Estuarine and Watershed Monitoring Using Remote Sensing Technology

Present Status and Future Trends

A WORKSHOP REPORT

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Executive Summary

The Scientific and Technical Advisory Committee (STAC) of the U.S. EPA Chesapeake Bay Program (CBP) and Maryland Sea Grant College (MDSG) jointly sponsored a workshop that was held 7-8 January 2002 in Annapolis, Maryland, entitled *Present Status and Future Trends in Estuarine and Watershed Monitoring using Remote Sensing Technology (Satellite, Airborne,* In-Situ*).* The impetus for the workshop was a recommendation from a STAC review of the CBP monitoring program that suggested the incorporation of remote sensing technologies into current monitoring efforts, including recent advances such as the global view of plant biomass as chlorophyll (*chl-a*) from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (Figure 1).

Larry Harding of MDSG/Horn Point Laboratories (HPL), Jonathan Kramer of MDSG and STAC, and Jonathan Phinney of NOAA and STAC served as the coordinators of the workshop. Participants included state and federal resource managers and members of the academic community within the Chesapeake Bay region and outside institutions with specific expertise and interest in remote sensing technology. The workshop was organized into three thematic areas, each represented by a panel of three scientists and a manager. This report summarizes oral presentations, panel discussions, and recommendations of the workshop, including presentations by twelve invited speakers.

Recommendations

This report provides a synopsis of material presented in the workshop on current and future capabilities for remote sensing of estuaries. Clearly, this topic was not covered exhaustively in a workshop of this scale. Rather, the meeting highlighted existing technologies and approaches that have direct bearing on management needs for Chesapeake Bay and that have shown promise when applied to estuarine and coastal waters and the watersheds that border them. Recommendations that emerged in the discussions coalesce into several categories:

- **Expand and Better Integrate *In-situ* Technologies.** *In-situ* technologies have been in use by the scientific community for many years and a variety of high-resolution data products are currently available. Expanding the use of a range of methodologies, from continuous underway sampling to new sensors on buoys, will greatly enhance monitoring capabilities, particularly in tributaries and the shallow reaches of the estuary.

- **Expand the Use of Aircraft and Satellite-based Sensors.** Remote sensing from aircraft and satellite platforms offers great promise to expand synoptic measurements and to examine understudied regions of the Bay. Partnerships with key agencies (NASA and NOAA) and better utilization of multiple data products, many available at no cost, should be pursued.

- **Increase the Use of Landsat Imagery.** Acquisition of Landsat images (e.g., Enhanced Thematic Mapper [ETM] and finer-scale commercial imagery) for the Bay watershed and increased use of processed imagery for specific applications will improve our understanding of changes on several spatial and temporal scales.

- **Improve and Expand Wetlands Mapping.** A variety of existing and new technologies can be used to examine and predict changes in wetlands. Both LIDAR altimetry and multi- and hyperspectral imaging should be pursued.

Introduction

Over twenty-five years ago, the National Aeronautics and Space Administration (NASA), the Environmental Protection Agency (EPA), and the University of Maryland, College Park (UMCP) convened a conference entitled *Application of Remote Sensing to the Chesapeake Bay Region* at the Coolfont Conference Center in Berkeley Springs, West Virginia. The stated goal of the conference was: "...discussing the complex technical and management issues surrounding the application of remote sensing to the Chesapeake Bay area." The conference was held 12-15 April 1977, just prior to the launch of the Coastal Zone Color Scanner (CZCS) late in 1977 and the development of technologies that we now use to study estuarine and coastal waters around the globe.

The keynote speaker for the conference, the Honorable Charles "Mac" Mathias, Jr., U.S. Senator from Maryland, remarked:

> The Chesapeake Bay, our nation's largest estuary, could, within our lifetime, become a dead sea. There is not time left to grope for solutions. With every year that passes, the Bay is diminished. Some day, unless we intercede, the wear and tear will become terminal. We must join together to ensure the health of the Chesapeake Bay as our legacy to the future.

The meeting addressed the following three main questions in the context of "measuring the state of the Bay." (1) What entities should be measured to develop a comprehensive database? (2) How close together should measurements be made in time and space? (3) What should be done with the data? Twenty-five years later, Bay managers and scientists are still asking similar questions. Fortunately, a better understanding of the structure and function of the ecosystem and breakthroughs in computer and sampling technologies have provided managers with better tools with which to address these questions. The commitment to improving the water quality of Chesapeake Bay remains clear. The technologies used to aid our assessments of the state of the ecosystem and to detect changes accompanying management actions have advanced significantly, now including aircraft, satellite, and *in-situ* instruments barely envisioned in 1977. Thus, it is timely to now revisit the questions posed 25 years ago, armed with potential solutions of the present and future as they pertain to Sen. Mathias's admonition to "ensure the health of the Chesapeake Bay."

Management Considerations

Remote sensing, broadly defined to include *in-situ*, aircraft, and satellite instruments, has revolutionized the observation and interpretation of large-scale biological and physical processes in coastal ecosystems. At present, remote sensing is well integrated into the research community, but is less commonly used by resource managers. Managers face a barrier in incorporating remote sensing into ongoing monitoring programs, because of a disconnect between needs and solutions, in developing ways to use new technologies to address management concerns.

Blanche Meeson of NASA posed the question, "Who should drive the process of applying data from remote sensing to management?" We might ask, "Is it incumbent on developers of technology to "sell" it to management or should management seek relevant technological solutions to existing problems?" In a needs-based system, resource managers must first identify problems and then decide whether or not remote sensing is an appropriate tool. To take this step, it is important for the manager to state requirements of resolution and coverage that pertain to a particular problem and to seek sources of data and information that meet those requirements. This early consideration requires that resource managers become informed about basic attributes of remote sensing platforms and instruments to determine if such an approach is part of a toolbox they might use. Clearly, remote sensing with instruments on aircrafts and satellites is not a solution to all problems, and the use of data and information from these sources should be driven by need rather than by capability. This truism helps identify an important role for those in the research and development community — one that argues for increased collaboration and a commitment to ongoing technology transfer.

Once a potential match of a management need to a remote sensing solution can be identified, several key questions emerge:

- Can data and information from remote sensing move a resource manager significantly toward a solution to a specified problem?

- What are the requirements in spatial and temporal resolution to address a particular need, and how are these matched by data availability?

- Can data be obtained reliably when they are needed and with sufficient coverage in time and space to be useful?

Another consideration is the distinction between operational and research applications. Relevant questions that should be posed to managers in this context are:

- Do you need to be able to acquire a specific measurement reliably every time you go out in the field?

- Do you need sustained measurements over a long period?

These considerations raise other issues, such as the longevity of a desired data set to support long-term monitoring. A long-term need is quite different from the relatively short-term need for data required to support an individual research effort. It is important for managers to specify their needs to assure that calibrated and validated data for a particular product are available over a desired timeframe, particularly in monitoring applications. A research instrument may be deployed for a prescribed period of time, perhaps several years, and as such might not be suitable for managers charged with tracking long-term changes. Although the needs of these researchers and managers may overlap, they are not identical. In order for managers to take advantage of emerging technologies, needs for data set longevity must be weighed carefully.

"Cost" is often an important consideration in deciding whether to obtain and use data from remote sensing. Some important questions are:

- What are the costs to collect and/or to purchase data and to process and reprocess the data for specific needs?

- Will it be necessary to support data archival to enable studies of long-term trends?

A user needs to be able to access data, to sustain a data flow, and to know the data are provided at a quality that makes them useful. There may also be a need for specialized algorithm development if "off-the-shelf" algorithms are not suitable for particular applications. Operational agencies (e.g., local government, states, EPA), must consider the requirements for developing and maintaining a workforce trained to use data effectively. A manager must take these considerations into account when determining whether or not to incorporate remote sensing in his/her program.

Applications for the Bay and its Tributaries

The way we view Chesapeake Bay and its watershed has changed significantly since the early 1980s. We have progressed from simply enumerating factors that have culminated in the degradation of water quality and loss of biota, to a focus on setting quantitative criteria to gauge how the ecosystem is responding to management actions. CBP has relied for 19+ years on sampling a set of fixed main stem and tributary stations in an aggressive monitoring program. While this effort is exemplary for estuarine and coastal waters of the U.S., major shortcomings in resolution and coverage have become increasingly evident. We now need to consider how to augment the monitoring program to fill holes in its design and to address scales that are better matched to habitat-level characteristics of the Bay. New technologies are not a substitute for traditional measurements, but with recent advances, we are now poised to integrate remote sensing into monitoring conducted by some of successful programs in the Bay.

From a management perspective, current technologies that generate data at a relatively high spatial resolution, including continuous underway sampling and aircraft remote sensing, lack fine temporal resolution and occur no more frequently than ship-based monitoring cruises. Other approaches, such as sensors mounted on buoys, give "point" data with high temporal resolution, but have limited spatial coverage. Sampling at fixed stations misses a significant part of the Bay's habitat. To date, programs that provide both high spatial and temporal resolution in these undersampled areas are relatively few and have stemmed largely from research projects. One of the major challenges facing scientists and managers is how to merge data and information derived from sampling on these different spatial and temporal scales, taking advantage of the strengths offered by different approaches, to develop the appropriate quantitative understanding of the ecosystem that is necessary to track changes over time.

Chesapeake Bay and its tributaries have been characterized as "impaired" in terms of nutrient and sediment levels, based on provisions of the Clean Water Act (Figure 2). "De-listing" the Bay from its impaired status depends on measurements of sufficient resolution that permit us to quantify improvements of water quality. With CBP's evolving management perspective of what comprises a "restored" Chesapeake Bay and new thinking about how to gauge progress toward this goal, there are growing opportunities to incorporate new technologies with *in-situ* and remotely sensed measurements into the monitoring program. As CBP has moved to define specific Bay criteria for ecosystem properties, including *chl-a*, water clarity, and dissolved oxygen (DO), it has become essential to capture the inherent variability of the ecosystem, — particularly to resolve which changes are the result of management actions from those resulting from largely climate-driven seasonal and interannual variability. If we are able to use contextual data from long-term data sets to improve our capabilities for sampling at higher spatial and temporal resolution, we will be better able to detect and quantify variability that has profound ecosystem ramifications.

Sampling Significant Habitat

Monitoring the main stem of the Bay provides very little data for the extensive shallow regions (1-2 m) that represent important habitat for living resources. To date, water quality in the shallows has been estimated by interpolation from a sparse sampling grid, but significant error accompanies this procedure. A graphical representation of Bay habitats (Figure 3) illustrates that some of these areas have been significantly undersampled. Submerged aquatic vegetation (SAV), for example, inhabits shallow regions of the Bay and has been critical in management attempts to link water quality to a key component of the biota. But the current emphasis on open water monitoring misses much of the preferred SAV shallow water habitat. This example highlights the mismatch of routine monitoring with the scales of variability for prospective criteria, such as *chl-a* and water clarity, and calls for the use of remote sensing or continuous underway sampling to improve spatial and temporal resolution in undersampled areas. It is also critical to take measurements that track ecosystem responses to reductions in nutrient loading (N and P) such as *chl-a*, water clarity, and DO. An important question for managers to pose, therefore, is "Can we build a remote sensing component that complements our shipboard measurements to obtain data for the shallows?"

Examples from the Severn River

The utility of new remote sensing technologies for management was demonstrated by data for the Severn River near Annapolis, Maryland presented by Rob Magnien, formerly of Maryland DNR. The Severn is one of many Bay tributaries that is significantly undersampled by routine monitoring, with samples taken from a single station in mid-river on a monthly basis. An examination of two of the water quality criteria, *chl-a* and DO, using an underway instrument and data logging system (Dataflow), revealed spatial and temporal variability not captured by station sampling alone (Figure 4). Transects conducted on two dates in May 2001 show a strong *chl-a* signal with "bloom" concentrations >60 mg m^{-3} over much of the river. An abrupt decline of *chl-a* was detected on a cruise just 10 days later, reflecting the "crash" of the bloom and a return of typical *chl-a* concentrations of 1 to 10 mg m^{-3}. The lesson from this example is that sampling at a single fixed monitoring station, if timed fortuitously, might allow the detection of a bloom, but would not give information on its spatial extent or longevity. A DO depression that accompanied the decline of *chl-a* as the bloom ended would also go undetected with routine sampling.

Undersampling occurs in other habitats as well, including open waters above the pycnocline, deep waters, and the deep channel. Any monitoring program needs to consider the seasonality of key properties, particularly in setting criteria. DO is one example of a strongly seasonal property of the Bay that has direct effects on the Bay's biota (Figure 5), and one that would benefit from expanded sampling.

Main Stem Bay Issues

The current monitoring program for the main stem Bay requires several ships and about three days to occupy ~49 stations. Although ships visit these stations at different times of day and on different days, the accumulated data are then used to reconstruct a month. In the case of *chl-a* and DO, variability within- and between-days can be quite high and cannot be resolved without adding specialized sampling to the core program. A narrow reliance on a traditional water quality program that is not equipped to quantify this variability can lead to significant failings of interpretation, illustrated by continuous measurements of DO (Figure 6).

Watershed Applications

The ability to track changes in land use and land cover is essential in managing watersheds and remote sensing can play an important role over relatively small spatial scales. Modeling and forecasting floods, for example, requires sophisticated digital elevation models (DEMs) at higher resolution than the current 30-m products that are readily available from the U.S. Geological Survey (USGS).

Todd Schroeder of the Canaan Valley Institute (CVI), a nonprofit, non-advocacy organization located in Thomas, West Virginia, presented examples of some watershed applications. CVI conducted a project on a 900-acre watershed, Fishing Creek in Smithfield, West Virginia (Figure 7), a site that has experienced serious flooding for several years. The existing DEMs were not sufficient to develop forecasts. CVI created an alternative 10-m product from hypsography, and also used LIDAR altimetry data to augment available DEMs and improve predictions of flood impacts. Schroeder indicated that local watershed models also benefit from improved land cover data. He showed an example of such data for part of Fishing Creek acquired with a multispectral digital camera system that helped improve Landsat classification for this watershed by revealing wooded meadows in previously logged areas (Figure 8). Data such as these have also been used in conjunction with DEMs from LIDAR to support advanced modeling of stream flow.

An important facet of the CVI effort is outreach, consisting of several "circuit riders" who organize local watershed groups and formalize efforts in community planning for small towns throughout the region, promoting the use of remote sensing to aid economic and environmental sustainability.

Conclusions

For remote sensing data to be useful in Chesapeake Bay, highly resolved data from buoys, towed bodies, aircraft, and satellites must be integrated with traditional data. One approach is to collect data at high frequency and superimpose them on the long-term record of observations. Fiscal reality will likely prevent CBP from developing its own remote sensing program or equipping the entire Bay with buoys. But remotely sensed or *in-situ* data made available to CBP could be used to improve the understanding of processes in particular areas of the Bay. A number of important management needs have been identified that call for new technologies, and first steps have been taken in test scenarios.

The decline of water quality in Chesapeake Bay, an "impaired" water body that is nutrient- and sediment-enriched and characterized by excess *chl-a*, reduced water clarity, and DO-depletion, has forced the community to re-define the meaning of a "restored" ecosystem. In so doing, we have had to include the underlying diagnostics, i.e., specific impairments associated with specific criteria. At present, data from existing monitoring lack spatial and temporal resolution sufficient to undertake these assessments and need to be supplemented by new technologies. Integrating remote sensing into an overall sampling plan that also uses *in-situ* water quality measurements with sensors moored on buoys, towed from boats or ships, or deployed as drifters, can generate data of high spatial and/or temporal resolution for a number of properties. A fuller utilization and integration of existing technologies, currently available mainly to the scientific community, can significantly impact monitoring in Chesapeake Bay. We must gauge whether a particular technological solution is sufficiently mature that it can be deployed in the near-term and provide sustained data over the long-term. Moreover, new technologies must help address areas of the Bay from the main stem to shallow waters, and measurements must be spatially and temporally integrated with other monitoring components to achieve the objectives of resource managers.

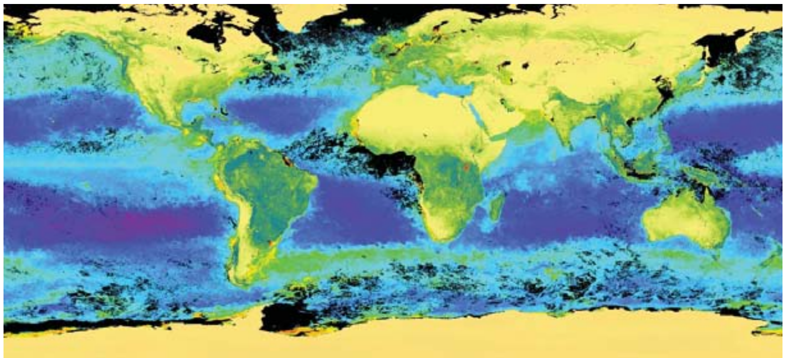

Figure 1. Global chlorophyll (chl-a) in the terrestrial and ocean biosphere from SeaWiFS.

Impaired Waters and Clean-up Plans

Portions of the Chesapeake Bay and its tidal rivers are listed under the Clean Water Act as "impaired waters" largely because of low dissolved oxygen levels and other problems related to nutrient pollution.

This "listing" requires the development of a clean-up plan for the Bay by 2010.

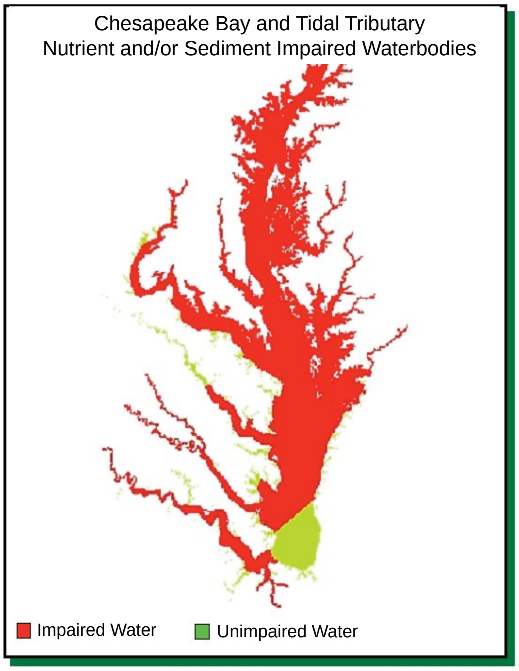

Figure 2. Management stimulus to measure water quality parameters that track nutrient over-enrichment and excess sediment, illustrated as regions of the Bay listed as "impaired" under provisions of the Clean Water Act.

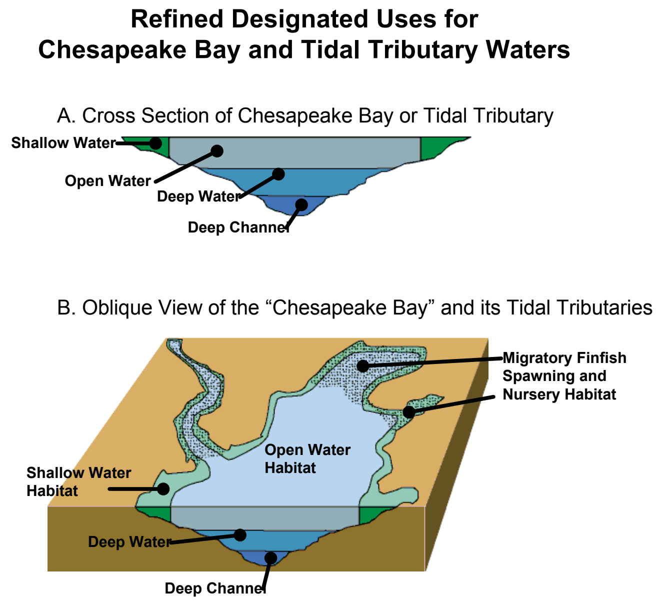

Figure 3. Categories of Bay habitat include shallow water, open water, deep water, and the deep channel. Seasonal water quality criteria for chl-a*, water clarity, and DO are being developed for these categories.*

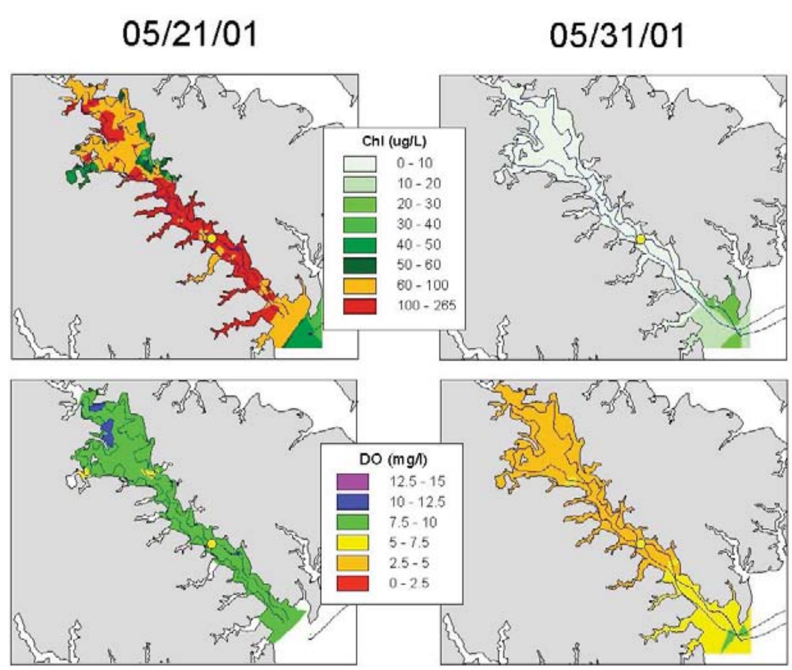

Figure 4. Examples of chl-a *and DO data from continuous underway sampling of the Severn River using the Dataflow system on cruises spaced 10 days apart. The single fixed monitoring station is shown as a yellow dot on each panel.*

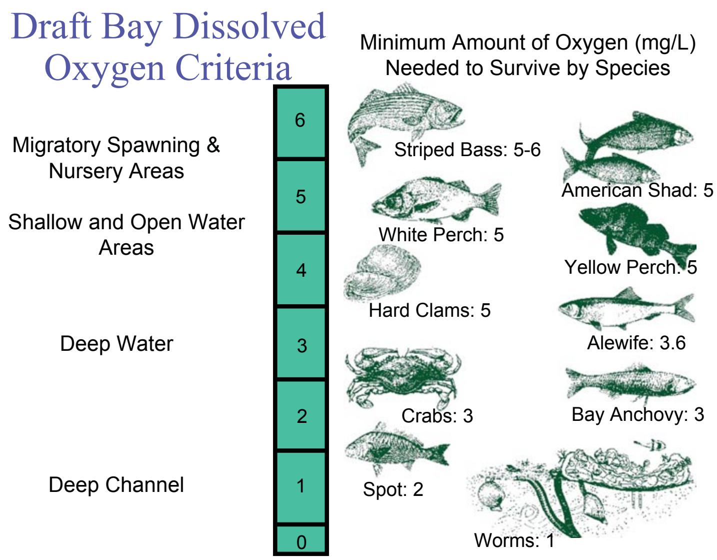

Figure 5. Proposed DO criteria for Bay habitats and the requirements of important macrofauna.

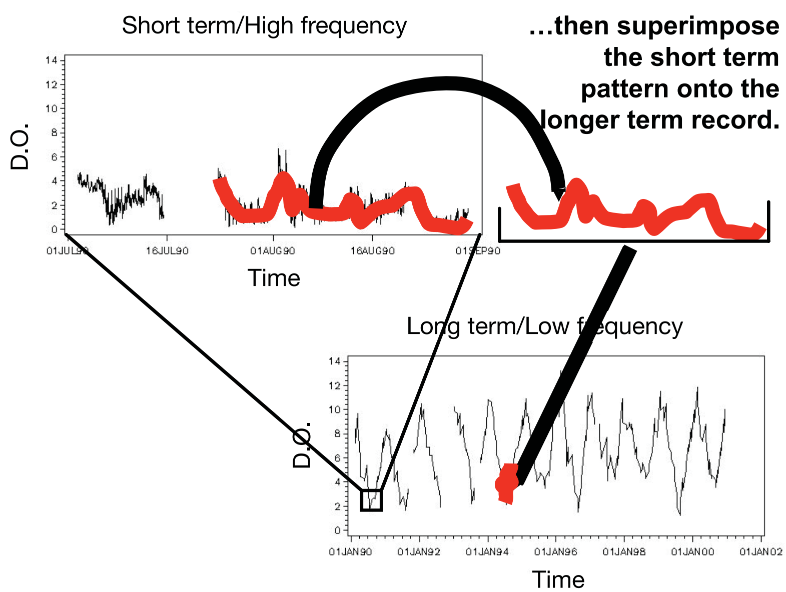

Figure 6. High frequency measurements of DO superimposed on the diel cycle, showing that instantaneous measurements such as those made at monitoring stations may not capture the temporal variability of this important water quality property.

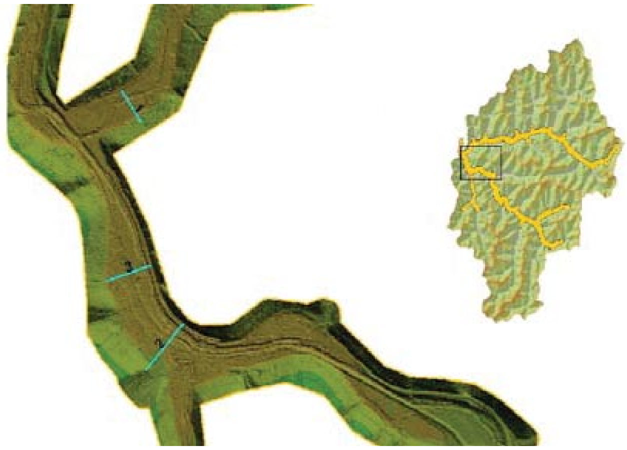

Figure 7. Local watershed in Smith Valley, West Virginia high resolution DEM product that enables flood modeling and mapping. The yellow lines indicate areas of LIDAR coverage that supported elevation mapping of features not resolved in coarser products.

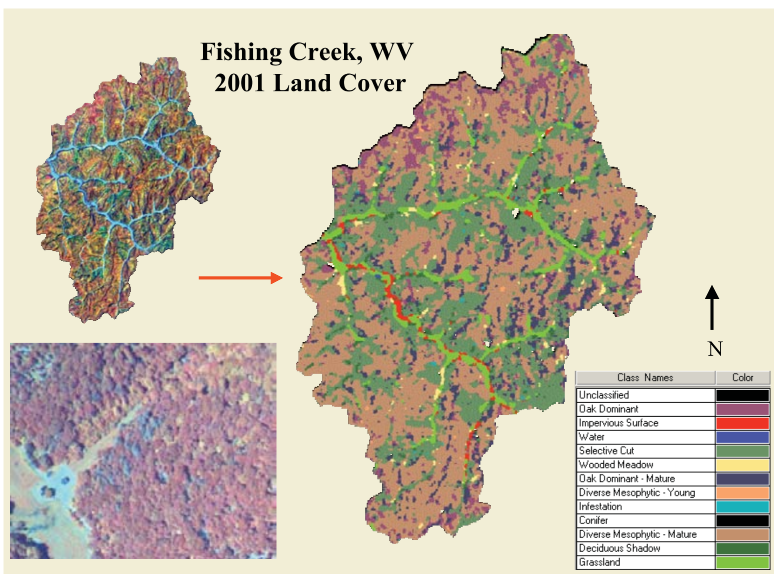

Figure 8. Land-cover classification for Fishing Creek, West Virginia using Landsat data aided by multispectral imagery that revealed wooded meadows in previously logged areas.