Intensive Water Quality Mapping of Nearshore and Mid-Channel Regions of the James River Relative to SAV Growth and Survival Using the DATAFLOW Surface Water Quality Mapping System

Ken Moore
Britt Anderson
Virginia Institute of Marine Science
David J. Wilcox
Virginia Institute of Marine Science

Follow this and additional works at: https://scholarworks.wm.edu/reports

Part of the Marine Biology Commons

Recommended Citation

This Report is brought to you for free and open access by W&M ScholarWorks. It has been accepted for inclusion in Reports by an authorized administrator of W&M ScholarWorks. For more information, please contact scholarworks@wm.edu.
Intensive Water Quality Mapping of Nearshore and Mid-Channel Regions of the James River Relative to SAV Growth and Survival Using the DATAFLOW Surface Water Quality Mapping System

Kenneth A. Moore, Britt Anderson, Dave Wilcox

The Virginia Institute of Marine Science
School of Marine Science
College of William and Mary
Gloucester Point, VA 23062

Special Report No. 385 in Applied Marine Science and Ocean Engineering

Funded By:

The Environmental Protection Agency
Chesapeake Bay Program
Annapolis, MD 21401

Grant Number 983501-01

October 2003
**TABLE OF CONTENTS**

| LIST OF FIGURES ............................................................................................................ | ii |
| EXECUTIVE SUMMARY ................................................................................................... | iv |
| INTRODUCTION ................................................................................................................ | 1 |
| METHODS ........................................................................................................................ | 3 |
| Description of DATAFLOW Mapping System .............................................................. | 3 |
| Area of Operation, Crusie Track and Sampling Frequency ........................................ | 3 |
| Calibration of Instrumentation ................................................................................... | 4 |
| Sampling Procedures ................................................................................................... | 4 |
| RESULTS AND DISCUSSION ........................................................................................... | 5 |
| Challenges and Solutions ........................................................................................... | 5 |
| Calibration Results .................................................................................................... | 9 |
| Cruise Results ............................................................................................................ | 10 |
| CONCLUSIONS ............................................................................................................ | 10 |
| LITERATURE CITED .................................................................................................... | 10 |
| APPENDIX OF FIGURES ............................................................................................... | 12 |
LIST OF FIGURES
(IN APPENDIX)

Figure 1  Site map of DATAFLOW Water Quality Mapping Study Area of the Lower James River

Figure 2  Original and Final DATAFLOW High Frequency Spatial Mapping Systems

Figure 3  Original and Re-designed DATAFLOW Flow-Through Chambers

Figure 4  Extracted Chlorophyll vs. DATAFLOW Fluorescence Measurements (5-1-02 and 10-18-02)

Figure 5  Extracted Chlorophyll vs. Corrected and Uncorrected DATAFLOW Fluorescence Measurements

Figure 6  Original and Modified DATAFLOW, Ram-Jet Intakes

Figure 7  Early and Later Versions of DATAFLOW, Computer Systems

Figure 8  Circular Cruise Tracks Testing Effects of Vessel Speed and Auxiliary Pump on DATAFLOW Sensor Readings

Figure 9  DATAFLOW Dissolved Oxygen Measurements Measured at Varying Vessel Speeds, With and Without Auxiliary Pump

Figure 10  Modified DATAFLOW Sampling Chamber

Figure 11  Comparisons of In situ (YSI 600) vs DATAFLOW (YSI 6600) Dissolved Oxygen Measurements

Figure 12  Comparisons of In situ (YSI 600), DATAFLOW (YSI 6600) and Surface Water, Winkler-Extracted Dissolved Oxygen Measurements

Figure 13  A. Regression of DATAFLOW YSI Dissolved Oxygen with Winkler Extracted Measurements of Dissolved Oxygen in Outflow
             B. Regression of DATAFLOW YSI Dissolved Oxygen with Winkler Extracted Measurements of Dissolved Oxygen in Surface Water
             C. Regression of Winkler Extracted Measurements of Dissolved Oxygen in Outflow with Winkler Extracted Dissolved Oxygen in Surface Water
Figure 14  Regressions of DATAFLOW NTU vs. Light Attenuation ($K_d$) Profile Measurements

Figure 15  A. Regression of DATAFLOW NTU Turbidity vs. Light Attenuation ($K_d$) Profiles for All James River Calibration Stations.
B. Regression of DATAFLOW NTU Turbidity vs. Light Attenuation ($K_d$) Profiles for Combined James River and York River Calibration Stations

Figure 16  Interpolated Surface Chlorophyll, Turbidity and Dissolved Oxygen Concentrations for the James River Study Area, June 3, 2002

Figure 17  Interpolated Surface Chlorophyll, Turbidity and Dissolved Oxygen Concentrations for the James River Study Area, August 1, 2002

Figure 18  Interpolated Surface Chlorophyll, Turbidity and Dissolved Oxygen Concentrations for the James River Study Area, October 18, 2002
EXECUTIVE SUMMARY

In this study a compact, self-contained surface water quality mapping system “DATAFLOW”, suitable for use in a small boat operating at speeds of about 25 KT was developed and tested. The system collects water through a pipe ("ram") deployed on the transom of the vessel, passes it through an array of water quality sensors, and then discharges the water overboard. DATAFLOW has a YSI 6600 Sonde equipped with a flow-through chamber. The system is also equipped with a Garmin GPSMAP 168 Sounder that provides chart plotting, position information to better than 3 meters 95% of the time, and depth. Custom software written in a LabVIEW ® environment provides for data acquisition, display, control and storage. The DATAFLOW mapping system collects sensor reading once every 2-4 seconds with resultant data points every 20-50 meters. Sensors report temperature, conductivity, salinity, pH, dissolved oxygen, turbidity, chlorophyll, longitude and latitude, depth and speed. At pre-selected stations during each cruise the vessel is stopped and water samples are collected for sensor verification.

Development of this version of the DATAFLOW resulted in a unit that was easily deployable on a variety of small vessels and was capable of sampling surface water quality conditions in shallow water of less than 2m in depth as well as in channel areas of the river. It also was capable of sampling in relatively small tributaries of the James River such as the Warwick River. A total of six cruises were conducted approximately monthly from May to October 2002 in the Hampton roads region of the lower James River.

The speed of the sampling vessel was not found to influence the sensor accuracy or precision therefore a great deal of flexibility is possible with vessel operation. No effects of the vessel or the vessel’s wake on the sensor measurements were found. Cruise patterns could be developed beforehand and previous cruise tracks could be repeated closely using the GPSMAP 168 Sounder display. In general, cruise tracks heading up or down the axis of the river were most efficient compared to sine-wave type tracks, however any type of track could be followed if necessary.

The incorporation of a commercially available sensor package (YSI 6600) greatly simplified sensor application as well as calibration over earlier versions. The development of a high volume, opaque, flow-through chamber with YSI, Inc. greatly improved system response and stability. Initial interferences by air bubbles and sunlight on sensor operation were overcome with system development.

The flow-through system was found to have good calibration with extracted samples of all measured parameters including dissolved oxygen and chlorophyll. Additional data will be needed to further develop these relationships, however this system was determined to be an accurate tool for very high spatial sampling of all the measured parameters in the surface waters.
The data output from the system was relatively easily interpolated into spatial coverage of each parameter using ArcMap 8.2 and the Geostatistical Analyst Extension. This interpolation provided a map of the estimated error in the interpolation that could be used to restrict the interpolated area to regions nearer the vessels track where the error was within an acceptable range. Further work will be needed to standardize the interpolation procedure before this approach can be used to evaluate surface water quality criteria for standards or other assessments.
INTRODUCTION

Low levels of Submerged Aquatic Vegetation (SAV) in the Chesapeake Bay over the past 30 years have been related to sub-optimal water quality conditions. Conditions and processes that influence water quality within the shallow littoral zones of the Chesapeake Bay and its tidal tributaries can be distinctly different from those in channel zones and can vary over short temporal and spatial scales. Recent EPA funded studies (Moore et al. 1995, 1996b) and their resultant peer-reviewed publications (Moore et al. 1996a, 1997) for high salinity regions of the Chesapeake Bay have demonstrated that water quality in vegetated shallows may be distinctly different from adjacent channel or unvegetated shoal areas.

Suspended particles (both sediment and phytoplankton derived) are of particular concern as they can dominate light attenuation in the shallows and can be the principal factor limiting natural SAV recovery and SAV transplantation success in many formerly vegetated areas. Phytoplankton levels are principally related to nutrient and light availability while fine-grained suspended sediments originate from riverine input as well as from shoreline and bank erosion. Once they have entered the body of an estuary, however, sediments may be deposited and re-suspended many times through natural processes (tidal currents and wind waves). Physical processes in the shallows can also lead to increased levels of phytoplankton compared to channel regions, as the shallow mixing depths can reduce the effect of light limitation in these turbid areas.

The structure of the SAV community and its capacity to modify local conditions may provide a key to their continued survival or recovery in some areas where water quality is marginal for growth, or stresses are seasonal or pulsed in nature (Zimmerman et al. 1991, Moore et al. 1996). Current modeling efforts (Cerco and Moore 2001) include density dependent relationships between SAV density and particle loads and therefore water clarity. However, many estimates of statistically derived water quality conditions needed for SAV recovery are obtained from water quality measurements in areas adjacent to existing beds (Batiuk et al. 1992, Dennison et al. 1993). In some cases they may underestimate the levels of water quality improvements required for recovery into unvegetated areas, given sufficient capacity of SAV beds to improve conditions within the beds (Moore 1997).

The continuing development and implementation of the Commonwealth of Virginia Tributary Strategies, recent 303(d) listing of the Virginia region of the Chesapeake Bay and its tributaries as degraded water, the development of water quality criteria for turbidity, chlorophyll, and dissolved oxygen, as well as the potential for change in the CBP water quality monitoring program procedures have placed increased emphasis on accurate measurements of the temporal and spatial variability of water quality constituents. Temporally intensive water quality studies (eg. Moore et al. 1995, 1996b) in vegetated and unvegetated shallows and adjacent channel areas in the bay have demonstrated that differences in water quality between the two can be significant. In contrast, spatial distributed studies using paired stations (eg. Bieber and Moore in Batiuk et al. 1992 and Karrh in Batiuk et al. 2000) have generally found that no significant
differences when compared using seasonal means or medians. However, predictions of SAV transplant growth and survival using the closest available mid-channel, water quality monitoring data, have had poor success (Fishman et al. 1999). Our understanding of the spatial variability of water quality constituents especially between channel and shoal regions and how this variability is related to SAV remains incomplete.

Until recently our capacity to measure, monitor, and evaluate water quality constituents in detail over ecologically relevant regions was limited. Currently Maryland, through the Chesapeake Biological Laboratory is employing a new DATAFLOW Surface Water Quality Mapping System for high speed, high resolution mapping of surface water quality from small vessels capable of sampling shoal, littoral areas. Such a mapping system can have practical application in the analysis and interpretation of data from the ongoing Chesapeake Bay Program water quality monitoring program as well as the evaluating the results of ongoing SAV transplantation studies.

The James River in Virginia has been the focus of intense efforts from federal and state agencies, academic and research institutions such as VIMS and many bay partners, to develop and implement effective management strategies for the restoration of living resources such as SAV to former levels (Moore et al 1998, 2000). The James River basin's population in 1990 was nearly 2 million and grew another 8 percent by the 2000. The basin's population comprises about 42 percent of Virginia's Chesapeake Bay watershed population, and roughly one-third of the state's total. Except for a small drainage area in West Virginia, the James' watershed is located almost entirely within Virginia. The river, which is 450 miles long, drains 10,102 square miles, one-fourth of the state's land base and 47 percent of Virginia's bay basin. Land use in the river's basin varies considerably from its headwaters to its mouth. Overall, about 71 percent of the land is forested, 23 percent is agricultural, and 6 percent is urban.

Currently there are several ongoing SAV restoration projects in the James ranging from formerly vegetated areas that have been planted with high salinity seagrass species in Hampton Roads, to areas planted with freshwater submerged aquatics in the Hopewell region of the estuary. In addition, beds of remaining native SAV have been observed in tributary creeks in the middle reaches of the tidal river in the vicinity of the Chickahominy River. Although, water quality parameters are monitored in mid-channel areas along the axis of the river as part of the Tributary Water Quality Monitoring Program as well as selected shallow water areas, the spatial distribution of water quality constituents (water clarity and phytoplankton) that have the greatest effect on SAV survival are poorly understood.

The objectives of this project are to:

1) Construct a DATAFLOW Water Quality Mapping System for use in Virginia waters;
2) Initiate spatially intensive monitoring in the lower region of the tidal James for water clarity and chlorophyll levels using the DATAFLOW Water Quality
Mapping System. These components of water quality potentially have the greatest impacts on SAV survival and recovery;

3) To evaluate the utility of this system in mainstem, shallow nearshore, as well as sub-tributary conditions.

METHODS

Description of DATAFLOW Mapping System

DATAFLOW is a compact, self-contained surface water quality mapping system, suitable for use in a small boat operating at speeds of about 25 KT. The system collects water through a pipe ("ram") deployed on the transom of the vessel, passes it through an array of water quality sensors, and then discharges the water overboard. DATAFLOW has a YSI 6600 Sonde equipped with a flow-through chamber. The sensors include a Clark-type YSI 6562 dissolved oxygen probe, a 6560 conductivity/temperature probe, a 6026 turbidity probe, and a 6025 chlorophyll probe. The entire system from intake ram tube to the return hose are shielded from light to negate any effect high intensity surface light might have on phytoplankton in the flow-through water that is being sampled. A blackened sample chamber is also used to minimize any effect of light on measurements by the fluorescence probe. The DATAFLOW system is also equipped with a Garmin GPSMAP 168 Sounder. This unit serves several functions including chart plotting, position information, and depth. The unit is WAAS (Wide Area Augmentation System) enabled providing a position accuracy of better than three meters 95 percent of the time. The NEMA 0183 data sentence containing all pertinent position and depth information as well as the data collected from the sonde is output to the SBC data acquisition system. The system is based on an 800 MHz Pentium processor with Windows 2000 on a ruggedized laptop computer (Toughbook 28, Panasonic, Inc.). Custom software written in a LabVIEW® environment provides for data acquisition, display, control, and storage. Real-time graphs and indicators provide feedback to the operator in the field, ensuring quality data is being collected. All data is collected simultaneously in one file, removing the chore (and possible errors) of merging separate files into one.

Area of Operations, Cruise Track and Sampling Frequency

The initial area of operations included the northern littoral zone of the lower James River along the cities of Newport News and Hampton, Va. downstream of the Warwick River. After consultation with representatives from Virginia Department of Environmental Quality, this area was then changed to include the mid-channel and northern shallow water region of the JMSMH bay segment from just downstream of Newport News Point and the Monitor Merrimac Bridge to just upstream of Skiffes Creek to include the Warwick River (Fig 1). During this same time period, cruises were being undertaken in the York River, Virginia to test the sampling system, establish more calibration data, and test different configurations of the DATAFLOW unit itself. Some of these results are relevant and are included in this report.
Cruises were scheduled monthly from May to October 2002 for a total of six cruises. During the first cruise we tested two types of cruise paths in the area between the Hampton Roads Bridge Tunnel and the Monitor Merrimac Bridge Tunnel. The first consisted of an approximate square wave pattern frequently traversing from shallow waters (as shallow as can be navigated in safety) out to channel depths, along the channel, back into shallow waters, paralleling the shoreline, then back to the channel. The same region was then covered using a of a series tracks running parallel to the shoreline along fixed depth contours. This second type of cruise track was then selected for the remaining five cruises. Due to the likely presence of many navigational hazards and limitations due to sea conditions, the actual cruise track were adjusted on the day of operation as necessary.

Calibration of Instrumentation

All instruments (YSI 6600) are maintained in accordance with manufacturer's specifications (YSI 6-series Environmental Monitoring Systems Manual; YSI, Inc. Yellow Springs, OH). Sensors involved in the collection of water quality data (temperature, conductivity, salinity, pH, dissolved oxygen, turbidity, and chlorophyll a) are calibrated just prior to each sampling cruise. Standards and reagents involved in the calibration of instrumentation are made according to a schedule of shelf life (ie. daily, weekly or seasonally) or if the supply is exhausted. All chemicals are handled, prepared and stored in accordance with standard laboratory practices. If any apparent problems arise the instrument is removed from use until the malfunction can be diagnosed and remedied.

For transmittance and fluorescence, the manufacturer also recommends that the instrument be calibrated against in situ properties measured in the field. This involves collecting approximately 10 calibration samples in each field deployment that are analyzed for total and active chlorophyll-a and total suspended solids concentrations. These field standards are related to sensor readings via multiple regression procedures. On all cruises, a YSI 600 sonde is also used at the calibration stations to compare dissolved oxygen in in situ water vs. water coming through the DATAFLOW system.

Sampling Procedures

The DATAFLOW mapping system collects a sample once every 2-4 seconds. The resulting distance between samples was therefore a function of vessel speed. A cruising speed of 20 knots results in data points being generated once every 20-50 meters. Stations for calibration samples were sampled at intervals along the cruise track.

The number of calibration stations varied between cruises, but the location and frequency of stations was selected to optimize the range of values that were seen along a cruise track (eg. when moving up a tributary with a salinity range samples were taken to get a high, medium, and low salinity value). At selected stations, the boat was stopped and water samples for total suspended solids, chlorophyll-a, chlorophyll-b and on selected cruises dissolved oxygen for processing with the Winkler method were collected from the effluent tubing of the DATAFLOW System. On cruises that include Winkler samples, a
sample of ambient water, from the same depth as the DATAFLOW intake was taken using a Van Dom style bottle sampler (Ben Meadows Co., Canton, GA). This was to determine if oxygen was being introduced into any segment of the DATAFLOW system, thereby giving elevated dissolved oxygen readings.

At each station a YSI 600 mini-sonde was deployed to verify dissolved oxygen and temperature readings. Samples for total suspended solids and chlorophyll were collected in darkened bottles, which were rinsed three times with ambient water before filling. These are then placed in a cooler on ice and were processed the same day upon return to VIMS. Total suspended solids were determined by filtration (10 TSS L01 (EPA 160.2) with slight difference in drying temperature and duration) and chlorophyll a by spectrophotometric methods (Bolhar_Nordenkampf & Oquist, 1993). At each station, water clarity down to the 1m of depth was assessed using a secchi disk as well as profiled using a Li-Cor 192-S downwelling sensor. The downwelling attenuation coefficient ($K_d$) was then calculated according to Beer’s Law.

Very little post-processing was required before the data could be used. However, there were two kinds of problems that occurred occasionally: misread positioning or depth information and erroneous values caused by electronic interference. A series of Microsoft Excel, macro-procedures were used to: 1) import the ASCII data to Microsoft Excel; 2) label and format the data; and 3) apply a series of validity checks to identify potentially erroneous observations. Post-calibrations of the transmissometer, fluorometer and dissolved oxygen sensors were applied to the Microsoft Excel data sets, if necessary. Maps of the surface water quality conditions were produced using GIS software (ESRI ArcInfo). Data from the DATAFLOW system was interpolated over 25m cells for the given study site using Kriging techniques with ESRI Geostatistical Analyst software package.

RESULTS AND DISCUSSION

Challenges and Solutions

Many challenges were met in the development and field-testing of the DATAFLOW system. The issues and their solutions will be discussed below.

1. Cruise pattern selection

As stated previously, the DATAFLOW program was designed in close cooperation with Maryland’s Chesapeake Bay Laboratory (W. Boyton). They utilize the flat sine wave cruise pattern in and out of the shallows. This works well in the systems that they monitor, such as the Magothy and Severn Rivers, Md., which are much smaller than the James and York River systems in Virginia. A comparative study of York River cruise patterns was done and it was determined that approximately 16 miles of river, including north and south littoral zones (<2 meters) and the channel, could be covered in 5.3 hours using the flat sine wave while 21.8 miles of river could be covered in 4.5 hours using tracks running parallel to shore, including the north and south shore littoral zones. This
second type of cruise track was then selected for the remaining five cruises to cover a
greater distance in less time.

2. Air Bubbles in the DATAFLOW system
Initially the DATAFLOW system consisted of the ramjet intake with 500gpm pump,
leading to a de-bubbler, flow meter, a second 500gpm pump, and then the YSI 6600
sonde. We found on initial test cruises that air bubbles were introduced into the system.
We began removing elements of the system to cut down on the number of joints and
areas that were potentially drawing in air. After removing the de-bubbler, flow meter,
and the second pump the problem improved significantly. We also inverted the YSI
sonde to allow any air in the system to collect at the top and easily be expunged. This
arrangement eliminated air entering into the system (Fig 2) and greatly simplified the
apparatus.

3. Interference of ambient light on phytoplankton and the 6025 chlorophyll probe
During the first test phase of the DATAFLOW system an effect of sunlight shining into
the clear flow through cell was noted. At certain angles, the sunlight seemed to affect the
chlorophyll readings resulting in very sporadic readings that constantly jumped around
and did not appear to be realistic. There was also a concern of using clear inflow tubing
because of the potential effect of high light on phytoplankton that had been brought up
from a depth of approximately 0.5 meter. Covering the intake tubing with black
electrical tape to darken the environment and covering the flow through cell with dark
neoprene solved this. Beginning with the October 3, 2002 cruise (on the York River) a
new flow through cell made of a dark, opaque material was constructed by YSI, Inc for
our use (Fig 3). This caused the chlorophyll reading to be much more stable and
correlate better with calibration samples. Figure 4 contains graphs of regressions
between extracted chlorophyll values and YSI fluorescence early in the trials with the old
flow through cell (A) and late in the trials with the opaque cell (B).

Multiple regressions relating YSI chlorophyll and turbidity (NTU) from all cruise dates
including both the York and James River were preformed and then that equation was
used to correct the chlorophyll values generated by the YSI (see Turner Designs
(www.turnerdesigns.com/t2/esci/turbidity_effects.html). To correct and convert the YSI
in vivo chlorophyll data into actual chlorophyll data the following equation was
determined:

\[ y = m_x x + m_z z + b \]

Where:

\( y \) = corrected chlorophyll value
\( m_x \) = coefficient (slope) for in vivo chl
\( m_z \) = coefficient (slope) for turbidity
\( b \) = y intercept
Figure 5 contains graphs of extracted chlorophyll and uncorrected chlorophyll values (Fig. 5A) and extracted chlorophyll and corrected chlorophyll (Fig. 5B). In this particular example the fit of the corrected *in vivo* chl and extracted chl readings improved with turbidity correction from a $R^2$ of approximately 0.85 to 0.88.

4. **Ramjet interference with depth sounder**
On the first cruise we noticed that the depth sounder readings were intermittent when the boat speed increased above ~5 knots. Original construction had the depth sounder mounted on the same plate as the ramjet (approximately 15cm apart) (Fig 6). The turbulence and splash caused by the ramjet interfered with the depth sounder and that resulted in erroneous depth readings. When it was mounted a greater distance from the ramjet (approximately 150cm) the disruption in the readings were constant.

5. **Weight and bulk of operating computer**
The original design of the DATAFLOW system included a waterproof case with a CPU, flat screen, GPS and batteries contained inside it (Fig. 7; top panel). It became apparent that the bulk and weight of this design was very cumbersome. We investigated other options and replaced it with a ruggedized laptop computer (Toughbook 28, Panasonic, Inc.), which is water resistant more likely to survive conditions in the field then a traditional desktop model. This cut down significantly the weight and bulk of the field equipment (Fig 7; bottom panel).

6. **Hazard of running at a 1-meter depth contour**
Our goal with the first cruises was to run the shallow tracks at the 1 meter MLW depth contour. This was problematic in that when the bathymetry changed suddenly it was difficult to adjust the cruise path quick enough to avoid skimming the bottom with the ramjet. In episodes where this occurred a host of issues arose including; clogged ramjet, high turbidity resulting not only in erroneous data but also potential damage to delicate membranes and optics on the YSI sonde, loss of time, and damage to the pump. Adjusting the target depth contour to 1.5 meter MLW allowed for a safer margin of error as well as less potential damage to equipment.

7. **500gpm pump failure**
After a number of cruises we began to see failure of the 500gpm pumps. They clogged easily if the ramjet brought up any sediment and debris in the water column such as small portions of twigs, leaves, etc. On sampling stations we would also see a marked decrease in flow through the system once the boat slowed and stopped. Replacing these smaller pumps with an 1100gpm version of the pump gave much more consistent flow and greater flow rates.

8. **Potential aeration of water with the ramjet/pump intake combination**
After meeting with and reviewing the sampling array with representatives from the YSI Corporation, concern was expressed about the system. They were concerned that we were aerating the water by adding a pump to the simple ramjet design and they were also wary of the amount of water we were introducing into the constrictive flow through cell with the speeds we were traveling (15-25 knots). We addressed these issues in two ways.
First a cruise was undertaken in the York River where approximately circular cruise tracks were run with the ramjet/pump combination at 4 different speeds (5-20 knots at 5 knot increments; Fig. 8) and then similar tracks were run without the pump only using a ramjet at different speeds. There was no effect of varying vessel speeds between 5 and 20 knots on dissolved oxygen measurements and no effect of the pump on measurements (Fig. 9). We found that not only did the pump not introduce air and bubbles, but also by keeping a constant flow in the sampling system starting and stopping at calibration sample sites was much less disruptive to the sampling system. Without the pump, the system had to be primed and purged of bubbles after each sampling site. Removing the pump also required speeds of 10+ knots to keep the system primed. Speed was not a factor in disruption of the sonde probes. Dissolved oxygen values with and without the pump were between 5.0 and 6.0 mg/l. Some of the variation between the readings at the different speeds was caused by the fact that the cruise paths in this trial were not exactly the same (Fig 8) The issue of the constricitive cell was addressed by replacing it with a larger cell with an inflow at the bottom and outflow at the top. With the larger cell the smallest diameter that constricts water flow went from 8mm to 15 mm. In combination with the larger pump (Fig 10) the flow through the system increase from 3.2gpm to 5.3gpm.

9. Difficulty with Dissolved Oxygen Readings

There were many issues that affected the consistency and accuracy of the dissolved oxygen readings during the initial cruises. No one solution drastically altered the readings but a combination of changes seemed to result in much more reliable numbers. The first two cruises (5-1-02 and 6-3-02) we had varying success maintaining consistent dissolved oxygen readings. The YSI 6600 always calibrated and post calibrated correctly but the readings at the verification stations typically were lower that those measured using a YSI 600 placed adjacent to the Dataflow intake. On the middle two cruises (7-3-02 and 8-1-02) the dissolved oxygen readings were consistent in the beginning but in both cases the readings began to deteriorate and in both cases, on post calibration, the sonde would not hold its calibration indicating that the membrane had suffered damage. On the final two cruises (8-30-02 and 10-18-02) dissolved oxygen values correlated well with the YSI 600. Examples of these three conditions can be seen in Figure 11.

After our first cruise on the York River we used a YSI 600XLM mini-sonde to compare dissolved oxygen and temperature in the ambient water and with water passing through the dataflow system. We first wanted to eliminate the possibility that we were affecting the dissolved oxygen by passing the water through the system. Dissolved oxygen was lower in the DATAFLOW then in the surrounding water. Calibration samples for comparison of dissolved oxygen readings from the YSI instruments to those done by the Winkler method (CBP METHOD ID: 37 DISSLOVED OXYGEN F03 EPA 360.2) were taken on select cruises (Fig 12). The problem was resolved by simplifying the system as discussed in #2 to reduce turbulence and introduction of bubbles, by very carefully purging the system of bubbles after the system is primed, running in slightly deeper water so there was less chance of sediment and debris abrading the membrane surface, adding a larger pump to give more consistent flow, and being careful to allow proper warm up time for the YSI 600XLM before comparing readings. We also employed a more precise
method for changing the dissolved oxygen membrane after consulting with YSI, Inc. There were still cruises (e.g. 7/3/02 and 8/1/02) where the membrane was damaged during the cruise, but implementing the above procedures greatly improved the reliability of the dissolved oxygen data.

10. Handling the lag time between water turnover, boat position, and reading
With the speeds at which the boat was run, there was a lag between the position of the boat, the amount of time that was required for the water to pass through the system and when the YSI completed its analysis of the water and record a reading. Increasing the flow from approximately 3.2gpm to 5.2gpm decreased the residence time of the water in the system from approximately 7 seconds to 4 seconds. At the highest speeds of 25 knots, this equaled a potential horizontal displacement decrease from 90m to 50m.

Calibrations Results
Comparisons of YSI fluorescence measurements vs. extracted chlorophyll for both several individual cruises and all cruises combined are presented in Figs. 4 and 5. The goodness of the fit of the relationships ($R^2$) will depend, in part, on the number of points, the range of points compared as well as the natural chlorophyll/fluorescence responses of the phytoplankton. Combining the data from all cruises resulted in improved fit in this study and correcting the fluorescence signal for turbidity improved the fit as well as improved the fit to the origin of the regression. Further data will be needed to elucidate these interrelationships.

Comparisons of the YSI dissolved oxygen and extracted dissolved oxygen measurements using Winkler titration are presented in Fig. 13. There was a good fit between the YSI measurements and either the DO samples taken at the DATAFLOW overboard outflow (Fig. 13A) or samples taken in the water immediately adjacent to the inflow (Fig. 13B). No effect of the DATAFLOW apparatus on the dissolved oxygen was evident as comparison of water immediately before and after flow through the system resulted in a nearly 1:1 relationship (Fig. 13C).

Comparisons to YSI NTU readings versus measured underwater light attenuation ($K_d$) throughout the surface meter are presented for three James River cruise dates (Fig. 14). Both the fit and the slope of the individual regression lines change among dates. This is most likely related to the few calibration stations on each date as well as potential differences in the turbidity (NTU) to light attenuation ($K_d$) relationships. Calculation of turbidity to light attenuation relationships for all calibration stations ($n=35$) in the five James River cruises undertaken in 2002 (Fig. 15A) reveals a poorer fit, but a consistent slope. This suggests that a combined relationship developed using calibration data from several cruises throughout the year may be useful. Additionally, if additional data taken from DATAFLOW cruises on the York River in Virginia in 2002 are combined with the James River station (Fig. 15B), the range of values is increased and the fit again improves. This suggests that seasonal data from several tributaries may possibly be combined to produce a relationship between turbidity measurements obtained with the
DATAFLOW and the light attenuation coefficients necessary to predict light availability at depth or percent light through the water (PLW).

Cruise Results

Examples of interpolated coverages of turbidity, chlorophyll, and dissolved oxygen generated from three cruises (June 3, 2002, August 1, 2002, and October 18, 2002) are presented in Figures 16, 17, and 18, respectively. The black lines are the cruise tracks formed by the individual 2-3 second DATAFLOW measurements taken at approximately 50m intervals. Spatial interpolations of the DATAFLOW data were performed using the Geostatistical Analyst Extension in ArcMap 8.2 (ESRI, Redlands, CA). Ordinary kriging was used to evaluate the spatial variation in each water quality parameter and generate a statistically optimized interpolated surface. In addition this analysis produced a map of the estimated error in the interpolation. This error map was used to restrict the interpolated area to regions nearer the boat track where the error was within an acceptable range.

These initial spatial interpolations demonstrate relatively higher chlorophyll concentrations in June and August (Figs. 16 and 17) compared to October (Fig. 18) with highest levels along the north shoreline and into the Warwick River, a tidal tributary of the James River, that is located in this area. Turbidity levels appear, overall, to be highest in June and lowest in October. Again, turbidity levels were higher along the north shore, especially in the vicinity of the Warwick River. Surface dissolved oxygen concentrations were high (<10 mg/l) throughout the entire study area in June and October. During the mid-summer, August cruise concentrations were lower in the mid-channel region of the river and higher along the northern shoreline.

CONCLUSIONS

Development of this improved version of the DATAFLOW resulted in a unit that was easily deployable on a variety of small vessels and was capable of sampling surface water quality conditions in shallow water of less than 2m in depth as well as in channel areas of the river. It also was capable of sampling in relatively small tributaries of the James River such as the Warwick River.

The speed of the sampling vessel was not found to influence the sensor accuracy or precision therefore a great deal of flexibility is possible with vessel operation. No effects of the vessel or the vessel's wake on the sensor measurements were found. Cruise patterns could be developed beforehand and previous cruise tracks could be repeated closely using the GPSMAP 168 Sounder display. In general, cruise tracks heading up or down the axis of the river were most efficient compared to sine-wave type tracks, however any type of track could be followed if necessary.

The incorporation of a commercially available sensor package (YSI 6600) greatly simplified sensor application as well as calibration. The development of a high volume,
opaque, flow-through chamber with YSI, Inc. greatly improved system response and stability. Initial interferences by air bubbles and sunlight on sensor operation were overcome with system development.

The flow-through system was found to have good calibration with extracted samples of all measured parameters including dissolved oxygen and chlorophyll. Additional data will be needed to further develop these relationships, however this system was determined to be an accurate tool for very high spatial sampling of all the measured parameters in the surface waters.

The data output from the system was relatively easily interpolated into spatial coverage of each parameter using ArcMap 8.2 and the Geostatistical Analyst Extension. This interpolation provided and map of the estimated error in the interpolation that could be used to restrict the interpolated area to regions nearer the vessels track where the error was within an acceptable range. Further work will be needed to standardize the interpolation procedure before this approach can be used to evaluate surface water quality criteria for standards or other assessments.

**LITERATURE CITED**


YSI 6-series Environmental Monitoring Systems Manual; YSI, Inc. Yellow Springs, OH

APPENDIX OF FIGURES
Figure 1: Site map of DATAFLOW Water Quality Mapping Study Area of the Lower James River
Site Map for Water Quality Mapping
Nearshore and Mid Channel Regions
Lower James River, Virginia

- Original Study Location
- Expanded Study Location
Figure 2: Original and Final DATAFLOW High Frequency Spatial Mapping Systems
Figure 3: Original and Re-designed DATAFLOW Flow-Through Chambers
YSI 6600 Sonde

Sensor Probes

Original transparent cell

Newly designed opaque flow thru cell
Figure 4: Extracted Chlorophyll vs. DATAFLOW Fluorescence Measurements (5-1-02 and 10-18-02)
A. 

JR Cruise 5-1-02
Extracted Chl vs. YSI Fluorescence

\[ y = 1.5482x \]
\[ R^2 = 0.7399 \]

B. 

JR Cruise 10-18-02
Extracted Chl vs YSI Fluorescence

\[ y = 1.3751x \]
\[ R^2 = 0.9116 \]
Figure 5: Extracted Chlorophyll vs. Corrected and Uncorrected DATAFLOW Fluorescence Measurements
A.

York/James River Data Flow

\[ y = 1.4659x + 0.6395 \]

\[ R^2 = 0.8498 \]

B.

York/James River Data Flow

\[ y = 0.9999x + 0.0015 \]

\[ R^2 = 0.8763 \]
Figure 6: Original and Modified DATAFLOW, Ram-Jet Intakes
Figure 7: Early and Later Versions of DATAFLOW, Computer Systems
A. Early Version DATAFLOW CPU

B. Later Version DATAFLOW CPU
Figure 8: Circular Cruise Tracks. Testing Effects of Vessel Speed and Auxiliary Pump On DATAFLOW Sensor Readings
8-16-02 York River Cruise
Intake Test

Red - with pump
Green - without pump
Figure 9: DATAFLOW Dissolved Oxygen Measurements Measured at Varying Vessel Speeds, With and Without Auxiliary Pump
Figure 10: Modified DATAFLOW Sampling Chamber
YSI, Inc. High Volume Flow-through Chamber
Figure 11: Comparisons of In situ (YSI 600) vs. DATAFLOW (YSI 6600) Dissolved Oxygen Measurements
Figure 12: Comparisons of In situ (YSI 600), DATAFLOW (YSI 6600) and Surface Water, Winkler-Extracted Dissolved Oxygen Measurements
Figure 13:  

A. Regression of DATAFLOW YSI Dissolved Oxygen with Winkler Extracted Measurements of Dissolved Oxygen in Outflow

B. Regression of DATAFLOW YSI Dissolved Oxygen with Winkler Extracted Measurements of Dissolved Oxygen in Surface Water

C. Regression of Winkler Extracted Measurements of Dissolved Oxygen in Outflow with Winkler Extracted Dissolved Oxygen in Surface Water
A.

YSI vs. Outflow Dissolved Oxygen Comparison (8-30-02)

\[ y = 0.9298x \]
\[ R^2 = 0.8855 \]

B.

YSI vs. Grab Sample Dissolved Oxygen Comparison (8-30-02)

\[ y = 0.9539x \]
\[ R^2 = 0.9483 \]

C.

Outflow vs. Grab Sample Dissolved Oxygen Comparison (8-30-02)

\[ y = 1.0249x \]
\[ R^2 = 0.937 \]
Figure 14: Regressions of DATAFLOW NTU vs. Light Attenuation ($K_d$)
Profile Measurements
Figure 15: A. Regression of DATAFLOW NTU Turbidity vs. Light Attenuation ($K_d$) Profiles for All James River Calibration Stations.

B. Regression of DATAFLOW NTU Turbidity vs. Light Attenuation ($K_d$) Profiles for Combined James River and York River Calibration Stations
A. James River NTU versus Kd

![Graph showing the relationship between YSI 6600 NTU and Measured Kd for James River data. The equation is $y = 0.1047x + 0.2784$ with $R^2 = 0.5191$.]

B. York & James River NTU versus Kd

![Graph showing the relationship between YSI 6600 NTU and Measured Kd for York & James River data. The equation is $y = 0.087x + 0.5849$ with $R^2 = 0.8469$.]
Figure 16: Interpolated Surface Chlorophyll, Turbidity and Dissolved Oxygen Concentrations for the James River Study Area, June 3, 2002
James River June 3, 2002

Chlorophyll (ug/l)
- 0 - 5
- 5 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- 30 - 40
- 40 - 50
- > 50

Turbidity (NTU)
- 0 - 5
- 5 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- 30 - 40
- 40 - 50
- > 50

Dissolved Oxygen (mg/l)
- 0 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8 - 10
- > 10
Figure 17: Interpolated Surface Chlorophyll, Turbidity and Dissolved Oxygen Concentrations for the James River Study Area, August 1, 2002
James River August 1, 2002

Chlorophyll (ug/l)
- 0 - 5
- 5 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- 30 - 40
- 40 - 50
- > 50

Turbidity (NTU)
- 0 - 5
- 5 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- 30 - 40
- 40 - 50
- > 50

Dissolved Oxygen (mg/l)
- 0 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8 - 10
- >10
Figure 18: Interpolated Surface Chlorophyll, Turbidity and Dissolved Oxygen Concentrations for the James River Study Area, October 18, 2002