Probabilistic Monitoring

Summary

The Commonwealth of Virginia is rich in water resources with a wide variety of aquatic environments from fresh to salt, and montane to coastal plain. But it's the quality of a resource that gives it value. So, the question that needs to be asked is "How good is Virginia's water quality, and does it vary across the State?" The Virginia General Assembly, environmentalists, citizens, and the USEPA have encouraged the Virginia Department of Environmental Quality (VDEQ) to answer this question. VDEQ answers this question from a compliance perspective through the biennial 305(b) Report (VDEQ 2002). This thorough report is based on tens of thousands of data points collected from more than a thousand stations in streams, lakes, and estuaries of the Commonwealth. It provides a comprehensive comparison of these monitored waters to the Water Quality Standards. However, it is based on sample locations selected through the observer's understanding of what samples are needed and knowledge of where to best collect them. This targeted sampling has great utility for monitoring regulatory compliance of pollution sources, identifying impaired waters, and for tracking local pollution events. While point estimates of water quality are made with these data, it is difficult to extrapolate the estimates to unsampled waterbodies or to a geographic area of the Commonwealth for two reasons. First, the sample locations were not randomly determined. Second, the target population is the individual sites themselves and not a region or stream type where all points had an equal chance of being sampled. Consequently, the question "How good is Virginia's water quality, and does it vary across the State?" cannot be answered accurately for the State as a whole from these ambient data.

In response to the need to evaluate water quality in whole river basins and the Commonwealth in general, VDEQ added probabilistic monitoring (ProbMon) to its freshwater monitoring program in 2001. The aim of ProbMon is to provide an accurate regional assessment of the chemical, physical, and biological conditions of Virginia's water resources. The station locations have been selected randomly to allow the expression of water quality conditions in statistical terms. That is, a point value can be generated with an estimate of its precision. For example, it is possible to determine the true percent of streams having good water quality with 95% confidence.

ProbMon's focus is on non-tidal perennial streams in Virginia. VDEQ's ProbMon survey will collect data from approximately 300 stream locations over a five-year period. The survey is evenly spread over the period 2001-2005, with approximately 60 locations sampled each year, to incorporate wet, dry, and normal years in the database. In the end, the survey will provide policy-makers and the public with estimates of the status of Virginia's aquatic resources with statistical confidence. It will also describe associations between indicators of natural and anthropogenic stress and aquatic resources. Finally, it will be used to statistically assess the Commonwealth's water resources.

This section of the monitoring chapter analyzes selected ProbMon water chemistry data from autumn 2001 and spring 2002. These two years of monitoring only provide enough data to generally assess Commonwealth-wide conditions. As data is collected during the remaining three years of the study the assessments will become specific for subsets of the Commonwealth's water resources including stream order, river basin, and ecoregion. Although many questions about Virginia's waters can be answered with ProbMon data, not all can be. The reason is, we only get a good estimate of a parameter for some portion of the aquatic resource when the sample size is sufficiently large. The sample design's focus on stream order and on non-tidal streams also put limits on the questions that can be answered. As ProbMon provides responses to long unanswered questions, we may find a future that demands a more thorough undertaking to answer other questions. The results in ProbMon reports will help guide that future.

Monitoring Objectives

ProbMon's goal is to assess the condition of Virginia's non-tidal streams and rivers. The survey provides 1) estimates of the geographic coverage and extent of the aquatic resource conditions with known confidence; 2) estimates of the current status, and a basis to determine trends, and changes in indictors of Virginia's aquatic resources with known confidence; 3) statistical summaries and assessments of Virginia's aquatic resources; and 4) a description of associations between indicators of natural and anthropogenic stressors and the condition of aquatic resources. ProbMon was designed in part to meet requirements of the Water Quality Monitoring and Information Act (WQMIRA 1997) and the JLARC Review (1996). JLARC and WQMIRA specifically encouraged an increase in chemical and biological monitoring, statistical analysis of monitoring data, and statewide sampling comparisons for all water quality criteria. ProbMon specifically provides the foundation for meeting these requests. The sampling design allows for answering a wide variety of questions with statistical accuracy including the following examples.

Policy: What water quality issues do policy makers need to address?
Science: What types of streams are most threatened and what are the threats?
The Commonwealth's aquatic resources: How many river kilometers meet water quality standards?
The benthic macroinvertebrate community: To what degree do non-tidal waters have balanced, healthy macroinvertebrate communities based on the benthic metrics?

Probabilistic Uses and Limitations

There are several ways to evaluate the quality of streams in Virginia. One method is to survey all the streams in each basin, which would be extremely time-consuming with about 80,000 kilometers (50,000 miles) of streams in Virginia. The basin rotation module in the VDEQ monitoring scheme will produce a very coarse census. A second method is to use an empirical model for the water quality in each river basin. Models have to be calibrated and verified based on historical water chemistry records. Such models are also time-consuming and expensive, and currently are ineffective in determining the biological integrity of waters. A third way is to collect data using targeted methods. Targeted monitoring networks have been in place in most States for decades and significant funds have been invested in collecting data from them. Generally, these stations are strategically located at places suspected of having degraded water quality. Examples are above and below the outfall of a wastewater treatment plant or manufacturing facility. Traditional monitoring stations have also been placed where it is easy to sample. For example, most of the Virginia's ambient monitoring stations are at bridges. Data collected in this manner can be used to answer questions such as "Is a manufacturing facility in compliance with its wastewater permit?" or "Should the stream segment be on the Impaired Waters List?" While targeted monitoring is excellent at answering these critical questions, it cannot be used to speculate on the overall condition of the Commonwealth's water resources. The reason is that the ratio of degraded to non degraded waters is unknown. The final monitoring option considered is the probabilistic method, which is used in the ProbMon survey.

The probabilistic method allows VDEQ to establish baseline water quality information for river basins, stream types, and geographic areas in the Commonwealth. If the probabilistic study is repeated at a later time, trends in the quality of the resources can also be estimated. Probabilistic monitoring can address regional questions such as "What percent of piedmont Virginia streams have a pH lower than 6.5?" Most important, the estimates can be made with statistical confidence.

Probabilistic Monitoring Design

Probabilistic sampling sites were randomly identified using EPA / EMAP protocols. VDEQ provided information on the type(s) of aquatic resources to be sampled and EPA/ORD of Corvallis, Oregon, provided random geographical coordinates to be sampled within stream size classes (Strahler stream order). The Strahler stream ordering system is a general way of describing the size of a stream or river (Strahler 1964). The smallest continually flowing headwater streams are called "first order". When two first order streams join to form a larger stream it becomes a second order stream. Two second order streams join to form a third order, and so on. Smaller streams entering a higher-ordered stream do not change its order number. Because Strahler stream order is expected to be an important determinant of aquatic condition, the random selection of sites was arranged so that approximately equal numbers were chosen from 1^{st} - 4^{th} and 5^{th}+6^{th} order streams each year.

To gauge water quality across the Commonwealth, field and chemical data were collected at each ProbMon site (VDEQ, 2003b). Dissolved oxygen, pH, specific conductance, and temperature were measured in mid-stream, 0.3 m below the stream surface. Water and sediment samples were collected and sent to the Virginia Division of Consolidated Laboratory Services in Richmond, Virginia for analysis. In all, 79 chemical and physical parameters were measured at each site along with four field parameters. Selected parameters are discussed and the results for these parameters are presented. Although, benthic macroinvertebrates and habitat were sampled at most sites, only conventional pollution parameters are presented in this report.

Data Analysis / Assessment

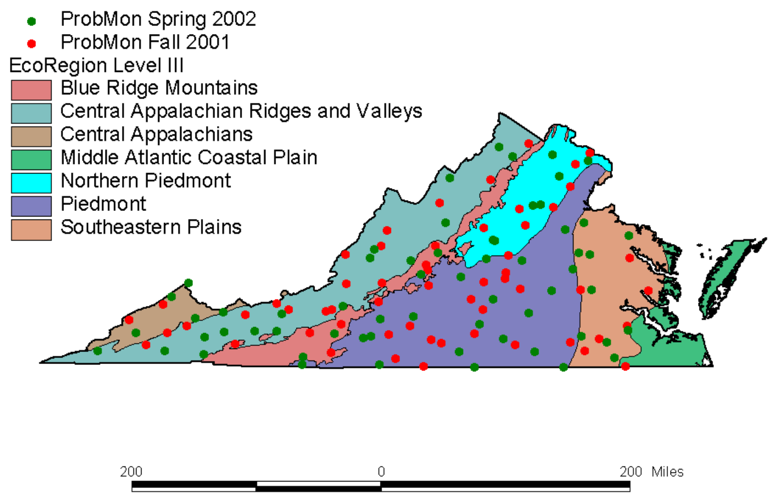
For this report, only a selection (DO, pH, temperature, and bacteria) of the 83 ProbMon parameters were analyzed through box plots, statewide maps, and data distributions. Boxplots were created to compare variables by Strahler order. Most water quality parameters are not normally distributed so the median was used to compare results across stream orders. Boxplots will eventually be used to compare other groupings as well. Maps showing the range of values for a variable across the State are a second method employed to detect patterns. The third method of analysis, following USEPA guidelines, involved the generation of cumulative distribution functions (CDF) for variables (USEPA 2002, Olsen 1999). The CDF is a statistical function that has been underutilized in environmental studies. Formally, it estimates the probability that a variable is less than or equal to some value. It is most useful displayed graphically so the viewer is able to determine the likelihood of any value. However, it can also provide the probability that a variable would be above a threshold or that it would be within a certain range. Importantly, because of the random sampling of ProbMon stations, these probabilities apply to all non-tidal streams in the Commonwealth. A detailed explanation of the CDF is available in the first year ProbMon report (VDEQ, 2003).

ProbMon Results

First-year results from the ProbMon survey are presented in the complete 2001 ProbMon report, available at the VDEQ web site at http://www.deq.state.va.us/water/probmon.pdf.

The analyses presented here are based on data collected in the autumn of 2001 and spring 2002. The map below shows these ProbMon sampling sites against Virginia ecoregions. Ecoregions are areas of uniform climate, topography, and biology that are expected to exhibit differences in chemical and biotic parameters. At present, VDEQ has collected too few samples to detect differences among ecoregions.

Figure 1. ProbMon stations sampled during fall 2001 (n=58) and spring 2002 (n=61) and the ecoregions of Virginia.



Dissolved Oxygen

Dissolved Oxygen (DO) is one of the most important determinants of habitat suitability for aerobic organisms. In streams, the concentration is altered by photosynthesis, respiration, nutrient input, reaeration, and temperature, all of which have seasonal cycles. These factors change gradually with the rise in elevation westward across Virginia. This natural variability is reflected in the water classes in Virginia's Water Quality Standards (Table 1). For example, a high-energy mountain stream in western Virginia (Class V and VI in Table 1) is expected to have higher DO than a low-gradient, warm water stream in eastern Virginia (Class III in Table 1). Although expectations vary, all waters in Virginia are required to have a DO of 4 mg/L or above. Streams that support stocked trout or naturally reproducing trout must have DOs of at least 5 mg/L and 6 mg/L, respectively.

Table 1. DO and temperature standards in Virginia by water Class (Commonwealth of Virginia 1997).

9 VAC 25-260-50. Numerical criteria for dissolved oxygen, pH, and maximum temperature.***

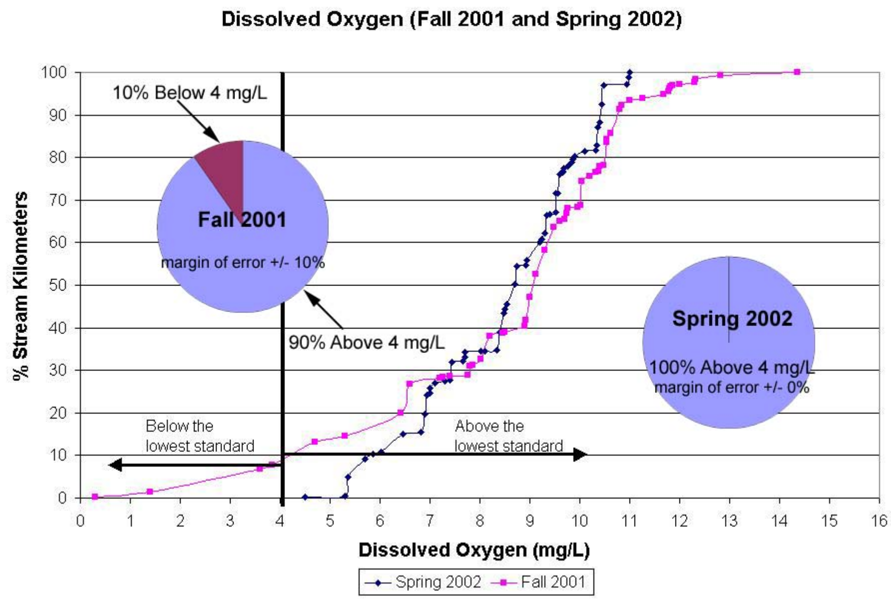
CLASS OF WATERS	DO (mg/l) Min.	DO (mg/l) Daily Avg.	pH	Maximum Temp. (°C)
I Open Ocean	5.0	--	6.0-9.0	--
II Estuarine Waters (Tidal Water- Coastal Zone to Fall Line)	4.0	5.0	6.0-9.0	--
III Nontidal Waters (Coastal and Piedmont Zones)	4.0	5.0	6.0-9.0	32
IV Mountainous Zones Waters	4.0	5.0	6.0-9.0	31
V Stockable Trout Waters	5.0	6.0	6.0-9.0	21
VI Natural Trout Waters	6.0	7.0	6.0-9.0	20
VII Wetlands	*	*	*	**

*This classification recognizes that the natural quality of these waters may fall outside of the ranges for D.O. and pH set forth above as water quality criteria; therefore, on a case-by-case basis, criteria for specific wetlands can be developed which reflect the natural quality of the waterbody.
**Maximum temperature will be the same as that for Classes I through VI waters as appropriate.
***The water quality criteria in 9 VAC 25-260-50 do not apply below the lowest flow averaged (arithmetic mean) over a period

Seasonal variations in DO concentration are directly related to temperature. Higher summer temperatures tend to produce lower DO concentrations because DO solubility is inversely proportional to temperature. During the winter months, most aquatic organisms have a lower metabolism and aquatic plants have died back so the demand for oxygen is less. In the summer, fish and aquatic insects require an adequate level of DO for feeding, growth, and reproduction. In addition, in the summer aquatic plants flourish and elevate DO levels in sunlight, but depress them in the dark.

Pollution plays an important role in DO concentration. Human and animal waste released into streams act as fertilizers. As microbes break down the organic matter, their respiration depletes the available DO so that aquatic animals may become stressed and die.

Figure 2. CDF curves and pie charts of DO from Fall 2001 and Spring 2002.



The utility of the CDF curve is that probabilities can be directly determined from the figure because the vertical axis is a cumulative probability. That is, it shows the chance of a DO value being the same size or smaller than that listed on the horizontal axis. Assuming the data in Figure 2 is representative of all Virginia non-tidal streams, we can pose questions such as "What percent of Virginia non-tidal streams had a DO below 4 mg/L during fall 2001?" To answer the question, on the figure draw a line up from the DO value of 4. Where the line intersects the fall 2001 CDF curve, draw a horizontal line to the vertical axis. The value on the vertical axis is approximately 10%. Then, the answer to the above question is, "10% of Virginia non-tidal streams have a DO less than 4 mg/L." Because the data set contains only 58 measurements, there is error associated with the answer. The confidence interval lines for the fall DO data occur at approximately 0% and 20% (not shown on Figure 2; represented by margin of error). See first year report for these confidence intervals. This means the precise answer to the above question is between 1% and 20% of the streams have DO less than or equal to 4 mg/L with 95% confidence.[1] The confidence intervals should narrow significantly as additional data are collected.

The two sampling periods covered by this report afford the opportunity to compare seasonal differences for the State. For example, and supported by Figure 2, during the spring 2002, the DO was above 4 mg/L 100% of the time. Meanwhile, in the fall DO fell below 4 mg/L 10% of the time. Although we are uncertain of the underlying reasons for the difference, we suspect it is a seasonal phenomenon rather than interannual climatic variation.

Figure 3. Spatial distribution of DO.

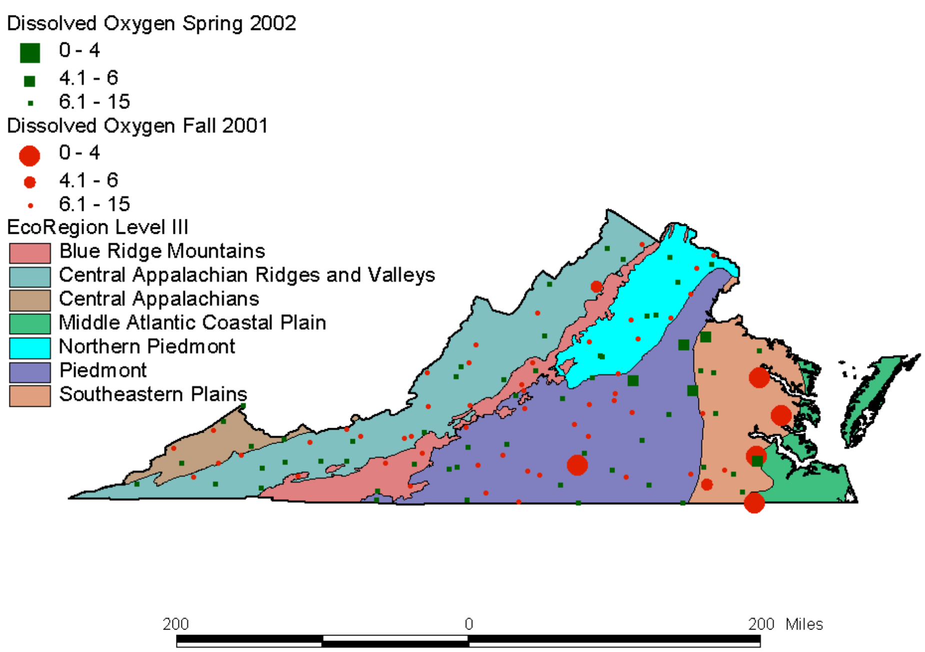


Figure 3 displays the DO measured across Virginia where larger dots and squares signify lower DOs. Several low concentrations occur in the Southeastern Plains and Middle Atlantic Coastal Plain ecoregions in the piedmont and tidewater areas. Streams in the east typically have a lower gradient so that snags, leaf packs, and fine

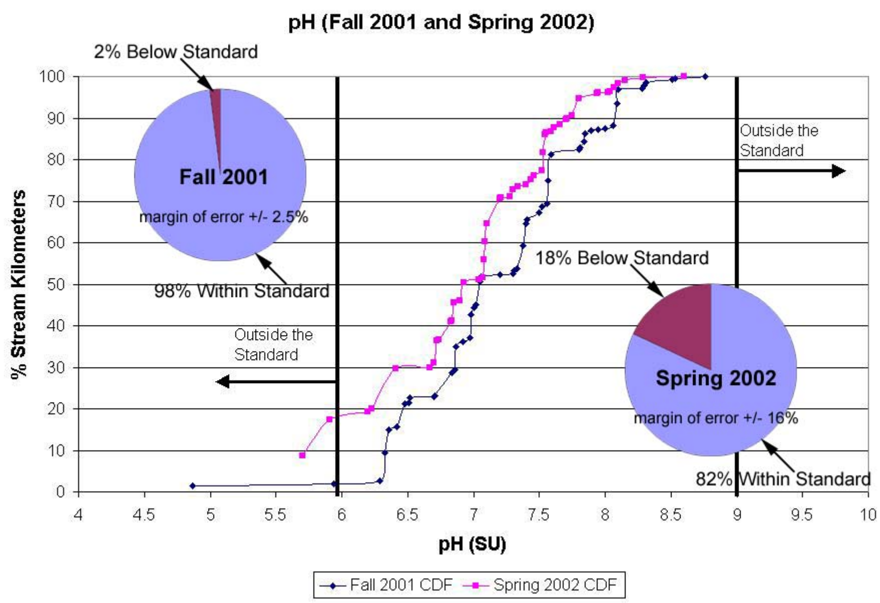
[1] When setting upper and lower limits for a statistic, a certain percent of the time the parametric value of the statistic will be contained within those limits. Thus, a 95% confidence interval in the figure suggests that in 95 out of 100 times we collect data and construct the intervals, they will cover the statistic. It is incorrect to say the statistic is contained in the interval 95% of the time; the interval changes, not the statistic (Sokal & Rohlf 1981).

sediments dominate the habitat. Lower gradient streams are slower moving and therefore have lower turbulence and reaeration and DOs. In addition, median temperatures are higher in the Piedmont and Southeastern Plains ecoregions. Because these eastern waters have lower DO solubility they are expected to have lower DO concentrations. During the Fall of 2001, severe drought may have contributed to low DO concentrations across the State.

pH

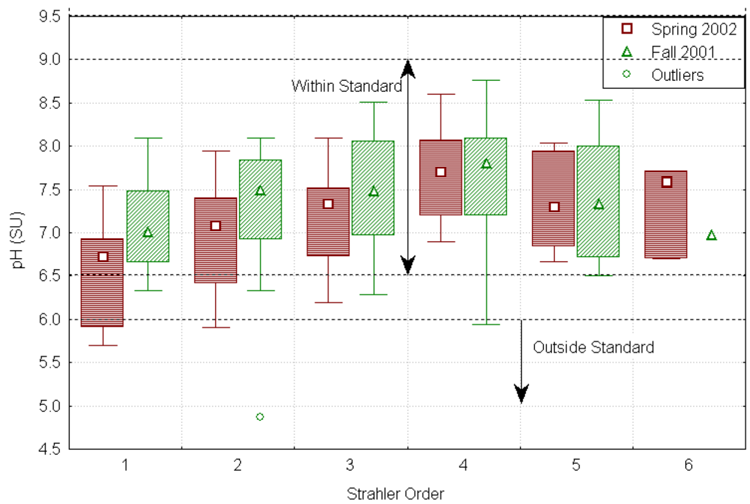
One of the primary indicators of water quality is pH. Stream pH depends on local ecology, the presence of inorganic and organic acids, and anthropogenic influences. Most aquatic organisms can withstand a pH as low as 6, but prefer a range between 7 and 8.5 (Barker et al. 1990). pH values harmful to aquatic life-use are the extremes; below 5 or above 9. This is reflected in Virginia's water quality standards, where all waters must have a pH range from 6 to 9, or 6.5 to 9.5 in certain streams (Table 1). pH standards are also determined case-by-case for natural conditions as in swamps and other wetlands (Commonwealth of Virginia 1997).

Figure 4. CDF curves and pie charts of pH from Fall 2001 and Spring 2002.



The regulatory pH boundaries are indicated on the CDF graph for pH in Figure 4. Based on the data collected thus far, pH violations are few in Virginia streams. Six sites had low pH readings. They were located in blackwater streams in eastern Virginia where the pH is naturally low due to the leaching of organics in these wetland-influenced streams. From the pH CDF curve in Figure 4, only 2% of sites sampled in the fall of 2001 had a pH below the lower regulatory limit of 6.0 and no streams exceeded the upper limit of 9.0. Spring 2002 probabilistic data showed 18% of Virginia non-tidal streams were below the pH standard. Again, the confidence intervals are quite large and predictions will be more refined as sampling continues. For now it appears pH violations occur on the acid side of the scale at a frequency that may be seasonally dependent.

Figure 5. Boxplot of pH from Fall 2001 and Spring 2002.



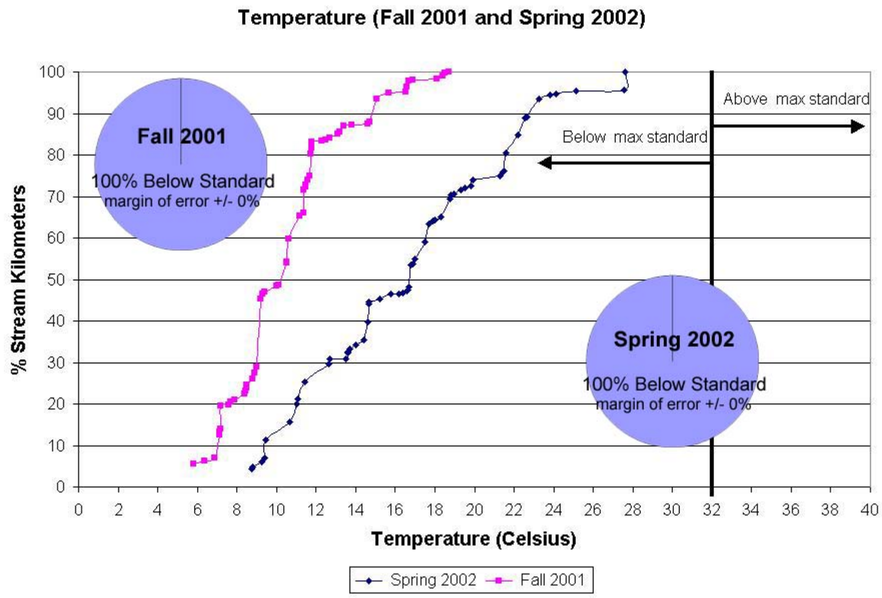
Box plots for pH by stream order are graphed in Figure 5. Because the max-min whiskers for all orders overlap, there is no statistical difference in pH between streams of different order. However, the medians suggest that pH initially increases from order 1 through order 4 streams and declines in higher orders. Most stream orders tend to exhibit lower pH in the spring. Future samples will help determine whether this is a consistent pattern.

Temperature

Temperature affects water quality by imposing a heat burden on aquatic life, and by limiting the level of dissolved gases in water. Temperature in streams varies in relation to seasonal and daily changes. Sunlight is the primary source of temperature change. However, stream temperature is also influenced by the temperature of the stream bed, groundwater inputs, and air in contact with the water surface. Temperature is inversely related to bank vegetation cover; less cover implies more exposure to the sun and higher temperature. Also, water temperature reflects the colder winter temperatures compared to the summer. Deviations from this trend occur especially in springs or in small streams. Also, runoff from impervious surfaces in urban areas typically increases water temperature. Finally, the effluent from dischargers tends to be warmer than the receiving stream and may elevate water temperature.

Stream temperature has a major effect on aquatic organisms. It can directly influence the types of organisms found in an aquatic system as well as their growth, behavior, metabolism, reproduction and feeding habits. The standards for water temperature reflect the maximum preferred temperatures for different forms of aquatic life across Virginia (Table 1).

Figure 6. CDF curves and pie charts of temperature from Fall 2001 and Spring 2002.



The majority of non-tidal freshwater streams in Virginia are designated Class III (coastal and piedmont zone waters) or Class IV (mountainous zones waters). The maximum temperature, a Class III water cannot exceed is 32°C and a Class IV water cannot exceed 31°C. Based on the CDF curve in Figure 6, all ProbMon sites from fall 2001 and spring 2002 had temperatures below 32°C. Therefore, is expected that nearly 100% of State waters are in compliance with temperature standards during the fall and spring seasons. These predictions will be further refined in the final ProbMon report through separate CDF curves for mountain and piedmont provinces.

Figure 7. Spatial distribution of temperature.

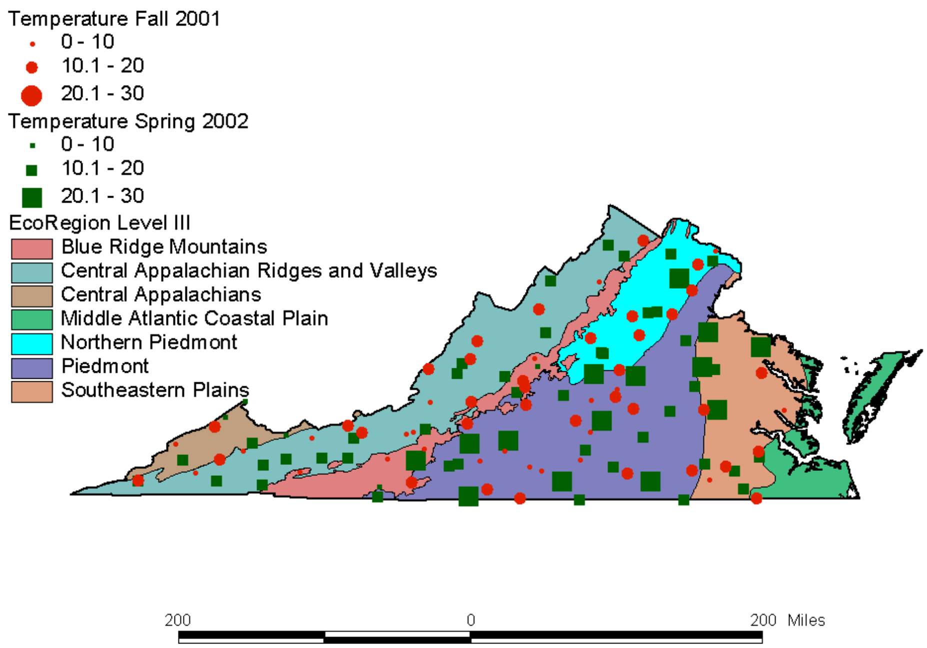
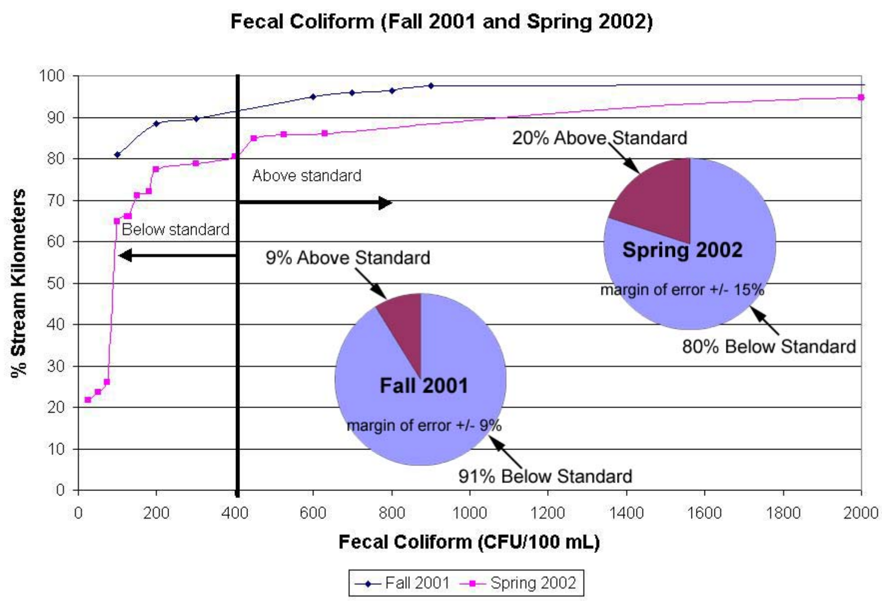


Figure 7 displays relative temperatures across the State. Large symbols indicate locations where water temperature was higher in the fall of 2001 (circles) and spring of 2002 (squares). Based on Figure 7, higher temperatures are found in the Piedmont and Southeastern Plains ecoregions. Stream temperatures are expected to be higher in these areas because of land use. The mountainous ecoregions, that is, the Central Appalachians and Appalachian Ridges and Valleys, tend to have lower temperatures because the streams are more rural or forested with more natural inputs.

Fecal Coliform Bacteria

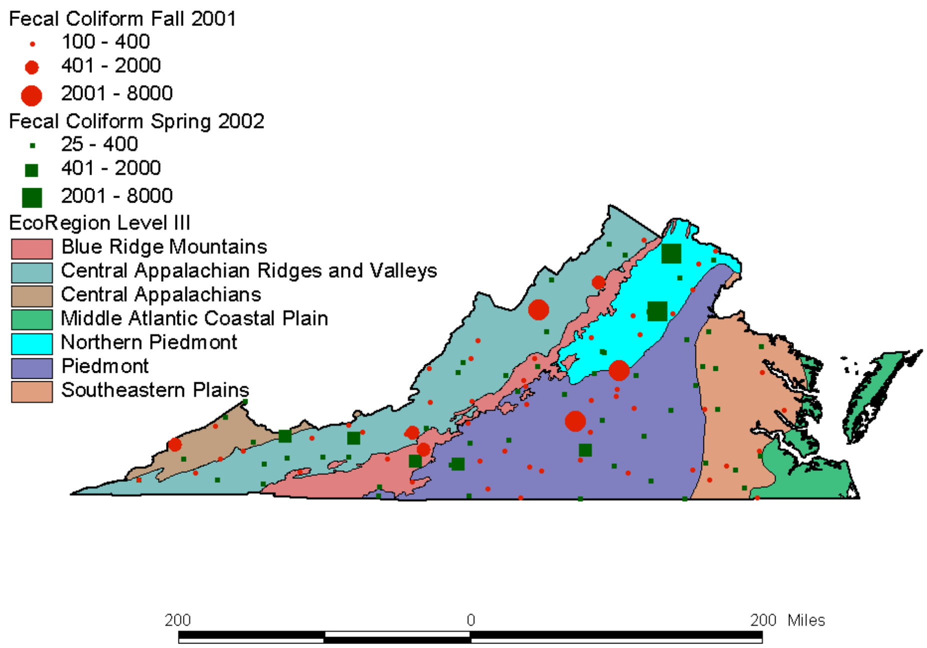
High counts of fecal coliform bacteria in a stream indicate that feces have entered the stream presenting the risk of human disease from pathogenic organisms. Fecal coliform bacteria are found in the fecal matter of all warm-blooded animals. By the Virginia water quality standard, a stream cannot exceed a geometric mean of 200 colony forming units (cfu) per 100 ml when sampled two or more times over a calendar month. The instantaneous standard is no more than 10 % of the samples in a calendar month exceeding 400 cfu/100 ml. *Escherichia coli* (*E. Coli*) became the official standard statewide in January 2003, but was not sampled during the first two years of ProbMon.

Figure 8. CDF curves and pie charts of fecal coliform bacteria from Fall 2001 and Spring 2002.



The bacterial count CDFs are graphed in Figure 8. In the fall of 2001, 81% of the counts were below the detection limit of 100 cfu/100 mL. Then approximately 9% of Virginia stream kilometers exceeded the interim bacteria standard of 400 cfu/100 mL. During spring 2002, nearly 20% of all Virginia stream kilometers exceeded the interim bacteria standard. These point estimates are currently very rough estimates; the confidence interval bounds are quite broad. Nevertheless, it is highly interesting that spring exceedances are nearly double those in the fall. Different hydrological regimes from spring to fall combined with land use differences could explain the elevated bacteria levels during the spring season. In highly agricultural areas spring rainstorms tend to wash accumulated bacteria-laden feces off pastures. The mechanism behind these seasonal differences needs to be explained as data accumulates.

Figure 9. Spatial distribution of fecal coliform bacteria.



Based on the bacteria map of the Commonwealth and its ecoregions in Figure 9, there is no relationship between bacterial counts and ecoregion except that high counts tend to occur in the middle and western parts of Virginia.

Conclusions

Two years of ProbMon data are discussed in this chapter based on date collection in fall 2001 and spring 2002. All sites were randomly selected by the USEPA using a stratification method developed in the EMAP program (Diaz-Ramos et al. 1996). The great value of random sites is that the estimates from the data apply to the entire population. Here, the population is the non-tidal waters of Virginia. Water chemistry was sampled at 58 sites in the autumn of 2001 and 61 sites in the spring of 2002.

The cumulative distribution function (CDF) was used with the chemical data to generate probabilities of a value being smaller or larger than a selected value. In this report a CDF graphs were used to determine the chance of DO, pH, temperature, and bacteria values in Virginia's streams exceeding state water quality criteria. The method also provides confidence limits that are important gages of the precision of the statistic. For these first two years, the estimated confidence limits for environmental conditions are fairly wide. That is, they are imprecise. As more data are collected the confidence limits will narrow. This will allow tight estimates of parameters of interest to facilitate the intelligent management of Virginia's aquatic resources.

Future Trends

In this brief glimpse into Virginia's ProbMon program, only a fraction of the program's data could be presented. ProbMon collects biological data using EPA's Rapid Bioassessment Protocols (RBP). A goal of VDEQ's biomonitoring program is to increase the number of reference sites across the State so that reference conditions can be translated into a multimetric index for macroinvertebrate communities. The data collected at random sites in the ProbMon program will accelerate this process and help refine reference conditions throughout the Commonwealth.

The Virginia ProbMon survey includes a habitat assessment component to determine the percent of non-tidal streams that have exceptional quality as well as the percentage of degraded streams. Habitat data are collected using the RBP visual habitat assessment methods. These methods use qualitative scoring that is subjective but comparable State wide when performed by trained biologists. In some regions of the State, biologists collected additional quantitative and qualitative habitat data. The goal of collecting quantifiable physical habitat data is to separate the difference between anthropogenic versus geologic processes in channel adjustment (Rosgen, 2001). One of the more elusive parameters to quantify is increased sediment supply to streams (Kappesser, 2002). According to Rosgen several factors control river channel form, principally streamflow, sediment regime, riparian vegetation, and direct physical modifications. Quantifiable physical data can predict an increase of sediment supply over natural conditions.

Another part of the freshwater ProbMon program collects and analyzes the land cover upstream of ProbMon sites. The land surrounding a water body can significantly impact in-stream water quality, and thereby alter the physical habitat and biological community. VDEQ intends to create a filtering matrix of habitat and chemical data to identify potential reference sites using land cover data. As ProbMon evolves, the quantity and variety of habitat data collected will expand to better define the range of physical habitat, and to allow the detection of relationships between physical habitat, biological communities, land cover and water quality.

References

Barker, J.P., D.P. Dernard, S.W. Christensen, and M.J. Sale. 1990. Biological effects of changes in surface water acid-base chemistry, in National Acid Precipitation Assessment Program, Acidic Deposition: State of Science and Technology, Vol. II, September 1990, State of Science and Technology Report 13.

Commonwealth of Virginia. December 10, 1997. Water Quality Standards (9 VAC 25-260-00 et seq.). Department of Environmental Quality, Richmond, VA.

Diaz-Ramos, S., D.L. Stevens, Jr., and A.R. Olsen. 1996. EMAP Statistics Methods Manual. EPA/620/R-96/002. Corvallis, OR: U.S. Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory. [see http://www.epa.gov/nheerl/arm/analysispages/techinfoanalysis.htm for downloadable file]

Kappesser, Gary B. 2002. A Riffle Stability Index to Evaluate Sediment Loading to Streams. Journal of American Water Resources Association. Vol 38, No 4, pp. 1069-1081

Olsen, A. 1999. Personal Communication with Environmental Protection Agency, Office of Research and Development, Corvallis, Oregon.

Rathbun, S.C., R. Houghton, and C. Laurin. 1996. Cramer-von Mises Tests for Environmental Monitoring Data. U.S. Environmental Protection Agency, Science and Ecosystem Support Division, Ecosystem Assessment Branch, Athens, Georgia.

Rosgen, David. A Stream Cannel Stability Assessment Methodology. Wildland Hydrology. http://www.wildlandhydrology.com/html/references_.html.

Sokal and Rohlf. 1981. Biometry. Freeman and Company, NY.

Strahler, A.N. 1964. Quantitative geomorphology of drainage basins and channel networks; section 4-2, in *Handbook of Applied Hydrology*, ed. Ven te Chow, McGraw-Hill, New York.

USEPA (United States Environmental Protection Agency). November 2002. Presentation "Coastal Design" (Virginia Engle) in: Coastal Monitoring Design and Analysis Technology Transfer Workshop for VA, NC and MD. Glen Allen, VA.

Virginia Department of Environmental Quality. 2003. The Quality of Virginia Non-Tidal Streams: First Year Report. Richmond, Virginia. VDEQ Technical Bulletin. WQA/2002-001. http://www.deq.state.va.us/water/probmon.pdf.

Virginia Department of Environmental Quality. 2003b. Probabilistic Monitoring Protocol SOP. Draft. July 2003.