National Water-Quality Assessment Program

Automated Routines for Calculating Whole-Stream Metabolism: Theoretical Background and User's Guide

Chapter 2 of
Book 4, Hydrologic Analysis and Interpretation,
Section C, Surface Water

Techniques and Methods 4–C2

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

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By Jerad D. Bales and Mark R. Nardi

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DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2007

Foreword

The U.S. Geological Survey (USGS) is committed to providing the Nation with credible scientific information that helps to enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (*http://www.usgs.gov/*). Information on the Nation's water resources is critical to ensuring long-term availability of water that is safe for drinking and recreation and is suitable for industry, irrigation, and fish and wildlife. Population growth and increasing demands for water make the availability of that water, now measured in terms of quantity and quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, State, and local information needs and decisions related to water-quality management and policy (*http://water.usgs.gov/nawqa*). The NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. From 1991–2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river basins and aquifers, referred to as Study Units (*http://water.usgs.gov/nawqa/studyu.html*).

Multiple national and regional assessments are ongoing in the second decade (2001–2012) of the NAWQA Program as 42 of the 51 Study Units are reassessed. These assessments extend the findings in the Study Units by determining status and trends at sites that have been consistently monitored for more than a decade, and filling critical gaps in characterizing the quality of surface water and ground water. For example, increased emphasis has been placed on assessing the quality of source water and finished water associated with many of the Nation's largest community water systems. During the second decade, NAWQA is addressing five national priority topics that build an understanding of how natural features and human activities affect water quality, and establish links between *sources* of contaminants, the *transport* of those contaminants through the hydrologic system, and the potential *effects* of contaminants on humans and aquatic ecosystems. Included are topics on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on aquatic ecosystems, and transport of contaminants to public-supply wells. These topical studies are conducted in those Study Units most affected by these issues; they comprise a set of multi-Study-Unit designs for systematic national assessment. In addition, national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, selected trace elements, and aquatic ecology are continuing.

The USGS aims to disseminate credible, timely, and relevant science information to address practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for cost-effective management, regulation, and conservation of our Nation's water resources. The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, regional, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
Area		
square meter (m^2)	10.76	square foot (ft^2)
Volume		
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
liter (L)	61.02	cubic inch (in^3)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

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

$$°F = (1.8 \times °C) + 32$$

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

Elevation, as used in this report, refers to distance above the vertical datum.

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

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

Abbreviations

C	concentration
C_f	units conversion factor
C_s	saturation concentration
d	day
D_{avg}	reach-averaged dissolved-oxygen deficit
DO	dissolved oxygen, in milligrams per liter
$DO_{corrected}$	dissolved-oxygen concentration corrected for initial error, fouling, and drift
DO_d	dissolved-oxygen concentration at downstream measuring station
DO_P	dissolved-oxygen solubility at barometric pressure (P_{atm})
$DO_{reading}$	uncorrected DO concentration obtained directly from the water-quality meter
DO_s	dissolved-oxygen saturation concentration
DO_{sl}	dissolved-oxygen solubility, in milliliters per liter
DO_u	dissolved-oxygen concentration at upstream measuring station
dt	measurement interval
E_e	error in dissolved-oxygen reading at the end of meter deployment
E_i	error in dissolved-oxygen reading at the beginning of meter deployment
F_r	reaeration flux
GPP	gross primary production
hr	hour
K_2	reaeration rate coefficient
min	minute
mm Hg	millimeters of mercury
$\mu mol/(m^2/s)$	micromoles per square meter per second
N_i	serial number of current water-quality meter reading, with the first reading having a serial value of 0
N_{total}	total number of readings during water-quality meter deployment
n_1	number of individual metabolism flux values during the first nighttime period
n_2	number of individual metabolism flux values during the second nighttime period
n_d	the total number of measurement intervals during daylight hours, including the first and last daylight readings
NM	net metabolism flux
NAWQA	National Water-Quality Assessment Program
NEET	Nutrient Enrichment Effects Team
NEP	net ecosystem production
NPP	net primary production
P	photosynthesis
P_{atm}	ambient barometric pressure
P_{sat}	saturation vapor pressure
PAR	photosynthetically active radiation
Q	streamflow
R	respiration
R_c	community respiration
R_d	daytime respiration
R_{con}	constant daytime respiration
R_p	plant respiration
$R_{pre\text{-}dawn}$	the average respiration rate calculated from individual net metabolism fluxes for the 1-hour period immediately before dawn
$R_{post\text{-}sunset}$	the average respiration rate calculated from individual net metabolism fluxes for the 1-hour period immediately after sunset
$R_{var}(t)$	variable daytime respiration at time (t)

S	salinity
S_{N1}	sum of net metabolism flux for the first nighttime period
S_{N2}	sum of net metabolism flux for the second nighttime period
SC	specific conductance, in millisiemens or microsiemens per centimeter
sec	seconds
SMP	Stream Metabolism Program
t	time
T	water temperature, in degrees Celsius
T_d	duration of the daytime period, in hours
T_K	water temperature, in degrees Kelvin
T_{N1}	duration of the first nighttime period, in hours
T_{N2}	duration of the second nighttime period, in hours
T_t	travel time through reach
t_u	time at which upstream measurement is made
U	mean stream velocity
USGS	U.S. Geological Survey
V_D	measured downstream value
V_R	reach-averaged value
V_U	measured upstream value
x	longitudinal distance along a stream

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Abstract

In order to standardize methods and facilitate rapid calculation and archival of stream-metabolism variables, the Stream Metabolism Program was developed to calculate gross primary production, net ecosystem production, respiration, and selected other variables from continuous measurements of dissolved-oxygen concentration, water temperature, and other user-supplied information. Methods for calculating metabolism from continuous measurements of dissolved-oxygen concentration and water temperature are fairly well known, but a standard set of procedures and computation software for all aspects of the calculations were not available previously. The Stream Metabolism Program addresses this deficiency with a stand-alone executable computer program written in Visual Basic.NET®, which runs in the Microsoft Windows® environment.

All equations and assumptions used in the development of the software are documented in this report. Detailed guidance on application of the software is presented, along with a summary of the data required to use the software. Data from either a single station or paired (upstream, downstream) stations can be used with the software to calculate metabolism variables.

Introduction

Stream metabolism is the net gain in dissolved oxygen (DO) associated with photosynthesis and the loss of DO through plant and animal respiration. Odum (1956) developed, and gave to it the now commonly used name, the upstream-downstream method of measuring community, or whole-stream metabolism, within a stream reach. Application of the method involved 1- to 6-hour (hr) measurements of DO concentration and water temperature (T), estimation of reaeration rate, and graphical data analysis of DO concentration (for example, Erdmann, 1979).

Whole-stream metabolism measurements have improved with the introduction of instrumentation that automatically measures and records DO, T, and other parameters (for example, Wagner and others, 2006) at short time intervals. The development of tracer-gas methods (Tsivoglou and others, 1968; Rathbun and others, 1978; Kilpatrick and others, 1989) to measure stream reaeration rates directly can reduce uncertainty in metabolism computations. Other improvements in the whole-stream metabolism method (Marzolf and others, 1994), including the continuous measurement of photosynthetically active radiation (PAR), have resulted in increased use of the procedure to understand stream ecosystem functioning.

Despite some standardization in measurement and data analysis procedures, metabolism variables can be calculated from the same set of whole-stream data using slightly different approaches. For example, daylight respiration (R) typically is extrapolated from nighttime R, but the exact value of nighttime R that is used and the method of extrapolation are subject to judgment. No protocol or standard software tool currently is available for computing whole-stream metabolism from continuous measurements of DO and T.

In 2001, the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program began an intensive study of nutrient enrichment—elevated concentrations of nitrogen and phosphorus—in streams draining agricultural basins across the Nation (Munn and Hamilton, 2003). One of the major objectives of this study is to determine the interrelations among nutrient conditions, algal communities, and stream metabolism.

As a part of the nutrient-enrichment study, which is conducted by the NAWQA Nutrient Enrichment Effects Team (NEET) and other NAWQA studies, whole-stream metabolism measurements have been, or are planned to be, made at more than 100 individual sites, with some replication of measurements at a subset of the sites. As previously noted, methods for calculating metabolism from continuous measurements of DO and T are fairly well known, although no standard set of procedures is available for all aspects of the measurements and calculations. In order to standardize methods and to facilitate rapid calculation and archival of stream-metabolism variables

for the large number of NAWQA study sites, the Stream Metabolism Program (SMP) was developed.

Purpose and Scope

The purpose of this report is to document the Stream Metabolism Program (SMP). The SMP is a stand-alone executable computer program written in Visual Basic.NET®, which runs in the Microsoft Windows® environment. The program calculates gross primary production, net ecosystem production, respiration, and selected other variables from continuous measurements of DO, T, and other user-supplied information. Data from either a single station or paired (upstream, downstream) stations can be used in the SMP to calculate metabolism variables.

The equations and assumptions used in the development of the software are documented in this report. Detailed guidance on application of the software is then presented, along with a summary of the data required to use the software.

Theoretical Background

The SMP was developed to facilitate computation of selected measures of stream metabolism using procedures first described by Odum (1956). This method is also known as the diurnal curve method because the method was first based on a graphical analysis of a plot of one or more days of DO in relation to time (for example, Erdmann, 1979). Data from either a single station or from two stations, one each at the upstream and downstream ends of the reach, can be used in the analysis. The theory supporting calculations by the SMP and all assumptions made in the application of the software are described in this section.

Overview

Detailed discussions of the processing of oxygen in streams can be found in a number of works, including Hauer and Lamberti (2006). Primary productivity is "the rate of formation of organic matter from inorganic carbon by photosynthesizing organisms and thus represents the conversion of solar energy to reduced chemical energy" (Bott, 2006). Some of the production is lost through plant respiration, R_p, so

$$GPP = NPP + R_p, \qquad (1)$$

where
$$\begin{aligned}
GPP \quad &= \text{gross primary production, and} \\
NPP \quad &= \text{net primary production, which is the portion} \\
&\quad \text{of } GPP \text{ stored in plant biomass.}
\end{aligned}$$

The variables in eq. 1 typically are expressed in units of mass of oxygen per unit wetted stream area per time (for example,

grams of oxygen per square meter per day). Equation 1 applies strictly to production and respiration by plants in the stream.

The change in DO concentration is an indication of the DO additions by reaeration and photosynthesis and DO losses by community respiration, R_c, which is respiration by both plants (R_p), or autotrophs, and heterotrophs, such as bacteria and insects. Estimates of R typically are based on measurements at night (or in the dark) when production is zero. Respiration during daylight often is assumed to be equal to nighttime R, so if daylight R differs substantially from nighttime R, estimates of plant GPP could be in error. Moreover, if heterotrophic respiration is a large part of R_c, the R_c measurements will not provide a good estimate of R_p, resulting in additional error in estimates of GPP. Heterotrophic respiration is often a large part of R_c when the stream receives high loads of carbonaceous, nitrogenous, or chemical oxygen demand from human-related sources or when streams are shaded and lack sufficient sunlight to maximize plant production. Because community respiration, and not plant respiration, is measured in the whole-stream metabolism method, eq. 1 may be more appropriately written as

$$GPP = NEP + R_c, \qquad (2)$$

where NEP = net ecosystem production.

The mass balance for a gas in a stream, which is the basis for the whole-stream metabolism calculation method (Ramaswami and others, 2005), is

$$\frac{\partial(C_s - C)}{\partial t} = U\frac{\partial(C_s - C)}{\partial x} + K_2(C_s - C) + sources - losses, \quad (3)$$

where
$$\begin{aligned}
C \quad &= \text{concentration, in (mass/volume);} \\
C_s \quad &= \text{saturation concentration, in (mass/volume);} \\
t \quad &= \text{time;} \\
U \quad &= \text{mean stream velocity, in (length/time);} \\
x \quad &= \text{longitudinal distance along the stream} \\
&\quad \text{channel; and} \\
K_2 \quad &= \text{air-water gas exchange (or reaeration)} \\
&\quad \text{coefficient, in (1/time).}
\end{aligned}$$

Equation 3 is based on the assumption that stream velocity is constant (steady flow) over the period of measurements and that there is no dispersion in the study reach.

Equation 3 can be simplified for selected conditions. If no ground-water or surface-water inputs are within the stream reach under consideration, the sources of DO to the reach are inflow at the upstream end, photosynthesis (P), and reaeration. The losses of DO are a result of outflow at the downstream end of the reach, deoxygenation in the case of super-saturated water, and R_c. Reaeration, P, and R_c can vary with time, even under steady flow conditions, primarily because of the effects of changes in water temperature and light.

The single-station method for estimating stream metabolism is valid only if the first term on the right side of eq. 3 is zero, or in other words, if the longitudinal gradient of the DO deficit (dissolved-oxygen saturation minus DO) is zero. The two-station method provides a measure of metabolism in a parcel of water flowing through the study reach. These values can be summed over a day to provide estimates of daily metabolism.

The SMP requires some site-specific data and time-series data. Data typically are obtained by using continuously recording water-quality meters that are deployed for at least 36 hours. The program produces graphs of the time-series data, corrects DO readings for sensor error and drift during deployment, summarizes data, calculates metabolism variables, and provides the user with options for exporting data to a spreadsheet or text files (fig. 1). Calculations performed by the SMP are

- Percent of saturation concentration for each DO reading;
- Adjustment of each DO reading for meter error, fouling, and drift;
- Automated selection of metabolism analysis periods;
- Reach-averaged values for water temperature, DO, and DO saturation concentration (DO_s);
- Reaeration flux for each time step;
- Net metabolism flux at each time step;
- Community respiration at each time step and 24-hour respiration; and
- Gross primary production and net ecosystem production.

Details of each of these calculations within the SMP are described in the following sections.
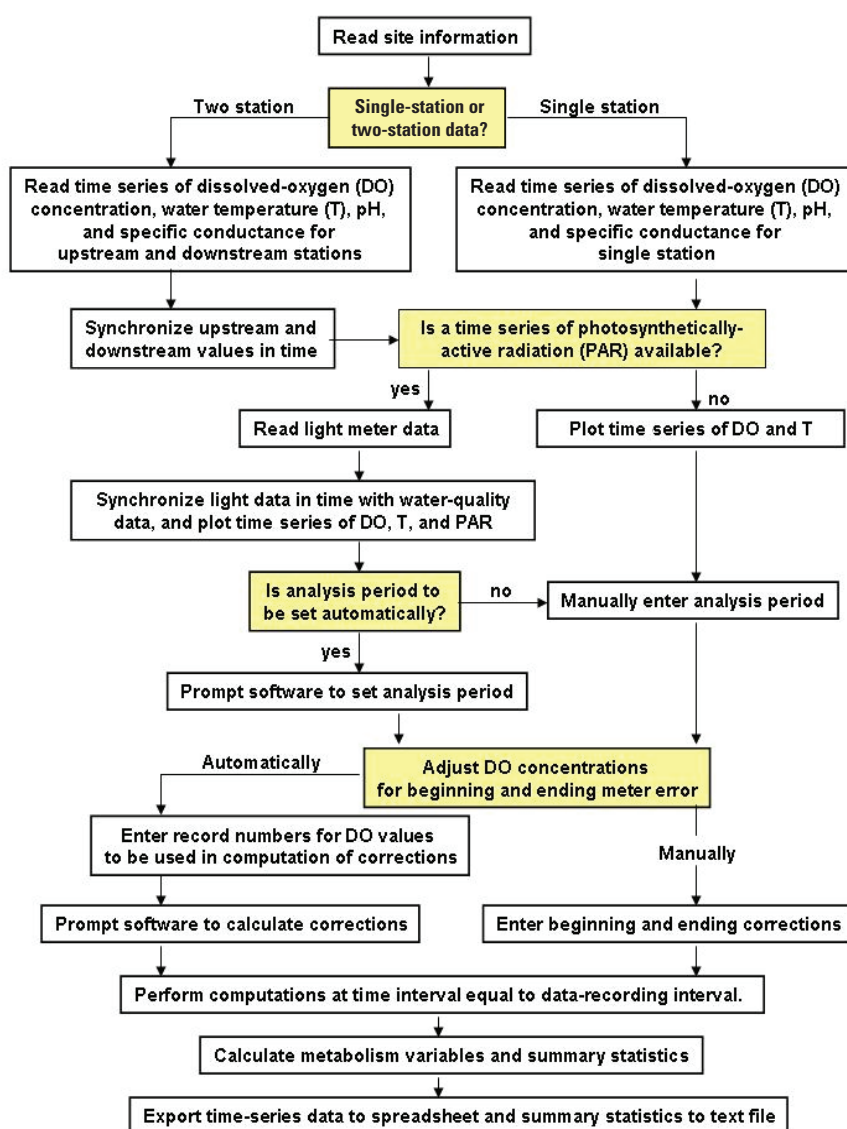

Figure 1.   Flow chart showing steps in metabolism calculations. (Yellow boxes indicate decisions to be made by user.)

Dissolved-Oxygen Saturation Concentration

The first calculation in the SMP is the determination of the DO saturation concentration (DO$_s$). The saturation concentration is the DO concentration in the stream at 100 percent saturation for a given water temperature, barometric pressure, and specific conductance.

The accepted relation for saturation concentration at the vertical datum (North American Vertical Datum of 1988 [NAVD 88]; Weiss, 1970) is

$$\ln(DO_{sl}) = [A1 + A2*(100/T_K) + A3*\ln(T_K/100) \qquad (4)$$
$$+A4*(T_K/100)] + S*[B1 + B2*(T_K/100)$$
$$+B3*(T_K/100)^2]$$

where

Al	$= -173.4292$;
A2	$= 249.6339$;
A3	$= 143.3483$;
A4	$= -21.8492$;
Bl	$= -0.033096$;
B2	$= 0.014259$;
B3	$= -0.001700$;
T_K	$=$ temperature, in degrees Kelvin, $= (273.15 + T)$;
S	$=$ salinity, in grams per kilogram or parts per thousand;
DO_{sl}	$=$ dissolved oxygen solubility, in milliliters per liter at NAVD 88;
ln	$=$ natural logarithm; and

barometric pressure at NAVD 88 = 760 millimeters of mercury.

DO_{sl}, in milliliters per liter, can be converted to the more standard units of milligrams per liter by multiplying DO_{sl} in milliliters per liter by 1.4276 (U.S. Geological Survey, 1981).

A simple conversion from specific conductance to salinity (U.S. Geological Survey, 1981) is

$$S = 5.572*10^{-4}*SC + 2.02*10^{-9}*SC*SC, \qquad (5)$$

where SC = specific conductance, in microsiemens per centimeter at 25 degrees Celsius. Equation 5 is not particularly accurate for converting specific conductance to salinity, but the error in conversion given by eq. 5 has negligible effect on the calculation of DO solubility from eq. 4, and eq. 5 is much simpler to program than the more accurate relations (for example, Lewis, 1980).

The correction of eq. 4 for barometric pressure (U.S. Geological Survey, 1981) is

$$DO_p = DO_{sl} * ((P_{atm} - P_{sat}) / (760 - P_{sat})), \qquad (6)$$

where

DO_p	$=$ saturation concentration, in milligrams per liter, at barometric pressure P_{atm}, in millimeters of mercury;
DO_{sl}	$=$ saturation concentration, in milliliters per liter at NAVD 88, calculated from eq. 4;
P_{atm}	$=$ ambient barometric (or atmospheric) pressure; and
P_{sat}	$=$ saturation vapor pressure, in millimeters of mercury, as described below.

Several formulations are available for calculating saturation vapor pressure of water (Vomel, 2004). At temperatures greater than about 0 degrees Celsius (°C), the various formulations give essentially the same result. The Bolton (1980) equation is one of the simpler equations (with temperature in degrees Celsius):

$$P_{sat} = 4.5844 * \exp[17.67*T/(T + 243.5)]. \qquad (7)$$

The general relation for DO saturation concentration (DO$_s$, in milligrams per liter) in natural waters at any barometric pressure, water temperature (greater than 0 °C), and specific conductance is obtained by combining eqs. 4–7:

$$DO_s = (1.4276*\exp(-173.4292 +(249.6339 \qquad (8)$$
$$*((100/(T+273.15))))+(143.3483$$
$$*(\ln((T+273.15)/100))) -(21.8492*((T+273.15)/100))$$
$$+(((0.0005572*SC)+(0.00000000202*SC*SC))$$
$$*(-0.033096+(0.014259*((T+273.15)/100))$$
$$-(0.0017*((T+273.15)/100)*((T+273.15)/100))))))$$
$$*((P_{atm}-(7.50062*0.6112*\exp(17.67$$
$$*(T/(T+243.5)))))/(760-(7.50062*0.6112*\exp$$
$$(17.67*(T/(T+243.5)))))).$$

Although barometric pressure changes during a whole-stream metabolism measurement period during which meters are deployed, a single value of barometric pressure is used in the SMP for all DO$_s$ calculations for each meter deployment because changes in P_{atm} that are likely to occur during a 24- to 72-hr deployment do not substantially affect DO$_s$. For example, at a temperature of 20 °C and a specific conductance of 150 microsiemens per centimeter (μS/cm), DO$_s$ is 9.00 milligrams per liter (mg/L) at P_{atm} = 755 millimeters (mm) mercury (Hg) and 9.12 mg/L at P_{atm} = 765 mm Hg. Moreover, continuous records of barometric pressure at the deployment site typically are not available. Saturation concentration is calculated in the SMP for each measurement interval by using T-, SC-, and DO-concentration data for the measurement intervals and the constant barometric pressure. Barometric pressure should be recorded when instruments are deployed and recovered, and an average pressure can be used in the calculations.

Correction of Measured Dissolved-Oxygen Concentration for Sensor Error and Drift

Measured DO concentrations are corrected for initial calibration error and for sensor fouling and calibration drift that can occur during the deployment (fig. 2). The initial calibration error (corrected DO minus measured DO) is added to all DO readings. The total ending error (sensor fouling plus calibration drift) is determined, and this error is linearly interpolated over time and added to each field reading. This approach is consistent with published USGS methods (Wagner and others, 2006) and is described by the following equation:

$$DO_{corrected} = DO_{reading} + (E_i + (((E_e - E_i)/N_{total-1})*N_i)),\quad (9)$$

where

$DO_{corrected}$ = DO concentration, in milligrams per liter, corrected for initial error, fouling, and drift;

$DO_{reading}$ = field-measured DO concentration, in milligrams per liter;

E_i = error in DO reading, in milligrams per liter, at the beginning of deployment;

E_e = error in DO reading, in milligrams per liter, at the end of deployment;

N_{total} = total number of readings during deployment; and

N_i = serial number of current meter reading, with the first reading having a serial value of 0.

The corrected DO value for the first reading ($N_i = 0$) is equal to the DO reading plus the initial error (E_i). Equation 9 is based on the assumption that field readings are made at equal time increments throughout the deployment.

Drift is calculated by the SMP as follows. Following meter calibration, DO readings are made in saturated air prior to deployment (pre-deployment); these readings are repeated after the meter is recovered (post-deployment). About four to six individual readings should be made at relatively short increments (3–5 minutes). Barometric pressure should be noted for pre- and post-deployment readings. The DO reading in saturated air should be equal to the DO_s concentration for the measured temperature and barometric pressure if the meter is exactly correct. Differences between the actual DO reading in saturated air and the C_s (obtained by using eq. 8) are calculated by the SMP for each reading during the pre- and post-deployment periods. The differences for each measurement interval are averaged for the pre-deployment period (E_i); a similar average is calculated for the post-deployment period (E_e). The error is positive if the DO reading is less than the saturation concentration, because the error is added to the reading to get the corrected value (eq. 9). This approach assumes that there are no errors in the temperature, specific conductance, and barometric pressure sensors, but that all of the error is associated with the DO sensor. This a reasonable assumption for a relatively short (1–5 days) deployment in waters that are not highly polluted.

As previously noted, the SMP accepts a single value of barometric pressure for the entire deployment period. Large differences in barometric pressure between pre-deployment and post-deployment meter calibrations can result in small errors in E_i and E_e. For example, at typical stream temperatures (5–35 ºC) and specific conductance values (2–20 millisiemens per centimeter [mS/cm]), a change in barometric pressure of 10 mm Hg results in about a 1.3 percent change in DO_s. The SMP allows users to directly input E_i and E_e when automated calculation of these values is not appropriate.

The approach used by the SMP to adjust DO readings for initial error, drift, and sensor fouling is based on the assumption that the correction can be linearly prorated by time over the deployment period. This is a reasonable assumption for the relatively short deployment periods typical of stream metabolism studies. Wagner and others (2006) suggest that the correction be linearly interpolated based on the final percentage error rather than the final measured error when the total error is large relative to the range in DO. This approach may be appropriate, for example, when the final DO error is 2 mg/L, and the range in readings is, for example, 4 mg/L. In this case, E_i and E_e should be computed by the user outside the SMP and then entered directly into the software, as demonstrated in the *User's Guide* section of this report. A third method for correcting meter readings is provided by Wagner and others
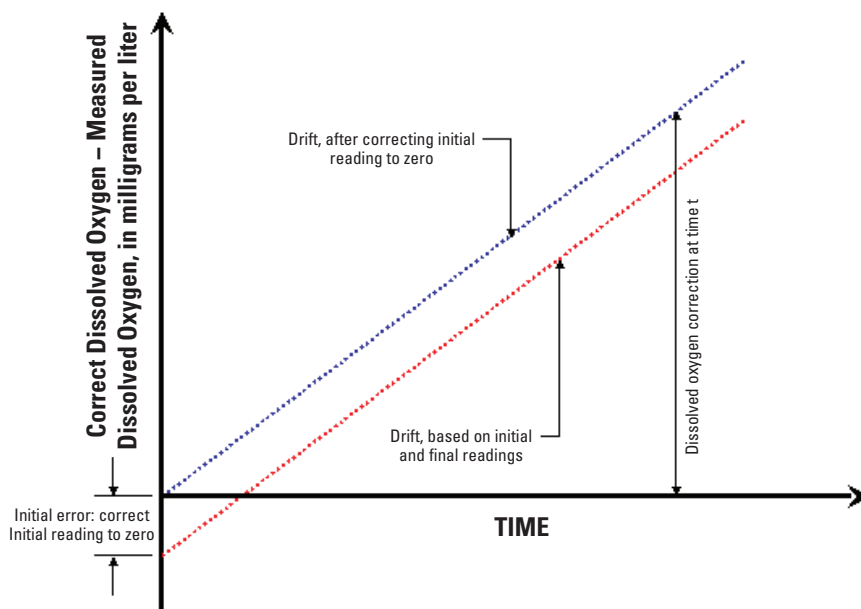

Figure 2. Schematic diagram showing initial error and sensor drift.

(2006) for use when the meter calibration is not linear over the range of readings. Modern in situ water-quality meters typically exhibit linear calibrations over the range of readings in flowing freshwater.

Determination of Analysis Period

The SMP offers two options for identifying the daylight and nighttime periods for which metabolism variables are to be calculated—an automated selection of the analysis period by the SMP or user-specified analysis periods. A combination of the two options also is available, in which the analysis period is automatically selected, and the user can adjust selected features of the analysis period (see the *User's Guide* section of this report). A continuous record of PAR data are required for the automated approach. The analysis periods should include a complete sunrise to sunset daylight period and at least one nighttime period that immediately precedes and one that immediately follows the daylight analysis period. Methods used in the automated selection of the analysis period are described in this section.

If the automated selection is used, the analysis period begins at the minimum DO concentration on the first night

(fig. 3). The period then extends forward for at least 24 hr and includes the minimum DO concentration on the following night. If the minimum DO on the second night occurs more than 24 hr after the minimum on the first night, the calculation period is greater than 24 hr. Respiration values are prorated so that 24-hr respiration is reported.

The analysis period is subdivided into daylight, night, pre-dawn, and post-sunset times (fig. 3). The daylight period is determined automatically by the SMP from the PAR data: the beginning of daylight is when the PAR reading exceeds 2 micromoles per square meter per second [μmol/(m^2/s)] and daylight ends when PAR becomes less than 2 μmol/(m^2/s) (fig. 3). PAR values typically are constant through the nighttime, increase quickly from the nighttime levels at sunrise, and do not ever approach the threshold of 2 μmol/(m^2/s) during daylight hours (fig. 3).

After the daylight period is determined from the PAR data, the SMP automatically assigns a 1-hr pre-dawn period that begins 1 hr before the beginning of the daylight period. Similarly, a 1-hr post-sunset period is automatically assigned, beginning immediately after the end of daylight (fig. 3). The pre-dawn and post-sunset periods are used for computing daytime respiration, as discussed in a subsequent section.
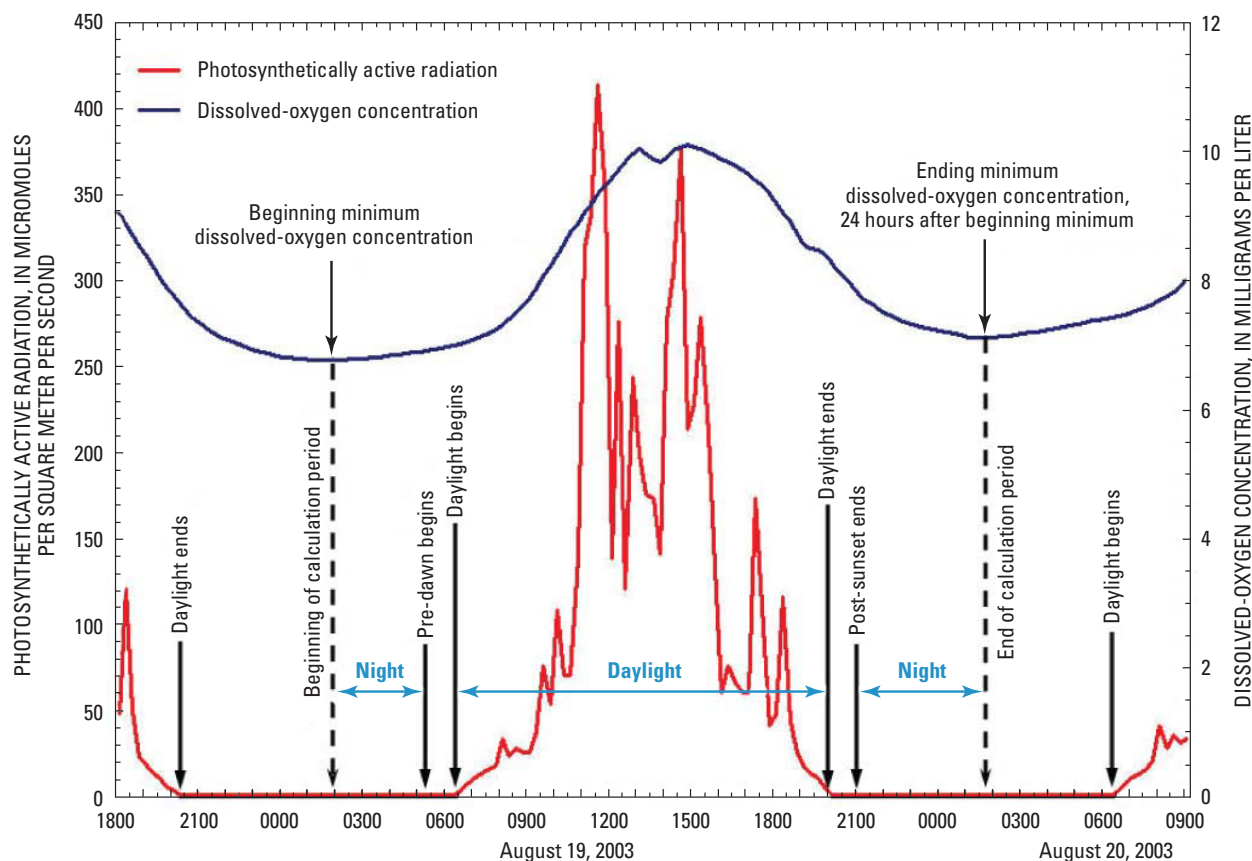

Figure 3.   Typical photosynthetically active radiation and dissolved-oxygen concentration data collected at Athanum Creek at Union Gap, Washington, August 18–20, 2003.

Two nighttime periods previously were noted. The first nighttime period begins at the time the minimum DO concentration occurs prior to the daylight period and extends to the beginning of the pre-dawn period (fig. 3). The second nighttime period begins at the end of the post-sunset period and extends to the time when the minimum DO concentration is recorded following the daylight period (fig. 3).

In some cases, the DO data may differ from the typical conditions shown in figure 3. In those cases, the user must select the beginning of the first nighttime period and the end of the second nighttime period (fig. 3). The SMP still will automatically identify the daylight, pre-dawn, and post-sunset periods. This approach is described in the *User's Guide* section of this report.

Reach-Averaged Water Temperature, Dissolved-Oxygen Concentration, and Dissolved-Oxygen Deficit

For the two-station method, reach-averaged values of water temperature, DO, and DO deficit $[DO_s(t) - DO(t)]$ are needed to solve eq. 3 for a parcel of water moving through the

study reach. These values are calculated for each measurement time (t). The travel time (T_t) of each water parcel is determined from measurements of time-of-travel made by using a conservative tracer, such as rhodamine dye or bromide (Kilpatrick and Wilson, 1989; fig. 4). The reach-averaged value is calculated as follows:

$$V_R(t) = [V_U(t-T_t) + V_D(t)]/2, \qquad (10)$$

where

$\quad V_R(t) \quad$ = reach-averaged value at a given measurement time;

$\quad V_U(t-T_t) \quad$ = measured upstream value at a given measurement time minus the travel time (T_t); and

$\quad V_D(t) \quad$ = measured downstream value at a given measurement time.

Equation 10 applies to T, DO, and DO deficit, but only strictly applies if the travel time is an integer multiple of the measurement interval (dt). For example, if the measurement interval is 5 minutes (min), the travel time must be 5 min, 10 min, 15 min, and so on. Reach-averaged values are
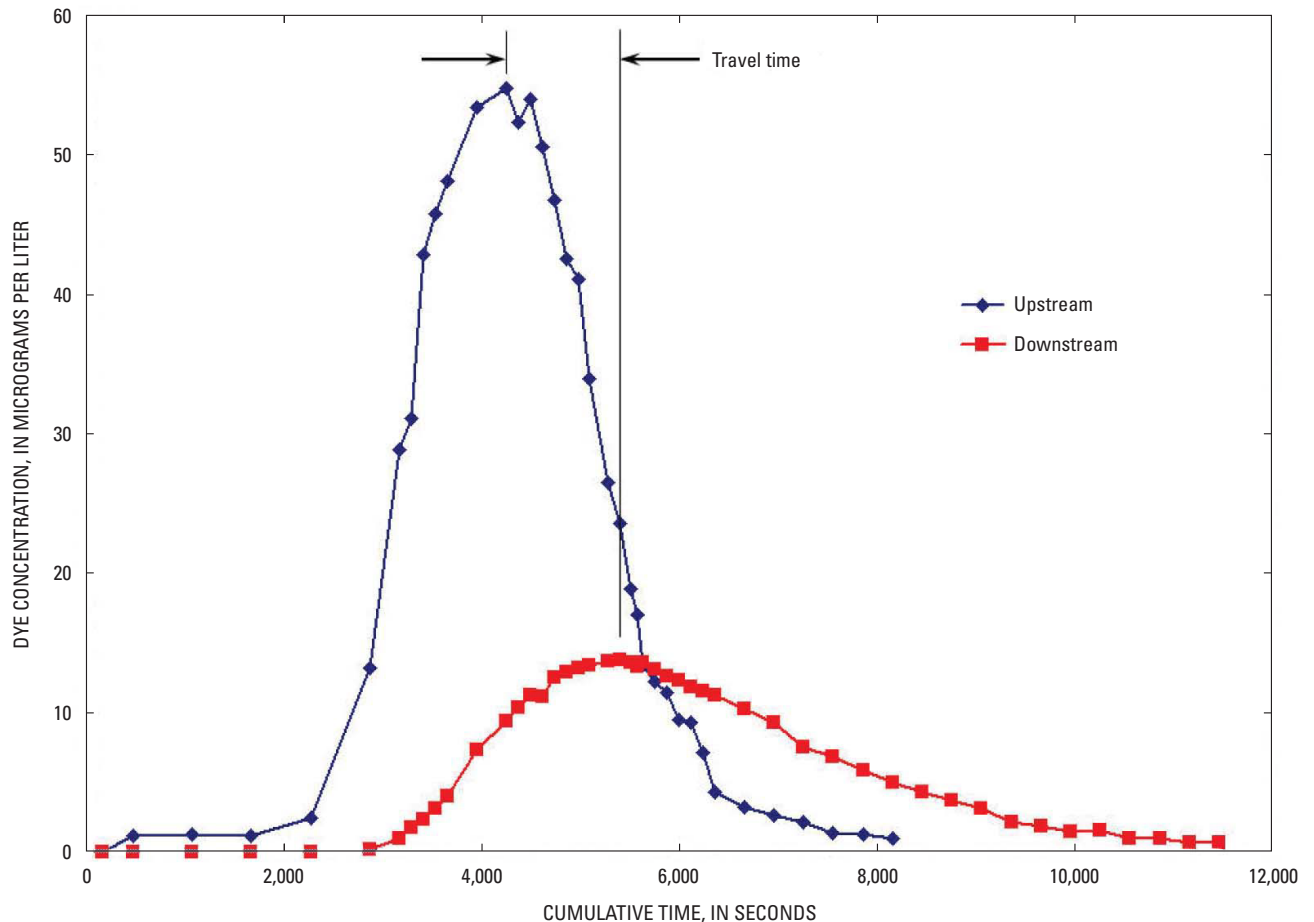

Figure 4. Example rhodamine dye curves used for estimating reach travel time, Skull Creek near Linwood, Nebraska, July 15, 2003.

estimated when the travel time is not an integer multiple of the measurement interval as in the following:

$$V_R(t) = [V_U(t_u) + V_D(t)]/2, \qquad (11)$$

where $V_U(t_u)$ = upstream value at the measurement time (t_u), for which $t_u - (t - T_t)$ is minimized. For example, if $t = 11{:}15$, $T_t = 8.0$ min, and the water-quality measurement interval = 5.0 min, the reach-averaged values would be calculated from downstream measurements at $t = 11{:}15$ and upstream measurements at $t_u = 11{:}05$. If $T_t = 7.0$, the reach-averaged values would be calculated from downstream measurements at $t = 11{:}15$ and upstream measurements at $t_u = 11{:}10$.

Reaeration

Dissolved-oxygen flux across the air-water interface is calculated as follows:

$$F_r(t) = D_{avg} * K_2(T) * Q * T_t * C_f, \qquad (12)$$

where

$F_r(t)$	= reaeration flux at time = t, in mass per time;
D_{avg}	= reach-averaged DO deficit calculated by using eq. 10 or 11, in mass per volume;
$K_2(T)$	= reaeration rate coefficient at water temperature (T), in $1/(t)$;
Q	= streamflow, in volume per time;
T_t	= travel time; and
C_f	= units conversion factor.

Note that F_r is positive when the DO deficit is positive (DO concentration is less than the saturation concentration); a positive F_r means that oxygen is being transferred from the atmosphere into the stream. F_r is calculated for each measurement interval and typically is reported in milligrams per minute when K_2 is given in 1/min.

The reaeration rate coefficient at any temperature (T) can be calculated from $K_2(T{=}20)$ by using the equation of Elmore and West (1961), which is the following:

$$K_2(T) = K_2(T{=}20) * 1.024^{(T-20)}. \qquad (13)$$

This equation can be rewritten as

$$K_2(T) = K_2(T{=}20) * (1+((T{-}20) * 0.0241)). \qquad (14)$$

Empirical relations for estimating K_2 from stream characteristics typically give K_2 at 20 °C. If K_2 is measured in the field using tracer-gas or other methods, eq. 13 is used first to adjust the field-measured K_2 to 20 °C. Then, K_2 is calculated for each measurement interval by using eq. 14 with the reach-averaged temperature for the measurement interval. As an example, assume the temperature when K_2 was measured in the field to be 0.092/min at a water temperature of 14.6 °C.

Further, assume the water temperature at a given measurement interval is 23 °C. Then, successive applications of eq. 13 gives the field-measured K_2 adjusted to 20 °C as 0.1046/min, and the $K_2(T{=}23)$ is 0.1123/min.

The K_2 can have a substantial effect on metabolism calculations, as demonstrated in figure 5. In this figure, T, DO, and site data from Skull Creek near Linwood, Nebraska, and Clear Creek near Columbus, Nebraska, were used to calculate R_c and GPP. K_2 values were calculated for each site using 29 individual empirical reaeration-rate estimation equations, and the lines in figure 5B extend over the range of those estimated K_2 values. At Skull Creek (fig. 5A), there is little difference between upstream and downstream DO curves; as a result, estimates of GPP and R are relatively insensitive to K_2 (fig. 5B). In contrast, the upstream and downstream maximum DO at Clear Creek differ by about 2 mg/L (fig. 5B), and GPP and R are quite sensitive to changes in K_2, with R varying by a factor of 5, depending on the empirical equation used to estimate K_2. It also is noteworthy that the best estimate of K_2 for Clear Creek is very near the condition at which the stream transitions from net DO production (GPP is greater than R) to net DO consumption (autotrophic to heterotrophic). Using the best estimate of K_2, Clear Creek is determined to be auto-trophic, but if a K_2 value that is 10 percent less than the best estimate of K_2 is used to calculate GPP and R, the conclusion is that the stream is heterotrophic under the measured conditions.

Net Metabolism

Net metabolism is the net change in DO in the study reach during a time interval, and represents the combined effects of photosynthesis and respiration on DO, minus any effects from reaeration. During the nighttime, net metabolism is assumed to be equal to respiration. Net metabolism is calculated at each measurement time as

$$NM(t) = \{[DO_d(t) - DO_u(t{-}T_t)] * Q\} - F_r(t), \qquad (15)$$

where

$NM(t)$	= net metabolism flux at time (t), in mass/time;
$DO_d(t)$	= downstream DO concentration at time (t); and
$DO_u(t - T_t)$	= upstream DO concentration at time (t) $- T_t$.

Respiration

Community respiration includes metabolism by heterotrophs (microbes and insects) and autotrophs (plants and selected bacteria) and can be directly measured only in darkness. Daytime respiration often is determined by some type of extrapolation of nighttime respiration. This approach, however, can be subject to errors associated with temperature-dependent respiration, light-dependent photorespiration by
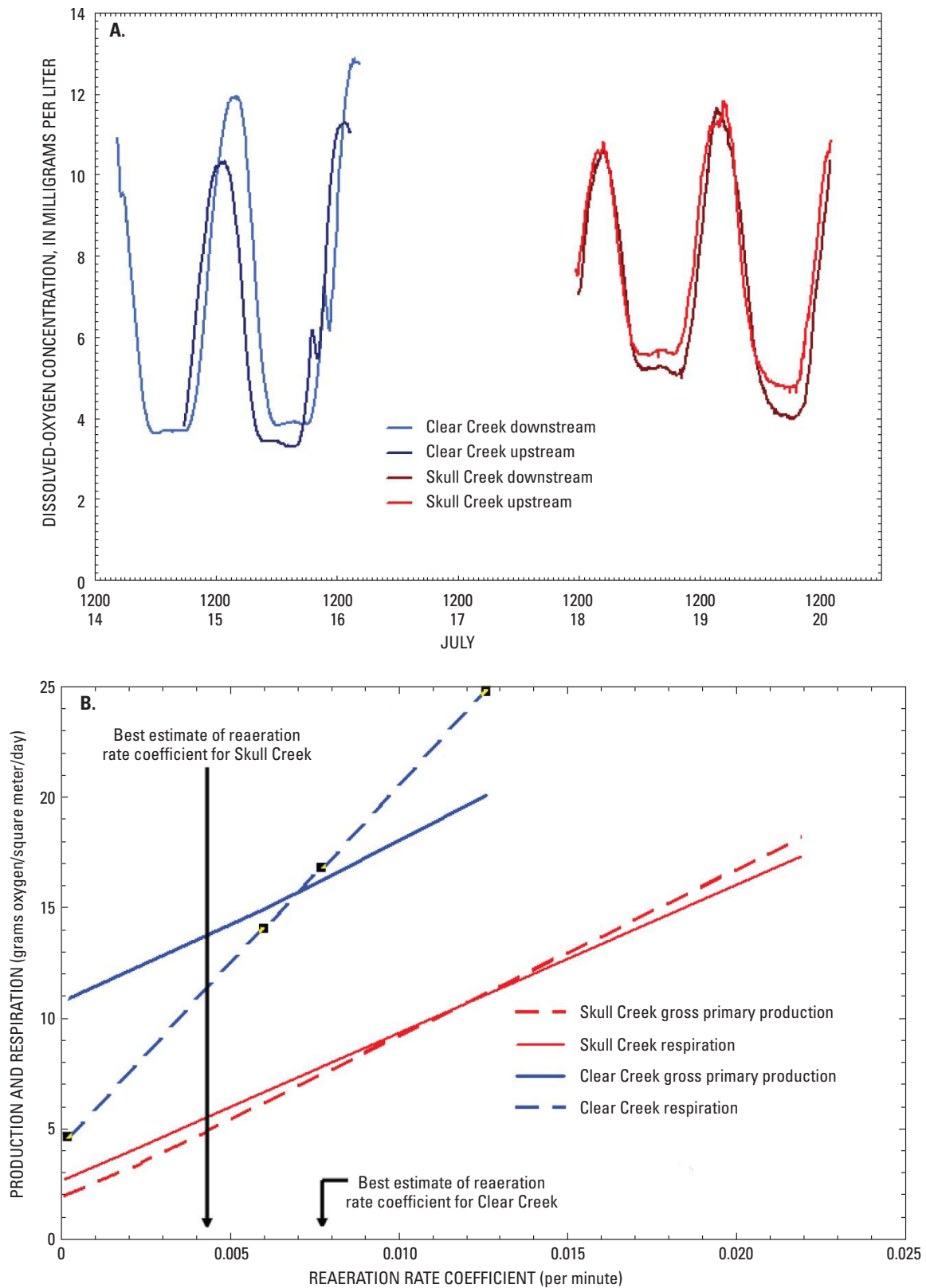
Figure 5.   (A) Measured upstream and downstream dissolved-oxygen concentrations for 150-meter reaches at Skull Creek near Linwood, Nebraska, and Clear Creek near Columbus, Nebraska, and (B) calculated gross primary production and respiration for Skull Creek and Clear Creek for a range of reaeration rate coefficients.

plants, and asynchrony between photosynthesis and metabolic costs (Bott and others, 1985).

The SMP uses two methods to calculate daytime respiration (for example, fig. 6). The first method uses the average respiration flux of two nighttime periods (see *Determination of Analysis Period* section) to calculate a constant daytime respiration rate. The approach can be written as follows:

$$R_{con} = [(S_{N1}/n_1) + (S_{N2}/n_2)]/2, \qquad (16)$$

where

R_{con} = constant daytime respiration throughout the daylight period;

S_{N1} = the sum of the net metabolism flux for the first nighttime period;

S_{N2} = the sum of the net metabolism flux for the second nighttime period;

n_1 = number of individual net metabolism flux values during the first nighttime period; and

n_2 = number of individual net metabolism flux values during the second nighttime period.

The daylight respiration rate calculated from eq. 16 is applied to each individual time increment during the daylight hours. For example, if the measurement interval is 5 min, the daylight respiration calculated from eq. 16 is in grams of oxygen per 5 min, which is applied to each daylight measurement interval.

Mulholland and others (2001) proposed using pre-dawn and post-sunset periods for calculating daytime respiration in order to reduce errors associated with extrapolation of nighttime respiration to daylight conditions. In this approach, the average respiration rate is calculated for a 1-hr period immediately before dawn; this average rate is assumed to be the respiration rate at the beginning of daylight. Similarly, an average respiration rate is calculated for the 1-hr period immediately following sunset, and this rate is assumed to be the respiration rate at the end of daylight. Respiration at each measurement interval during daylight then is extrapolated between these beginning and ending rates. The approach can be written as

$$R_{var}(t) = R_{pre\text{-}dawn} + [(R_{post\text{-}sunset} - R_{pre\text{-}dawn})/(n_d-1) * N_i], \qquad (17)$$

where

$R_{var}(t)$ = respiration rate at a given time during daylight;

$R_{pre\text{-}dawn}$ = the average respiration rate calculated from individual net metabolism fluxes for the 1-hr period immediately before dawn;

$R_{post\text{-}sunset}$ = the average respiration rate calculated from individual net metabolism fluxes for the 1-hr period following sunset;

n_d = the total number of measurement intervals during daylight hours, including the first and last daylight readings; and

N_i = the serial number of the daylight measurement interval for which $R_{var}(t)$ is calculated, with $N_{i=1} = 0$.

In this application, $R_{var}(t=1)$ is $R_{pre\text{-}dawn}$, and $R_{var}(i=n_d)$ is $R_{post\text{-}sunset}$.

A 24-hr respiration value (grams of oxygen per day) for community respiration, R_c, is calculated from the two night-time periods and the daylight period as follows:

$$R_c = \sum_{t=1}^{t=nd} R_d(t) + (S_{N1} + S_{N2})[(24 - T_d)/(T_{N1} + T_{N2})] \qquad (18)$$

where

R_d = daytime respiration, in grams of oxygen per measurement interval;

T_d = duration of the daytime period, in hours;

T_{N1} = duration of the first nighttime period, in hours; and

T_{N2} = duration of the second nighttime period, in hours.

The first term on the right side of eq. 18 is the summation of the incremental daylight respiration values for each measurement interval. The second term on the right side of eq. 18 is the sum of the total respiration for the two nighttime periods (see eq. 16), adjusted so that the duration of the sum of these two periods and the daylight period equals 24 hr. Community respiration in eq. 18 is in grams of oxygen per day.
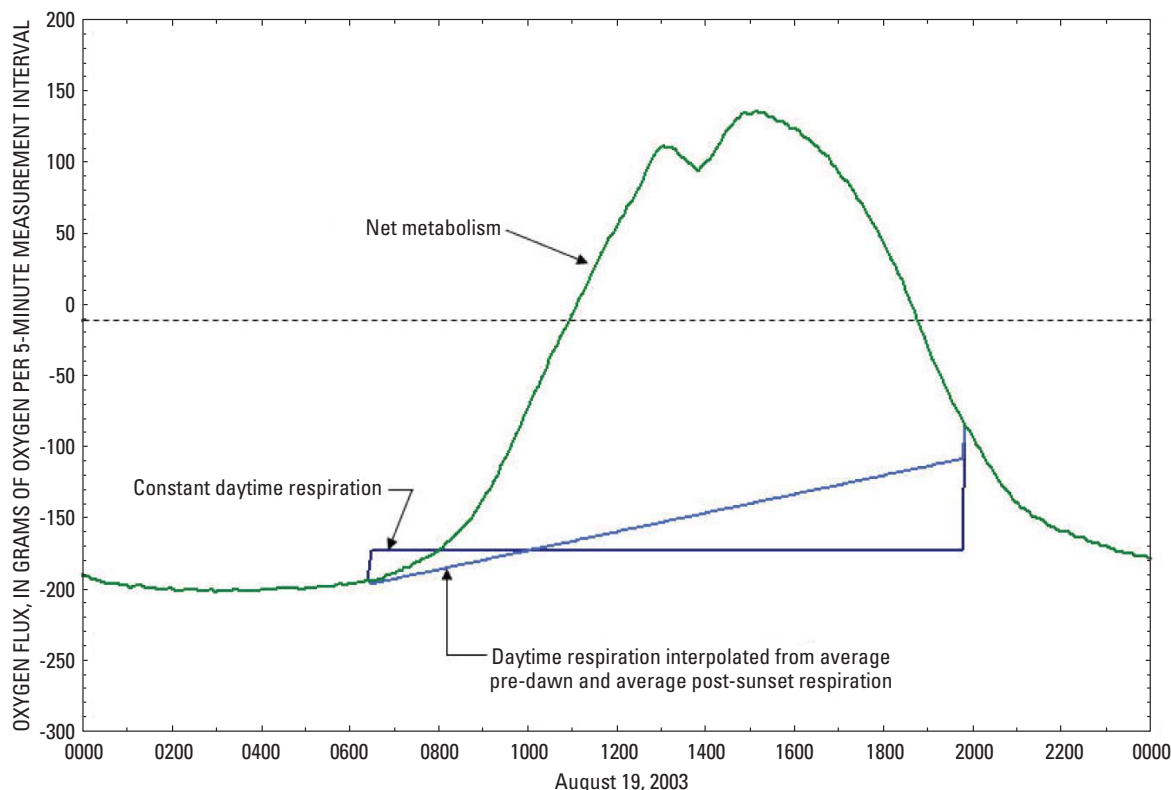
Figure 6. Calculated daytime respiration for Athanum Creek at Union Gap, Washington, August 19, 2003.

Gross Primary Production and Net Ecosystem Production

Gross primary production for a measurement interval is computed as the difference between the net metabolism flux and community respiration for the time interval, or

$$GPP(t) = NM(t) - R_c(t), \qquad (19)$$

which is a form of eq. 2 and is in grams of oxygen per measurement interval.

User's Guide

This section provides step-by-step instructions for importing data into the Stream Metabolism Program (SMP), completing required data fields, and performing various calculations. Guidance is provided first for using the SMP to analyze two-station whole-stream metabolism data. The differences between application of the SMP for analyzing two-station and single-station data also are presented. Required and optional data required to apply the SMP are summarized in table 1.

Two-Station Method

Instructions for completing and executing each page (or tab) of the SMP for the two-station whole-stream metabolism method are presented below. The active page is indicated by the red rectangle around the active tab (see, for example, fig. 7). Data used in the example are from Skull Creek near Linwood, Nebraska.

Site Data

Relevant site information is entered on the *Site Data* page (fig. 7). Most of the information on this page is for documentation only and is not used in the calculations. The **Metabolism Method 2-Station** button should be selected (indicated by red arrow, fig. 7). Other fields can be populated as desired. The fields for **Instrument Start Recording Data** and **Instrument Finish Recording Data** represent the beginning and ending times for data collected by the in situ water-quality meters, and the fields are automatically populated by the software after the meter data are imported (*Meter* page). Likewise, the **Light Meter Number** is read from the light meter input file. The **Instream Meter Recording Interval** is the average interval, in minutes, between readings at both the upstream and downstream meters and is calculated by the SMP after meter data are imported. Similarly, the **Light Meter Recording**

Table 1.   Required and optional data for the Stream Metabolism Program.

[—, not applicable]

Data	Measurement frequency	Comments
Required data		
Reach length	Once	—
Travel time through the reach	Once, at the same flow for which whole-stream metabolism variables are measured	See Kilpatrick and Wilson (1989).
Reach-averaged wetted width	Once, at approximately the same flow as that during the metabolism measurements	See Fitzpatrick and others (1998).
Stream discharge	At least once during the time whole-stream metabolism variables are measured	Discharge at upstream and downstream ends of the reach should be equal, within the limits of measurement accuracy.
Dissolved-oxygen concentration	Continuously for at least 30 hours and including 2 nighttime periods	Pre- and post-deployment calibrations should be performed.
Water temperature	Concurrent with dissolved-oxygen measurements	—
Barometric pressure	At the beginning and end of the meter deployment	—
Optional data		
Photosynthetically active radiation (PAR)	Continuously during the metabolism measurements	Used to automatically establish calculation period and to adjust gross primary productivity for PAR.
Reaeration rate coefficient	Once, during metabolism study	See Kilpatrick and others (1989). Optionally, the reaeration rate coefficient can be estimated by using one of several empirical relations.
Selected stream metrics	Water-surface slope, average depth, velocity (calculated as reach length divided by travel time) measured once at the same flow as metabolism measurements	These metrics might be needed for use in estimating the reaeration rate coefficient from empirical equations.

Figure 7.   Screen capture of the *Site Data* page in the Stream Metabolism Program.

Interval is the average time, in minutes, between light meter readings during the deployment and is calculated by the SMP after meter data are imported.

The DO concentration from independent DO measurements that are performed during the data-collection period should be entered in the **Field DO Verification** fields (indicated by yellow arrow, fig. 7), along with the time the measurements were made. Fields are available for measurements made at the upstream and downstream ends of the study reach and at the beginning and end of the deployment.

In order to determine if the streamflow at the start and end of the deployment are the same, water-surface elevation measurements are often made by measuring down to the water surface from a fixed point. These measurements are noted in the **Water-surface elevation referenced to arbitrary datum** fields, with the first value entered in the left-most field (indicated by blue arrow, fig. 7) being the measurement at the upstream end of the reach at the beginning of the deployment. Complete dates and times (for example, "7/18/2003 12:05 PM") of independent DO measurements and water-surface elevation measurements can be entered in the appropriate fields, although the size of the fields on the *Site Data* page do not permit full display of the date and time values. Information on this page should be supplemented by complete field notes.

Stream Metrics

The *Stream Metrics* page (fig. 8) contains information on hydrologic and physical conditions in the study reach. Some of the data are needed to perform other calculations. All units on this page (and others) are metric. Fields on the *Stream Metrics* page are populated with default values when the page is first opened, but these default values should be replaced with measured information. Data entered on this page include the following:

- **Reach Length** (in meters) is needed to calculate the channel wetted area, which is used to determine production per unit area. Channel wetted area is calculated as the reach length multiplied by the reach-averaged wetted width.

- **Travel Time** (in minutes) is required in the calculation of reach-averaged T, DO, and DO_s and may be required for some forms of empirical equations used to estimate the reaeration rate coefficient. The meter-recording interval should be less than the travel time through the reach.

Figure 8.   Screen capture of the ***Stream Metrics*** page in the Stream Metabolism Program.

- **Ave. Velocity** (in meters per second), or average stream velocity, may be required for some forms of the empirical equations used to estimate the reaeration rate coefficient. Average velocity should be determined from the reach length divided by the travel time. This value is not required and is not used by the SMP.

- **Reach Ave. Wetted Width** (in meters), or reach-averaged wetted stream width, is needed to calculate the channel wetted area, which is used to determine production per unit area and may be required for some forms of the empirical equations used to estimate the reaeration rate coefficient. Average width should be determined from detailed morphometric measurements made at the site (for example, Fitzpatrick and others, 1998).

- **Reach Ave. Depth** (in meters), or reach-averaged water depth, may be needed for some forms of the empirical equations used to estimate the reaeration rate coefficient. This value is not required and is not used by the SMP.

- **Slope** (meter/meter) is the water-surface slope measured over the study reach and may be required for some forms of the empirical equations used to estimate the reaeration rate coefficient. This value is not required by the SMP.

- **Flow** (in liters per second) is the stream discharge that is determined from measurements made at the site. It often is appropriate to measure discharge at the upstream and downstream ends of the study reach to determine if ground water is discharging to the stream or if the stream is losing flow in the reach. Ideally, flow is steady throughout the study period.

- **Barometric Pressure** (reported in millimeters of mercury [mm Hg]) is needed to calculate DO_s (see eq. 8). The barometric pressure is assumed to be constant throughout the deployment, including the pre- and post-calibration period. The mean barometric pressure determined from readings when meters are deployed and when meters are recovered is an appropriate value to enter in this field.

- **Meter Measurement Interval** (in minutes) is the time interval at which the in situ water-quality meter was pre-set to collect data. The exact measurement interval for both the in situ water-quality meters and the light meter are calculated by the SMP, and the appropriate fields are populated automatically on the ***Site Data*** page (fig. 7) after the meter data have been imported into the SMP.

- **Light Meter Measurement Offset** (in minutes) is populated only if the light meter and the water-quality meters were not set at exactly the same clock time. For

example, if the water-quality meters were set at standard time and the light meter was set at daylight-saving time, the offset will be –60 to correct the light meter to standard time. If there is no offset, the field can be left blank.

- **Reaeration Coefficient**, or K_2, can be estimated from available empirical equations or determined from tracer-gas tests at the study site (for example, Kilpatrick and others, 1989). Empirical equations for predicting K_2 were reviewed by Rathbun (1977), Gromiec (1989), and Moog and Jirka (1998), and numerous others. The reaeration rate coefficient is reported in min^{-1}, and empirically estimated values of K_2 should be corrected to 20 °C (Elmore and West, 1961; eq. 15). Most empirical equations, however, provide estimates of K_2 at 20 °C, so no conversion is needed. If the reaeration rate coefficient is determined from tracer-gas measurements, the water temperature at which the measurements were made is entered (indicated by red arrow, fig. 8), and the SMP will adjust the measured K_2 to the water temperature during the metabolism measurements.

Meter—Importing Data

Two time-series of water-quality (DO, T, pH, and SC) data are imported into the SMP on the *Meter* page (fig. 9). As an option, a single time series of PAR data also can be imported on the *Meter* page. Data are synchronized in time on the *Meter* page, and corrections for DO sensor error and drift are determined.

Water-quality data files must be comma delimited and have the format shown in figure 10. The maximum number of lines of data that can be imported into the SMP is 64,000.

The first two lines in the water-quality data files are the same for every in situ meter data file that is imported and should be exactly like the first two lines in figure 10. The first line of the data file provides the name of each parameter in the data file, with the name enclosed by double quotation marks. The parameters are date, time (24-hr clock), water temperature, specific conductance, DO concentration, DO sensor charge (a troubleshooting parameter available on some in situ water-quality meters), pH, and pH sensor voltage (also a troubleshooting parameter available on some in situ water-quality meters). The second line of the data file gives the units in which each parameter is reported: date, in month/day/year; time, in hours:minutes:seconds; water temperature, in degrees
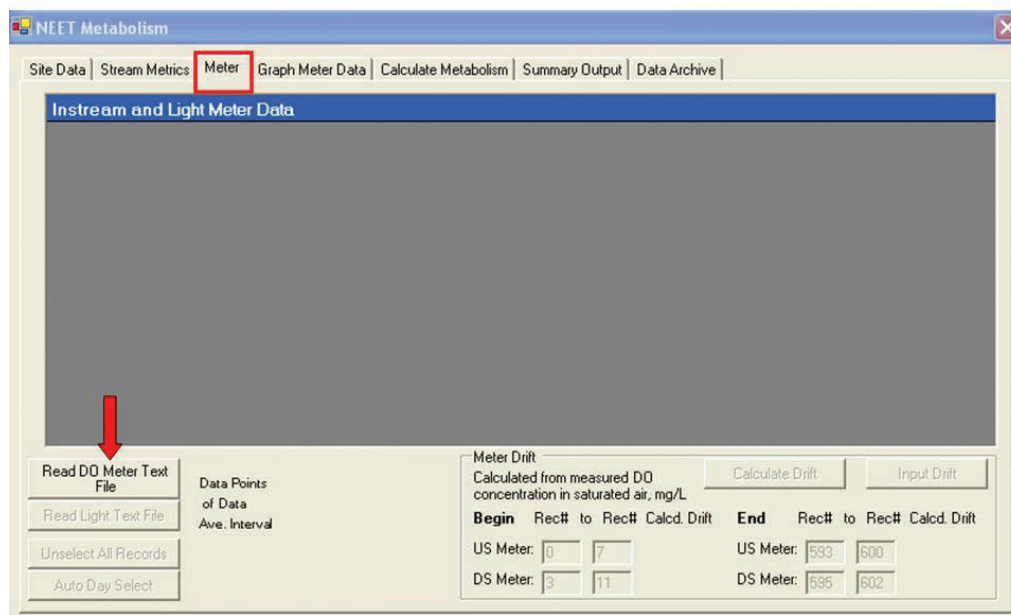

Figure 9. Screen capture of the unpopulated *Meter* page in the Stream Metabolism Program.

```
"Date","Time","Temp","SpCond","DO Conc","DO Charge","pH","pHmV"
"M/D/Y","hh:mm:ss","C","mS/cm","mg/L","","","mV"
"07/18/03","11:30:40",26.82,0.007,7.68,45,9.46,-160.9
"07/18/03","11:35:39",26.83,0.006,7.62,45,9.47,-161.7
"07/18/03","11:40:39",26.85,0.006,7.59,45,9.48,-162.3
"07/18/03","11:45:39",26.90,0.005,7.56,45,9.49,-162.7
```

Figure 10.   Example of text file format required for importing water-quality data into the Stream Metabolism Program.

Celsius; specific conductance, in millisiemens per centimeter; DO concentration, in milligrams per liter; DO sensor charge, dimensionless; pH, in standard units; and pH sensor voltage, in millivolts. The remaining lines are the data in the same order given on the first line of the file. Date and time are always enclosed by double quotation marks. The only readings that are required by the SMP are date, time, water temperature, specific conductance, and DO. If the other parameters are unavailable, a zero can be entered in the appropriate field of the data file. For example, if only the required data were available, the first line of data in figure 10 would be:

"08/18/03","15:40:39",23.89,0.001,8.28,0,0,0

The file format shown in figure 10 is produced by YSI Environmental's EcoWatch® for Windows® software when using data from YSI multiparameter instruments. Data files from any source, however, can be processed by the SMP as long as the files have the format shown in figure 10. Simple scripts can be written, for example, to convert data files from other multiparameter water-quality meters to the format required by the SMP.

Water-quality meter data are imported by clicking the **Read DO Meter Text File** button (indicated by red arrow, fig. 11). A Windows Explorer® window will appear, allowing the user to browse to the directory containing water-quality monitoring data. Select the data file from upstream meter
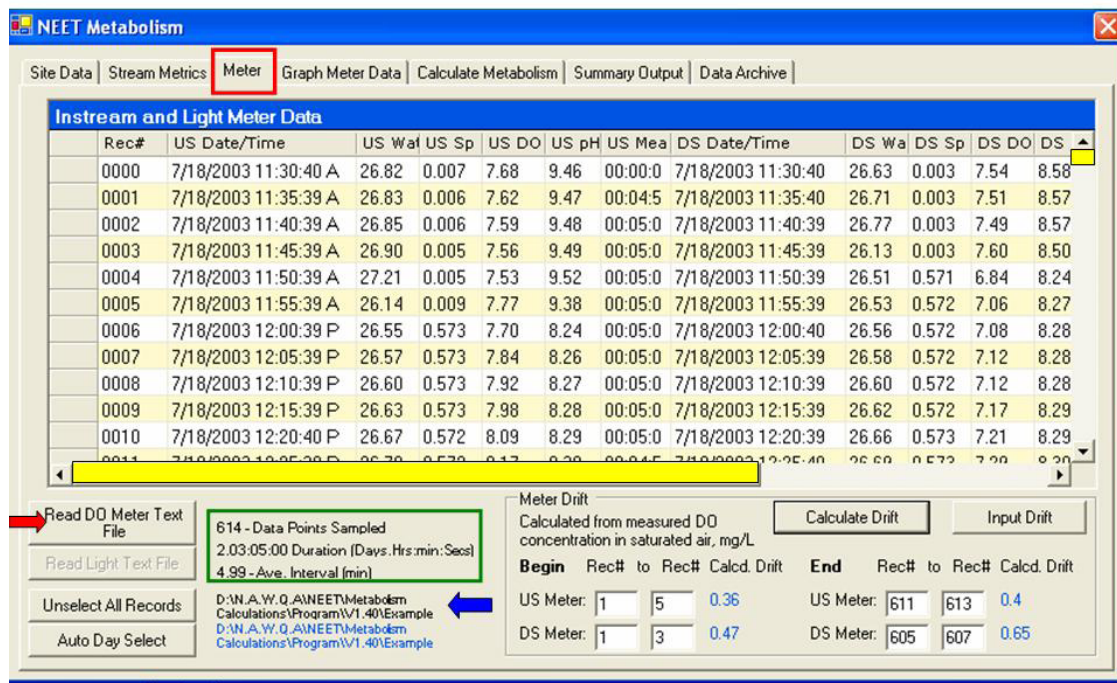

Figure 11.   Screen capture of the *Meter* page populated with data from upstream and downstream water-quality meters, and prior to importing light-meter data, in the Stream Metabolism Program.

first, then select the underlined downstream data file. After both files are selected, the data table will be populated (fig. 11).
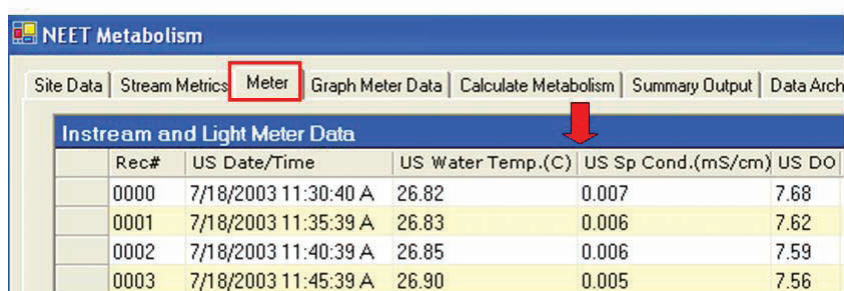
Several pieces of information are produced automatically after the in situ meter data are imported (compare figs. 10 and 11). The path name from which the in situ meter data were read is documented (indicated by blue arrow, fig. 11). The number of rows in the spreadsheet (or **Data Points Sampled**), the total time of data collection (**Duration**), and the average interval, in minutes, between in situ meter readings (**Ave. Interval**) are all reported (fig. 11, green box). In this example (fig. 11), the spreadsheet contains 614 values, and data were collected for 2 d, 3 hr, and 5 min.

As discussed previously, several fields on the *Site Data* page (fig. 7) are automatically populated when the in situ meter data are imported. Other features of the *Meter* page include the following:

- The first data value is assigned a record number (**Rec#**) of "0" (fig. 11, left-most column).

- Column widths can be changed by dragging the cell boundary for the title cell (indicated by red arrow, fig. 12). Note that the fields for **US Water Temp.** (upstream water temperature) and **US Sp Cond.** (upstream specific conductance) contain the complete column titles when cell widths are increased (compare figs. 11 and 12). The size of the entire window, however, cannot be changed, so the bottom scroll bar (highlighted in yellow, fig. 11) must be used to view all of the columns. Likewise, the scroll bar to the right of the window (highlighted in yellow,

fig. 11) can be used to scroll through the rows of data.

- All columns for water-quality monitoring data are populated even if no data were collected. In the example shown in figure 13, recording at the downstream meter was stopped while the upstream meter continued to record for 30 additional min. A DS **Date/Time** value of "1/1/0001 12:00:00" (fig. 13, green box) is assigned if no data were collected at one meter but were collected at the companion site. Such an occurrence could be at the beginning or the end of the data-collection period.

- Data cannot be edited on the *Meter* page. Any changes in the data must be made in the raw data file before the data are imported to the SMP.

- Data can be exported from the *Meter* page by selecting a single or multiple rows of data. The cursor is placed on the cell to the left of **Rec#** on the first row of data to be selected (red arrow at **Rec#** 0001 in fig. 14) and dragged to the last record number to be selected (**Rec#** 0007 in fig. 14). Selected rows are highlighted in blue (fig. 14). Then, by using the keyboard command Ctrl-C, the selected rows can be pasted into a spreadsheet. Data cannot, however, be copied from a spreadsheet back into the *Meter* page. Rows can be unselected by clicking the **Unselect All Records** button (yellow arrow, fig. 14).

Figure 12.   Screen capture of a section of *Meter* page in the Stream Metabolism Program showing a boundary that can be dragged to expand column width and full column headings for upstream water temperature and upstream specific conductance data.
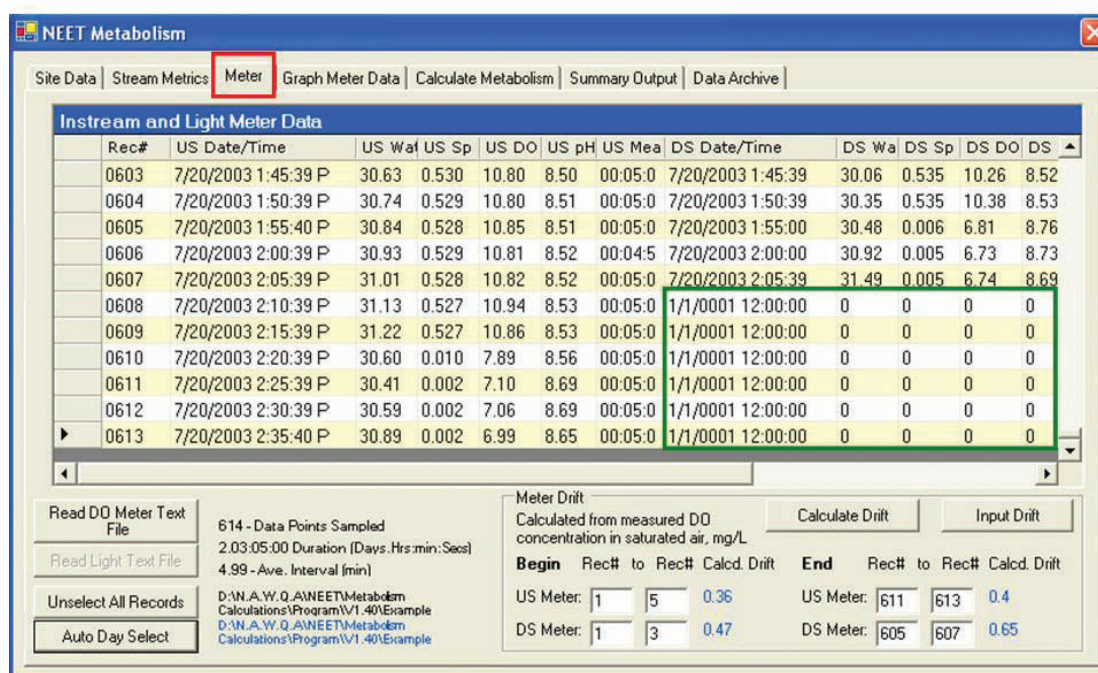
Figure 13.   Screen capture of a *Meter* page in the Stream Metabolism Program showing condition in which data were collected at only one of the two in situ water-quality meters for a portion of the deployment period.
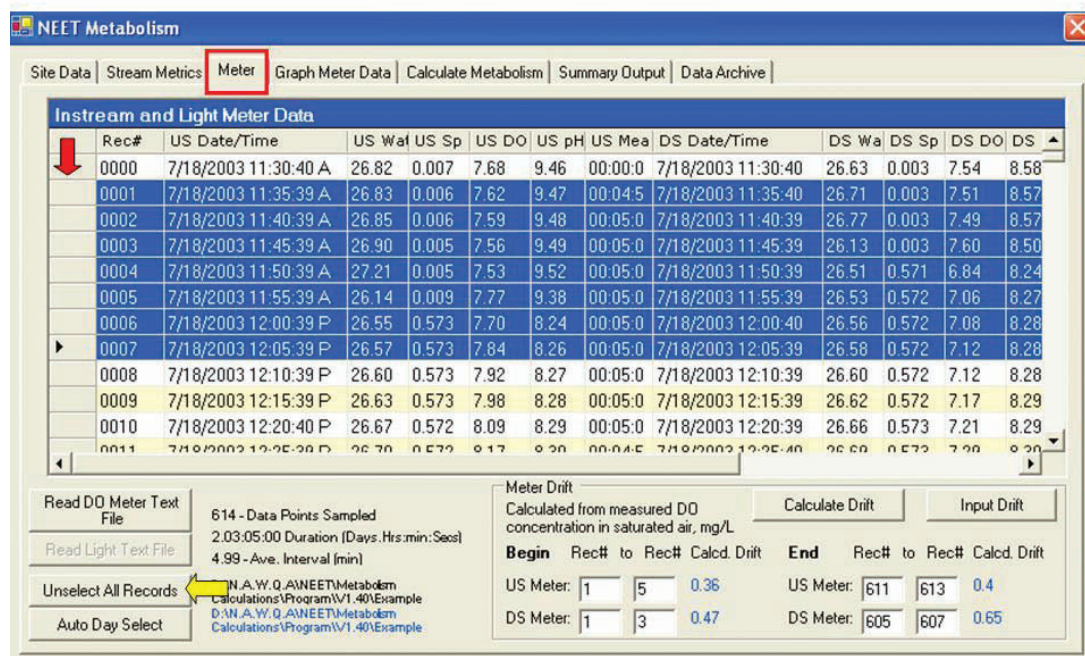

Figure 14.   Screen capture of the *Meter* page in the Stream Metabolism Program showing rows selected for copying into a spreadsheet application.

Light data from a single site can be imported into the SMP, but these data are not required. If light data are imported, however, they must be in the format shown in figure 15. These data were collected by Onset Computer Corporation's HOBO® data loggers, and data files were downloaded and processed into tab-delimited ASCII text files using Onset's BoxCar Pro 4®. The first line of the light-data file identifies header information and includes the instrument identification number (in this case, #672162). The remaining lines list the data, which include the date (month/day/year), time (hour:minute:seconds), and PAR values in micromoles per square meter per second [$\mu mol/(m^2/s)$]. Light-data files from any source can be imported into the SMP as long as the file format is the same as shown in figure 15.

Date Time	PAR [$\mu mol/(m^2/s)$]
#672162	
08/18/03 16:00:42.0	53.8
08/18/03 16:15:42.0	66.3
08/18/03 16:30:42.0	63.8

Figure 15. Example of file format required for importing light-meter data into the Stream Metabolism Program.

Light data are imported by clicking the **Read Light Text File** button (blue outline, fig. 16). The **Read Light Text File** button will be visible only after water-quality monitoring data have been imported. As with the water-quality data, the user is prompted to browse to the directory with light data and select a data file to import. After light data have been added to the data table (indicated by yellow arrow, fig. 16), the **Read Light Text File** button is no longer highlighted.

The following data columns are on the *Meter* page (from left to right):

- The record number, with the first record number being "0;"
- Date and time when upstream meter reading was made;
- Upstream meter water temperature (°C);
- Upstream meter specific conductance (mS/cm);
- Upstream meter DO concentration (mg/L);
- Upstream meter pH (standard units);
- Upstream meter measurement interval (hours:minutes:seconds);
- Date and time when downstream meter reading was made;
- Downstream meter water temperature (°C);
- Downstream meter specific conductance (mS/cm);
- Downstream meter DO concentration (mg/L);
- Downstream meter pH (standard units);
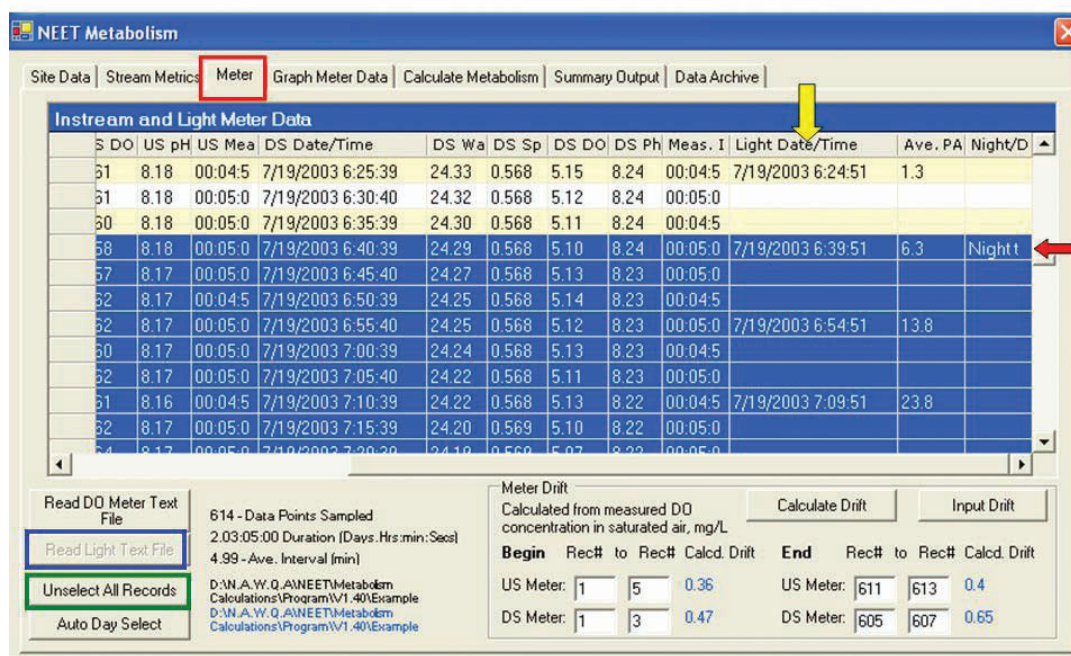- Downstream meter measurement interval (hours:minutes:seconds);

Figure 16. Screen capture of the *Meter* page in the Stream Metabolism Program populated with water-quality monitoring data and light-meter data.

- Date and time when light meter reading was made;
- Light meter reading [$\mu mol/(m^2/s)$];
- An index ("**Night to Day**") for the beginning and ending ("**Day to Night**") of daylight. Daylight is assumed to end when PAR becomes less than 2 $\mu mol/(m^2/s)$ and is assumed to begin when PAR exceeds 2 $\mu mol/(m^2/s)$ (indicated by red arrow, fig. 16; also see fig. 3).

Meter—Calculation of Dissolved-Oxygen Adjustments

Adjustments to DO readings are calculated on the *Meter* page. Adjustments may be required because of inadequate meter calibration, sensor drift, and fouling during deployment. The adjustments can be calculated automatically or directly. Direct adjustments may be required if the barometric pressures at the beginning and end of the deployment are markedly different.

Adjustments to DO readings are calculated by using data from the pre-deployment and post-deployment periods when DO in saturated air is recorded. The text boxes on the bottom right of the *Meter* page (for example, fig. 17) should be completed. Record numbers (**Rec#**) are entered in the boxes corresponding to the time when the pre-calibration period began and the time when the pre-calibration period ended. The pre-calibration period is on the left (see red outlined **Begin**, fig. 17), and the post-calibration period is on the right (see red outlined **End**, fig. 17). In this case, pre-calibration of the upstream meter (fig. 11) began at 11:35 AM on July 18 (Rec# = 1) and ended at 11:55 AM (Rec# = 5). The pre-calibration period for the downstream meter also began at 11:35 AM (Rec# = 1) but ended at 11:45 AM (Rec# = 3).

The pre- and post-calibration periods can be identified in two ways. The first way is to refer to field notes. The second way the pre- and post-calibration periods can be identified is to review the data in the spreadsheet. Specific conductance during calibration in saturated air should be near zero. So in the example in figure 11, specific conductance for the upstream meter was between 0.005 and 0.009 mS/cm for the first five readings in saturated air and increased to 0.573 mS/cm after the meter was placed in the stream.

Temperature fluctuations should be small during the pre- and post-deployment calibration periods. In fact, it is possible

that record number 5 for the upstream meter should not be used in the drift calculation because the temperature increased almost 1 °C, and the specific conductance almost doubled between 11:50 and 11:55, indicating some disturbance to the meter. The first readings (record number 0) were not used in order to ensure stability of the sensors.

The pre- and post-calibration periods should be no longer than 1 hour, even if calibration data were recorded for longer than 1 hr. The period (no more than 1 hr) immediately prior to and immediately after deployment should be used for the drift calculations.

The blue values shown in figure 17 are the result of clicking the **Calculate Drift** button after the appropriate record numbers have been entered in the text boxes. The **Calcd. Drift** values represent the average error, in milligrams per liter, for each period (pre- and post-deployment) and meter (upstream and downstream). For example, the average initial error for the upstream meter during the pre-calibration period (fig. 17) was 0.36 mg/L (meter was reading lower than correct values), and the average error for the upstream meter during the post-calibration period was 0.40 mg/L. Consequently, the drift during the deployment was 0.04 mg/L. The section on theoretical basis for calculations describes the internal procedures used to correct the measured DO data for initial error and drift.

In some cases, calculated net ecosystem production (NEP) can be sensitive to the DO values used in the drift calculations. Such effects on NEP of the DO readings used in the drift calculations should be carefully evaluated, particularly if there is some uncertainty about the appropriate record numbers to be used in the calculations (for example, record number 5 for the upstream meter beginning error, as discussed above).

Adjustments to DO readings for initial error and drift can be entered manually by clicking the **Input Drift** button (blue outline, fig. 17), which results in the pop-up window shown in figure 18. The text boxes then can be completed with the appropriate values. Recall that the error is positive if the meter reading is less than the actual DO concentration in saturated air. If the automated drift calculation is not used, zero values should be entered into the record number fields (fig. 17) in the **Meter Drift** section of the *Meter* page.

Figure 17. Screen capture of the Meter Drift section of the *Meter* page used for dissolved-oxygen sensor drift calibration in the Stream Metabolism Program.
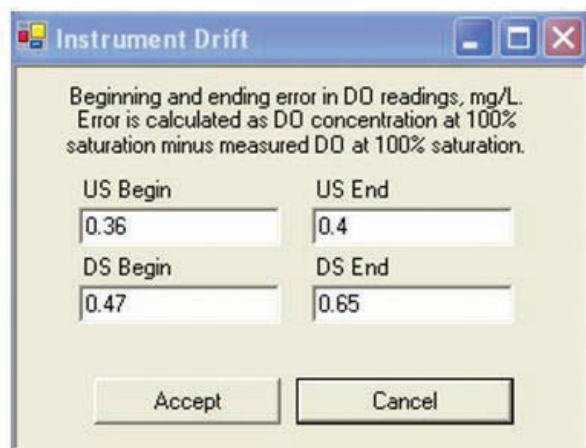
Figure 18. Screen capture of the Instrument Drift window for entering beginning and ending errors in dissolved-oxygen meter readings in the Stream Metabolism Program.

Graph Meter Data—Automated Selection of Analysis Period

Water temperature, DO concentration, and PAR are automatically plotted against time (horizontal axis) on the

Graph Meter Data page after data are imported (fig. 19). Data are not plotted to scale. Rather, the plots are given for a quick visual inspection to ensure that the data sets do not include any obvious outliers. Yellow bars are PAR, the red line is water temperature, and the white (or gray) line is DO.

The analysis period is selected automatically (also see fig. 16) and is shown on the *Graph Meter Data* page (fig. 19). The vertical white lines (adjacent to white arrows) depict the beginning (left) and end (right) of the daylight period, respectively. The vertical blue lines (adjacent to blue arrows) depict the beginning (left) and end (right) of the analysis period, respectively. These periods (daylight and analysis) also are depicted in figure 3, which depicts values plotted to scale. Information regarding the various components of the analysis period are shown at the lower left side of the *Graph Meter Data* page (green outline, fig. 19). The components of the analysis period are described in the *Theoretical Background* section of this report. The information contained under the heading "Gross Primary Production Calculation Periods" (green outline, fig. 19) is as follows, starting with the column on the left, from top to bottom:

- **Day Start**

- **Night Start**: The value within the field (outlined in blue) is the number of hours from the beginning of daylight when the first nighttime period begins. A
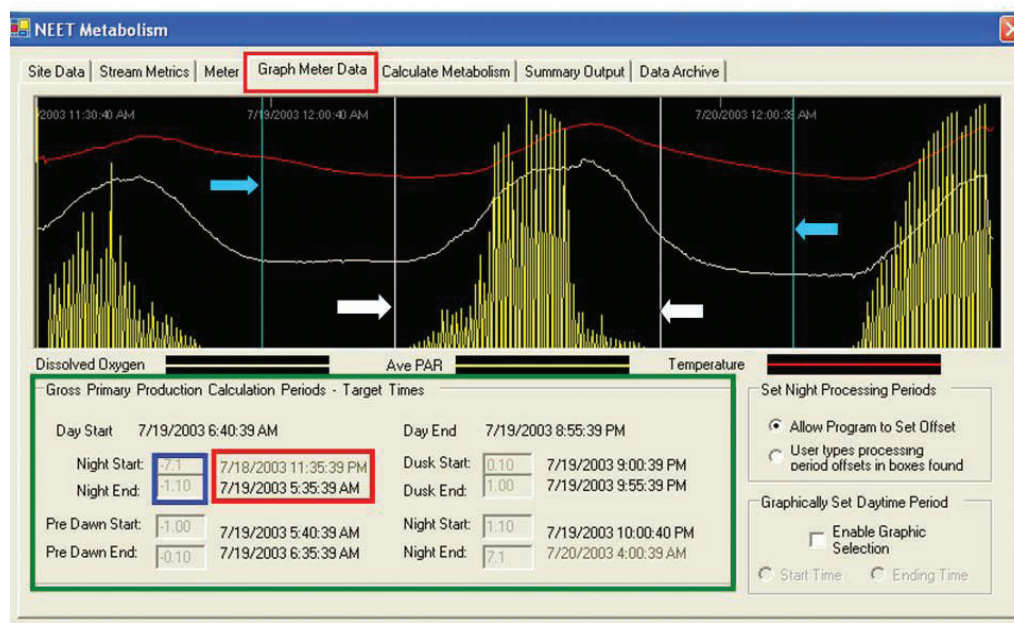

Figure 19. Automatically graphed data showing time-series plots of dissolved-oxygen concentration, water temperature, and photosynthetically active radiation, though not to scale, and identified gross primary production calculation periods, as a feature of the Stream Metabolism Program.

negative value indicates hours before the beginning of daylight period. Adjacent to this field is the date and time (outlined in red) of the beginning of the first nighttime period.

- **Night End**: The first nighttime period ends 1 hr plus one water-quality meter reading before the beginning of daylight. The value within the field is the number of hours from the beginning of daylight when the first nighttime period ends. As before, a negative value indicates a time before the beginning of daylight period. Adjacent to this field is the date and time of the end of the first nighttime period. In the example, the measurement interval is 5 min, so the first nighttime period ends at 5:35 AM, or 65 minutes before the beginning of daylight at 6:40 AM.

- **Pre Dawn Start**: The pre-dawn period is always 1 hr long and always begins 1 hr before the beginning of daylight, as indicated by the –1.0 in the example data field (fig. 19). Adjacent to the field is the date and time of the beginning of the pre-dawn period.

- **Pre Dawn End**: The end of the pre-dawn period is one water-quality meter measurement interval before the beginning of daylight; in the example, the measurement interval is 5 min and daylight begins at 6:40 AM, so the pre-dawn period ends at 6:35 AM.

- Values in the right column under the heading "Gross Primary Production Calculation Periods" have meanings analogous to those in the left column, except these values are for the end of daylight, the post-sunset period, and the second nighttime period.

Meter and *Graph Meter Data*—Manual Selection of Analysis Period

After the light-meter data are imported, the SMP automatically selects the first full day of data for analysis. The daylight period selected for analysis is highlighted in blue on the *Meter* page (fig. 16) and is shown on the *Graph Meter Data* (fig. 19) page as previously described. Users may choose to manually select the analysis period for certain cases, such as when multiple days of data are available or when PAR readings are unavailable. The user can override the automatically selected analysis period in one of two ways. The steps for the first approach are as follows:

1. Click **Unselect All Records** on the *Meter* page (green outline, fig. 16). The rows that were previously highlighted in blue (fig. 16) will no longer be highlighted, and the vertical white lines on the *Graph Meter Data* page (fig. 19) will disappear.

2. Review the data on the *Meter* page and select a daylight beginning time on the day when the analysis is to be performed. If PAR data are available, this typically will

be the time corresponding to the first PAR value greater than 2 μmol/(m²/s). For the purposes of this example, it is assumed that no PAR data are available and that published values of sunrise and sunset are used to identify daylight beginning and end times.

3. Click the cell in the left column on the *Meter* page corresponding to the selected time (fig. 20, red arrow). The selected row is highlighted in blue.

4. Scroll down the table and locate the daylight ending time. Again, if PAR data are available, this typically will be the time corresponding to the last PAR value for the day with a value greater than 2 μmol/(m²/s). Click on the cell of the corresponding row of the left column while holding down the Shift key. The entire daylight period will be highlighted in blue, and the two vertical lines on the *Graph Meter Data* page are re-plotted for the new daylight period (fig. 21). For the purposes of this example, daylight is assumed to begin at 6:30 AM and end at 9:00 PM.

5. Although the daylight period is indicated on the *Graph Meter Data* page, the beginning of the first nighttime period and end of the second nighttime period and the correct clock times are not shown on this page (fig. 21). In order to complete selection of the analysis period, click on the button **User types processing period offsets in boxes found** (blue outline, fig. 22). After this button is clicked, the fields for **Night Start** and **Night End** become active. Backspace over the default value, enter the desired value, and click the Tab button. At this point, all of the dates and clock times on the page accurately reflect the components of the analysis periods, and the blue vertical lines representing the beginning and end of the analysis period are shown on the graph (fig. 23).

The analysis period also can be set graphically as follows:

1. Repeat previous step 1.

2. Click **Enable Graphic Selection** (green outline, fig. 24).

3. Click **Start Time** button (red arrow, fig. 24).

4. Click in the plot window at the desired starting time (white arrow, fig. 24). The **Day Start** (or beginning of daylight) time is then displayed. The beginning of daylight time can be adjusted by continuing to click in the plot window until the desired time is selected.

5. Repeat steps 3 and 4 for the end of daylight (**Ending Time**). After the ending time is selected, the beginning of the first nighttime period and the end of the second nighttime period (vertical blue lines, fig. 23) also are shown, along with the beginning and end of daylight (vertical white lines, fig. 23).

6. Uncheck the **Enable Graphic Selection** box.

7. Nighttime beginning and end times can be adjusted as previously described.
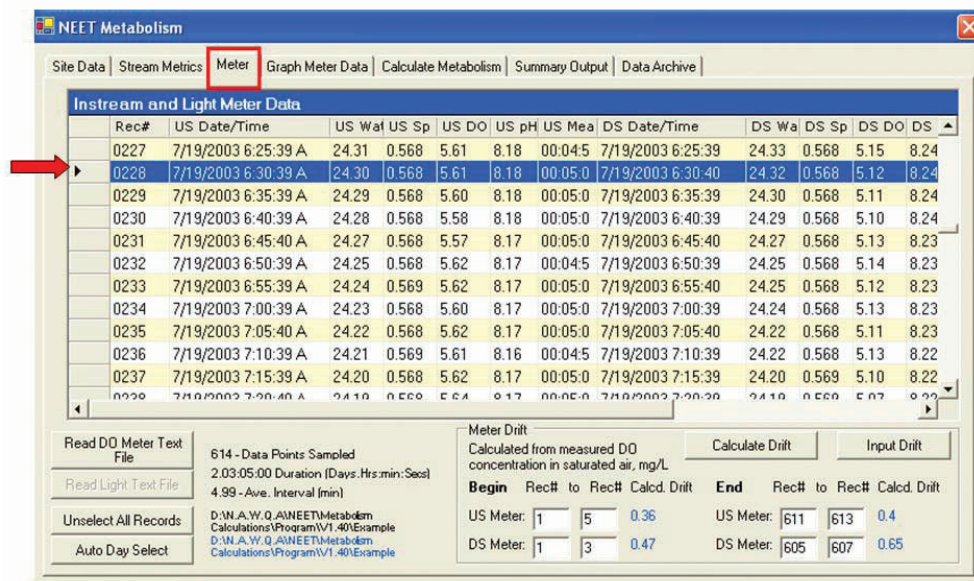
Figure 20.   Screen capture of the **_Meter_** page showing user-selected daylight beginning time in the Stream Metabolism Program.
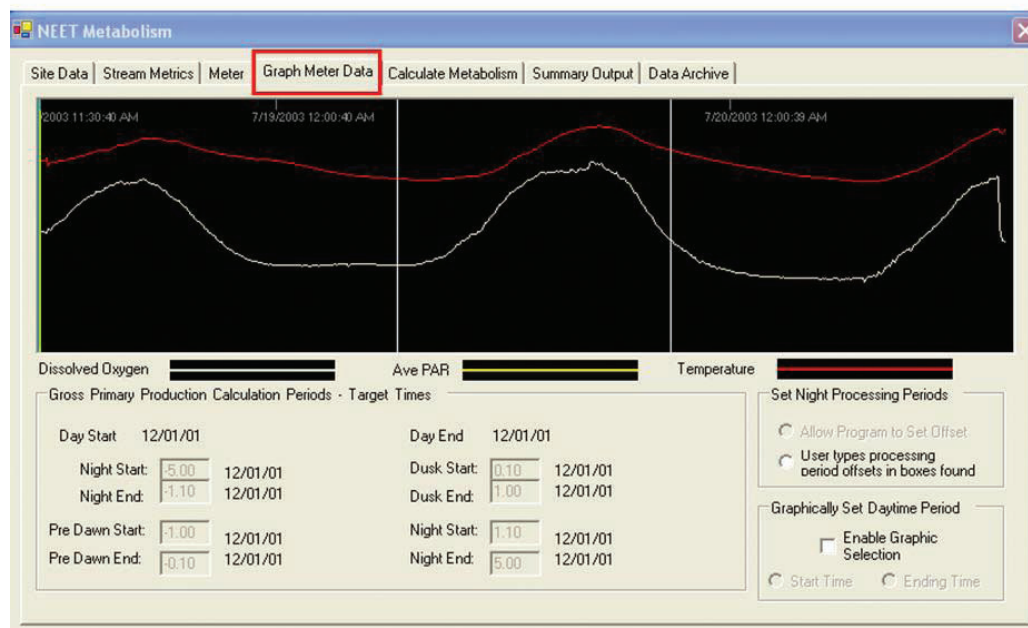

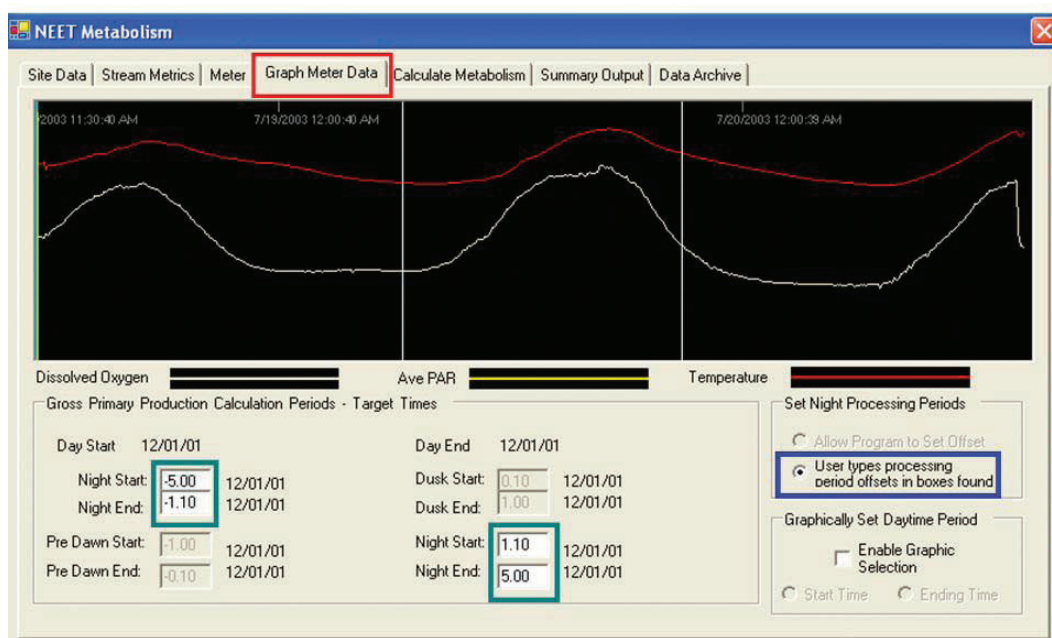**Figure 21.**   Automatically re-graphed data after manually selecting a daylight period in the Stream Metabolism Program.

Figure 22.   Screen capture of the *Graph Meter Data* page showing manually entered nighttime periods in the Stream Metabolism Program.
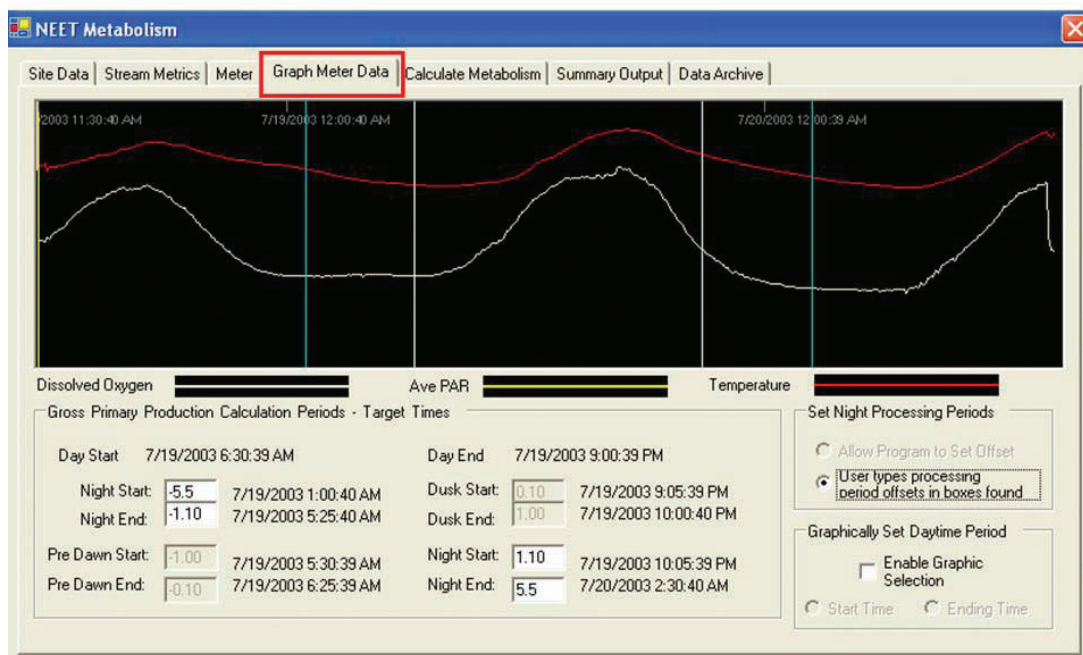

Figure 23.   Screen capture of the *Graph Meter Data* page following manual entry of all analysis period information in the Stream Metabolism Program.

Figure 24. Screen capture of the *Graph Meter Data* page showing graphical selection of the beginning of the daylight period for graphical analysis in the Stream Metabolism Program.

Calculate Metabolism

The next step is to calculate the various metabolism measures, which is done by clicking the "Calculate Metabolism" button on the *Calculate Metabolism* page (green outline, fig. 25). If the instrument drift has not been entered or calculated (figs. 17, 18), a pop-up window is displayed reminding the user to perform this operation before the metabolism measures can be calculated. **Calculated Metabolism Values** (white arrow, fig. 25) can be exported to an Excel® spreadsheet by clicking the **Write to Excel** button (yellow outline, fig. 25). This process is somewhat slow and can take as long as 20–30 seconds to complete. An Excel® window opens when the process is completed.

Calculated values for each time step are given on the *Calculate Metabolism* page (fig. 25). These same values are the values exported to the Excel® spreadsheet; measured values also are exported to the spreadsheet. The variables on the *Calculate Metabolism* page are as follows:

- Rec#, the record number;

- Date Time, the date and time of observation;

- US DO Corr. (mg/L), the DO concentration at the upstream meter, corrected for instrument error and drift [Note that the first value is for record number 6 (blue arrow, fig. 25). Recall that record numbers 1–5 were used to calculate the drift and error (fig. 17). The initial error for the upstream meter was 0.36 mg/L (fig. 17), and the instrument reading was 7.70 mg/L (fig. 11). Hence, the corrected reading for record number 6 is (7.70 + 0.36) = 8.06 mg/L (eq. 9; fig. 25). All subsequent calculations, with one exception described later, are based on the corrected DO values.];

- DS DO Corr. (mg/L), DO concentration at the downstream meter, corrected for instrument error and drift;

- US DO Sat. (mg/L), DO saturation concentration at the upstream meter;

- DS DO Sat. (mg/L), DO saturation concentration at the downstream meter;

- Ave Reach Temp (°C), reach-averaged water temperature, calculated by using eq. 11 [In this example, the travel time through the reach is 85 min, so the first reach-averaged temperature is calculated 85 min (or at 1:25 PM) after the temperature reading corresponding to the first DO reading at 12:00 PM (blue arrows, figs. 25, 26).];
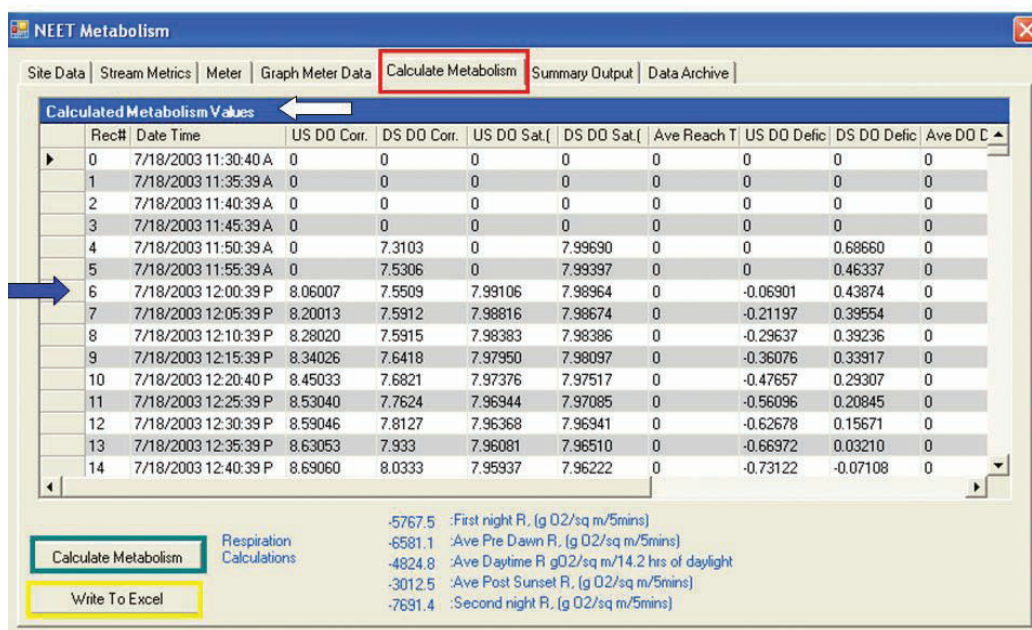
Figure 25. Screen capture of the *Calculate Metabolism* page in the Stream Metabolism Program.
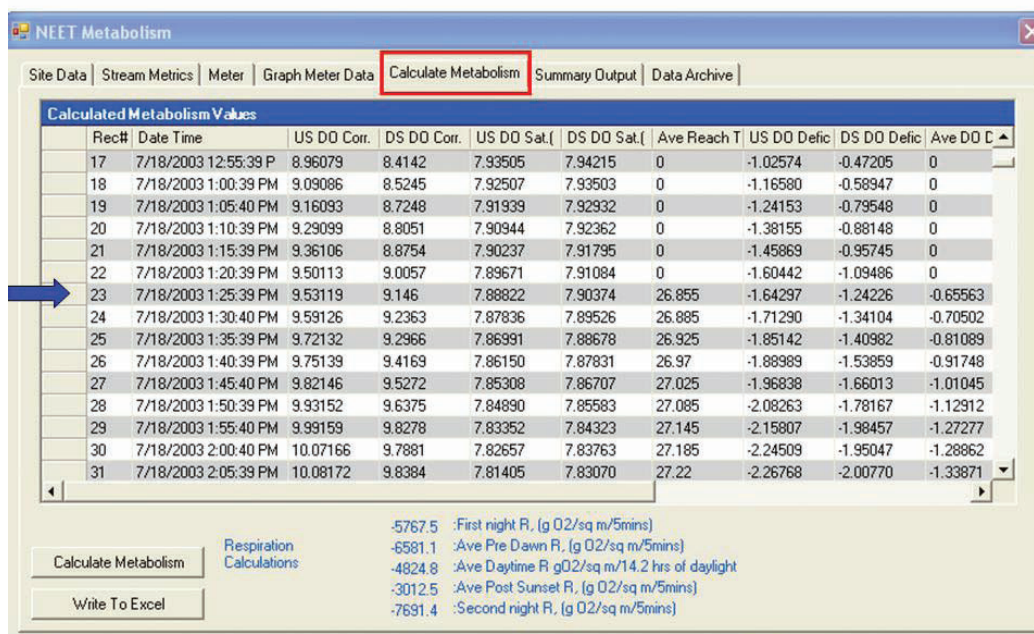

Figure 26. Screen capture of the *Calculate Metabolism* page showing reach-averaged calculations in the Stream Metabolism Program.

- US DO Deficit (mg/L), DO deficit (DO_s – DO) at upstream meter;

- DS DO Deficit (mg/L), DO deficit at downstream meter;

- Ave DO Def. Reach (mg/L), reach-averaged DO deficit;

- DO Diff. Reach (mg/L), the difference between the downstream DO and the upstream DO, offset by the travel time (the term in brackets in eq. 15);

- Reaeration Flux (mg/min), value calculated using eq. 12;

- Metabolism Flux (mg/min), value calculated using eq. 15;

- GPP Flux (mg/min), gross primary productivity calculated from eq. 19; values are reported for the daylight period; and

- Extrapolated Daytime Respiration (mg/min), respiration for the measurement interval calculated from eq. 17; values are reported for the daylight period.

A summary of respiration values during various time periods also are reported on the *Calculate Metabolism* page. All of the reported values are average respiration rates, in grams of oxygen per square meter per recording interval.

Total respiration for a particular period can be calculated by multiplying the value reported on this page by the recording interval (5 min for this example). **First night *R*** is the average respiration rate from the beginning of the first nighttime period until 1 hr before daylight, or in this example, from 11:35 PM on July 18 until 5:35 AM on July 19 (fig. 19). **Second night *R*** is calculated similarly for the second nighttime period. **Ave Pre Dawn *R*** and **Ave Post Sunset *R*** are the average respiration rates for the 1-hr period before dawn and the 1-hr period after sunset, respectively. The **Ave Daytime *R*** is calculated from the daylight respiration values interpolated between the average pre-dawn *R* and and average post-sunset *R*.

Summary Output

Information on the *Summary Output* page is generated when the "Calculate Metabolism" button (green outline, fig. 25) is clicked. Input values from the *Stream Metrics* page are summarized along with the calculated reach wetted area on the *Summary Output* page (blue outline, fig. 27). The next group of variables is related to daylight and PAR (green outline, fig. 27). The **Total daylight PAR** is calculated by summing the PAR values (in micromoles per square meter per second) for the daylight period, and multiplying the sum by the number of seconds in the PAR measurement interval. **Maximum Daily PAR** is the highest instantaneous PAR reading during the daylight period, and **Average Daylight PAR** is the **Total daylight PAR** divided by the **Daylight length**.
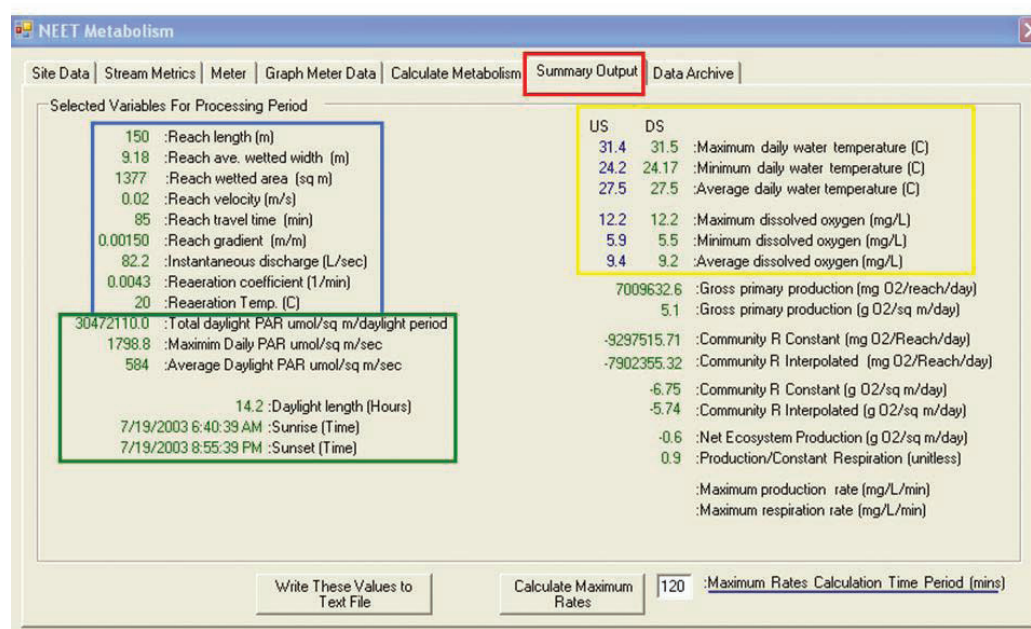

Figure 27.   Screen capture of the *Summary Output* page in the Stream Metabolism Program.

Some general statistics on DO and water temperature also are summarized on the *Summary Output* page (yellow outline, fig. 27). "US" indicates the upstream monitoring location, and "DS" is the downstream site. The "average" values are for the daylight period, and the "maximum" and "minimum" values are for the calendar date for which metabolism variables are calculated; in this example, July 19, 2003.

The maximum and minimum rate of change in DO concentration also can be calculated on the *Summary Output* page. The interval (in minutes) over which the rate of change is to be calculated is entered in the field adjacent to **Maximum Rates Calculation Time Period (mins)** (blue underline, fig. 27), and the **Calculate Maximum Rates** button is clicked. **Maximum production rate** is the largest positive rate, given in milligrams per liter per minute, and the **Maximum respiration rate** is the largest negative rate. The time associated with the maximum and minimum rates is the beginning of the period with the largest rate. For example, the period with the maximum production rate is between 10:35 AM and 12:35 PM, because the rate was calculated for a 120-min period. These rates are calculated using uncorrected DO data from the upstream station.

Information on the *Summary Output* page can be written to a text file. Data are comma delimited and written on one continuous line. This approach is advantageous when data from multiple sites are analyzed, so that the text file can be imported to a spreadsheet.

Data Archive

The *Data Archive* page (fig. 28) contains information that is useful primarily to those involved in modifying the program code. The page does, however, contain one important feature—the **Save Current Setup to Text File** button (blue outline, fig. 28), which allows the user to save all of the work that has been completed, including information from each of the other pages in the SMP. In a subsequent session, the user can open the software, click on the *Data Archive* tab, and then click on the **Read Saved .txt File** button (blue outline, fig. 29), browse the directory in which the saved setup file is located (default file name is setup.txt), and import the file into the SMP. Everything from the previous session will be restored with one exception. The metabolism calculations from the previous session will not be restored, so the user must again click on the **Calculate Metabolism** button (green outline, fig. 25) on the *Calculate Metabolism* page.

Single-Station Method

The SMP can be used with single-station data to compute a subset of the variables computed using the two-station method. The approach for the single-station method is generally the same as for the two-station; only the differences between the two methods will be highlighted here.
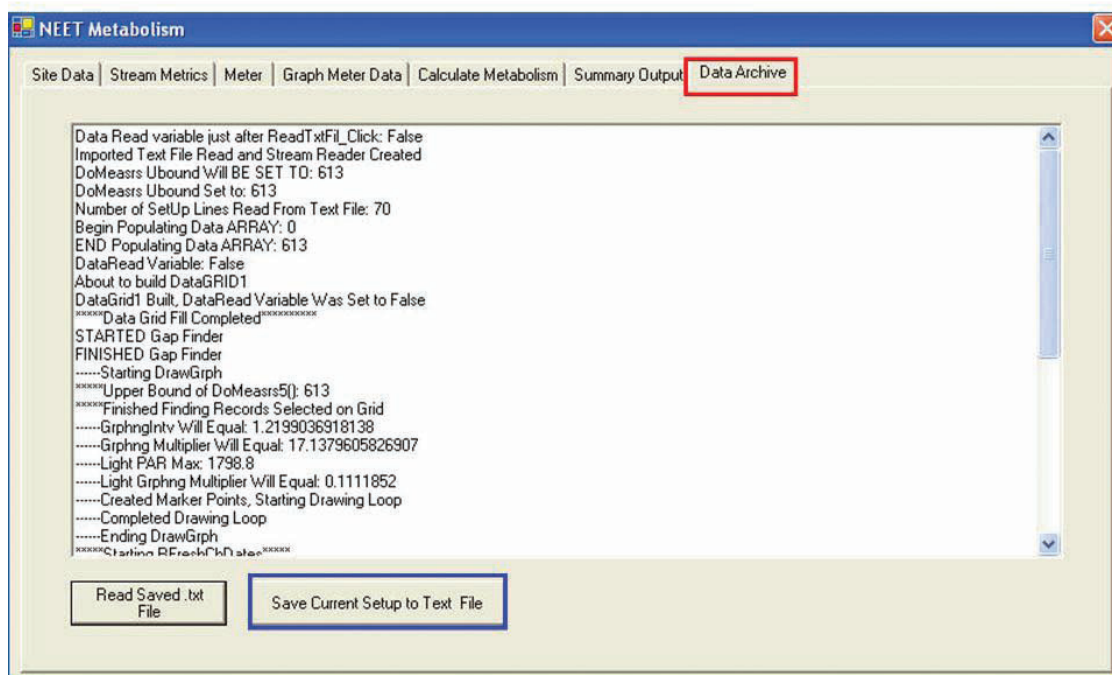

Figure 28.   Screen capture of the populated *Data Archive* page in the Stream Metabolism Program.
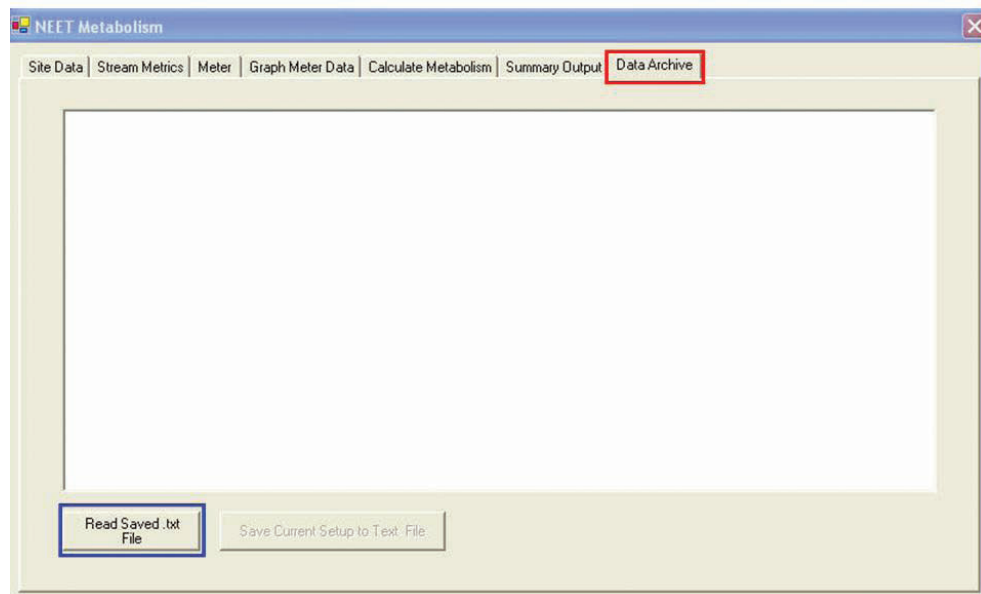
Figure 29.   Screen capture of an unpopulated *Data Archive* page in the Stream Metabolism Program.

The only differences between single- and two-station applications on the *Site Data* page are (1) the "1-Station" method is selected (blue arrow, fig. 30), and (2) data for only one set of readings are entered. Most of the fields on the *Stream Metrics* page are not active for the single-station application (fig. 31); only information on flow, barometric pressure, recording interval, and meter offset are required.

Single-station information is entered into the *Meter* page in the same way as the two-station information (fig. 32), except the software only accepts data from one recording

Figure 30.   Screen capture of the *Site Data* page for single-station application in the Stream Metabolism Program.

Figure 31.   Screen capture of the ***Stream Metrics*** page for single-station application in the Stream Metabolism Program.

Figure 32.   Screen capture of the ***Meter*** page for single-station application in the Stream Metabolism Program.

meter. Light data may or may not be entered, just as with the two-station method. Meter drift calculations are performed similarly to the two-station application. The analysis period can be selected automatically, as before, or manually on the *Graph Meter Data* page.

In some studies (for example, Mulholland and others, 2005), assumptions are made about the length of the reach over which the single-station measurement is applicable, and metabolism variables then can be calculated. Other applications of the single-station method (Wilcock and others,

1998) report the maximum rate of DO change and compute metabolism variables using a steady-state flow model. The approach used here is to make no assumptions about the length of the stream reach for which the single-station measurement applies but rather to report the calculations based only on the measurements. As a result, information on the *Calculate Metabolism* (fig. 33) and *Summary Output* (fig. 34) pages is fairly limited, with the primary result being the maximum and minimum rate of change in DO concentration.
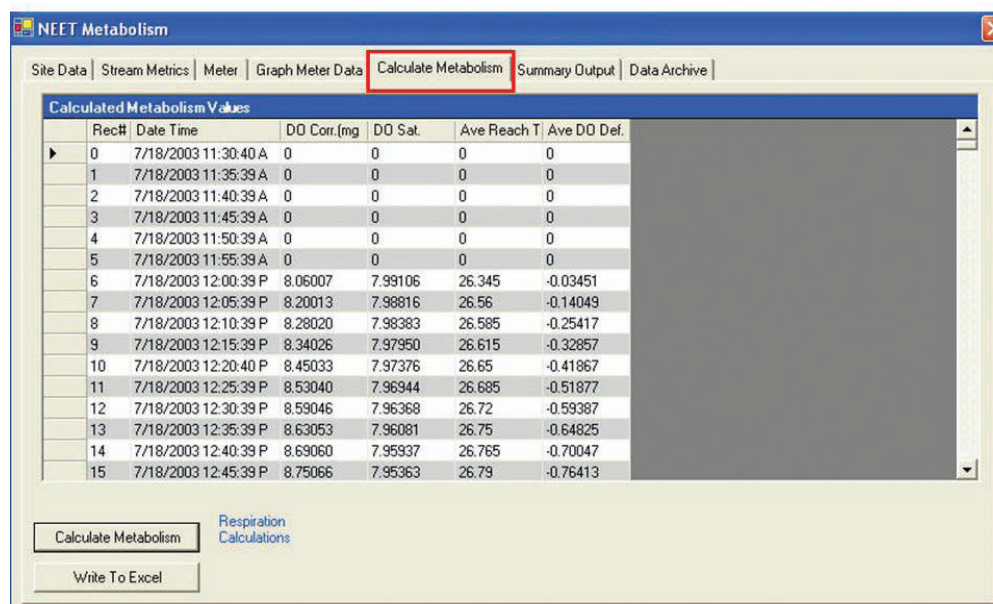

Figure 33.   Screen capture of the *Calculate Metabolism* page for single-station application in the Stream Metabolism Program.
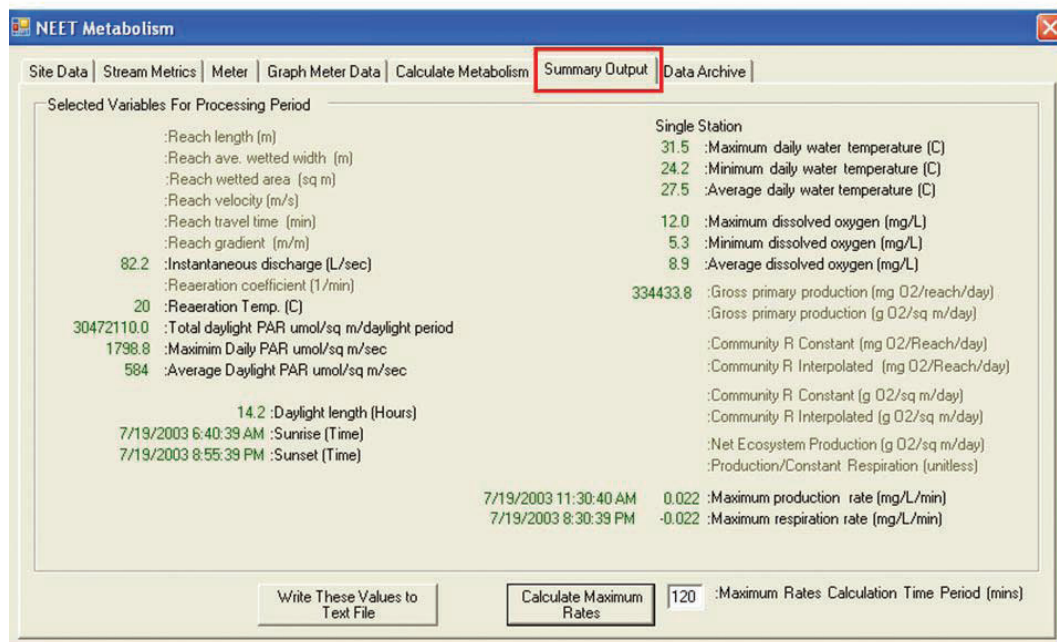
Figure 34.   Screen capture of the *Summary Output* page for single-station application in the Stream Metabolism Program.

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