Prepared in cooperation with the
Vermont Department of Environmental Conservation

Effects of Urban Best Management Practices on Streamflow and Phosphorus and Suspended-Sediment Transport on Englesby Brook in Burlington, Vermont, 2000–2010

Scientific Investigations Report 2012–5103

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By Laura Medalie

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U.S. Geological Survey
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Contents

Figures

Tables

Conversion Factors, Datum, and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
short ton per day (ton/d)	0.9072	metric ton per day (t/d)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

ANCOVA	analysis of covariance
BMP	best management practice
DEC	Vermont Department of Environmental Conservation
ED	extended detention
GCLAS	Graphical Constituent Loading Analysis System
LOADEST	Load Estimator program
LOWESS	locally weighted scatterplot smoothing
MDV	mean daily value
SSC	suspended-sediment concentration
TSS	total suspended solids
USGS	U.S. Geological Survey

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Effects of Urban Best Management Practices on Streamflow and Phosphorus and Suspended-Sediment Transport on Englesby Brook in Burlington, Vermont, 2000–2010

By Laura Medalie

Abstract

An assessment of the effectiveness of several urban best management practice structures, including a wet extended detention facility and a shallow marsh wetland (together the "wet extended detention ponds"), was made using data collected from 2000 through 2010 at Englesby Brook in Burlington, Vermont. The purpose of the best management practices was to reduce high streamflows and phosphorus and suspended-sediment loads and concentrations and to increase low streamflows. Englesby Brook was monitored for streamflow, phosphorus, and suspended-sediment concentrations at a streamgage downstream of the best management practice structures for 5 years before the wet extended detention ponds were constructed in 2005 and for 4 years (phosphorus and suspended-sediment concentrations) or 5 years (streamflow) after they were constructed.

The period after construction of the best management practice structures was wetter and had higher discharges than the period before construction. Despite the wetter conditions, streamflow duration curves provided evidence that the streamflow regime appeared to have shifted so that the percentages of low streamflows have increased and those of high streamflows may have slightly decreased. Two other hydrologic measures showed improvements in the years following construction of the best management practices: the percentage of annual discharge transported during the 3 days with highest discharges and the number of days with zero streamflow have both decreased.

Evidence was mixed for the effectiveness of the best management practices in reducing phosphorus and suspended-sediment concentrations and loads. Annual phosphorus and suspended-sediment loads, monthly loads, low-streamflow concentrations, storm-averaged streamflow-adjusted concentrations, and total storm loads either did not change significantly or increased in the period after construction. These results likely were because of the wetter conditions in the period after construction. For example, monthly loads assessed using analysis of covariance, which compensated for the effects of streamflow on loads, suggested no difference in phosphorus or suspended-sediment loads between the two periods, whereas the comparison of monthly loads without factoring in streamflow showed an increase. This result could be viewed as evidence that the ponds may have mitigated the effect of greater discharges in the period after construction by preventing a corresponding increase in loads. In another analysis used to adjust for the difference in discharge between the two comparison periods, annual and monthly load results were grouped into dry and wet years. Large (50 percent) reductions in annual loads were observed when data from dry (or wet) years before construction were compared with data from dry (or wet) years after construction. When paired monthly loads of each constituent were grouped into dry and wet years, approximately the same number of months had increases as did decreases with the magnitudes of the decreases generally larger than the magnitudes of the increases. These differences in magnitude explain the decrease in annual loads for dry and wet years. The close association of phosphorus with suspended-sediment data suggested that most of the phosphorus was in the particulate form and was controlled by suspended-sediment dynamics.

Introduction

Englesby Brook is a 0.9-square mile urban stream in Burlington and South Burlington, Vermont, that flows westward into Burlington Bay of Lake Champlain. The brook received some local attention in the 1990s because it was targeted for restoration as the central component of the settlement of the Pine Street Barge Canal Superfund Site, nearby in Burlington. Decades of urbanization in the Englesby Brook watershed had resulted in increased surface runoff during high streamflows, channel enlargement to accommodate high-energy streamflows, manmade channel modifications, degradation of in-stream habitats, presence of fish barriers, increased concentrations of metals, and reduction in aquatic diversity (Quackenbush, 1995; Center for Watershed

Protection, written commun., 2000). The total maximum daily load study for Englesby Brook in 2007 demonstrates biological impairment for fish and macroinvertebrates caused by stressors associated with stormwater runoff, such as increased watershed and in-stream sediment loads (Vermont Department of Environmental Conservation, 2007). Blanchard Beach, at the outlet of Englesby Brook in Lake Champlain, was closed for several years during the 1990s and 2000s because of elevated concentrations of *Escherichia coli* bacteria.

The Englesby Brook restoration effort had water-quality and hydrologic restoration goals of reducing bacteria and contaminant [toxics, total suspended solids (TSS), nutrients] loads, reducing stream channel erosion, improving stream habitat, and maintaining stream baseflow (Center for Watershed Protection, written commun., 2000). The U.S. Geological Survey (USGS) conducted nutrient, sediment, and hydrological monitoring for this project; the remainder of the monitoring, including bacteria monitoring, was the responsibility of the City of Burlington or the State of Vermont. Although reducing peak flows was not listed as an explicit goal in the Center for Watershed Protection restoration document, the effects of urbanization on flooding is a prominent implied restoration goal.

Restoration included construction of four structural best management practices (BMPs) in the watershed (fig. 1, table 1). Together, these structures treat about 54 percent of runoff from the watershed. In this report, the two structures built in 2005 together are called the “wet extended detention (ED) ponds.” An investigation into the effectiveness of the irrigation pond retrofit, evaluated using data through 2005 collected from Englesby Brook (Medalie, 2007), found in the post-BMP period nonsignificant decreases in phosphorus and suspended-sediment concentrations (SSC) at streamflow

Figure 1. The forebay of the wet extended detention facility that is designed to trap sediment from a redirected segment of Englesby Brook in Burlington, Vermont.

Table 1. Description of structural best management practices built in the Englesby Brook watershed in Burlington, Vermont, between 2001 and 2006.

[BMP, best management practice]

BMP type	Year built	Area treated, in acres
Irrigation pond retrofit	2001–02	152
Wet extended detention facility	2005	118
Shallow marsh wetland	2005	38
2 stormwater treatment ponds	2006	43

greater than 3 cubic feet per second (ft^3/s) and decreases (of mixed significance) in cumulative monthly loads of phosphorus and suspended sediment. Although results presented in this 2012 report represent the integrated effects of all of these efforts in the watershed, the discussion focuses on periods before and after the construction of the wet ED ponds because the completion of the wet ED ponds in 2005 signaled the end of most BMP construction in the watershed (except for two ponds built in 2006 near the headwaters). The wet ED ponds treat a large part of the watershed and are located further downstream and closer to the streamgage than the other BMP structures. Nonstructural efforts led by several local agencies and volunteer groups included public education on lawn care, pet waste, youth education, and low input (of phosphorus) ground care for businesses. Formation of the Chittenden County Regional Stormwater Education Program in 2003 brought in a strong outreach component for area residents with the goal of reducing stormwater pollution into Lake Champlain.

To evaluate the effectiveness of the restoration efforts, in cooperation with the Vermont Department of Environmental Conservation (DEC), the USGS monitored streamflow and collected streamwater samples for water-quality analysis at a streamgage near the outlet of Englesby Brook for water years[1] 2000 through 2010. Medalie (2007) evaluated the first five years of the data collection effort.

Purpose and Scope

This report summarizes data on Englesby Brook streamflow for water years 2000 through 2010, and on loads and concentrations of total phosphorus and suspended sediment for water years 2000 through 2009. The purpose of the report is to investigate, using statistical and nonstatistical tests, whether there were differences in streamflow and in phosphorus and suspended-sediment concentration and loads from Englesby Brook for two distinct periods: before and after the wet ED structural BMPs were built. For most of the before and after construction comparisons, the before construction period was water years 2000 through 2004 and the after construction period was water years 2006 through 2009 for phosphorus and suspended sediment and 2006 through 2010 for streamflow. Data from the year 2005 were omitted from the comparison because construction took place during the summer of that year. For one test that was based on cumulative monthly streamflow and loads, the before-construction period was October 1999 through May 2005 and the after-construction period was June 2005 through September 2009. The effectiveness of the irrigation pond retrofit in 2001–02 as well as other structural and nonstructural (education and outreach) projects, although possibly influential, was not able to be evaluated separately with this study design of a single monitoring station near the mouth of Englesby Brook.

Description of Study Area

Englesby Brook is in western Chittenden County in northwestern Vermont (fig. 2). The brook's headwaters begin in a residential cluster of buildings known as the Redstone Campus of the University of Vermont and the Burlington Country Club areas (fig. 3). Land use in the watershed consists of 40 percent agriculture (including golf course), 34 percent urban (including commercial, industrial, transportation), 18 percent residential, 4 percent forest, and 4 percent water. Greater detail on the study area is provided in a report that provided interim results for this project (Medalie, 2007). It empties into Burlington Bay on the eastern shore of Lake Champlain. Land use in the 0.9-square mile Englesby Brook watershed is primarily suburban residential with many commercial enterprises along Pine Street and Shelburne Road.

Methods of Sampling and Analysis

Sample Collection and Processing

The streamgage consisted of an impoundment created by a 120-degree v-notch weir with a sloping concrete wall (fig. 4). Stream stage was measured above the weir continuously at USGS streamgage 04282815 by a pressure transducer mounted on the concrete wall. Water samples were collected according to protocols from the USGS National Field Manual (U.S. Geological Survey, variously dated). Water samples were collected monthly as either manual grabs (for low streamflows when stream velocity was less than or equal to 1.5 feet per second) or using the equal-width-increment method (for high streamflows). Water samples also were collected during many storms by an automated sampler

[1]A water year is the 12-month period October 1 through September 30 and is designated by the calendar year in which it ends.

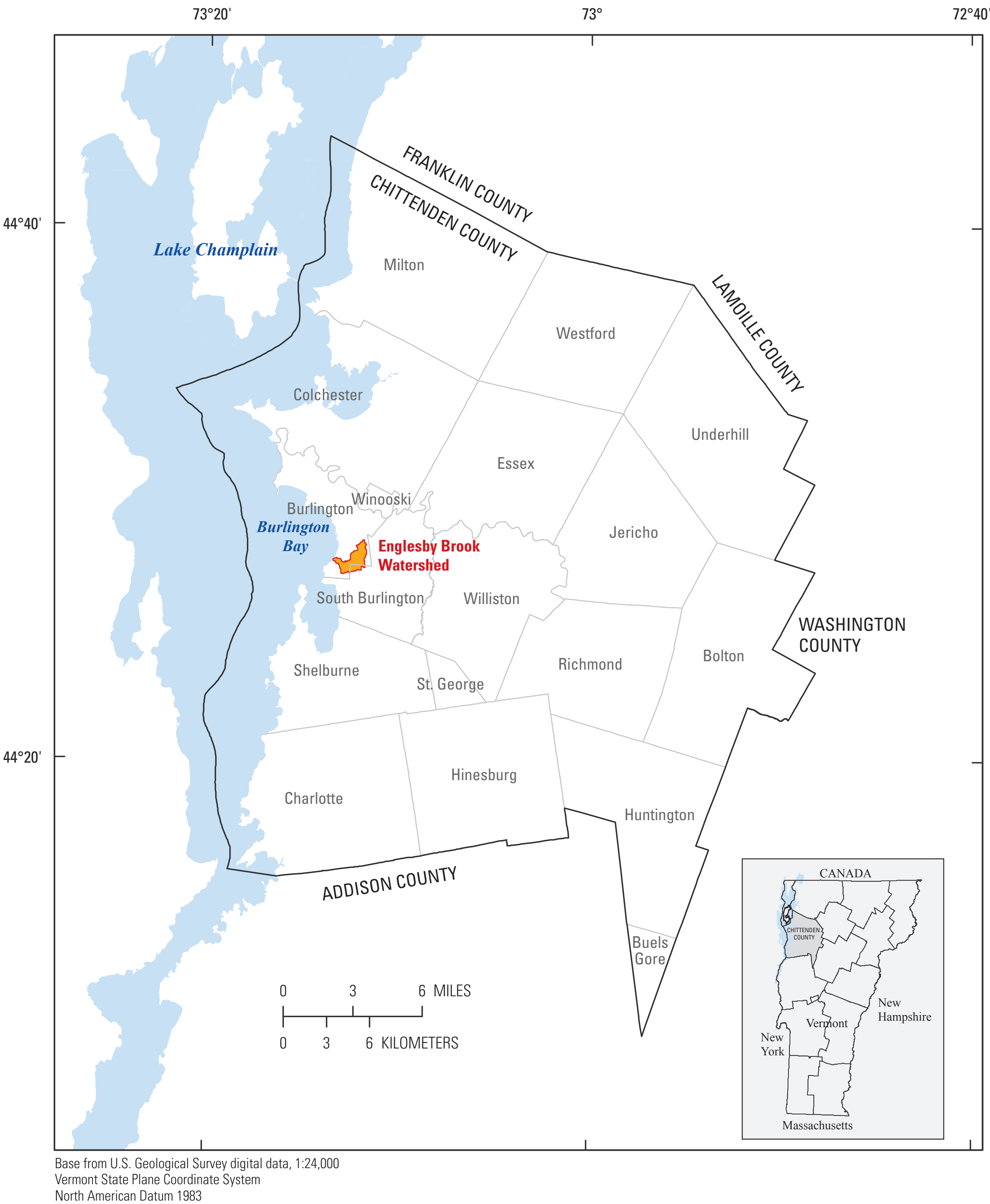

Figure 2. The location of the Englesby Brook watershed in Burlington, Vermont, relative to Lake Champlain and towns in Chittenden County.

Figure 3. Englesby Brook in Burlington, Vermont, and its watershed. The locations of best management practices structures are indicated in yellow. The location of the U.S. Geological Survey streamgage 04282815 is shown with a black diamond.

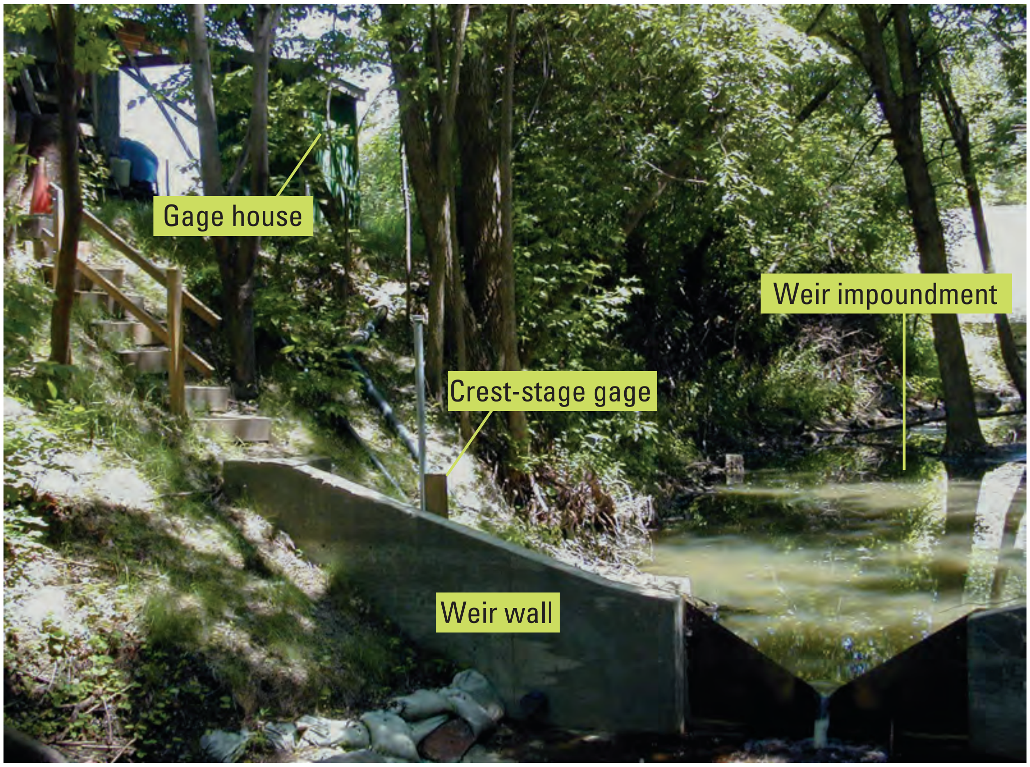

Figure 4. U.S. Geological Survey streamgage 04282815 on Englesby Brook in Burlington, Vermont, from below the weir, looking upstream.

triggered by stage and rates of change threshold values. Samples collected by the automated sampler were analyzed as discrete samples. Between water years 2000 and 2009, 2,153 water samples were collected and analyzed for either or both total phosphorus concentration and TSS or SSC. Of those water samples, about 85 percent were collected using the automated sampler during high-flow events and the rest were collected manually during various streamflow conditions. A detailed description of the study design, sample-collection procedures, analytical procedures, and quality controls can be found in Medalie (2007).

Total phosphorus in water samples was analyzed at the DEC LaRosa laboratory using method number 4500–P H (Eaton and others, 2005). Suspended sediment in water samples was analyzed at the DEC laboratory as TSS using method 2540–D (Eaton and others, 2005) from October 1999 through May 2004. To comply with USGS policy, beginning in February 2001, suspended sediment in water samples was analyzed at the USGS Sediment Laboratory in Louisville, Kentucky, as SSC using a method (Shreve and Downs, 2005) adapted from Guy (1969). During the time period that the two laboratory analyses overlapped, 45 samples that were split and subject to both analyses were used to establish a relation so that SSC could be estimated for the early TSS samples and then used throughout the study. The comparative analyses yielded a coefficient of determination (r^2) of 0.995. Similarly, beginning in June 2008, turbidity was measured in the USGS Montpelier, Vt., laboratory for most of the water samples collected with the automated sampler, from which a subset also was analyzed for SSC. For the concurrent samples of turbidity and SSC, the resulting r^2 (0.93) was used to extend the number of samples that had SSC data. To summarize, all sediment data and analyses in this report, including those analyzed as SSC as well as those estimated from TSS or turbidity, are expressed in terms of SSC.

Load Estimation

Loads of phosphorus and suspended sediment were estimated on a daily basis and for individual storms. The daily loads were then aggregated to monthly and annual loads. Two USGS software programs were used to estimate loads. The Graphical Constituent Loading Analysis System (GCLAS; Koltun and others, 2006) was used to calculate daily loads of phosphorus and suspended sediment for storm days for which the automated sampler captured at least four representative samples from the rise, peak, and recession of the event. Daily loads for low-streamflow periods and nonsampled storm loads were calculated using the USGS Load Estimator (LOADEST) program (Runkel and others, 2004) and were merged with the GCLAS loads to calculate aggregated monthly and annual loads (Medalie, 2007). Between 2006 and 2009, GCLAS was used to calculate loads 9 percent of the time for phosphorus and 5 percent of the time for suspended sediment, which accounted for 27 to 58 percent of total annual loads for phosphorus and 36 to 63 percent of total annual loads for suspended sediment. This hybrid approach was intended to minimize error in estimating continuous loads. When sufficient data were available during measured storms, results from GCLAS were of higher quality compared with those from LOADEST because GCLAS used the observed values to calculate loads, thus capturing the “flashiness” and asymmetry of a small urban stream, which is not a capability of LOADEST (or any other regression-based modeling programs). LOADEST was best suited to filling in the gap between high-streamflow events when sampling did not occur. In addition to daily loads, GCLAS was used to estimate the mean storm discharge and concentration and load of phosphorus and suspended sediment for storm events.

Data Analysis

For all statistical tests, the significance level was established as $\alpha = 0.05$. The nonparametric Wilcoxon rank-sum test was used to test for significant differences among groups of data from the periods before and after the construction (Wilcoxon, 1945). When the median or mean of monthly data were compared for the two groups, for example, when the October median before construction was compared with the October median after construction, the nonparametric Wilcoxon signed-rank test was computed for the paired data (Wilcoxon, 1945). Seasonal differences in stream responsiveness to construction of the wet ED ponds were examined through polynomial regression lines of various hydrologic measures that were fitted using a local weighted scatter plot smoothing (LOWESS) technique (Cleveland and McGill, 1984).

Analysis of covariance (ANCOVA) is a parametric test that can be used to determine whether there is a significant step trend (for example, a discernable increase or decrease in loads) in a long-term dataset when a known event, such as construction of BMP structures that may have impacted water quality or streamflow, has occurred (Helsel and Hirsch, 2002). For the ANCOVA applied to this study, data were divided into two groups corresponding to periods before (October 1999 through May 2005) and after (June 2005 through September 2009) construction of the wet ED ponds in the watershed; monthly loads of phosphorus or suspended sediment were the dependent variable, and average monthly streamflow was the independent variable. The natural logarithms of monthly loads and streamflow were used in the ANCOVA because transformed variables improved the parametric model by increasing linearity, homogenizing the variance, and improving normality of residuals. The double-mass curve graphic visually represents the ANCOVA test by plotting cumulative monthly loads against cumulative monthly streamflow. This gives a visual determination of whether there was a change in the relationship (slope) between the two factors due to the potential step change of the wet ED pond construction.

A visual comparison was made for annual and pairs of monthly phosphorus and suspended sediment loads. Parts of the study period was grouped into dry or wet years based on annual precipitation (moderately dry or wet years were not included). Data from dry years in the before construction period were compared with data from dry years in the after construction period and the same was done for wet years. Because there was only one dry and one wet year before construction, statistical comparisons were not made.

Mean storm concentrations of phosphorus and suspended sediment that were estimated using GCLAS were adjusted to remove possibly confounding effects of streamflow. Regressing the natural logarithm of streamflow as the independent variable and the natural logarithm of phosphorus concentration or SSC as the dependent variable met the assumptions of robust regression models (Helsel and Hirsch, 2002). Residuals of each model, calculated as the observed concentration minus the predicted concentration, created the flow-adjusted average concentrations of phosphorus or suspended sediment for storms; these residuals were grouped as “before” or “after” relative to BMP construction and were compared for statistical significance using the Wilcoxon rank-sum test. There was no need to make streamflow adjustments for phosphorus concentration or SSC for samples collected during low-streamflow conditions because concentrations were not influenced by or related to streamflow.

Final streamflow, phosphorus and suspended-sediment concentration data, field parameters, and all other sample data are stored in the USGS National Water Information Program database. Data can be retrieved from the Englesby Brook project Web site at http://vt.water.usgs.gov/projects/champlain_bmp/index.htm.

Effects of Best Management Practices

This section presents analyses and interpretations for the various techniques of comparing data from the periods before and after construction of the wet ED ponds. Monthly and annual streamflow and loads of phosphorus and suspended sediment are listed in table 2. Results of all statistical tests are listed in table 3.

Table 2. Monthly and annual phosphorus and suspended-sediment loads for water years 2000 through 2009 and average streamflow for water years 2000 through 2010 at Englesby Brook in Burlington, Vermont.

[Annual values for phosphorus and suspended sediment are totals and for streamflow are means]

Year	October	November	December	January	February	March	April	May	June	July	August	September	Annual
	Phosphorus, in metric tons												
2000	0.011	0.004	0.002	0.003	0.033	0.004	0.022	0.064	0.004	0.037	0.006	0.004	0.196
2001	0.001	0.003	0.015	0.000	0.002	0.006	0.069	0.001	0.002	0.000	0.004	0.002	0.106
2002	0.000	0.001	0.001	0.001	0.006	0.005	0.006	0.011	0.024	0.004	0.000	0.014	0.072
2003	0.004	0.012	0.003	0.001	0.001	0.020	0.005	0.008	0.003	0.001	0.001	0.004	0.062
2004	0.012	0.014	0.020	0.004	0.000	0.008	0.006	0.011	0.006	0.040	0.169	0.012	0.303
2005	0.002	0.003	0.014	0.008	0.002	0.005	0.018	0.001	0.008	0.021	0.014	0.004	0.101
2006	0.015	0.012	0.003	0.020	0.001	0.000	0.003	0.061	0.023	0.007	0.008	0.004	0.156
2007	0.020	0.005	0.025	0.003	0.000	0.011	0.011	0.002	0.002	0.010	0.002	0.002	0.093
2008	0.012	0.009	0.005	0.009	0.004	0.011	0.014	0.001	0.010	0.040	0.020	0.001	0.135
2009	0.015	0.002	0.005	0.000	0.002	0.005	0.003	0.010	0.005	0.022	0.006	0.008	0.084
	Suspended sediment, in metric tons												
2000	3.238	1.387	0.894	1.221	18.718	1.452	12.317	53.764	1.564	28.506	3.155	2.838	129.052
2001	0.129	0.830	8.611	0.069	0.659	2.157	33.196	0.544	0.950	0.040	1.977	0.656	49.818
2002	0.028	0.252	0.108	0.173	1.948	1.080	1.621	6.185	15.102	1.725	0.065	6.624	34.909
2003	1.307	4.759	0.627	0.114	0.151	10.272	1.996	4.614	1.453	0.216	0.674	1.675	27.859
2004	7.324	7.929	8.128	1.208	0.007	1.906	2.552	7.635	2.395	26.278	163.885	6.889	236.134
2005	0.881	1.023	8.036	3.358	0.694	2.081	9.023	0.509	5.465	9.941	10.609	1.590	53.210
2006	10.859	5.033	1.124	21.792	0.401	0.128	1.993	48.526	13.026	2.844	4.443	1.681	111.848
2007	9.489	2.201	24.100	1.113	0.037	6.522	8.411	1.109	0.566	5.604	0.952	0.937	61.042
2008	5.738	4.285	2.225	4.920	2.157	6.442	9.514	0.447	22.595	28.398	12.522	0.469	99.713
2009	8.888	0.732	2.054	0.088	1.116	2.049	1.627	7.257	3.548	15.350	4.906	4.223	51.837
	Mean daily streamflow, in cubic feet per second												
2000	0.600	0.387	0.301	0.306	1.590	0.740	2.140	2.130	0.431	0.479	0.361	0.221	0.807
2001	0.087	0.324	0.698	0.095	0.354	0.605	2.990	0.215	0.216	0.018	0.213	0.128	0.495
2002	0.017	0.171	0.118	0.155	0.711	0.536	0.587	0.863	1.490	0.329	0.026	0.632	0.470
2003	0.301	0.909	0.386	0.115	0.048	1.010	0.728	0.704	0.308	0.072	0.062	0.156	0.400
2004	0.684	1.110	1.490	0.400	0.010	0.700	0.781	0.775	0.442	1.110	2.670	0.520	0.891
2005	0.122	0.249	1.070	0.587	0.363	0.547	1.620	0.232	0.482	0.588	0.342	0.133	0.528
2006	1.070	1.050	0.422	1.250	0.230	0.085	0.280	2.150	1.190	0.386	0.375	0.353	0.737
2007	1.290	0.696	1.070	0.563	0.081	1.310	1.220	0.179	0.111	0.436	0.134	0.239	0.611
2008	0.724	0.965	0.727	1.210	0.802	1.590	1.520	0.202	0.471	1.250	0.697	0.093	0.854
2009	0.638	0.380	0.702	0.127	0.517	0.695	0.535	0.728	0.393	0.897	0.227	0.275	0.510
2010	0.239	0.738	0.445	0.430	0.343	1.350	1.030	0.410	0.653	0.139	0.238	0.207	0.519

Table 3. Summary of statistical tests comparing phosphorus and suspended-sediment data from before and after construction of best management practices in the Englesby Brook watershed in Burlington, Vermont, for water years 2000 through 2009.

[Statistical test results refer to the period after construction of wet extended detention ponds in the watershed (2006–2009) relative to the period before construction (2000–2004); Statistical tests are Wilcoxon (1945) or analysis of covariance (ANCOVA)]

Type of data	Statistical test	Statistical test *p*-value	
Precipitation and streamflow			
Total annual precipitation	Wilcoxon rank-sum	0.11	No difference
Pairs of median monthly precipitation	Wilcoxon signed rank	0.03	Increase
Average annual discharge	Wilcoxon rank-sum	0.56	No difference
Pairs of median monthly discharge	Wilcoxon signed rank	0.01	Increase
Pairs of mean monthly discharge	Wilcoxon signed rank	0.47	No difference
Pairs of mean or median monthly discharge divided by precipitation	Wilcoxon signed rank	0.91	No difference
Phosphorus and suspended sediment			
Phosphorus:			
Annual loads	Wilcoxon rank-sum	1.00	No difference
Pairs of median monthly loads	Wilcoxon signed rank	0.05	Increase
Pairs of median monthly loads for dry years	Wilcoxon signed rank	0.27	No difference
Pairs of median monthly loads for wet years	Wilcoxon signed rank	0.73	No difference
Monthly loads[1]	ANCOVA	0.85	No difference
Low-streamflow concentrations	Wilcoxon rank-sum	0.18	No difference
Storm-averaged, flow-adjusted concentrations	Wilcoxon rank-sum	0.08	No difference
Total storm loads	Wilcoxon rank-sum	0.05	Increase
Suspended sediment:			
Annual loads	Wilcoxon rank-sum	0.73	No difference
Pairs of median monthly loads	Wilcoxon signed rank	0.01	Increase
Pairs of median monthly loads for dry years	Wilcoxon signed rank	0.38	No difference
Pairs of median monthly loads for wet years	Wilcoxon signed rank	0.97	No difference
Monthly loads[1]	ANCOVA	0.52	No difference
Low-streamflow concentrations	Wilcoxon rank-sum	0.25	No difference
Storm-averaged, flow-adjusted concentrations	Wilcoxon rank-sum	0.01	Increase
Total storm loads	Wilcoxon rank-sum	<0.01	Increase

[1]For this test only, the before construction period was October 1999 through May 2005 and the after construction period was June 2005 through September 2009.

Streamflow

The 11-year time series of annual precipitation (fig. 5A) and annual discharge (fig. 5B) in Englesby Brook show ranges of values nearly or slightly more than twofold—from 27 to 47 inches for precipitation and from 147 to 329 ft^3/s for discharge. Although a comparison of total annual precipitation was not significantly different in the periods before and after construction of the wet ED ponds (the lack of difference is because of the wet year 2004, which leveraged upward the otherwise relatively dry years before construction), paired values of the monthly medians show that the period after construction was significantly wetter (table 3; National Oceanic and Atmospheric Administration, 2004). Similarly, there was no difference in average annual discharge between the two periods, but paired median monthly discharges indicate a significant increase in the period after construction (fig. 6A, table 3), most noticeable in the fall and winter months. Median annual discharge increased for all months except May in the later period. Mean total snowfall for the months of December, January, and February in the period after construction was greater than mean total snowfall for the same months in the period before construction (by 1.2, 1.3, and 1.8 times for the 3 months). Greater snowfall amounts usually result in more salt and sand applications to roadways and, consequently, additional potential sources of imported sediment into the watershed.

The result of the division of annual stream discharge values by precipitation (fig. 5C) creates a dampened replica of the pattern of annual stream discharge where the range of values becomes narrower and climatic influences are reduced. Normalizing discharge by precipitation also has a marked effect on monthly discharges. Figure 6B and table 3 show that the systematic difference of larger monthly discharges (significant increase of $p = 0.01$) in the period after construction disappears when discharges are normalized by precipitation (no statistical difference). In addition, normalizing monthly discharges underscores decreases in streamflows seen in March and April, the 2 wettest months, perhaps as a result of the presence of the ED ponds.

The pattern of peak values of instantaneous discharge (fig. 5D) nearly replicates the pattern of values of annual discharge (fig. 5B), which indicates that the largest storms have a considerable impact on the total annual discharge. In theory, by increasing storage through BMPs in the watershed, the potentially erosive impact from the largest storms could be mitigated by spreading out concentrated pulses of streamflow and defusing the energy. This was one of the goals of the BMP restoration projects. Data showing the percentage of annual stream discharge carried by the 3 days with the highest amounts of streamflow during each year (fig. 5E) appear to provide evidence for overall reductions in peak streamflow; the discharge for the period before the construction of BMPs ranged between 13 and 20 percent, and the discharge for the period after the construction of BMPs ranged between 6 and 12 percent (with one exception of 21 percent in 2006). However, the same effect could be observed whether peak streamflows were truly reduced or there were more days with high streamflows. Because we know streamflows were higher in the period after construction, the extent that peak streamflows might have been reduced is unclear.

By indicating the percentage of time that the continuum of streamflows in a particular stream were equaled or exceeded, streamflow duration curves can be used to assess changes in the streamflow regime over time. When all streamflows in the period before construction of the wet ED ponds were grouped together and compared with all streamflows in the period after construction, the streamflow duration curve for the period after construction shows a slightly lower percentage of high streamflows [best seen in the inset] and a higher percentage of low streamflows compared with the curve for the period before construction (fig. 7A). The result that there was a lower percentage of high streamflows is especially important given that the period after construction was wetter than the period before construction.

Streamflow duration curves for years with similar precipitation can be compared for the periods before and after construction in an attempt to remove the factor of variable year-to-year precipitation. Two sets of water years were grouped where precipitation within the groups varied by only about 3 percent. The group of years with lower precipitation was 2000, 2007, 2009, and 2010 (precipitations of 37.3, 37.8, 38.1, and 36.8 inches). The group of years with higher precipitation was 2004, 2006, and 2008 (precipitations of 46.4, 47.2, and 45.6 inches). Examining the group with low precipitation (fig. 7B), the streamflow duration curves repeat the effect (fig. 7A) of a lower percentage of high streamflows and a higher percentage of low streamflows in the period after construction compared with the period before construction. For the group of years with high precipitation, there were no clear differences in the streamflow duration curves between the periods before and after construction (fig. 7C); the curve for the period before construction, most of the time, was in between the two curves for the period after construction. Based on this result, the group of years when precipitation was low appears to have had more of an influence on streamflows by the BMPs over the entire period than the second group of years when precipitation was high.

Fitted LOWESS lines of monthly precipitation in the periods before and after construction of the BMPs show that, although precipitation increased in every month in the period after construction, the increases were greatest (at least 30 percent) between December and April (fig. 8, gray lines). LOWESS curves of monthly peak values of instantaneous discharge (fig. 8, blue lines) generally mimicked those of monthly precipitation, except that the peak discharges from August through October were slightly larger in the period before construction compared with the period after construction, suggesting that more storage capacity in the watershed from the wet ED ponds may have attenuated the relative size of peak discharges, especially from flashy summer storms that before construction may have quickly overwhelmed summertime soil moisture deficits and caused runoff directly into the brook.

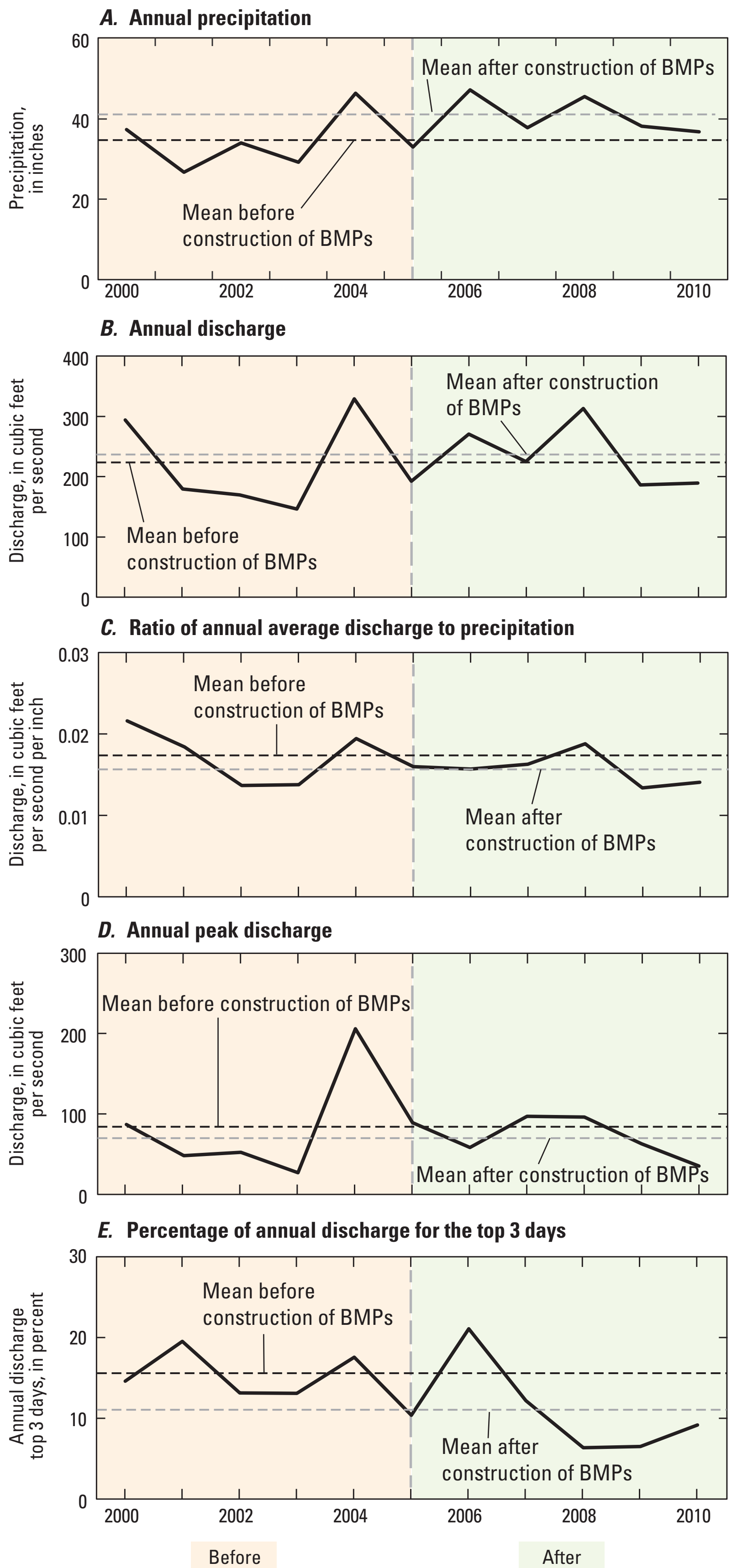

Figure 5. Annual climatic and hydrologic parameters for Englesby Brook in Burlington, Vermont, for water years 2000 through 2010. *A,* Annual precipitation; *B,* annual discharge; *C,* ratio of annual average discharge to precipitation; *D,* annual peak discharge; and *E,* percentage of annual discharge from the sum of the 3 days with the highest discharges. Vertical dashed lines demark periods before (2000–2004) and after (2006–2010) construction of wet extended detention ponds.

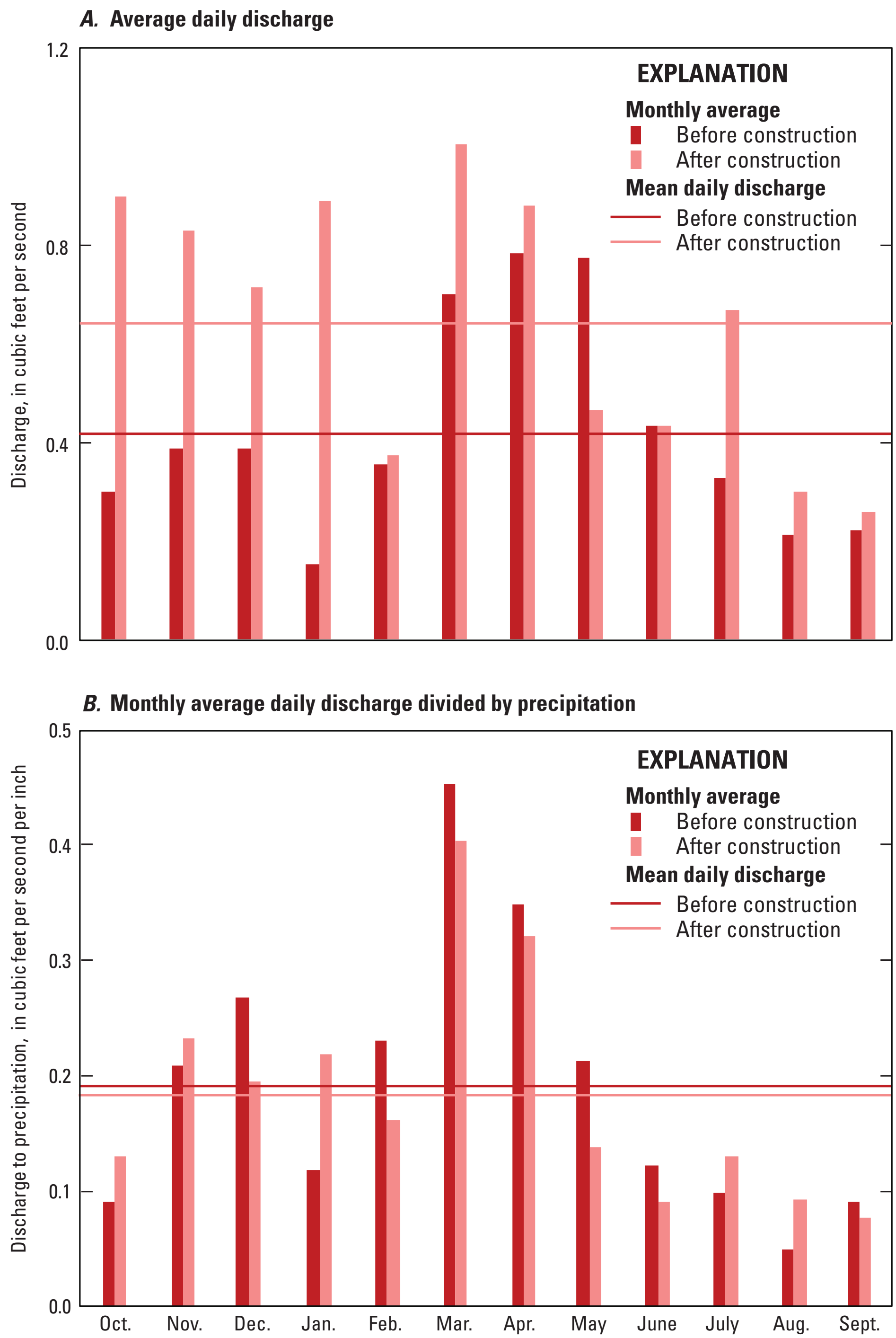

Figure 6. Monthly medians of *A,* average daily discharge and *B,* monthly average daily discharge divided by precipitation before (2000–2004) and after (2006–2010) construction of the wet extended detention ponds at Englesby Brook in Burlington, Vermont, for water years 2000 through 2010.

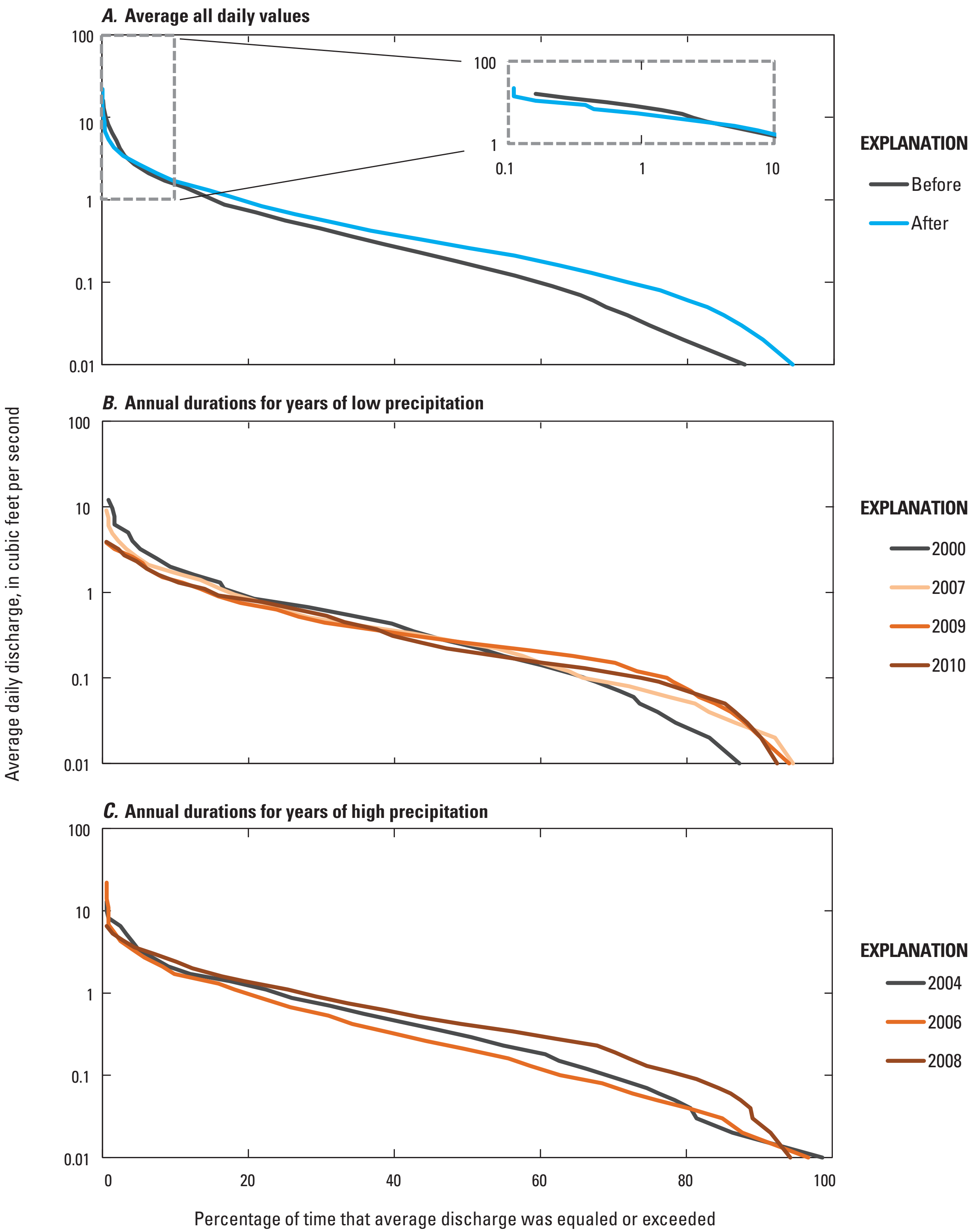

Figure 7. Flow streamflow duration curves for discharge at Englesby Brook in Burlington, Vermont, for water years 2000 through 2010. *A,* Comparison of the average of all daily values in data grouped as before (2000–2004) and after (2006–2010) construction of wet extended detention ponds; *B,* comparison of the annual durations for years with low precipitation (dry years); and *C,* comparison of the annual durations for years with high precipitation (wet years).

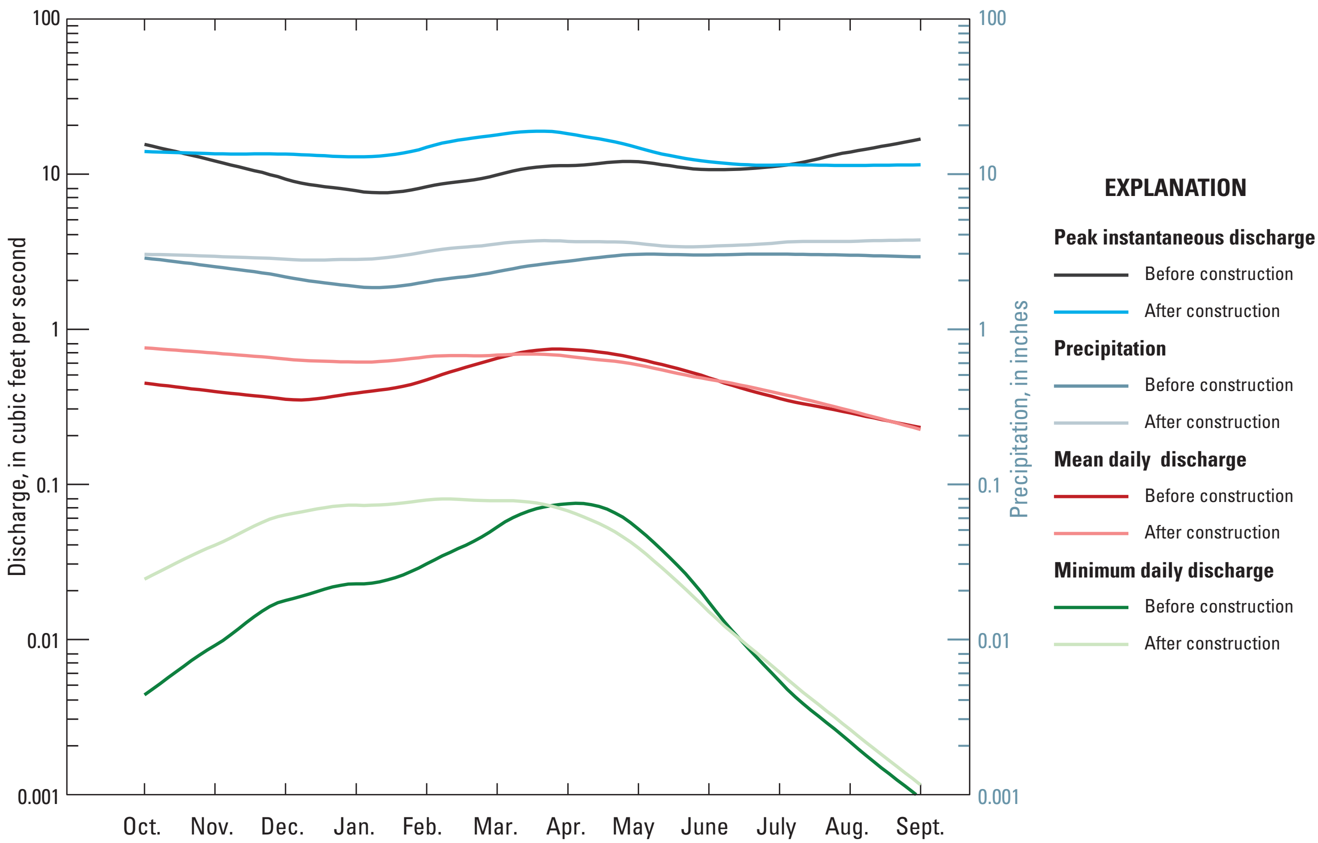

Figure 8. Best-fit lines for peak instantaneous discharge, monthly precipitation, mean daily discharge, and minimum daily discharge before (2000–2004) construction and after (2006–2010) construction of wet extended detention ponds in the Englesby Brook watershed in Burlington, Vermont, for water years 2000 through 2009.

In the case of mean daily streamflows, the largest divergence between the periods before and after construction was from October through February (fig. 8, red lines), where streamflows were greater in the period after construction by 15 to 35 percent more than the corresponding differences in precipitation in the period before construction. Again, we see the importance of the fall and winter months. For the rest of the year there was virtually no difference in mean daily streamflow between the periods before and after construction.

Figures 6A and 8 (red lines) show different results for some individual months because figure 6A presents the median of observed values, and figure 8 shows mean data as a smoothed line. For instance, the July median daily discharge is clearly larger in the period after construction compared with that in the period before construction of the wet ED ponds in figure 6A, but July mean daily discharges appear approximately equal for the two periods in figure 8. The intention of this representation of smoothed LOWESS lines is to provide an overall sense of the general differences in hydrology between the two periods of interest rather than absolute differences.

Minimum daily discharge (fig. 8, green lines) in the period after construction increased substantially between October and February, by as much as 460 percent (logarithmic scale) in October. This increase was a greater percentage, by at least a factor of three, than the increase in precipitation for the same months. Thus, storage provided by the ponds could have contributed to the increase beyond the increased precipitation in the period after construction, although it is difficult to separate effects from storage from effects from wetter weather. This feature addresses an important objective of the BMPs, to increase storage capacity in the watershed in order to increase minimum streamflows for fish survival and to protect the health of aquatic biological communities.

Before construction of the wet ED ponds, Englesby Brook often dried up completely for days or weeks, usually during the summer. In the water years before construction of the wet ED ponds [2000–2003 (2004 was an anomalously wet year with only 5 completely dry days)], the number of days out of the year with mean daily streamflow values (MDV) of zero ranged from 47 to 64; for water years after construction, the number of days where the MDV equaled zero ranged from

12 to 28, and this period after construction included two years (2007 and 2009) that were relatively dry. Worth noting is that days with no streamflow in the period before construction, but had some measurable streamflow in the period after construction, occurred in the fall and winter but not the summer; in other words, improvements in minimum streamflows were not seen in the summer, likely because of the basic lack of water in the watershed either in soil or in the wet ED ponds. In the fall, when evapotranspiration becomes less of a conduit for water out of the watershed, the effect of increasing storage capacity in the watershed became evident in the low- to moderate-streamflow regimes. Although the increase of minimum streamflows in the fall and winter is one step towards restoring biological health, full hydrologic improvements needed to support a sustainable fish community are year-round streamflow and a lessening of the deleterious effects to habitat from scouring during high-streamflow episodic events (Vermont Department of Environmental Conservation, 2007).

Total Phosphorus and Suspended-Sediment Loads and Concentrations

Results for phosphorus and suspended sediment are similar and are presented together. This outcome was expected because phosphorus is commonly attached to sediment particles and is transported with sediment in runoff (Dubrovsky and others, 2010).

Annual Loads

Total annual phosphorus loads ranged from a low of 0.062 metric tons (t) in 2003 to a high of 0.303 t in 2004 (fig. 9; table 2). Total annual suspended-sediment loads ranged from 28 to 236 t for the same years. Phosphorus and suspended-sediment loads were higher by 35 and 45 percent in 2004, an anomalous year compared with those of 2000, the year with the next largest load. After construction of the wet ED ponds, the median values of annual phosphorus and suspended-sediment loads increased (fig. 9); however, the differences in annual loads for phosphorus and suspended sediment were not significant (table 3). Median values were provided as the measure of central tendency because the mean values can be inordinately influenced by outliers. For instance, 51 percent of the 2004 annual suspended-sediment load was transported on a single day, August 31, when instantaneous discharge reached the maximum for the period of record, 206 ft^3/s. This record discharge came about when 1 inch of rain fell onto already saturated ground in the midnight hour on August 31 (National Climatic Data Center, 2004).

Figures 9B and D show the same annual loads rearranged into groups of years that were relatively dry and relatively wet. As stated in the “Streamflow” section, 2000, 2007, and 2009 were all similarly dry, whereas 2004, 2006, and 2008 were all similarly wet. Separate analyses of the periods before and after construction by dry and wet years show approximately 50 percent reductions in annual loads for phosphorus and suspended-sediment loads. This reduction cannot be tested statistically because too few values are available for valid statistical analysis.

Monthly Loads

Median phosphorus and suspended-sediment monthly loads for the periods before and after construction of the wet ED ponds were compared (fig. 10). For all months except May and September for phosphorus and suspended sediment and additionally February for phosphorus, phosphorus and suspended-sediment monthly loads increased after the BMPs were built. Paired monthly loads from the periods before and after construction show that this increase is significant (table 3). This result, which was opposite of the desired goal, can be explained by the median monthly discharge (fig. 6A) that showed a very similar pattern, with conditions month-by-month wetter in the period after construction compared with the period before construction.

It is possible to remove the effect of the wetter period after construction by constructing separate plots of monthly pairs for groups of years that were dry and wet (fig. 11), in a similar approach as was done with annual loads. The bars show either 1 year of data or the average of 2 years (with just two values, the calculation for mean and median are the same). This depiction shows that, for the dry and wet groups of years for loads of phosphorus (fig. 11A) and suspended sediment (fig. 11B), there was no difference between the periods before and after construction of the BMP structures. In contrast to figure 10, there are no cases where the bars for the period after construction are consistently larger than the bars for the period before construction. Indeed, all four graphs comparing phosphorus and suspended-sediment loads for wet and dry years (figs. 11A, B) show that, for several months, the magnitude of the bars for the period before construction is substantially larger than the corresponding bars for the period after construction. The large magnitude of the differences does not impact the nonparametric statistical comparison based on ranks (table 3), but does influence total annual loads (fig. 9). For reference, monthly pairs of precipitation grouped by dry and wet years (fig. 11C), with virtually equal monthly means for the periods before and after construction, also show no systematic difference in the periods before and after construction.

The double-mass curve lines for phosphorus and suspended sediment in figure 12 show that the slopes decreased in the period after construction compared with the period before construction, indicating the potentially improved condition of decreased transport of these constituents relative to streamflow. An important caveat, however, must be noted. A conspicuous break is seen in both graphs of figure 12 in the data for the period before construction (black dots) during which cumulative phosphorus and suspended-sediment loads had large jumps of 0.17 and 164 t, respectively. The large increase in loads occurred in August 2004, which, as previously noted, was the single month with the largest loads and second largest

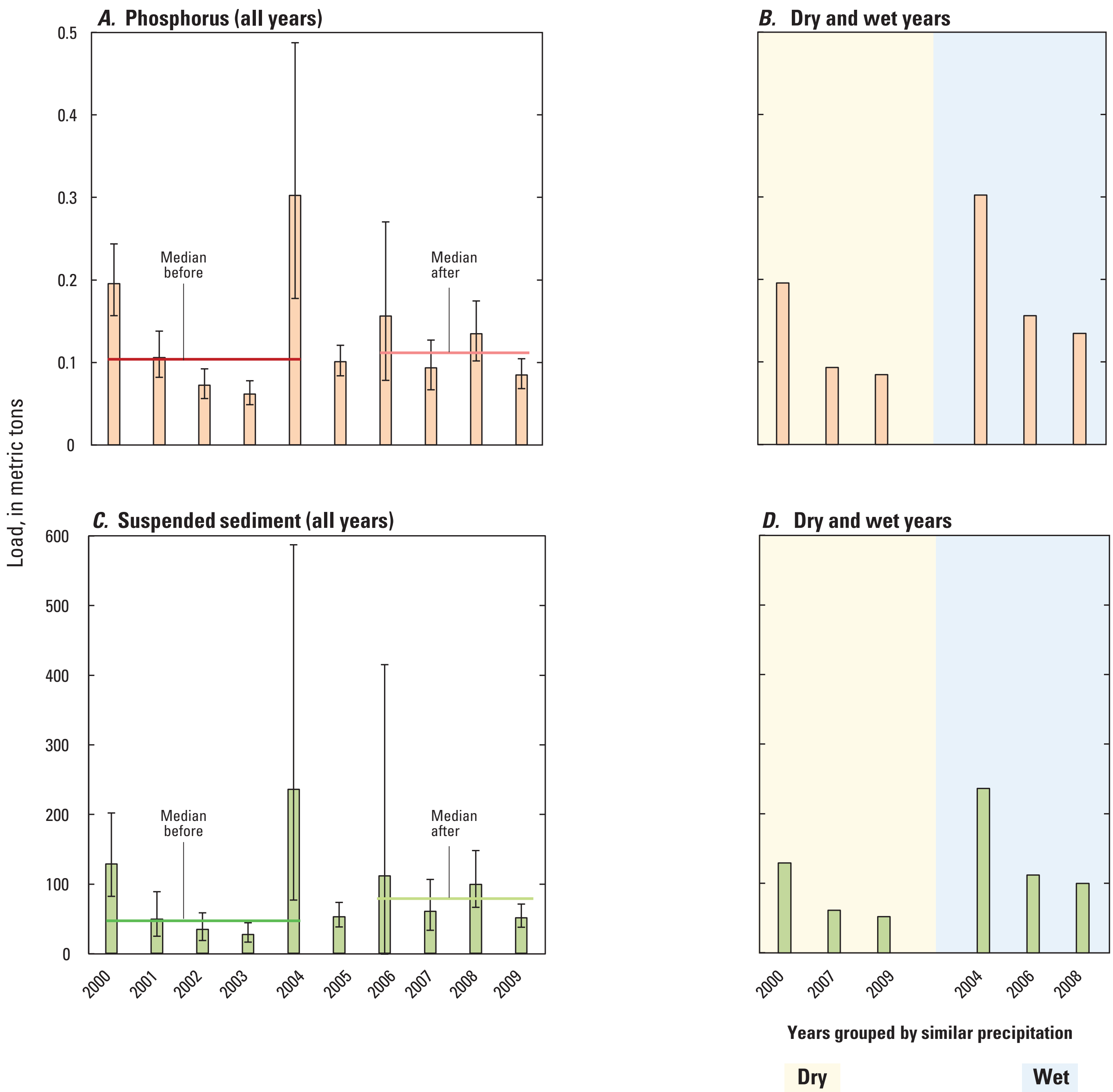

Figure 9. Total annual loads of *A* and *B*, phosphorus and *C* and *D*, suspended sediment in Englesby Brook in Burlington, Vermont, before (2000–2004) and after (2006–2009) construction of wet extended detention ponds in the Englesby Brook watershed for water years 2000 through 2009. The median annual loads before and after construction of the wet extended detention ponds also are shown for comparison. Annual loads are of phosphorus for *A,* all years in the study period and *B,* for dry and wet years and of suspended sediment; *C,* for all years in the study period and *D,* for dry and wet years. Dry years are years with low [94–97 cm (37–38 inches)] total annual precipitation, and wet years are years with high [117–119 cm (46–47 inches)] total annual precipitation. Error bars show 95th-percentile confidence intervals from the U.S. Geological Survey Load Estimator program output only and do not reflect the reality that part of the annual estimates were generated using the Graphical Constituent Loading Analysis System.

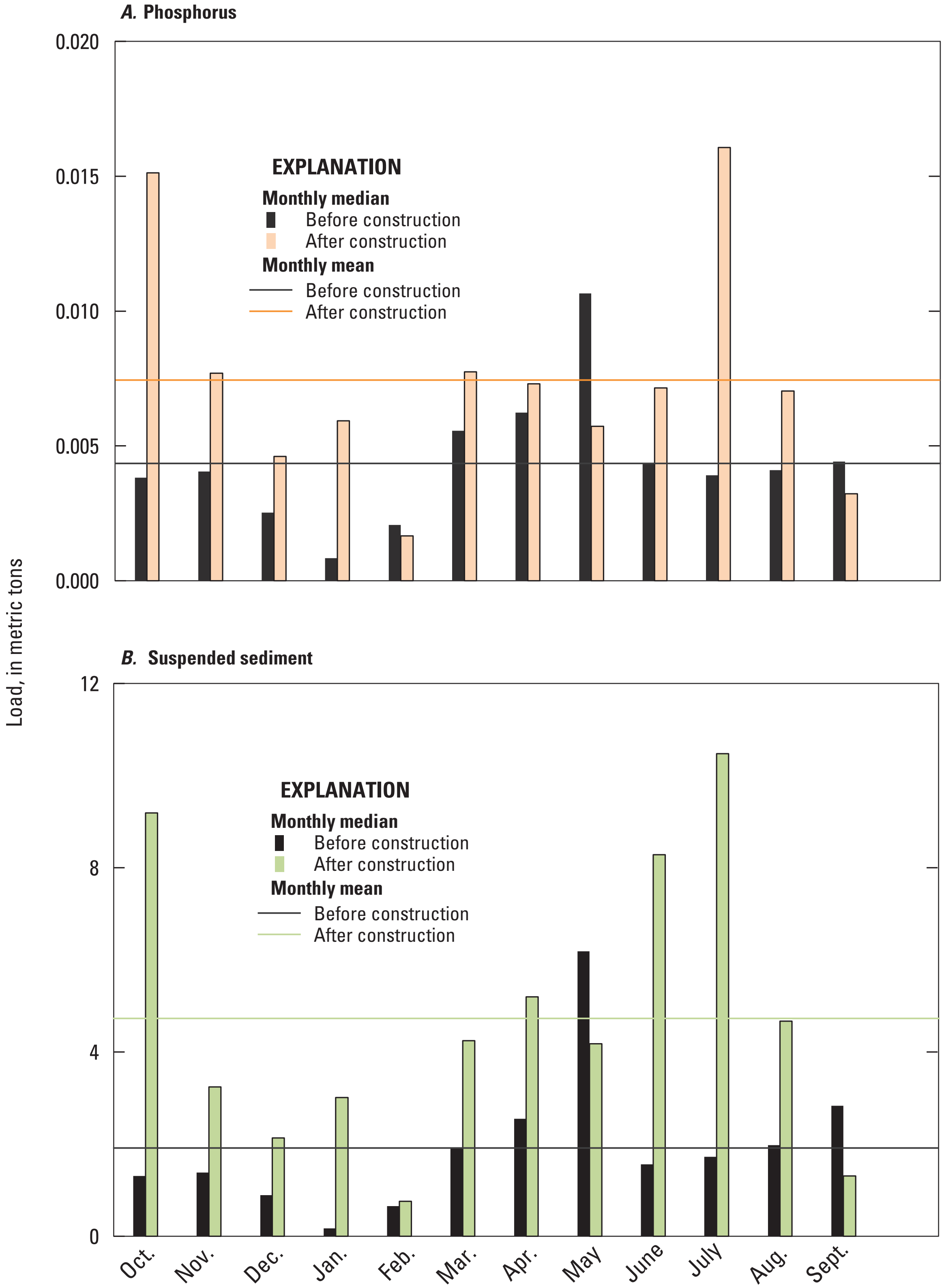

Figure 10. A comparison of monthly median loads for *A,* phosphorus and *B,* suspended sediment before (2000–2004) and after (2006–2009) construction of the wet extended detention ponds in the Englesby Brook watershed in Burlington, Vermont, for water years 2000 through 2009.

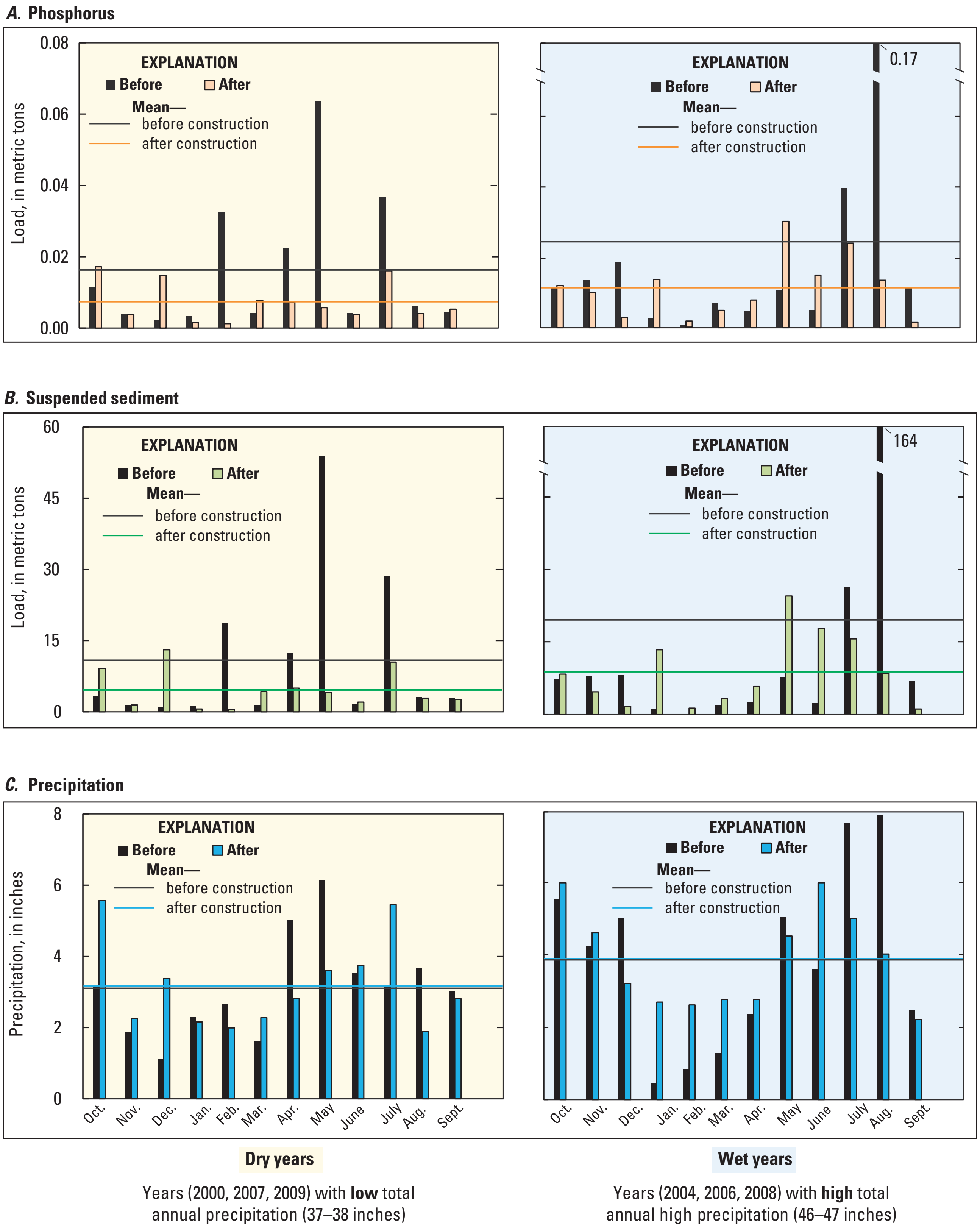

Figure 11. Comparisons of monthly median values before and after construction of the wet extended detention ponds in the Englesby Brook watershed in Burlington, Vermont, for *A,* phosphorus load, *B,* suspended-sediment load, and *C,* precipitation. Water year (WY) means for dry and wet years are shown as horizontal dashed lines. Years with low total annual precipitation (94–97 cm (37–38 inches); 2000, 2007, and 2009; yellow background) and years with high total annual precipitation (117–119 cm (46–47 inches); 2004, 2006, and 2008; blue background) are charted separately.

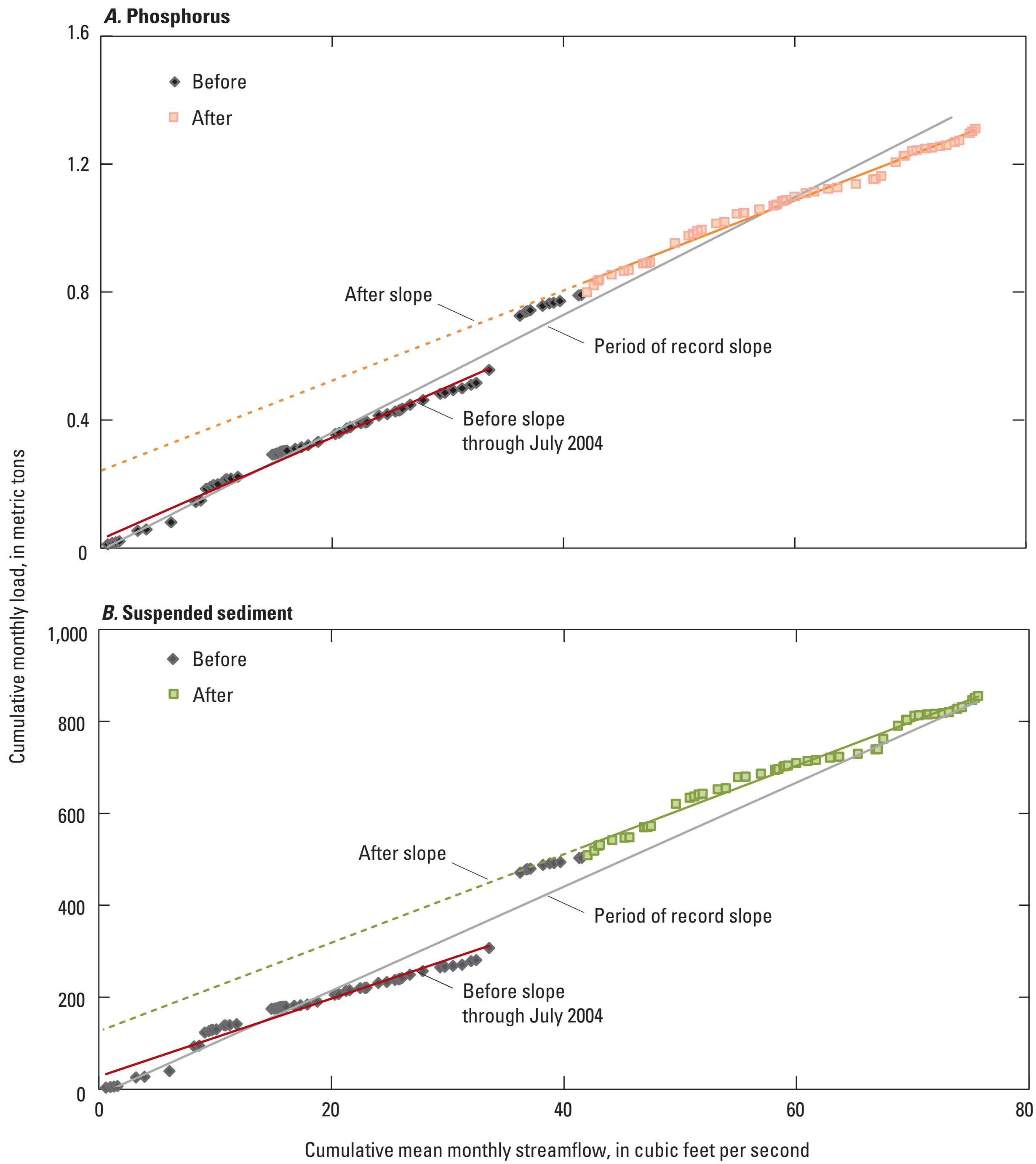

Figure 12. Double-mass curves for cumulative monthly streamflow and monthly loads of *A,* phosphorus and *B,* suspended sediment transported by Englesby Brook in Burlington, Vermont, in water years 2000 through 2009. The graphs contrast data before and after construction of wet extended detention ponds in the watershed. The red lines show the slope of data points before construction (through July 2004, about 1 year less than the time of the full period before construction, which extends from October 1999 through May 2005), and the orange and green lines show the slope of data points after construction (June 2005 through September 2009) for phosphorus and suspended sediment, respectively, backward in time to October 1999. The dashed parts of the orange and green lines are extensions beyond the data points that correspond to the period after construction and are shown to present contrasting slopes with the red and grey slope lines. The grey lines show the slope of data for the entire period of record.

daily discharge on record. If the trend lines for the period before construction for each graph were plotted to not include values after August 2004 (as would be indicated by the red lines in the two graphs), then their slopes would be similar to (indistinguishable from) slopes of the trend lines for the period after construction (as shown by the green and orange lines). Thus, without the hydrologic anomaly of August 2004, there appears to be no difference in loads resulting from the BMPs.

Results of the ANCOVA test for a step trend showed that the slopes decreased in the period after construction compared with the period before construction by 0.08 metric ton per cubic foot per second (t/ft^3/s) for phosphorus and by 0.03 t/ft^3/s for suspended sediment, although these differences were not statistically significant (table 3). This is a different result than the Wilcoxon signed-rank test of paired median monthly loads, which showed increases for phosphorus and suspended sediment. These different results were expected because the ANCOVA test adjusted for streamflow by factoring in the dependence of load on streamflow in the regression, whereas the signed-rank test made no adjustments for streamflow. The ANCOVA results of no difference in monthly loads confirm the same conclusion observed nonstatistically in figures 9 and 11 that showed the before and after conditions separated by dry and wet years.

Low-Streamflow Concentrations

Neither phosphorus nor suspended-sediment median concentrations were statistically different for the period after construction of the wet ED ponds compared with the period before construction for samples collected during low-streamflow conditions (table 3). Low-streamflow conditions were determined as the flat part of the hydrograph between storms. They account for a small percentage of annual loads; in 2005, a year with moderate precipitation, low-streamflow conditions contributed about 9 percent of the annual phosphorus load. Although not significantly different, the summary boxplots (fig. 13) for phosphorus concentrations show that all quartiles and the 90th and 10th percentiles decreased in the period after construction compared with the period before construction. In the boxplot showing suspended-sediment concentrations, the median, 25th, and 10th percentiles increased, and the 90th and 75th percentiles decreased for low-streamflow samples collected in the period after construction compared with the period before construction of the BMPs.

High-Streamflow Concentrations and Loads

High-streamflow conditions occur during rain events or snowmelt. The Englesby Brook hydrograph typically has a well-defined, rapid rise and a relatively rapid descent, often within a few hours after cessation of rainfall. Boxplots illustrating the average concentrations of phosphorus and suspended sediment in samples collected during high-streamflow conditions (fig. 14) show that all percentiles (90th, 75th, 50th, 25th, and 10th percentiles) have increased in the period after construction compared with the percentiles in the period before construction for phosphorus and suspended sediment, with the exception of the 10th percentile for phosphorus, which has stayed about the same. The increase in the phosphorus median concentration (table 3) is not significant at $\alpha = 0.05$ (although it is close with $p = 0.08$), and the increase in the suspended-sediment median concentration is significant ($p = 0.01$). The data for the periods before and after construction had outliers with high concentrations (not shown in fig. 14, which truncates data whose values are less than 10 percent or more than 90 percent).

Boxplots of total phosphorus loads from high-streamflow conditions grouped into periods before and after construction of the wet ED ponds show that all percentile measures have barely changed between the periods except for the 90th percentile, which decreased (fig. 14A). The boxplots of total storm suspended-sediment loads, similar to those for flow-adjusted concentrations, show increases in all percentile measures except for the 90th percentile, which decreased. The increase in median values is significant for total storm loads of phosphorus and suspended sediment (table 3). The previous discussion about increases seen in monthly loads applies equally to total storm loads—loads of any kind have streamflow as a factor; streamflow increased in the period after construction, therefore loads unadjusted for streamflow are not appropriate as the sole criterion of BMP effectiveness.

Are the Best Management Practices Meeting Restoration Goals?

The latter part of the study period was wetter than the beginning years, resulting in sustained higher discharges. Either wetter conditions or the BMP storage structures could be responsible for an increase in low streamflows. There is some evidence that peak streamflows may have decreased slightly in the period after the construction of BMP structures.

Overall, the data from this study have been inconclusive in determining whether the BMPs have helped to reduce phosphorus or suspended sediment exported to Lake Champlain from Englesby Brook. Despite wetter conditions in the years after construction of BMPs, there is some evidence that the BMP structures might have had some beneficial effects for phosphorus. Annual loads of phosphorus and suspended sediment appear to have been reduced by approximately half when compared in separate groupings of dry and wet years for the periods before and after construction of the ponds. These reductions could not be confirmed statistically because data were available for only 1 or 2 years for each comparison. Although the distribution of larger and smaller monthly loads within years was closely related to the relative distribution of monthly precipitation, there were some exceptions. For instance, for the group of dry years, precipitation in July was greater in the period after construction, but phosphorus and suspended-sediment loads in July were greater in the period

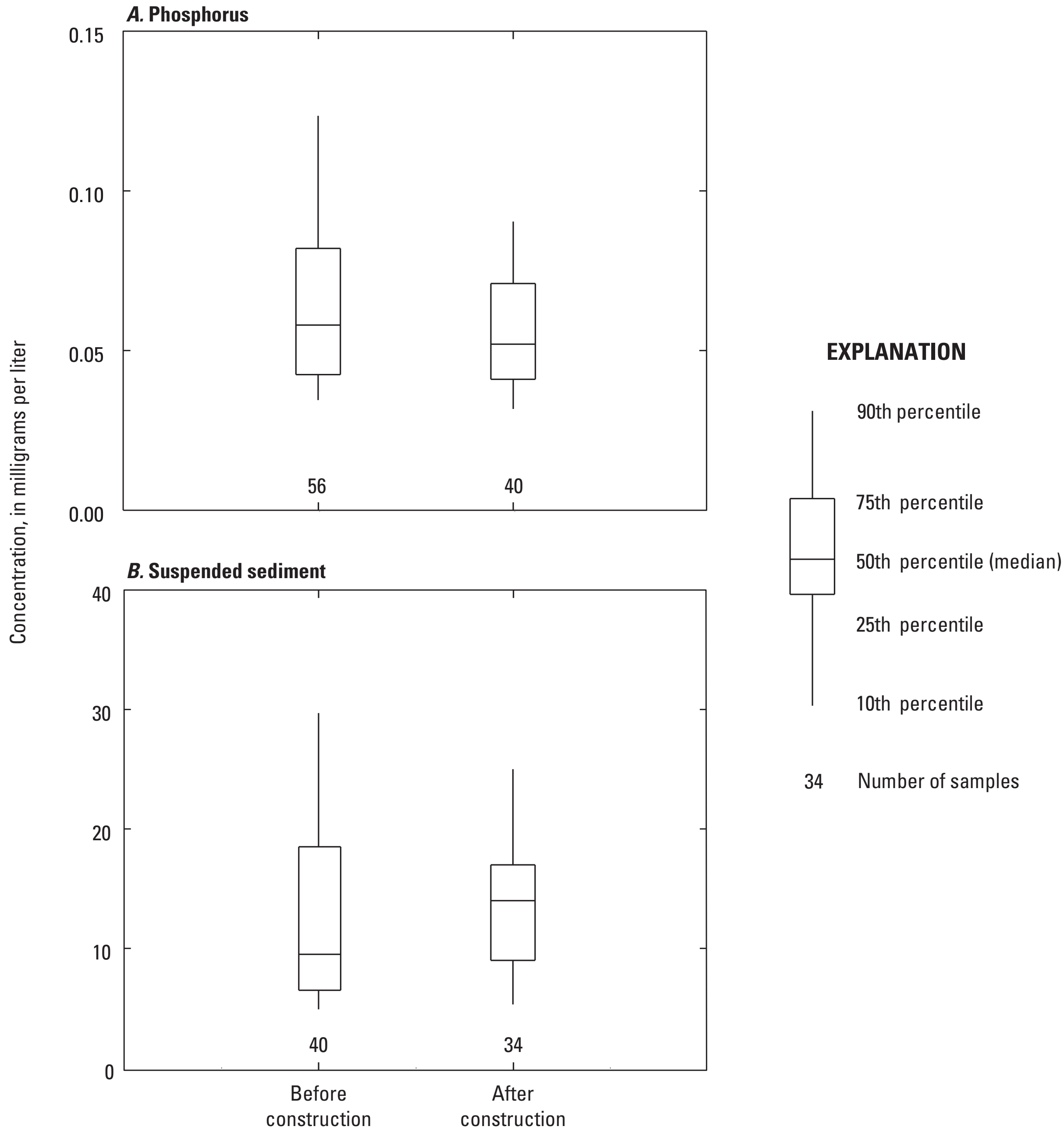

Figure 13. *A,* Phosphorus and *B,* suspended-sediment concentrations for samples collected during low-streamflow conditions before (2000–2004) and after (2006–2009) construction of the wet extended detention ponds in the Englesby Brook watershed in Burlington, Vermont, in water years 2000 through 2009.

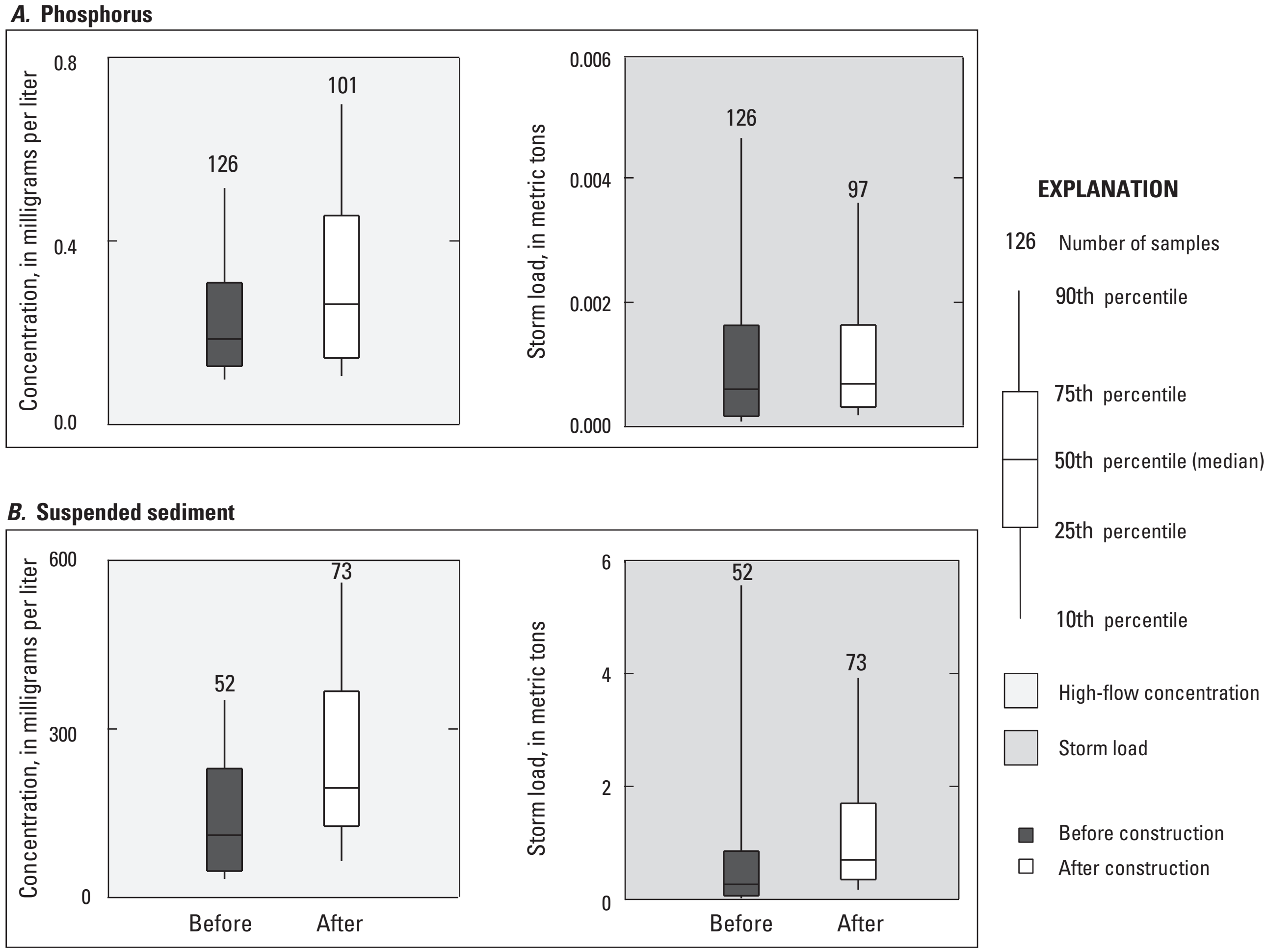

Figure 14. Comparison of flow-adjusted high-streamflow average concentrations and total high-streamflow loads of *A,* phosphorus and *B,* suspended sediment for water samples from Englesby Brook in Burlington, Vermont, before (2000–2004) and after (2006–2009) construction of wet extended detention ponds for water years 2000 through 2009. High-streamflow average concentrations (light grey background) and storm loads (medium grey background) are charted separately.

before construction. Also, the magnitudes of the reductions in loads for February and May in the dry years and for August and September in the wet years were much greater than the differences between precipitation for those same months. Results of other statistical tests showed that phosphorus and suspended-sediment loads either did not change or increased over time; these increases were all probably related to the increased discharges. When discharge was factored in as a covariant in the ANCOVA analysis, monthly loads showed no statistical difference between pre- and post-BMP implementation periods.

The four structural BMPs together treat about 54 percent of the watershed. Other known programs or activities in the watershed during the study period that may have influenced streamflow or water-quality results include detection and repair in 2001 of an illicit sewer line connection to the city stormwater collection system and several educational and outreach programs aimed at reducing stormwater pollution. Activities such as street sweeping and catch-basin cleaning probably did not change much in the watershed until after the end of this project in 2009. Many other activities in the watershed unrelated to the BMPs, such as small construction projects, also could have had an effect on the observed phosphorus and suspended sediment results in one way or another.

The inevitable lag between the implementation of management practices and the detection of responses in streams (Meals and others, 2010) exists because of scale and distance factors, physical and chemical process, type of management action, indicator selection, and monitoring system design. A frequently cited factor in delayed responses to BMPs is control exerted by preexisting phosphorus content of soils (Carpenter and others, 1998; Sharpley and others, 1999; Kara and others, 2011). Scale factors that may contribute to the uncertain success of BMPs for phosphorus relate to whether effects at the field or structure scale can be expected to apply to the watershed scale. For example, BMP-scale processes may be overwhelmed by landscape processes (such as mechanisms that control the dissolution of phosphorus and the erosion of particulate phosphorus, differential flow pathways, and variation in overland flow across the landscape) and in-stream processes (sediment and biotic controls, and effects of changes in pH, organic phosphorus speciation, and dissolved oxygen) (McDowell and others, 2004; Sharpley and others, 2009). A small-watershed agricultural study in Wisconsin, for instance, noted that, although 70 percent of barnyards were treated with BMPs designed to reduce phosphorus, potential benefits were masked by a continuous supply of phosphorus from upland erosion and by moderate distances between barnyards and the receiving water (Graczyk and others, 2003). Meals and others (2010) cited several studies that showed response lag times equal to or greater than 10 years even at the small watershed scale.

Although some of these factors may be contributing to the lack of clear phosphorus reduction at the Englesby Brook streamgage, the very close connection between phosphorus and suspended sediment seen in the data for this study suggests that a large percentage of the observed phosphorus is particulate and is associated with suspended sediment. For Englesby Brook, the rate of sediment transport appears to be the dominant factor controlling phosphorous loads to the lake. In addition to those listed previously, several explanations may be offered for the lack of reduction of sediment transport in the period after the construction of the BMP structures. The period after construction was not only wetter but snowier, which may have resulted in sediment import to and use in the watershed for treating icy roads. There could be other unidentified sources of sediment between the outlet of the BMP structures and the streamgage. It is possible that sediment temporarily removed by the wet ED ponds or sediment that settled out in the pool behind the streamgage weir[2] became resuspended during high-streamflow events and was ultimately exported or that the retention time of the wet ED pond was insufficient to allow for the full amount of sediment removal that was designed (U.S. Environmental Protection Agency, 1999). Also, it is possible that the channel may need a longer period of stabilization following the BMP construction work. Monitoring sediment loads along more reaches of the brook under various streamflow conditions could help assess the effectiveness of the BMPs and identify mechanisms that control sediment transport. Longer-term monitoring of phosphorus and suspended sediment at the Englesby Brook streamgage may ultimately show the long-term effectiveness of the BMPs.

Streamflow, sediment, and phosphorus data can be further assessed in terms of metrics that integrate processes in the watershed, such as biological and habitat assessments. During the course of the study period, several measures of community assemblage health have shown no change (Richard Langdon, Vermont Department of Environmental Conservation, written commun., 2012). One tangible improvement has been potentially attributed to the restoration effort: Blanchard Beach was reopened in 2007 with occasional closures reported after heavy storms. This indicates the bacteria levels in Lake Champlain near the confluence of Englesby Brook have been reduced.

Summary and Conclusions

In cooperation with the Vermont Department of Environmental Conservation, the U.S. Geological Survey collected data from 2000 through 2010 on streamflow and from 2000 through 2009 on concentrations of phosphorus and suspended sediment in Englesby Brook in Burlington, Vermont, to investigate the effectiveness of urban best management practices (BMPs) in improving water quality in a small urban stream. In 2001–02, an irrigation pond was retrofitted near the headwaters of the watershed; in 2005, about halfway through the study period, a wet extended detention (ED) facility and a shallow marsh wetland (collectively known as the wet ED ponds) were constructed further downstream; and in 2006, a set of two small stormwater ponds were built, also near the headwaters. Together, these structures treat about 54 percent of the watershed and had several goals, including reducing the movement of sediment (and attached particles such as phosphorus) from Englesby Brook to Lake Champlain and reducing peak streamflow and increasing low streamflows. Because the wet ED ponds were closest to the streamgage and treated the largest area of the watershed, this report focuses on their effectiveness, although no single treatment could be singled out. Annual, monthly, and total storm loads and streamflow-adjusted and low-streamflow concentrations of phosphorus and suspended sediment were calculated to provide the basis of comparison of water quality before (water years 2000 through 2004) and after (water years 2006 through 2009) construction of the BMPs. The year of construction (2005) was not included in this study.

The group of years after construction of the BMPs were wetter and had higher discharges in Englesby Brook than the group of years before construction, with the exception of 2004 and in particular the exceptionally wet August of that year. This pattern is confirmed with paired bar charts of monthly

[2]The hypothesis that sediment in the weir pond might be resuspended during high streamflows was tested during two storms by manually collecting grab samples upstream of the weir pool concurrently with samples collected by the automated sampler at the weir. During a third storm, 10 concurrent samples were taken by the project's automated sampler and a second automated sampler that was temporarily installed upstream of the weir pool. There was no difference in concentrations of phosphorus or sediment for the samples at the two locations that would indicate an issue with resuspension of sediment that had collected in the weir pool.

medians of precipitation and discharge and from significance tests of paired monthly precipitation and discharge data.

This report presents some evidence that the construction of the BMPs has beneficially improved the hydrology of the watershed, which is especially noteworthy given the wetter weather that occurred after construction. High streamflows that potentially caused the greatest erosive damage appear to have been partially mitigated by the presence of the ponds. The percentage of annual discharge transported during the 3 days with highest streamflows has decreased. Streamflow duration curves suggest that the frequency of highest streamflows may be marginally reduced. Minimum streamflows have increased in the period after construction, particularly in the fall and winter months, by a factor greater than increases in precipitation. The number of days with zero streamflow has been reduced substantially in all the years after construction of the ponds.

At first glance, it appears as though the post-BMP period did not show reductions in phosphorus and suspended sediment—statistical increases in pairs of median monthly phosphorus and suspended-sediment loads, increases in storm-averaged flow-adjusted concentrations, and increases in total storm loads. However, there is evidence that these results were all related to the increased discharge in the period after construction of BMPs in the watershed. Confirmation of the influence of discharge was provided by use of analysis of covariance, whereby the comparison of pairs of median monthly phosphorus and suspended-sediment loads before and after construction using discharge as a covariate was rerun. When discharge was factored into the analysis, no difference in monthly loads was found over time.

The effects of a generally wetter period after construction were removed in a simple way by grouping annual and monthly load results into dry and wet years. The years 2000, 2007, and 2009 had similar precipitation and were relatively dry, whereas the years 2004, 2006, and 2008 had similar precipitation and were relatively wet. Large (approximately 50 percent) reductions in annual loads were observed when dry (or wet) years before construction were compared with dry (or wet) years after construction, although there were too few values to compare statistically. Paired monthly loads of each constituent also were grouped into dry and wet years for a comparison of the data from the periods before and after construction. This depiction of paired monthly loads showed no increase in the period after construction; rather, it showed that approximately the same number of months had increases and decreases with the magnitudes of the decreases generally larger than the magnitudes of the increases (hence the decrease in annual loads for separated dry and wet years).

Although results collected during low-streamflow conditions did not indicate a statistically significant change in phosphorus or suspended-sediment concentration after construction of BMPs in the watershed, the interquartile ranges and the 90th percentiles for phosphorus and suspended sediment have been reduced compared with before the construction of the BMPs.

Results from this study demonstrate that, while peak streamflows have been reduced and duration of low streamflows has improved, reductions in phosphorus or suspended-sediment load that may be attributed to installation of the structural BMPs upstream in the watershed have not been confirmed by statistical analysis. However, a simple restructuring of data to adjust for complex climatic influences indicates that reductions in phosphorus and suspended-sediment loads probably have occurred. These unproven reductions were seen when annual and monthly loads were separated by dry and wet years before comparing for the periods before and after construction.

Other watershed-scale studies across the United States also have found it difficult to make the connection between monitoring locations at some distance downstream from BMPs installed further up in the watershed. In this study, the nearly identical results of phosphorus and suspended sediment suggest that most of the phosphorus observed at the streamgage is particulate and thus is controlled by processes that influence suspended-sediment dynamics. Monitoring sediment loads along more reaches of the brook under various flow conditions could be useful in determining the efficacy of the BMPs and mechanisms that control sediment transport. Additional monitoring conducted after a number of years have passed from the time of construction of the BMPs may yield results that compensate for lag time effects that typically characterize watershed-scale responses to management actions.

References Cited

Burlington [Vermont] Office of the Mayor, 2007, Blanchard Beach fact sheet: Burlington, Vermont, Office of the Mayor, 3 p., accessed January 3, 2012, at http://www.ci.burlington.vt.us/mayor/press_release/docs/Press%20Releases/20070627Blanchard%20Beach%20Fact%20Sheet.pdf.

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., and Smith, V.H., 1998, Nonpoint pollution of surface waters with phosphorus and nitrogen: Ecological Applications, v. 8, no. 3, p. 559–568.

Cleveland, W.S., and McGill, Robert, 1984, The many faces of a scatterplot: Journal of the American Statistical Association, v. 79, no. 388, December [year], p. 807–822.

Dubrovsky, N.M., Burow, K.R., Clark, G.M., Gronberg, J.A.M., Hamilton, P.A., Hitt, K.J., Mueller, D.K., Munn, M.D., Nolan, B.T., Puckett, L.J., Rupert, M.G., Short, T.M., Spahr, N.E., Sprague, L.A., and Wilber, W.G., 2010, The quality of our Nation's waters—Nutrients in the Nation's streams and groundwater, 1992–2004: U.S. Geological Survey Circular 1350, 174 p. (Also available at http://pubs.usgs.gov/circ/1350/.)

Eaton, A.D., Clesceri, L.S., Rice, E.W., and Greenberg, A.E., 2005, Standard methods for the examination of water and wastewater (21st ed.): American Public Health Association, American Water Works Association, and Water Environment Federation, [variously paginated].

Graczyk, D.J., Walker, J.F., Horwatich, J.A., and Bannerman, R.T., 2003, Effects of best-management practices in the Black Earth Creek priority watershed, Wisconsin, 1984–98: U.S. Geological Survey Water-Resources Investigations Report 03–4163, 24 p. (Also available at http://pubs.usgs.gov/wri/wri034163/.)

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. C1, 58 p. (Also available at http://pubs.usgs.gov/twri/twri5c1/.)

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A3, 522 p. (Also available at http://pubs.usgs.gov/twri/twri4a3/.)

Kara, E.L., Heimerl, Chad, Killpack, Tess, Van de Bogert, M.C., Yoshida, Hiroko, and Carpenter, S.R., 2011, Assessing a decade of phosphorus management in the Lake Mendota, Wisconsin watershed and scenarios for enhanced phosphorus management: Aquatic Sciences, June 30, accessed [date], at http://rd.springer.com/article/10.1007/s00027-011-0215-6.

Koltun, G.F., Eberle, Michael, Gray, J.R., and Glysson, G.D., 2006, User's manual for the Graphical Constituent Loading Analysis System (GCLAS): U.S. Geological Survey Techniques and Methods, book 4, chap. C1, 51 p., accessed [date], at http://pubs.usgs.gov/tm/2006/tm4C1/.

McDowell, R.W., Biggs, B.J.F., Sharpley, A.N., and Nguyen, L., 2004, Connecting phosphorus loss from agricultural landscapes to surface water quality: Chemistry and Ecology, v. 20, no. 1, p. 1–40.

Meals, D.W., Dressing, S.A., and Davenport, T.E., 2010, Lag time in water quality response to best management practices—A review: Journal of Environmental Quality, v. 39, no. 1, p. 85–96.

Medalie, Laura, 2007, Concentrations and loads of nutrients and suspended sediments in Englesby Brook and Little Otter Creek, Lake Champlain Basin, Vermont, 2000–2005: U.S. Geological Survey Scientific Investigations Report 2007–5074, 50 p. (Also available at http://pubs.usgs.gov/sir/2007/5074/.)

National Oceanic and Atmospheric Administration, 2004, Local climatological data, August 2004—Burlington, VT (BTV): National Oceanic and Atmospheric Administration, 8 p., accessed February 2, 2012, at http://www1.ncdc.noaa.gov/pub/orders/IPS-EC4D5C12-5D83-4AB4-A7AF-B22872B00E20.pdf.

Quackenbush, Alan, 1995, Identifying toxic constituents of urban runoff from developed areas within the Champlain basin—Draft interim report: Lake Champlain Basin Program, [unknown pagination].

Runkel, R.L., Crawford, C.G., and Cohn, T.A., 2004, Load Estimator (LOADEST)—A Fortran program for estimating constituent loads in streams and rivers: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A5, 69 p., at http://pubs.usgs.gov/tm/2005/tm4A5/.

Sharpley, A.N., Gburek, W.J., Folmar, G., and Pionke, H.B., 1999, Sources of phosphorus exported from an agricultural watershed in Pennsylvania: Agricultural Water Management, v. 41, p. 77–89.

Sharpley, A.N., Kleinman, P.J.A., Jordan, Philip, Bergström, Lars, and Allen, A.L., 2009, Evaluating the success of phosphorus management from field to watershed: Journal of Environmental Quality, v. 38, p. 1981–1988.

Shreve, E.A., and Downs, A.C., 2005, Quality-assurance plan for the analysis of fluvial sediment by the U.S. Geological Survey Kentucky Water Science Center Sediment Laboratory: U.S. Geological Survey Open-File Report 2005–1230, 28 p., at http://pubs.usgs.gov/of/2005/1230/.

U.S. Environmental Protection Agency, 1999, Preliminary data summary of urban storm water best management practices: U.S. Environmental Protection Agency EPA–821–R–99–012, August, [variously paginated], accessed February 2, 2012, at http://water.epa.gov/scitech/wastetech/guide/stormwater/.

U.S. Geological Survey, 2011, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, accessed February 2, 2012, at http://water.usgs.gov/owq/FieldManual/.

Vermont Department of Environmental Conservation, 2007, Total maximum daily load to address biological impairment in Englesby Brook (VT05–10) Chittenden County, Vermont: U.S. Environmental Protection Agency, 28 p., accessed February 2, 2012, at http://www.epa.gov/waters/tmdldocs/33609_sw_eng_tmdl_approved.pdf.

Vermont Department of Environmental Conservation, [undated], Aquatic life support assessment of Englesby Brook: Vermont Department of Environmental Conservation, 10 p., accessed December 9, 2011, at http://www.vtwaterquality.org/bass/docs/bs_Englesby_Brook_Biological_Assessment.pdf.

Wilcoxon, Frank, 1945, Individual comparisons by ranking methods: Biometrics, v. 1, no. 6, December [year], p. 80–83.

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