Prepared in cooperation with the Houlton Band of Maliseet Indians

Primary Productivity in Meduxnekeag River, Maine, 2005

Scientific Investigations Report 2009–5029

U.S. Department of the Interior
U.S. Geological Survey

Cover. Meduxnekeag River near Houlton, Maine.

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Conversion Factors and Abbreviations

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	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)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

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

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L). Concentrations of chemical constituents in sediment are given in milligrams per kilogram (mg/kg).

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Abstract

During August and September 2005, dissolved oxygen, temperature, pH, specific conductance, streamflow, and light intensity (LI) were determined continuously at six sites defining five reaches on Meduxnekeag River above and below Houlton, Maine. These data were collected as input for a dual-station whole-stream metabolism model to evaluate primary productivity in the river above and below Houlton. The river receives nutrients and organic matter from tributaries and the Houlton wastewater treatment plant (WWTP). Model output estimated gross and net primary productivity for each reach. Gross primary productivity (GPP) varied in each reach but was similar and positive among the reaches. GPP was correlated to LI in the four reaches above the WWTP but not in the reach below. Net primary productivity (NPP) decreased in each successive downstream reach and was negative in the lowest two reaches. NPP was weakly related to LI in the upper two reaches and either not correlated or negatively correlated in the lower three reaches. Relations among GPP, NPP, and LI indicate that the system is heterotrophic in the downstream reaches. The almost linear decrease in NPP (the increase in metabolism and respiration) indicates a cumulative effect of inputs of nutrients and organic matter from tributaries that drain agricultural land, the town of Houlton, and the discharges from the WWTP.

Introduction

Summer algal blooms in Meduxnekeag River in northeastern Maine have been a recurring problem for the Houlton Band of Maliseet Indians (HBMI) for many years. Cooperative projects between HBMI and the U.S. Geological Survey (USGS) since 2003 have addressed or are addressing the occurrence of nutrients (nitrogen and phosphorus) in streambed sediments and surface water (Schalk and Tornes, 2005), sources of fecal bacteria and indicator coliphages in surface water, and locations of possible point sources of nutrients by use of remote-sensing instruments (data on file with the USGS, Augusta, Maine). These projects represent a continuing effort by HBMI and USGS to characterize Meduxnekeag River watershed, determine the conditions under which algal blooms develop, and discover the means whereby such conditions can be monitored effectively.

During the summer of 2005, as part of the effort described above and in cooperation with HBMI, the USGS (1) monitored primary productivity indicators at as many as six stations on Meduxnekeag River and water-quality conditions at these and additional stations, (2) obtained incident light-intensity (LI) data as a factor in algal primary productivity, (3) monitored continuous and periodic streamflow, and (4) developed stage-discharge ratings for several locations on Meduxnekeag River and selected tributaries. These data-collection activities were achieved by use of water-quality sondes that continuously measured pH, specific conductance, water temperature, and dissolved-oxygen concentration (one sonde recorded turbidity also), in-stream meters that continuously collected LI, and continuous and (or) periodic measurements of river stage and (or) discharge. The data collected during the summer of 2005 subsequently were used to calculate estimates of primary productivity between monitoring stations on Meduxnekeag River by use of a model developed by the USGS.

Purpose and Scope

This report presents the results of a dual-station model that calculates primary productivity in Meduxnekeag River by use of the data described above. Background information about primary productivity and the dual-station model is presented as introductory material. The discussion of model results places them in a spatial and temporal context to help answer questions about the role of algae in the health of Meduxnekeag River. Assumptions of the model and data limitations of the study are discussed.

Description of Study Area

Meduxnekeag River flows through mostly rolling terrain in northeastern Maine. From its sources in hills west of Houlton, Meduxnekeag River flows eastward to its confluence with South Branch, then turns northward through Houlton toward the Canadian border. The study area (fig. 1) includes that part of the Meduxnekeag River watershed between the Tate and Lyle starch-processing plant in the town of Houlton

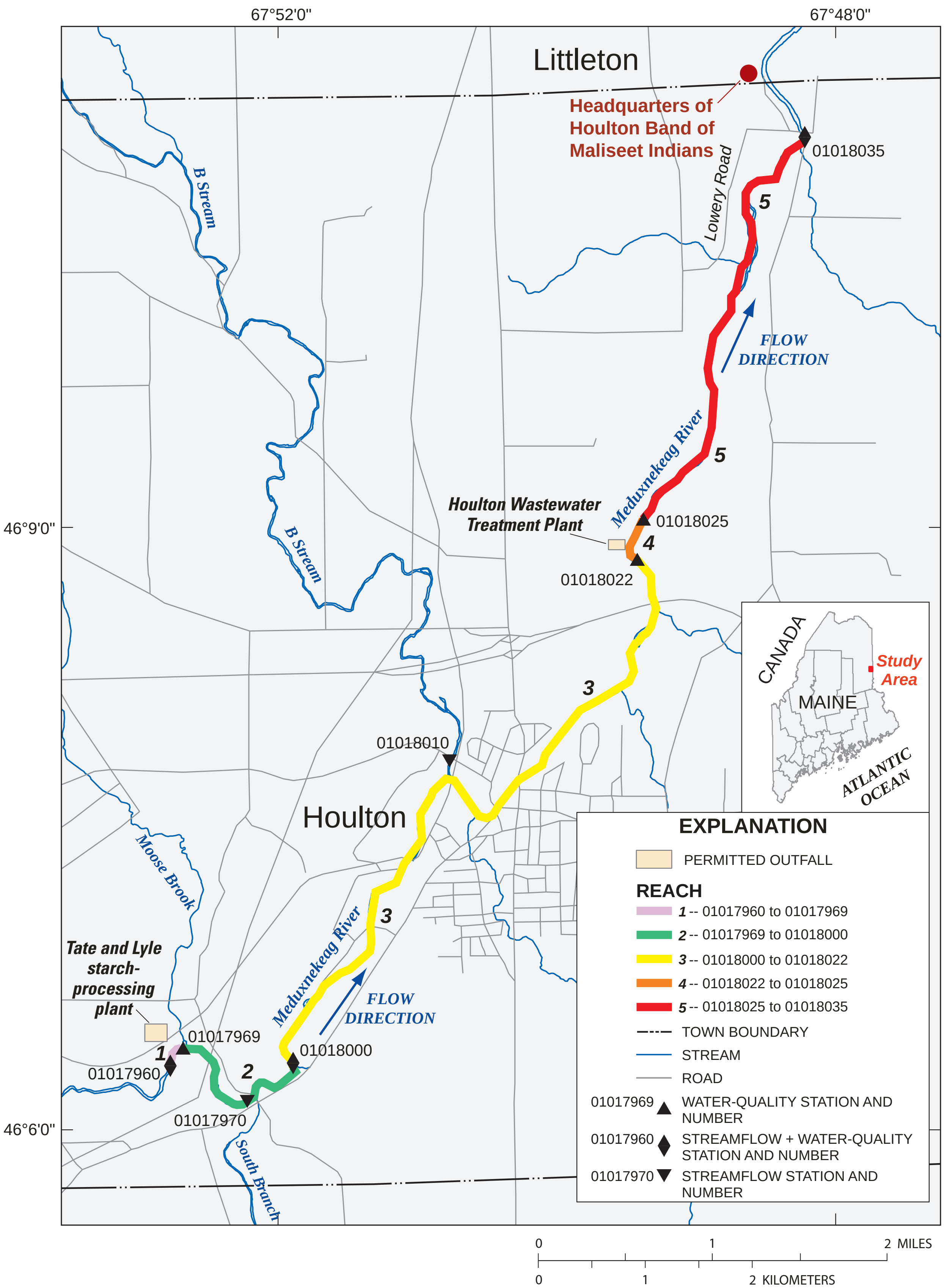

Figure 1. Meduxnekeag River above and below Houlton, Maine, with U.S. Geological Survey streamflow and water-quality stations and stream reaches.

and the Lowery Road bridge over Meduxnekeag River near HBMI headquarters in Littleton. The drainage area of Meduxnekeag River at Lowery Road is 257 mi^2. Principal tributaries to Meduxnekeag River in the study area include Moose Brook, South Branch Meduxnekeag River, and B Stream.

The primary uses of land in the Meduxnekeag River watershed are agriculture and timber. Potatoes are the most commonly grown crop.

Houlton Water Company withdraws about 0.75 Mgal/d from wells in and around Houlton and operates a wastewater treatment plant (WWTP) downstream from Houlton town center (Houlton Water Company, 2006a). The treatment plant normally discharges its processed water into Meduxnekeag River, but under high-volume conditions, sometimes applies processed water to land near the WWTP. Houlton Water Company maintains a water-quality program that consistently is in compliance with standards set by Maine Department of Environmental Protection (DEP) (Houlton Water Company, 2006b).

Previous Studies

A mid-1990s study by Maine DEP for the purpose of establishing total maximum daily load (TMDL) standards for Meduxnekeag River found nuisance algal growth downstream from the Houlton Water Company WWTP as a result of high concentrations of phosphorus (Maine Department of Environmental Protection, 2000). Maine DEP subsequently set a limit of 0.25 mg/L (monthly average concentration of total phosphorus) for the period June 1 through September 15. Part of the standard includes cessation of effluent discharge from the Tate and Lyle starch-processing plant when streamflow in Meduxnekeag River is less than 30 cubic feet per second (ft^3/s) at station 01017960 (see next paragraph). Treatment and discharge of effluent by the starch-processing plant and the Houlton Water Company were modified to meet the new TMDL standards. The Tate and Lyle starch-processing plant did not discharge to Meduxnekeag River during most summers of the TMDL study, even when flows were greater than 30 ft^3/s. In addition, several best-management practices have been put into place since 1995 to reduce nonpoint-source contributions of nutrients from agriculture (soil erosion, livestock) (Maine Department of Environmental Protection, 2000).

Because of the need for consistent streamflow data, streamflow-gaging stations upstream from the confluence of Meduxnekeag River and its South Branch (USGS station 01017960) and between South Branch and the town of Houlton (USGS station 01018000) became operational in 2003 (table 1). Station 01018000 had been active previously from 1940 to 1982. These stations were used to quantify streamflow in Meduxnekeag River above the town of Houlton and allowed estimation of flow from South Branch but did not include flow from B Stream or several smaller tributaries to Meduxnekeag River. Subsequently, a third station was established at Lowery Road (USGS station 01018035) during the summer of 2005. Stage-discharge ratings were established for all three streamflow-gaging stations as well as Meduxnekeag River at Porter Settlement Road (USGS station 01017970) and B Stream at Houlton (USGS station 01018010) (fig. 1), although continuous streamflow data were not collected at the last two stations (table 1). A typical annual hydrograph of flow at station 01018000 is dominated by high spring runoff (late March to middle May) with relatively low flows during most of the rest of the year. Autumn rains can cause secondary peaks in October and November. Based on the period of record, the highest mean daily flow at station 01018000, about 1,520 ft^3/s, is in April, and the lowest mean daily flow, about 63 ft^3/s, is in late July. Stations established solely for water-quality monitoring (no streamflow measurements) are described in the Methods section of this report.

Table 1. Streamflow-gaging stations and their characteristics, Meduxnekeag River basin, Maine.

[USGS, U.S. Geological Survey; coordinates in North American Datum of 1983]

USGS station number	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	Period of record	Comments
01017960	Meduxnekeag River above South Branch Meduxnekeag River near Houlton, Maine	46.1049639	-67.8812861	2003–current	Continuous
01017970	Meduxnekeag River at Porter Settlement Road near Houlton, Maine	46.1019975	-67.8722408	2003–current	Periodic
01018000	Meduxnekeag River near Houlton, Maine	46.1049167	-67.8666306	1940–1982, 2003–current	Continuous
01018010	B Stream at Route 2 at Houlton, Maine	46.1300525	-67.8475185	2003–current	Periodic
01018035	Meduxnekeag River at Lowery Road near Houlton, Maine	46.1811627	-67.8039074	2005–current	Continuous

Results of the 2003 cooperative effort of USGS and HBMI are reported in Schalk and Tornes (2005). The 2003 study investigated the possible role of streambed sediment as a source of nutrients to surface water during summer periods of low flow. Sediments in general were difficult to find because of the rocky nature of the Meduxnekeag River streambed; those sediments found were shallow and sandy, containing little organic matter. Concentrations of phosphorus in bed sediment were less than 700 mg/kg in all samples. Phosphorus was not detected or was at concentrations below the reporting limit (40 mg/kg) in most surface-water samples, whereas nitrate was detected in every surface-water sample at concentrations greater than the reporting limit but less than or equal to 0.50 mg/L. Analysis of instantaneous nitrogen loads indicated that, on the basis of flow percentages and drainage areas, loads during two medium- to high-flow events were disproportionately higher in the part of the watershed downstream from station 01018000, which includes the town of Houlton and its WWTP, than in other parts of the watershed.

Fretwell (2006) studied the relations among nutrient concentrations, algal growth, and nutrient sources in the Meduxnekeag River watershed during the summers of 2004 and 2005. During that study, sampling was conducted at 2-week intervals and did not target specific flow conditions. Although overall concentrations of nutrients were low, mean concentrations of nitrate and total phosphorus increased with distance downstream during both summers, and mean nutrient concentrations spiked at sampling sites downstream from substantial inputs, such as the confluence of South Branch (significant agricultural land use in its watershed) and the Houlton WWTP. Mean concentrations of orthophosphate were above the reporting limit (1.0 micrograms per liter) only below the WWTP. On the watershed scale, agricultural areas contributed the largest amount of nitrate, whereas the WWTP contributed the largest amount of phosphorus. No correlation was found between algal growth and nutrient concentrations or loads. Fretwell (2006) concluded that phosphorus was limiting in the ecology of Meduxnekeag River, but other factors—light, substrate, and temperature among them—may have been more important.

Review of Primary Productivity in Streams

The term *primary productivity* refers to “the rate of formation of organic matter from inorganic carbon by photosynthesizing organisms” (Bott, 1996), or autotrophs, including algae and larger aquatic vascular plants. Gross primary productivity (GPP) is very nearly equal to total photosynthesis (Reid, 1961); net primary productivity (NPP), which is the amount of productivity available for plant growth and reproduction, is the difference between GPP and 24-hour community respiration (CR–24), or sustenance at its current state. A river segment is autotrophic if it contains enough organic matter to sustain organism respiration within its reach (NPP is positive) and is heterotrophic if it needs an import of organic matter from an upstream reach to sustain organism respiration within its reach (NPP is negative) (Grimm and Fisher, 1984; Bott and others, 1985). Generally, autotrophic streams are dominated by GPP, whereas heterotrophic streams are dominated by CR–24. Primary productivity in small streams can be heavily supported by imported (allochthonous) organic matter from the watersheds (Minshall, 1967), whereas primary productivity in large, open streams commonly is less dependent on allochthonous organic matter and more dependent on organic matter imported from upstream.

Bott and others (1978) provide a review of methods that can be used for measuring GPP, NPP, and CR–24 in streams. Among these methods are whole-stream analysis (oxygen and (or) carbon dioxide change), biomass-accumulation measurements, and component analysis (isolation of functional components [macrophytes, periphytes, phytoplankton] and measurement of their oxygen, phosphorus, or carbon changes, usually by use of light and dark chambers). Whole-stream analysis of oxygen change provides information on primary productivity and community respiration rates without apportioning those rates among the functional components (Odum, 1956; Fisher and Carpenter, 1976). Utility of the whole-stream analysis requires a reliable estimate of the atmospheric reaeration rate (see below) and some means of accounting for biomass accumulation. Net primary productivity of macrophytes can be estimated from changes in the biomass and should be corrected for mortality considerations, losses by grazing animals, excretion of dissolved organic matter, and net primary productivity after maximum growth is achieved (Fisher and Carpenter, 1976).

Another component that can be considered in the O_2 balance is the role of biological activity in shallow and deep sediments (Grimm and Fisher, 1984). Whereas oxygen consumption in shallow sediments can be measured by use of large chambers on site, oxygen consumption in deep sediments must be determined in the laboratory under conditions designed to simulate those of the stream environment. The measurement of oxygen change in the functional components is extremely laborious and was not attempted for this study. As part of their study, Grimm and Fisher (1984) showed that primary productivity measured in shallow and deep sediments was similar to that obtained by the whole-system analysis.

Sources of dissolved oxygen in a stream reach include atmospheric reaeration and the photosynthetic contribution of algae, whereas sinks of dissolved oxygen are the respiratory functions of bacteria and algae in the planktonic and benthic environments (O’Connor and Di Toro, 1970). An influx of oxygen may also be attributed to ground- and surface-water inputs to the stream reach, but this influx commonly is considered negligible with respect to the other sources (Odum, 1956). In natural streams, the dissolved-oxygen concentration fluctuates fairly consistently near the saturation point; sources and sinks of oxygen balance one another. In a stream receiving untreated sewage effluent, however, two factors may upset the natural balance: first, a large influx of bacteria may be present in the effluent, and second, the nutrients in the effluent may trigger abnormally high growth of algae, which use dissolved oxygen for respiration (Odum, 1956). Because the activities of aquatic organisms respond relatively quickly to availability of dissolved oxygen, it is important that dissolved-oxygen concentration be monitored at frequent intervals. A given stream receiving processed sewage effluent, such as from the Houlton WWTP, would most likely have smaller amounts of bacteria and nutrients than a stream receiving untreated sewage.

Methods

This section presents a summary of the methods used to collect and analyze the data. Quality-assurance measures for each of the data-collection methods are discussed. Of special importance are the methods used to determine hydrologic inputs to the primary productivity model used during analysis.

Data Collection

USGS collected streamflow, continuous water-quality measurements, and light-intensity data to support the investigation of primary productivity. This section describes the methods used to collect the data and obtain estimates derived from the data.

Stream Hydraulic Data

One of the hydrologic parameters required for the whole-stream metabolism computer program (WSMP) is time of travel between stations. Travel times were estimated by dividing the distance between streamflow-gaging stations by the average velocity of the stream at the upstream station, using velocities measured at low flow. Travel times were verified within a reasonable range by analysis of a small rise in the hydrograph from upstream to downstream stations during a period of low flow.

Stream widths and depths were calculated from discharge-measurement records. Stream slope was calculated from topographic maps of the study area. These physical measurements were used to evaluate the stream-reaeration coefficient used in the model.

Data for input to the model were collected at stations on Meduxnekeag River. In addition to stations 01017960, 01018000, and 01018035, three additional sampling stations were established. Station 01017969 was established to bracket the Moose Brook inflow (with 01017960), and stations 01018022 and 01018025 were established to bracket inflow from the WWTP. The six stations defined reaches (the stream between the stations) that are identified in figure 1 and table 2.

Continuous Water-Quality Indicators

USGS collected 15-minute interval readings of specific conductance, dissolved-oxygen concentration, dissolved-oxygen percent saturation, water temperature, and pH at as many as six stations in Meduxnekeag River during the summer of 2005. Most of these data were collected by use of Yellow Springs Instruments (YSI), but some were collected by use of Hydrolab sondes. Instrument calibration and cleaning was a regular part of the field program. All YSI and Hydrolab sondes were calibrated before deployment according to specifications of the manufacturer and USGS guidelines (Wagner and others, 2006). Barometric pressure data, which were used to estimate partial pressures of dissolved oxygen, were compiled from field notes recorded during instrument calibration and (or) deployment.

Light Intensity

USGS deployed HOBO™ Pendant (Onset Computer Corporation, Pocasset, Mass.) LI and temperature sensors in the stream at each of the six monitoring stations, recording at 10-minute intervals. The sensors were mounted to concrete blocks by use of copper pipe hangers, which tended to discourage the attachment of algae to the sensors (fig. 2). The

Table 2. Characteristics of sampling reaches and stations along Meduxnekeag River, in order from upstream to downstream.

[Refer to figure 1 for locations of stations]

Sampling reach	Upstream station	Downstream station	Length, in feet	Gradient, in foot per foot	Average velocity, in feet per second	Average depth, in feet
1	01017960	01017969	725	0.014	1.0	0.4
2	01017969	01018000	5,540	.002	1.2	.4
3	01018000	01018022	22,930	.001	1.1	.31
4	01018022	01018025	3,250	.0003	0.4	1.0
5	01018025	01018035	13,450	.0007	.4	.82

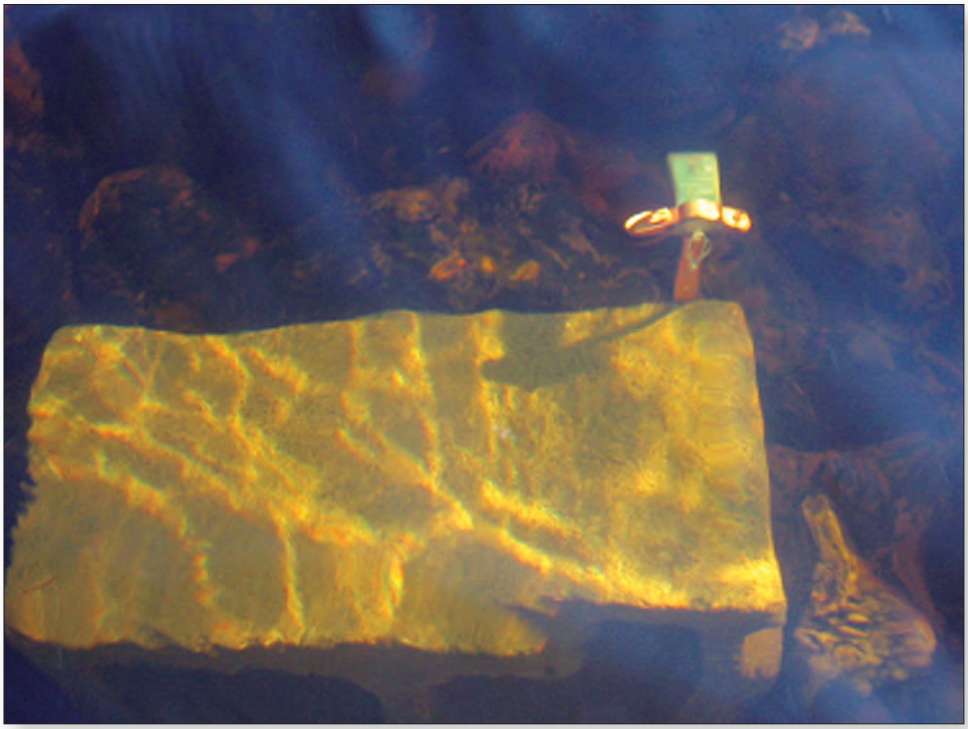

Figure 2. HOBO (TM) Pendant sensor mounted to cement block in stream.

sensors were positioned underwater and pointing upstream originally; at times during the monitoring period, the blocks had to be repositioned so that the sensors would remain submerged slightly as stage decreased.

Data Analysis

The WSMP (Bales and Nardi, 2007) was developed to facilitate computation of GPP, NPP (which is calculated by the WSMP as GPP minus an interpolated CR that does not include night hours), and CR–24 (metabolism), which includes respiration of autotrophs (plants, including algae) and heterotrophs (bacteria and insects) in a stream. In this method, the rate of change in dissolved oxygen is equal to the rate of GPP minus the rate of CR–24 plus the rate of reaeration plus the rate of drainage accrual, all of which are measured in terms of oxygen per unit area or volume (Hynes, 1972). The method of computation, called the diurnal-curve method because it is based on a plot of one or more days of dissolved-oxygen concentration over time, was first described by Odum (1956). WSMP calculates mass balance for a gas in a stream according to equations described in Bales and Nardi (2007). Inputs to WSMP include station information, such as sample dates and times, river stage, reach length, travel time, and a few other hydrologic factors; light data from a depth of 1 m for the purpose of estimating the daytime period (LI data from a depth generally less than a foot below the water surface were used because the stream was too shallow); a value for reaeration; and time-series water-quality data, including water temperature, dissolved-oxygen concentration, specific conductance, and pH. The steps that WSMP uses to compute primary productivity are described generally in figure 3.

Limitations of the whole-stream method of analysis are described in Kent and others (2005) and Hynes (1972). Among these are sensitivity to the estimation of the amount of reaeration; assumption that carbonaceous BOD and sediment oxygen demand (both potential losses of dissolved oxygen that are not accounted for) are negligible; asynchronicity between photosynthesis and its associated metabolic costs (which can arise from localized zones of low-flow velocity or chemical gradients); potential losses of dissolved oxygen in the form of air bubbles during daytime supersaturation; and the rate of basin accrual can be measured or is negligible. Of the assumptions, the estimation of reaeration and the amount of BOD are probably the most critical in this analysis. The estimation of reaeration is important because the gradient and hence the turbulence of the river that influence the amount of reaeration differ among the reaches. BOD is important because one major tributary drains agricultural land, which tends to increase the amount of nutrients and organic matter to the river, and the WWTP, which also creates a carbonaceous BOD.

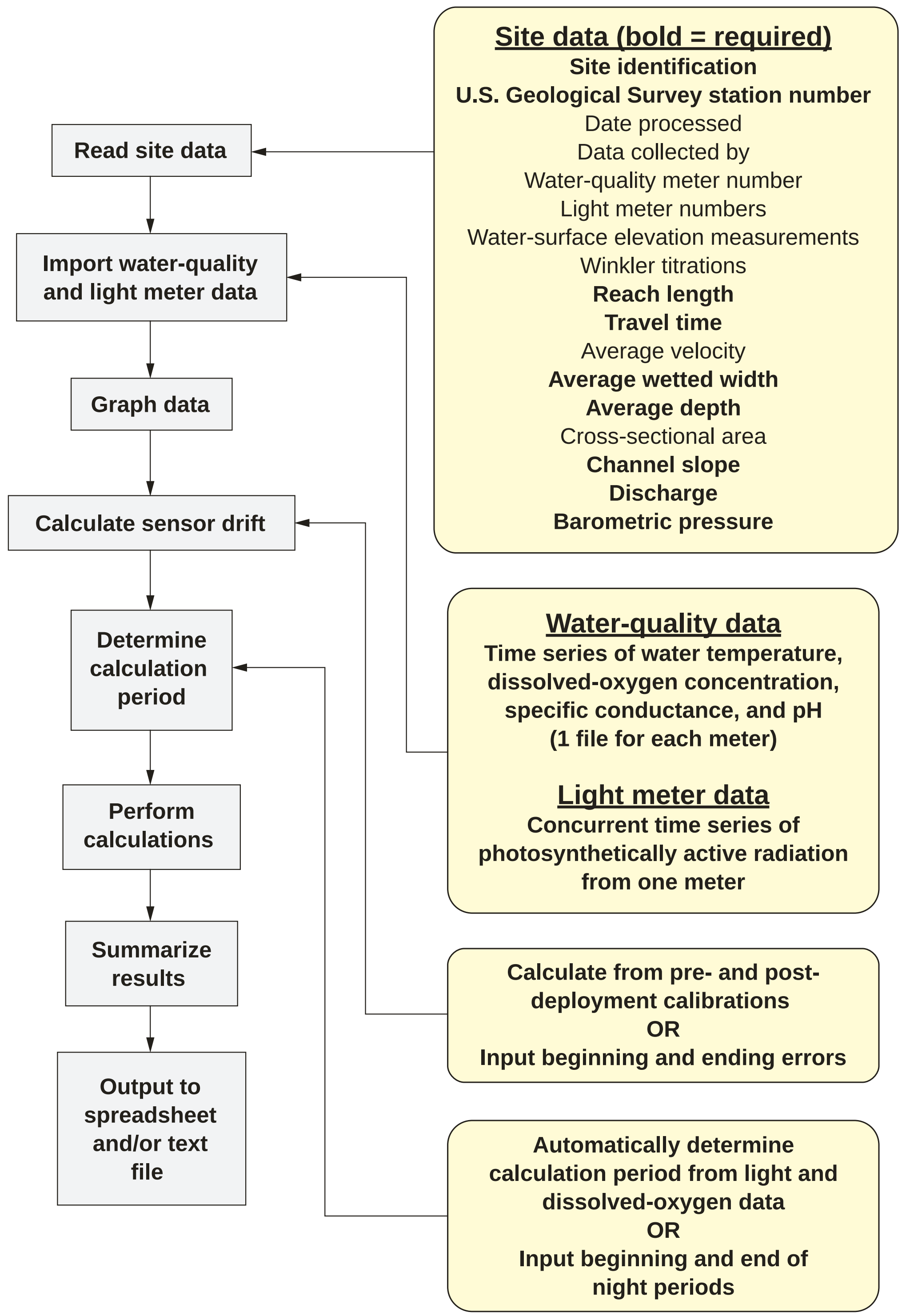

Figure 3. Diagram of whole-stream metabolism computer program model data, calculations, and output (from Bales and Nardi, 2007).

Benefits to using the whole-stream analysis include (1) the method is not influenced by spatial variability within a stream reach but aggregates the analysis over the entire reach; (2) the collection of data is somewhat easier and more reliable than that required by the chamber method; and (3) the method inherently includes all the components of the stream system.

The WSMP was used to estimate daily GPP and NPP for each reach. The daily values were examined graphically to determine consistencies and differences among the reaches with an emphasis on differences in NPP among reaches in downstream sequence.

Mean daily values of GPP and NPP, water temperature, LI, specific conductance, and pH were compared among the reaches. Pearson correlation analysis was applied to determine correlations between primary productivity and temperature, LI, specific conductance, and pH in each reach such that relations could be compared among reaches in downstream sequence.

Multiple linear regression was applied to the daily values from each reach such that GPP and NPP were the dependent variables and water temperature, LI, and pH were the independent variables. In this application, the multiple linear regression identifies the proportion of variance in primary productivity explained by the independent variables. The amount of variability in primary productivity explained in each reach is compared among reaches in downstream sequence.

Prior to any statistical analyses, all data were examined with normal probability plots to determine distribution. Only specific conductance could not be normalized because of a bimodal distribution. Therefore, specific conductance was not used in any statistical testing requiring a normal distribution.

Primary Productivity In Meduxnekeag River, Maine, 2005

The WSMP calculated GPP and NPP for each of the five reaches for each day during the sampling period (figs. 4–8). GPP varied in each reach but generally was positive and similar among the reaches. NPP, however, decreased progressively from upstream reaches to downstream reaches (figs. 4–8). The greatest mean daily GPP was in reach 3, and the greatest mean daily NPP was in reach 1 (table 3). The lowest mean daily GPP was in reach 2, and the lowest mean daily NPP was in reach 5. Mean daily temperature, LI, and pH were comparable among the reaches, but specific conductance increased in reaches 4 and 5 (table 3).

Correlation analysis indicated consistently positive relations among GPP and LI and water-quality measurements in reaches 1–4 (table 4). Relations among the variables in reach 5 were much different than those in reaches 1–4, however.

Correlations between NPP and the other variables were neither consistent nor similar across the reaches (table 5). The relations among NPP and LI, specific conductance, and pH went from positive to negative in reach 4 or 5, proceeding downstream. The relation between NPP and temperature was consistently negative across all the reaches.

The multiple linear regressions of GPP and NPP with water-quality data (not including specific conductance because of its non-normal distribution, which occurred because of a major storm and runoff event) confirmed the other analyses. About 37 to 49 percent of the total variability in GPP in reaches 1 through 4 was explained by the mean daily LI (table 6) and 3 to 38 percent was explained by mean daily pH. In reach 5, the variability in GPP could not be explained by LI. Variability in GPP was not explained by mean daily water temperature in any of the reaches. Similar analysis indicated that about 11 and 15 percent of the variability in NPP in reaches 1 and 2, respectively, were explained by LI and about 45 percent of the variability of NPP in reach 5 was explained by LI (table 7). Temperature and pH explained from about 17 to 46 percent of the variability in NPP in most of the reaches.

The basis for primary productivity is the light required to fuel photosynthesis. Without other sources of oxygen (for example, reaeration), both GPP and NPP, as indicated by dissolved-oxygen concentrations, commonly are correlated directly with light (Marsh, 1970; Kevern and Ball, 1965). Relatively strong relations between GPP and LI were observed in reaches 1 through 4 (tables 4 and 6), but only a weak relation was observed between GPP and LI in reach 5. Because NPP is the difference between GPP and CR–24, GPP and NPP should show similar relations with LI only in systems that are dominated by GPP (as opposed to CR–24). Somewhat weak relations between NPP and LI were observed in reaches 1 and 2 (tables 5 and 7), indicating that CR–24 was dominant in those reaches. These data indicate that in reaches 1–4, light availability was a strong factor in primary productivity and the system was autotrophic, but in reach 5, the system was heterotrophic.

Because NPP is calculated as the difference between GPP and CR–24, the reaches in which CR–24 is dominant (and the system is heterotrophic) are those in which NPP is negative. In reach 1, NPP is negative for about 15 percent of the duration of the study (fig. 4). With distance downstream, NPP is negative for increasingly greater percentages of the duration of the study (reach 2, 26 percent; reach 3, 34 percent; reach 4, 66 percent; and reach 5, 77 percent) (figs. 5–8). The degree to which NPP is negative increases with distance downstream as well; minimum NPP is about -3 grams of oxygen per square meter per day ($gO_2/m^2/day$) in reach 1 and about -30 $gO_2/m^2/day$ in reach 5.

The amounts of GPP as estimated by the WSMP (table 3) indicated high levels of GPP in reaches 1 and 3 but lower levels in the other reaches. In reach 1, the stream gradient is the highest of any of the reaches (table 2), so reaeration may be a strong factor in productivity; in reach 3, time of travel is twice as long as in any other reach. South Branch Meduxnekeag River flows into reach 2, and its contribution, evident in the higher specific conductance

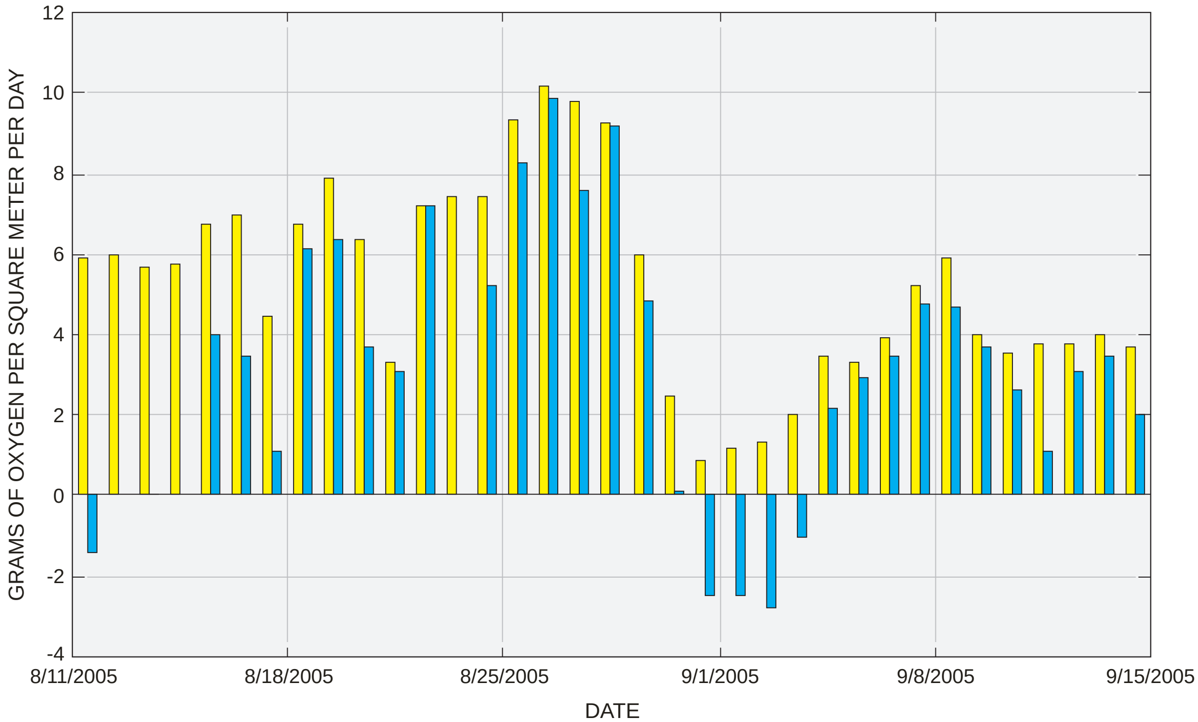

Figure 4. Daily gross (yellow) and net (blue) primary productivity in Meduxnekeag River reach 1, between stations 01017960 and 01017969.

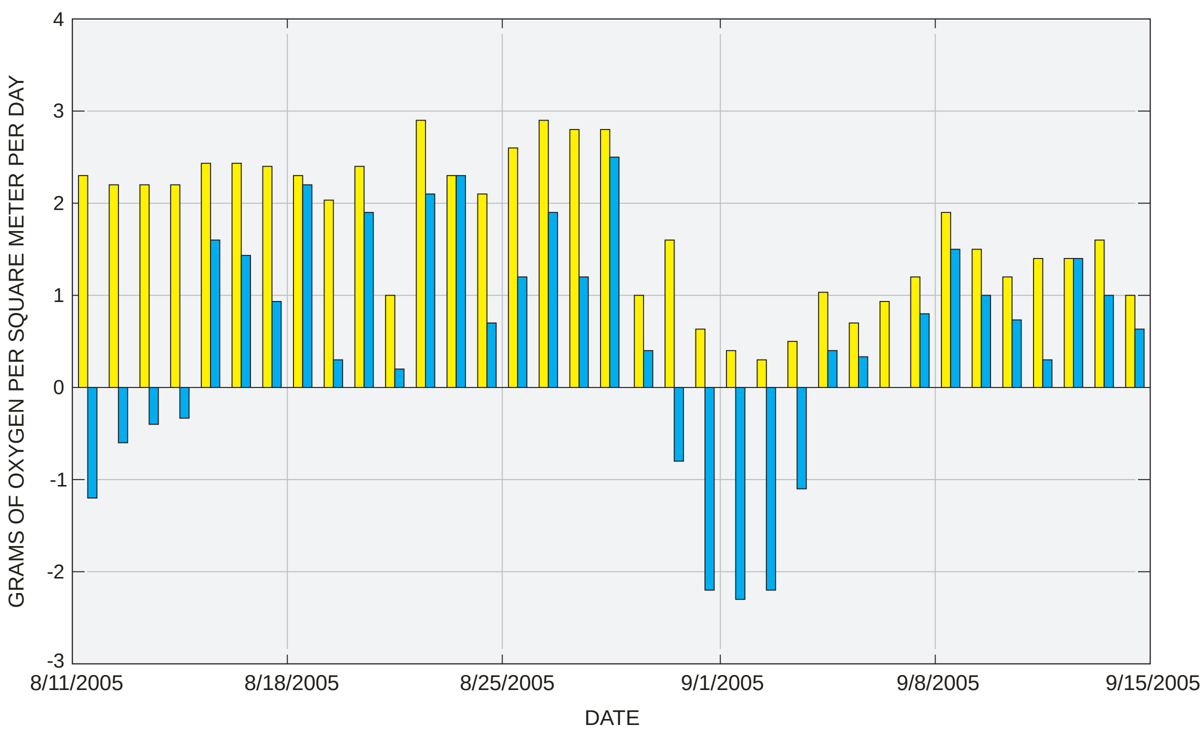

Figure 5. Daily gross (yellow) and net (blue) primary productivity in Meduxnekeag River reach 2, between stations 01017969 and 01018000.

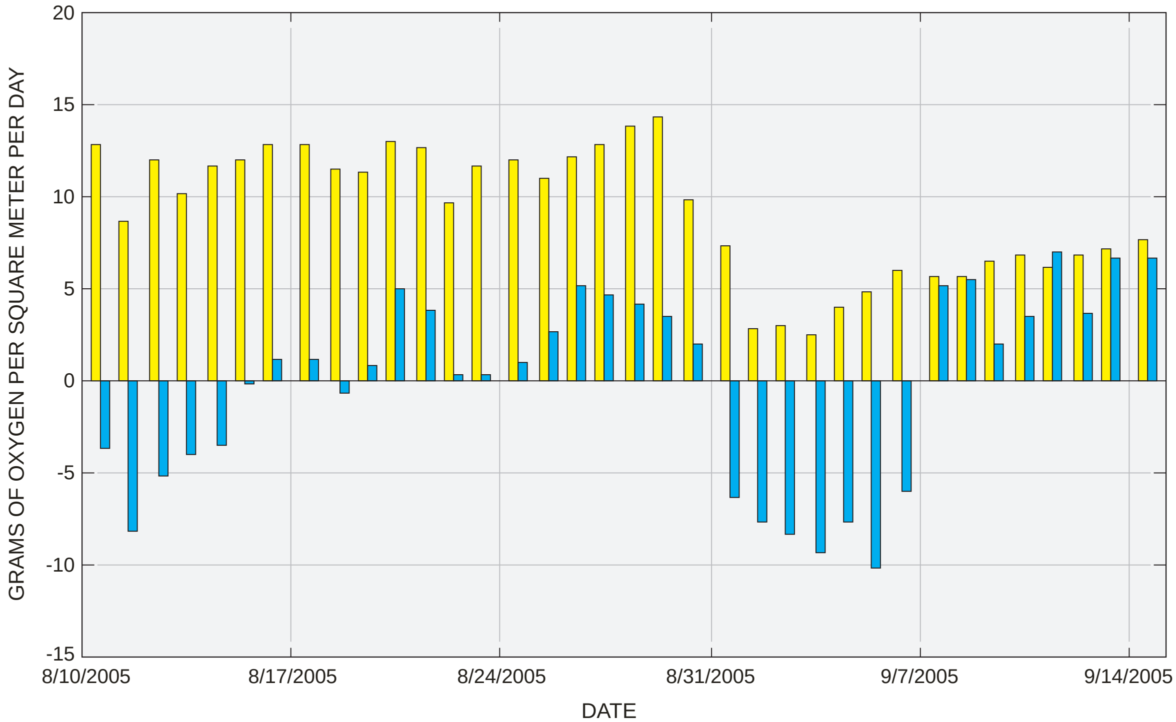

Figure 6. Daily gross (yellow) and net (blue) primary productivity in Meduxnekeag River reach 3, between stations 01018000 and 01018022.

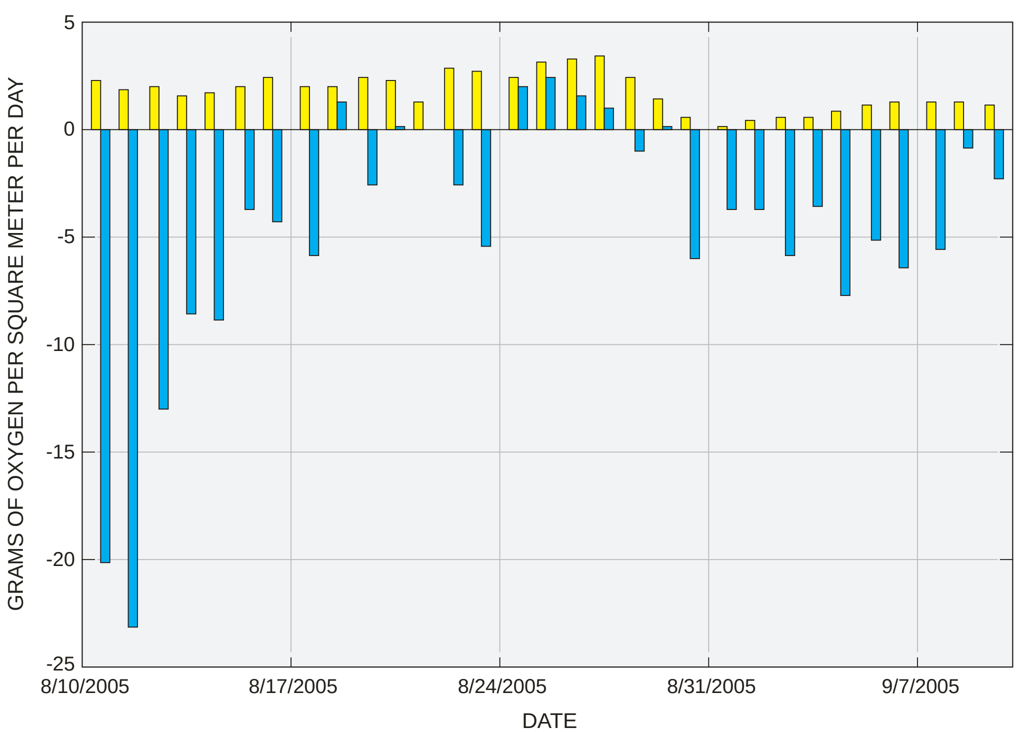

Figure 7. Daily gross (yellow) and net (blue) primary productivity in Meduxnekeag River reach 4, between stations 01018022 and 01018025.

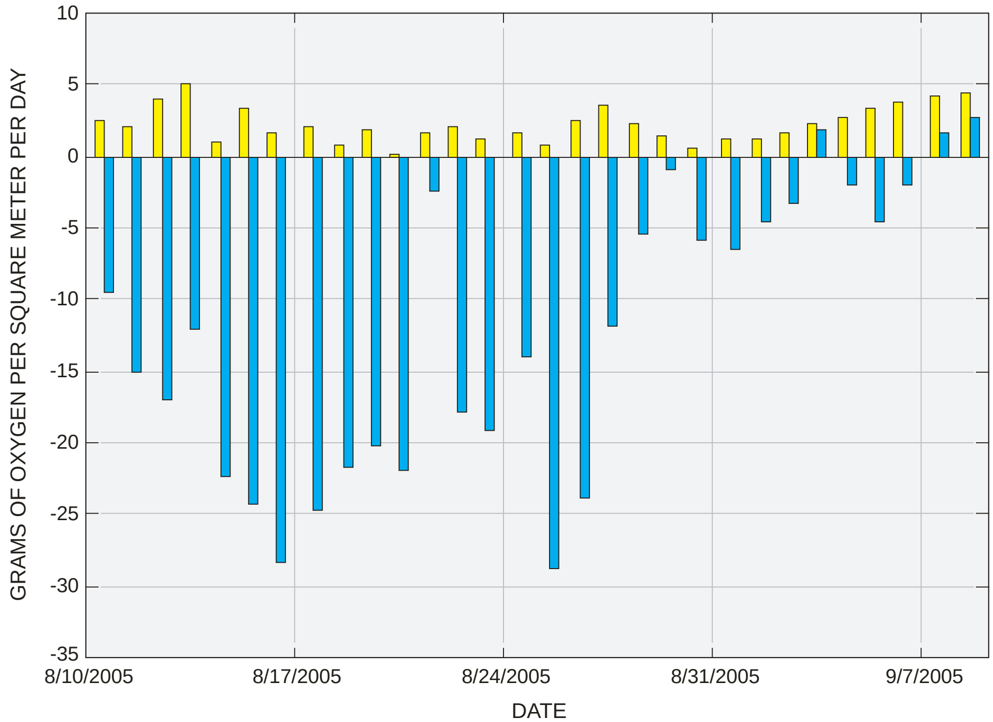

Figure 8. Daily gross (yellow) and net (blue) primary productivity in Meduxnekeag River reach 5, between stations 01018025 and 01018035.

Table 3. Mean daily values for gross (GPP) and net primary production (NPP), temperature, light intensity, specific conductance (SpC), pH and time of travel by reach for Meduxnekeag River, August 10–September 14, 2005.

[Negative values for net primary production indicate that respiration/metabolism consumed more oxygen than was generated by photosynthesis]

Sampling reach	GPP (grams of oxygen per square meter per day)	NPP (grams of oxygen per square meter per day)	Temperature (degrees Celsius)	Daytime light intensity (lumens per square foot)	pH (standard units)	SpC (microsiemens per centimeter)	Time of travel estimated from discharge records, in hours
1	5.3	3.1	20.8	1,455.8	8.0	170	0.5
2	1.7	.5	20.0	1,433.6	8.0	181	3.7
3	9.1	-.2	19.9	1,525.6	8.0	177	20.6
4	1.8	-4.5	20.5	1,577.0	7.8	223	1.1
5	2.2	-12.0	20.6	1,570.7	9.0	241	9.8

Table 4. Pearson correlation coefficients of gross primary productivity with light intensity, temperature, specific conductance, and pH for five reaches in Meduxnekeag River above and below Houlton, Maine.

[Units are Light intensity, lumens per square foot; temperature, degrees Celsius; specific conductance, microsiemens per centimeter]

Independent variable	Location				
	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
Light intensity	0.62	0.70	0.69	0.71	0.15
Temperature	.28	.25	.27	.32	.16
Specific conductance	.59	.72	.92	.78	-.28
pH	.80	.86	.85	.72	-.09

Table 5. Pearson correlation coefficients of net primary productivity with light intensity, temperature, specific conductance, and pH for five reaches in Meduxnekeag River above and below Houlton, Maine.

[Units are lumens per square foot; temperature, degrees Celsius; specific conductance, microsiemens per centimeter]

Independent variable	Location				
	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
Light intensity	0.33	0.38	0.15	-0.22	-0.68
Temperature	-.20	-.33	-.51	-.68	-.32
Specific conductance	.30	.42	.29	.20	-.67
pH	.65	.74	.62	.03	-.68

Table 6. Percent of total variance in mean daily gross primary productivity explained by mean daily light intensity, temperature, and pH in Meduxnekeag River above and below Houlton, Maine.

[Results of multiple linear regression: --, not significant at $P < 0.01$ level]

Independent variable	Location				
	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
Light intensity	36.7	49.3	46.8	49.2	--
Temperature	--	--	--	--	--
pH	35.2	34.0	3.0	--	37.7

Table 7. Percent of total variance in mean daily net primary productivity explained by mean daily light intensity, temperature, and pH in Meduxnekeag River above and below Houlton, Maine.

[Results of multiple linear regression: --, not significant at $P < 0.01$ level]

Independent variable	Location				
	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
Light intensity	10.7	14.6	--	--	45.4
Temperature	16.8	25.1	25.6	45.7	--
pH	29.3	23.4	42.3	--	18.5

and lower temperature, may account for the decrease in GPP from reach 1. Differences in the physical characteristics of the reaches (table 2) make direct comparisons difficult even when using rates of productivity. However, the trends observed in the analyses are indicative of changes in productivity and a trend toward a heterotrophic condition downstream.

NPP decreases with distance downstream from reach 1 through reach 5 (fig. 9), indicating that metabolism and respiration increase such that all oxygen produced is consumed, resulting in an oxygen deficit. Inflow from several sources, including small streams in the urban environment of Houlton, tributaries draining agricultural basins, and discharge from the WWTP, can contribute to the increasing rates of respiration and metabolism. The likely reason for the decrease in dissolved oxygen is the BOD created by inputs of organic matter and nutrients from the above sources (Viessman and Hammer, 1985, p. 238). The effects of these oxygen demands are cumulative; therefore, net primary productivity deceases almost linearly from reach 1 to reach 5. Although these inputs affect the amount of NPP, LI is still correlated to GPP and NPP in the first four reaches. The effects of inflow from the tributary sources and the WWTP apparently overwhelm oxygen production, such that no correlation with LI was evident in reach 5 and NPP was negative.

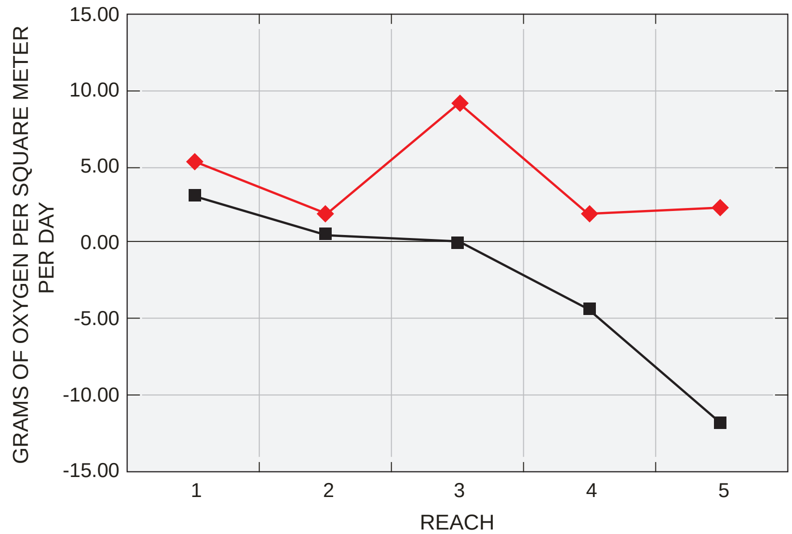

Figure 9. Mean daily gross (red) and net (black) primary productivity in five reaches of Meduxnekeag River above and below Houlton, Maine.

Limitations of the Study and Suggestions for Future Investigations

Although algal blooms developed during parts of the summer of 2005, the blooms were not as severe as in the recent past (C. Ellis, Houlton Band of Maliseet Indians, oral commun., 2005). Consequently, the results of this study cannot be considered predictive of the severity of future algal blooms. Also, because this study was conducted during a single open-water season, the results may not be representative of blooms that might develop during other periods of the year. Because some parameters required by the model and some that would have been useful ancillary information were not collected, model results are presented in general terms.

The 2005 study relied on whole-stream analysis of oxygen change to draw general conclusions about the primary productivity of algae in several reaches of Meduxnekeag River. Several of the factors that are important, as described previously, were not evaluated or were minimally evaluated in this study. These factors include direct measurement of travel time between stations; measurement of BOD, especially downstream of Houlton; and measurement of the stream reaeration rate in each stream reach.

The effects of carbonaceous biochemical oxygen demand (BOD) probably played a role in the estimates of primary productivity, especially downstream from Houlton, but BOD data were not collected. Some analysis of the probable effects of BOD on the results of the model was described previously.

In the absence of measurement of stream reaeration, a default value for all stream reaches was used (0.09 min^{-1}). The default value was within the range of those found in the literature (Wilcock, 1982; Jha and others, 2001). Several equations for calculating reaeration (Jha and others, 2001) using stream slope, average velocity, and average depth were evaluated using data collected for the study. In most cases, the values were less than 0.09 min^{-1}. For reach 1, which has the steepest gradient (table 2), the equations yielded reaeration coefficients in the range of 0.004–0.093 min^{-1}; the average was about 0.04 min^{-1}. A decrease in reaeration coefficient from 0.09 to 0.04 resulted in an average decrease of 48

Table 8. Sensitivity of metabolism rate to stream-reaeration coefficient in reaches 1 and 4.

[min, minute]

Reach number	Decrease in stream reaeration coefficient from 0.09 min^{-1}, in percent	Decrease in daily metabolism rate, in percent
1	55	47
	89	76
4	91	87
	99.6	95

percent in the daily metabolism rate during the first 2 weeks of the study, whereas a decrease to 0.01 min^{-1} resulted in an average decrease of 76 percent in the daily metabolism rate. For reach 4, the equations yielded reaeration coefficients in the range of 0.0003–0.008 min^{-1}; the average was about 0.003 min^{-1}. A decrease in reaeration coefficient from 0.09 to 0.008 resulted in an average decrease of 87 percent in daily metabolism rate during the first 2 weeks of the study, whereas a decrease to 0.0003 min^{-1} resulted in an average decrease of 95 percent in the daily metabolism rate. These data illustrate the importance of determining stream-reaeration coefficient with a high degree of certainty.

Although biomass accumulation is important in determining the absolute rate of primary productivity, it was not included because the study focused on relative differences in primary productivity among several reaches of the river, assuming that biomass accumulation would be fairly similar in each of the reaches. This seemed to be the case, from observations of the reaches during the study; each reach had some development of algae and macrophytes in areas where the substrate was amenable.

The results of this study indicate that primary productivity is affected by inputs to Meduxnekeag River from urban and agricultural land use in the basin and direct discharges from the WWTP. Additional data concerning the volume and composition of nutrients and organic matter from each of the sources could be examined in the future and seasonal loads estimated from each source. Additional determinations of primary productivity by direct-measurement techniques described earlier would help to compartmentalize productivity among water and sediments, which in turn would help relate the results of this study more closely with the results of the bed-sediment study done earlier (Schalk and Tornes, 2005). Quantification of algal biomass and (or) chlorophyll *a* could be integrated into a future study design along with more detailed water-quality measurements, including BOD. The benthic communities above and below major input sources could be compared to estimate their effect on oxygen consumption. The existing dataset could be reexamined on smaller time scales to derive comparisons of primary productivity among reaches when hydrologic conditions are stable. Future studies along these lines would aid in determining the sources and magnitude of factors affecting primary productivity in Meduxnekeag River.

Summary and Conclusions

Summer algal blooms in Meduxnekeag River in northeastern Maine have been a recurring problem for the Houlton Band of Maliseet Indians (HBMI) for many years. During the summer of 2005 in cooperation with HBMI, the USGS monitored primary productivity indicators and water-quality conditions at six stations on Meduxnekeag River to collect data for a dual-station model that calculates primary productivity.

Data for input to the whole-stream metabolism computer program (WSMP) were collected at six stations on Meduxnekeag River that defined five reaches. Data collected include dissolved oxygen, temperature, specific conductance, and pH. Light-intensity (LI) data were measured by use of HOBO™ Pendant sensors set in the streams slightly below the water surface. Travel times were estimated by dividing the distance between streamflow-gaging stations by the average velocity of the stream at the upstream station and verified by analysis of a small rise in the hydrograph from upstream to downstream stations during a period of low flow. Stream slope was calculated from topographic maps. Barometric pressure data were compiled during instrument calibration and (or) deployment.

The model estimated gross (GPP) and net primary productivity (NPP) in grams of oxygen per square meter per day. Mean daily values of productivity, LI, temperature, specific conductance, and pH were examined graphically, with correlation analysis, and with multiple linear regression analysis. GPP varied in each reach but generally was positive and similar among the reaches. NPP, however, decreased progressively from upstream reaches to downstream reaches. Mean daily temperature, LI, and pH were comparable among the reaches, but specific conductance increased in reaches 4 and 5 below the Houlton wastewater treatment plant (WWTP). Correlation analysis indicated consistent relations among GPP and LI and water quality in reaches 1, 2, 3, and 4. Relations among GPP and LI and water quality were dissimilar in reach 5 compared to the upstream reaches. The relations among NPP and LI, specific conductance, and pH went from positive to negative proceeding downstream in either reach 4 or 5. The multiple linear regressions of GPP and NPP with water-quality constituents confirmed the other analyses. The likely reason for the decrease in NPP, as indicated by dissolved-oxygen concentrations, is the biochemical oxygen demand (BOD) created by inputs of organic matter and nutrients from urban, agricultural, and waste-treatment sources. The effects of these oxygen demands apparently were cumulative; therefore, NPP deceased almost linearly from reach 1 to reach 5.

The magnitude of the effects of increased BOD from the tributaries, combined with input from the WWTP, seemed to overwhelm oxygen production, such that no correlation or strong negative correlation of NPP with LI was evident in the lowest reaches and net productivity was negative.

During analysis of the data and model results, the need to quantify BOD and the reaeration coefficient were identified as critical data needs. Results indicate that it may be possible to reduce the number of reaches while increasing the collection of data to facilitate estimation of primary productivity on a real-time basis. Such a tool could be valuable in helping local managers understand better the interactions among streamflow, water-quality constituents, and algal productivity in Meduxnekeag River.

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