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Investigating Water Quality with a Towed Sensor Array

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PURPOSE: This technical note describes the use of a towed sensor array to conduct in situ water quality investigations and to identify water quality patterns in reservoirs and rivers. Guidelines are given for design and methodology, performance and efficacy are assessed, and potential applications are identified.

BACKGROUND: Limnological studies traditionally involve collecting water samples or in situ measurements at discrete depths at a limited number of sampling locations assumed to be representative of regions of a lake or reservoir. In small reservoirs, a single location may be used, usually at the deepest location or in front of the dam. Large systems demand more sampling locations, which are sometimes selected using statistical design criteria (Thornton et al. 1982; Gaugush 1986, 1987). Regardless of the approach followed, there is an implicit assumption that each sample location characterizes a region of the reservoir whose extent is limited by half the distance to the next sample location, often on the scale of kilometers.

Because important differences in water quality can occur over relatively short vertical and horizontal distances (e.g., Kennedy, Thornton, and Gunkel (1982)), any effective means of increasing the spatial and temporal resolution of sampling will greatly enhance the assessment of reservoir water quality. Moreover, developing modeling approaches that employ three dimensions will demand longitudinal, lateral, and vertical sampling for model support and verification.

New instrumentation enables rapid three-dimensional assessment of water quality based on several traditional water quality parameters. These instruments consist of programmable towed platforms, which enable a measurement sonde to interrogate a large number of depths and locations over a short period of time. In principle, their design is simple and consists of a controllable dive plane coupled with a platform that can carry a multi-parameter measurement sonde. This assembly is then tethered from a conventional watercraft and towed through areas of interest.

These towed platforms have been employed in marine environments (e.g., Rudnick and Ferrari 1999; Creed, Glenn, and Chant 1998; Barth 1997) where they were developed for data needs similar to those identified for fresh water. Marine versions usually are larger and heavier, and usually require substantial physical surface support. Instruments developed for marine systems have not, as a rule, been easily adapted for reservoir applications. Recently, new versions of these towed platforms have been developed that can be applied in reservoir systems. These are capable of deployment from many types of watercraft and can be operated manually or automated.

This new capability greatly increases the opportunity to describe water quality variation and distribution in highly variable freshwater systems. At the same time, it diminishes the potential error

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associated with discrete sampling. The ability to gather fine-scale data in three dimensions is an undeniable improvement in water quality monitoring, but this new technology also has limitations and specific requirements for application. This document illustrates these uses and limitations, as well as the potential applications to reservoir water quality studies.

METHODOLOGY

Towed Vehicle

Design and Construction. Most towed platforms capable of automated operation and data gathering have similar design features. These include a structure to house measurement instrumentation, a moveable dive plane allowing control and variation of vertical position in the water column, and additional stabilizing fins to control the motion of the platform as it is towed through the water. A means of data acquisition and management is also required.

Figure 1 illustrates the Minibat (manufactured by Guildline Instruments, Inc., Lake Mary, FL), the towed vehicle employed in this demonstration. The Minibat is a small platform suitable for one or two small instrument packages. Its size and weight allow deployment from watercraft as small as 6 m in length and by as few as two experienced personnel. The Minibat is constructed from stainless steel and consists of a dive plane (the wing), a frame in which instrumentation is mounted, a stabilizing fin assembly, and a remotely controlled servo-motor that varies the angle of the dive plane. A 50-m kevlar cable containing eight electrical lines was employed as both tether for towing and electronic control cable. The Minibat is manufactured as a single configuration, but the cable is available in a variety of custom lengths.

Figure 1. Guildline Minibat with Hydrolab water quality sonde attached

Operational Parameters. Several positional parameters are required for both automated and manual operation of the Minibat, and for subsequent data processing. These include:

- Bottom depth.
- Depth of towed platform.
- Depth of sonde.
- Cable length (distance behind tow boat).
- Latitude and longitude.
- Time/date.

This information is acquired automatically using an integrated GPS (global positioning system) and hydroacoustic depth-sensing equipment on board the tow boat. GPS time is used as the time standard for all instrumentation and the length of the cable is used to calculate the “setback” or actual distance of the towed platform behind the boat. Software supplied by the manufacturer (Guildline Instruments, Inc. 1999) allows water depth, depth of the platform, and GPS position to be continuously logged using a notebook computer. The same program also controls the operation and position of the Minibat, and graphically displays its progress in relation to the lake surface and bottom. A commercially available Apelco marine GPS unit with integral depth-sounding capability was interfaced with the Minibat controls and the computer software (Raytheon Electronics 1998).

Although only four of the eight control lines in the cable were used by the Minibat and its controls, this demonstration did not ‘hardwire’ the sonde to the remaining available control lines. Because the sonde is capable of internal logging, the decision was made to employ that capability, carefully matching the time base of both platforms to ensure accurate association of the two databases. This arrangement eliminated the need for more than one notebook computer during the deployment.

Deployment Methods. The Minibat was deployed manually for this demonstration from a 7.6-m MonArk boat powered by a 150-hp outboard motor. Because of the research nature of this demonstration, three personnel were employed: a boat pilot for the watercraft, a computer control operator, and a cable deployment person. In practice, and once the proper configuration of this system has been determined, the control operator should also be able to deploy the cable manually. As an alternative, a slip-ring-equipped manual winch for the kevlar cable is available at extra cost and should lengthen the life of the cable as well as increase the ease of deployment. This option is also available from the manufacturer.

The procedure for each demonstration deployment involved locating a suitably large and relatively deep area of the lake, then releasing the assembly from the moving (3-5 knots) boat while carefully unspooling the cable astern. Once the maximum cable length was reached, the terminated end was secured to a cleat near the stern. Towing was attempted at speeds varying from 3 to 10 knots. However, best results were attained at speeds of 3-5 knots.

Software Interface. The software employed to control the position of the towed platform in the water column is capable of allowing manual or automated vertical position control. The computer displays a graphical view of the track of the platform as its vertical position varies with forward motion. The computer display also contains control ‘buttons’ available for real-time adjustment of vertical position or the automated parameters.

The automated control features of the software were employed during this demonstration. To achieve proper descent and ascent behavior of the towed platform, the program parameters were custom adjusted for the Minibat configuration. Moreover, the Minibat was configured through careful application of trial-and-error adjustments to optimize the balance of the load and provide the desired towing behavior. For the purpose of this demonstration, the goals were to control the vertical position of the towed platform in the water column and to allow automated vertical variation (undulation).

New or modified sensor packages or changes to the study depths require careful testing of the configuration prior to deployment to ensure proper towing behavior. Once determined, however, the system behavior can be faithfully reproduced under similar conditions. Forward velocity was also an important component of performance, as is the manner in which the boat responds to the pilot. It is anticipated that each boat/platform/sonde system will require extensive testing to identify the best working configuration.

Water Quality Data Collection

Description of sonde. Preliminary evaluations of the Minibat's performance when transporting a payload employed a Hydrolab water quality sonde (Hydrolab Corporation, Austin, TX). However, a YSI model 9620 multiparameter sonde (Yellow Springs Instruments, Yellow Springs, OH) was selected for the data collection demonstration, since it offered an appropriate suite of water quality sensors. These included:

- Time/date.
- Depth.
- Temperature.
- Dissolved oxygen concentration.
- pH.
- Specific conductance.
- Chlorophyll fluorescence.

With the exception of dissolved oxygen and chlorophyll fluorescence, the sensors on this sonde were of conventional design. The dissolved oxygen probe used a design proprietary to YSI. Instead of the conventional continuous polarographic electrode, this technology employs a pulsed technology with predicted longer life for the electrode. The probe for chlorophyll fluorescence was also a YSI design, but incorporated conventional features of other fluorescence measuring devices, including a blue LED source as an excitation source and a photo-detector designed to preferentially detect the longer wavelengths associated with the in vivo fluorescence of chlorophyll.

Deployment method. The sonde was programmed for internal logging for these demonstrations using a notebook computer and software provided by the manufacturer (YSI, Incorporated 1999). All parameters were programmed to log at 1-sec intervals and options for data averaging or smoothing (e.g., running average) were disabled on the assumption that 'raw' data would better enable analysis of the final data set. Once programmed, the sonde was mounted inside the frame of the Minibat using cable ties to prevent vibration and a stainless quicklink to secure it in the frame.

The Minibat-sonde system was then checked onboard for signal continuity and control of the dive plane, then deployed overboard for the actual data collection.

Software interface. Because the sonde was programmed to log internally, the software interface for observing 'real-time' water quality data was not employed. Following retrieval of the Minibat/sonde assembly, the sonde was removed and downloaded using software supplied by the manufacturer (YSI, Incorporated 1999). Once downloaded, the water quality data logged during the deployment were available for analysis or display using the same software. This graphical display simultaneously plots all parameters as a time series (Figure 2). This is useful for quick identification of trends that may need further examination or for identification of depths or locations requiring additional deployments. The data were also exported in coma-delimited format allowing importation to other databases or statistical software packages.

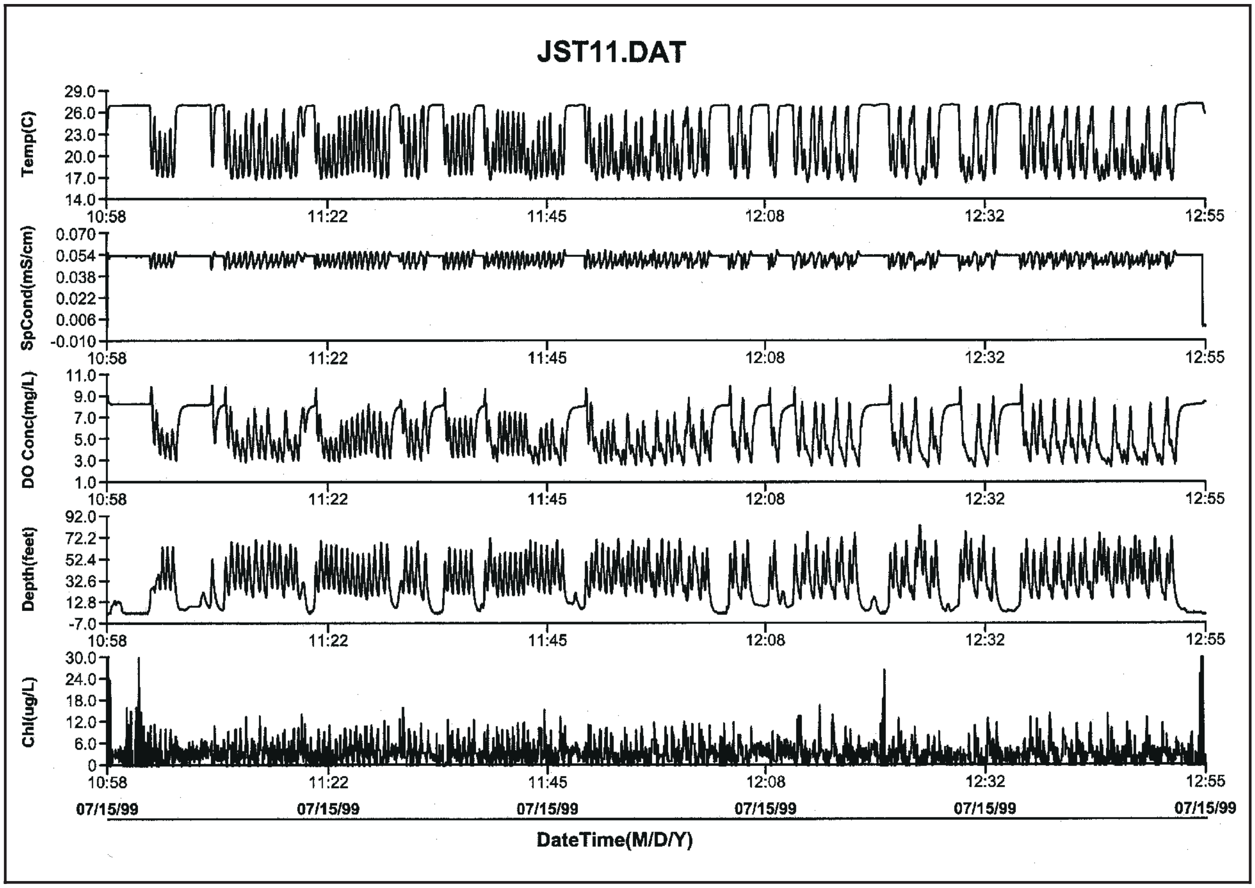

Figure 2. Example of temporal changes in temperature, specific conductance, dissolved oxygen, depth and chlorophyll concentration recorded by the YSI sonde and displayed using the Ecowatch software interface (YSI, Incorporated 1999)

APPLICATION

Deployment Strategies

Two basic strategies are appropriate for deploying the platform-sonde system; level flight, during which the system is maintained at a single depth, and undulating flight, for which the system is programmed to ascend and descend between pre-selected depths. In both cases, the deploying boat can follow transects (lateral or longitudinal) or predetermined courses designed to adequately cover a region of interest.

Data collected using the constant depth approach specifically allow characterization of a single depth. For example, if the depth of an interflow or of the metalimnetic zone is known, the towed platform could easily be used to collect data describing the spatial extent or variation within the depth stratum. The towed platform could also be used in this manner to follow a tracer known to occupy a certain depth stratum.

Undulating flight of the towed platform-sonde system allows depthwise data collection. Navigating a single transect (either lateral or longitudinal) would produce a two-dimensional ‘snapshot’ of water quality. Combining information obtained from two or more transects offers the opportunity to display data three-dimensionally. It should be noted that a depthwise subsampling of the data also allows identification of data collected at the same depth.

Field evaluations of the towed platform-sonde system followed two sample design strategies during demonstration deployments: varying or undulating the Minibat between upper and lower depth limits (a vertical range of approximately 25 m) along a longitudinal track that followed the thalweg of the reservoir; and undulating flight with repeated lateral transects throughout a region of the lake for the collection of data in three dimensions. Both strategies have potential application for a variety of limnological investigations.

Data Management

Application of this technology generates large quantities of multi-parameter data, and because it is possible to repeat a survey several times during one day, careful management of data sets is essential. Every precaution must be taken to ensure that collected data are entered into a data management system immediately following completion of surveys. Because data are spatially referenced and extremely time sensitive, even small time errors (a few seconds) can cause great errors in the location of water quality measurements. If the towed platform is in an undulating mode, these location errors are also manifested as serious errors in depth placement. Great care must be taken to correctly reference time and position in order to successfully interpret data during the analysis phase.

Two data logging configurations for the towed platform-sonde system are currently available. First, the control software and position data are logged on a real-time basis into an onboard computer. In addition, it is also possible to directly connect the measurement sonde to an onboard computer. In this configuration, both data collection processes occur simultaneously and, with additional interfacing, the system can be operated in an automatic manner, merging water quality, and control and position data into a single data file. This approach is technically challenging but possible and it avoids some potential errors associated with the second approach (see discussion below).

The second approach, as used for this demonstration, involves separate data collection efforts (i.e., independent logging of control and position data, and water quality data) and the merging of resulting data sets during the data management phase. In this approach, the sonde acts as the second data collection platform and its clock is set to match the time given for the GPS system. The second data collection platform is the onboard computer that logs control and position data. Each of the two platforms can export a file that is in a format capable of importation to database and statistical software. Time for each of the two data sets is used to match water quality data with control and position data. Because measurement of depth is redundant (Minibat control and sonde), the two measurements serve as an independent check on this data merging procedure, since depths should also match at each time increment.

GPS Post-processing

Geographic position, bottom depth, depth of towed platform, and time/date are contained in a file created by the software supplied by the towed platform manufacturer. These data can be used to create plots for display of the tow history or exported to a database for further analysis. However, there is intentional error in the position data, which must be corrected through post-processing. The process is relatively simple and consists of downloading the position data for a fixed ‘community base station’ and then subtracting out the variance for the community base station. Post-processing the data in this manner will ensure increased position accuracy.

PERFORMANCE

Towed Vehicle

Hardware selection. The type of boat, the choice of water quality sonde, the length of the cable, and the means of deployment from the boat are all important considerations. It is not recommended that a towed platform be deployed from a small craft. This demonstration employed a 7.6-m, metal-hulled boat with a cabin and 150-HP motor. While this boat was more than adequate for demonstration trials, this experience indicates that the deployment could have been equally successful using a boat as small as 5.0-5.5 m in length. The mass of the hull and the power of the engine will be the primary factors contributing to a successful deployment. If deployment is accomplished manually, sufficient deck space for proper handling of the cable will be required. The kevlar cable is very strong but can be damaged if twisted or kinked while supporting the load of a towed platform.

The size and weight of the water quality sonde are also important factors influencing vehicle performance. Initial trials showed that a heavy sonde tended to unbalance the towed platform and influence controllability. Successful deployment eventually required compensating for buoyancy with flotation attached to the sonde to render it neutrally buoyant.

Cable length is specified during the construction of the towed platform and is determined by the maximum depth desired during deployment. Longer cables can still be towed at shallow depths but are a cost consideration. This demonstration employed a 50-m cable that was sufficient to carry the platform to depths of over 40 m, although most data were collected from depths less than 30 m.

The towed platform was deployed from the stern on one side of the boat. Although a more balanced position would have been from the center of the stern, the side position avoided interference of the cable with the outboard engine. Once in the water, the platform must be kept in motion during all phases of deployment, including during release and retrieval, for it to maintain vertical position.

Control surfaces and initial settings. The configuration of the towed platform is critical for successful deployment. Care must be taken to ensure that once at depth, the platform can successfully return to the surface. Trials for each new configuration are necessary to optimize the relative positions of all control surfaces, including the main dive plane and the angle of the stabilizing fins. Approximately one full day was required during this demonstration to optimize these settings by trial and error. Once the physical configuration is set, the automated control settings can be optimized based on the requirements of the study.

Ease of use. While it is essential to optimize the vehicle’s physical configuration and automated controls for successful operation, additional considerations were identified during this demonstration trial. The towed platform tends to dive at a steeper angle than during its ascent. The potential hazards resulting from unexpectedly rapid dives, particularly in shallower waters, are obvious. This effect, while disconcerting initially, was partially controlled by careful configuration of the dive plane angles, the sonde balance, and the control settings. An additional means of controlling this problem is to set the angle of stabilizing fins to minimize the tendency to dive or to vary the attachment point of the tow cable, thus affecting the balance.

Submerged objects such as standing trees, old bridges, etc., pose another potential hazard in reservoirs. The software can be set to avoid the bottom but this control depends on the depth sounder to correctly resolve such objects. It is possible for the bottom elevation to rise suddenly and for the controls not to be able to respond quickly enough. Conservative operation is recommended, whereby the operator carefully monitors bottom depths and the behavior of the towed platform, ready to manually override the controls and bring the unit to the surface if necessary. The control software and hardware both allow this capability.

Balance and stability. The towed package is best deployed for the first time with little or no load attached. This allows new operators to concentrate on learning the system and how the platform tends to behave with no load. By incrementally adding and changing loading on the towed platform, operators can identify the loading factors to which the platform is most sensitive.

Once the operating parameters have been identified, other factors such as forward velocity can also affect the behavior of the system. Greater velocity made the towed platform perform with less stability. Programmed increases in depth proceeded with disproportionately greater rates and the programmed maxima and minima for depth tended to be overshot under greater forward velocity. Rapid changes in depth were detrimental to water quality measurements using instruments with slow response times (see below).

Control software contains a number of adjustable parameters that modify the rate of change for ascending and descending functions. Relationships between some of these parameters are not intuitive, but much of the control is available by modifying just a few of the most important parameters, particularly the upper and lower depth limits. Some control is possible through management of boat speed, although below a critical velocity (approximately 3 knots) the towed platform did not respond well, or slowly at best. The demonstration data were gathered at speeds of approximately 4 knots.

As expected for hydrodynamic systems, beyond some limit the behavior of the system is unstable. This instability is manifested as excessively steep ascents and descents. In extreme conditions system instability concluded with the towed vehicle becoming inverted with complete loss of control. A more forward position of the tether attachment seemed to result in greater stability. The control configuration supplied from the factory is a recommended starting configuration.

Under normal operation, descents to greater depths tended to occur more quickly than ascents to the shallower depth limit. Figure 3 displays data collected using an optimized configuration with specified depth limits of 5 and 20 m. Figure 3 is a time-series plot of towed platform depth. Assuming constant velocity, distance could be substituted for the time axis. Ideal behavior would have been represented by a sinusoidal pattern exactly meeting the 5- and 20-m depth limits. As shown in the lower panel of Figure 3, the control program depth limits were approximately met, although they were usually exceeded or ‘overshot.’ This tendency was more severe if the forward speed of the watercraft was increased without some compensating modifications to the control program. Figure 3 also shows that the descent to greater depth occurred at a rate nearly twice as great as the ascent to the shallower depth. This important factor greatly affected data analysis.

Except under very controlled forward velocities, a constant depth for the towed platform was difficult. Constant depth was more easily maintained for shallower depths owing to the steeper tow angle if the platform was at a greater depth. Constant depth was relatively easy to achieve either automatically or manually for depths to 15 m and at speeds of approximately 3 to 4 knots.

Water Quality Sonde

Sensor response to changing water quality conditions was evaluated in J. Strom Thurmond Lake. This was accomplished by comparing data collected from a stationary boat on the previous day using traditional profiling techniques and those collected near the same location using the Minibat-sonde system. Resultant profile data for selected variables and corresponding data collected during both ascent and descent of the Minibat-sonde system are presented in Figure 4. It should be noted that profile data for chlorophyll concentrations were not collected.

The temperature sensor responded relatively rapidly with changes in depth; however, the slower rate of ascent allowed more accurate estimates than those obtained during the more rapid descent. The result was a pronounced hysteretic effect (Figure 4). Differences between the ascending estimates and profile data may reflect temporal changes or may be due to the averaging of temperatures over short depth intervals (due to the ascending movement of the sonde).

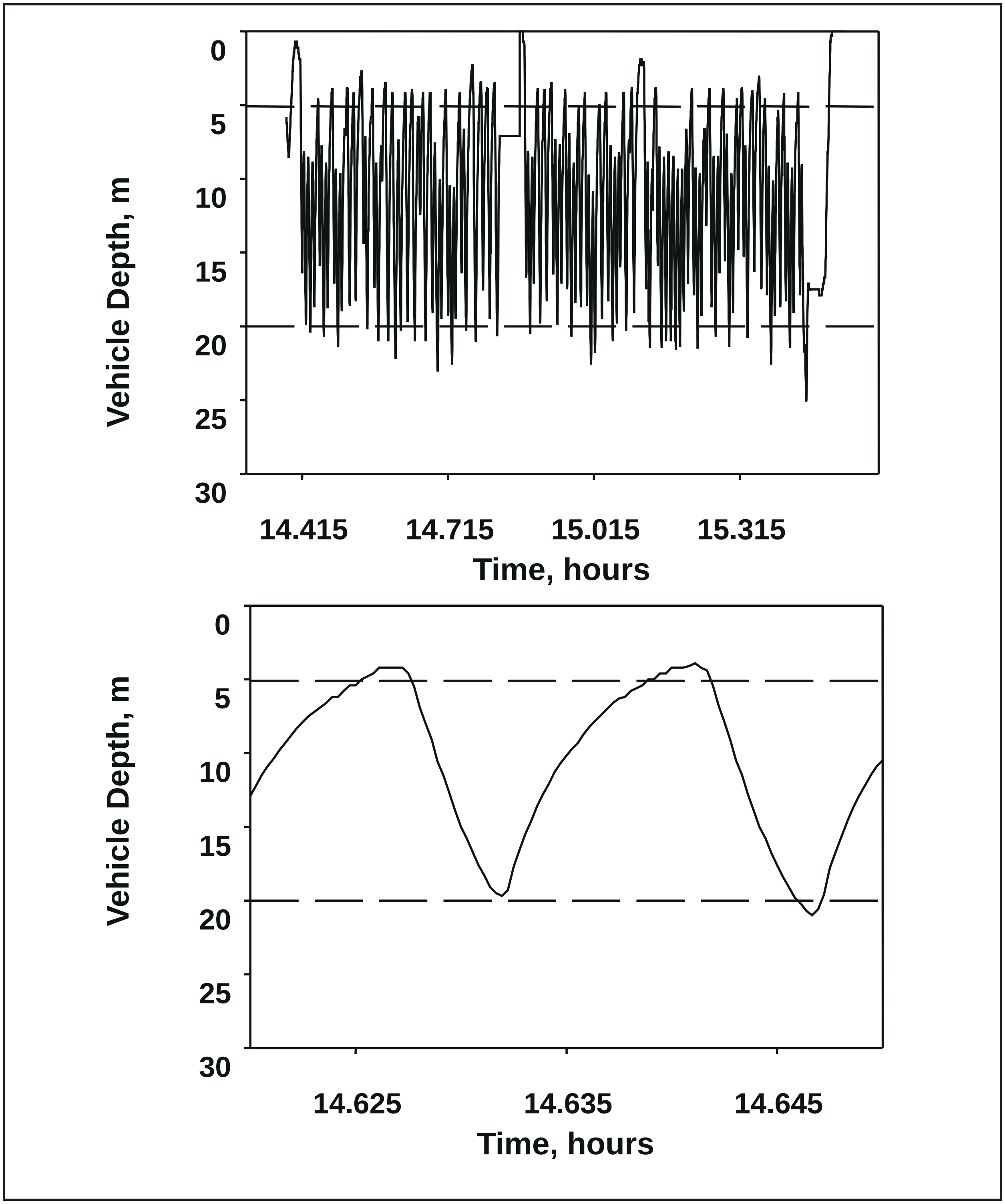

Figure 3. Changes in vehicle depth during a 1-hr deployment of the Minibat in J. Strom Thurmond Lake (upper). Changes in vehicle depth are also displayed on an expanded scale (lower) during two cycles of ascent and descent. Ascending and descending rates averaged 0.53 m/sec and 0.92 m/sec, respectively

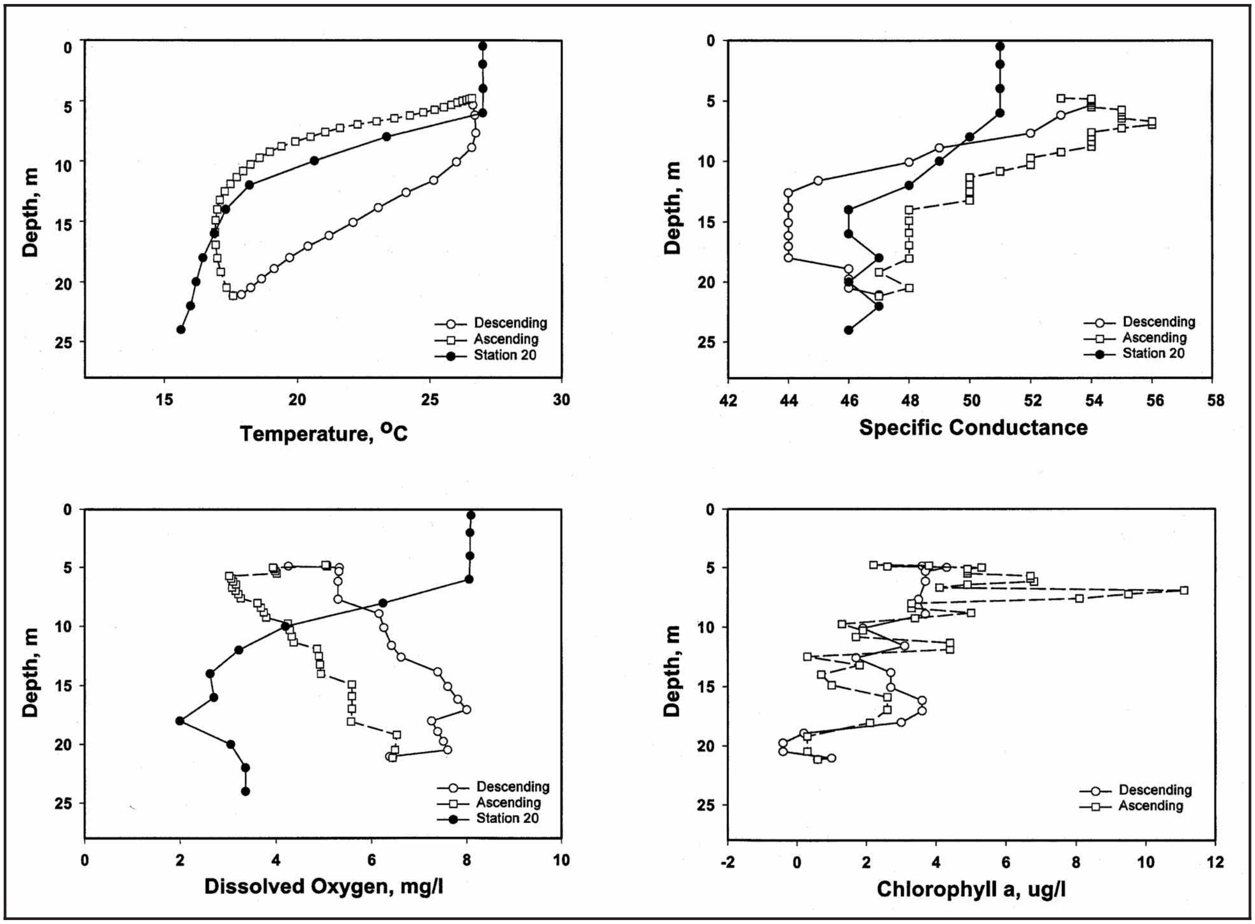

Figure 4. Correspondence between temperature (upper left), specific conductance (upper right), dissolved oxygen (lower left) and chlorophyll concentration (lower right) measured in profile at Station 20 in J. Strom Thurmond Lake and using the YSI sonde towed on the Guildline Minibat in the vicinity of Station 20. Profile data for chlorophyll concentration were not collected. Values measured during ascent and descent are identified by squares and circles, respectively

The specific conductance sensor responded rapidly to changing conditions and is well-suited to the towed platform approach to water quality studies (Figure 4). It is reasonable to conclude that the principle of the measurement of specific conductance and the fact that specific conductance is not highly variable resulted in close correspondence with the profile data. While there are clear differences between data collected during descending and ascending data, both are within ±2 µS of the profile value. This is within the range of variability commonly observed for such instruments.

Correspondence between values of dissolved oxygen concentration measured during profile sampling and those obtained by the Minibat-sonde system on either ascent or descent was limited (Figure 4). The slow response of the dissolved oxygen probe was clearly a severe limitation to the collection of accurate data in rapidly changing environments. The rate at which the towed platform moves between regions of differing dissolved oxygen concentration far exceeded the rate at which the sensor could respond. Current technology in the design of dissolved oxygen sensors does not provide a sufficiently rapid response for such applications. To compensate for this lack of rapid response, either much slower rates of change in depth or tows at constant depth must be employed if water quality is to be described accurately. In situations requiring dissolved oxygen characteristics in three dimensions, the towed platform can still be useful, but its rate of ‘undulation’ would have to be greatly decreased. However, multiple tows at different depths may be the best approach to data collection in such situations.

Chlorophyll fluorescence could not be compared to profile data since the latter data were not collected. Alternatively, ascending and descending data were compared to assess sensor performance under the assumption of similarity between both types of data. While exhibiting considerable variability, there was strong correspondence between consecutive ascending and descending fluorescence profiles (Figure 4). A rapid response would be anticipated since optical sensors do not require a period of equilibration.

For most of the data comparisons, although the ‘undulation’ of the towed platform is capable of rapid ascent and descent, its performance is capable of exceeding the capacity of water quality sensors to respond rapidly enough. This is particularly true for dissolved oxygen sensors. Chlorophyll fluorescence, conductivity, and depth responded most quickly. These parameters could reliably respond to rapid changes in water quality conditions. It is assumed that any other optical sensor such as turbidity could, in theory, also respond quickly, although actual field tests would still need to be performed.

EXAMPLE APPLICATIONS

Longitudinal Transect

The Minbat-sonde system was first demonstrated in R. B. Russell Lake, SC and GA. Deployment involved towing the system along a longitudinal transect extending from the forebay to a location approximately 9 km upstream (Figure 5). The transect closely followed the thalweg, although the flexibility of the approach would have allowed a more circuitous route if necessary. Traversing the transect resulted in the collection of over 50 ascending profiles and required approximately 1 hr. Based on prior experiences, the same duration of effort would have allowed traditional profile data collection at only three discrete locations.

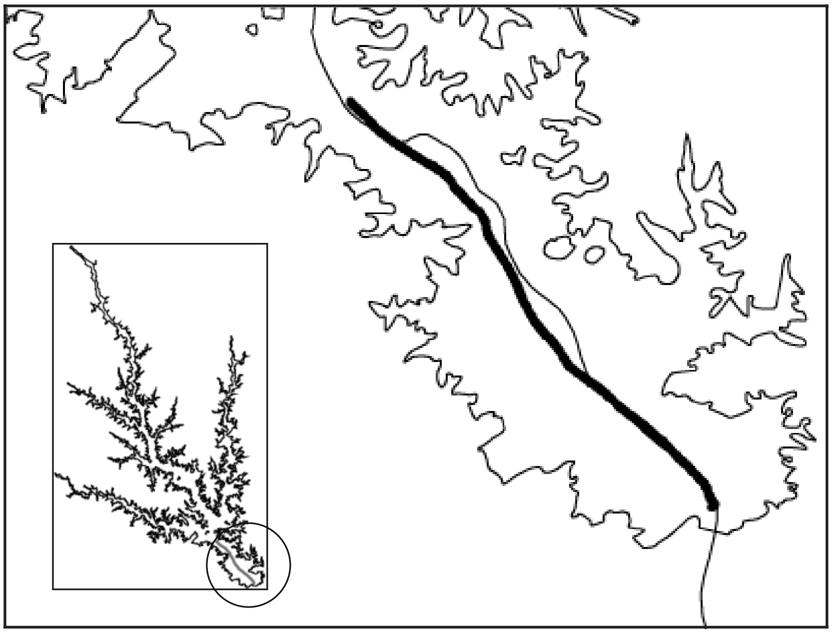

Figure 5. Longitudinal transect (bold line) along the thalweg (thin line) in the downstream reach of Richard B. Russell Lake. Locations based on GPS navigational information

Data collected during this effort illustrate the potential advantages of the approach. Temperature and chlorophyll concentrations were "mapped" by interpolating observations collected during the deployment using the contouring program Surfer (Golden Software, Inc. 1995). As was noted above, only data for periods of ascent were used to reduce errors associated with slow sensor responses during descent. The data allowed depthwise description of the thermocline and associated concentrations of chlorophyll along the transect (Figure 6).

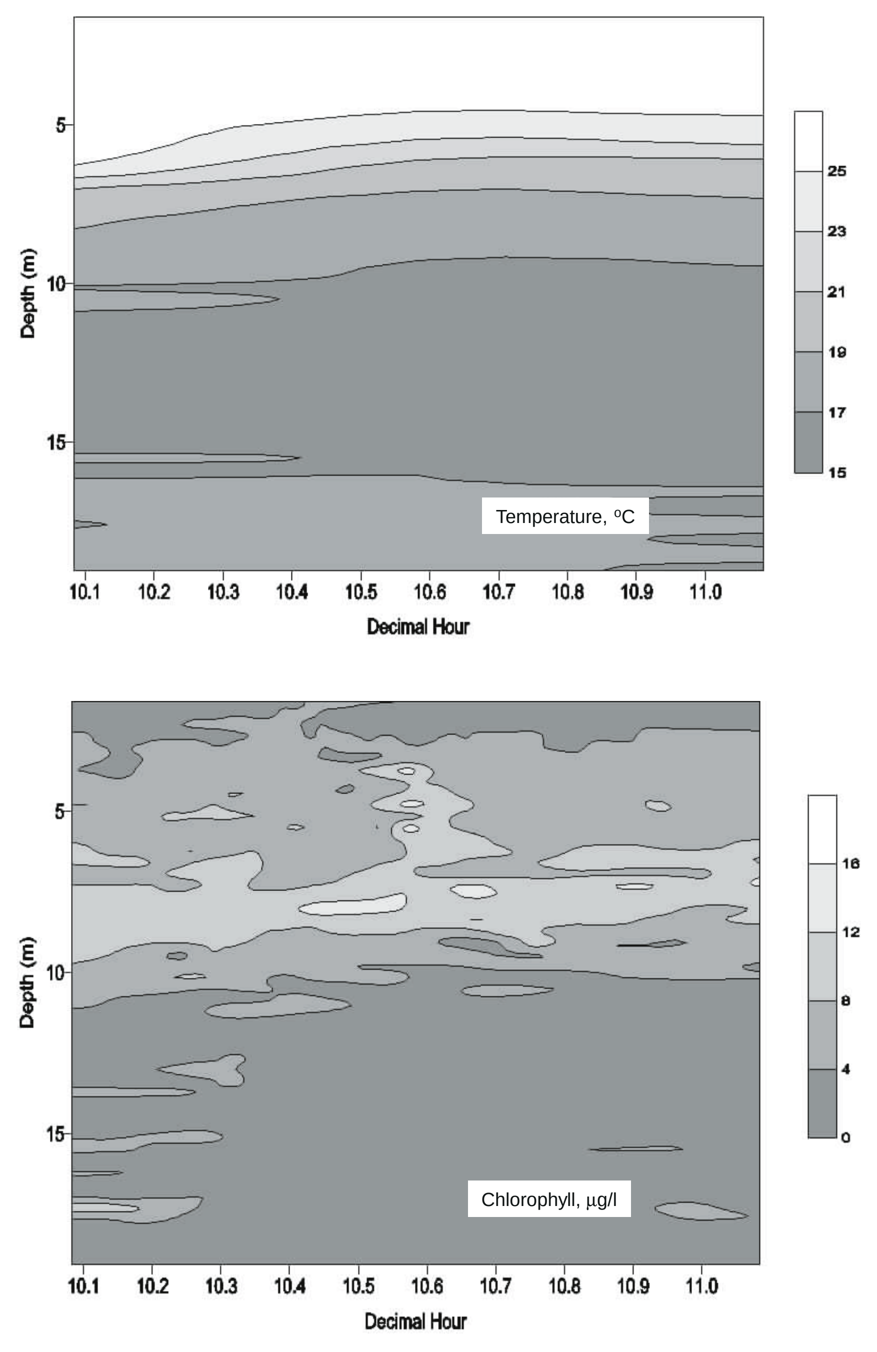

Figure 6. Depth distribution of temperature and chlorophyll concentration along a longitudinal transect in the downstream reach of Richard B. Russell Lake

Lateral Transects

The utility of the Minibat-sonde system for collecting three-dimensional water quality data was demonstrated in the forebay of J. Strom Thurmond Lake, SC. The sample design involved the establishment of a series of lateral transects (Figure 7) and undulating movement by the Minibat-sonde system. Automatic depth control was selected for the purposes of the demonstration and the shallower near-shore or littoral zone areas were not included.

Figure 7. Lateral transects (bold line) in the downstream reach of J. Strom Thurmond Lake. Locations based on GPS navigational information

Resultant data were subsampled by 1-m depth strata for ease of analysis using Surfer. The depth ranges were selected to provide adequate data density. In Figure 8 the various interpolated estimates of the data distributions are displayed. In this example, clear trends in the spatial (both vertical and horizontal) distribution of chlorophyll fluorescence were observed. While limited to a visual comparison, there is marked correspondence in the locations of the chlorophyll maxima between depth strata, indicating a degree of internal consistency assessment. These data document the occurrence of important water quality trends in this region of the lake. These include pronounced vertical stratification and horizontal heterogeneity of phytoplankton communities.

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> *www.wes.army.mil/el/elpubs/wqtncont.html*

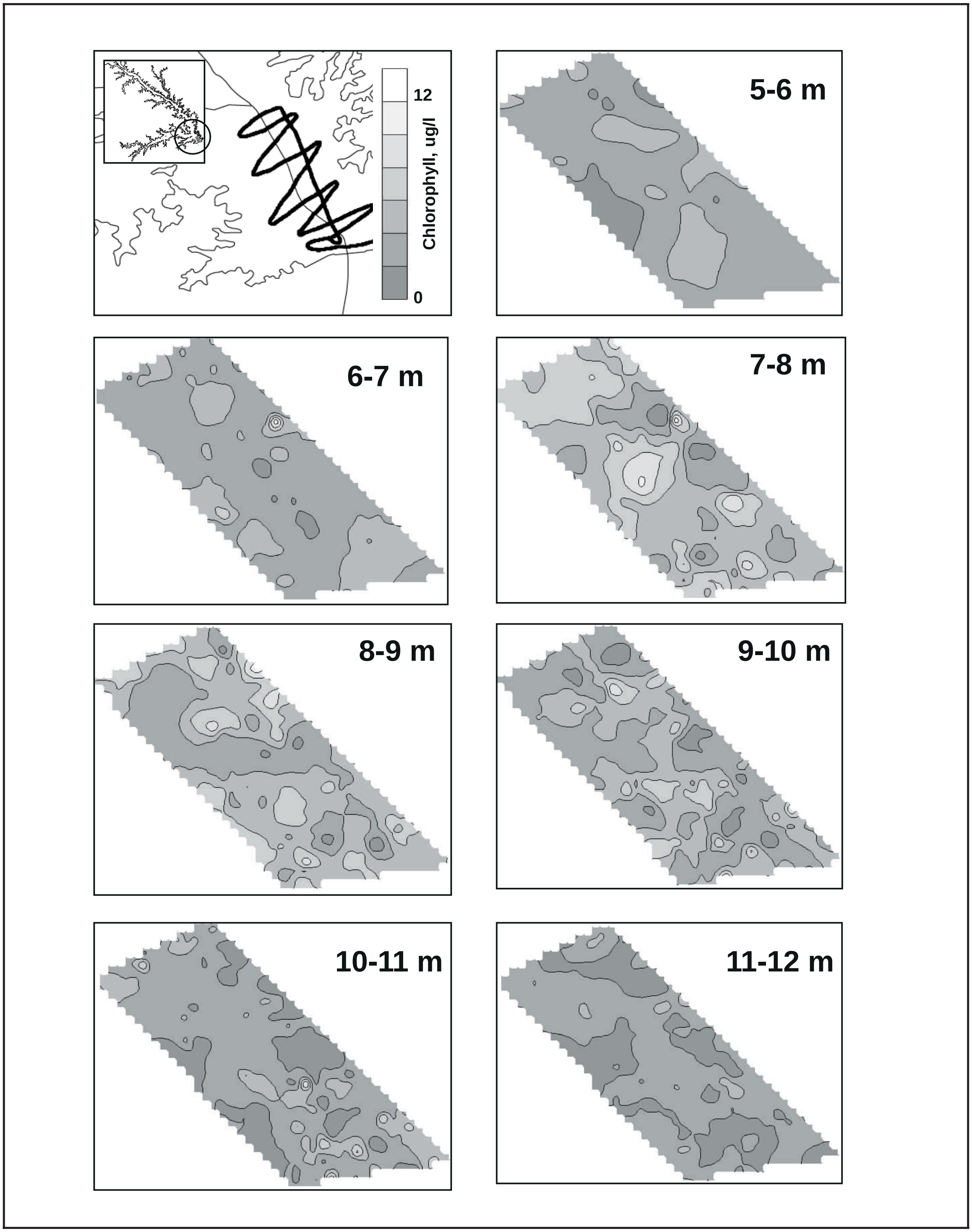

Figure 8. Navigational track on J. Strom Thurmond Lake (upper left), and the distributions of integrated chlorophyll concentrations for the 6- to 7-m, 7- to 8-m, 8- to 9-m, 9- to 10-m, 10- to 11-m and 11- to 12-m strata

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