Interactive Technologies for Collecting and Visualizing Water Quality Data

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Abstract: *New technologies for remote sensing of the environment coupled with interactive visual displays of information have made data on water quality more accessible to resource managers and to the general public. We have developed a robotic water-sampling device known as the "Remote Underwater Sampling Station" that transmits near-real time data on lake temperature, oxygen concentration, electrical conductivity, turbidity, and pH at programmed depths in the water column to an Internet Web site. A suite of interactive tools is available over the Web to view and manipulate vertical water-quality profiles collected by these units at various temporal resolutions. The tools provide for static and animated two- and three-dimensional views of the data. The integration of these hardware and software technologies has proved valuable for education and for providing the public with interpretable data on the water quality of their lakes.*

Introduction

The water quality of our lakes, rivers, and streams is of primary importance to the public and is the focus of numerous federal, state, and local agencies. Innumerable citizen and governmental programs are focused on monitoring and maintaining water quality, and massive amounts of data are collected and archived through efforts such as the Environmental Protection Agency (EPA) STORET (STOrage and RETrieval) program. Raw data by itself, however, is of little value to the general public, and the skills of even exploratory data analysis (*sensu* Tukey 1977) tend to be outside the domain of typical resource managers. It is possible, however, to convey complex and massive amounts of data with two- and three-dimensional graphics, interactive data applications, and animations (Tufte 1997). This field of information processing, which goes beyond the simple graphical display of data, is generally known as data visualization.

Recent advances in remote sensing technologies coupled with data visualization tools have the potential to allow scientists and resource managers to more easily understand and respond to the increasing flow of water-quality information. These advances also have the capacity to bring water-quality data and interpretive information to a much broader audience, with the dual objectives of increased public education and increased involvement in issues of local resource management. This paper describes a new water-quality remote sensing technology known as the "Remote Underwater Sampling Station" (RUSS) and a suite of data visualization tools designed toward visualizing the spatial and temporal dynamics of important water-quality parameters. These tools represent interactive methods by which water resource managers, students, and the general public can manipulate, interpret, and understand large, complex data sets on water quality.

The RUSS units and data visualization tools are integral parts of two ongoing education projects. Water on the Web (WOW) is a National Science Foundation (NSF)-funded initiative to develop Web-based high school- and college-level science curricula around data collected by the RUSS units in four Minnesota lakes. Lake Access is an EPA-funded project to deliver real-time water-quality information and interpretive information on Minneapolis metropolitan lakes to the public, with provisions for providing public feedback back into the decision-making process. In both WOW and Lake Access, RUSS technology, data visualization tools, and interpretive information are integrated to allow students and the public to understand and respond to real-time changes in water quality.

Remote Underwater Sampling Station Technology

Remote Underwater Sampling Stations were developed at the Natural Resources Research Institute of the University of Minnesota–Duluth, in cooperation with a number of departmental and commercial partners. Now produced and distributed by Apprise Technologies, Inc. (www.apprisetech.com), the RUSS unit represents the state of the art in water-quality sampling technology. The unit consists of a floating platform containing solar panels, a series of deep-cycle batteries, and an on-board computer and communications package (Figure 1). A data cable connects the computer to a combination leveling device and sensor package that floats freely below the platform. A buoyancy compensation unit within the leveler is used to move the sensor system up and down the water column; the leveler can sample at user-specified intervals to depths of 100 m with a precision of 0.2 m of a target depth. The leveler is designed to accommodate standard water-quality sensor packages (e.g., Yellow Springs Instruments© or Hydrolab© sensors). The sensors transmit data via the com-

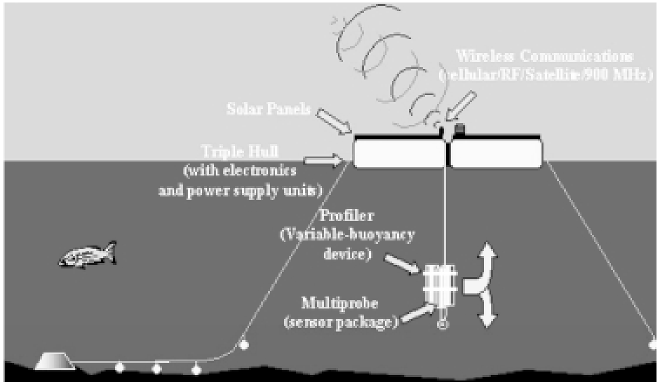

Figure 1. Schematic of the Remote Underwater Sampling Station.

munication cable into a memory buffer within the on-board computer, where it can be downloaded on demand via a combination modem/cell phone. RUSS units are thus able to provide near real-time water-quality data at user-specified sampling intervals, virtually independent of lake conditions (Water Environment Federation 1997, Betts 1998).

Our RUSS units currently sample five critical water-quality parameters: pH, conductivity, turbidity, dissolved oxygen, and temperature. The only effective time limitations to sampling frequencies are the times required for the sensor unit to descend to a specified depth and for the individual sensors to equilibrate. In reality, the relevance of the data is specific to the event being sampled; turbidity, temperature, and electrical conductivity might be relevant on a daily basis, whereas oxygen profiles may change hourly. The appropriate sampling interval depends, therefore, on the question being asked. The RUSS units currently in place as part of the WOW and Lake Access projects have been initially programmed to collect 1-m interval profiles at 4- and 6-hour intervals, respectively. The units are active 24 hours a day, 7 days per week, during open water and ice-on lake conditions; units are only removed from the lake during freezing and thawing conditions.

RUSS units are currently deployed on five Minnesota lakes, representing a wide range in size, morphometry, depth, and seasonal dynamics (Figure 2). Ice Lake is a small (16 ha area, 16 m depth) lake in a residential district of Grand Rapids, MN. Grindstone Lake, in contrast, is nearly 50 m deep and supports a cold-water fishery. Three units are located in the suburban Minneapolis region, two in contrasting bays of Lake Minnetonka and one in the largely agricultural watershed of Lake Independence. The differences in size, morphometry, and surrounding land use among these lakes provide a unique opportunity to compare and contrast fine-scale temporal dynamics in water quality variables.

Figure 2. Locations of the Water on the Web and Lake Access RUSS units.

Data stored on the RUSS computer is transmitted on demand to a data directory on the WOW server (http://wow.nrri.umn.edu/data). A resident program on the server parses and evaluates the data for internal consistency (e.g., ensure that the appropriate numbers of variables and depths are present in the data file). Data are stored in its native ASCII format, in a spreadsheet format, and are added to a comma-separated value data archive. Data are also incorporated into an object-oriented database for access by customized data visualization utilities. This use of multiple formats allows the data to be accessed with a variety of tools ranging from simple visual inspection of the raw data to analysis by standard spreadsheet and statistical software and to the more advanced analytical tools described below.

The ability to collect full-lake profiles several times per day coupled with the diversity of lakes sampled by Lake Access and WOW provides a rich data set for the development of high school- and college-level curriculum exercises, as well as a set of baseline data for resource managers monitoring trends in lake-water quality over time. However, the sheer amount of data generated over a season for each lake has raised new issues of data management, quality assurance, and visualization that are not a problem with the monthly or biweekly sampling protocols characteristic of traditional lake monitoring programs (Barten 1997). For this reason, we have developed a suite of data visualization tools that allow interactive manipulations of the data and are collectively known as DVT-Interactive.

DVT-Interactive: Data Visualization Tools for Exploring Water-Quality Data

DVT-Interactive consists of a set of four applications that can be used to explore lake data as they vary with depth and over variably sized time slices. The applications are coded in the Java programming language to allow the programs to run on a wide variety of platforms, including Windows 95/98/NT, Unix/Linux, and Macintosh. In reality, we have found that not all platforms are fully compliant with Java specifications but expect that this will

Lake Access Live: Latest Surface Readings

	Date/Time	Temperature	Oxygen (mg/L)
Lake Minnetonka - Halsted Bay	WED 4/12 06:03	45.3 °F	9.7
Lake Minnetonka - West Upper Lake	WED 4/12 06:06	48.3 °F	10.5
Lake Independence	WED 4/12 00:03	44.4 °F	13.6

Figure 3. Lake Access–Live. A display of latest surface conditions for three lakes situated in the suburban Minneapolis region.

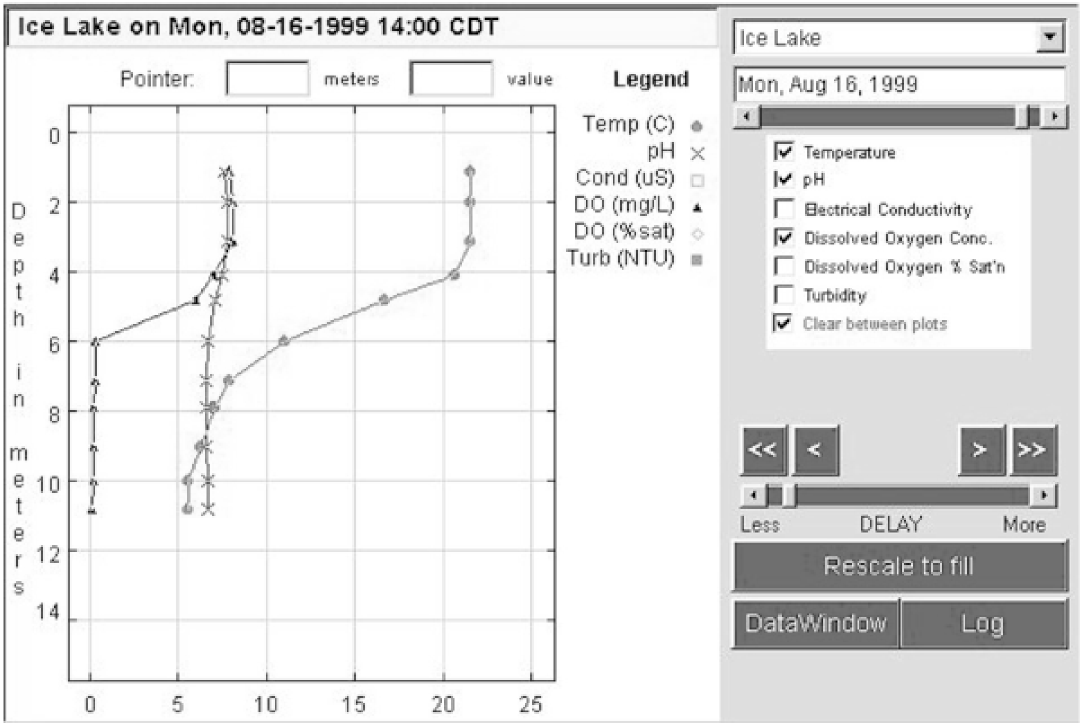

Figure 4. Screen capture of the Profile Plotter.

change as standards become more fully developed. These utilities exist both as applets that can be run over the Web and as downloadable executables that can be run locally.

Lake Access–Live: Near Real-Time Display of Numeric Data

Lake Access–Live is a simple utility developed for Lake Access that provides live data feeds to a Web site. A Java program monitors the data directory for new data, selects the most recent data from selected fields (currently, surface temperatures and surface oxygen readings), and embeds these data into a GIF image posted on our Web site http://www.nei.umn.edu/cmpact (Figure 3). The image is updated hourly.

Profile Plotter

The Profile Plotter is a utility that allows a user to plot a variable with depth. Limnologists typically display data in the form of lake profile plots, in which the upper end of the Y-axis represents the surface of the lake and the values of selected variables are plotted along the X-axis. Because four to six profiles are acquired per day, a utility was developed to allow a user to "step through" the data sets and observe how various factors (such as temperature) change on a daily or seasonal basis. The animation of time-series data is a powerful and intuitive technique for visualizing trends in numeric data (MacEachren and DiBaise 1991, MacEachren et al. 1997). The Profile Plotter contains a control panel that allows the user to select a lake, a date, and which variables to plot (Figure 4). The key feature of the Profile Plotter, however, is the ability to animate the profiles. The single- and double-arrow VCR controls in the center of the control panel allows the user to move forward or backward through individual data sets (single arrow) or lets the program automatically step through the data sets. In the automatic option, the user can set the rate at which the "movie" will play.

Color Mapper

The Color Mapper is an extension of the Profile Plotter described above. It allows one variable to be mapped as a color ramp in the background while a second variable is superimposed as a line plot. Figure 5 shows the temperature mapped in the background with oxygen concentration as a line plot and illustrates a striking depletion of oxygen below the thermocline. The temperature color ramp follows an intuitive sequence: red representing the warmer temperatures and blue the cool temperatures. As with the Profile Plotter, the Color Mapper can step through data sets using either a manual or an automatic format.

The translation of point data into a color ramp requires the ability to interpolate values vertically between data points. We use a simple linear interpolation to predict values at intermediate points between the 1-m depth samples. There are also provisions for extrapolating from the shallowest reading (1 m below the surface) to the actual surface, and from the deepest reading to the bottom of the lake. Under frozen lake conditions, the surface temperature is set to 0°C, and ice thickness can be superimposed onto the image.

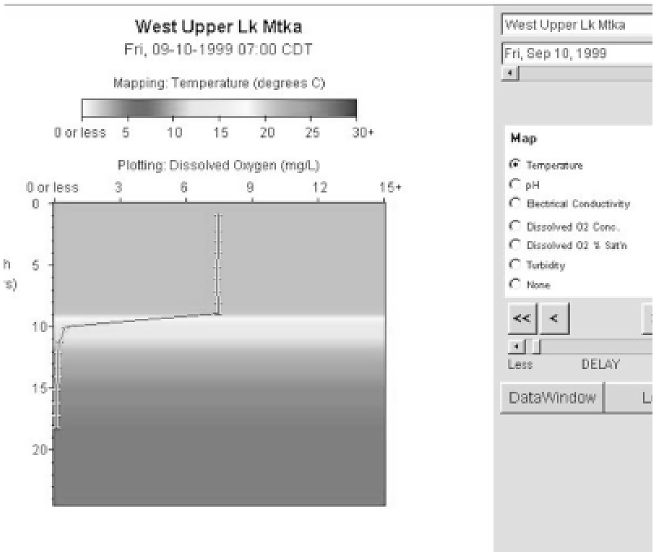

Figure 5. Screen capture of the Color Mapper.

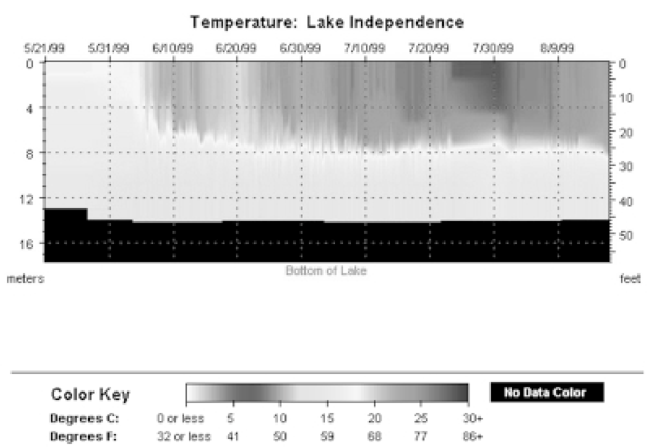

Figure 6. Seasonal temperature map of Lake Independence produced by the DxT Profiler.

Depth x Time (DxT) Profiler

The final utility in the DVT-Interactive suite allows the creation of depth x time plots, as shown in Figure 6. The DxT Profiler allows a user to select specific time windows for plotting a selected variable by depth and time. The Profiler is quite flexible, allowing the user to set the time window for the display, add grid lines, show the actual data points, and perform various degrees of interpolation (Figure 7). The DxT Profiler interpolates both vertically (depth) and horizontally (time). For both, the user can manually set the range of depths or hours over which the interpolations will occur. Currently, this utility is used to create GIF images for posting to our Web site http://www.nei.umn.edu/cmpact; a future version will be an interactive tool that allows users to illustrate temporal trends at varying levels of resolution (e.g., hourly, daily, and seasonal).

The DxT Profiler requires both vertical (depth) and horizontal (time) interpolation. The interpolation between time steps becomes a potential issue when the time between readings is long, such as during the freezing and thawing periods, or when problems with the RUSS units result in extended periods of down time. The user can set the number of hours over which the utility will interpolate; an arbitrarily high number will fill in large gaps in the data set.

Figure 7 shows the changes in oxygen concentration in a highly eutrophic bay of Lake Minnetonka. The color map chosen for oxygen reflects some biological thresholds that are important in fisheries management. The areas in green reflect an acceptable level of oxygen for fish populations. The colors change from dark green to brown at approximately 5 mg/L oxygen, the point at which chronic oxygen levels are too low to support trout and other cold-water fish populations (Baker 1993, MPCA 1998). The colors change from blue to black at ~1 mg/L oxygen, when oxygen concentrations are too low to support any fish populations (hypoxia). The use of a color breakpoint at this concentra-

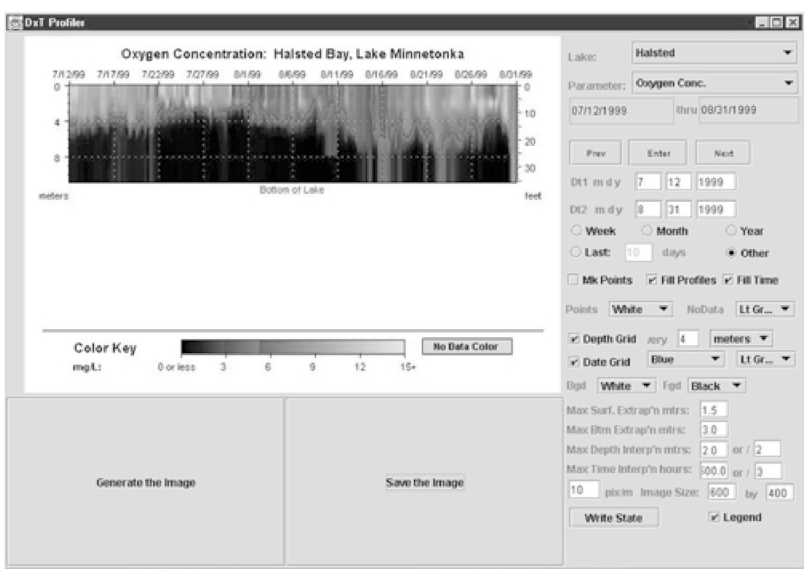

Figure 7. Screen capture of the DxT Profiler control panel.

tion clearly shows the depth at which oxygen becomes a critical factor (c.f. Brewer 1996). The black colors that persist through most of the season in the deeper waters of Halsted Bay illustrate the fact that fish can only survive in the upper warmest waters. In addition, the periodic oxygen depletions that occur throughout the profile in mid-August result from mixing events associated with severe storms; these events create difficult or critical stress conditions for fish populations.

Lake Cross-sectional Animations

In addition to the utilities described above, we have created a set of 2-D and 3-D animations that show temporal changes in a water column superimposed over a cross-section of a lake. These were created for the educational purpose of showing students how temperature stratification in a lake develops and breaks down over a season. Of course, even in a morphometrically simple lake such as Ice Lake, extrapolating temperature values from shore to shore overextends the data; this is important to note when presenting the animation. Nonetheless, a cross-sectional animation of changes in the thermocline over the season provides a clear illustration of how the data collected by the RUSS units relate to the bathymetry of the lake (Figure 8).

A related animation using a technique called “slicing” to display the layers of this cross-sectional data set stretched out over time in a 3-D graphic. Slicing is a computer animation technique in which a 2-D plane is passed through a semi-transparent 3-D object, allowing the internal structure of the 3-D object to be revealed. This technique is commonly used in tomography and has been used by the authors to illustrate variations in soil moisture within a 3-D soil volume (Host et al. 1996, http://www.nei.umn.edu/ecophys/soil.html). In our lake example, the animation shows the actual data layers, including the periods in which data were not collected (indicated by the presence of a question mark in the lower right corner of the figure). The animation concludes by having the full data set “materialize” and rotate into the DxT plane, which links this animation to the output of the DxT Profiler (Figure 9). This display thus illustrates the 3-D nature of the lake cross-section by the time data set, and the perspective of the DxT output.

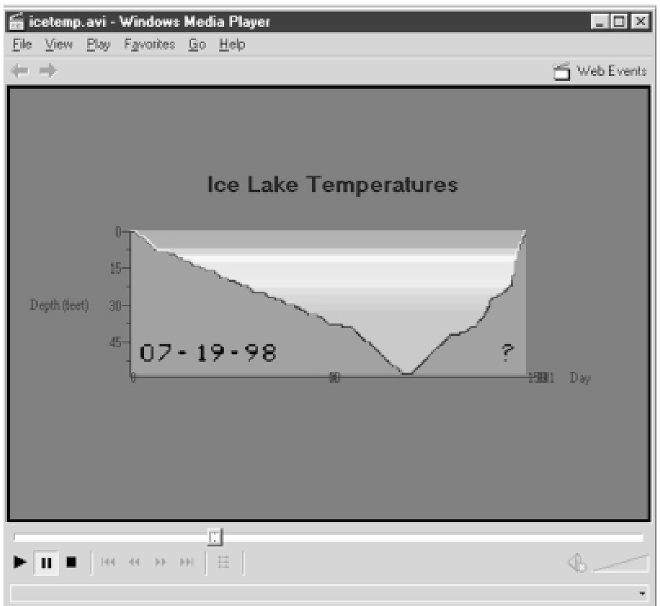

Figure 8. Screenshot from 2-D bathymetric profile animation.

Summary

We have presented a series of data visualization tools and examples that demonstrate how a comprehensive set of high-resolution water-quality data can be shown in a manner that allows the detection of short- and long-term trends in water quality.

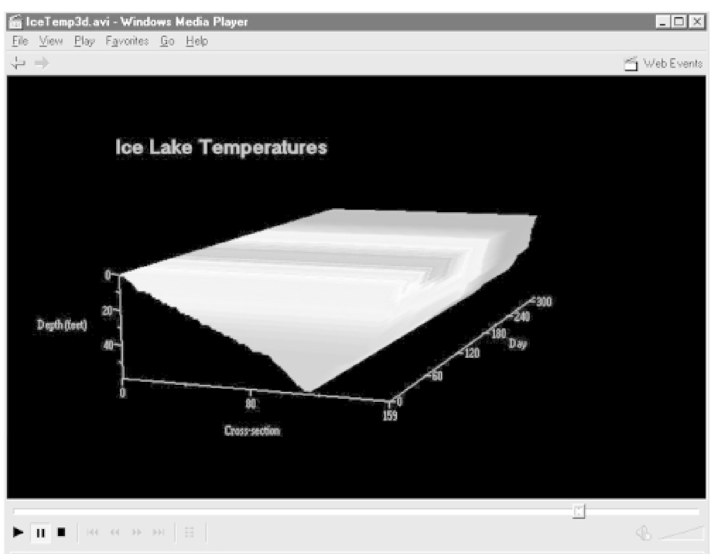

Figure 9. Screenshot from 3-D lake cross-section x time animation.

While the DVT-Interactive tools have been designed for data sets generated using RUSS technology, they could easily be applied to the data sets collected in typical lake monitoring programs, as well as to data stored in public archives such as STORET. Coupled with appropriate interpretive materials, such visualization tools will be useful not only to resource managers and scientists, but to inform and involve the public in understanding and acting on the water quality of their lakes.

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