Remote Biological Monitoring in an Open Finished-Water Reservoir

Brian N. White, Dale A. Kiefer, John H. Morrow, and Gary F. Stolarik

A prototype instrument array known as REOS1, for remote electro-optical sensor, provided automated surveillance of a nuisance algal population in an open drinking-water reservoir. The high-resolution data base provided by moored sensors enabled reservoir managers to detect algal blooms before water quality was aesthetically compromised. A remote data link also provided immediate feedback on the efficacy of algicide treatments in the reservoir. A simple decision matrix included in this article shows how REOS data can be used to diagnose the biological status of an open reservoir and to guide daily operations.

Planktonic algae are a leading cause of taste, odor, and appearance problems in potable water supplies. They are also an important source of trihalomethane precursors.[1] Oxygen depletion following the die-off of a planktonic bloom can cause fish kills and other water quality problems. Early bloom detection is the weak link in modern algae-control strategies because phytoplanktonic growth rates typically overwhelm the resources of manned reservoir surveys.

A prototype instrument package deployed by the Los Angeles Department of Water and Power in an open treated-water reservoir has demonstrated the technical feasibility of continuously monitoring the status of planktonic algae populations. During a 6.5-month study from mid-May through November 1990, the instrument array christened REOS1, for remote electro-optical sensor, captured all of the major algal events in Silver Lake, an open, 2,500 acre-ft, finished-water reservoir near downtown Los Angeles. By characterizing both diurnal and seasonal variations in the biological activity in Silver Lake, the prototype showed that with minor modifications, a REOS-type system can be a reliable, low-maintenance, and cost-effective approach to reservoir surveillance. A second-generation system, REOS2 (Figure 1), is scheduled for installation in October 1991.

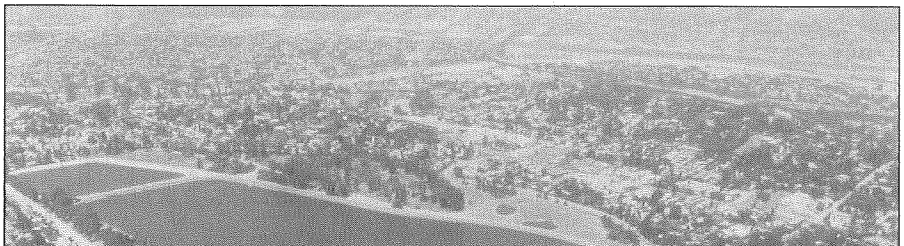
The continuous optical measurement of photosynthetic rates offers a new management strategy to the water industry. Photosynthesis and other metabolic rates such as nitrogen fixation, respiration, and electron transfer have been identified as useful indicators of reservoir water quality.[2] Although several procedures are available to monitor these processes, few are cost-effective. The REOS data link has real potential for detecting, and thereby reducing the response time to, nuisance algal blooms in open reservoirs.

System hardware

The REOS1 instrument array included four instruments.

1. A radiometer* provided continuous measurements of natural fluorescence (from which photosynthetic rates and concentrations of chlorophyll-a were calculated), photosynthetically available radiation (PAR) at the surface and at depth, water temperature, and pressure (depth of deployment).
2. A transmitter† provided continuous measurements of pH, dissolved oxygen (DO), conductivity, and oxidation–reduction potential (ORP).
3. A beam transmissometer‡ provided continuous measurements of the attenuation by suspended particles of a collimated beam of 670-nm light.
4. A strobe fluorometer‡ provided continuous measurements of concentrations of chlorophyll-a.

Data were logged by an IBM-compatible 286 microcomputer located in the reservoir outlet tower. The host computer, connected to the instrumentation package by a floating electrical umbilicus, was equipped with a telephone modem for



This open finished-water reservoir in Los Angeles was the testing ground for a prototype instrument package that continuously monitors the status of planktonic algae populations, which can help in the early detection of blooms.

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*Model PNF-300, Biospherical Instruments Inc., San Diego, Calif.

†Scout model, Hydrolab Corp., Austin, Tex.

‡Seatech Inc., Corvallis, Ore.

remote interrogation. Silver Lake Reservoir, which provides water to central and east Los Angeles, was the site of deployment of the REOS package. Additional information on system architecture is available elsewhere.[3] The basic optical principles underlying the radiometer are as follows.

Photosynthesis and natural fluorescence

All photosynthetic plants convert solar energy into chemical energy, but the process is not 100 percent efficient. Some of the energy is lost as heat, and a small fraction is re-emitted as fluoresced light at a longer wavelength. This fluorescence is centered in a very narrow region of the visible spectrum: red light that peaks at a wavelength of 683 nm.

It was not until the mid-1980s that an instrument was developed to measure photosynthetic rates using natural fluorescence. The PNF-300 radiometer has been used by scientists worldwide to measure natural fluorescence in marine environments ranging from the poles to the tropical South Pacific.[4] The results from 76 such measurements covering a 1,500-fold range in photosynthetic production at depths ranging between 2 and 150 m indicate that the instantaneous rate of photosynthesis is highly correlated with natural fluorescence ($r > 0.9$).[4] The theory relating natural fluorescence to photosynthesis is well developed.[4,5]

Various complications exist in the interpretation of aquatic productivity measurements. Natural fluorescence is a measure of instantaneous gross primary production, the supply side of the carbon cycle. The demand side, e.g., respiration by phytoplankton and other organisms, is unrelated to the fluorescence signal. In addition, the natural fluorescence signal may be contaminated by fluorescence from degradation products of chlorophyll, such as phaeopigments. High light intensities may also inhibit natural fluorescence. Finally, aquatic biologists are only starting to consider the contribution to total primary production of blue-green algae, which fluoresce weakly at 683 nm.

Despite these limitations, natural fluorescence sensors provide a rapid, inexpensive measurement of photosynthesis in situ. Such sensors also allow spatial and temporal information on photosynthetic rates, which is too costly to collect with more traditional methods, to be gathered.

System placement

The usefulness of any moored sensor package depends on its proper placement. REOS1 was moored approximately 100 m east of the Silver Lake outlet tower at a depth of 5 m. That depth was chosen based on the need to place the radiometer deep enough to avoid contamination of the fluorescence signal by backscat-

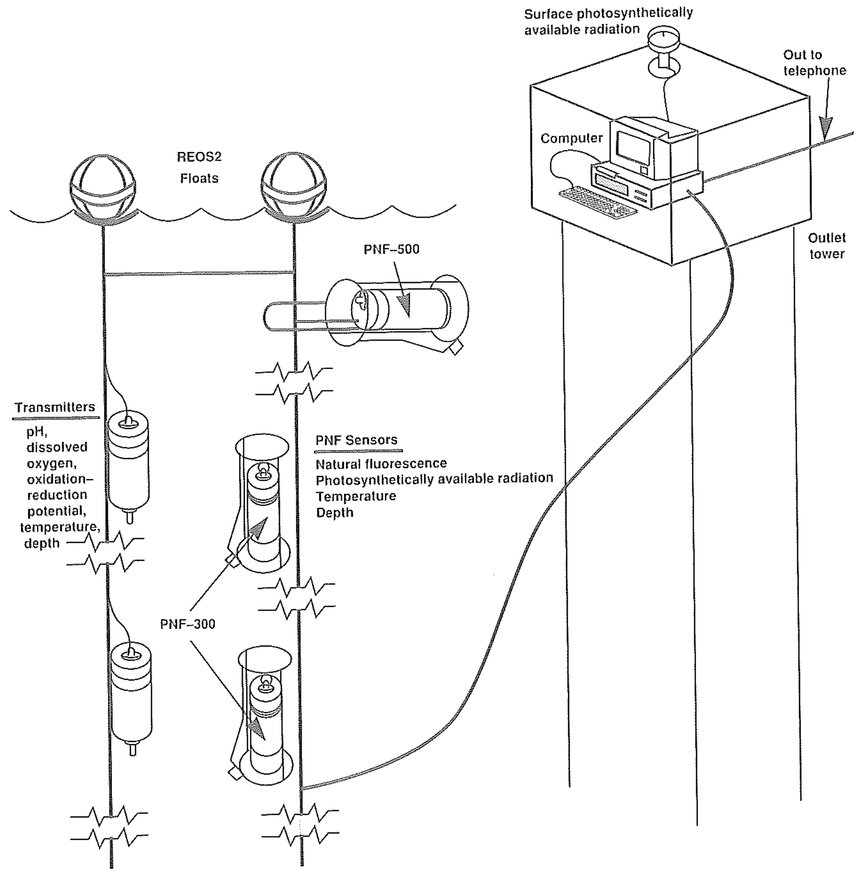

Figure 1. REOS2 instrument array

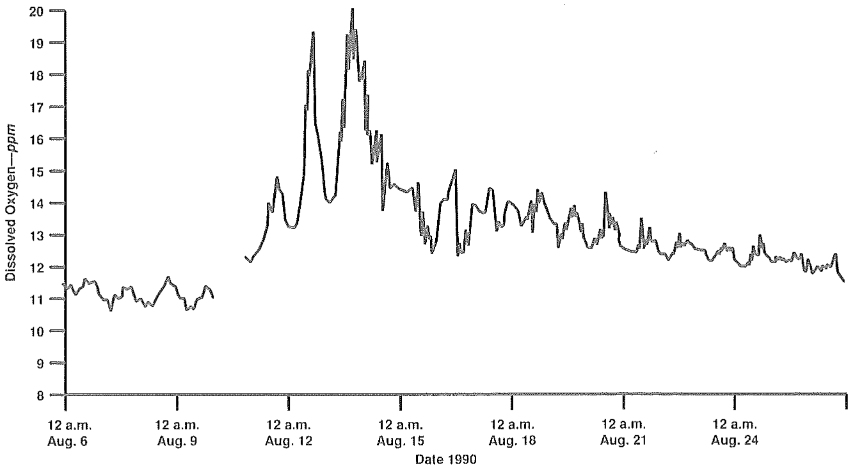

Figure 3. Daily time series of dissolved oxygen concentration, Aug. 6–Aug. 26, 1990, at Silver Lake *(note surge in oxygen concentration presumably associated with increase in photosynthesis starting on the Aug. 11 transition between lag and exponential growth phases of second 1991* Hypnomonas *bloom cycle; Aug. 10 hiatus caused by electrode calibration)*

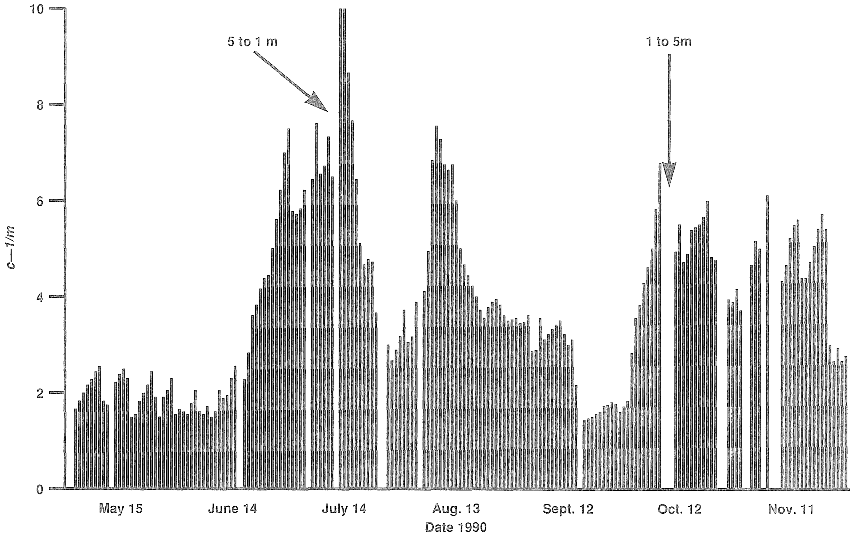

Figure 2. Average daily coefficient of attenuation (*c*) of a collimated beam of 670–nm light by absorption and scattering across a 0.5–m path length at Silver Lake, May 1–Nov. 30, 1990 *(note three periods of reduced water transparency associated with blooms of the green alga* Hypnomonas *occurring June 28–July 23, Aug. 7–20, and Oct. 2–Nov. 20)*

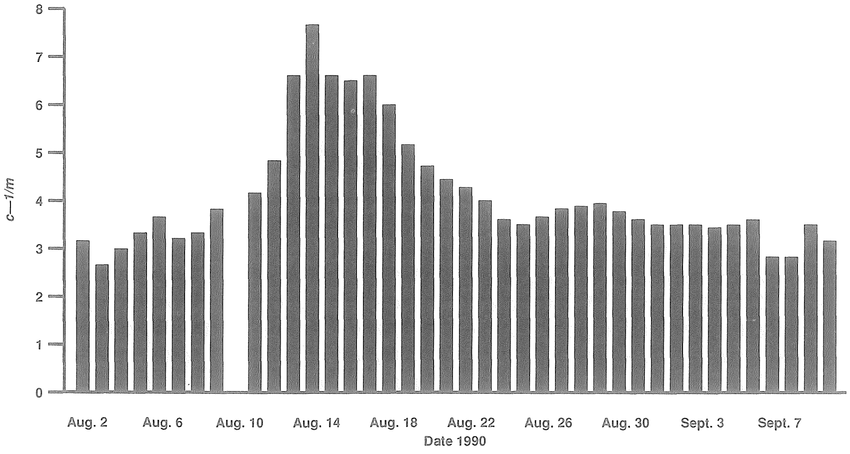

Figure 4. Average daily coefficient of attenuation (*c*) of a collimated beam of 670–nm light by absorption and scattering across a 0.5–m path length during second *Hypnomonas* bloom cycle *(note Aug. 11 transition between lag and exponential growth phases; Aug. 10 hiatus caused by electrode calibration)*

tered sunlight but shallow enough that the region of most rapid growth could be measured. On the basis of past experience, Silver Lake was thought to be well mixed throughout the year. In mid-July, however, thermal stratification did occur, and an algal bloom developed in the warmer, less-dense waters overlying the sensor package. In response, REOS1 was repositioned on July 20 at a depth of 1 m. It remained there until October 9, when workers suspected saturation of the radiometer by backscattered red light in the clear surface waters. At that time, REOS1 was returned to a depth of 5 m. The second-generation system, REOS2, will be fitted with a new five-channel radiometer, the PNF-500, that corrects for backscattered solar radiation near the surface and is therefore deployable in shallow water.

System reliability

Though the sensor instruments never failed, technical difficulties took the system off line on 22 days of the 197-day study period. These problems were addressed in the design of REOS2. System failure had two main causes. The humid, chlorinous environment of the outlet tower caused miscellaneous electrical problems with the host computer, and stretching of a nonweight-bearing cable in the umbilicus to the outlet tower caused intermittent interruptions of the data stream. A long-term solution to these problems would be the design of an intelligent, stand-alone system that is not tethered to the outlet tower. Short-term solutions include the exclusive use of weight-bearing cables, regular maintenance of electrical contacts, and a ready supply of spare computer equipment. In the outlet tower, an unweatherized host computer can be expected to function only 9 to 12 months.

Biological fouling of the optical instruments was not a problem, despite the fact that the detector ports were not coated with antifoulant. Settling particles did, however, obscure the optical ports of the beam transmissometer on several occasions, which compromised the beam transmission data base. Biweekly calibration of the transmitter electrodes prevented significant drift. The only regular maintenance required by the PNF-300 radiometer is annual factory service and recalibration.

Bloom prediction

Detection and characterization of a phytoplanktonic bloom cycle was a major goal of this project. A phytoplanktonic bloom cycle has four main phases. During the lag phase, cell numbers slowly increase. During the exponential phase, cell numbers increase exponentially. In the stationary phase, cell numbers are high, but stable, and in the death phase, cell numbers decline rapidly.

The feature of the algal bloom cycle of greatest interest to reservoir managers is the transition between the lag and exponential phases, because chemical control is lost when the exponential phase begins. Early recognition of the lag phase might therefore be the most practical strategy for predicting blooms.

REOS1 detected three algal events (Figure 2). The first two, June 28–July 23 and August 7–August 20, were associated with blooms of the resident chlorophyte *Hypnomonas* sp. The last, October 2–November 20, resulted from the introduction of large numbers of *Hypnomonas* cells from a bloom that was occurring in an upstream reservoir. These transported cells were apparently stressed by their journey through the distribution system and, unlike the cells associated with the previous, indigenous blooms, produced little oxygen during the day.

The data base obtained for the second bloom cycle, when the instrument package was consistently within the zone of maximum productivity, illustrates most clearly the capabilities of the REOS system to predict blooms.

The oxygen time-series data clearly show that the exponential phase of the second bloom cycle began on August 11 (Figure 3). Exaggerated daily pH excursions, which occurred during the first bloom cycle, were not observed during the second cycle. This discrepancy is probably because the higher chlorine dosages used during the second bloom cycle moderated reservoir pH.

Four optical trends preceded by several days the August 11 surge in photosynthetic oxygen production. These lag-phase characteristics may be useful early warning signals of an impending algal population explosion.

The beam attenuation coefficient *c* expresses the rate of attenuation of a collimated beam of 670-nm light at the depth of deployment. The record for *c* (Figure 4) clearly shows the mid-August *Hypnomonas* bloom, including the lag phase.

The diffuse attenuation coefficient *k*(PAR) expresses the rate of attenuation of sunlight through the water column. The August *k*(PAR) record (Figure 5) generally resembles that of the beam attenuation coefficient *c* and documents a reduction in water transparency during the lag and exponential phases of the second *Hypnomonas* bloom.

The chlorophyll-a concentration (Figure 6) and primary production (Figure 7) time series calculated from the natural fluorescence signal also document the second 1990 bloom and are consistent with the *c* and *k*(PAR) records.

Concomitant water quality trends were noted only during bloom events. Table 1 illustrates how these trends may be used to diagnose reservoir conditions and guide operations. As the table shows, water quality trends consistent with the

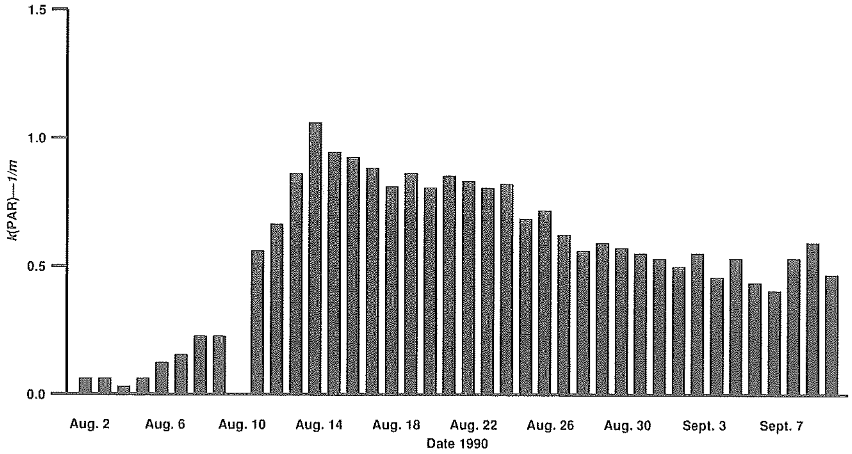

Figure 5. Average daily coefficient of attenuation [*k*(PAR)] of sunlight to depth of deployment by overlying water column during second *Hypnomonas* bloom cycle. *(note Aug. 11 transition between lag and exponential growth phases; Aug. 10 hiatus caused by electrode calibration)*

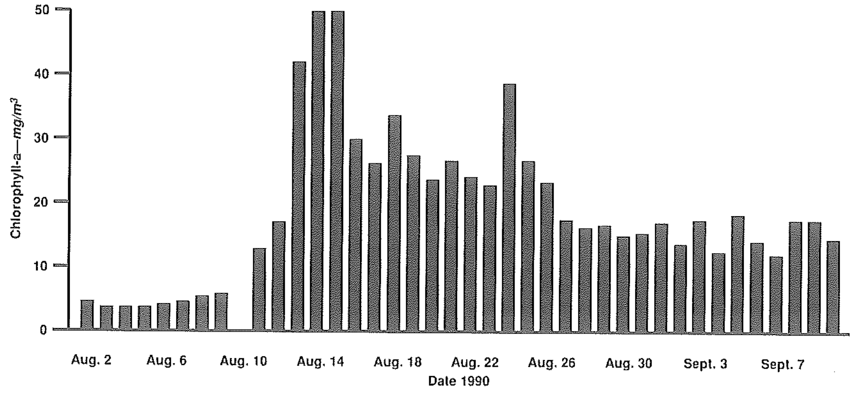

Figure 6. Average daily chlorophyll-a concentration during second *Hypnomonas* bloom cycle *(note Aug. 11 transition between lag and exponential growth phases; Aug. 10 hiatus caused by electrode calibration)*

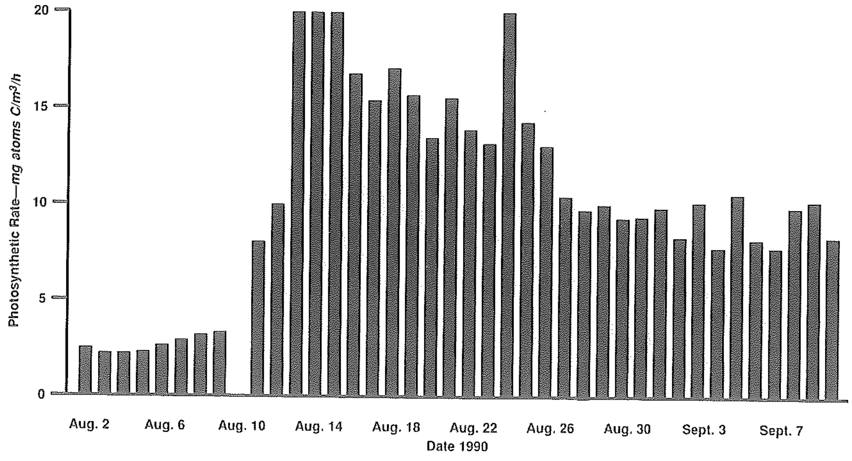

Figure 7. Average daily photosynthetic rate during second *Hypnomonas* bloom cycle *(note Aug. 11 transition between lag and exponential growth phases; Aug. 10 hiatus caused by electrode calibration)*

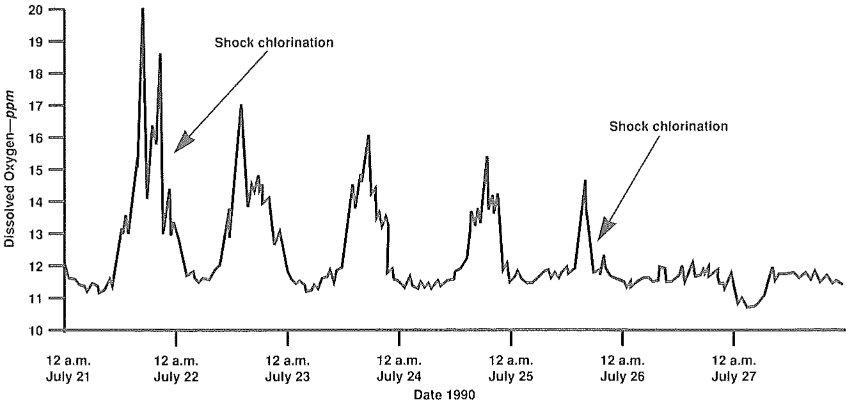

Figure 8. Daily time series of dissolved oxygen concentration, July 21–27,1990, tracks reduction in photosynthetic oxygen production following shock chlorination treatments of Silver Lake

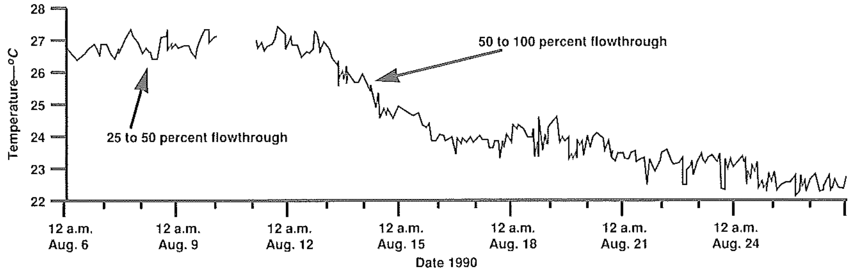

Figure 9. Daily temperature time series, Aug. 6–26, 1990, tracks effects of Silver Lake flowthrough adjustments *(Aug. 10 hiatus caused by electrode calibration)*

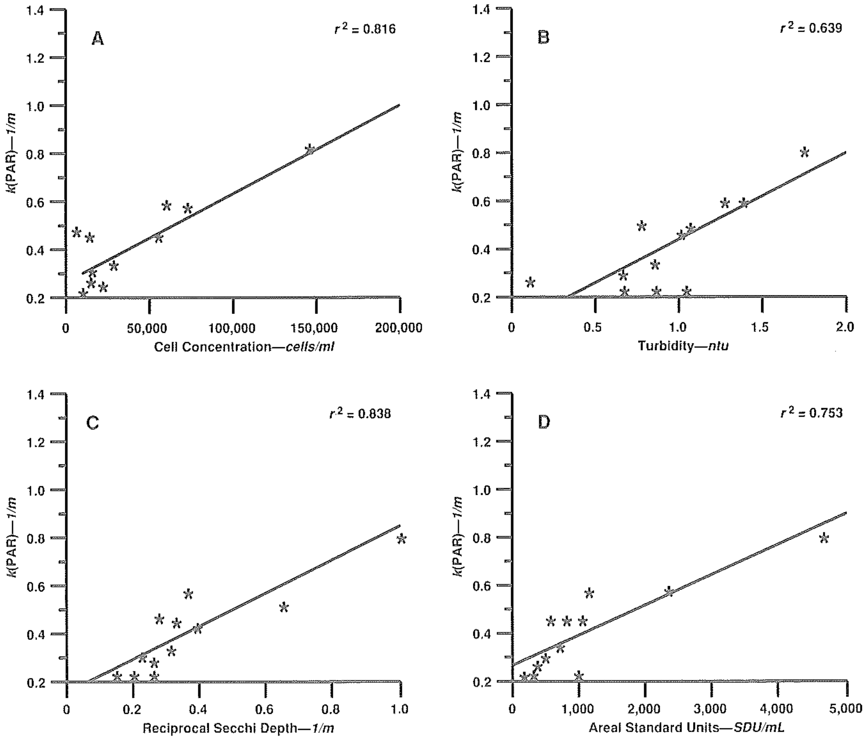

Figure 10. Linear regressions of *k*(PAR) on (A) cell concentration, (B) turbidity, (C) reciprocal Secchi depth, and (D) areal standard units

lag phase of an algal bloom warrant immediate inspection of the reservoir.

Treatment assessment

The REOS data link can be useful in tracking the effects of a reservoir treatment. The impact of shock chlorinations on the first algal bloom is apparent in real-time changes in DO (Figure 8). Temperatures fell when flows through the reservoir were increased in mid-August in an attempt to control the second bloom (Figure 9).

REOS validation

The variables that have long been included in weekly biological surveys as a means of assessing water quality and the current algicidal demands of Silver Lake are in broad agreement with the REOS1 data base. Although the weekly sampling period does not allow detailed temporal resolution, the same algal events detected by REOS1 are apparent in the routine measurements of phytoplanktonic cell concentrations, planktonic cell counts in areal standard units (asu), turbidity, and transparency (Secchi depth).

Although the chronology of these four algal indexes is qualitatively similar, the covariation among the four is not particularly close. Linear regression analyses of asu on cell concentration, turbidity, and reciprocal Secchi depth indicate considerable unexplained variance. Such variance about the regression may be due to lack of precision in the measurements, to fundamental differences in the variables themselves, or to a combination thereof. Linear regressions of *k*(PAR) on cell concentration (Figure 10, part A), turbidity (Figure 10, part B), reciprocal Secchi depth (Figure 10, part C), and asu (Figure 10, part D) exhibit a fair amount of covariation and support two conclusions—first, that reservoir status cannot be adequately assessed by a single variable; and second, that the precision of remotely sensed variables compares favorably with routine field measurements.

Conclusions

Since its deployment, REOS1 has provided reliable information on temperature, pH, DO, ORP, conductivity, solar radiation, primary production, and the concentration of chlorophyll-a at one location in Silver Lake. Economical solutions have been found for the hardware problems that took the prototype system off line approximately one day out of ten. The second-generation system is expected to be on line nearly 100 percent of the time.

During the summer of 1990, interpretation of the REOS1 data base was hampered by thermal and biological stratification of the water column. This unforeseen circumstance made it difficult to fully describe the dynamics of

TABLE 1
REOS decision matrix

Variable	Contributing Factors	Observed Conditions				
Chlorophyll-a*	1. Algal growth/death 2. Algal inflow/outflow	0	+	+	–	0/–
Photosynthesis*	1. Sunlight 2. Temperature 3. Nutrients	0	+	+	–	0/–
Transparency*	1. Resident algae 2. Suspended particles 3. Dissolved substances 4. Wind/waves	0	–	–	+	–
Dissolved oxygen†	1. Photosynthesis 2. Respiration 3. Mixing	0	0	+	–	0/–
pH†	1. Photosynthesis 2. Chlorine	0	0	0/+	0/–	0/–
Diagnosis		Stable	Bloom imminent	Bloom in progress	Bloom in decline	Unidentified particle load
Action		Routine operations	Inspect, treat	Inspect, treat	Inspect	Inspect

*9 a.m.–3 p.m. average: + = three consecutive increases >5 percent; 0 = no three-day trend; – = three consecutive decreases >5 percent
†Magnitude of diurnal fluctuation: + = increase over previous day >20 percent; 0 = no change from previous day; – = decrease over previous day >20 percent

the entire water column from a single depth and forced the repositioning of the mooring during the course of a bloom.

To overcome the stratification problem, REOS2 will deploy a set of three natural fluorometers (Figure 1). A new five-channel radiometer will correct for the contamination of the natural fluorescence signal by scattered solar radiation in shallow water and will be positioned at a depth of 1 m. A second will be placed at a depth of approximately 3 m and a third at approximately 8 m. This array should provide nearly complete coverage of natural fluorescence in the water column at Silver Lake, because the natural fluorometers are capable of measuring algal fluorescence through several metres of water and Silver Lake has a maximum depth of only 13 m. In deeper reservoirs, deployment of radiometers at the 50 and 10 percent light levels is suggested. In both deep and shallow reservoirs, PAR sensors provide full optical coverage of the overlying water column.

The combination of PAR sensors and natural fluorescence detectors is a strength in the REOS approach that lends sensitivity to the detection of chlorophyll bands wherever they occur in the water column. Benthic algal populations may be monitored by placing a radiometer close to the bottom. A REOS system should be applicable to a wide range of source- and finished-water reservoirs.

Because the beam transmissometer is sensitive to the settlement of suspended particles on the detector ports and because percentage of light transmission can be calculated from the radiometer PAR sensors, REOS2 does not include a beam transmissometer. The strobe fluorometer also provides redundant information and has been excluded from the REOS2 system.

The REOS1 data base clearly shows how rapidly an algal bloom can develop in an open reservoir. Though a bloom may be preceded by several days of declining water quality, control of a resident algal population can be lost in a single day. Under these circumstances, weekly surveys do not provide the monitoring resolution needed to prevent impairment of water quality. When operating under such tight time constraints, response time is also critical. Treatment must be available on demand. The REOS system promises to provide reservoir managers with the high-resolution data needed to detect and control nuisance algal blooms before water quality is aesthetically compromised.

Acknowledgment

Jay Negrin performed field validation and assisted in data analysis. Patricia Cascallar contributed to system design. C. Digby Morrow helped to design, build, and install REOS1. Edward Milligan and Marina Busatto provided support in the field and laboratory. Two peer reviewers provided helpul criticism.

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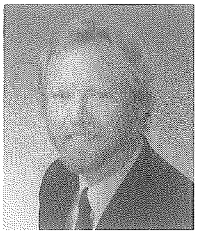

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