts Creek at Brigham Hill Road) had the lowest dissolved and total phosphorus concentrations on all sampling dates. The second conclusion is that during the two high flow events, high total phosphorus concentrations were due to sediment transport; at high flows land use had less impact on sediment and total phosphorus concentrations than other (not quantified) factors. This conclusion is supported by the strong correlation documented between turbidity and total phosphorus concentrations and by especially weak associations between total phosphorus and land use on these high flow events. Stream channel erosion may be a major source of peak sediment and phosphorus concentrations under high flow conditions.

Segments of streams potentially impacted by onsite wastewater treatment systems (septic systems) and animal wastes were identified where possible. The Village Drive area sampling location (site VI) had substantially elevated dissolved phosphorus during low flow conditions. Elevated dissolved phosphorus concentrations are of more certain and immediate concern than total phosphorus concentrations, because most dissolved forms of phosphorus are immediately available for uptake by algae and aquatic plants, contributing to eutrophic conditions in receiving waters. We did not conclusively establish the cause of the elevated dissolved phosphorus at this site, but we speculate that malfunctioning onsite wastewater treatment systems may contribute dissolved phosphorus to the Village Drive stormdrain. This speculation is supported by elevated *E. coli* levels (reported separately) and ammonia concentrations at the outfall. The sampling location in the Pond Brook tributary at Route 7 (site EH) immediately north of Pond Brook

also had moderately elevated dry weather dissolved phosphorus concentrations; livestock impacts observed immediately upstream may have contributed to these elevated concentrations.

The water quality benefit of stormwater treatment was indirectly apparent in the sampling results. The Champlain Drive sampling location on a southern tributary of Sunderland Brook (site CD) is an interesting example of a highly impervious watershed with relatively low total and dissolved phosphorus concentrations and turbidity on the sampling dates. This watershed is mainly commercial and industrial; the residential population density is low. Many of the commercial properties have stormwater treatment systems and wetlands are present along much of the stream channel length. Although prevalence of stormwater treatment systems was not considered in watershed statistical models and wetland area was rarely a significant variable in these models, the raw water quality data suggest that stormwater management and riparian wetlands may reduce peak flows and sediment and phosphorus transport from this watershed. The dissolved and total phosphorus concentration data at site CD were substantially lower than at another small tributary to Sunderland Brook (site SBT) that lacks stormwater treatment.

Agricultural land and population density appear to control phosphorus transport under low and moderate flow conditions. A whole range of agricultural and urban best management practices may be implemented to reduce these contributions. Most agricultural management practices related to water quality protection are implemented through state and federal programs, with less involvement by municipal government. However, one critical agricultural practice that the Town of Colchester could affect is livestock exclusion from stream channels, which may be required and enforced under municipal law. The study was not able to adequately characterize phosphorus concentrations in the large area of drained cropland in the Winooski River floodplain on and surrounding Pine Island; therefore, additional monitoring in this area is recommended. Strong, positive associations were found between population density and dissolved phosphorus concentration under all monitored flow conditions and between population density and total phosphorus under low flow conditions. Among the three small urban watersheds, high phosphorus concentrations were only found at the Village Drive stormwater outfall, which has a similar percentage of impervious surface to the other two small urban watershed sites but a higher population density. The Village Drive site represents a critical phosphorus source area and the source of the elevated phosphorus (and *E. coli* and ammonia) concentrations should be investigated further, due to the potential public health and ecologic risks.

Overall, the results are consistent with expected results in Lake Champlain tributaries. The findings documented herein reinforce the prevailing scientific understanding of stormwater processes in the basin:

- Streams draining watersheds dominated by agricultural and/or higher density residential land tend to have elevated phosphorus concentrations relative to reference (forested) conditions.
- Runoff during wet weather events may be mitigated by increased implementation of stormwater treatment systems in developed areas and best management practices for agricultural land.

The results also suggest that stream channel adjustment may be a dominant source of total phosphorus under high flow conditions.

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1. INTRODUCTION

Nutrient enrichment is the leading cause of water quality impairment in Lake Champlain. Under most conditions, phosphorus is the limiting nutrient in Lake Champlain—if the concentration of phosphorus is increased, the growth of living organisms, particularly algae, increases as well. The Town of Colchester has 30 miles of shoreline on Lake Champlain, with 10 miles surrounding inner Malletts Bay. Several streams discharge to Malletts Bay, however, prior to the study described herein, the contribution of phosphorus from Colchester streams to the lake had not been investigated.

The Town of Colchester voluntarily initiated this survey of stream phosphorus concentrations to help inform its water resources management decisions. With the exception of Malletts Creek and Pond Brook, the streams sampled in this study were quite small (3-600 hectares or 9-1,400 acres). There is little phosphorus data available at this scale in Vermont with which to compare these data, nor was this type of comparison the intent of the study.

This survey of stream phosphorus is part of the Town's wider Integrated Water Resources Management Project. Although the discussion in this report is limited to phosphorus, it should be viewed within the larger context of local land use, existing water infrastructure, and other indicators of surface water quality in Colchester.

1.1. The Role of Phosphorus in Surface Waters

Phosphorus pollution is not unique to Vermont. We are interested in phosphorus because pollution of surface waters (such as streams, rivers, ponds and lakes) with nutrients accelerates eutrophication, the process by which the biological productivity of these waterbodies increases in response to increased nutrient concentrations (Vollenweider, 1968; Horne and Goldman, 1994). Associated with increased biological productivity are changes in aquatic food web structure and species composition (Tilman et al., 1982; Pace and Funke, 1991), and impairment of recreational and water supply uses of surface waters (Sharpley et al., 1994; U.S. Environmental Protection Agency, 1995). In temperate regions, phosphorus (P) is the nutrient primarily responsible for accelerating the eutrophication of freshwaters, because P is usually the nutrient in limited supply relative to plant demand (Schindler, 1977; Hecky and Kilham, 1988). Lakes rich in phosphorus tend to have low water clarity, taste and odor problems, and large fluctuations in dissolved oxygen, which can impact fish and other aquatic life.

Phosphorus pollution from point sources has been substantially abated in the United States since passage of the Clean Water Act in 1972, but comparatively little progress has been made in controlling P pollution from diffuse, or nonpoint, sources (Pucket, 1995). Controlling nonpoint source P is inherently difficult because most land surface exports some amount of P, and the flow-dependent, intermittent nature of nonpoint sources confounds regulation. Management of P increasingly involves prioritizing watersheds based on their potential or actual P contribution to receiving waters in order to ensure effective use of limited funds (Sharpley et al., 1994; Pucket, 1995; U.S. Environmental Protection Agency, 1995).

Native soils in Vermont contain phosphorus in greater or lesser amounts. Surface runoff erodes soil, transporting soil and soil-bound phosphorus to surface waterbodies. Stream channels are also a large source of soil-bound phosphorus, as sediments are scoured from the channel bed and banks as the stream adjusts its course over time. Even without applying phosphorus in any form, humans can dramatically increase phosphorus loading to surface waters by accelerating soil erosion. Application of commercial fertilizer, animal manure, domestic wastewater or septage, or process wastes to agricultural land and use of lawn fertilizer will increase soil phosphorus concentrations and impart additional phosphorus in runoff.

1.2. Field Study Rationale

This field study involves collection of water quality samples and laboratory analysis. This type of data is generally known as empirical data. Another form of data is derived from the literature, extrapolation of data collected in other locations, or estimates of typical ranges of results for a given set of conditions. Empirical water quality data is of greater use to managers than predictions based on literature values (Stanford and Ward, 1992). Because specific land use practices and land cover types, local geology, topography, soils, and climate all influence P concentrations and export rates (Dillon and Kirchner, 1975; Beaulac and Reckhow, 1982), literature values typically span a range of more than an order of magnitude between study areas (Loehr, 1974; Beaulac and Reckhow, 1982; Budd and Meals, 1994). Mean literature values do not reflect this spatial variability in P concentrations and export rates in the landscape.

Empirical assessments of phosphorus concentrations in small watersheds can help to identify watersheds with relatively high P concentrations and time periods or flow conditions when concentrations are highest. Information about the P contribution from different land uses and the periods when greatest P losses occur can be used to select appropriate management practices and to target critical areas in the landscape in which to implement these practices.

2. OBJECTIVES

The study objectives were as follows:

- Identify subwatersheds in Colchester drained by streams with relatively high phosphorus concentrations (hot spots).
- Assess the relative contributions of phosphorus among differing land uses (e.g., agricultural, forested, impervious cover, developed lands, and wetlands).

There are presently no water quality data for Colchester streams that are adequate to meet these objectives. Locating “hot spots” with elevated phosphorus concentrations will enable Colchester to focus management efforts in these areas. Describing relationships between phosphorus levels and land use will enable Colchester to focus management on certain land classes. This study has been designed and executed as a preliminary analysis to begin to understand the relationships between land use and phosphorus concentrations.

3. METHODS

To accomplish the study objectives within the available resources, a synoptic survey (rather than an extensive, long-term monitoring program) was designed to acquire data at critical locations in the landscape and at critical times. Selection of sampling sites, sampling and water analysis methods, spatial analysis, and statistical analysis are described in the following sections.

3.1. Site Selection

Monitoring locations were selected in consultation with the Town of Colchester, Department of Public Works based on fieldwork performed under Task 1; water resource mapping completed under Task 2; review of existing orthophotography, hydrography, and storm sewer mapping; and targeted field reconnaissance. Thirteen sites were selected for the study, which is near the minimum number of sites typically required to enable the intended statistical analyses. A 14th site was added at the mouth of Crooked Creek for the final sampling event to make up for the inability to sample site S4. The sampling sites are shown in Figure 1 and are described in Table 1. The criteria for selection of monitoring sites included stream size (order), watershed land use, and proximity to Malletts Bay. The primary consideration in selecting these sites was to represent watersheds of differing land use composition, including primarily agricultural, forested, and developed land. Selected sites were generally accessed from public roadways.

Table 1. Stream sampling site descriptions

Site ID	Site Description
BH	Headwater tributary of Malletts Creek at Brigham Hill Road
CC	Crooked Creek outlet
CD	Sunderland Brook tributary at Champlain Drive
EH	Pond Brook tributary at Route 7 immediately north of Pond Brook
MC	Malletts Creek at Route 7
MS	Moorings Stream outlet
PB	Pond Brook at Route 7
PI	Stream 4 at Pine Island Road
PP	Stormwater outfall near the intersection of Route 127 and Porters Point Road
S4	Stream 4 outlet at Macrea Farm Park
SB	Sunderland Brook at Route 7
SBT	Sunderland Brook tributary at Route 7 immediately north of Sunderland Brook
SC	Smith Hollow Creek at East Lakeshore Drive
VI	Village Drive/Linden Drive stormwater outfall

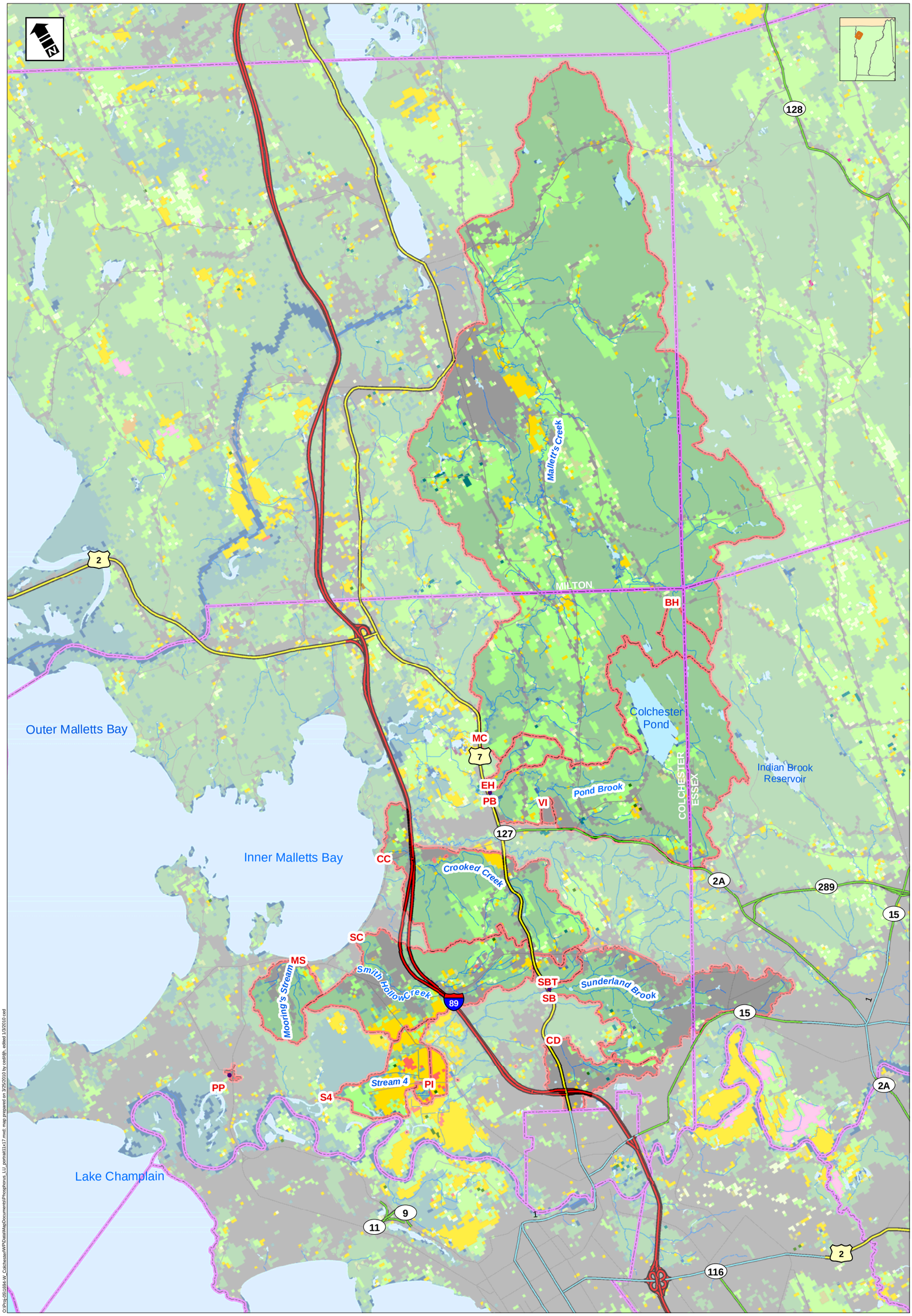

Figure 1. Land Use for Phosphorus Sampling Locations

Integrated Water Resources Management Program

Town of Colchester, Vermont

XX Sampling Locations
Watershed Boundaries
Corn
Soybeans
Sunflowers
Sweet Corn
Barley
WinterWheat
Oats
Alfalfa
Other Hays
Vegetables/Fruits
Fallow/Idle Cropland
Pasture/Grass
Christmas Trees
Other Tree Nuts
Open Water
Developed - Open Space
Developed - Low Intensity
Developed - Medium Intensity
Developed - High Intensity
Barren
Deciduous Forest
Evergreen Forest
Mixed Forest
Shrubland
Woody Wetlands
Herbaceous Wetlands
Pumpkin

0 0.5 1 Miles

Sources: VCGI: Streams, Roads; USDA: Land Use

The land cover data for Colchester was extracted from USDA's 2009 NASS dataset. The NASS dataset is part of an annual time series in which several states are categorized annually based on the extensive field observations collected during the annual NASS June Agricultural Survey. The imagery was collected between the dates of 03/01/1997 and 09/14/2006. (USDA/NRCS)

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3.2. Sample Collection

Individual samples of surface water collected at discrete locations are called “grab samples”. Grab samples were collected at monitoring sites during three wet weather events and two dry weather periods in 2010. Timing of wet weather runoff sampling is critical. In small streams, the majority of phosphorus transport in a given year can occur during short periods of high flow (for example, in less than a week). Our goal was to sample immediately following three of the largest rain events between March and August 2010. A high flow event was sampled in March, 2010, but with the exception of two major events in June that were missed due to unavoidable conflicts, there were no more large events (approaching or exceeding 1-inch of rainfall) until September 30. Because the end of the proposed monitoring period was approaching, a moderate wet weather event was sampled on August 3 after 0.74 inches of rain was recorded at the Burlington International Airport the previous day. Afterward, a decision was made to extend the monitoring period until a large event, approaching or exceeding 1-inch of rainfall, could be sampled.

The timing of dry weather events is less critical. A sampling event was considered to be representative of dry weather conditions as long as there were at least two days of dry weather preceding the sampling date.

Sampling was initiated in March 2010. The monitoring dates are given in Table 2 below. At each site, duplicate samples were collected for total phosphorus (TP) and dissolved phosphorus (DP) analysis by DEC’s LaRosa Laboratory. Samples were collected in 50-mL glass digestion vials supplied by the LaRosa Laboratory. A second set of samples was collected at 1-2 sites during each event for quality control purposes, to ensure duplicate analysis of approximately 10 percent of all samples. On August 3, no samples were collected for DP analysis due to an oversight by the sampling team. Site PI on Stream 4 at Pine Island Road was dry on three of the five events.

Table 2. Sampling dates

Date	Event Type	Parameters Measured
3/23/10	Wet weather event	TP, DP, ammonia, and turbidity. No flow measurement or *E. coli*.
5/24/10	Dry weather event	TP, DP, *E. coli*, ammonia, turbidity, and flow rate.
8/3/10	Wet weather event	TP, *E. coli*, ammonia, turbidity, and flow rate. No DP.
8/19/10	Dry weather event	TP, DP, *E. coli*, ammonia, turbidity, and flow rate.
10/1/10	Wet weather event	TP, DP, ammonia, turbidity, and flow rate. No *E. coli*.

Turbidity, ammonia concentration, and flow rate were measured at the time of sample collection. Flow measurements were made using a Global Water Flow Probe to measure current velocity and a field tape measure and ruler to measure the cross-sectional area of the flow stream. It was not always possible to measure streamflow. At sites MC, PI, and S4, measuring flow rate at the sampling site was not possible due to deep water (sites MC and S4) and/or lack of a bridge at the sampling station (sites PI and S4). Considering sample holding times and laboratory hours, there was insufficient time during a sampling

event to make exacting flow measurements, which typically take 30-40 minutes in wadeable streams by USGS methods. Approximately 5 minutes was allowed per stream flow measurement in this study, to enable samples to be taken at all sites to capture the wet weather event.

For the May 24, August 3, and August 19 events, samples were also collected for *E. coli* analysis by Endyne Laboratories, Inc. to complement data collection for the bacteria source tracking study. These data will be presented separately. Samples collected for *E. coli* analysis were collected in sterile, 100-mL plastic bottles preserved with sodium thiosulfate.

3.3. Water Analysis

Samples were field-tested for ammonia concentration immediately upon collection using Aquacheck ammonia test strips. Turbidity was measured in the field using a LaMotte 2020e portable turbidity meter. The high turbidity standard used in meter calibration was 100 NTU; measured turbidity values greater than 100 NTU may be less accurate than values within the calibrated range. Total and dissolved phosphorus analyses were conducted by DEC's LaRosa Laboratory using Standard Methods, 20th edition, method 4500-P H. For the dissolved phosphorus analysis, the sample was filtered in the laboratory using a 0.45 µM, 47-mm diameter membrane filter prior to persulfate digestion in the glass sample vial. For the total phosphorus analysis, the entire sample was digested in the glass sample vial.

3.4. Spatial Analyses

The Town of Colchester has a wealth of information regarding the natural and cultural landscape and land uses that has been digitized and incorporated into a Geographic Information System (GIS). The analysis of this GIS data is referred to as spatial analysis. The objective of the spatial analysis component of the study was to define characteristics of the study watersheds that were expected to be associated with water quality variables in the sampled streams. The watershed characteristics defined include watershed area, land use composition, impervious area, and population. The derivation of these watershed characteristics involved delineating the watershed boundary corresponding with each sampling point and intersecting these boundaries with available land use, impervious surface, and population datalayers. These operations were performed in ArcGIS version 9.3.

3.4.1. Sampling Points and Watershed Boundaries

The first steps in the analysis were to digitize the sampling locations and define the watershed boundary corresponding to each sampling location. Table 3 lists the data sources used for these tasks:

Table 3. Spatial datasets used in delineation of study watersheds

Dataset
Imagery: 2004 Chittenden County 1:1250 color infrared ortho-rectified imagery
Topography: 2-foot contour interval topography data developed by USGS from bare earth LiDAR data capture performed in 2004; available from the Vermont Center for Geographic Information
Hydrography: Vermont 1:5000 hydrography dataset, published in 2004; available from the Vermont Center for Geographic Information
Colchester watershed boundaries: Developed by Stone Environmental in 2009 for the Town of Colchester (as part of this study)
Colchester stormwater infrastructure: Developed by Stone Environmental in 2009 for the Town of Colchester (as part of this study)
Bridge and culvert data: Transtruc dataset maintained by the Vermont Agency of Transportation. The Town of Colchester owned culverts were inventoried by Stone Environmental in 2009 (as part of this study)

Sample locations were defined by digitizing points over the high resolution imagery. The watershed corresponding to each sample point was then defined by combining the existing Colchester Watershed Boundaries layer with heads-up digitization at the watershed outlet and in any other areas where the boundary was not defined in the Colchester Watershed Boundaries datalayer. Adjustments were then made in places where transportation and stormwater drainage infrastructure clearly alter the topographically-defined boundary. The watershed delineation process was as follows:

1. From the Colchester Watershed Boundaries datalayer, select watershed boundary segments that are consistent with the study watershed boundaries. In the large study watersheds, this entailed merging smaller subwatersheds from the Colchester Watershed Boundaries datalayer.
2. Using the high resolution topography, perform heads-up digitization of the watershed boundary near the watershed outlet and in any other areas where the boundary was not defined in the Colchester Watershed Boundaries datalayer. The digitized segments of the study watershed boundaries were intersected with the selected segments from the Colchester Watershed Boundaries datalayer. The combined boundaries were then checked for consistency with the stream networks defined in the Vermont Hydrography dataset.
3. In developed areas, the watershed boundaries defined in steps #1 and #2 above were overlain on the high resolution imagery to identify areas where transportation infrastructure determines flow paths. Stormwater infrastructure data from Stone Environmental's comprehensive infrastructure mapping work for the Town and culvert locations in VTrans' Transtruc dataset were also reviewed. Watershed areas bisected by roadways were evaluated and were either included or removed from a study watershed based on the evident drainage pattern. In certain areas the actual flow path could be determined from the presence of road crossing culverts. Where road crossing culverts or closed drainage systems were not present, the watershed boundary was generally interpreted to follow the road centerline. In many cases road ditches and other shallow channels could be observed in the imagery. Particularly

in the PI (Pine Island Road) and S4 (Stream 4) watersheds, which have very little slope, field ditches, contiguous areas of saturated soils, and/or open water courses apparent in the imagery were used to guide the watershed boundary delineation.

The final study watershed boundaries (Figure 1) were used to compute the land area draining to each sampling site.

3.4.2. Land Use Analysis

The Study Watershed Boundaries datalayer was used in combination with a recent land use dataset to calculate the extent of different land uses in each watershed. The land use dataset used was the 2009 Vermont Cropland Data Layer (CDL) produced by the National Agricultural Statistics Service (NASS) from satellite imagery. The NASS datalayer includes 24 land use classes among the study watersheds. The original 56-meter grid size was maintained throughout the spatial analysis. The land use composition of the study watersheds was tabulated using the Tabulate Area tool in ArcGIS 9.3. Table 7 summarizes these land use data.

3.4.3. Impervious Cover Analysis

Impervious surfaces include roofs, roads, sidewalks, driveways, and other structures that prevent rainfall and snow-melt from directly infiltrating into the soil, and concentrate runoff along the edge of the structure or in stormwater drainage systems. The Study Watershed Boundaries datalayer was used in combination with a recent land cover dataset developed by the Spatial Analysis Laboratory at the University of Vermont (UVM) to calculate the impervious cover area in each watershed. The UVM land cover dataset was based primarily on the LiDAR imagery flown in 2004 for Chittenden County; supplementary data sources included the State of Vermont's E-911 Esite point dataset and Chittenden County road polygons. The UVM land cover dataset has seven land cover classes. Stone reclassified the UVM dataset to derive an impervious cover datalayer using the scheme presented in Table 4.

Table 4. Reclassification of land cover classes in the UVM datalayer

Code	Classification	Reclassification
1	Tree Canopy	non-impervious
2	Grass/Shrub	non-impervious
3	Bare Soil	non-impervious
4	Water	non-impervious
5	Buildings	Impervious
6	Roads/Railroads	Impervious
7	Other Paved Surface	Impervious

Due to the large size of the dataset, the gridded land cover data was converted to a polygon feature class before any spatial analyses were run. The land cover feature class was then "unioned" with the Study

Watershed Boundaries datalayer. The impervious cover values were than summarized for each study watershed.

An additional step was required to calculate the impervious cover area of the Malletts Creek watershed because a small portion (193 ha or 478 acres) of the watershed lies outside the extent of the impervious cover datalayer, in the Town of Milton. The extent of impervious cover in this portion of the watershed was estimated as 0.78 ha (1.9 acres). This estimate was based on there being one Class-3 road, 1,372 m (4,500 feet) in length, and approximately 10 houses in the outlying area. The road area was calculated as the road length multiplied by an assumed road width of 5 m (16 feet), which is based on previous observations of Colchester's Class 3 roads. The impervious cover area associated with the houses was calculated based on an assumed footprint of 111 square meters (1,200 square feet) multiplied by the number of houses. The estimated impervious and non-impervious areas outside the extent of the impervious surface datalayer were then included in the totals for the Malletts Creek watershed.

3.4.4. Population Analysis

The Study Watershed Boundaries datalayer was used in combination with the E-911 Esite datalayer available from the Vermont Center for Geographic Information to estimate the population in each study watershed. An average household population of 2.5 was used for the population density calculation. This figure was taken from a 2010 report by M.J. Munson titled *Colchester, Vermont Recreation Facility Impact Fee Analysis*. The E-911 datalayer includes six residential unit classes. Table 5 shows the population per unit that was assumed for each class.

Table 5. Assumed population per residential unit in the E-911 Esites datalayer

Code	Classification	Households	Population
R1	Single family home	1	2.5
R2	Multi-family home	5	12.5
R3	Mobile home	1	2.5
R4	Other residential	1	2.5
R5	Seasonal single family	0.5	1.25
R6	Seasonal home	0.5	1.25

By calculating the number of units in each class in each watershed and multiplying this number by the assumed population per unit, a population total was estimated for each study watershed.

3.5. Statistical Analysis

The objective of the statistical analysis was to define and evaluate how land use may influence water quality. In this section the major statistical tools used are referred to as regression models. These models are used to test the strengths of relationships between water quality measurements and land uses.

Relationships between water quality variables and land use were examined for each sampling date through stepwise regression and standard least squares multiple linear regression analysis. The dependent variables used were DP and TP concentration on each sampling date. The independent variables evaluated for their ability to explain variation in the dependent variables were population density, impervious surface percentage, and various combinations of land use categories, expressed in percent of watershed area. Given the small number of sampling sites, a maximum of three independent variables could be used in any given regression model. Therefore, certain specific land use/cover classes were combined into broader classes prior to analysis if they were expected to have similar function with respect to phosphorus transport. For example, deciduous forest, evergreen forest, mixed forest, and shrubland were combined into one "Forest/shrub" category. Similarly, the 12 subclasses of agricultural land in the original data (including crops such as feed corn, sweet corn, alfalfa, pumpkins, and pasture/grass) were combined into three classes prior to analysis: 1) hay/pasture, 2) cultivated land, and 3) all agricultural land. Note that the land area planted in Christmas trees was not included in the "All Agricultural Land" class because this is an atypically low intensity use of land as compared with other types of farmland. Developed land and wetland classes were included in statistical models either as general classes ("All Developed Land" and "All Wetlands") or as distinct subclasses (such as "Herbaceous Wetlands", "Woody Wetlands", "Low Density Developed Land", "High Density Developed Land", et cetera).

Land use variable sets were tested in regression models for each sampling date in order to determine which combination of variables was the best predictor of total and dissolved P concentrations. The levels of the dependent (phosphorus concentration) variables were different for every sampling date, while the levels of the explanatory (land use) variables were assumed to remain constant. Initial multiple regression models were developed through a stepwise procedure. Of all the independent variables, All Agricultural Land and Population Density entered the stepwise regression models most consistently. Therefore, these variables were fixed in all regression models and various third variables were tested to improve the model fit.

The degree to which each combination of land use variables explained the variation in the dependent variable on a given date was assessed by comparing the regression R^2 values among models. Because all models contained the same number of explanatory variables (three), the R^2 values for all models on all sampling dates could be compared directly. Logarithmic transformations of the dependent variables invariably improved the fit of some models, while causing models on other dates to fit less well. Because there was no consistent improvement made by logarithmic transformation of the dependent variables, these data were not transformed.

Independent variables were not used together in final regression models if they were determined to be correlated. Pairs of independent variables were judged to be correlated if the Pearson product-moment correlations between the variables exceeded 0.50. Correlation was only tested among variables that were significant in one or more models. Among significant variables, All Agricultural Land was correlated

with Herbaceous Wetland (Pearson's r= 0.78). Therefore, Herbaceous Wetland was excluded from models containing the All Agricultural Land variable, which was the stronger of the two variables.

To regression models containing the All Agricultural Land and Population Density variables, other independent variables were added one at a time to assess how the third variable affected the model fit. Herbaceous Wetland percentage, Impervious Surface percentage, and Forest/shrub percentage were the only variables to significantly affect the fit of one of more models. The Herbaceous Wetland variable was excluded because it is correlated with All Agricultural Land, although this variable improved the fit of the DP model on the May 24 event, in which it was significant at $p < 0.10$. In most models, inclusion of the Impervious Surface percentage variable reduced the significance of the All Agricultural Land variable and/or the Population Density variable, and it was only significant ($p < 0.10$) in two cases: DP on August 19 and TP on May 24. The only good candidate for a third explanatory variable was Forest/shrub percentage. Although the Forest/shrub percentage variable was only significant at $p <0.10$ in two models (DP on August 19 and TP on May 24), inclusion of this variable tended to improve the overall fit of most models and increased the significance of the All Agricultural Land and Population Density variables. Based on these considerations, the final multiple regression models for DP and TP on each date included the Forest/shrub variable in addition to All Agricultural Land and Population Density.

4. RESULTS AND DISCUSSION

Measurements and findings of the phosphorus sampling program and above data analysis are presented in this section of the report. Potential implications of these findings are discussed in Section 5.

4.1. Spatial analysis

The estimated population of each watershed upstream of the sampling point is presented in Table 6. The Malletts Creek watershed (MC) is the most populous among the study watersheds, with an estimated population of 3,128 (Table 6). The next most populous watersheds are Sunderland Brook (SB) at Route 7 (2,028), Pond Brook (PB) at Route 7 (1,795), and Smith Creek (SC; 1,086), in that order. Stream 4 at Pine Island Road (PI) has zero population. Because the Malletts Creek watershed is primarily rural and is much larger than the other study watersheds, its population density is actually quite low, only 0.26 people per acre. The watersheds with the highest population densities are small urban drainages; VI (17.84 people per acre) is the Village Drive stormwater outfall and PP (3.36 people per acre) is the outfall near the intersection of Route 127 and Porters Point Road.

Table 6. Population and population density in study watersheds

Study Watershed	Households	Population	Area (ha)	Area (acres)	Population Density (person/ha)	Population Density (person/acre)
BH	2	5	67.5	166.7	0.07	0.03
CC	356	890	567.6	1402.5	1.57	0.63
CD	6	15	135.4	334.5	0.11	0.04
EH	24	60	63.9	157.9	0.94	0.38
MC	1251	3128	4835.0	11947.4	0.65	0.26
MS	137	343	139.8	345.6	2.45	0.99
PB	718	1795	1022.6	2526.9	1.76	0.71
PI	0	0	37.8	93.4	0.00	0.00
PP	12	30	3.6	8.9	8.31	3.36
S4	46	115	196.8	486.3	0.58	0.24
SB	811	2028	494.1	1220.8	4.10	1.66
SBT	42	105	43.8	108.2	2.40	0.97
SC	435	1086	478.5	1182.3	2.27	0.92
VI	180	450	10.2	25.2	44.08	17.84

Table 7 presents the land use composition of the study watersheds. The calculated land use data confirm the judgments made during selection of the sampling sites. Watersheds PI and S4 are the most agricultural among the study watersheds. Watershed EH, a northern tributary of Pond Brook, is approximately 50% agricultural, but it has comparatively little land in cultivation. The CD (Sunderland Brook tributary at Champlain Drive), SB (Sunderland Brook at Route 7), PP (storm sewer discharging at the Route 127 and Porters Point intersection), and VI (Village Drive storm sewer outfall) watersheds are the most urbanized. These watersheds have the highest percentage of developed land (Table 7) and impervious surface (Table 8). Watershed BH is entirely forested, with the exception of one or two houses; it is a useful point of comparison in evaluating water quality data from the more developed and agricultural watersheds.

Table 7. Land use areas in study watersheds as a percentage of watershed area

Study Watershed	Cultivated Land	All Agricultural Land	Developed Open Space	All Developed Land	Forest/ shrubland	Wetland	Open Water
BH	0.0	0.0	0.0	0.0	100.0	0.0	0.0
CC	3.0	19.8	8.9	15.1	61.3	3.7	0.0
CD	2.6	9.6	15.5	76.6	8.3	5.5	0.0
EH	0.5	48.4	6.4	8.2	41.6	0.9	0.9
MC	1.9	22.4	4.7	8.0	67.6	1.7	0.3
MS	1.3	6.1	13.8	17.6	69.0	7.3	0.0
PB	1.4	14.1	6.2	9.8	66.5	2.1	7.4
PI	82.3	83.1	0.0	0.0	9.2	7.7	0.0

Study Watershed	Cultivated Land	All Agricultural Land	Developed Open Space	All Developed Land	Forest/ shrubland	Wetland	Open Water
PP	0.0	0.0	7.7	92.3	7.7	0.0	0.0
S4	57.7	78.6	0.0	0.1	10.2	10.3	0.7
SB	0.8	6.8	17.4	48.2	42.6	2.3	0.1
SBT	4.6	7.9	16.6	28.5	58.9	3.3	1.3
SC	9.4	19.6	15.9	31.3	45.5	3.6	0.0
VI	0.0	0.0	29.4	94.1	5.9	0.0	0.0

The extent of impervious cover in a watershed has been shown to be strongly associated with stream condition indicators such as aquatic insect diversity and abundance (Allan 2004). As the percentage of impervious cover in a watershed increases, stormwater volume and peak flow rates increase, which often accelerate or precipitate stream channel adjustments to accommodate the increased flows. Sediments eroded from the channel bed and banks impair aquatic habitat and carry phosphorus and other sediment-bound contaminants to receiving waters. Wash off of sediment from impervious surfaces is also a source of phosphorus and a cause of aquatic habitat degradation. 10% impervious cover in the watershed is often cited as a threshold above which the biotic integrity of streams is typically impaired (Allan 2004). No similar threshold is recognized with respect to phosphorus transport, but many of the same mechanisms apply: increases in impervious surface result in more runoff, which destabilizes stream channels, resulting in more sediment and phosphorus loading from the stream.

Table 8. Impervious surface area in study watersheds

Study Watershed	Impervious Area (ha)	Impervious Area (acres)	Non-impervious Area (ha)	Non-impervious Area (acres)	Total Area (ha)	Total Area (acres)	Impervious Percentage
BH	0.1	0.3	67.4	166.5	67.5	166.7	0.17
CC	27.6	68.1	540.0	1,334.4	567.6	1402.5	4.86
CD	46.5	114.8	88.9	219.7	135.4	334.5	34.32
EH	3.4	8.4	60.5	149.5	63.9	157.9	5.34
MC	169.6	419.0	4,665.5	11,528.4	4,835.0	11947.4	3.51
MS	7.2	17.9	132.6	327.7	139.8	345.6	5.18
PB	48.8	120.5	973.8	2,406.4	1,022.6	2526.9	4.77
PI	0.2	0.5	37.6	92.9	37.8	93.4	0.56
PP	1.6	4.0	2.0	4.9	3.6	8.9	45.21
S4	4.2	10.3	192.6	476.0	196.8	486.3	2.12
SB	112.6	278.2	395.9	978.3	508.5	1256.5	22.14
SBT	3.0	7.3	40.8	100.9	43.8	108.2	6.75
SC	43.5	107.5	435.0	1,074.9	478.5	1182.3	9.09
VI	3.8	9.3	6.4	15.9	10.2	25.2	36.82

4.2. Water quality data

The five monitoring dates are given in Table 9, with event precipitation totals from a cooperating weather station (Weather Underground network station KVTCOLCH4) on Belaire Drive in Colchester. The precipitation totals in Table 9 are for the day of and the day prior to sampling. On October 1, 2010, approximately 0.45 inches of rain fell between collection of the first sample at 08:50 and the last sample at 14:10. An insignificant amount of rain (<0.01 inch) was recorded on October 1, 2010 after sampling was completed.

The events of March 23 and October 1, 2010 were major events. The one-year return interval, 24-hour rainfall total for Colchester is 1.91 inches (Northeast Climate Data Center, 2011). Rainfall on March 23rd (1.43 inches) approached this amount and wet spring conditions and approximately 0.46 inches of rain on March 22 added to the streamflow. Local flooding was evident in the Winooski River floodplain and along Malletts Creek. On March 23, floodwaters from the Winooski River inundated the sampling station on Stream 4 in Macrea Farm Park (S4). The October 1 event rainfall total (2.00 inches) exceeded the one-year return interval, 24-hour rainfall total and over 1 inch of rain on the preceding day added to the streamflows. The National Weather Service station at the Burlington International Airport recorded more than an inch of rain on eight days in 2010 and four days during the monitoring period.

The wet weather event on August 3 was minor in comparison to the March 23 and October 1 events. Negligible rainfall was recorded in the week prior to each dry weather sampling event.

Table 9. Sampling dates and antecedent precipitation totals

Sampling Date	Start Time (1st sample)	Event Type	Sampling Day Rain Total (in.)	Prior Day Rain Total (in.)
3/23/10	13:30	Wet weather	1.43	0.45
5/24/10	10:05	Dry weather	0.00	0.00
8/3/10	10:29	Wet weather	0.29	0.41
8/19/10	08:41	Dry weather	0.00	0.00
10/1/10	08:50	Wet weather	2.00*	1.10

*Approximately 0.45 inches of rain fell during sampling

Total and dissolved phosphorus concentration data for the five monitoring events are presented in Table 10 and Figure 2. Summary statistics for total phosphorus concentrations on each date are provided in Appendix A. On average, wet weather total phosphorus concentrations were substantially higher than dry weather total phosphorus concentrations. The total phosphorus concentration was highest on October 1 for eight of the sites. The mean total phosphorus concentration among sampled sites on this date was 684 µg/L. The sites with exceptionally high (>1,000 µg/L) total phosphorus concentrations on October 1 were SBT (2,540 µg/L), EH (2,300 µg/L), and SB (1,200 µg/L). The date with the second highest mean total phosphorus concentration, 359 µg/L, was March 23. The site with the highest total phosphorus concentration on March 23 was SBT (1,010 µg/L). Total phosphorus concentrations at sites SC (705

µg/L), EH (575 µg/L), MC (462 µg/L), and SB (439 µg/L) were also quite high on this date. The lowest total phosphorus concentrations were measured on the two dry weather sampling dates. The mean total phosphorus concentration among sampled sites on May 24 and August 19 were 85 and 87 µg/L, respectively (Appendix A).

Site BH, the forest stream, had the lowest total phosphorus concentration of all sites on all five sampling dates. Site PP, the stormwater outfall at the intersection of Route 127 and Porters Point Road, and site CD, the Sunderland Brook tributary at Champlain Drive, also has relatively low total phosphorus concentrations on most sampling dates.

Table 10. Total and dissolved phosphorus concentrations by sampling date

Study Watershed	P Fraction (µg/L)	3/23/2010	5/24/2010	8/3/2010	8/19/2010	10/1/2010
BH	DP	9.83	7.01	NS	19.4	15.6
	TP	27.3	11.6	15.3	10.5	52.5
CD	DP	12.5	10.3	NS	15.7	19.3
	TP	35.3	19.3	30.3	34.8	145
EH	DP	45.3	70.4	NS	54.8	70
	TP	575	113	252	104	2300
MC	DP	29.7	13.8	NS	31.3	55.1
	TP	462	65.45	108	37.1	344
MS	DP	24.1	9.36	NS	18.7	110
	TP	298	71.5	134	38.2	493
PB	DP	15.6	16.2	NS	17.8	127
	TP	244	44.2	64.2	49.2	440
PP	DP	19.7	<5	NS	9.47	18
	TP	33.4	13.1	48.4	25	56
S4	DP	12.5*	46.4	NS	34.5	NS
	TP	260*	116	NS	66.3	NS
SB	DP	18.45	18.2	NS	32.4	29.1
	TP	439	70.8	163	31.7	1200
SBT	DP	26.6	25.9	NS	29.2	31.8
	TP	1010	66.1	144	45	2540
SC	DP	25.8	14	NS	22.8	54
	TP	705	27	40.6	17.4	660
VI	DP	94.1	240	NS	515	104
	TP	254	400	428	582	151
CC	DP	NS	NS	NS	NS	74.1
	TP	NS	NS	NS	NS	238
PI	DP	34.7	Dry	Dry	Dry	152
	TP	324	Dry	Dry	Dry	266

NS = no sample collected; * = mixed with Winooski River floodwaters

Dissolved phosphorus concentrations were generally low during wet and dry weather events except at site VI, the Village Drive stormwater outfall. Appendix B provides summary statistics for dissolved phosphorus concentrations on each sampling date. Dissolved phosphorus concentrations at site VI, Village Drive, were markedly higher than at other sites and revealed a different pattern, highest during dry weather and lower during the major storm events on March 23 and October 1. These data suggest a dilution effect. The highest dissolved phosphorus concentration (515 µg /L) was seen at site VI during the August 19 event, when conditions were driest. On this date the dissolved fraction constituted 88% of the total phosphorus concentration at site VI. Site PI on October 1 had a dissolved phosphorus concentration of 152 µg /L. It is difficult to interpret this high dissolved phosphorus concentration because this site was dry three events out of five; however, the fact that the PI watershed has no inhabitants, little impervious surface, and is more than 80% cultivated land suggests that some agricultural practice applied prior to the October 1 sampling may have caused the result.

The dissolved phosphorus fraction is of particular environmental concern because the primary forms of dissolved phosphorus are readily available for uptake by aquatic plants. This contrasts with particulate phosphorus, which is chemically bound to sediment particles or contained within organic matter. The particulate phosphorus fraction may be calculated as the difference between the total and dissolved fractions. Over time, phosphorus in particulate forms may be released to the water column as dissolved phosphorus or it may remain in unavailable, particulate forms essentially indefinitely, such as when it becomes buried in deep lake sediments.

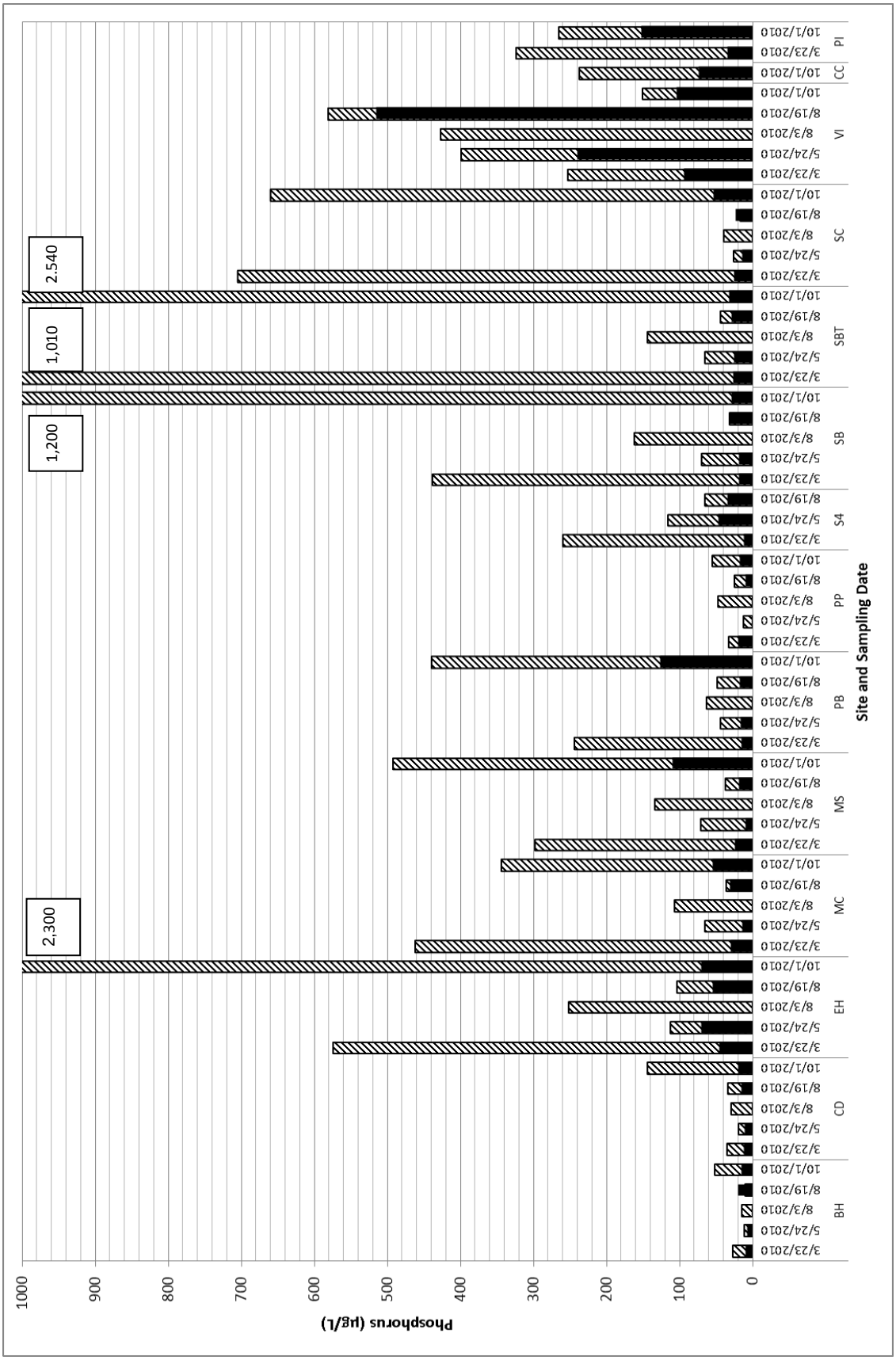

Figure 2: Dissolved and total phosphorus by site and date

Notes: TP is shown as crosshatched columns and DP is shown as superimposed solid black columns. No DP samples were collected on the August 3, 2010 event.

Table 11 presents turbidity data collected in the field on each sampling date. Turbidity levels were very high at certain sites on March 23 and October 1. The mean turbidity levels across all sites on these dates were 172 and 243 nephelometric turbidity units (NTU), respectively (Appendix C). For comparison, the mean turbidity levels on the dry weather events were 8 NTU on May 24 and 9 NTU on August 19. The mean turbidity level for the relatively minor wet weather event sampled on August 3 was intermediate, 27 NTU. The Sunderland Brook tributary sampled at Route 7 (SBT) and the Pond Brook tributary sampled at Route 7 (EH) had substantially higher turbidity than other sites on March 23 (745 and 647 NTU, respectively) and October 1 (1,242 and 1,340 NTU, respectively). These streams appeared very muddy. Channel erosion is evident in the vicinity of both sampling points. Figure 3 is a photograph illustrating turbid streamflow, taken at SBT the week prior to the March 23 sampling event.

Table 11. Turbidity by sampling date

Study Watershed	3/23/2010	5/24/2010	8/3/2010	8/19/2010	10/1/2010
BH	2.54	0.81	1.98	1.21	9
CD	9.14	0.79	5.09	4.39	7.45
EH	647	15.9	74.3	6.27	1340
MC	159	7.53	35.2	7.33	83.1
MS	130	24.6	92.7	37.3	87.9
PB	74.1	6.59	7.98	6.64	48.9
PP	3.77	2.99	10.32	3.31	8.78
S4	111*	15.8	NS	24.6	NS
SB	78.5	8.92	36.4	5.38	129
SBT	745	13.6	29.9	7.61	1242
SC	150	0.63	4.19	0.35	71
VI	5.04	3.68	2.63	4.86	3.43
CC	NS	NS	NS	NS	40.8
PI	127	Dry	Dry	Dry	83.2

NS = no sample collected; * = mixed with Winooski River floodwaters

Figure 3. Turbid streamflow upstream of site SBT

Because phosphorus at all sampling sites except site VI is primarily in the particulate form, we can expect to find a positive relationship between total phosphorus and turbidity. Figure 4 illustrates the strong relationship between paired total phosphorus and turbidity data across all sampling dates. To linearize these data, the data were transformed to their base 10 logarithms. For all sites except VI, this linear relationship could be used to approximate total phosphorus concentration from turbidity readings. On all five sampling dates, the site VI data are clearly outliers. This is consistent with the fact that the dissolved phosphorus fraction is high and turbidity was always very low at this site. As stated in the Executive Summary, we believe there is an explanation for this data, which warrants further investigation.

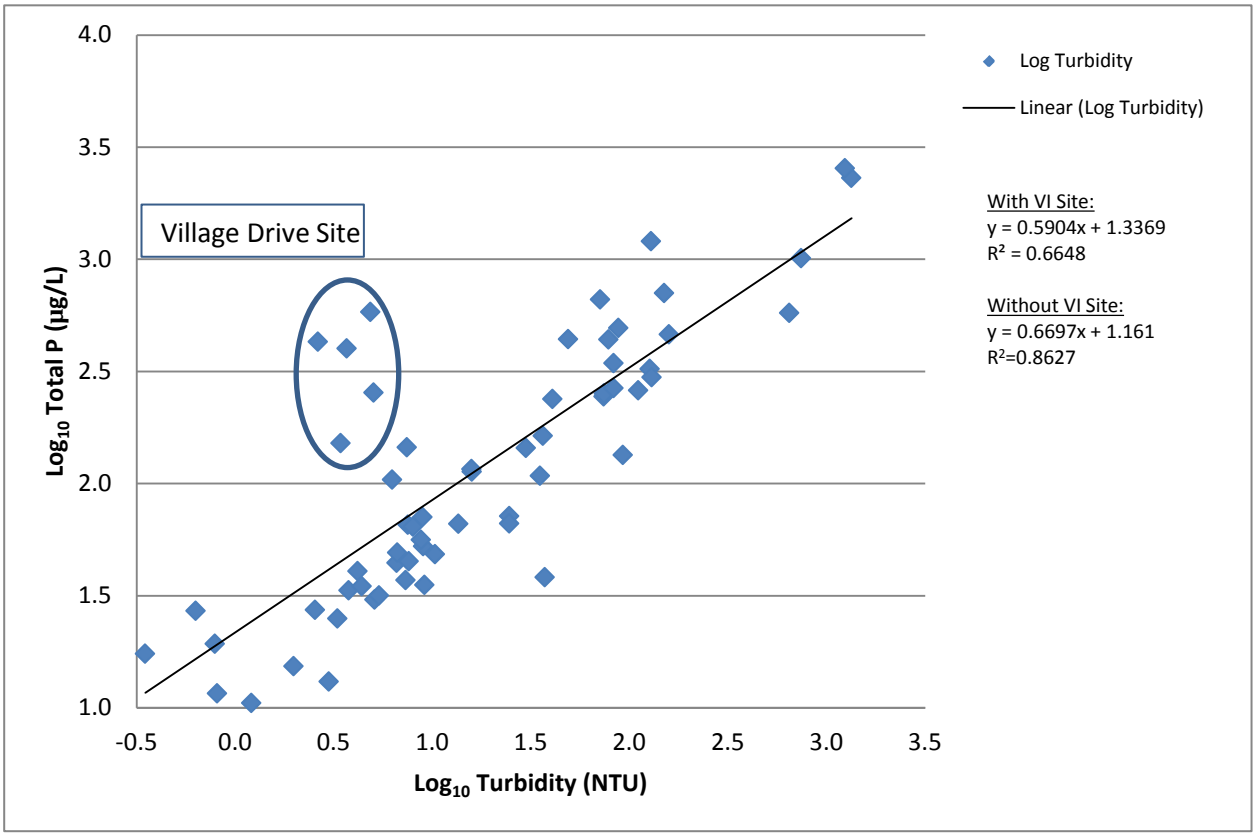

Figure 4. Regression on paired measurements of total phosphorus and turbidity

As described in the methods, the ammonia test performed during sample collection is an insensitive test strip method with a minimum detection limit of 0.25 mg/L; therefore we were not expecting to find detectable levels of ammonia in natural streams using this method. Table 12 presents ammonia concentration data for all sampling dates. No detectable ammonia was measured on the March 23 sampling date; however, detectable levels were found at site VI on the remaining four dates. Elevated levels were also found at site MS (the outlet of Mooring's Stream). The levels could be associated with a wastewater contribution or decomposition of organic nitrogen in the wetlands upstream of both sampling points.

Table 12. Ammonia concentration data (mg/L)

Study Watershed	3/23/10	5/24/10	8/3/10	8/19/10	10/1/10
BH	<0.25	<0.25	<0.25	<0.25	<0.25
CC	NS	NS	NS	NS	<0.25
CD	<0.25	<0.25	<0.25	<0.25	<0.25
EH	<0.25	<0.25	<0.25	<0.25	<0.25
MC	<0.25	<0.25	<0.25	<0.25	<0.25
MS	<0.25	<0.25	0.5	1.0	<0.25
PB	<0.25	<0.25	<0.25	<0.25	<0.25
PI	<0.25	Dry	Dry	Dry	<0.25
PP	<0.25	<0.25	<0.25	0.3	<0.25
S4	<0.25*	<0.25	NS	0.25	NS
SB	<0.25	<0.25	<0.25	<0.25	<0.25
SBT	<0.25	<0.25	<0.25	<0.25	<0.25
SC	<0.25	<0.25	<0.25	<0.25	<0.25
VI	<0.25	1.0	1.0	1.0	0.25

NS = no sample collected: * = mixed with Winooski River floodwaters

The study did not adequately characterize phosphorus concentrations in the large area of drained cropland in the Winooski River floodplain on and surrounding Pine Island. The primary stream in this area is referred to as Stream 4. This stream was sampled at site PI on Pine Island Road and at site S4 in Macrea Farm Park. Unfortunately site PI was dry on the summer sampling dates and site S4, a low gradient slough, was a problematic site due to backwater conditions and stagnant water impounded by beaver dams. We found no other publically accessible sampling locations to this stream. The only samples collected at site PI, on March 23 and October 1, had moderately high TP and DP concentrations. Based on these results, further monitoring of this stream during high groundwater conditions in the spring may be warranted.

4.3. Statistical associations between phosphorus concentrations and land use

Table 13 summarizes the statistical fit of the multiple regression models and provides estimates for each term in the multiple regression equations.

Comparison of R^2 (coefficient of determination) values among regression models suggested that no set of land use variables tested in this study was consistently the best predictor of DP and TP concentrations. The two variables that were most often significant among the models tested were All Agricultural Land (%) and Population Density. Inclusion of the Forest/shrub variable with All Agricultural Land and Population Density resulted in marginal improvement in the models for most dates. With these three independent variables, the multiple regression equation can be written as:

DP or TP conc. = Intercept + β_1 x All Agricultural Land + β_2 x Forest/Shrub + β_3 x Population Density + ε,
where β_1, β_2, and β_3 are the regression coefficients (partial slopes) for the three independent variables and ε is the statistical error.

The percentage of All Agricultural Land, percentage of Forest/shrub, and Population Density explained 54% of the variation in DP concentration on October 1 and more than 90% of the variation on March 23, May 24, and August 19 (Table 13). These variables explained 95% of the variation in TP concentration on May 24, 84% on August 3, and 97% on August 19. However, the variables failed to explain the variation in TP concentration on March 23 ($R^2 = 0.10$) and October 1 ($R^2 = 0.06$), the two wet weather flow events. No combination of land use variables had power to explain the variation in TP concentration on these dates. This result and the exceedingly high turbidity readings at certain sites on these dates suggest that the source of total phosphorus on these dates was not primarily runoff from the contributing watersheds. **During these high flow events, total phosphorus concentration in the stream may be more a function of stream channel erosion than surrounding land use.**

Table 13. Summary of fit and parameter estimates for regression models

Parameter estimates in bold are significant at p < 0.10. Estimates in bold and underlined are significant at p < 0.05.

Response DP (µg/L) on 3/23/10

Summary of Fit		Parameter Estimates				
RSquare	0.93	Term		Agriculture (%)	Forest/shrub (%)	Pop. density (#/ha)
RSquare Adj	0.90	Estimate	5.64	**<u>0.44</u>**	0.12	**<u>1.98</u>**
Root Mean Square	7.23	Std Error	6.22	0.10	0.09	0.22
Mean of Response	29.70	t Ratio	0.91	4.16	1.32	8.88
Observations	12	Prob>|t|	0.3911	0.0032	0.2242	<0.0001

Response TP (µg/L) on 3/23/10

Summary of Fit		Parameter Estimates				
RSquare	0.10	Term	Intercept	Agriculture (%)	Forest/shrub (%)	Pop. density (#/ha)
RSquare Adj	-0.24	Estimate	167.56	3.58	2.83	2.04
Root Mean Square	327.91	Std Error	282.21	4.75	4.02	10.14
Mean of Response	367.25	t Ratio	0.59	0.75	0.70	0.20
Observations	12	Prob>|t|	0.5691	0.4722	0.5010	0.8452

Response DP (µg/L) on 5/24/10

Summary of Fit		Parameter Estimates				
RSquare	0.95	Term	Intercept	Agriculture (%)	Forest/shrub (%)	Pop. density (#/ha)
RSquare Adj	0.93	Estimate	-25.46	**<u>1.02</u>**	0.31	**<u>5.88</u>**
Root Mean Square	17.44	Std Error	15.03	0.26	0.21	0.54
Mean of Response	39.51	t Ratio	-1.69	3.91	1.47	10.89
Observations	12	Prob>|t|	0.1287	0.0045	0.1801	<0.0001

Response TP (µg/L) on 5/24/10

Summary of Fit		Parameter Estimates				
RSquare	0.95	Term	Intercept	Agriculture (%)	Forest/shrub (%)	Pop. density (#/ha)
RSquare Adj	0.93	Estimate	-30.09	**<u>1.85</u>**	**0.65**	**<u>9.55</u>**
Root Mean Square	27.11	Std Error	23.36	0.41	0.33	0.84
Mean of Response	84.84	t Ratio	-1.29	4.54	1.95	11.40
Observations	12	Prob>|t|	0.2337	0.0019	0.0867	<0.0001

Response TP (µg/L) on 8/3/10

Summary of Fit		Parameter Estimates				
RSquare	0.84	Term	Intercept	Agriculture (%)	Forest/shrub (%)	Pop. density (#/ha)
RSquare Adj	0.77	Estimate	-5.27	**<u>4.07</u>**	0.55	**<u>9.80</u>**
Root Mean Square	58.84	Std Error	50.98	1.41	0.73	1.83
Mean of Response	129.80	t Ratio	-0.10	2.89	0.75	5.36
Observations	11	Prob>|t|	0.9205	0.0233	0.4763	0.001

Response DP (µg/L) on 8/19/10

Summary of Fit		Parameter Estimates				
RSquare	0.97	Term	Intercept	Agriculture (%)	Forest/shrub (%)	Pop. density (#/ha)
RSquare Adj	0.96	Estimate	**-50.76**	**<u>1.08</u>**	**0.64**	**<u>12.52</u>**
Root Mean Square	26.87	Std Error	23.15	0.40	0.33	0.83
Mean of Response	66.76	t Ratio	-2.19	2.67	1.93	15.06
Observations	12	Prob>|t|	0.0597	0.0282	0.0892	<0.0001

Response TP (µg/L) on 8/19/10

Summary of Fit		Parameter Estimates				
RSquare	0.97	Term	Intercept	Agriculture (%)	Forest/shrub (%)	Pop. density (#/ha)
RSquare Adj	0.95	Estimate	-44.05	**<u>1.52</u>**	0.59	**<u>13.87</u>**
Root Mean Square	33.98	Std Error	29.28	0.51	0.42	1.05
Mean of Response	86.77	t Ratio	-1.50	2.99	1.41	13.20
Observations	12	Prob>|t|	0.1709	0.0173	0.1973	<0.0001

Response DP (µg/L) on 10/1/10

Summary of Fit		Parameter Estimates				
RSquare	0.54	Term	Intercept	Agriculture (%)	Forest/shrub (%)	Pop. density (#/ha)
RSquare Adj	0.39	Estimate	1.10	**<u>1.60</u>**	0.53	**2.28**
Root Mean Square	35.27	Std Error	30.35	0.51	0.43	1.09
Mean of Response	66.15	t Ratio	0.04	3.14	1.24	2.09
Observations	13	Prob>|t|	0.9720	0.0119	0.2463	0.0657

Response TP (µg/L) on 10/1/10

Summary of Fit		Parameter Estimates				
RSquare	0.06	Term	Intercept	Agriculture (%)	Forest/shrub (%)	Pop. density (#/ha)
RSquare Adj	-0.26	Estimate	444.77	5.64	3.71	-5.81
Root Mean Square	931.00	Std Error	801.05	13.46	11.29	28.79
Mean of Response	683.50	t Ratio	0.56	0.42	0.33	-0.20
Observations	13	Prob>|t|	0.5923	0.6850	0.7498	0.8444

Comparing the significance of regression coefficients is another way to assess the explanatory power of the independent variables. In Table 13, coefficients in bold face are significant at $p < 0.10$ and coefficients in bold and underlined are significant at $p < 0.05$. Coefficients for both the All Agricultural Lands and the Population Density variables were significant in all four regression models using DP concentration as the dependent variable and in three of the five models using TP concentration as the dependent variable. With the exception of the very poor model for TP concentration on October 1, coefficients for both All Agricultural Lands and Population Density were positive in every case, meaning that an increase in either the agricultural land area or the population density is associated with an increase in DP and TP. The Forest/shrub variable was never statistically significant at the $p < 0.05$ level and was only significant at $p < 0.10$ in two models, TP concentration on May 24 and DP concentration on August 19. Whether a significant variable or not, the sign of the coefficient for Forest/shrub was positive in all nine models described in Table 13, indicating that increase in the forest land area is associated with increased DP and TP. While positive, the Forest/shrub coefficient was substantially lower that the All Agricultural Land coefficient in all nine models, which indicates that **a given percentage of watershed area in agriculture is associated with a higher phosphorus concentration that the same percentage of land area in forest**. Stated differently, both agricultural land and forest land are sources of phosphorus, but **streams draining watersheds with more agricultural land have higher phosphorus concentrations than streams draining more forested watersheds**.

The coefficients for the Population Density variable are not directly comparable to the coefficients for All Agricultural Land and Forest/shrub. The sign of the Population Density coefficient is positive in every case except the model for TP concentration on October 1. This indicates that **streams draining watersheds with higher population density have higher phosphorus concentration**s. This result must be interpreted with some caution, because **there are many related factors not captured in the final models that are presumably correlated with population density, such as construction activities, impacts of roads (alteration of runoff flow paths, erosion of road ditches, increased impervious surface area), density of onsite wastewater systems, stream channel alteration, et cetera**. The Population Density variable is an overall measure of the intensity of residential development. With many more sampling sites the multitudinous impacts of land development might be separately resolved, but in this study Population Density was the only variable related to development that had reasonable statistical power.

Finally, in the exploratory, step-wise regression analysis wetland variables were significant in several of the models. Herbaceous Wetlands and All Wetlands Plus Open Water (lakes and ponds) entered more step-wise models than Forested Wetlands, Open Water alone, or other combinations. Because Herbaceous Wetlands were correlated with All Agricultural Land and because the power of the wetland variables were highly inconsistent across sampling dates, wetland variables were not included in the final models presented in Table 13. However, **there was some support in these data for the finding by some researchers that wetlands can act as a sink for P in the landscape under certain conditions** (Windhausen et al, 2003; Jordan et al., 1986; Nixon and Lee, 1986; Johnston, 1991). Where a wetland

variable entered the step-wise model, the sign of the coefficient was usually negative (except for the poor TP model on October 1), which suggests that an increase in wetlands area is associated with decreased DP and TP concentrations. A more extensive sampling program would be required to resolve the net impact of wetlands on stream phosphorus concentrations in Colchester.

5. MANAGEMENT IMPLICATIONS OF FINDINGS

During the dry weather events and for the moderate wet weather event of August 3, 2010 strong associations were found between total phosphorus concentrations and agricultural land and population density. The main conclusion to draw from these results is that **it appears major land uses are controlling stream phosphorus concentrations under most conditions**. However, the highest total phosphorus concentrations measured in this study occurred during the high flow events of March 23 and October 1 and land use variables were poor predictors of total phosphorus concentrations on these events.

During the March 23 and October 1 high flow events, the turbidity was very high in the small tributaries of Pond Brook (site EH) and Sunderland Brook (site SBT) sampled at Route 7. Turbidity was moderately high at sites MC, MS, S4, SB, SC, and PI. Dissolved phosphorus concentrations were small fractions of the total at these sites on these dates, except for site PI on October 1 where DP was elevated. A strong correlation was documented between turbidity and total phosphorus concentration at all sites except VI. Therefore, a second general conclusion is that **high total phosphorus concentrations measured during the spring and fall high flow events were due to sediment transport, and that other (not quantified) factors had greater impact on sediment and total phosphorus concentrations than land use during high flow events**. The factors contributing to high turbidity and high total phosphorus concentration during high flow events could not be investigated in this study. However, we suspect that stream channel adjustments are a major source of the phosphorus under high flow conditions. Figure 5 shows active channel adjustment in unconsolidated sediments of Sunderland Brook upstream of the Route 7 crossing. Whether from historic or modern sources, there is evidentially a great deal of sediment storage in this reach and the lack of vegetation along the active channel makes these sediments prone to erosion. These conditions may contribute sediment and phosphorus to the stream for many years to come.

Figure 5. Sunderland Brook upstream of the Route 7 crossing

While total phosphorus can contribute to water quality impairment after release from sediments and organic matter in the receiving environment, elevated dissolved phosphorus concentrations are of more certain and immediate concern, because most forms of dissolved phosphorus are immediately available for uptake by algae and aquatic plants, contributing to eutrophic conditions in receiving waters. Dissolved phosphorus concentrations in streams should be low, especially under dry weather conditions when stream baseflows are sustained by groundwater discharge. The stormwater outfall from the Village Drive neighborhood (site VI) had very high dissolved phosphorus concentration during the dry weather sampling dates, 240 µg /L on May 24 and 515 µg /L on August 19. We did not establish the cause of the elevated dissolved phosphorus at this site, but we speculate that malfunctioning onsite wastewater treatment systems may contribute dissolved phosphorus to the Village Drive stormdrain. This speculation is supported by elevated *E. coli* levels (reported separately) and ammonia concentrations at the outfall. Site EH also had moderately elevated dry weather dissolved phosphorus concentrations; livestock impacts observed immediately upstream may have contributed to these elevated concentrations.

The Champlain Drive (CD) sampling location on a southern tributary of Sunderland Brook is an interesting example of a highly impervious watershed (34%) with relatively low total and dissolved phosphorus concentrations and turbidity on the sampling dates. Site CD is illustrated in Figure 6. This watershed is mainly commercial and industrial; the residential population density is low (0.11 person/hectare). Many of the commercial properties have stormwater ponds and there are wetlands present along much of the stream channel length. Although stormwater ponds were not considered in the watershed statistical analysis and wetland areas were rarely significant in regression models, based on these data **we suspect that stormwater management practices and riparian wetlands are dampening peak flows and reducing sediment and phosphorus transport from this watershed. The DP and TP**

concentration data at this site were substantially lower than at site SBT, which is also a small tributary to Sunderland Brook, but which lacks stormwater ponds.

Figure 6. Sunderland Brook Tributary at Champlain Drive (site CD)

Given the preliminary nature of this study, we cannot recommend highly specific management actions based on these results. **Agricultural land and population density appear to control phosphorus transport under low and moderate flow conditions. A whole range of agricultural and urban best management practices may be implemented to reduce these contributions.** Most agricultural management practices related to water quality protection are implemented through state and federal programs, with less involvement by municipal government. However, **one critical agricultural practice that the Town of Colchester could affect is livestock exclusion from stream channels, which is a problem near site EH and likely in other areas as well**. Livestock exclusion improves stream habitat and can reduce animal wastes and phosphorus discharge to the stream (Meals, 2001). Livestock exclusion may be required and enforced under municipal law. The study was not able to adequately characterize phosphorus concentrations in the large area of drained cropland in the Winooski River floodplain on and surrounding Pine Island; therefore, further monitoring in this area is recommended.

Strong associations were found between population density and dissolved phosphorus concentration under all monitored flow conditions and between population density and total phosphorus under low flow conditions. While this is a meaningful scientific result, it is not a particularly useful result from the standpoint of water quality management. Among the three small urban watersheds (sites CD, PP, and VI), high phosphorus concentrations were only found at site VI; site VI has a similar percentage of impervious surface (37%) to sites CD and PP but a higher population density. **Site**

VI represents a phosphorus critical source area and the source of the elevated phosphorus (and *E. coli* and ammonia) concentrations should be investigated.

The generally low phosphorus concentrations measured at site CD suggest that conventional stormwater management and naturally occurring wetlands and ponds in this watershed are mitigating the effects of stormwater runoff. Although not supported by exhaustive data, this is a recommendation for stormwater treatment. However, **an equally important result occurred during site selection when it became obvious that there were no streams to sample west of Church Road. Precipitation and most of the collected stormwater in this area infiltrates the ground. Successfully infiltrating stormwater eliminates urban runoff and the associated loading of phosphorus and other contaminants to surface waterbodies**.

Overall, the results, although not definitively conclusive, are consistent with expected results in Lake Champlain tributaries. The detailed findings documented herein reinforce the prevailing scientific understanding of stormwater processes in the basin: that **streams draining watersheds dominated by agricultural and/or higher density residential land uses tend to have elevated phosphorus concentrations relative to reference (forested) conditions**. The results also suggest that **stream channel adjustment may be a dominant source of total phosphorus under high flow conditions. Runoff during wet weather events may be mitigated by increased application of stormwater treatment systems in developed areas and best management practices for agricultural land**.

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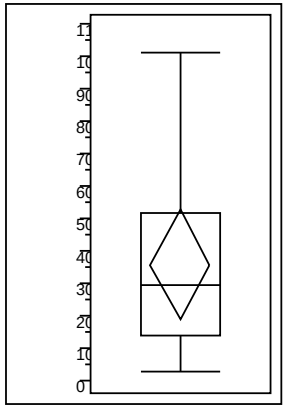
APPENDICES

APPENDIX A: DISTRIBUTION OF TOTAL PHOSPHORUS CONCENTRATIONS AMONG MONITORING SITES

Distributions

TP (ug/L) 3/23/10



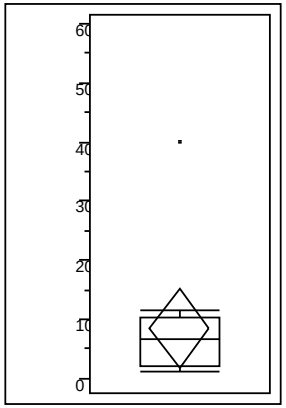
Quantiles

100.0%	maximum	1010
99.5%		1010
97.5%		1010
90.0%		888
75.0%	quartile	518.5
50.0%	median	298
25.0%	quartile	139.65
10.0%		29.74
2.5%		27.3
0.5%		27.3
0.0%	minimum	27.3

Moments

Mean	359
Std Dev	283.87217
Std Err Mean	78.731956
Upper 95% Mean	530.54224
Lower 95% Mean	187.45776
N	13

TP (ug/L) 5/24/10



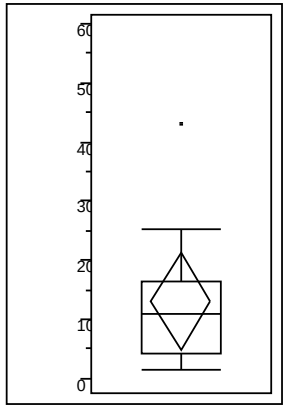
Quantiles

100.0%	maximum	400
99.5%		400
97.5%		400
90.0%		314.8
75.0%	quartile	102.625
50.0%	median	65.775
25.0%	quartile	21.225
10.0%		12.05
2.5%		11.6
0.5%		11.6
0.0%	minimum	11.6

Moments

Mean	84.8375
Std Dev	105.31136
Std Err Mean	30.400798
Upper 95% Mean	151.74914
Lower 95% Mean	17.92586
N	12

TP (ug/L) 8/3/10



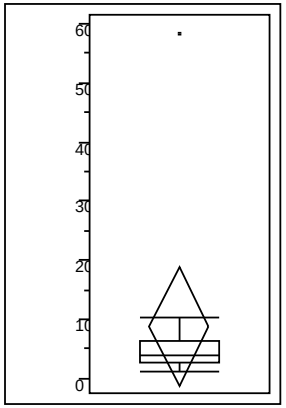
Quantiles

100.0%	maximum	428
99.5%		428
97.5%		428
90.0%		392.8
75.0%	quartile	163
50.0%	median	108
25.0%	quartile	40.6
10.0%		18.3
2.5%		15.3
0.5%		15.3
0.0%	minimum	15.3

Moments

Mean	129.8
Std Dev	121.46997
Std Err Mean	36.624545
Upper 95% Mean	211.40457
Lower 95% Mean	48.195429
N	11

TP (ug/L) 8/19/10



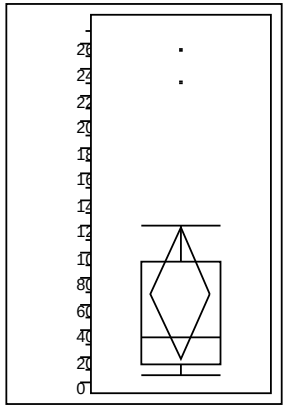
Quantiles

100.0%	maximum	582
99.5%		582
97.5%		582
90.0%		438.6
75.0%	quartile	62.025
50.0%	median	37.65
25.0%	quartile	26.675
10.0%		12.57
2.5%		10.5
0.5%		10.5
0.0%	minimum	10.5

Moments

Mean	86.766667
Std Dev	157.86302
Std Err Mean	45.571245
Upper 95% Mean	187.0683
Lower 95% Mean	-13.53497
N	12

TP (ug/L) 10/1/10



Quantiles

100.0%	maximum	2540
99.5%		2540
97.5%		2540
90.0%		2444
75.0%	quartile	930
50.0%	median	344
25.0%	quartile	148
10.0%		53.9
2.5%		52.5
0.5%		52.5
0.0%	minimum	52.5

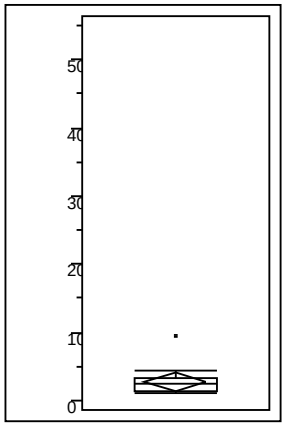
Moments

Mean	683.5
Std Dev	830.464
Std Err Mean	230.329
Upper 95% Mean	1185.34
Lower 95% Mean	181.655
N	13

APPENDIX B: DISTRIBUTION OF DISSOLVED PHOSPHORUS CONCENTRATIONS AMONG MONITORING SITES

Distributions

DP (ug/L) 3/23/10



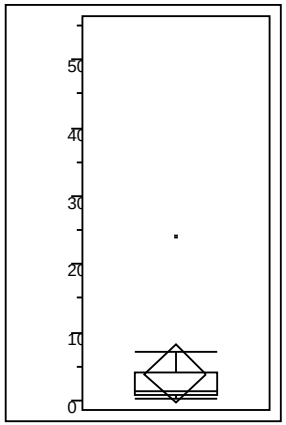
Quantiles

100.0%	maximum	94.1
99.5%		94.1
97.5%		94.1
90.0%		74.58
75.0%	quartile	32.2
50.0%	median	24.1
25.0%	quartile	14.05
10.0%		10.898
2.5%		9.83
0.5%		9.83
0.0%	minimum	9.83

Moments

Mean	28.375385
Std Dev	22.100375
Std Err Mean	6.129457
Upper 95% Mean	41.730326
Lower 95% Mean	15.020443
N	13

DP (ug/L) 5/24/10



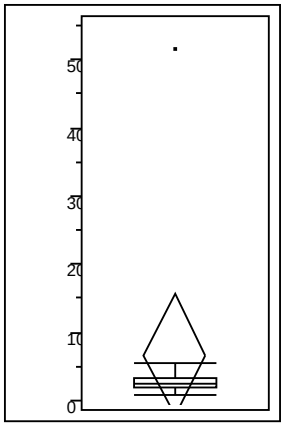
Quantiles

100.0%	maximum	240
99.5%		240
97.5%		240
90.0%		189.12
75.0%	quartile	41.275
50.0%	median	15.1
25.0%	quartile	9.595
10.0%		3.853
2.5%		2.5
0.5%		2.5
0.0%	minimum	2.5

Moments

Mean	39.505833
Std Dev	65.975622
Std Err Mean	19.045521
Upper 95% Mean	81.424743
Lower 95% Mean	-2.413077
N	12

DP (ug/L) 8/19/10



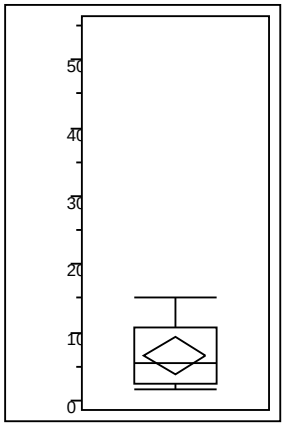
Quantiles

100.0%	maximum	515
99.5%		515
97.5%		515
90.0%		376.94
75.0%	quartile	33.975
50.0%	median	26
25.0%	quartile	18.025
10.0%		11.339
2.5%		9.47
0.5%		9.47
0.0%	minimum	9.47

Moments

Mean	66.755833
Std Dev	141.65361
Std Err Mean	40.891874
Upper 95% Mean	156.75824
Lower 95% Mean	-23.246577
N	12

DP (ug/L) 10/1/10



Quantiles

100.0%	maximum	152
99.5%		152
97.5%		152
90.0%		142
75.0%	quartile	107
50.0%	median	55.1
25.0%	quartile	24.2
10.0%		16.56
2.5%		15.6
0.5%		15.6
0.0%	minimum	15.6

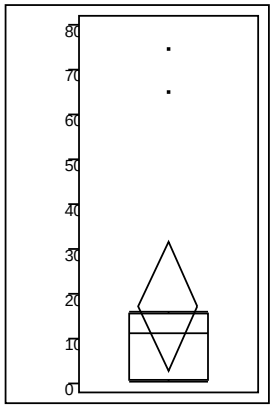
Moments

Mean	66.153
Std Dev	45.090
Std Err Mean	12.505
Upper 95% Mean	93.401
Lower 95% Mean	38.906
N	13

APPENDIX C: DISTRIBUTION OF TURBIDITY AMONG MONITORING SITES

Distributions

Turbidity (NTU) 3/23/10



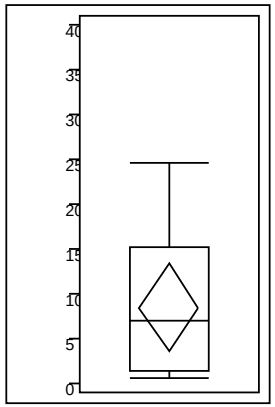
Quantiles

100.0%	maximum	745
99.5%		745
97.5%		745
90.0%		705.8
75.0%	quartile	154.5
50.0%	median	111
25.0%	quartile	7.09
10.0%		3.032
2.5%		2.54
0.5%		2.54
0.0%	minimum	2.54

Moments

Mean	172.46846
Std Dev	240.11418
Std Err Mean	66.595692
Upper 95% Mean	317.56801
Lower 95% Mean	27.368913
N	13

Turbidity (NTU) 5/24/10



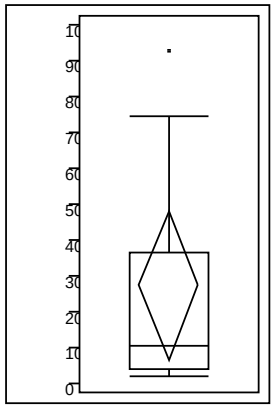
Quantiles

100.0%	maximum	24.6
99.5%		24.6
97.5%		24.6
90.0%		21.99
75.0%	quartile	15.25
50.0%	median	7.06
25.0%	quartile	1.355
10.0%		0.678
2.5%		0.63
0.5%		0.63
0.0%	minimum	0.63

Moments

Mean	8.4866667
Std Dev	7.5807344
Std Err Mean	2.1883656
Upper 95% Mean	13.303235
Lower 95% Mean	3.6700979
N	12

Turbidity (NTU) 8/3/10



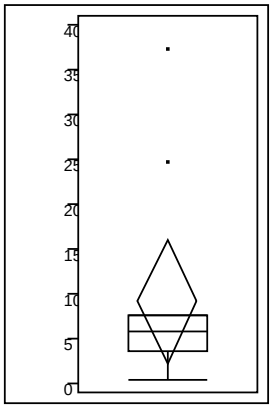
Quantiles

100.0%	maximum	92.7
99.5%		92.7
97.5%		92.7
90.0%		89.02
75.0%	quartile	36.4
50.0%	median	10.32
25.0%	quartile	4.19
10.0%		2.11
2.5%		1.98
0.5%		1.98
0.0%	minimum	1.98

Moments

Mean	27.335455
Std Dev	30.946367
Std Err Mean	9.3306858
Upper 95% Mean	48.125507
Lower 95% Mean	6.5454021
N	11

Turbidity (NTU) 8/19/10



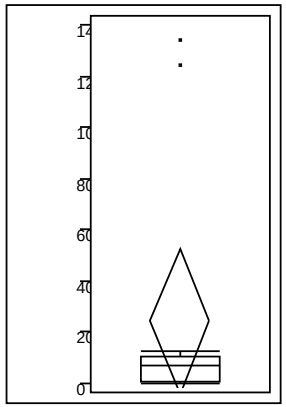
Quantiles

100.0%	maximum	37.3
99.5%		37.3
97.5%		37.3
90.0%		33.49
75.0%	quartile	7.54
50.0%	median	5.825
25.0%	quartile	3.58
10.0%		0.608
2.5%		0.35
0.5%		0.35
0.0%	minimum	0.35

Moments

Mean	9.1041667
Std Dev	10.79243
Std Err Mean	3.1155063
Upper 95% Mean	15.96135
Lower 95% Mean	2.2469835
N	12

Turbidity (NTU) 10/1/10



Quantiles

100.0%	maximum	1340
99.5%		1340
97.5%		1340
90.0%		1300.8
75.0%	quartile	108.45
50.0%	median	71
25.0%	quartile	8.89
10.0%		5.038
2.5%		3.43
0.5%		3.43
0.0%	minimum	3.43

Moments

Mean	242.6584
Std Dev	467.2794
Std Err Mean	129.6
Upper 95% Mean	525.0326
Lower 95% Mean	-39.71567
N	13