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Project Summary

Numerical and Graphical Procedures for Estimation of Community Photosynthesis and Respiration in Experimental Streams

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A numerical dissolved oxygen (D.O.) routing model DORM is developed to determine total stream community photosynthesis (P) and community respiration rates (R) through successive routing of two-station diel D.O. measurements in a stream. The model differs from existing procedures for diel curve productivity analysis in that it uses the complete D.O. transport equation, including D.O. surface exchange, longitudinal dispersion, dependence of respiratory rates on water temperature and D.O. The model is applied to the experimental field channels at the USEPA Monticello Ecological Research Station to compute P and R values at different seasons and under different water temperature, solar radiation, and pH conditions. A sensitivity analysis shows that computed P and R values are most sensitive to residence times and surface oxygen exchange (reaeration) coefficients. New equations for surface exchange, including the effect of wind, have been developed and summarized.

A graphical, simplified routing procedure produced P and R values which were 82 and 89 percent, respectively, of those obtained by complete routing, with a standard deviation of less than 5 percent. Nighttime longitudinal D.O. gradients were used to derive respiration rates, R.

Maximum values of P and R in the MERS channels were 14.8 g m^{-2} day^{-1} and 10.7 g m^{-2} day^{-1}, respectively. P/R ratios ranged from 0.3 to 2.1. A seasonal dependence of P and R values was found, as expected.

Hysteresis in plots of hourly P versus photosynthetically active radiation (PAR) intensity was observed frequently. It was of such magnitude that it could not be caused by errors in surface exchange estimates or other physical processes.

This Project Summary was developed by EPA's Environmental Research Laboratory, Duluth, MN, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Dissolved oxygen, an important stream water quality indicator, is used for respiration by organisms. Plant organisms produce oxygen by photosynthesis and account for most of the oxygen production and respiration in many aquatic systems.

For streams which do not have a large chemical waste load, the oxygen sources and sinks may be represented as

Sources-Sinks = total community photosynthetic rate
- total community respiratory rate
+ surface exchange (reaeration)

Photosynthesis occurs only during daylight hours, and surface exchange varies with stream hydraulic features, water temperature, and D.O. concentration. Total community respiratory rate is usually assumed to remain fairly constant. For this reason, the diel (daily) D.O. cycle in a water body shows D.O. concentration as decreasing throughout the night and increasing during daylight hours (see Fig. 1). Since D.O. concentration is usually high during the day and low at night, surface oxygen exchange is typically a D.O. sink during daylight hours and a source during night hours.

A graphical analysis of the diel D.O. curve is often used (Odum's and other methods) to quantify stream community productivity or to measure the functional response of the autotrophic and heterotrophic community to pollutant stresses such as heat loading or toxic substances. If D.O. surface exchange is known, night D.O. measurements may be used to determine total community respiratory rate. Then total community photosynthetic rates may be determined from D.O. measurements taken during daylight hours.

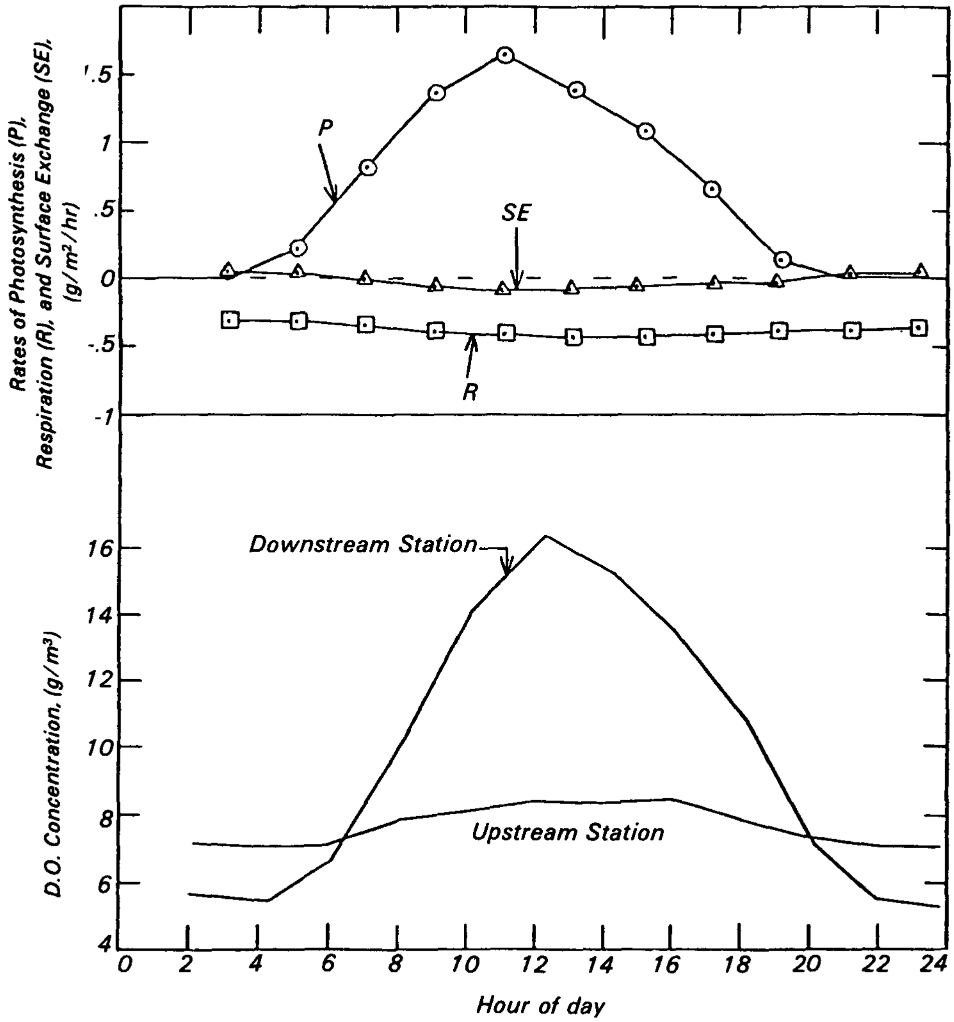

Figure 1. D.O. concentrations and resulting photosynthetic, respiratory, and surface exchange rates for field study stream reach.

This study focuses on several aspects of diel D.O. curve analysis using both graphical and numerical procedures and accomplishes the following objectives:

- A numerical D.O. routing model (DORM) is developed to incorporate aspects of D.O. routing normally neglected in diel D.O. curve analysis of stream productivity. DORM includes surface exchange, longitudinal dispersion, inhibition of respiration at low D.O. concentration, and dependence of respiratory rate on water temperature.
- A theory for the prediction of air/water oxygen exchange which includes the effects of surface shear due to wind and secondary currents is developed. Experiments for surface exchange conducted at the USEPA Monticello Ecological Research Station (MERS) are described and the results are related to the developed theory.
- DORM is applied to diel curve productivity analysis for the MERS channels. Results are compared with those which can be obtained by a simple graphical routing method.
- The contributions of several subcommunities to the stream D.O. budget have been investigated in the field channels of the USEPA Monticello Ecological Research Station.

Conclusions

1. The D.O. transport equation was expressed in the form:

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left(D_L\frac{\partial C}{\partial x}\right) + \frac{K_s}{h}(C_s - C) + P - R \quad (1)$$

where C = D.O. concentration (cross-sectional mean) (g/m³)
C_s = saturation D.O. concentration (g/m³)
U = flow velocity (cross-sectional mean) (m/s)
D_L = longitudinal dispersion coefficient (m²/s)
K_s = bulk surface exchange coefficient for oxygen (m/s)
P = total community photosynthesis (g m^{-3} s^{-1})
R = total community respiration (g m^{-3} s^{-1})
t = time (t)
x = longitudinal distance (m), and
h = mean depth (m).

Respiration is expressed as a function of temperature and limited by low D.O.

$$R = R_{20}\theta^{(T-20)}\frac{C}{C+C_{KM}}, \qquad (2)$$

where T = water temperature (°C), θ = temperature coefficient, and C = Michaelis-Menton coefficient for respiratory inhibition at low D.O. concentrations.

By the routing procedure (DORM) one finds R_{20} and P(t). R(t) values are subsequently computed from Eq. (2). Implicit, hybrid differences are used in the routing program. The routing involves iterative prediction of downstream D.O. versus time values with increasingly accurate estimates of P (for daytime) and R (for nighttime), until a match of desired accuracy between predicted and measured values is achieved. The parameters U, D_L, h, K_s, θ and C_{KM} in Eq. (1) must be known for each channel segment. The input data to DORM are:

a. *initial longitudinal D.O. profile*
b. stream segment lengths
c. cross-sectional areas of stream segments
d. surface widths of stream segments
e. stream segment orientation (direction)
f. water surface slope
g. *channel flow rate*
h. day of year
i. longitude and latitude of study site
j. measured D.O. concentrations and corresponding measurement times at the upstream and the downstream locations
k. measured water temperature versus time at the upstream and the downstream locations
l. measured wind velocity, wind direction and air pressure (mb) at the stream site as a function of time

2. **A theory for the prediction of the air-water oxygen exchange coefficient** K_s in Eq. (1) was also developed. It considers the effects of shear stresses on a stream bed due to gravity, wind shear on the water surface, wind generated waves, and in a qualitative way, secondary currents. The relationships proposed for the prediction of K_s values are of the form:

   a. For streams without wind effects

$$K_s = A_1 u^*_b \left[0.804\,(A_5\,Pe)^{-1/3} + 0.468\,(A_5\,Pe)^{-1/20}\right] \qquad (3)$$

where $Pe = \frac{u^*_b h}{D_m}$ = a shear Peclet number

$u^*_b = \sqrt{\tau_b/\rho}$ = shear velocity (m/s)

τ_b = *gravity flow induced bed shear* (N/m²)

ρ = water density (g/m³)

D_m = molecular diffusivity of D.O. in water (m²/s)

A_1 = coefficient related to bed shear induced turbulence

$A_5 = A_1\,(1 + a_5)$

a_5 = coefficient related to secondary currents in a stream reach

The coefficient $A_1 = 5.44 \cdot 10^{-4}$ was determined from literature data, while a_5 is stream specific and must be *evaluated in the field.*

   b. For streams with wind effects

$$K_s = 4(u^*_c + a_5\,u^*_b)\cdot F_{sa}\cdot X/\ln\left(\frac{X+1}{X-1}\right) \qquad (4)$$

where $X = \left[1+\frac{D_s}{4D_{to}}\right]^{1/2}$

$$\frac{D_s}{D_{to}} = \frac{D_m + A_4\nu\,W_s^3}{A_1 h\,(u^*_c + a_5\,u^*_b)}$$

$u^*_c = [(\tau_s + \tau_b)/\rho]^{1/2}$

τ_s = wind induced surface shear (N/m²)

F_{sa} = coefficient for increase in water surface area without waves (-)

ν = kinematic viscosity of water (m²/s)

W_s = wave parameter (-)

The parameters F_{sa} and W_s are both related to wind waves. For moderate wind velocities ($u^*_a/g \leq 0.02$ m) the following relationships have been proposed:

$$F_{sa} = \left[1 + \left(\frac{\overline{ga}}{\pi c^2}\right)^2\right]^{1/2} \qquad (5)$$

$$\frac{\overline{ga}}{\pi c^2} = 0.112\pi\left[\frac{F_2}{F_2-F_1}\left(\frac{g\,F_2}{u^{*2}_a}\right)^{1/2}\left(\frac{\rho g\,F_2^2}{\sigma}\right)^{-1/3} - \frac{F_1}{F_2-F_1}\left(\frac{g\,F_1}{u^{*2}_a}\right)^{1/2}\left(\frac{\rho g\,F_1^2}{\sigma}\right)^{-1/3}\right] \qquad (6)$$

$$W_s = 2.64 \cdot 10^{-3} K_a\left[\frac{F_2}{F_2-F_1}\left(\frac{g\,F_2}{u^{*2}_a}\right)\left(\frac{\rho g\,F_2^2}{\sigma}\right)^{-1/6} - \frac{F_1}{F_2-F_1}\left(\frac{g\,F_1}{u^{*2}_a}\right)\left(\frac{\rho g\,F_1^2}{\sigma}\right)^{-1/6}\right] \qquad (7)$$

where g = acceleration of gravity = 9.81 m/s²

a = wave amplitude (m)

c = wave speed (m/s)

F_2 = wind fetch at downstream end of stream reach (m)

F_1 = wind fetch at upstream end of stream reach (m)

u^*_a = air shear velocity = $\sqrt{\tau_s/\rho_a}$ (m/s)

ρ_a = air density (kg/m³)

ρ = density of water (kg/m³)

σ = surface tension (N/m)

$K_a = u^{*3}_a/(g\nu)$ = Keulegan parameter

Similar relationships were developed *for strong winds* ($u^*_a/g > 0.02$ m). The theory implies the following:

a. The circulation of the water under wind waves makes an important contribution to surface oxygen exchange. Therefore, wind speed and fetch are important factors.
b. Secondary currents in the water provide an important contribution to surface oxygen exchange. Since these currents cannot be predicted, a parameter related to secondary currents must be estimated or measured in each stream reach.

3. **Night D.O. measurements in the field** channels of the USEPA Monticello Ecological Research Station were used to determine surface exchange coefficients. Parameters related to secondary currents and wind in the equations for surface exchange coefficients were back-calculated from the surface exchange coefficients. These parameters are specific to the MERS channels. Predictions *made with these parameters for the* MERS channels were superior to predictions made with equations from the literature. Values of surface exchange coefficients in the MERS channels predicted by literature equations spanned three orders of magnitude. *The large scatter in* surface exchange coefficients from literature equations is very likely due to omission of secondary currents and

wind effects. Each equation for a surface exchange coefficient is applicable only to the stream reach from which data were taken.

4. Thirty-two diel D.O. surveys in four stream reaches were made in the MERS experimental streams in late summer and fall of 1978 and spring and summer of 1979. Diel curve productivity was estimated with DORM, using data from each survey. A temperature coefficient for total community respiratory rate, θ = 1.045, was determined from a sequence of predawn longitudinal D.O. surveys in September 1978 with a temperature range from 15 to 24°C. A half-saturation coefficient for respiratory inhibition at low D.O. concentration, C_{KM} = 2.3 g/m^3, was determined from diel D.O. data obtained in a channel reach during three consecutive nights. Computed R values ranged from 2.6 g m^{-2} day^{-1} D.O. in October 1978 to 10.7 g m^{-2} day^{-1} in August 1979, and P values ranged from 1.50 g m^{-2}day^{-1} in October 1978 to 14.8 g m^{-2} day^{-1} in June 1979. P/R ratios varied between 0.3 in September 1978 and 2.1 in May 1979. In the MERS channels, the P/R ratio is a good indicator of community photosynthetic efficiency.

Diel curve analysis was performed in three channel reaches with a respective pH of 8.0, 6.3, and 5.4. The channel reaches with low pH reached maximum total community photosynthetic and respiratory rates earlier in the growing season than the one with highest pH. Although this could be due to the lower pH, it is more likely attributable to a difference in vegetation history and shading by emergent vegetation in the low pH channel reaches.

Total community photosynthetic rates (P) over the day were plotted against photosynthetically active radiation (PAR) for each diel D.O. survey. The relationship between P and PAR was usually nonlinear, and hysteresis in the P versus PAR curves was frequent. Counterclockwise hysteresis was observed for three channel reaches on a cloudy day in late July 1979 and a clear day in mid-September 1979. Other surveys in May, June, and August generally gave clockwise hysteresis. Sensitivity analysis with the D.O. routing model indicates that in the MERS channels, physical parameters cannot be held responsible for the hysteresis; rather, it is believed to be caused by biological processes. Several hypotheses have been proposed to explain the cause of hysteresis, but further studies are needed to determine it.

5. The potential errors in P and R values for the MERS channels resulting from several simplifications of the D.O. transport equation and from inaccurate data input were investigated.
   a. Neglecting D.O. surface exchange (K_2 = 0) gave substantially reduced values of P and R (typically 8% and 16%, respectively).
   b. Longitudinal dispersion can be neglected for the MERS channels. Only small (< 2%) changes in P and R are produced when $D_L \neq 0$ is included in Eq. (1).
   c. Using a linear interpolation between upstream D.O. input data collected at two-hour intervals is acceptable. More complete curve fitting to input D.O. data resulted in only minor (0.4%) changes in P and R.
   d. Correct residence times are required. Using incorrect residence times (± 20%) changed P and R values significantly (± 18%).
   e. Temperature dependence of respiratory rates is of importance in the MERS channels. A diel variation of 5°C would result in a 7 percent error in respiratory rates.

6. **A graphical method by which the upstream measured D.O. curve, corrected for residence time of flow of the water mass to the downstream station,** is subtracted from the downstream measured D.O. curve was also applied to the MERS data. The method solves the simplified equation graphi-

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = P - R \qquad (8)$$

cally. Of all the processes included in the complete Eq. (1), Eq. (8) considers only advection, community photosynthesis and community respiration and ignores surface oxygen exchange and longitudinal dispersion. The graphical method gave P and R values which were on the average 89 and 82 percent, respectively, of the values obtained by the complete DORM. The standard deviation was ± 5 percent. The P/R ratio given by the graphical method was on the average 1.07 times that obtained by the complete DORM with a standard deviation of 0.04.

7. Separate studies were conducted in the MERS channels to answer several additional questions related to the diel curve analysis.
   a. It was examined to determine whether the water pumped into the channels from the Mississippi River had enough nutrients from the observed plant growth in the channel. Nutrient limitation is not believed to be a limiting factor.
   b. Biochemical oxygen demand (B.O.D.) in the channels is included in the reported R values. It was established that the water supply contained less than 12 g/m^3 BOD_5, which made no significant contribution to R because of the short residence times of 2 to 5 hours in the channels and the effect of the first pool as a settling basin.
   c. The sedimentary oxygen demand in the bed of a stream pool was estimated using dark cylinders and was found to be on the order of from 0.01 to 0.04 g m^{-2} hr^{-1}. With water residence times from 2 to 5 hours this uptake was considered negligible in the D.O. routing process.
   d. Diel D.O. measurements and control volume techniques in several riffles and pools helped to subdivide the total community P and R values into contributions by macrophytes, epiphyton, and phytoplankton. During August 1978, the macrophytic and epiphytic subcommunities in pools 14 contributed on the average of 5.3 g 0^2 m^{-2} day^{-1} to photosynthesis and 10.5 g 0^2 m^{-2} day^{-1} to respiration, while the planktonic contributions were only 0.4 g O_2 m^{-2} day^{-1} and 0.6 g O_2 m^{-2} day^{-1}, respectively. In riffle 13 the dominance of the subcommunity over the planktonic community was equally pronounced. However, the photosynthetic rate of the benthic subcommunity in the more shallow riffle was higher (9.9 g O_2 m^{-2} day^{-1}) than in the pool, while its respiration rate was about equal (9.8 g O_2 m^{-2} day^{-1}) to that in the pool.

8. The limitation of macrophyte respiration rates by less than 3.5 g/m^3 D.O. in the water was observed using incubation experiments. This provided verification of the C_{KM} value determined through D.O. routing with DORM.

9. The following reports and papers contain details of the studies conducted:

a. Numerical and Graphical Procedures for Estimation of Community Photosynthesis and Respiration in Experimental Streams, by John S. Gulliver, Tedd W. Mattke, and Heinz G. Stefan, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 198, 123 pp.
b. Photosynthesis and Respiration Rates in the Monticello Experimental Streams: 1978-79 Diel Field Data and Computed Results, by John S. Gulliver and Heinz G. Stefan, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, External Memorandum No. 172, February, 1981, 57 pp.
c. Graphical Method to Estimate Stream Community Respiration and Primary Productivity from Dissolved Oxygen Measurements, by Tedd W. Mattke and Heinz G. Stefan, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, External Memorandum No. 169, December, 1980, 53 pp.
d. Air-Water Oxygen Exchange: Theory and Application to Experimental Streams, by John S. Gulliver and Heinz G. Stefan, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, External Memorandum No. 173, May, 1981, 108 pp.
e. Community Photosynthesis and Respiration in Experimental Channels, by M.K. Taylor and S.P. Sheldon, Dept. of Ecological & Behavioral Biology, University of Minnesota, Minneapolis, Minnesota, Nov., 1979 (accepted by Hydrobiologia, 1981).

Recommendations

Diel D.O. measurements should be analyzed with a complete routing model such as DORM in order to minimize error in estimates of photosynthetic production and respiration rates. Surface exchange coefficients of oxygen (reaeration coefficients) are stream specific and wind dependent. Values of surface exchange coefficients predicted with literature equations for the MERS experimental streams spanned three orders of magnitude. Empirical surface exchange equations are dependent on secondary water movement and surface waves and are therefore not readily transferable from one stream to another.

Regarding general diel curve analysis the following recommendations are made:

1. Field measurements of D.O. should be made in cross sections which are well-mixed. D.O. analysis by the Winkler method is much more reliable than D.O. measurements by sensors and continuous recording. Channel geometry, channel orientation, and flow rates need to be documented with precision.
2. Extreme care should be taken to accurately determine stream reach residence time. This requires precise documentation of channel geometry and flow rates. Effects of diurnal thermal stratification on residence time measurements need investigation in the MERS channels.
3. Surface exchange of oxygen (reaeration) should be measured in the stream reach of interest. Surface oxygen exchange is often dependent upon wind. Therefore, wind velocity and wind direction need to be measured.
4. Longitudinal dispersion need not be included in the diel curve productivity analysis in the MERS channels but should be included in a highly dispersive system.
5. The temperature dependence of respiratory rates should be included in diel curve analysis when the diel variation in water temperature is 2°C or greater.
6. Respiratory inhibition at low D.O. concentrations should be included in diel curve analysis when D.O. concentrations below 4 g/m^3 are encountered.
7. A linear interpolation between upstream D.O. measurements is acceptable when the data are collected in two-hour intervals. Greater time intervals may require a higher order interpolation.
8. Further investigations should be conducted to investigate the causes of hysteresis in plots of photosynthetic production versus light intensity.
9. Additional research should also be conducted on the D.O. limitation and the effect of temperature on respiration rates (parameters C_{KM}, R_{20}, and θ). Values of θ may vary seasonally. Only late summer data were used to derive a θ value herein.

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***Kenneth E. F. Hokanson** is the EPA Project Officer (see below).*

The complete report, entitled "Numerical and Graphical Procedures for Estimation of Community Photosynthesis and Respiration in Experimental Streams," (Order No. PB 82-220 765; Cost: $13.50, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

The EPA Project Officer can be contacted at:

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