VIRGINIA WATER RESOURCES RESEARCH CENTER

PROTECTING OUR WATER RESOURCES FOR THE NEXT GENERATION: WHERE DO WE GO FROM HERE?

PROCEEDINGS

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
BLACKSBURG, VIRGINIA

2001

Funds for the support of this symposium and publication are provided by the Virginia Water Resources Research Center. The contents of this publication do not necessarily reflect the views or policies of the Virginia Water Resources Research Center, nor does the mention of commercial products, trade names, or services constitute an endorsement or recommendation.

Additional copies are available while the supply lasts and may be obtained from the

Virginia Water Resources Research Center
10 Sandy Hall
Blacksburg, VA 24061
(540) 231-5624
FAX: (540) 231-6673
e-mail: water@vt.edu
homepage address: http://www.vwrrc.vt.edu

Leonard A. Shabman, Director

PROCEEDINGS

Virginia Water Research Symposium 2001

Protecting Our Water Resources for the Next Generation

Where Do We Go From Here?

Judy Poff, Editor

November 14-16, 2001

Doubletree Hotel
Charlottesville, Virginia

Sponsored by
Virginia Water Resources Research Center

P7-2001

TABLE OF CONTENTS

OPPORTUNITIES FOR ALTERNATIVE WATER SUPPLY

Chris DeWitt
Vanasse Hangen Brustlin, Inc. (VHB)
477 McLaws Circle
Suite One
Williamsburg, VA 23185
(757) 220-0500
(757) 220-8544 fax
cdewitt@vhb.com

KEYWORDS: crest controls, siltation, conservation, regulatory climate, public involvement

ABSTRACT

PROBLEM STATEMENT

Based on an increasing demand due primarily to population growth, and coupled with a decreasing supply due to siltation in its primary reservoir, the Rivanna Water and Sewer Authority faces an acute water supply deficit in the near future. To provide additional supply, for years the RWSA has planned on constructing a new reservoir on land it currently owns. Implementation, however, is complicated by the current regulatory climate and local political environment, both of which favor development of less environmentally intrusive alternatives.

RESEARCH APPROACH

Research included a range of alternatives, including the proposed reservoir. As a starting point, an exhaustive analysis of future demand and supply was conducted, using a 50-year planning horizon. Long-term demand, in particular, received a great deal of attention as the major factor driving the planning process. Several methods were used to estimate future water use, resulting in a range of figures from 18 to 21 mgd. Projections indicated that by the year 2050 the water supply deficit will be roughly 15 mgd.

More than thirty alternatives were screened against criteria including effectiveness, practicability/cost, and environmental impact. Generally speaking, the alternatives included new reservoirs, indirect reuse, groundwater, conversion of existing reservoirs to pumped storage, increased storage capacity at an existing reservoir, sediment reduction, and demand management. In addition to the technical analysis, the screening process included public meetings that attracted several hundred participants, as well as close coordination with regulatory agencies.

MAJOR FINDINGS

Given the topographic conditions at the RWSA's primary reservoir, along with public support for a phased implementation strategy, viable alternatives are available that would provide the needed supply and avoid new reservoir construction at least into the middle of the planning period. Specifically, installation of 4' crest controls on an existing dam would increase safe yield sufficiently to provide roughly 35 years of additional supply. This strategy would also provide ample time to monitor demand, sedimentation, water conservation, and drought management, allowing the RWSA to reassess

its long-term needs. At this time there appears to be significant regulatory support for the proposed strategy.

INTRODUCTION

The Rivanna Water and Sewer Authority (RWSA) is responsible for providing potable water to the city of Charlottesville and the urban areas of surrounding Albemarle County in central Virginia. Together, these areas comprise the RWSA's Urban Service Area. In 1985, the RWSA purchased 670 acres of undeveloped land on which it planned to construct a water supply reservoir to meet future water demand in the Urban Service Area. The land is located on Buck Mountain Creek in northern Albemarle County. Studies completed in the 1970s and 1980s had resulted in the conclusion that the Buck Mountain site offered the best alternative for a future water supply reservoir (Malcolm Pirnie 1972, Camp Dresser & McKee 1977, 1983), and the RWSA purchased the property as a planning measure.

In 1996, the RWSA sought to permit and develop Buck Mountain Reservoir in accordance with their plan. While the RWSA originally envisioned the effort as permitting of a new reservoir, the approach taken by the study team was broader in scope. The process involved an assessment of future supply and demand, evaluation of a wide range of alternatives, and identification of the most practicable, least environmentally damaging alternative. As a result of this process, it now appears that other, less environmentally intrusive alternatives are capable of meeting the current and future needs of the Urban Service Area until at least the middle of the year 2050 planning period. Specifically, the consultant team has recommended a comprehensive water supply strategy whose primary elements are water conservation, controlling siltation in existing reservoirs, and installation of 4' crest controls on an existing dam at the area's largest water supply. This strategy responds to the reality of the current regulatory climate and the local political climate, both of which favor alternatives to reservoir construction.

Supply and Demand

As a starting point in the alternatives analysis process, the study team investigated water supply and demand within the Urban Service Area over a 50-year planning horizon. As the basis for the decision making process, considerable up-front effort was spent to establish the potential need for and quantity of additional supply. To develop acceptable estimates for long-term supply and demand, the study team worked closely with the RWSA, local officials, and regulatory agencies as described below. As our investigations indicate, the need for additional water supply in the Urban Service Area results from two primary factors: a decreasing supply from reservoir siltation and increasing demand associated with population growth.

Supply

The RWSA currently relies on several surface water supply sources, but its primary source is the South Fork Rivanna Reservoir (SFRR), constructed in 1965. During design of the facility, two issues were considered that are particularly relevant to the current project. First, the dam was designed to accommodate 4' crest controls in the event additional yield was needed at some future time (Polglaze and Basenberg 1959). Second, engineers predicted significant siltation in the reservoir due to natural conditions in the area, estimating an annual loss of 19.6 million gallons of storage volume (Polglaze and Basenberg 1959). The siltation issue has proven to be the most important factor in analyzing long term supply.

Recent bathymetric surveys have indicated that actual loss of storage volume has been 13 million gallons per year, less than originally predicted (Black & Veatch 1994). In order better to understand the causes of siltation, Vanasse Hangen Brustlin, Inc. (VHB) utilized a Geographic Information System (GIS) platform to help analyze the relationships among soils, elevation, slope, land cover, water quality, and water features. Two important factors emerged from this analysis – watershed size relative to reservoir size and erosion indices. At 401 acres, the SFRR receives runoff from a watershed of 165,000 acres – extremely large relative to the reservoir's size. In terms of factors contributing to the erosion, the watershed is characterized by the presence of steep slopes, slow to moderate soil infiltration rates, and high erosion hazard. A combination of factors contributing to erosion results in the classification of 82% of the watershed as "very high" on the erosion index.

In part to address reservoir siltation, Albemarle County has implemented an increasingly aggressive sediment control program since 1977. The program currently includes a full-time Water Resource Manager, public education, requirements for Best Management Practices (BMPs), and a riparian buffer requirement, among other elements (Albemarle County 2000). Although it is difficult to quantify the effects of these efforts, it appears that they have prevented an increase over time in the rate of sedimentation. While development in the watershed has grown, the rate of siltation has not shown a corresponding increase. As predicted by the reservoir's original designers, it appears that the watershed is experiencing a naturally high rate of erosion that is a function of its size, and natural and geologic conditions.

As a result, the SFRR (and thereby the entire existing water supply system) continues to lose capacity. By the year 2050, the system will provide only 5 mgd in safe yield – far less than even the current demand of 12 mgd.

Demand

As the supply in the RWSA system has decreased over time, demand has increased at a steady rate (see Figure 1). In order to estimate the future water demand through the year 2050 planning horizon, several different methods were used. These various methodologies resulted in a total water demand by the year 2050 in the range of 18 to 21 mgd to supply the Urban Service Area. Forecast methodologies and results were reviewed with local planning officials to ensure consistency with planned growth. As shown in Figure 1, the demand in the year 2050 will exceed the supply by roughly 15 mgd, the net water deficit for the year 2050. Furthermore, as the graph indicates, current demand could potentially exceed existing safe yield during the next severe drought.

Given the importance of demand in planning for the future water supply, the study team sought input from the regulatory agencies, especially the United States Environmental Protection Agency (EPA), on both the projection methodology and the resulting numbers. As a result of this involvement, the EPA provided the team with a written opinion on the demand analysis prior to the completion of the alternatives analysis discussed below. Although the EPA has reserved the option to request additional demand analyses should the recommended strategy require an environmental impact statement, the agency has agreed to move forward with the demand projection at this time (EPA 2000). Receipt of their comments early in the study process allowed the focus to shift from demand to alternatives.

Alternatives Analysis

The next step in the study process involved identifying and screening a comprehensive set of project alternatives. The study team screened more than 30 alternatives against criteria including effectiveness (ability to meet the projected water deficit), practicability/cost, and environmental impact. To facilitate review of the alternatives, a comparative matrix was developed.

Regulatory coordination played a key role in the project development, and the early stages of the analysis included meetings and field visits with regulatory and advisory agencies. These meetings helped all the parties understand the details of the various alternatives, and also provided an early opportunity to discuss potential issues and impacts. Public involvement also occurred early in the process; the study team held several public meetings as part of the initial screening effort. Both the agencies and the public were given opportunities to participate throughout the process.

The alternatives generally fall into three broad categories: new water supply facilities (i.e. reservoirs, water intakes, etc), improvements to the existing facilities, and demand management. Due to their potential for environmental impacts, cost, and the availability of other options, the construction of new reservoirs appeared progressively less attractive over the course of the study. The following section focuses on the alternatives that comprise the strategy recommended to the RWSA by the study team.

ALTERNATIVES RECOMMENDED FOR IMMEDIATE IMPLEMENTATION

Water Conservation and Drought Management

By the year 2050, we estimate that aggressive water conservation could result in average demand reductions totaling 1.7 mgd, and that drought management could save 2.4 mgd. The combined effects of these measures would result in an overall demand reduction of 21% in the year 2050. This figure compares well with similar programs investigated as part of this study (city of Asheville, city of Greensboro, New Mexico Water Conservation Alliance). Although the full benefit of these measures will not be realized until the end of the planning period, proportionately smaller benefits could accrue in the short-term.

Sediment Control

If the rate of sedimentation in the SFRR could be reduced, it would be possible to increase its projected yield through the year 2050. Albemarle County currently implements a strong sediment control program. Although the effects of this program on reservoir siltation cannot be easily quantified, it is possible that control measures have prevented an increase in the rates of sedimentation as development in the watershed has continued. In fact, based on the available data, it appears that sediment rates have remained relatively constant over time, and that the actual rate has been slightly less than predicted when the reservoir was constructed. Furthermore, anecdotal evidence suggests that reservoir water quality may have improved over time. It is possible that sediment control measures have contributed to this phenomenon. Therefore, the study team has recommended that Albemarle County's program continue, and that studies (including regular bathymetric surveys) be pursued to determine whether the program can be enhanced.

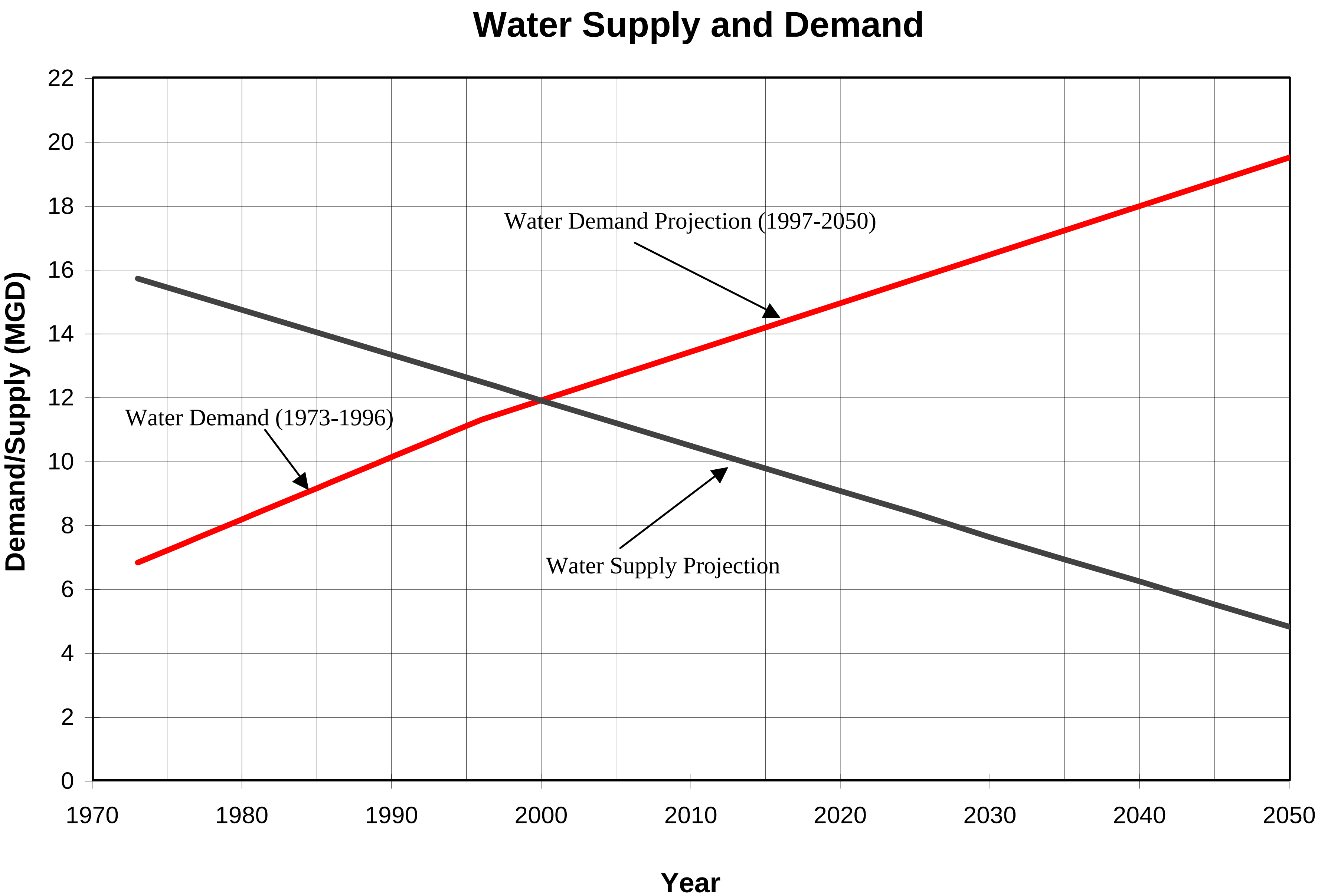

Water Supply and Demand
Demand/Supply (MGD)
22
20
18
16
14
12
10
8
6
4
2
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Year
Water Demand Projection (1997-2050)
Water Demand (1973-1996)
Water Supply Projection

Figure 1

Four-foot Crest Controls

Adding 4' crest controls to the SFRR dam would provide an immediate increase in the reservoir's safe yield of approximately 11 mgd. The actual increase in safe yield as of the year 2050 would be 7 mgd, assuming a constant 8 mgd mandatory minimum release is imposed at the SFRR and assuming sedimentation continues at its present rate. The alternative would make use of the existing SFRR as well as treatment and transmission facilities, and would extend the useful life of the reservoir. Furthermore, based on current projections of supply and demand, it would provide approximately 35 years of additional supply, significantly delaying the need for other more costly or environmentally intrusive alternatives. Should sedimentation decrease, or should demand management prove more effective than estimated, this alternative could meet future water needs for an even longer period.

The crest controls would allow the RWSA to institute a minimum 8 mgd constant release, thereby augmenting downstream flow during severe droughts. Also, the alternative involves relatively minor wetland impacts that could be offset through mitigation.

CONCLUSIONS

A fortuitous combination of factors in the Urban Service Area makes possible the implementation of water supply strategies that could delay or eliminate the need for more costly alternatives with greater environmental impacts. The area's topography is a significant factor – steep slopes around the reservoir minimize the amount of required land purchase. Furthermore, the existing dam was designed to accommodate crest controls. Finally, public support for conservation and other alternative supply sources is strong.

Public and regulatory involvement proved critical to the planning process. The public process continues as RWSA prepares to decide on the recommended strategy – their decision will benefit from a major public meeting and input from both local governing bodies. Engaging the regulatory agencies in the supply and demand analysis, as well as the alternatives analysis, helped to avoid surprises late in the process. Although the EPA reserved final judgement on the demand forecast, the proposed combination of implementation measures makes any additional demand analysis unlikely.

ACKNOWLEDGEMENTS

The author would like to acknowledge the following organizations that contributed to the study process:

The Rivanna Water and Sewer Authority
The Albemarle County Service Authority
The Albemarle County Department of Engineering & Public Works
The Charlottesville Public Works Department
O'Brien & Gere Engineers, Inc.
McSweeney, Burtch & Crump, PC
Ellis & Thorp, LLC

In addition, the following individuals provided invaluable editorial support: Ms. Karin Ertl and Ms. Christina Shumate, VHB

REFERENCES

Black & Veatch. November 1994. Interim Memoranda for the Urban Raw Water Management Plan.

Camp Dresser & McKee. July 1977. Report on Alternative Water Supply Sources.

Camp Dresser & McKee. October 1983. Buck Mountain Feasibility Study: Phase IV – Preliminary Design Memorandum.

City of Asheville, NC, Water Resources Department web page. Regional Water Authority "Drought Performance." http://www.ci.asheville.nc.us/water/annual.htm

City of Greensboro, NC, Water Conservation Program. "City of Greensboro Water Fact Sheet." January 13, 1999. http://www.ci.greensboro.nc.us/waters/H2Oconserv/waterfaq.htm

Letter of December 8, 2000 from Regina Poeske, Environmental Protection Agency, to Nancy G. Barker, VHB.

Malcolm Pirnie, Inc. 1972. Feasibility Report on Regional Water Supply and Wastewater Disposal.

Memorandum of May 15, 2000 from Stephen Bowler and David Hirschman, Albemarle County, to Karin Ertl, VHB.

New Mexico Water Conservation Alliance. Spring 1999. *Conservation Current*, "Water Budgeting Achieves Results." http://wrri.nmsu.edu/wrdis/conserve/news/spring99/current.html

Polglaze and Basenberg Engineers. December 1959. Report on Water Works System, Charlottesville, Virginia.

MUNICIPAL WATER SUPPLIES AND WATERSHED PLANNING

Richard C. Collins
Urban and Environmental Planning
University of Virginia
Charlottesville, VA
Rcc3f@virginia.edu

KEYWORDS: land-use planning, water supply planning, integrated resource management

ABSTRACT

Planning for municipal water supplies is an increasingly complex task. Particularly problematical is the relationship between land use planning and water supply planning in a community/region where the rate, timing, and location of growth is a political issue. Policy congruence between those who are directly accountable to the electorate, and the political/ corporate entity that is created to supply regional water and waste-water treatment, and is one step removed from direct political accountability, may be limited by differences in planning practices for land and water.

This paper will discuss the appropriateness of integrated resource management (IRP) as it is utilized in the electrical utility industry and in some states in the American West. The IRP process emphasizes competing uses for water and their allocation rather than as a municipal water supply orientation that responds to land use growth demands. The relevance of IRP concepts and practices of prior appropriation "growing communities" allocations to riparian doctrine states such as Virginia will be explored and analyzed.

Particular attention will be directed to comparing and contrasting water supply planning and land-use planning processes in the Charlottesville/Albemarle region.

WATER DEMAND FORECASTING: GUIDELINES FOR NAVIGATING THE REGULATORY MAZE

William Cox
Civil and Environmental Engineering
Virginia Tech
Cox@vt.edu

Kurt Stephenson
Agricultural and Applied Economics
Virginia Tech
Blacksburg, VA 24061
Kurts@vt.edu

KEYWORDS*:* demand, water, forecasting, planning, permits

INTRODUCTION

Water demand forecasting is an increasingly important aspect of water supply management. The principal task of water supply managers has always been to maintain a balance between available supplies and the demand for water exerted by those served by the system. However, the nature of this task has undergone a major transformation within the past few decades. Traditionally, demand forecasting was a relatively simple exercise of projecting future water usage as a continuation of current trends or as a direct function of a basic factor such as population. The primary emphasis of water supply planning was to identify and evaluate options for expanding supply on a schedule to avoid significant potential for occurrence of supply deficits where demand could not be met.

This approach remained acceptable to the public and consistent with public policy and governmental regulatory programs as long as increasing the development of natural water supplies was viewed as their highest use. A primary impact of this approach is the continuing construction of water storage reservoirs and the associated loss of natural water conditions such as free flowing streams and wetlands. Decreasing public acceptance of such losses of natural environmental conditions has been reflected in changes in public policy and regulations that reduce the feasibility of traditional water supply practice.

In the current regulatory environment, projected increases in water demand that underlie proposals for additional supply development undergo substantial scrutiny. The validity of demand projections is a primary target of opponents of water development projects. Special emphasis is placed on the extent to which such projections incorporate efforts to control demand as a means to avoid supply deficits as an alternative to the traditional practice of relying almost exclusively on supply expansion.

This paper reviews current demand projection methods and examines the potential accuracy of various approaches as well as the varying requirements for data associated with alternative methods. It then evaluates the acceptability of these demand projection practices within the current regulatory maze confronting proponents of water development projects. This regulatory analysis will be based on review of the records of regulatory proceedings associated with examples of recent project proposals.

DEMAND PROJECTION METHODS

In general, water demand forecasts can be distinguished by the degree of disaggregation of water user types and the type of causal analysis. User type is a specific category of water user. For instance, water use could be classified as residential, commercial, industrial users, and agricultural users. Causal analysis refers to the way a water planner relates past water use to future water use. Causal analysis may simply extrapolate past water use trends into the future (trend analysis) or attempt to identify the underlying determining causes of total water use (explanatory analysis) (Shabman 1987). Explanatory causal analysis can use either a behavioral approach, derive water forecasts by distinguishing observed water consumption behavior under different demographic, economic, climate, and policy factors, or through identification of the water consumption requirements of technologies used by a particular type of water user.

Trend Analysis. In trend analysis water use is simply a function of time. The simplest form of trend analysis would be to extrapolate the total historical water consumption into the future. A variation of trend analysis would separate total water use into two elements: per capita consumption and total population (see Figure 1). The water planner would then project past per capita water consumption and population trends into the future. A more sophisticated trend analysis would disaggregate water use into different categories of users (see Figure 2). For each water use type, a separate projection is made for per unit water consumption (water use per household, per employee, or per irrigated acre) and the number of new user types within a category (number of households, employees, or irrigated acres).

Figure 1: Simple Trend Analysis

Per unit water consumption per capita use = *f* (time)	**X**	*Number of consumption units* population = *f*(time)	⇨	**Forecasted Water Use**

Figure 2: Disaggregated Trend Analysis

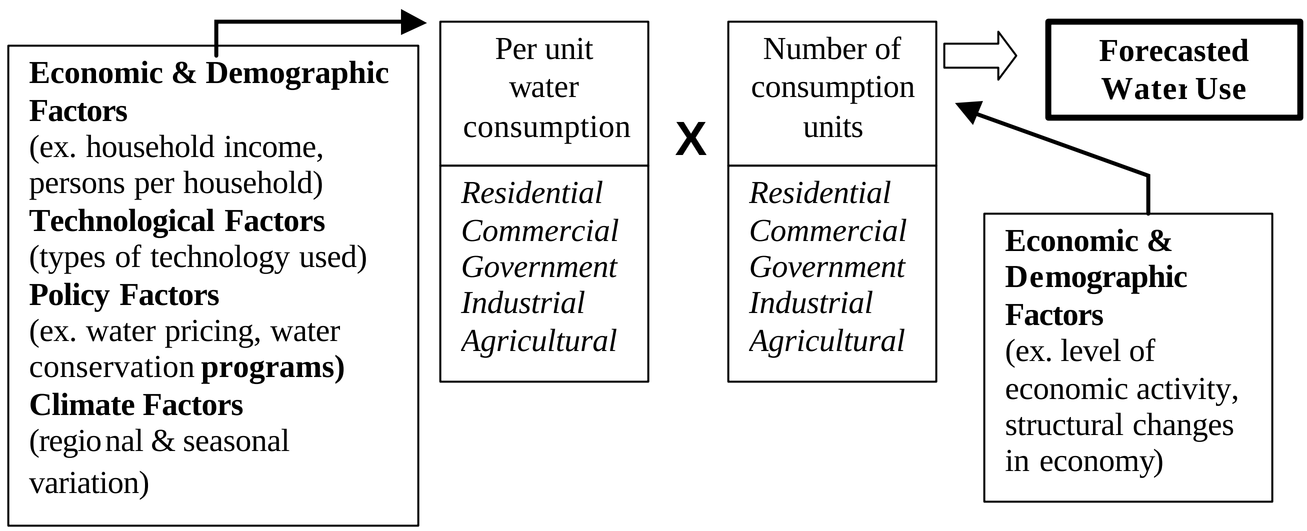
Per unit water consumption	**X**	Number of consumption units	⇨	**Forecasted Water Use**
Residential *Commercial* *Government* *Industrial* *Agricultural*		*Residential* *Commercial* *Government* *Industrial* *Agricultural*		

Behavioral Explanatory Analysis. A behavioral approach to explaining water use is to isolate how specific explanatory factors, such as economic/demographic, technology, policy, and climate variables may influence per unit water consumption (see Figure 4). The approach could be called behavioral explanatory analysis because the water planner seeks to articulate and quantify how the behavior of individual water users (residents, industrial users, agricultural users, etc) changes in response to different conditions and situations (different income levels, lot sizes, water price, and climatic conditions). The relationship between water use and these explanatory factors is established statistically using primary data or estimated based on the results from previous water demand statistical studies.

Policy factors are the factors that influence water use that are under the direct control of the water planner (see Figure 3). The water planner can directly change these determinants of per capita water use in order to influence overall water consumption. Water pricing structures and education programs are both policies that can be used to alter per capita use. Explanatory analysis provides the water planner with insights into how responsive water use will be to such policies.

An explanatory analysis may also be used to identify determinants of changes in the number of water consuming units. Changes in the population or business activity levels are influenced by a number of economic and demographic factors (see Figure 4). For instance, explanatory analysis would identify how projected economic growth might influence population growth in a given region.

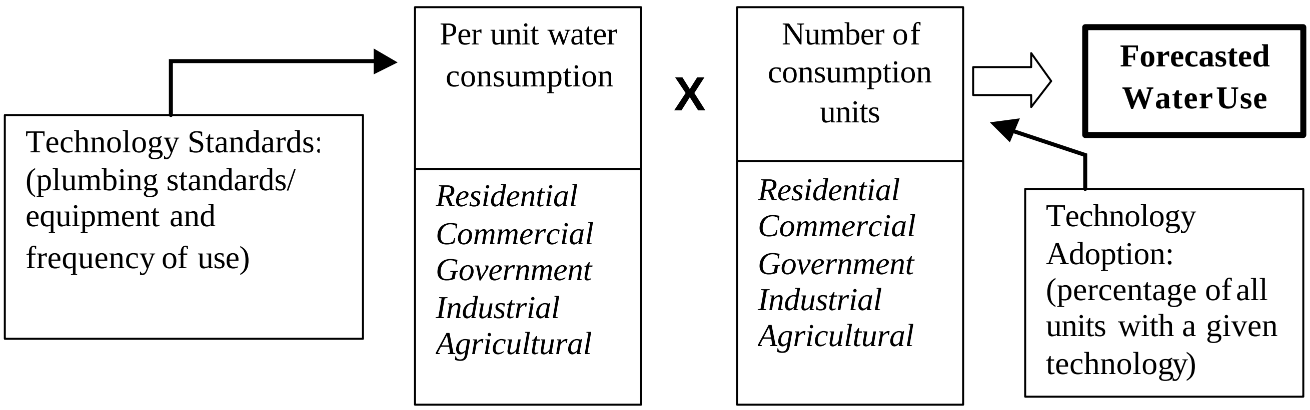
Figure 3: Behavioral Explanatory Analysis



Engineering Explanatory Analysis. An engineering approach to explanatory analysis seeks to explain past and future water use by calculating the engineering or technical water use requirements of specific technologies used by a particular type of user (see Figure 4) (Billings and Jones 1996). The assumption is that total water use is primarily explained by the type of water related technologies and equipment being used by different water users (PMCL 2001). An engineering analysis of the residential water uses, for example, would begin by identifying the different end uses of water — showers, baths, dishwashing, laundry, lawn watering, car washing, and toilets — within the household. A variety of technologies are available for each use. Toilets are designed with different gallons per flush and showerheads have different flow rates. A per capita water use estimate can then be derived by multiplying the water use efficiency of different technologies by the frequency of use of that technology (e.g. flushes per day or minutes per shower). Total water use is then calculated by multiplying the per capita water use by the number of residents using a given technology (percentage of total households with low flow toilets).

Forecasting future water demand with an engineering approach requires projections about the water consumption requirements of future technologies and adoption rates of present and future technologies. The types of technologies available in the future and rate of technological adoption can be established by expert opinion. The rate of technological adoption could also be formed by the statistical studies that relate the adoption rates to factors such as water rates, household income, and the existence of water conservation educational programs.

Figure 4: Explanatory Analysis: Engineering Approach



DEMAND PROJECTION: WHAT IS ACCEPTABLE TO THE REGULATORS?

As this brief description of water demand methods illustrates, water demand forecasting methods can vary substantially in the level of sophistication of the causal analysis and the amount of disaggregation in the types of water use. Obviously, more sophisticated and disaggregated analysis can improve the accuracy of the forecast through an improved understanding of the underlying factors determining total water consumption. Yet, regardless of how sophisticated the analysis, all demand projections face the fundamental and unavoidable uncertainty of predicting future events. Behavioral models require projections of future economic, social, and demographic conditions. Engineering explanatory models require projections about the rate of technological change and technology adoption rates.

The inescapable uncertainty about future water needs is an element of the water supply consumers' risk that the available water supply will be inadequate at some point within the planning period. The process within which water supply management decisions are formulated and given approval involves multiple perspectives regarding the risk issue. One of the extreme positions on the risk issue will be that of the water purveyor. Based on tradition and an inherent desire to provide a high level of service to the consumer, this party desires to keep the risk as low as possible. Water demand projections of any type of causal analysis may be conservative but reasonable projections of future conditions so as to reduce the risks of future shortages. At the other end of the spectrum, environmental and other interest groups desiring to prevent the impacts of additional water development will accept a higher risk of shortage. Some of the individuals in these groups will be remote to the water supply service area and will not be impacted by the denial of project authorization. The acceptability of a higher risk of shortage will be reinforced by the knowledge that adverse impacts of shortages are often inconveniences such as prohibitions on lawn watering and do not usually threaten human life or health.

These fundamental differences. in perspective. can be expected to result in a major conflict as proposals move through the regulatory process.

The current regulatory framework provides several mandatory approval points for water development proposals, each of which provides a forum for project proponents to raise challenges. These decision points exist at the various levels of government, with the most prominent consisting of the federal permitting programs. One of the most significant in terms of breadth of coverage of water development proposals is the permit program applicable to the “discharge of dredged or fill material” administered by the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency under section 404 of the Clean Water Act (CWA sec. 1244). While the 404 permitting process serves as a forum for project proponents and opponents to debate the desirability of the individual proposals, the process is not neutral. The perspective of the regulator is similar to that of the project opponents since the process is intended to implement environmental mandates and is not subject to a mandate to ensure a particular level of water supply service to the consumers.

The recent decision of the COE Norfolk District regarding the application of the city of Newport News, Virginia to expand water supply to meet projected demand increases is informative with respect to the treatment of demand projections (the application is still under consideration at higher levels of COE as a result of Virginia Governor Gilmore’s disagreement with the district’s decision). The district’s decision was to deny the requested permit, in part due to the perceived lack of adequate documentation of demand projections. The decision to subject the demand analysis to strict scrutiny was made because the proposed impoundment was found to have potentially significant environmental and socio-cultural impacts.

The Norfolk District’s decision came after an extensive review of demand projections. The district first requested a review by the COE’s Institute for Water Resources, which in turn contracted with a consultant to conduct a review. This review was followed by an evaluation by a panel of experts. The applicant responded to these reviews with rebuttal documents and ultimately prepared and submitted a new demand study. When added to the initial permit application materials, these additional documents produced a large, contradictory information base for the decision. Alternative views are presented for most of the decisions made within the demand projection process, including positions on appropriate population growth rates, water use rates for residential and other uses, and the types and extent of demand reduction that should be incorporated into the analysis.

The decision of the Norfolk District Engineer rejects the position taken by the city of Newport News on enough of the demand projection issues to conclude that the need for the additional water as requested in the permit application has not been documented. This position suggests that one of the alternative views was more acceptable; however, the discussion generally does not unequivocally accept a particular view such that a definitive standard for acceptable performance can be established. Nevertheless, the discussion does provide a basis for a few observations regarding the requirements for demand projection that would be acceptable within the section 404 regulatory process.

First, a sophisticated demand analysis will increasingly become necessary, but perhaps not a sufficient condition for approval under section 404. The regulatory process appears increasingly unlikely to view straightforward trend analysis as an adequate demand projection. In particular, demand reduction programs will be viewed as an essential part of future demand analyses. Neither the components nor outcomes of an adequate demand reduction program have been specified in the form of standards or guidelines. The COE District Engineer appeared to favor the incorporation of “drought management,” which involves the acceptance of periodic water shortages within the planning period, but this approach was not required due to contrary policy of the Virginia Health Department. This decision indicates the important role that state government can play in establishing policies and standards for demand projections and the other aspects of water supply planning.

Second, even sophisticated and elaborate water demand forecasts may be subject to intense scrutiny. Every analysis must ultimately make projections about the determinants of final water demand and any of the projections can be debated and questioned. Substantiation of population projections is critical to credible demand projections. In the Newport News case, the fact that the applicant's projections were higher than alternative projections made by others resulted in a determination that there was an overestimation on the part of the applicant. The treatment of this issue makes clear the special burden placed on an applicant to establish the validity of population growth rates higher than state or regional averages. Population growth is often characterized by non-uniformity, but local assertion of high growth rates are unlikely to be accepted without a challenge.

The same scrutiny also applies to the estimation of water use rates. The response by the IWR consultant reviewing of the Newport News demand estimate illustrates a tendency characteristic of project opponents to select extreme values at the low end of the spectrum for unit use rates to compare to those adopted by a permit applicant. The transferability of water use rates depends on the similarity of the underlying causal factors and cannot be generally assumed without substantial effort to determine comparability. An applicant must be prepared to defend against attempts to apply use rates originating under fundamentally different conditions.

A final observation (and perhaps the one with the greatest potential impact) from recent regulatory proceedings is that the existence of water supply demand, regardless of how well documented, does not necessarily ensure approval of a proposed water supply expansion project under the section 404 process. The authority of the Environmental Protection Agency to veto a section 404 permit issued by COE solely on the basis of an unacceptable environmental impact was upheld by the U.S. Circuit Court for the Fourth Circuit in the case reviewing the EPA's veto of the permit for James City County's proposed Ware Creek Project (James City County v. EPA). The availability of alternatives to meet the established demand was held not to be a necessary consideration. In the Newport News case, the COE district engineer suggested that the recommended denial of the permit would stand even if the entire projected need could be demonstrated (Final RROD, p.14).

The outcome in the James City County case and the COE suggestion in the Newport News case that demand may not matter in the permit determination reflects an imbalance in the current federal institutional structure that controls water development activities. The federal government has established policy in favor of environmental protection but has not adopted a policy in support of adequate water supply. Federal law declares that the state's authority to allocate water among competing interests will not be superceded (CWA sec. 1251(g)), but procedures such as the section 404 permitting process for implementing the federal environmental protection mandate do not ensure any state decision-making role.

This situation places water supply managers in an increasingly difficult position. The traditional bias in favor of water supply development relative to other social and environmental values has been reversed. The assumed inevitability of water demand growth has been replaced with the requirement that future demand be better documented and controlled to a significant extent. Only when demand reduction efforts are considered adequate, which is a determination for which there are no fixed standards, are supply expansion projects feasible. Where supply expansion is attempted as part of the total effort to keep water availability and demand in balance, water suppliers may be precluded from selecting project alternatives on the basis of cost minimization. The only acceptable options may be more costly alternatives such as desalination in areas where federal regulatory officials consider alteration of streams as adverse to environmental and socio-cultural values.

The Newport News proposal for the King William reservoir, the permit for which the COE District has recommended denial, illustrates the extent of the difficulty confronted by project proponents since it has a variety of features that lessen environmental and associated social impacts. It is an offstream reservoir to be filled by the diversion of high flows, it does not require the dislocation of people, it incorporates pumping stations and facilities designed to be relatively unobtrusive, and it provides an extensive mitigation program for the replacement of destroyed wetlands. Most of the potential adverse impacts (other than the number of wetlands acres to be destroyed) cannot be quantified but consist of general concerns such as possible impacts on fisheries and the possible negative, but mostly unspecified, effects on Native American cultures (no lands currently held by Virginia's Native Americans are involved in the construction of the project facilities). While these concerns are valid considerations, they remain relatively subtle and somewhat speculative. The weight being given by the Norfolk District indicates the high degree of protection for such values being enforced within the section 404 process.

Water supply planners must recognize these new realities. Federal regulators, through the interpretation of a variety of federal laws and policies, have created a hostile environment for water developers in cases involving what are perceived to have significant social and environmental impacts. In the absence of such potential, the heightened the level of review of demand projections may not be applied and a water supplier may not need to apply resources for sophisticated demand projections. But those responsible for demand projections generally must be aware of the somewhat undefined but well-entrenched constraints that govern acceptability of final demand estimates. Where adverse project impacts are possible, the project owner must recognize the basic importance of the demand projections to the process of obtaining necessary project approvals. Approval of supply expansions is likely to be a difficult undertaking under most circumstances, but the probability of failure is great for many projects that rest on an inadequate demand projection foundation.

REFERENCES

Billings, R. Bruce and C. Vaughn Jones. 1996. *Forecasting Urban Water Demand.* Denver: American Water Works Association

Clean Water Act, U.S. Code Ann., Title 33, sec 1251 et seq. (cited as CWA)

James City County v. EPA, No. 92-2294, December 30, 1993.

Final Recommended Decision of the District Commander on Permit Application Number 93-0902-12, U.S. Army Corps of Engineers Norfolk District, July 2, 2001 (Cited as Final RROD).

PMCL. 2001. *IWR-MAIN User Manual,* Carbondale Illinois.

Shabman, Leonard. 1987 "Water-Use Forecasting – Benefits and Capabilities" *National Water Summary 1987 – Water Supply and Use: Water Use Forecasting*, United States Geological Survey, pp. 117-122.

REPORT ON THE DRAFT OF DEQ'S REGULATIONS FOR WASTEWATER RECLAMATION AND REUSE

Judy Poff
Virginia Water Resources Research Center
10 Sandy Hall
Virginia Tech
Blacksburg, VA 24061
jupoff@vt.edu

KEYWORDS: water reclamation, water reuse, wastewater

ABSTRACT

In 1999, HJR662 required that a study be conducted to investigate the issues surrounding land irrigation, and reclamation and reuse of wastewater. An advisory ad hoc group recommended that the proposed regulation encompass the following six water reuse categories as outlined in House Document 92:

1. Land irrigation for agricultural, forest, and landscape use
2. Ground water recharge for certain purposes (i.e., saltwater intrusion control)
3. Industrial processes (i.e., cooling, boiler feed, stack scrubbing, and process water)
4. Non-potable urban (i.e., fire protection, street washing, and vehicle washing)
5. Environmental (i.e., stream flow augmentation/fishers sustainability)
6. Miscellaneous (i.e., snowmaking, dust control, and construction)

The 2000 General Assembly passed House Bill 1282 requiring the State Water Control Board to encourage and establish requirements for the reclamation and reuse of wastewater that are protective of state waters and public health as an alternative to directly discharging pollutants into state waters. While there is a regulatory framework for wastewater reclamation and reuse involving land irrigation, these regulations do not prescribe any technical standards for this type of operation. The use of reclaimed wastewater for other purposes (such as industrial cooling processes, fire protection, street washing, dust control, etc.) does not currently require a permit.

The three following alternatives were considered:

1. Promulgate a water reuse regulation that establishes technical standards for various potential reuse categories. The permitting mechanisms established in the VPA and VPDES Permit Regulations could be incorporated by reference.
2. Amend the VPA Permit Regulation by incorporating the technical standards for various potential reuse categories. These standards could then be used as criteria for a VPDES permit issued to facilities that may employ any reuse options in addition to the wet weather discharge.
3. Take no action to adopt the regulation. Instead, establish requirements by issuing a staff guidance. This option was not recommended because the result is not as predictable or certain as a regulation.

Alternative 1 was tentatively considered to be the most appropriate to satisfy the mandate. A Technical Advisory Committee was formed and met in mid-October 2001 for the purpose of assisting in the development of the draft regulation for wastewater reclamation and reuse.

PRELIMINARY RESULTS FROM CHLOROFLUOROCARBON-BASED DATING FOR DETERMINATION OF AQUIFER SUSCEPTIBILITY IN VIRGINIA

David L. Nelms
George E. Harlow, Jr.
U.S. Geological Survey
1730 East Parham Road
Richmond, VA 23228
dlnelms@usgs.gov

KEYWORDS: Aquifer susceptibility, ground-water dating, Source Water Assessment Program

ABSTRACT

The U.S. Geological Survey, in cooperation with the Virginia Department of Health, sampled water from more than 150 wells and springs across the Commonwealth between 1998 and 2000 as part of the Virginia Aquifer Susceptibility study. The fundamental premise of the study is that ground water age determinations can be used as a guide for classifying aquifers in terms of susceptibility to contamination. Concentrations of chlorofluorocarbons (CFCs) greater than 5 pg/kg (picograms per kilogram) were used as a threshold to indicate that parts of the aquifer sampled have a component of young water (younger than 50 years) and are, therefore, susceptible to near-surface contamination. Concentrations of CFCs exceeded the threshold in 22 percent of the wells and in one spring sampled in the Coastal Plain Physiographic Province. The maximum depth to the top of the screened interval for wells that contained CFCs was less than 150 ft. Wells completed in the deep confined aquifers in the Coastal Plain generally contain water older than 10,000 years, as indicated by carbon-14 dating, and are not considered to be susceptible to contamination under natural conditions. More than 95 percent of the water samples from wells and springs in the fractured rock terranes contained concentrations of CFCs above the threshold limit. No relation between well depth and presence of CFCs is evident from samples in the fractured rock terranes. Several samples contained concentrations of CFCs in excess of air-water equilibrium, which indicates that sources other than the atmosphere (such as sewage effluent) have introduced CFCs into the ground water system. Preliminary results from CFC-based dating suggest that shallow wells and springs in the Coastal Plain and most wells and springs in the fractured rock terranes contain a component of young ground water and are, therefore, classified as susceptible to contamination from near-surface sources.

AQUIFER-TEST ANALYSIS IN A FAULT-DOMINATED AQUIFER SYSTEM, BLUE RIDGE PROVINCE, VIRGINIA

Thomas J. Burbey
Dept. of Geological Sciences
Virginia Tech
Blacksburg, Virginia 24061-0420
tjburbey@vt.edu

William J. Seaton
ATS International, Inc.
40 Nancy Ct.
Christiansburg, Virginia 24073
wjs_ppco@hotmail.com

KEYWORDS: Blue Ridge Province, fracture flow, aquifer test

ABSTRACT

A nearly six-day aquifer test was performed in the fractured and faulted crystalline rocks of the Blue Ridge Province in Floyd County, Virginia. Time-drawdown data from observation wells penetrating bedrock fractures, including an ancient fault zone in the bedrock exhibit near unit linear slopes when plotted on log-log paper, supported the existence of a highly transmissive fracture network that behaves as an "extended well" to the pumping well. Wells penetrating a shallow aquifer composed of unconsolidated regolith overlying bedrock exhibited strongly delayed responses to pumping with estimated hydraulic conductivities typically at least six orders of magnitude less than the wells in the fault-zone aquifer. Recovery after pumping was rapid in wells penetrating the fault zone and recovery response suggests radial flow, which may indicate that this fracture network is of limited lateral extent. Water-level recovery asymptotically approached a level about 3.5 feet lower than the pre-pumping level indicating that the aquifer reservoir was depleted at a rate greater than the natural recharge rate. These results indicate that:

1. the aquifer in the highly variable fault-zone aquifer dominates the flow system;
2. the overlying unconsolidated aquifer has limited and localized connections with the fault-zone aquifer. This causes a very slow recharging of the fractures associated with the fault zone following extended pumping events; and
3. the lower saprolite and upper fractured bedrock aquifer together behave as an extensive confining unit restricting flow from the saprolite aquifer to the lower fault-zone aquifer.

BACKGROUND

The Blue Ridge Physiographic Province is characterized and strongly dictated by the repeated compressional and extensional tectonism that occurred from Precambrian through Paleozoic time. The Blue Ridge metamorphic rocks in Floyd County are within a system of generally northeast striking thrust faults stacked vertically and shingled laterally. The oldest thrust sheets have undergone multiple periods of deformation throughout the Paleozoic and have been crosscut by younger thrust faults. The Blue Ridge Fault (figure 1) underlies Floyd County and is the master decollmont separating the Precambrian metamorphic rocks of the Blue Ridge Province from the Paleozoic age sedimentary rocks below it. Numerous near vertical, predominantly north-south and northwest-southeast oriented joints formed during the latest stages of Appalachian tectonism are expressed as lineaments in the surface topography (Bartholomew and others 1999; Henika, personal communication; VDMR 1999). Bedrock is composed of layered Precambrian biotite gneiss, granitic gneiss, augen gneiss, massive, highly fractured vein quartz, and phyllite that generally strikes northeast and steeply dips to the southeast. The study area for this report is located 30 kilometers southwest of Roanoke, Virginia, near the western edge of the Blue Ridge Province in Floyd County, Virginia (figure 1).

The Blue Ridge Province, although geologically complex, typically has been viewed as a somewhat simplistic two-layered system (as is the Piedmont Province) (LeGrand 1967; Heath 1984). This system is built upon the assumption of a relatively homogeneous unconsolidated layer of soil and weathered rock (saprolite) containing a water table aquifer of high storage capacity supplying water to an underlying variably fractured homogeneous crystalline bedrock aquifer that has low overall porosity and low storage capacity. Interconnected fractures are thought to serve as conduits for predominantly downward vertical and limited horizontal flow and the number of fractures is believed to decrease with depth. Wells in the region are often limited to 100 m depths because of this accepted perception.

DATA COLLECTION AND ANALYSIS PRIOR TO AQUIFER TESTING

Numerous 250-500 m two-dimensional surface electrical resistivity data profiles were collected throughout the study with 2, 6, or 10 m electrode spacings using a dipole-dipole array configuration (Seaton and Burbey 2000). Two-dimensional surface resistivity profiling accounts for the spatial variation in earth resistivities associated with complex subsurface environments along the plane of the profile. In addition to the resistivity surveys, borehole geophysical logs were collected at each of the 10 wells (fig. 2) at the site using caliper, natural gamma ray, spontaneous potential (SP), formation resistivity, water temperature, and heat pulse flow meter (HPFM) probes. These tools helped to characterize the subsurface geology and hydrogeologic conditions prior to the aquifer test described here (Seaton and Burbey 2000).

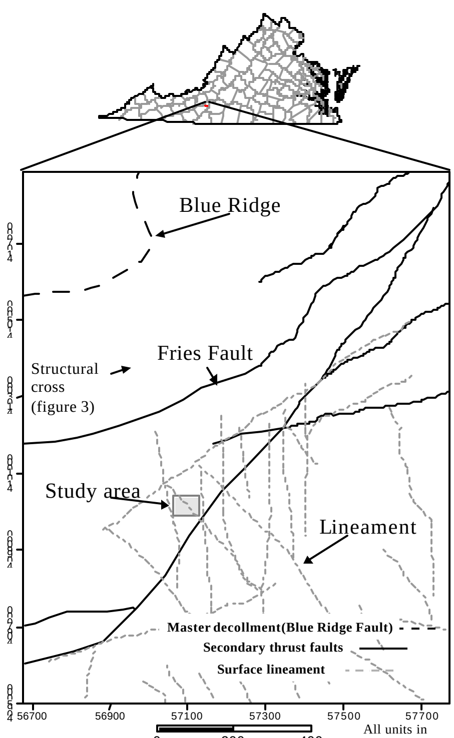


Figure 1. Location of the study area showing major geologic features.

Use of these tools, along with careful hydrogeologic mapping, indicates that the zone between the regional thrust faults shown in figure 1 likely represents a duplex system in which phyllonite sequences expressed as mica schists outcrop within the area and are believed to represent the unit associated with ductile deformation during active thrusting during the Late Cambrian time (W. Henika, VDMR, personal communication 1999). The adjacent overlying granulite gneisses became highly fractured above the ductile deformation zones. These intensely fractured granulites now include highly permeable fault zones, whereas the mica schists may now form a generally impermeable lower unit and a ramp for deep groundwater flow above this fault plane. This region of high permeability can be manifest locally as a 30-foot thick zone or as small as a single 1-foot fracture. The fault is expressed as a northeast-southwest trending arcuate feature exposed near the crest of the hill through wells 1 and 2. The fault then dips steeply and becomes semi-horizontal beneath wells 3 and 7 at a depth of 150-200 feet below land surface. The regional fracture and lineament sets associated with tensional forces and unloading are also imprinted on the bedrock. The fault zone and fractured bedrock, as well as the overlying saprolite, have been fairly well characterized within the study and it has been found that the saprolite aquifer is hydraulically connected to the deeper fracture-zone aquifer in discrete locations, but that the shallow fractured bedrock beneath the saprolite typically behaves as a confining unit. Thus, a distinction is made between the shallow fractured bedrock and the fault-zone aquifer that lies beneath. The fault-zone aquifer also has an interconnected fracture network, but the hydraulic conductivity of these fractures that intersect the fault zone is significantly greater than the fractured bedrock that is not interconnected with the fault zone.

Several deep wells (figure 2) penetrate the fault-zone aquifer, while others are open only within the unconsolidated saprolite or penetrate the very shallow fractured bedrock-confining unit. Hydraulic-head differences between the wells in the bedrock aquifers and those in the saprolite are variable. Along the crest and adjacent slope of the northeast-southwest trending hill (figure 2), heads within the saprolite are higher than the water level in the deeper wells tapping the bedrock fractures. The difference in head values decreases to the south and southwest. Near the spring (figure 2) the head differences are minimal. Single-well borehole testing indicates that the shallow saprolite and the fault-zone aquifer are separated by an aquitard that significantly limits vertical flow between these units. This aquitard incorporates the lowest part of the saprolite and the fractured bedrock beneath the saprolite.

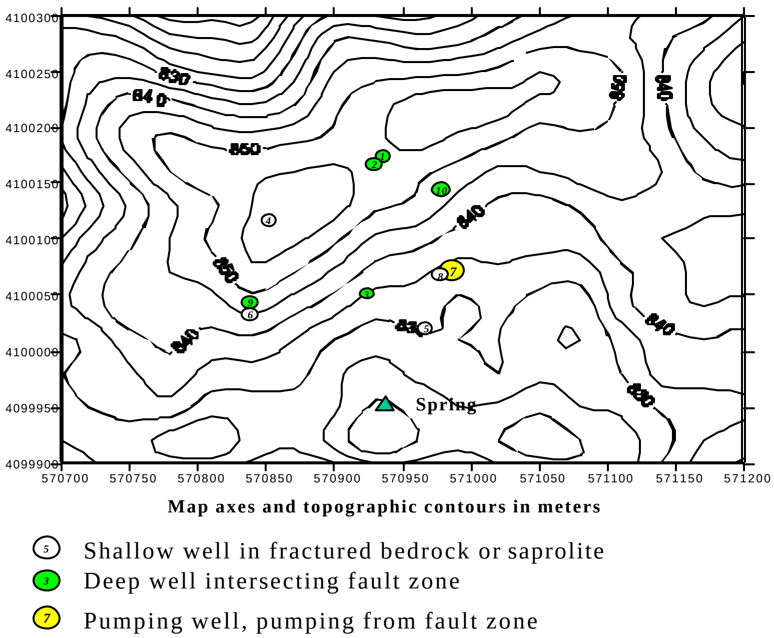


Figure 2. Topographic map showing well and spring locations.

AQUIFER-TEST ANALYSIS

Well 7 (figure 2) was used as the pumping well during the nearly six-day aquifer test that occurred in the late spring 2001 and is hydraulically connected to the fault-zone aquifer but isolated from the saprolite aquifer. Pressure transducers were installed in each well to monitor water levels prior to, during, and after the six-day test. Wells were not packed off to isolated fractures so borehole storage effects must be taken into account during analysis. The pump installed in well 7 was placed below the open fracture zone. The initial pumping rate was approximately 1.75 ft^3/min and was gradually reduced during the course of the six-day test to maintain a fairly constant head in the pumping well of about 85 feet below pre-pumping levels. The final pumping rate was 0.75 ft^3/min. A total of just over 8,000 ft^3 of water was pumped at an average rate of nearly 1 ft^3/min over the duration of the test. After the pumping well was shut off, recovery was monitored in all the wells until water levels asymptotically reached new equilibrium values. Generally, recovery was extremely rapid in wells penetrating the fractured bedrock network.

Time-drawdown plots were constructed for wells completed in shallow saprolite and fault-zone aquifers. Drawdown response in all wells open to the fault zone responded similarly. Figure 3 is a time-drawdown plot during pumping for well 3, which is open to the fault zone and is located 281 feet, west-southwest of the pumping well. Early-time response to pumping indicates the time-drawdown plot has a unit linear slope on log-log paper. This response may indicate an extremely transmissive fracture network (Gringarten 1982) or more realistically a transmissive fracture set with significant wellbore storage effects (Kruesman and de Ridder 1990). After approximately one-half day the plot follows a straight line with a slope of 0.5. The abrupt change is likely due to a lowered pumping rate corresponding to this time; however, the slope likely represents horizontal parallel flow in a highly transmissive fracture similar to an extended well (Gernand and Heidtman 1997; Jenkins and Prentice 1982). Late-time response corresponds to a period of pseudo-radial flow, which may indicate contributing flow from lower permeable fractures that intersect the fault zone. The response in well 3 is nearly identical to the response observed at the pumping well. The difference is that the total drawdown is an order of magnitude less than that of the pumping well where well loses during pumping were a factor.

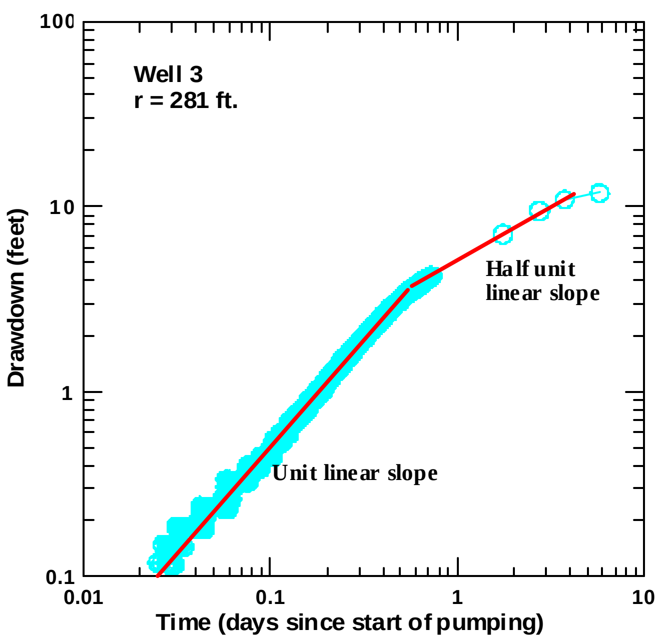


Figure 3. Time-drawdown plot during duration of aquifer test for well 3, which penetrates the fault

Hydraulic conductivity of the overlying saprolite aquifer was estimated from time-drawdown plots during pumping by assuming that the vertical distance from the saprolite aquifer in the shallow wells to the fault-zone aquifer represented the distance to the pumping well. Because the fault zone behaves much like an extended well, this is considered to be a valid assumption.

Well 8 is completed in the shallow saprolite aquifer and is located (horizontally) seven feet from the pumping well. The actual distance to the pumping well is taken to be 80 feet in the vertical direction, which is the distance between the saprolite aquifer in well 8 and the open fracture zone in well 7. Figure 4 shows the results of the aquifer test for well 8. Of particular interest is the large time lag between the start of pumping and the commencement of drawdown in well 8. The time lag is indicative of low connectivity between the saprolite and the fault-zone aquifer. The vertical hydraulic conductivity was estimated for the intervening lower saprolite and upper bedrock-confining unit using a Hantush type-curve. Most of the thickness of this section occurs within fractured bedrock and, therefore, storage is considered not to be a factor. This assumed confining unit slowly contributes water to the fault-zone aquifer and depends on the degree of interconnectivity of the fracture network. Although it is typically perceived that the shallow bedrock in these metamorphic terranes is more permeable than deeper portions of this terrane, this aquifer test clearly indicates otherwise. The estimated hydraulic conductivity of this confining unit based on this aquifer test is 1.4×10^{-6} ft/s or 0.12 ft/day, and is approximately six orders of magnitude less than the estimated value for the fault-zone aquifer.

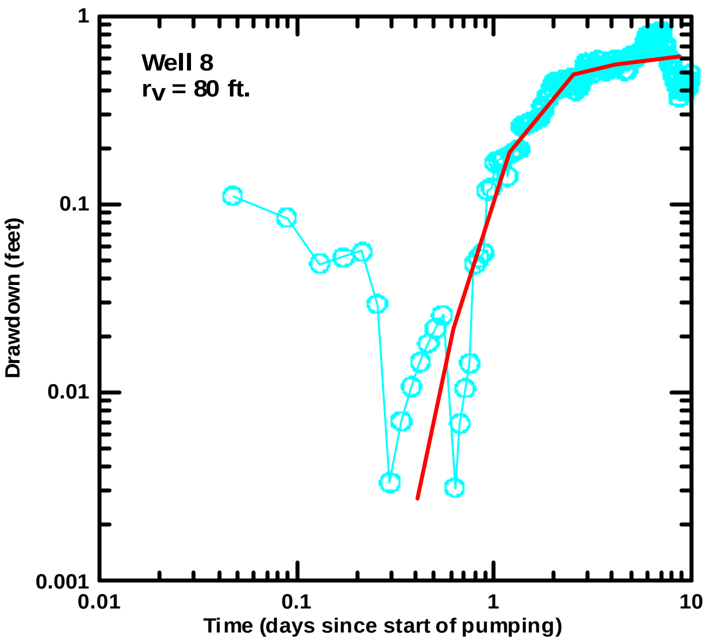


Figure 4. Time-drawdown plot during duration of aquifer test for well 3, which is open to the fractured bedrock. Solid line is Hantush type curve for the data set.

After approximately six days of continuous pumping, the wells were allowed to recover. Recovery tests were performed on all wells. Wells open to the fault-zone aquifer experienced immediate response and rapid recovery while those open to the saprolite exhibited significant delays before measurable recovery occurred. However, once recovery in these shallow wells began, they recovered rapidly to their pre-pumping levels. However, wells open to the fault-zone aquifer asymptotically approached a new equilibrium head value below that of the pre-pumping static water level. Figure 5 shows the pumping and recovery data for well 10 (208 feet from the pumping well and completed in the fault-zone aquifer. Its recovery head was 3.5 feet below the pre-pumping static head value. Similarly, well 3, located 281 feet from the pumping well, also had a recovery head that was 3.5 feet below the pre-pumping static head value. The more distant well 9 (557 feet from the pumping well) had a recovery head only 0.5 feet below the pre-pumping static head. The recovery in these wells was not complete because the volume of water removed during the nearly six-day test lowered the storage reservoir of the fault-zone aquifer system.

Without directly knowing the porosity or aquifer thickness from which the water was extracted, it is difficult to project the extent of the radius of influence due to the aquifer test. Heterogeneities in the system and locally non-radial flow conditions also make projecting the size of the reservoir and the distance of pumping influence difficult to estimate. Nonetheless, even with porosities on the order of 0.1 percent, the maximum radial extent that experienced affects of pumping was probably not much more than 1,000 feet. However, the total size of the aquifer or "reservoir" could be considerably larger than the affected radius.

Time-drawdown plots of recovery data after pumping reflected a radial type flow system and may suggest that the fault-zone aquifer has a limited amount of water and are ultimately being fed from the overlying saprolite in localized areas referred to as breach zone (see the accompanying paper by Seaton and Burbey, this sueCo). The time-drawdown recovery data were matched with Hantush leaky type curves that assume no confining-unit storage. Estimated transmissivity values using type-curve matching from recovery data at all wells intersecting the fault zone are between 40-150 ft^2/day. This range signifies the importance of the fault zone aquifer system as a highly permeable water-producing and storage zone relative to the overlying saprolite aquifer or shallow bedrock.

CONCLUSIONS

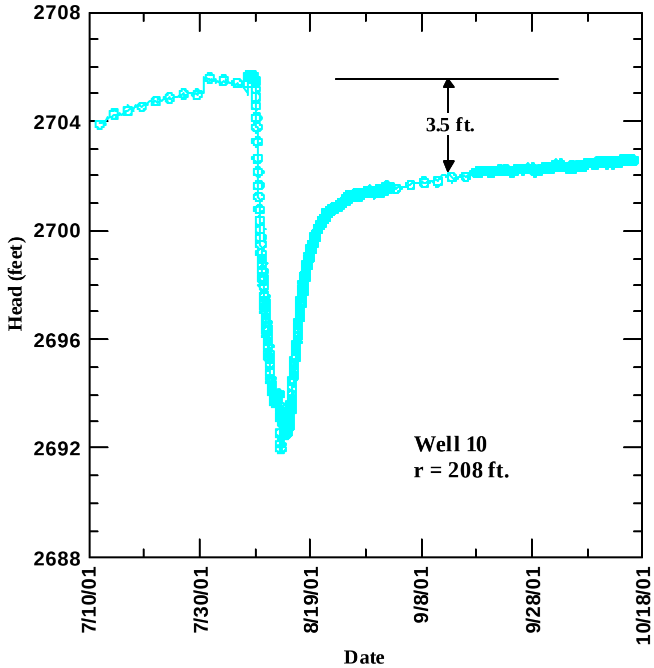


Figure 5. Aquifer pumping and recovery test results for well 10 indicating permenant reservoir

The results of a nearly six-day aquifer test performed in the fractured and faulted crystalline rocks of the Blue Ridge Province in Floyd County, Virginia reveaed the presence of a highly transmissive fault-zone aquifer with considerable storage overlain by a relatively low transmissivity saprolite aquifer. Between these two units lies an intervening saprolite and fractured bedrock aquitard. Aquifer test results indicated that vertical flow in the aquitard is extremely low. These results combined with our previous research throughout this area support the formation suggest that a new conceptual model is needed to adequately describe this system. Previous reports have suggested that the shallow bedrock is fairly permeable and that the saprolite acts as a storage reservoir that feeds the bedrock fractures fairly uniformly. The aquifer tests described here clearly indicate that this former model is not valid.

In this new conceptual model, the geometry of the shallow saprolite aquifer conforms to the land surface and overlies the top of the bedrock. The geologic variability of the saprolite gives rise to both the water table and confined conditions in this shallow aquifer. Most of the recharge occurs in the areas with the water table conditions prevailing. Localized breaches in the underlying confining unit of the saprolite provide a pathway for waters to move from the saprolite into the deeper fault-zones that have a high transmissivity fracture network.

The fault-zone aquifers can display a high degree of geologic and fracture variability but are typically associated with ancient thrust faults that are ubiquitous throughout the Blue Ridge Province. The fractures associated with the fault zones provide the large majority of stored water for this entire saprolite-crystalline bedrock system. The fault-zone aquifer can act as an "extended well" during pumping indicating a very high transmissivity and connectivity of fractures. Hydraulic head values can be significantly different in the fault zone aquifers than in the overlying saprolite aquifers before, during, and after pumping showing the hydraulic separation of these units. Topography often plays a significant role in the variability of these head values. Recharge to the fault-zone aquifers may occur very slowly via the saprolite, from direct exposure to surface waters at outcrops, or from breach zones within the shallow bedrock.

These conclusions support the reassessment of existing regulations regarding wellhead protection, watershed management, and sewage-wastewater disposal in the Blue Ridge Provence. Understanding the variability of the bedrock geology and the potential for high transmissivity bedrock aquifers can provide insights allowing more accurate characterization of contaminant movement in the subsurface and also the location of high yielding water supply wells.

ACKNOWLEDGEMENTS

The authors would like to thank the Virginia Water Resources Research Center for their financial support, which has allowed us to conduct this research at our fractured-rock research facility in Floyd County, Virginia.

REFERENCES

Bartholomew, M.J., Schultz, A.P., Lewis, S.E., McDowell, R.C., and Henika, W.S., 1999, Bedrock geologic map of the Radford 30 by 60 minute quadrangle, Virginia-West Virginia: Virginia Div. of Mineral Resour., Digital publication (in press).

Gernand, J.D., and Heidtman, J.P., 1997, Detailed pumping test to characterize a fractured bedrock aquifer. *Ground Water*, v. 35, no. 4, p. 632-637.

Gringarten, A.C., 1982, Flow-test evaluation of fractured reservoirs: *Geol. Soc. of Amer*. Special Paper 189, p. 237-263.

Heath, R.C., 1984, Ground-water regions of the United States: U.S. Geological Survey Water-Supply Paper 2242, 78p.

Jenkins, D.N., and Prentice, J.K., 1982, Theory for aquifer test analysis in fractured rocks under linear (nonradial) flow conditions: *Ground Water,* v. 20, no. 1, p. 12-21.

Kruseman, G.P., and de Ridder, N.A., 1990, Analysis and evaluation of pumping test data. International Institute for Land Reclamation and Improvement, Pub. 47, Wageningen, The Netherlands, 377 p.

LeGrand, H.E., 1967, Ground water of the Piedmont and Blue Ridge provinces in the southeastern States: *U.S. Geol. Survey Circular* 538, 11 p.

Seaton, W.J., and Burbey, T.J., 2000, Aquifer characterization in the Blue Ridge physiographic province using resistivity profiling and borehole geophysics: geologic analysis. *Jour. of Environmental and Engineering Geosciences*, v. 5., issue 3, p. 45-58.

AQUIFER CHARACTERIZATION IN THE BLUE RIDGE PHYSIOGRAPHIC PROVINCE

William J. Seaton
ATS International, Inc.
40 Nancy Ct.
Christiansburg, Virginia 24073
wjs_ppco@hotmail.com

Thomas J. Burbey
Dept. of Geological Sciences
Virginia Tech
Blacksburg, Virginia 24061-0420
tjburbey@vt.edu

KEYWORDS: Blue Ridge Province, hydrogeology, pump test

ABSTRACT

Current models of the hydrogeology in the Blue Ridge and Piedmont Provinces in the eastern United States generally use a simplified two-layer system consisting of shallow unconsolidated and relatively homogeneous regolith with a water-table aquifer slowly supplying water downward to the underlying variably fractured crystalline bedrock. In these models, interconnected fractures in the crystalline bedrock act as conduits for predominantly downward vertical and limited horizontal flow, and fracture density is correlated with proximity to topographic lineaments.

In this research, detailed hydrogeologic studies in the Blue Ridge Province in Floyd County, Virginia reveal a relatively complex set of unconfined and confined aquifers in the shallow unconsolidated regolith and deeper fractured crystalline rock aquifers. Confined flow generally occurs in thin zones within the clay-rich unconsolidated saprolite directly above the bedrock and in the fractured bedrock aquifers. Unconfined conditions are relatively rare and generally exist in localized shallow sand-prone intervals in the saprolite.

High fracture density in the bedrock can be correlated with both ancient shear zones that originated from thrust faulting and from more recent vertical fracture zones that may be expressed as topographic lineaments. The ancient shear zones intercept the regolith-bedrock interface at high angles and become more horizontal with depth. Brecciated rock adjacent to the shear zones, as well as the shear zones themselves, can be hydraulically conductive and serve as pathways for vertical and horizontal groundwater movement from source-recharge areas to distant wellbores.

Pump testing of the regolith-bedrock fracture system over a six-day period produced rapid and relatively uniform drawdowns in surrounding wells completed in the fractured bedrock aquifers. This information, combined with the geophysical logging data, indicates that horizontal, isotropic flow is predominant in the bedrock fractures. The shallow regolith aquifers experienced minimal drawdowns from the pump test indicating low vertical hydraulic conductivity and limited communication between the regolith and bedrock aquifers. Recharge of the fractured aquifers may be occurring in localized areas where significant hydraulic communication exists between shallow water sources at the surface or in the regolith and the underlying fractured bedrock. A new conceptual model for the Blue Ridge aquifers is proposed based on this new information.

INTRODUCTION

Aquifers in the Blue Ridge Province have generally been characterized as a simple two-part system composed of a shallow water table aquifer in unconsolidated regolith overlying fractured crystalline rocks (figure 1a,b). In this model the downward vertical movement of water from the water table aquifer recharges the fractures in the bedrock. The water table aquifer is considered as the primary storage reservoir for the entire aquifer system and is recharged by vertical percolation of water through the unsaturated zone. Bedrock fractures are thought to result from tectonic stress and erosional unloading that occurred during the geological history of the region. These fractures may be expressed as topographic lineaments. The bedrock has no significant permeability other than the interconnected fracture network. Fracture porosity is assumed to diminish with depth and hydraulic conductivities of bedrock and regolith are thought to be similar, ranging from 0.001 to 1.0 m per day (Heath 1984; LeGrand 1967).

Fig. 1a.

Fig. 1b.

Figures 1a,b. Current conceptual model of aquifers in the Blue Ridge and Piedmont provinces (Heath, 1984).

Research and field observations over the last five years by these authors and others in the Blue Ridge and Piedmont provinces in Virginia and North Carolina have often conflicted with the conceptualization described above. A groundwater research field site has been established in the Blue Ridge Mountains in southwest Virginia to investigate the character of the aquifers in this region. Seaton and Burbey (2000) described the geologic framework of the Blue Ridge aquifers at this research field site and proposed addition aquifer tests to substantiate their findings. This paper includes the latest aquifer test results and presents a new conceptual model of the aquifers in the Blue Ridge Province.

AQUIFER ANALYSIS

Two primary aquifers have been identified in the Blue Ridge Province (Seaton and Burbey 2000):

1) a shallow unconsolidated aquifer located near the base of the saprolite extending into the shallow portions of the fractured bedrock.

2) a deeper aquifer entirely in fractured bedrock composed of interconnected fracture networks.

SHALLOW AQUIFER

Earlier models conceptualize the shallow aquifer as a simple water table aquifer serving as the main storage reservoir in direct communication with the underlying fractured bedrock (figure 1a,b). Our experience shows the shallow aquifer as having significant geologic variability and during drilling is often represented as a thin, confined aquifer, which overlies bedrock. Locally, this shallow aquifer is represented as a water table aquifer where the overlying unsaturated zone is permeable to percolating water from precipitation. Confining conditions are often observed following drilling operations as water levels stabilize several feet above the top of the aquifer.

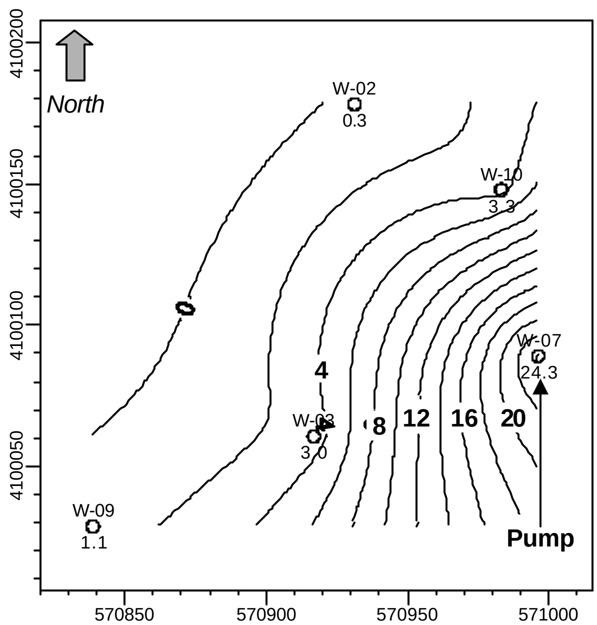


Fig. 2a Drawdown contours in deep aquifer

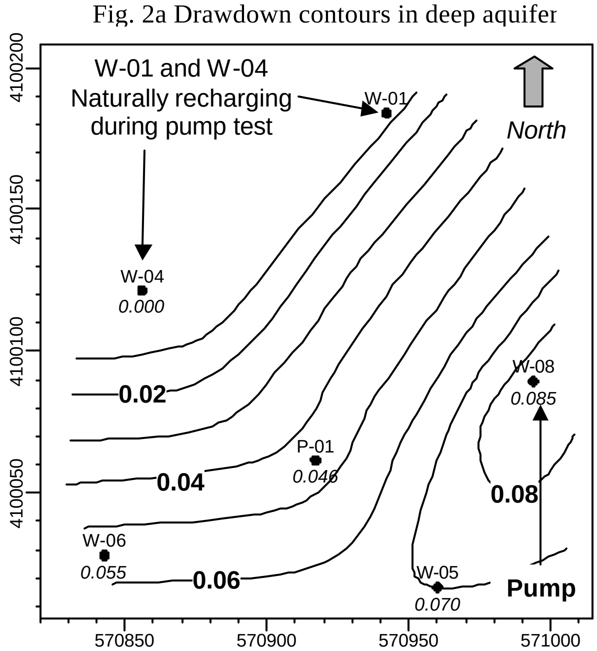


Fig. 2b Drawdown contours in shallow aquifer

0 50 100

All units in meters

Pump testing reveals very low vertical hydraulic conductivity between the shallow aquifer and the deep underlying bedrock fractures (Burbey and Seaton 2001). Pump tests conducted in the fractured bedrock caused minimal drawdown in nearby wells in the overlying shallow aquifer. Pump testing of the bedrock aquifer over a 5-day period produced approximately 24 meters of drawdown in the fractured aquifer (figure 2a) but only a maximum of 0.08 meters of drawdown in the overlying shallow aquifer (figure 2b).

These data and logged rock cuttings from drilling operations indicate that the base of the shallow aquifer is impermeable bedrock forming a confining unit between the shallow aquifer and the deeper fractured bedrock aquifer. Pump testing the shallow aquifer separately usually yields 0.25-0.30 gpm. The low yield and limited thickness of this aquifer diminishes its role as a storage reservoir for the aquifer system.

The shallow aquifer is recharged in areas where there is direct contact with surface waters or where water table conditions exist. Forested areas and steep slopes are likely to have minimal vertical recharge to the underlying shallow aquifer due to confined conditions in the regolith, high runoff due to steep slopes, or impermeable forest cover.

Contours of the hydraulic head for the shallow aquifer generally parallel the ground surface (figure 3a) having approximately 20 m of relief across the well field. The water levels in the deep fractured

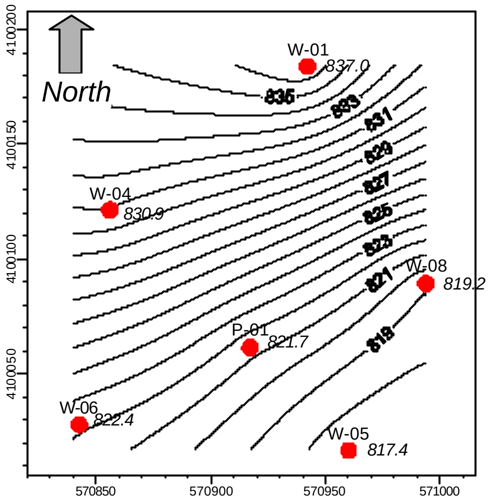


FIG. 3A. Shallow aquifer contoured water levels

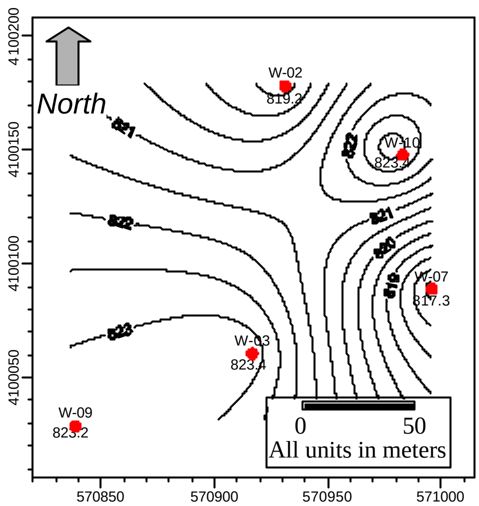


Fig. 3b. Deep Aquifer contoured water levels

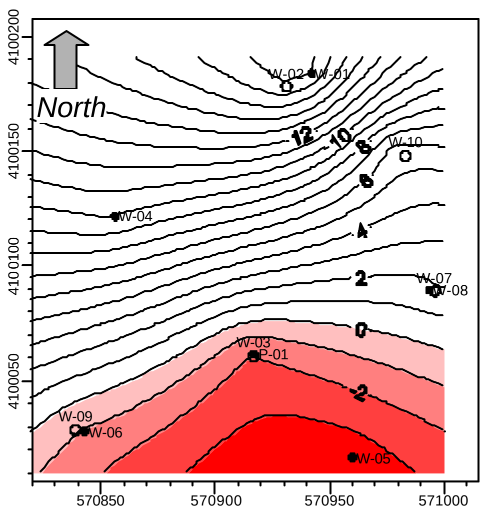


Fig. 3c. Map of difference between shallow and deep contoured water levels

aquifer have only 6 m of relief (figure 3b). Substantial differences in hydraulic head can exist between the shallow and deep aquifers at any given location supporting the presence of a confining unit between these aquifers. In the southern end of the well field the hydraulic heads for the shallow aquifer dip below the heads for the deep aquifer.

DEEP AQUIFER IN FRACTURED BEDROCK

The fractured aquifer has significant geologic variability including fault shear zones as seen in surface resistivity profiles, logged boreholes, and direct observations from outcrops (figure 4a-c). The fracture network may include highly transmissive fractures on top of the fault shear zones associated with ancient thrust faults. Extended pump testing of the fractured aquifer (Burbey and Seaton 2001) revealed the presence of a highly transmissive fracture set that behaved like an extended well. In addition, a late time response in the pump test data represents contributions to flow from a lower permeability fracture set that intersects the highly transmissive fault zone.

The fracture network contains the large majority of water storage for this system. Water levels in wells with bedrock fractures returned to 70% of pre-pumping levels within 8 days. Following this initial period, water level recoveries slowed significantly. Fifty-four days after pumping, wells had only recovered to 77% of their pre-pumping levels. The incomplete recovery in these wells was due to the lowering of the water level in the storage reservoir (fracture network) as a result of the removal of water during the pump test. The slow recovery also indicates a limited connection and/or supply of water to the fracture network from the outside source of recharge.

Figure 5 illustrates the difference between the ground surface topography and the contoured water level surface from the deep aquifer. These two surfaces meet together at the bottom of the map in the vicinity of a perennial spring. The primary source of recharge to the deep aquifer may be the area-limited zone where the ground surface and the water level from the deep aquifers meet. The water level from the shallow aquifer is also approximately at the same elevation as the topographic surface and the deep aquifer in the

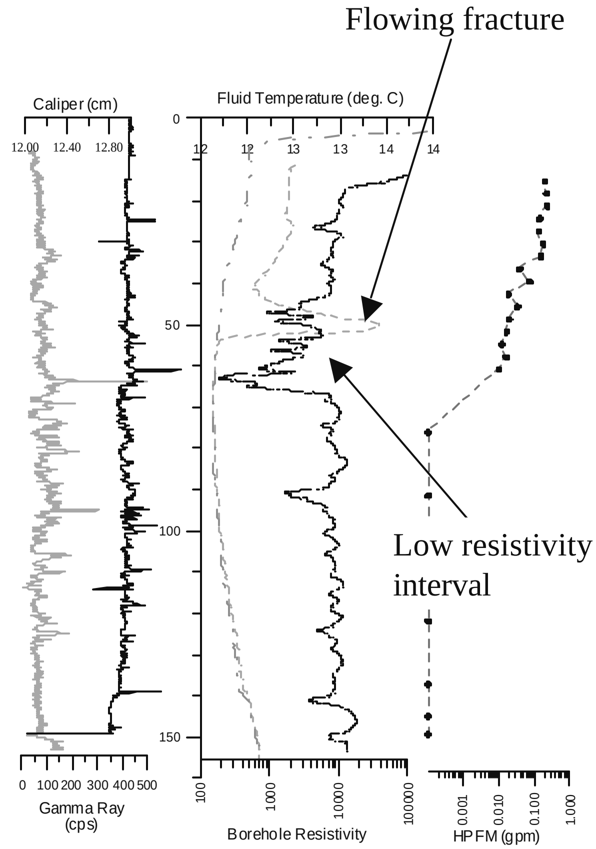


Fig. 4a. Borehole logs through a low resistivity fault shear zone.

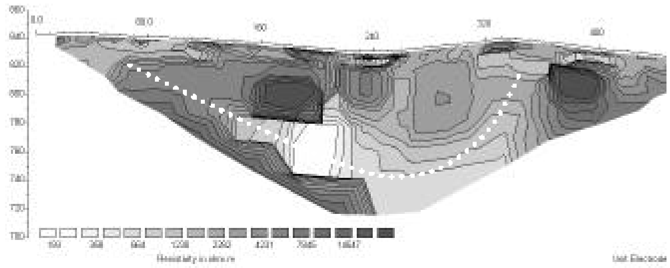


Fig. 4b. Resistivity profile across a low resistivity fault shear zone (dotted line).

Fig. 4c. Small fault shear zones in outcrop

southern part of the map (figure 3c). Large masses of fractured vein quartz have been observed to outcrop in this area and also have been encountered during the drilling of well W-05. Vein quartz commonly occurs throughout the Blue Ridge and Piedmont provinces as a by-product of low-grade metamorphism. Under the elevated temperatures and pressures experienced in these provinces during times of tectonic stress and deep burial, quartz could mobilize and accumulate along fractures or fault planes. Subsequent cooling and fracturing of the massive quartz could provide paths for vertical movement of groundwater. This fractured quartz may breach the hydraulic barrier between the shallow and deep aquifers and also provide a pathway for recharge of the deep aquifer.

NEW CONCEPTUAL MODEL OF BLUE RIDGE AQUIFERS

Figure 6 is a schematic representation of the new conceptual model for Blue Ridge aquifers. Throughout most of this model the shallow aquifer is hydraulically separated from the deep fractured bedrock aquifer. Recharge to the deep aquifer occurs through localized breaches in the confining unit that separates the shallow and deep aquifers or through direct contact of surface waters with the deep fracture system. Recharge to the shallow aquifer can occur in areas where unconfined conditions exist or where surface waters are in direct communication with the shallow aquifer. Significant geologic

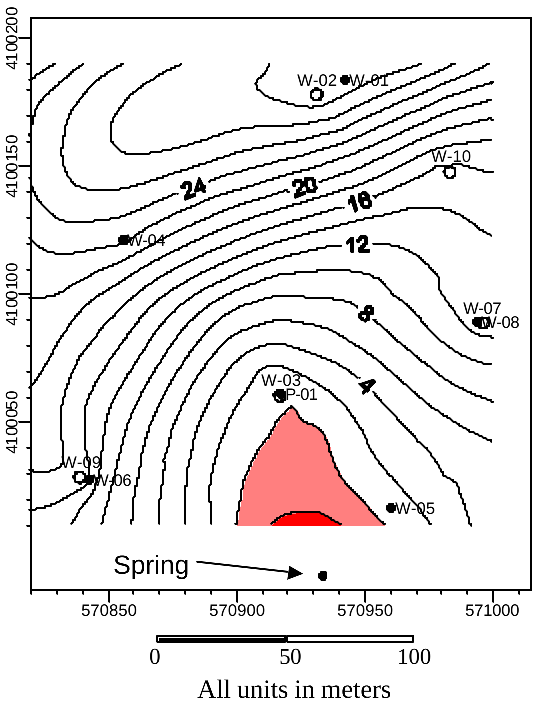


Fig. 5. Map of difference between ground surface and deep contoured water levels. Shaded area indicates that the projected water levels from the deep aquifer extend ABOVE the ground surface.

complexity associated with ancient thrust faulting exists within the deep bedrock in the Blue Ridge Province. High transmissivity zones parallel and adjacent to thrust plane surfaces may be the major conduits for fracture flow in this system. A secondary interconnected set of fractures with lower hydraulic conductivity also exists in the bedrock. Together this fracture network provides the storage "container" and the pathway for groundwater movement. Limited areal extent of fracture networks reduces the storage volume of these aquifers.

Existing regulations regarding wellhead protection, watershed management, and sewage-wastewater disposal in the Blue Ridge Province are based on the older and relatively simple models of Blue Ridge aquifers. This new model underscores the need to locate and protect the localized watersheds and recharge areas responsible for supplying water to the aquifers. Current regulations require that wells be drilled at certain minimum distances from surface features or sources of contamination. These regulations may have a limited effect on reducing contamination if the underlying geology is not more fully considered. Understanding the variability of the bedrock geology and the potential for high transmissivity bedrock fractures can also provide insights allowing more accurate location of high yielding water supply wells and a more realistic understanding of the volume of water available from these wells.

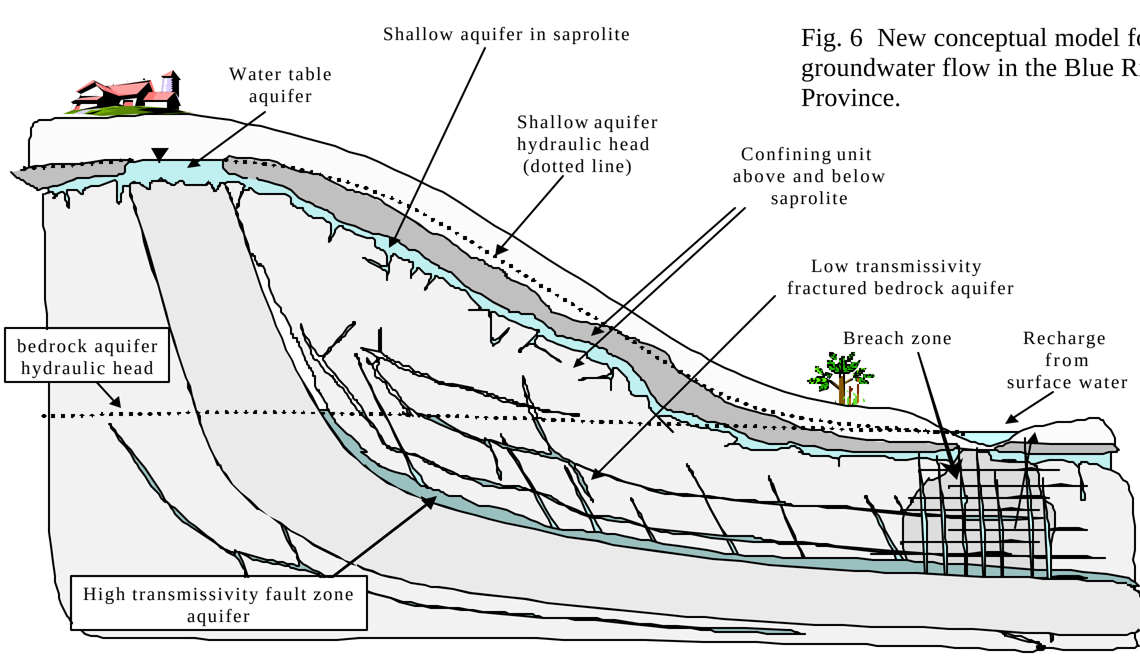


Fig. 6 New conceptual model for groundwater flow in the Blue Ridge Province.

ACKNOWLEDGEMENTS

The authors would like to thank the Virginia Water Resources Research Center for their financial support, which has allowed us to conduct this research at our fractured-rock research facility in Floyd County, Virginia.

REFERENCES

Burbey, T.J., and Seaton, W.J., 2001, Aquifer-Test Analysis in a Fault-Dominated Aquifer System, Blue Ridge Province, Virginia: *Virginia Water Research Symposium 2001, Charlottesville, Virginia.*

Heath, R.C., 1984, Ground-water regions of the United States: U.S. Geological Survey Water-Supply Paper 2242, 78p.

LeGrand, H.E., 1967, Ground water of the Piedmont and Blue Ridge provinces in the southeastern States: *U.S. Geol. Survey Circular* 538, 11 p.

Seaton, W.J., and Burbey, T.J., 2000, Aquifer characterization in the Blue Ridge physiographic province using resistivity profiling and borehole geophysics: geologic analysis. *Jour. of Environmental and Engineering Geophyssics*, v. 5., issue 3, p. 45-58.

BLUE RIDGE PROVINCE SPRING CHARACTERIZATION: RECENT EVIDENCE OF DEEPER FLOW PATHWAYS

W.M. Gentry
T.J. Burbey
Department of Geological Sciences
Virginia Tech
4044 Derring Hall
Blacksburg, VA 24060
miles@vt.edu

KEYWORDS: spring, Blue Ridge Province, hydrograph, resistivity

ABSTRACT

Low discharge (<6gal/min) springs are ubiquitous in the fractured crystalline rocks of the Blue Ridge Physiographic Province in Virginia. Many of these springs flow perennially with little variation in discharge between seasons. Recent investigations using resistivity surveys and springflow hydrographs indicate that the source recharge area for these springs may be connected with intensely fractured fault zones that are common in the Blue Ridge Province.

Within the fractured-rock research site in Floyd County, three or more flow regimes may be responsible for the discharge at the springs on the research site. These regimes include: variable phreatic flow through highly heterogeneous regolith and saprolite, interconnected fracture pathways within the crystalline bedrock, and a porous media type flow along intensely fractured fault zones. These flow regimes may be defined on their relative depth in the subsurface. Flow through regolith and saprolite is typically characterized as shallow unconfined flow, flow through interconnected fractures occurs through the upper part of the crystalline bedrock, and flow along fault zones is characterized as mixed shallow and deep depending on the location of the fault plane within the subsurface.

Investigation of the various pathways is being approached using several surface geophysical datasets. Surface resistivity, seismic refraction, and ground penetrating radar surveys are planned for the study area. These data will be integrated with springflow hydrographs and chemical water analysis to reveal the source of the water discharged at the springhead.

Multiple pathways produce characteristic recession curves on springflow hydrographs. Springflow hydrographs collected in the study area reveal one or two dominate pathways that respond quickly to rainfall events. Recent surface resistivity surveys combined with chemical groundwater characterization indicate a deeper source of water and possible mixing of shallow and deeper water for the same spring in the study area.

BEYOND THE SOURCE WATER ASSESSMENT PROGRAM WITH GIS AND THE INTERNET

Michael D. Lawless
William D. Newcomb
S. Michael Futrell
Draper Aden Associates
2206 South Main Street
Blacksburg, VA 24060
mlawless@daa.com

KEYWORDS: source water assessment, watershed management, GIS, water resources

ABSTRACT

The Safe Drinking Water Act Amendments of 1996 require each state to implement a Source Water Assessment Program (SWAP) for all public water systems that will:

- Delineate the source water assessment area,
- Inventory potential sources of contamination within the assessment area, and
- Determine the susceptibility of the source water.

Ideally, the SWAP is to be completed with the goal of establishing a program to protect source waters that provide drinking water. Implementing a SWAP results in the collection and centralization of large quantities of data useful to many different parties from waterworks operators to planners and developers. A Geographic Information System (GIS) provides a powerful tool for data management and analysis. One of the requirements of the SWAP is to make the collected information available to the public. The Internet is a readily available means of fulfilling this requirement. A website can be designed to allow stakeholders and the general public to query the SWAP GIS and analyze the associated data, with various levels of secure access.

Source water assessment areas are typically delineated at hydrologic boundaries. Much of the data required for the SWAP is generated through compliance with other federal, state, or local regulatory programs. The nature of GIS, which links databases to maps, enables an efficient mechanism for compiling and organizing existing data, conducting data analysis, and displaying results. Therefore, GIS technology is generally the tool of choice for completing the assessments.

The SWAP GIS can include topographic maps, aerial photographs, satellite imagery, hydrologic features, soils maps, and geologic maps, linked to databases showing surface water intakes, groundwater supply wells, NPDES discharges, landfills, Superfund sites, RCRA-regulated facilities, industries, and other regulated sites. Additional features and data can be added to augment the GIS including tax map information, land use plans, wetlands, threatened and endangered species habitat, zoning data, major transportation corridors, etc. This information is valuable to municipal governments, planning district commissions, emergency response personnel, and the general public, as well as waterworks personnel.

A successful SWAP can lead to the establishment of a regional watershed management and water resources protection program. A case study is presented here to illustrate this approach.

INTRODUCTION

Section 1453 of the Safe Drinking Water Act Amendments (SDWA) of 1996 requires each state to implement a Source Water Assessment Program (SWAP) for all public water systems that will:

- Delineate the source water assessment area,
- Inventory potential sources of contamination within the assessment area, and
- Determine the susceptibility of the source water.

Ideally, the assessment is to be completed with the objective of establishing a source water protection program to protect drinking water resources from contamination, in accordance with the goals of Section 1454 of the SDWA. At this time, assessment is mandated but protection is not; however, it is likely that protection will eventually be mandated. The SWAP requirements overlap with other state and federal environmental initiatives including the Wellhead Protection Program, Sole Source Aquifer Program, Underground Injection Control Program, and incorporate data collected in compliance with other regulatory programs including RCRA, CERCLA, TRI, UST/AST, among others. The incorporation of this data from multiple sources and regulatory programs into a SWAP is well suited to organization and management in a Geographic Information Systems (GIS) platform.

GIS technology affords an efficient and comprehensive means of organizing, managing, and evaluating data, and provides enhanced visual representation that aids in interpreting data. GIS enables the illustration of topography, surface drainage, geology, and manmade features, among other information, in a basemap, linked to databases describing water quality, aquifer characteristics, geophysical signatures, potential contaminant sources, and other pertinent information at specific locations within the study area.

GIS comprises two types of data: spatial and attribute data. Spatial data can be defined as data that has a geographic reference location and can include CAD drawings, scanned maps, digital elevation models (DEM), aerial photography, and satellite imagery. Attribute data is non-spatial information related to or describing the spatial data, usually in tabular form, including coordinates, name of the feature, etc. Features in a GIS are not only represented in a pictorial form, as in conventional paper maps, but as information or data.

The most important feature of a GIS is that spatial data are stored in a structured format, referred to as a spatial database. The storage of data in an easily accessible digital format enables complex analysis and modeling.

OBJECTIVES

Two case studies are presented to illustrate the benefits of using GIS and the Internet to prepare Source Water Assessment Plans, implement those plans, and develop source water protection plans. The case studies also illustrate how the source water assessment and protection process integrates with EPA's watershed management approach to protecting environmental quality and implementing sustainable development practices at the local level. ESRI's ArcView® and ArcIMS® were the software packages used to generate the GIS.

WATERSHED AND HYDROGEOLOGY DELINEATION

Source water assessment and protection areas are delineated based on watershed boundaries for surface water sources and hydrogeologic boundaries for groundwater sources. Watershed boundaries can be quickly delineated using GIS tools. In contrast, hydrogeologic boundaries may be more challenging to delineate than a watershed, and the delineation relies on the availability of local and regional geologic and hydrologic data. Managing and evaluating large data sets via GIS greatly aids in identifying hydrogeologic boundaries. State SWAPs typically establish two or three zones for delineation at successively greater distances from the water source; the zones closest to the source being evaluated the most intensively.

POTENTIAL CONTAMINANT SOURCE INVENTORY

The initial step in conducting the potential contaminant source inventory is to conduct a review of regulated sites within the source water assessment area. This is completed by searching such regulatory databases as: RCRIS, CERCLIS and NPL, NPDES, TRI, state environmental remediation projects not under RCRA or CERCLA (i.e., UST/AST, VRP), solid waste facilities, spills and releases, BMPs, among others. Many of these databases are available on the Internet or from the pertinent regulatory agency. Alternatively, an environmental database vendor can be contracted to conduct the search. Often the latter is the more economical option based on time saved and time-sensitivity of records. A further benefit is that most vendors can provide the database for the area of interest in an electronic format that can be readily input into the project GIS. Additionally, since the states are responsible for completing the SWAPs, many of the responsible agencies (e.g., Virginia Department of Health) have potential contaminant source database information readily available and it is often in a GIS format.

The critical step in the inventory is verifying the information both within the GIS and in the field. Often the regulatory databases are incomplete or sites are improperly located or unmapped. Additionally, there are potential sources that may not be regulated and, therefore, may not appear in the databases. As a result, field verification is important. Locations in the field can be mapped using GPS and the data can be downloaded directly into the GIS.

SUSCEPTIBILITY DETERMINATION

The susceptibility determination evaluates the likelihood that a public water supply system would be impacted by a release of contaminants from a source within the watershed. Surface water sources are relatively susceptible to contamination since they are exposed to the atmosphere. Such water supply systems are typically considered moderately or highly susceptible depending on the proximity of potential sources of contamination or land use activities of concern to the intake.

WATERSHED MANAGEMENT

In recent years, stakeholders have become increasingly aware of, and active in, developing watershed management plans for sustainable development within their watershed. The focus of these strategic plans is to address concerns for economic vitality as well as those of environmental protection. Population growth and associated land development is occurring at a rapid pace in many areas of the country. In areas of southwestern Virginia and West Virginia, where the economy has suffered from the loss of coal mining and manufacturing jobs, municipalities are trying to attract new industries to the area to spur economic growth. These efforts, combined with the reality of dealing with the environmental degradation caused by past industrial and mining activity, have lead stakeholders to prepare a plan for future development.

The watershed management approach that has been championed by EPA and the U.S. Army Corps of Engineers, among other regulatory agencies, has several advantages including a geographic focus, continuous improvement based on science, and stakeholder involvement. The geographic focus allows plans to address needs within an area delineated by natural boundaries. It is the area within these natural boundaries that will be affected by development, rather than an area delineated by artificial political boundaries. Basing the plan on scientific data and using scientific techniques ensures the plan will be useful and effective. It also allows for the continuous updating and refining of the plan as additional data becomes available, or as circumstances within the basin change. Involving stakeholders will ensure that those who will be most affected by the development of the watershed have input into the criteria used for managing that development. Ideally, the stakeholders involved will include local government representatives, planners, and developers so that the plan has a reasonable chance of being implemented and enforced.

The source water assessment and protection plans that are developed through the SWAP program provide similar benefits as the watershed approach. The SWAP areas are delineated along watershed (geographic) boundaries. The SWAP plan results in a GIS that presents a comprehensive current view of development and potential sources of contamination within the watershed. The GIS platform allows information to be easily added as the characteristics of the basin change. Additionally, analysis of the data in the GIS allows an evaluation of the effects of future development within a watershed before that development occurs. This allows informed decisions to be made in an efficient timeframe, which is critical when promoting economic development. The SWAP requirement of providing the plan to the public can serve as a starting point for involving stakeholders in the watershed management planning process, and the GIS provides a baseline for preparing and implementing a strategic plan.

CASE STUDY, UPPER NEW RIVER WATERSHED, VIRGINIA

The Upper New River Watershed comprises approximately 2,200 square miles in the Valley and Ridge Physiographic Province of southwestern Virginia (Figure 1). A SWAP for the 12 surface water-derived drinking water intakes in the watershed was developed using a GIS platform with the goal of making the GIS available over the Internet. When completed, the website will allow waterworks personnel, emergency response personnel, planning district commissions, municipal governments, and the public to access and query the SWAP data without requiring the GIS software to be loaded on their personal computers. The website will also fulfill the SWAP requirement of making the assessment available to the public. The purpose of the project was not only to satisfy the Virginia Department of Health (VDH) requirements, but also to produce a database useful to stakeholders within the basin.

The study area was delineated along hydrologic boundaries to include the entire Upper New River Watershed in Virginia. In accordance with the VDH SWAP, the Zone 1 assessment area around each intake was delineated as a 5-mile radius upriver bounded by the watershed, except in the case of one of the intakes which was in an impoundment (Claytor Lake) and was, therefore, delineated both upriver and downriver of that intake (Figure 1). Zone 2 was delineated as the remainder of the watershed. The VDH SWAP requires a more detailed inventory of potential sources of contamination and land use activities of concern to be completed in Zone 1. The inventory for Zone 2 can be completed solely through a regulatory database search. However, in the case of this particular project, the objective was to complete a more thorough inventory throughout the watershed.

The inventory for the Zone 1 areas was completed by field reconnaissance to verify the regulatory database information, and identify any sites not included in the databases. The remainder of the watershed was evaluated from the aerial photographs used in the GIS. The aerial photographs were obtained on the Internet from USGS in their digital orthophoto quarter quadrangle (DOQQ) format. Since much of the watershed is sparsely developed, and given the large area covered by the watershed, the review of the aerial photographs allowed field reconnaissance in Zone 2 to be limited to selected areas of potential concern. In this way, potential contaminant sources in the watershed were inventoried efficiently and cost-effectively.

In addition to the aerial photographs, USGS topographic maps were used as basemaps. For the overall view of the watershed the 1:250,000-scale map was used. The GIS was designed so that as the user zooms in to a larger scale the typical 7.5-minute quadrangle map would be displayed as the basemap. One of the difficulties encountered in obtaining the digital maps was balancing the cost with the limitations of the licensing agreements since the objective was to publish the GIS on the Internet. Many of the least expensive versions virtually prohibit the use of the maps on a web site without significant royalty fees. Those that allow flexible use are often prohibitively expensive.

The susceptibility of each intake was evaluated based on the proximity of the land-use activities of concern and potential contaminant sources. The VDH SWAP defines surface water sources as either moderately or highly susceptible. If a land-use activity of concern is present within Zone 1, or a PSC is located within Zone 2, the source is considered highly susceptible. Since Zone 2 encompasses the entire Upper New River Watershed and numerous PSCs are present within the watershed, all the intakes in the basin are considered highly susceptible under a strict interpretation of the VDH SWAP. However, as indicated on Figure 1, some of the intakes in the western portion of the basin are in less developed areas (e.g., Ivanhoe/Max Meadows and Hillsville) and are clearly at less risk to contamination than those in the more developed areas (e.g., city of Radford and Blacksburg-Christiansburg-VPI).

The attribute data associated with each spatial feature contains tabular information regarding the nature of the feature (Table 1). Attribute data associated with potential contaminant sources and pertinent to the SWAP includes the facility name, contact information, type of chemicals used, location coordinates, distance to water, permit numbers, and other pertinent information. The attribute data distinguishes GIS from CAD-type graphics or other static graphical representation programs. The attribute data allows users to acquire and analyze information from the GIS through the use of queries. For example, the user could query the GIS to find all leaking underground storage tank sites within a one-mile radius of each drinking water intake.

Additionally, one of the features of the GIS under consideration is linking the system to USGS stream gaging data at each of the gaging stations in the watershed, and hydropower dam release schedules. It is anticipated that with this real time data and estimations of channel geometry the flow velocity can be estimated, and from this the time from a point-source impact to the river at a known location to an intake can be calculated. In such a case, the waterworks operator would know the amount of time they have before the contaminant plume reaches their intake. They will, therefore, be able to take the appropriate precautions, including pumping and storing additional water in the time before the plume reaches the intake. One of the goals of the project is to make this sort of information available to waterworks operators, emergency response personnel, and other stakeholders on their desktop in real time.

The Upper New River Watershed Source Water Assessment Program and associated web site will provide a baseline of current land use patterns and potential contaminant sources, which will be critical information for managing the natural resources of the basin. Other applications for the GIS, not directly related to the SWAP website, are also likely to be discovered once the site is made public. For example, recent conversations with VDH representatives indicate the GIS would be useful for their water supply well siting program.

SUMMARY

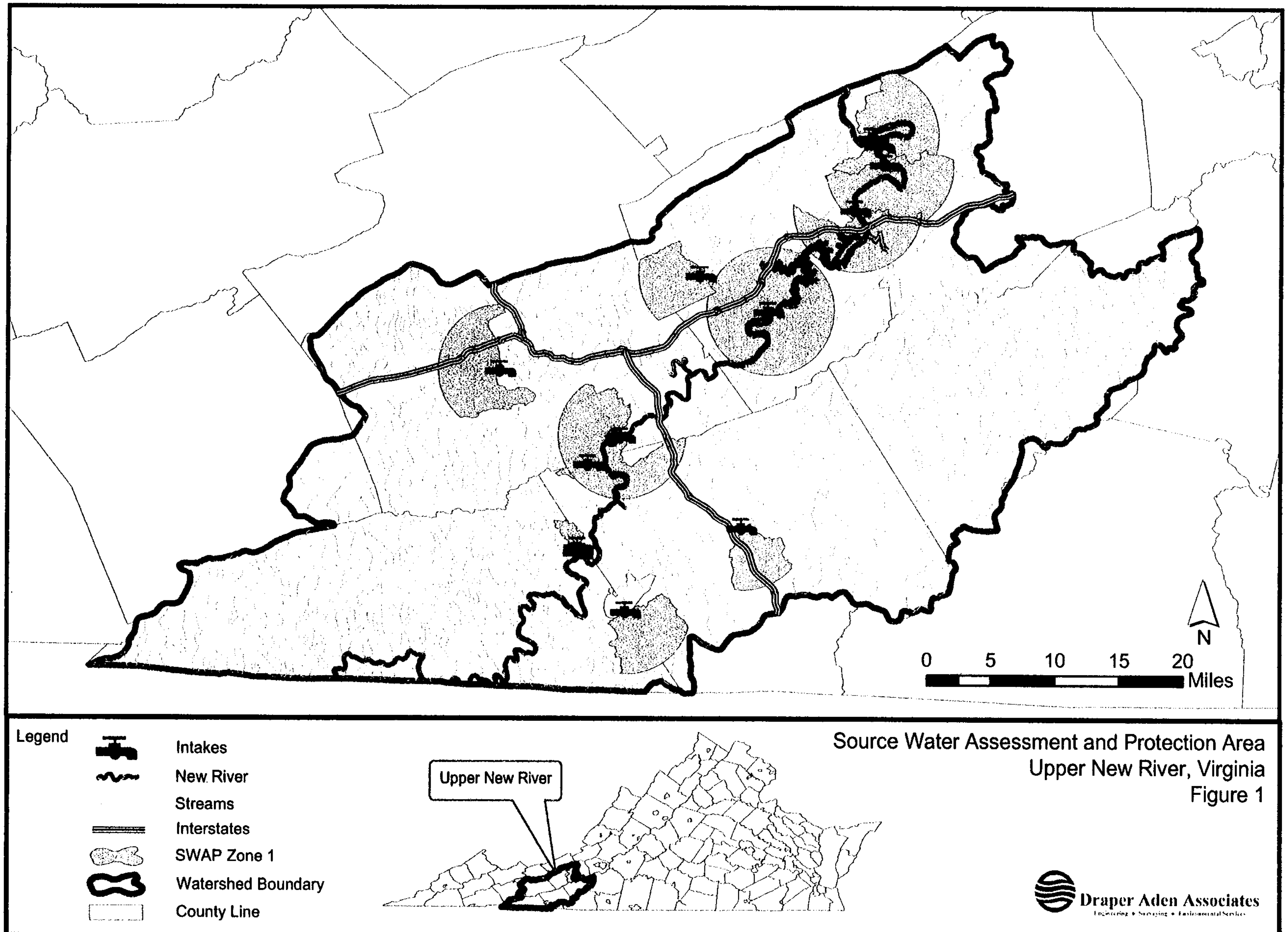
As illustrated by these case studies, a successful SWAP can lead to the establishment of a regional watershed management and water resources protection program. The GIS prepared for the SWAP provides a baseline of current conditions within a watershed including locations of water supplies and an inventory of potential sources of contamination. This information can be used to plan further development with the watershed in a way that will protect the water resources and enhance the quality of life for the stakeholders.

The GIS allows the information to be continuously and efficiently updated as development occurs within the watershed. Potential effects of future development on the watershed can be evaluated and development plans modified in order to meet goals for sustainable development set forth in the watershed management plan. Additionally, the GIS, SWAP, and watershed management plans can be provided to stakeholders through the Internet.

Table 1. Public Water Supply Intake Data, Upper New River, Virginia.

SYSTEM NAME	FACILITY NAME	LATITUDE_D	LONGITUDE_
RIEGEL TEXTILE COMPANY	EAGLE BOTTOM CR	36.727500	-80.983611
BLACKSBURG-CHRISTIANSBURG-VPI WA	NEW RIVER (RAW WATER) PUMP STATION	37.162294	-80.551664
RADFORD ARMY AMMUNITION PLANT	NEW RIVER	37.182814	-80.559158
PULASKI, TOWN OF	PEAK CREEK	37.035772	-80.811867
PULASKI COUNTY PSA	CLAYTOR LAKE	36.994500	-80.715794
RADFORD ARMY AMMUNITION PLANT	NEW RIVER	37.192533	-80.568322
WYTHEVILLE, TOWN OF	REED CREEK	36.928689	-81.094703
RADFORD, CITY OF	INTAKE	37.110717	-80.593281
HILLSVILLE, TOWN OF	LITTLE REED ISLAND CREEK	36.748756	-80.753456
FRIES, TOWN OF	EAGLE BOTTOM CREEK	36.720603	-80.984111
AUSTINVILLE	NEW RIVER	36.852353	-80.924808
IVANHOE/MAX MEADOWS	POWDER MILL BRANCH	36.821100	-80.969800
GALAX, CITY OF	CHESTNUT CREEK	36.653992	-80.917197

COUNTY/CITY	X_COORD	Y_COORD
GRAYSON	-80.98381	36.72737
MONTGOMERY	-80.55188	37.16217
MONTGOMERY	-80.55938	37.18269
PULASKI	-80.81207	37.03565
PULASKI	-80.71600	36.99438
PULASKI	-80.56854	37.19241
WYTHE	-81.09489	36.92857
RADFORD	-80.59350	37.11059
CARROLL	-80.75366	36.74863
GRAYSON	-80.98431	36.72048
WYTHE	-80.92501	36.85223
WYTHE	-80.97000	36.82098
GALAX	-80.91740	36.65386



Source Water Assessment and Protection Area
Upper New River, Virginia
Figure 1

ENABLING WEB-BASED WIRELESS DATA TRANSFER: STROUBLES CREEK WATERSHED CASE STUDY

Pramod Thota
Randy Dymond
David F. Kibler
Civil and Environmental Engineering
Virginia Tech

Dennis G. Sweeney
Center for Wireless Telecommunications
Virginia Tech

Tamim Younos
Virginia Water Resources Research Center
Virginia Tech

Saied Mostaghimi
Biological Systems Engineering
Virginia Tech

Thomas J. Burbey
Geological Sciences
Virginia Tech
Blacksburg, VA

KEYWORDS: Watershed Management, Wireless, and GIS

ABSTRACT

Developing advanced watershed monitoring and data transfer systems that would facilitate rapid and informed decision-making is a top priority for implementing an effective watershed management program. A critical need exists for the development and implementation of a cost-effective monitoring system for small tributaries. The overall objective of the project is to test and integrate wireless watershed instrumentation real time data transfer to a Web based GIS in a small watershed for research and educational purposes.

In the short term, the goal is to integrate the hardware, software, network communications, and Internet map server for real-time Web GIS data reporting and access. Following this testing phase, additional data collection stations will be incorporated into the system.

Consequently, the system will be used for educational purposes within several curricular areas at Virginia Tech. Ongoing research efforts of this Outdoor Watershed Laboratory will focus on the feasibility and applicability of various monitoring technologies to small tributaries and watersheds.

DEVELOPING DIGITAL MONITORING PROTOCOLS FOR FACILITATING TMDL REPORTS

Jason Anderson
Jaander1@vt.edu
John Randolph
energy@vt.edu
Department of Urban Affairs and Planning
Virginia Tech

Tamim Younos
Virginia Water Resources Research Center
Virginia Tech
Blacksburg, Virginia 24061

KEYWORDS: Digital protocols, TMDL, GPS, PDA

ABSTRACT

Field data requirements demanded by the TMDL process for nonpoint source assessment can quickly overwhelm a regulatory agency's manpower and resources. Currently, regulatory agencies primarily rely on traditional data collection methods. Agency personnel in the field complete a standard evaluation form, which is then returned to the office and entered into a computer database for storage and analysis. Recent technological developments (sometimes referred to geospatial information technologies) have changed the method of data collection and management.

The overall goal of this study was to develop, demonstrate, and evaluate a digital protocol for the use of geospatial information technologies in the TMDL planning and monitoring process. The protocol includes digital evaluation forms and systematized directions for their use. The digital evaluation forms are based on DEQ/DCR-approved paper evaluation forms developed by the Save Our Streams organization, as well as input from the DEQ/DCR personnel. The standard forms were developed using available hardware and software. Collected data can be downloaded directly from the PDA and stored in a folder on a hard drive and entered into a GIS database to enhance the visualization and usefulness of the information. The GIS will allow monitors to view the relationships among the many factors affecting the stream, as well as preparing the data for input into a more specialized water quality software package if desired. The developed digital protocol was field-tested and demonstrated on streams currently listed for TMDL development. Factors, such as the ease of use, man-hours, clarity of the required information, and data processing for each method were noted during the testing and demonstration. The results from the demonstration are compared to typical results from the current DEQ/DCR monitoring methods.

DATABASE MANAGEMENT FOR STREAM CORRIDOR SURVEY AND WATERSHED ASSESSMENT

Raymond de Leon
Urban Affairs and Planning
Virginia Tech
raleon@vt.edu

Tamim Younos
Virginia Water Resources Research Center
Virginia Tech
Blacksburg, VA 24061
tyounos@vt.edu

KEYWORDS: watershed management, stream corridor assessment, database management, PDA, GPS

ABSTRACT

Conventional data collection and management in watershed science have relied heavily on paper data sheets and file boxes to store information collected from the field. This method has proven to be inefficient, sometime unreliable, and often space and time consuming. In recent years, there has been a shift to convert archived data into digital format and to perform new data acquisition and storage in a computer database environment. This shift is due greatly to the availability of increasingly inexpensive, easy to use, faster, and more reliable computer hardware and software. Data management using a database system is cost-effective, user friendly, space saving, and more reliable and adaptable. The objective of this presentation is to describe a Microsoft Access database system for watershed data management developed at the Virginia Water Resources Research Center, Virginia Tech. A handheld Personal Digital Assistant (PDA), equipped with a Global Positioning System (GPS), is being used to collect field survey information for the Stroubles Creek Corridor Assessment, a case study watershed, in Blacksburg, Virginia. The collected field survey data is then downloaded to the developed database system. The database system will allow various uses of the data by stakeholders, researchers, and for citizen information.

AN EXPLORATION OF SPATIAL COLLABORATION: STROUBLES CREEK WATERSHED CASE STUDY

Wendy Schafer
Douglas Bowman
Center for Human-Computer Interaction
Computer Science Department
Virginia Tech
Blacksburg, Virginia
wschafer@vt.edu

Keywords: map software, computer-supported cooperative work, Strouble's Creek watershed

ABSTRACT

Protecting our water resources is an effort that requires multiple organizations to work together. Often times these partnerships are based on an interest in a common body of water. For example, the Strouble's Creek Focus Group in Blacksburg, Virginia was formed to coordinate protection efforts for the Strouble's Creek Watershed.

Supporting collaboration among multiple organizations with a common interest is not trivial. For instance, meetings can be difficult to schedule, phone calls often involve only two parties, and writing email notes can be time-consuming. To address these problems, Computer-Supported Cooperative Work suggests that group software support both synchronous and asynchronous communication.

Developed by the Center for Human-Computer Interaction at Virginia Tech and accessible through the Internet, MOOsburg provides a collection of collaboration tools (http://moosburg.cs.vt.edu). These tools support both forms of communication, such as a message board, which is also used for real-time chat.

Most of the tools in MOOsburg allows people to share textual information. These would be beneficial to a partnership of multiple organizations, allowing them to share calendar dates, leave messages, etc. Yet, collaborative water activities often relate to spatial locations. For example, a partnership based on a common water interest, such as a stream, will need to discuss stream locations.

One way to meet this need is to develop a collaboration tool for MOOsburg that allows people to share spatial information using a map interface. For example, multiple organizations might use this tool to coordinate monitoring station locations or discuss the names of spatial locations.

This work is part of an exploration of new ways map software can support collaboration. This work is different from most map applications because it supports asynchronous and synchronous collaboration. It is also unlike other research involving maps and collaboration, which is focused on group decision making using a GIS.

EFFECTS OF IMPERVIOUSNESS ON BENTHIC MACROINVERTEBRATE ASSEMBLAGES, WATER QUALITY, AND HABITAT CONDITIONS IN NORTHERN VIRGINIA'S BULL RUN WATERSHED

J. Arciszewski
R. C. Jones
Environmental Science and Public Policy Department
George Mason University
Fairfax, VA, 22030
jarcisze@gmu.edu
rcjones@gmu.edu

KEYWORDS: Imperviousness, biomonitoring, macroinvertebrate

ABSTRACT

Located in Northern Virginia, Bull Run is a fourth order stream with a watershed that is a major source of drinking water, but is subject to rapid suburban development. For two years, we analyzed differences in the biotic, chemical, and habitat characteristics of about 20 sites representing three levels of imperviousness. Impervious surface cover was determined for each site by calculating the percentages of land-use types within each subwatershed. Six biotic metrics were calculated and composited for a final Index of Biotic Integrity (IBI) score. Imperviousness ranged from 9% to 59%. IBI scores ranged from 3 to 36 out of a possible 36. ANOVA revealed a significant difference between the IBI scores of low versus medium and high imperviousness sites. Linear regression showed a significant relationship between IBI scores and imperviousness. Statistically significant differences were found for all six metrics as a function of imperviousness. Habitat score means were significantly different between the low and high imperviousness sites and regressions of habitat scores versus imperviousness were also significant. Principal component analysis showed a distinct separation of low imperviousness sites from medium and high level sites. Imperviousness was confirmed as a strong predictor of biotic and habitat conditions.

IMPACT OF THE VIRGINIA TECH DUCK POND ON ESCHERICHIA COLI NUMBERS IN STROUBLES CREEK

K. Seat
S. Coe
B. Haines
E. Stevens
B. Black
Virginia Tech Microbiology Club
G. W. Claus, Faculty Advisor
Biology Department
Blacksburg, VA 25061
clausgw@vt.edu

KEYWORDS: Stroubles Creek; SW Virginia; *Escherichia coli*; Virginia Tech Duck Ponds.

ABSTRACT

Stroubles Creek is a sub-watershed of the New River Basin in southwestern Virginia. Two tributaries of the Stroubles Creek run through the town of Blacksburg and under the Virginia Tech "core" campus, and then each tributary flows into separate ponds on campus (upper and lower). Water from the upper pond flows down a concrete cascade and into the lower pond. The water exiting from the lower pond forms the main channel of Stroubles Creek. It is commonly believed that both tributaries and both ponds on the Virginia Tech campus are contaminated with fecal matter, but we can find no published data that either supports or contradicts that hypothesis. Therefore, the Virginia Tech Microbiology Club (undergraduates) recently began a long-term project to periodically determine *Escherichia coli* numbers in the Virginia Tech duck ponds, their feeder tributaries, and the water exiting each pond, to determine the affect of these ponds on *E. coli* numbers in Stroubles Creek. To date, samples have been taken four times at each of the five sites. The numbers of *E. coli* were determined using membrane filtration and plating on m-ColiBlue24® medium (Hach Co., EPA approved method #10029). From these limited samplings, we have drawn the following *tentative conclusions*. *First*, in three out of the four sampling times, *E. coli* numbers in the water exiting each pond were lower than that flowing into each pond. The one exception occurred in samples collected the day following 0.5 inches of rain. *Second*, one tributary consistently exhibited *E. coli* numbers that were from two- to many-times higher than allowed by the Commonwealth of Virginia's Department of Environmental Quality (VDEQ (9-VAC 25-260-5, p. 24). One of four samples taken from the tributary flowing into the lower pond contained numbers higher that the maximum allowed at any time by the VDEQ. And *third*, *E. coli* numbers at each of the five sampling sites were from two- to six-times higher following the rain. Our investigation to date, on this limited number of samples, suggests that the Virginia Tech duck ponds do not increase the numbers of *E. coli* in Stroubles Creek, but the majority of these samples contained *E. coli* numbers that exceed the VDEQ requirements.

FECAL COLIFORMS: WHERE DO THEY COME FROM AND WHERE DO THEY GO?

Carolyn L. Thomas
David M. Johnson
Life Sciences Division
Box 1000
Ferrum College
Ferrum, VA 24088
cthomas@ferrum.edu

KEYWORDS: fecal coliform, Smith Mountain Lake, bacterial source tracking, water quality

ABSTRACT

Fecal coliforms have long been considered a human health problem but have only recently been identified as a health problem associated within lakes and streams. In Smith Mountain Lake, VA and its tributaries fecal coliform populations have been studied for 6 years (1995-2000). In an effort to determine the source of fecal coliform their populations were measured using *Standard Methods* for fecal coliforms and fecal streptococci populations. Marina and non-marina coves of the lake were compared and found to be significantly different but not in violation of the state standards. DNA fingerprinting of fecal coliforms and bacterial source tracking (antibiotic resistance assay) were used to determine the animal sources of these bacteria. In at least one tributary, 86% of the colonies came from a human source. In 1999, an intensive 96-hour study was done during a rain event at 6 sites along a major lake tributary (Blackwater River) to determine the input and variability of nonpoint source runoff on fecal coliform populations. The fecal coliform population peak was observed at time intervals consistent with its movement down the tributary until the bacteria reached the lake and the population peak was no longer detectable. Another rain event study was done on Beaverdam Creek in the Roanoke River watershed in 2000. A additional population study was done in 2000 on a lake cove of Becky's Creek comparing fecal coliform population variability with site, depth, and time of day. This study lasted 48 hours, and studied 7 sites at 8 depths. All three variables were found to be significant in their effect on fecal coliform populations but not were predictable in their effect.

RADON IN POTABLE WELL WATER

Fiorella Simoni
George Mushrush
Douglas Mose
Chemistry Department
George Mason University
4400 University Drive
Fairfax, VA 22030
dmose@gmu.edu

KEYWORDS: radon, potable water, water well

ABSTRACT

In the Piedmont Physiological Province of Virginia and Maryland, potable water from reservoirs is devoid of radon (US EPA proposed Maximum Contamination Level for Radon in Potable Water = 300 pCi/L). However, a significant number of homes use municipal or private water wells. Levels of dissolved radon in excess of 40,000 pCi/L have been discovered. The average well has a level of about 2000 pCi/L. In our study, wells in granite average about 3000 pCi/L, in schist and phyllite about 2000 pCi/L, in sandstone about 1500 pCi/L, and in quartzite about 1000pCi/L. Only about 10 percent of the dissolved radon is lost between the wellsite storage tank and the surrounding homes. Aeration experiments using municipal well water storage tanks show that about 90 percent of the dissolved radon can be removed prior to distribution using tank aeration or by passing the well water through large tanks of activated charcoal.

ABILITY OF THREE MODELS TO PREDICT WATER TEMPERATURE IN AN UNREGULATED STREAM AND HYDRO-PEAKING RIVER

Colin W. Krause
T.J. Newcomb
D.J. Orth
Department of Fisheries and Wildlife
100 Cheatham Hall
Blacksburg, Virginia
cokrause@vt.edu

KEYWORDS: stream temperature model, thermal water quality, predictive ability

ABSTRACT

Stream temperature models can be used to predict thermal regimes following changes in watershed hydrology, land use, and riparian conditions. To produce accurate predictions and answer chosen management questions the appropriate model must be used. We evaluated the performance of three software packages that model stream temperature (SNTEMP, QUAL2E, and TVA River Modeling System) for use on two stream networks (a third-order stream and hydropeaking tailwater). We assessed model predictive ability, parameter sensitivity, data collection requirements, and user friendliness. Steady-state models, SNTEMP and QUAL2E, predicted similarly for both the third-order stream where daily flow was relatively constant, as well as for the hydropeaking tailwater where flow fluctuated daily. Though SNTEMP required more collection of data than QUAL2E, SNTEMP had fewer limitations, which makes it better for evaluating alternate shade and flow scenarios. The TVA model, a dynamic model, was better suited to model the rapidly changing flows of the tailwater by predicting hourly rather than daily temperature. The TVA model required the most intensive data collection, therefore, it was less efficient for use in the third-order stream. Each model had sensitive parameters, air temperature, relative humidity, and starting water temperature, which required accurate collection for optimal predictive ability. Consideration of stream type and modeling objectives are imperative factors for choosing a stream temperature modeling approach.

ASSESSING FLASH FLOOD POTENTIAL WITH THE AID OF GPS INTEGRATED WATER VAPOR ESTIMATES

G.V. Loganathan
S. Gorugantula
T. Eisenberger
D.F. Kibler
Department of Civil Engineering
Room 200 Patton Hall
Virginia Tech
Blacksburg, VA 24061
gvlogan@vt.edu

S. J. Keighton
M. Gillen
National Weather Service Forecast Office
1750 Forecast Dr.
Blacksburg, VA 24060

KEYWORDS: flash flood, rainfall prediction, GPS, radar, water vapor

ABSTRACT

The mountainous southwest Virginia is the home of the head water areas for the New, the Roanoke, and the James rivers. The region is prone to flash flooding, typically the result of localized precipitation. Fortunately, within the region, there is an efficient system of instruments for real-time data gathering with IFLOWS' (Integrated Flood Observing and Warning System) gages, the National Weather Service's WSR-88D Doppler radar and high precision GPS (Global Positioning System) receiver. The present study focuses on utilizing the GPS technology for estimating the integrated water vapor content towards forecasting the rainfall amount. Considering that the GPS signals are received every 30 minutes in comparison to the NWS' 12 hour radiosonde data, there is a good potential for an improved forecast. This study concentrates on improving the forecast lead time for a flash flood producing rainfall by combining WSR88-D Doppler radar, radiosonde, IFLOWS, and GPS integrated water vapor data.

INTRODUCTION

The National Weather Service (NWS) currently relies on the radar for short-term forecasting. The WSR-88D Doppler radar estimates rainfall (R) using the lowest beam angles to detect reflectivity (Z) and applies an empirical relationship (Z-R) to convert to an estimated rainfall rate. Forecasters have access to a new radar volume scan and updated precipitation estimates (totals of one hour or more) every five or six minutes. In addition, near-realtime rain gage data is obtained at select locations every minute, and available in 15 minute or greater intervals. Rainfall readings from rain gages and radar estimates can provide forecasters with a short lead time (usually around 30 minutes) before flash flooding occurs from convective storms. However, when other data sets are incorporated that reveal information about the environment, particularly the mesoscale environment, the lead time can often be increased if certain trends are observed on the radar or satellite imagery.

One of the environmental parameters that plays a key role in the development of flash-flood producing storms, is the total available moisture, measured one way by the vertically integrated precipitable water vapor (IPW) in an atmospheric column. Most commonly this is measured twice per day by radiosonde instruments, at approximately 75 synoptically-spaced upper-air sites around the U.S., including the Blacksburg, VA National Weather Service Forecast Office (RNK). These observations of IPW are useful for understanding the synoptic environment, and the moisture profiles are important input into numerical weather prediction models, but they reveal little about smaller scale features which are often responsible for the development or increase in convective activity.

GPS Technology

Recently, the NOAA Forecast Systems Laboratory (FSL), as well as other federal government agencies, have begun employing global positioning system (GPS) technology to measure IPW from sensors at select locations around the U.S. Currently there are more than 50 of these sensors that are a part of the FSL Demonstration Network, and the plan is to increase this number to as many as 200 within the next few years. The temporal resolution of these data is 30 minutes,
and new implementation of near real-time processing techniques has made the data available within 75 minutes of real-time. One of these sensors was installed at NWS RNK in 1999 (BLKV), and is co-located with the upper air observation site. While the horizontal spacing sensors cannot yet provide a mesoscale analysis over southwestern Virginia, the temporal resolution is more than enough to reveal potentially important short-term fluctuations in IPW that may be precursors to convective activity. The GPS systems do not suffer from the calibration problems associated with the radiometers; they also overcome the cloud cover problem associated with the infrared sensors used on satellites (microwave sensor estimates are currently possible only over the oceans). The GPS technology provides unattended, frequent, and accurate measurements at low cost. Being a new technology, how to effectively exploit the GPS measurements in operational forecasting remains a research problem.
The description given here is based on Borbas 1997; Duan et al. 1996; Rocken et al. 1995; and Bevis et al. 1992. GPS satellites transmit microwave signals at 1.2 and 1.6 GHz through the earth's atmosphere. The ionosphere and neutral atmosphere (interchangeably called the troposphere for this discussion and is made of a mixture of dry gases and water vapor) slow down the speed of these signals. Because the ionospheric delay is approximately proportional to the inverse square of the signal frequency, by utilizing dual frequencies (L1 and L2 dual band receiver), it is possible to measure it. The neutral delay is obtained by subtracting the ionospheric delay from the total delay obtained from the GPS (See http://www.paroscitific.com/gpsmet).

neutral atmospheric delay, ZND = total delay from the GPS – ionospheric delay (1)

The neutral delay, ZND, the sum of the hydrostatic, ZHD, and wet components, ZWD and

$$ZND = ZHD + ZWD \tag{2}$$

The hydrostatic component in the zenith direction, ZHD is primarily made up of the dry gases in the atmosphere plus the nondipole contribution of the water vapor. It can be determined by surface pressure measurements given by

$$ZHD = \frac{(2.2779 \pm 0.0024)P_S}{1 - 0.00266\cos 2l - 0.00028H} \tag{3}$$

in which: Ps is the total pressure in (hPa) at the earth's surface, the denominator is the variation of the gravitation acceleration with latitude, λ, and the height, H above the ellipsoid for the station in Km. Typical value of ZHD is 2.3 m at the sea level in the zenith direction and it is about 90 percent of the total tropospheric delay (See: http://pecny.asu.cas.cz/meteo/Info.html).

The ZWD (zenith wet delay) is hard to model by surface measurements due to the irregular distribution of the water vapor in the atmosphere. The wet component, ZWD, is due to the water vapor's dipole moment contribution to its refractivity. For most of the troposphere, the dipole component of the refractivity is about 20 times larger than the nondipole component (Bevis et al., 1992). To obtain the wet delay, ZWD by

$$ZWD = ZND - ZHD \tag{4}$$

The value of zenith-wet delay (ZWD) can be less than 1 cm in arid regions and its maximum can reach about 40 cm in humid areas.

Precipitable water (PW) is the depth of water that would result if the atmospheric water vapor were to condense into liquid. One centimeter of PW causes about 6.5 cm of GPS wet signal delay. This 6.5-fold amplification is crucial for accurate PW measurement with GPS. The derived ZWD is converted into precipitable water vapor PW in units of length by

$$PW = K\ ZWD \tag{5}$$

with (Bevis et al., 1994)

$$k = \frac{10^6}{\left(r_w R_v \left(\frac{K_3}{T_m} + K_2' \right) \right)} \tag{6}$$

where: ρ_w is the density of water, Rv = 461.495 Jkg-1K-1 is the specific gas constant of water vapor, $K'_2 = 22.1 \pm 2.2$ (K/hPa) and K3 = $(3.739 \pm 0.012)105$ (K2/hPa). The weighted mean temperature of the atmosphere Tm is defined as

$$T_m = \frac{\int \left(\frac{P_v}{T} \right) dz}{\int \left(\frac{P_v}{T^2} \right) dz} \tag{7}$$

in which: Pv is the partial pressure of water vapor and T is the absolute temperature. T_m can be estimated by $T_m = 70.2 + 0.72 T_S$ (K), where T_S is the surface temperature.

APPLICATION

Figure 1 shows the monthly climatology of PW for Blacksburg based on six years of radiosonde measurements. From Figure 1, the 75th percentile and (mean + 2SD) cutoff values are selected as the threshold for forecasting impending significant rainfall events based on the GPS-PW observations. These thresholds are applied in Figure 2. A leadtime of 3 to 4 hours is typically noticed. For example, the July 4th data (Figure 2, Julian day 185) based on the crossing of the 75th percentile at 184.5 Julian day, there would be an alert about a possible rain event. Table 1 shows a listing of identified events solely based on the GPS-PW values. Column 4 contains Yes or No flags based on whether the 75th percentile threshold was exceeded for that day. An exceedance is indicated by a Yes. In column 3, the areal average rain is given. All events that had at least 0.1 inch of rain were identified. Figure 3 shows a comparison between the GOES satellite estimate of PW against the GPS-PW estimate. The estimates are quite close.

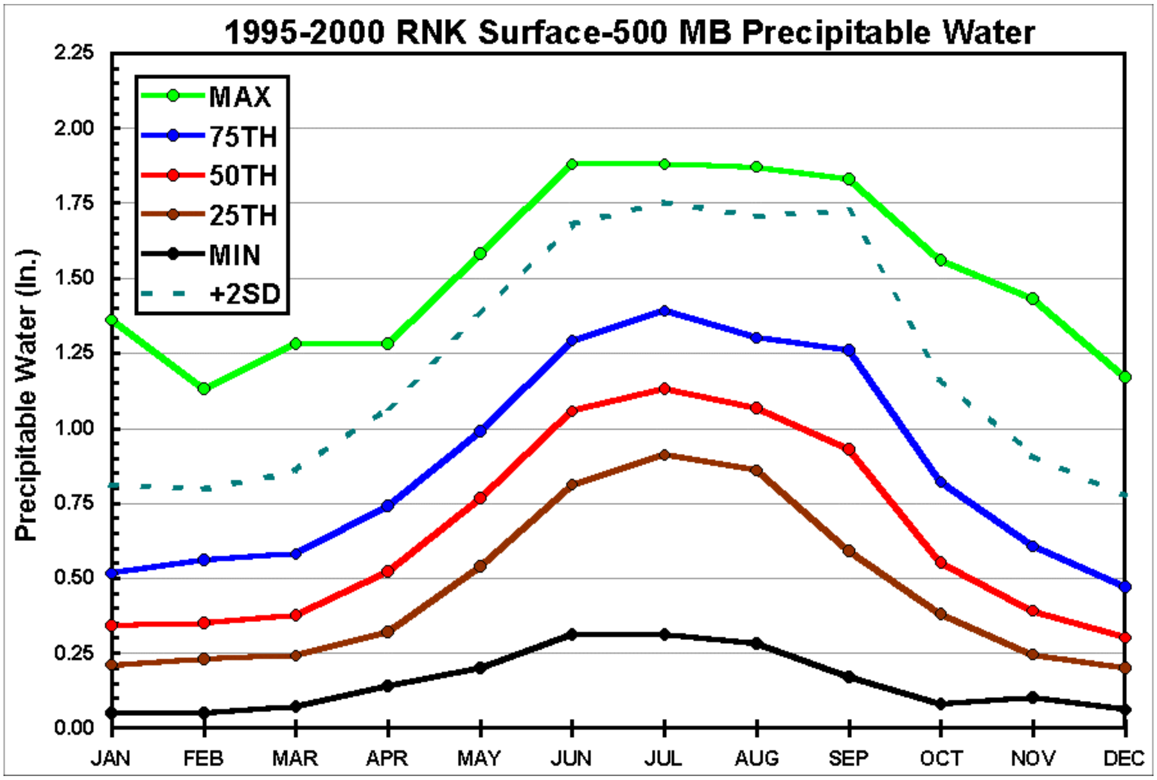


FIGURE 1. MONTHLY CLIMATOLOGY OF RADIOSONDE PW FOR BLACKSBURG

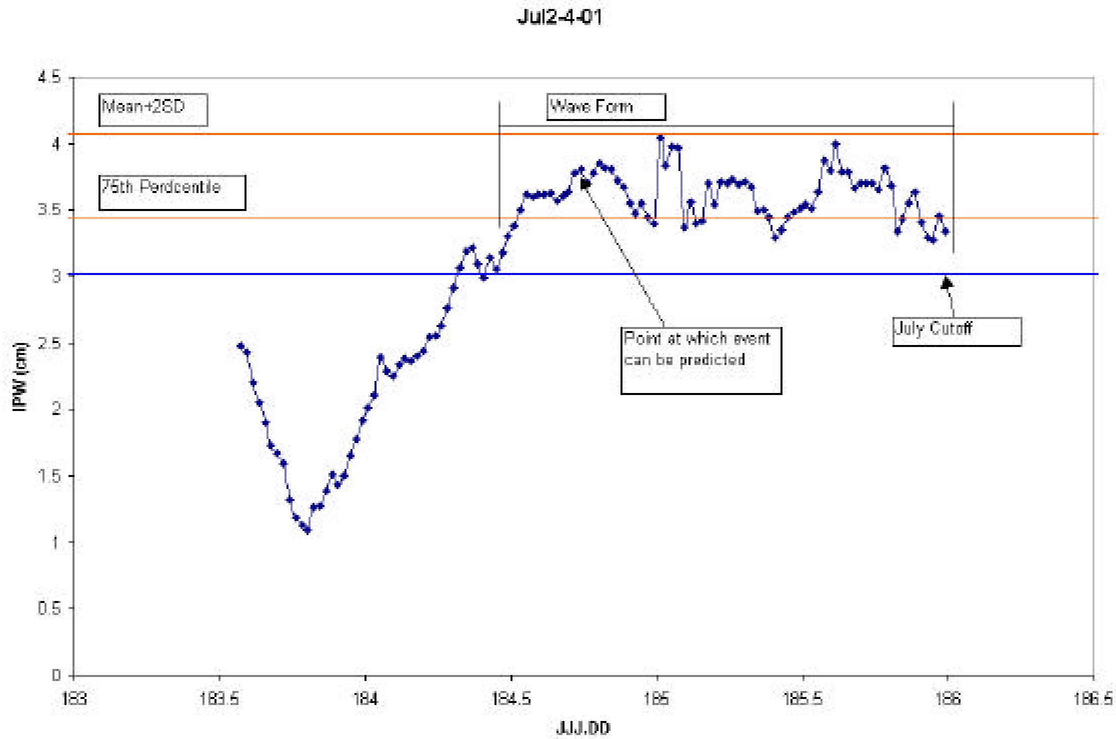


FIGURE 2. GPS-PW PLOT FOR JULY 2-4, 2001

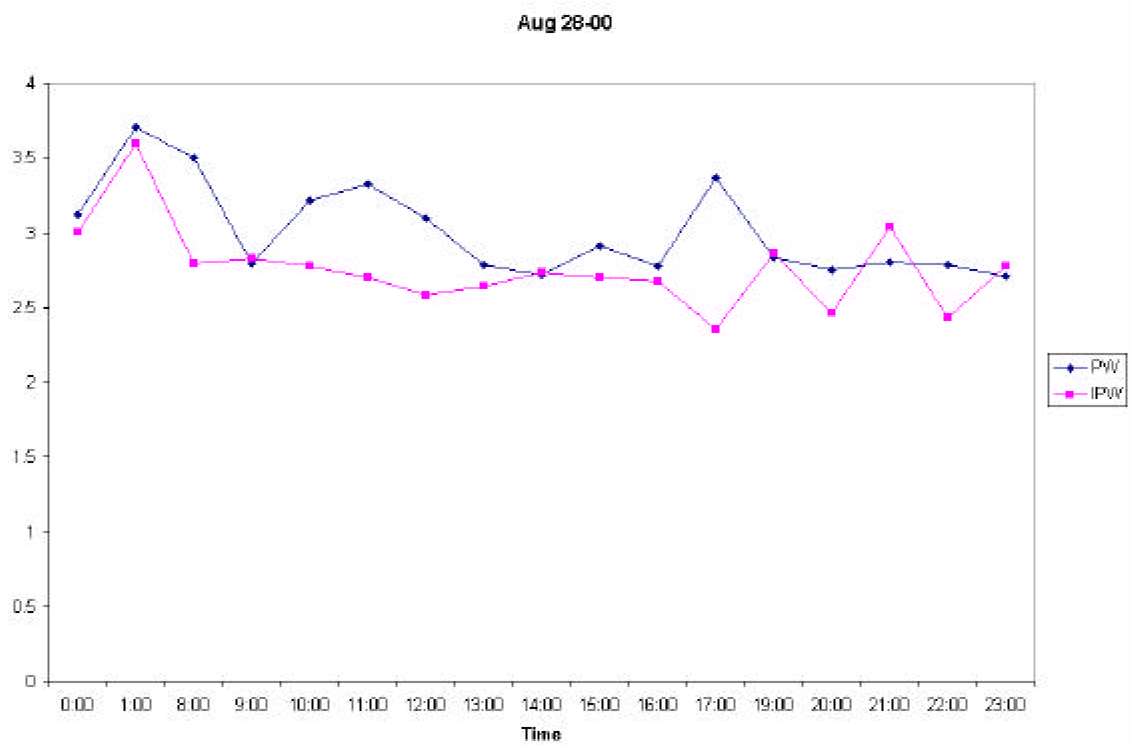


FIGURE 3. COMPARISON OF GOES-PW VERSUS GPS-PW

TABLE1. EVENT PREDICTION FOR AUGUST 2000

Julian day	Calendar day	Rain (inches)	Predicted Days using 75th Percentile cutoff
214	1	0.4662	yes
215	2	0.2421	yes
216	3	0.1441	yes
217	4	0.1000	yes
218	5	0.0145	no
219	6	0.0254	yes
220	7	0.2238	yes
221	8	0.1605	yes
222	9	0.2668	yes
223	10	0.2742	yes
224	11	0.0125	no
225	12	0.0136	no
226	13	0.0845	no
227	14	0.0109	no
228	15	0.0100	no
229	16	0.0160	no
230	17	0.0111	no
231	18	0.2371	yes
232	19	0.0202	no
233	20	0.0170	no
234	21	0.0157	no
235	22	0.0111	no
236	23	0.0227	yes
237	24	0.0878	yes
238	25	0.1554	yes
239	26	0.0311	yes
240	27	0.7932	yes
241	28	0.2990	yes
242	29	0.0186	no
243	30	0.1411	yes
244	31	0.3586	yes

SUMMARY

The frequently available GPS-PW data identifies impending events correctly. There is a lead time of 2 to 4 hours for a significant number of events providing sufficient warning in the case of a flash flood. While the rain events can be identified with confidence, flooding depends on the ground conditions as well and, therefore, the problem becomes complex.

ACKNOWLEDGEMENT

The writers gratefully acknowledge the financial support provided by the Virginia Water Resources Research Center and the UCAR/COMET of the National Weather Service which made this research possible. The writers wish to thank Seth Gutman and Kirk Holub from NOAA/FSL for their installation of the GPS sensor as well as their technical expertise interpreting the data. Efforts by William Riehl and Brian Campbell from the NWS Blacksburg are crucial in establishing the communications from the sensor to the data logger. The autors also thank Matthew Bunkers from the Rapid City, SD NWS office for creating the PW climatology chart for Blacksburg.

REFERENCES

Bevis, M., S. Businger, T. Herring, C. Rocken, R. Anthes, and R. Ware. 1992. "GPS Meteorology: Remote Sensing of Atmospheric Water Vapor Using the Global Positioning System", *J. Geophys. Res.*, 97, pp.15,787-15,801.

Bevis, M., S. Businger, T. Herring, R. Anthes, C. Rocken, R. Ware, and S. Chiswell. 1994."GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water", *J. Appl. Meteorol.,* 33, pp.379-386.

Borbas, E. 1997. "Determination of Precipitable Water for a Fixed Site Using Global Positioning System Technique", *Quarterly Journal of the Hungarian Meteorological Service*, 10, 4, 261-273.

Duan, J., M. Bevis, P. Fang, Y.Bock, S. Chiswell, S. Businger, C. Rocken, F. Solheim, T. VanHove, R. Ware, S. Mc Clusky, T. A. Herring, and R. W. King. 1996. " GPS Meteorology: Direct Estimation of the Absolute Value of Precipitable Water", *J. of Applied Met.,* Vol. 35, No. 6, pp 830-838.

Rocken,C., Van Hove, T., Johnson, J., Solheim, F., Ware, R., Bevis, M., and Businger, S. 1995. " GPS/STORM-GPS Sensing of Atmospheric Water vapor for Meteorology", *J. Of Atmospheric and Oceanic Technology*, Vo.12, pp.468-478.

VARIABILITY IN CONCENTRATION-DISCHARGE PLOTS - MODELING RESULTS WITH IMPLICATIONS FOR FIELD STUDIES

Jeffrey G. Chanat
George M. Hornberger
Department of Environmental Sciences
Clark Hall
University of Virginia
Charlottesville, VA 22903
Jgc33n@virginia.edu

Karen C. Rice
2U.S. Geological Survey
P.O. Box B
Charlottesville, VA 22903

KEYWORDS: concentration-discharge plots, catchment hydrochemistry, computer models

ABSTRACT

Concentration-discharge (c-Q) plots are a convenient and increasingly popular tool for analyzing the episodic hydrochemical response of small catchments. Because c-Q plots are based only on observed streamflow and solute concentration, their interpretation requires assumptions about the relative volume, hydrograph timing, and solute concentration in the streamflow end-members. Evans and Davies (1998) propose a taxonomic classification of c-Q plot shapes into six classes based on clockwise ("C") or anticlockwise ("A") rotation direction, and whether the loop excursion is strictly above ("2"), strictly below ("3"), or brackets ("1") the baseflow concentration. Their results suggest a unique relationship between loop type and rank order of end-member solute concentrations. The authors base their analysis on a fixed three-component hydrograph template consisting of surface-event, soil, and ground water. However, many catchments exhibit variability in component contributions to stormflow in response to antecedent conditions or rainfall characteristics. Starting with the scheme of Evans and Davies (1998), we characterize the variability in c-Q plot shapes resulting from variation in end-member hydrograph timing, volume, and solute concentration using a simple computer model.

Within the broad constraints of the hydrograph template used by Evans and Davies (1998), a given rank order of end-member solute concentrations can result in more than one type of c-Q plot, depending on end-member hydrograph timing and volume. When all three end-member concentrations are within the same order of magnitude, loop types A3 and C2 are most likely to assume ambiguous shapes or reverse rotation direction. As the separation between concentrations increases, loop types C2 and A2 become more robust to variability in timing and volume, while loop types C3 and A3 become less robust. In contrast, loop types A1 and C1 are universally robust to variability in timing, volume, and concentration. In ambiguous cases, the relative "distinctness" in a solute mass-transfer sense, of the surface-event and soil water components is the key factor in determining c-Q plot shape and rotation direction. The modeling results indicate that plausible hydrometric variability in field situations can confound the interpretation of c-Q plots and potentially undermine their diagnostic power, even when fundamental end-member mixing assumptions are satisfied.

A STUDY OF VIRGINIA WATER QUALITY, 1978 – 1995

C. E. Zipper
Crop and Soil Environmental Sciences
Virginia Tech
czip@vt.edu

G.I. Holtzman
Department of Statistics
Virginia Tech
Blacksburg, VA 24061

P.F. Darken
EQMetric, L.L.C.
Durham, NC 27705

J.J. Gildea
Tetra Tech, Inc.
Cleveland, Ohio 44138

R.E. Stewart
Virginia Department of Environmental Quality
Richmond, VA

KEYWORDS: Seasonal Kendall analysis, surface water quality; water-quality trends, watershed.

ABSTRACT

Surface water-quality data for 9 variables at 180 Virginia locations were analyzed for trends over the 1978 - 1995 period using the seasonal Kendall technique. The analyses were conducted using water-quality data assembled by Virginia Department of Environmental Quality (DEQ) through ongoing monitoring activities. Median values and Kendall's *tau*, a trend indicator statistic, were generated for dissolved oxygen saturation (DO), biochemical oxygen demand (BOD), pH, total residue (TR), non-filterable residue (NFR), nitrate-nitrite nitrogen (NN), total Kjeldahl nitrogen (TKN), total phosphorus (TP), and fecal coliform (FC) at each monitoring location. Results characterized by low precision and/or poor representation of the study period were eliminated from the subsequent analyses. Because flow data were unavailable at the majority of the locations studied, flow adjustments could not be applied to the trend analyses. Each monitoring location was assigned to one of four regions (Appalachian, mountain valley, Piedmont, or coastal), and statewide and regional means were calculated. Water quality exhibited widespread improvement with respect to BOD and NFR while FC improvements occurred in the state's western regions and TP improvements were noted regionally. Throughout the state, TR and TKN exhibited predominantly increasing trends. BOD, NFR, TKN, and TR medians were higher in coastal areas than in other areas of the state, while DO medians were lowest in the coastal region. FC medians were highest in the Appalachian region, while NN medians were high in the mountain valley region compared to Piedmont and coastal areas. NN, TKN, and TR exhibited predominantly increasing trends in regions with median concentrations that were high, relative to other regions, while declining trends predominated in regions with relatively high BOD, FC, and NFR medians. Appalachian monitoring stations exhibited the greatest regional water-quality improvements for four of the nine variables – BOD, FC, NFR, and TKN.

RECYCLED WATER FOR LANDSCAPE PLANT IRRIGATION

Laurie J. Fox
Virginia Tech Hampton Roads Agricultural Research & Extension Center
1444 Diamond Springs Rd.
Virginia Beach, VA 23455
ljfox@vt.edu

KEYWORDS: : Reclaimed water, Waste water, Water reuse, Sewage effluent, Non-potable water, Water quality, Water management

ABSTRACT

ABSTRACT

Recycled treated effluent water is a viable alternative source for landscape irrigation, which is currently not used in Virginia. A two-year study was initiated March 2000 at the Hampton Roads Sanitation District (HRSD) Virginia Initiative Plant in Norfolk, Virginia to evaluate the use of recycled water for irrigation of landscape plants. Raised beds were constructed, common landscape plants installed, and irrigation applied for six months. For 2000, injury from recycled water was most severe on coneflower, cherrylaurel, azalea, and red maple. Observed injury symptoms included marginal leaf burn, chlorosis, browning, and in some cases crown rot. No salt residues were observed on any plants.

INTRODUCTION

Water is a finite resource, and water quality and availability are key environmental issues. Maintaining healthy landscapes while balancing growing industry and environmental concerns requires research into alternative water management techniques. Recycled (or reclaimed) water is a viable alternative for the irrigation of landscape plants. Recycled water is the liquid waste collected in sanitary sewers and treated in municipal wastewater treatment plants (Pettygrove and Asano 1985).

Across the United States, water treatment plants are producing large quantities of high quality, low-cost recycled water. Recycled water is currently relied upon in areas where ground water supplies are limited or strained due to heavy populations. While the most common recycled water use is for turf irrigation on golf courses, athletic fields, and sod farms, the practice of irrigating landscapes with recycled water is widespread and even mandated in parts of California and Florida (Parnell 1988). As the U.S. population continues to grow and regulation of public water use increases, recycled water use will continue to increase. However, a more thorough understanding of recycled water quality, and site and plant sensitivities is necessary before recycled water will be commonly used by the landscape industry. Recycled water is generally higher in soluble salts than potable water (Hayes et al. 1990; Matheny and Clark 1998), which can potentially lead to salt residues on plants and salt buildup in the soil. Therefore, the objectives of this research were to evaluate the recycled water produced by the Hampton Roads Sanitation District Virginia Initiative Plant as an irrigation source for landscape plants, and to identify any adverse effects the recycled water might have on landscape plants common in the Hampton Roads Virginia area.

MATERIALS AND METHODS

On March 20, 2000, six 16’ X 16’ X 12” raised beds were constructed in the courtyard of the Hampton Roads Sanitation District (HRSD) Virginia Initiative Plant in Norfolk, Virginia . The beds were equipped with Hunter SRS-12 pop-up nozzles in each corner and set for 90° degree overlapping patterns. Three beds were connected to the city of Norfolk's potable waterline and three beds were connected to the HRSD recycled (nonpotable) waterline. The beds were filled with a sandy loam soil, and plants installed on April 11. Two inches of chipped hardwood mulch was applied on April 20, 2000. Plots were irrigated twice a week beginning May 5 for a total of 1" of water per week (Virginia's landscape standard). Plants were visually rated once a month May through October for their aesthetic quality using a scale of 1=dead to 5=no injury. A soil test and water analysis were conducted each month at the same time as the visual ratings. The study was a randomized complete block design with two treatments [potable and recycled (nonpotable) water] and three replications per treatment. Data were analyzed using the Analysis of Variance.

A literature search was conducted and two plant lists were compiled. The first list was comprised of species commonly used in landscapes in the Hampton Roads area. The second list was comprised of species rated as either salt sensitive or salt tolerant. After crossreferencing the two lists, the following species were selected for the study.

Annuals: begonia (*Begonia semperflorens*), dianthus (*Dianthus chinensis*), geranium (*Pelargonium hortulanum*), petunia (*Petunia* x *hybrida* 'Midnight'), vinca (*Catharanthus roseus* 'Pink Cooler'), marigold (*Tagetes erecta* 'Antiqua Yellow'). **Perennials:** coneflower (*Echinacea purpurea* 'Magnus'), dwarf daylily (*Hemerocallis* 'Stella de Oro'), variegated liriope (*Liriope muscari* 'Variegata'), black-eyed Susan (*Rudbeckia fulgida* var. *sullivantii* 'Goldsturm'), sage (*Salvia nemorosa* 'May Night'), stonecrop (*Sedum* x 'Autumn Joy'), verbena (*Verbena canadensis* 'Homestead Purple'). **Shrubs:** butterfly bush (*Buddleia davidii* 'Nanho Blue'), boxwood *(Buxus sempervirens* 'Suffruticosa), gardenia (*Gardenia jasminoides* 'Chuck Hayes'), juniper (*Juniperus chinensis* var. *sargentii* 'Viridis'), dwarf nandina (*Nandina domestica* 'Firepower'), mugo pine (*Pinus mugo*), cherrylaurel (*Prunus laurocerasus* 'Otto Luyken'), azalea (*Rhododendron* x 'Delaware Valley White'), Japanese spiraea (*Spiraea japonica* 'Neon Flash'), dwarf viburnum (*Viburnum tinus* 'Compactum'). **Trees:** red maple (*Acer rubrum*), river birch (*Betula nigra*), Eastern redbud (*Cercis canadensis*), crape myrtle (*Lagerstroemia* x 'Natchez').

RESULTS AND DISCUSSION

Duncan's Mean Separation test ($P<0.05$) showed significant main effects for irrigation treatment, month, and species. There were also interactions for irrigation by month and species by irrigation. Injury from recycled water was most severe onsage, coneflower, cherrylaurel, azalea, vinca, mugo pine, and red maple. Observed injury symptoms included marginal leaf burn, chlorosis, browning, and in some cases, crown rot (Figure 1). No salt residues on plants were observed.

Injury worsened over time, indicating that detrimental effects from irrigating with recycled water may be cumulative. Also, fluctuations in the levels of salts and chlorine in the recycled water might contribute to worsening injury symptoms and/or residues (Table 1). Unfortunately, by September the Hampton Roads area received approximately 12" above average rainfall. Some injury symptoms could be attributed to excessive water over an extended period of time, while expression of even more severe salt injury symptoms may have been lessened due to leaching of salt residues from the soil (Table 2).

The aesthetic quality of plants is subjective. Unless a plant is very obviously off color, deformed, or dying, most people do not look beyond the pretty flowers and general appearance of a plant. Most plants in this study, even the species with some injury, would be acceptable to the average observer. This study was repeated in 2001.

Fig. 1. Coneflower, red maple and azalea after five months of irrigation with potable water (top) and with recycled water (bottom).

Table 1. Water analysis data.

		May	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**
Sodium	Potable	9	10	11	12	11	12
	Recycled	471	278	275	160	170	185
Chloride	Potable	15	16	17	19	25	18
	Recycled	830	380	360	210	210	200
pH	Potable	6.9	7.1	6.8	6.8	6.9	7.5
	Recycled	6.9	7.3	7.0	7.6	7.0	7.0

TABLE 2. SOIL ANALYSIS DATA FROM BEDS TREATED WITH POTABLE AND RECYCLED WATER.

		May	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**
Sodium	Potable	16	15	9	7	13	14
(ppm)	Recycled	16	84	77	72	66	86

SIGNIFICANCE TO INDUSTRY

Water is a resource too valuable to be used only once. Recycled water can be an excellent irrigation source for landscape plants, conserving potable water supplies. Sanitation districts can market a recycled product so that landscape managers have an alternative, less expensive water supply for irrigation, and so that landscapes can be maintained in a healthy and environmentally sound manner.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Rhonda Bowen, Sami Ghosn, Todd McGovern and George Kennedy with the Hampton Roads Sanitation District and Patricia King with Old Dominion University for their support on this project.

REFERENCES

Hayes, A., C. Mancino, and I. Pepper. 1990. Irrigation of turfgrass with secondary sewage effluent: I. Soil and leachate water quality. Agron. J. 82:939-943.

Matheny, N., and J.R. Clark. 1998. Managing landscapes using recycled water. In The Landscape Below Ground II. Neely, D., and G. Watson, eds. International Society of Arboriculture, Champaign, IL. 265pp.

Parnell, J. 1988. Irrigation of landscape ornamentals using reclaimed water. Proc. Fla. State Hort. Soc. 101: 07-110.

Pettygrove, G., and T. Asano. 1985. Irrigation with Reclaimed Municipal Wastewater – A Guidance Manual. Lewis Publishers, Chelsea, MI.

LIVESTOCK WASTE MANAGEMENT AND LAKE REHABILITATION BY CHEMICAL PRECIPITANTS

Christopher B. Lind
General Chemical Corporation
90 East Halsey Road
Parsippany, NY 07054
clind@genchemcorp.com

KEYWORDS: nutrient inactivation, phosphorus, eutrophication, livestock waste

ABSTRACT

The technologies for nutrient inactivation and interception in poultry litter and other animal wastes have associated economic benefits for the grower as well as demonstrated environmental efficacy. Aluminum sulfate has been employed for the reduction of (litter) pH for the past few years to provide buffering against the high pH animal waste, and provides a longer lasting effect than monobasic acid salts like sodium bisulfate. Insoluble aluminum phosphate formed in the litter is not in a form that is bio-available as a nutrient in runoff. Aluminum phosphate precipitate is the least soluble over a wider pH range of the three common cations used for P control, those being iron, aluminum and calcium.

Nutrient inactivation in an impacted water body has been used for over thirty years. Chemical coagulation and clarification are an important means of nutrient inactivation and management in surface waters. Microbial proliferation from excessive P causes eutrophication of the lake and degradation of the water supply. Nutrient inactivation serves to avoid or mitigate the eutrophication and improve the water quality.

The paper reviews livestock nutrient concentration and management technologies including nutrient inactivation, alternative disposal techniques, and dietary modifications to reduce total P in manure. Also discussed are soil and lake rehabilitation technology specific to phosphorus binding and the positive impact on surface water quality.

INTRODUCTION

Poultry manure and spent bedding material or litter has been used for crop fertilizer based on its nitrogen value. The phosphorus content of the manure is roughly 1/3 –1/2 the numeric value of the nitrogen value, that is 26-73 lb. N/ton and 7-37 lb. P/ton for Broiler and caged layer manures and litter. (Zublena et al 1996). Crop needs for nitrogen are in several fold excess of P requirements. The soil can become saturated with P being classified as eutrophic at > 75 mg P/kg soil (Lind 1997). The P binding capacity of the soil is dependent upon many factors including iron, aluminum and calcium concentrations, pH, oxygen levels, other ligands and moisture. The P, in excess of crop requirements and not bound in soil, can enter the surface and subsurface waters through runoff and percolation. This P, either inorganic like dicalcium phosphate or organically bound, is largely soluble and immediately available as an alga nutrient. A large input of P to surface waters is erosion of the P-laden soil. The receiving water chemistry will have an impact on the rate and mechanisms of the release of P from the soil particles and the more loosely sorbed P will be released as bio-available P. The results of the degradation of surface water supplies, fisheries, and alleged toxic algae blooms have been well-publicized (Shreve et al 1995).

The technologies for alum nutrient inactivation and interception have associated economic benefits for the poultry grower. These live production benefits are obtained from reduced levels of ammonia volatilization with reduced pH and moisture in litter. The binding of phosphorus and minimization or elimination of atmospheric ammonia emissions is demonstrated environmental benefits of the litter amendment programs. Various litter amendments have been marketed for odor control over the past two decades. The major classifications have been acids, enzymes, and adsorbents. The major objective is reduction or elimination of the evolution of ammonia. Ammonia in excess of 25 ppm in the poultry house air is harmful to chicks as well as workers. The chicks can become blind and are susceptible to any number of diseases that can kill them or make them unusable as a food. Enzymes and adsorbents have met with very limited success and are not in widespread commercial use. They do nothing for P control.

Aluminum sulfate has been employed for reduction of litter pH for the past few years (Moore and Miller 1994). It forms aluminum hydroxide that provides buffering against the high pH chicken waste as well as the generation of three moles of acid per mole through hydrolysis. It is far more long-lived than sodium bisulfate, producing the desired low pH (pH 4-6) for 14-21 days. A benefit of lowering the litter pH is that the low pH environment has been shown by others to be less hospitable to vermin, insects, and pathogenic bacteria (Worley at al 1999, Worley et al 2000). Further, the aluminum binds the phosphorus into an insoluble aluminum phosphate. In that way, when the litter is used as a crop fertilizer, the runoff P is in a form that is unavailable as a nutrient to support large algae populations in the surface water. The loss of nitrogen through ammonia volatilization is reduced making the litter more valuable as a fertilizer. The grower gets a larger, healthier, more valuable bird, and the environment sees less soluble reactive phosphorus and gaseous ammonia.

Aluminum phosphate is the least soluble precipitate of the three common cations used for P control, those being iron, aluminum, and calcium (Stumm and Morgan 1981). It is insoluble between pH 2 and 9 (US EPA), well within the range of soils and surface waters. The presence of organic material, wood fiber (bedding material as well as plant debris), silica, unreacted P in receiving waters and soils, and hydrolysis will essentially remove the bulk of monomeric or polymeric aluminum species present in the waste.

Other techniques involve P interception by binding the P in eutrophic soils. The use of water treatment residuals—predominantly aluminum and/or iron hydroxides—in soil amendment has been shown to reduce the soluble reactive P in runoff (Haustein et al 1998; Peters and Basta 1996). Further the high hydroxide content has been shown to buffer the soil against the effects of acid rain (Novak et al 1995; Bugbee and Frink 1985) with no significant release of primary metal coagulant (Fe or Al) or heavy metals.

The use of chemical precipitants is well established to restore nutrient impacted water bodies. Chemical coagulation and clarification are an important means of nutrient inactivation and management in surface waters. The precipitation and removal of the phosphorus from the water column and subsequent deposition and sealing in sediments has a thirty-year history of lake restoration when used in conjunction with sound watershed management practices. The impetus of providing high quality recreational waters is underscored by the agenda for improving surface water qualities used as potable water sources. Microbial proliferation will manifest as the NOM (natural organic matter) or TOC (total organic carbon). NOM may include the disinfection by product precursors (DBP'S) that can "ignore" activated carbon and must be chemically coagulated out of the water supply; and compounds that cause color and tastes and odors (themselves potential DBP'S). These taste and odor causing compounds often do not respond to adsorbents and oxidants like powdered activated carbon and ozone, respectively. So, coagulants are one of the most important chemicals fed to purify drinking water supplies and manage the quality of the source waters. Table 1 introduces the precipitants discussed regarding their use in nutrient inactivation in lake restoration.

POULTRY LITTER PRODUCTION AND NUTRIENT VALUE

The value of poultry manure or spent litter is primarily as a source of nitrogen. It is higher in nitrogen and phosphorus than other types of manure such as swine or cattle as table 1 below shows.

Table 1
Manure Assay and Production

Animal	%N	%P	1999 Inventory(000's)[1]
Laying Hen	1.8	1.2	308,477
Turkey	2.5	1.2	265,194
Broiler Chicken	2.2	1.1	8,145,010
Hog	0.43	0.33	60,486
Dairy Cow	0.55	0.13	9,177
Beef Cattle	0.24	0.13	87,826

The concentrated nutrient value of poultry manure makes for a viable agronomic product but is also an environmental problem if allowed to run off the fields. Add to that the staggering number of birds raised each year in the United States and the potential for runoff-caused eutrophication is clearly seen. The EPA estimated in 1999 that 1055 watersheds have moderate levels of potential impact from agricultural runoff and an additional 529 watersheds have a high potential for agricultural impact.

NUTRIENT REDUCTION STRATEGIES

The strategies for nutrient reduction, inactivation, or interception form a menu of options for the farmer to best address the phosphorus runoff situation. There is no one silver bullet and they all have valid reasons for implementation.

- Alternative Manure Disposal systems such as incineration, pelletizing, gasification, and composting
- Dietary modifications such as High Available Phosphorus Corn (HAP), enzymes, and feed additives to improve nutrient uptake by the birds allowing for lower concentration in manure
- Phosphorus Binding by metal salts such as Calcium and Aluminum that reduce the soluble bioavailable fraction of the P in manure

Incineration is really a volume reduction technology. The phosphorus is not converted into an insoluble form so the ash is still a disposal/reuse issue. Plus, the air pollution impact needs to be assessed. Composting also reduces the manure and litter to a more usable form but the soluble P is still there. Pelletizing into a more easily transported fertilizer allows for the waste to be shipped more economically to areas with nutrient deficient soils. Gassification and energy recovery produce a solid fertilizer that, like pellets, can be transported greater distances.

[1] Feedstuffs 2000, v72

Dietary modifications were marketed as one of the silver bullets to reduce the amount of phosphorus in poultry manure. Feeding birds enzymes like phytase made more of the phosphorus digestible and thus lowered the amounts of P needed in the birds' ration. The reality of the situation appears to be that the amount of total phosphorus is reduced in the manure but the soluble fraction is higher. The net effect is more P in the runoff (Moore et al 2000). Table 2 shows the difference in the fractions and types of phosphorus in litter and runoff for a normal ration ("Normal") high available P corn (HAP Corn), phytase feed additive (Phytase) and a HAP + phytase ration.

Table 2
Effect of Diet Modification on Soluble P in Litter

Ration	Total P mg/L	Soluble P mg/L	Soluble/Total (%)
Normal	111	8	7.2
HAP Corn	84	14	16.7
Phytase	66	18	27.2
HAP+ Phytase	56	4.7	8.4

Feed additives and alternative technologies are not effective in reducing the evolution of ammonia during the growout cycle. However, reagents that reduce the litter pH are effective. Aluminum sulfate reduces the pH, absorbs litter moisture, and ties up soluble phosphorus into an insoluble, non-bioavailable form.

PHOSPHORUS BINDING

For several years, field trials and commercial application of alum in poultry houses involving millions of birds continuously demonstrate soluble phosphorus reductions of up to 84%. In liquid waste applications like swine waste and cattle feed lot runoff, the reduction in soluble phosphorus has exceeded 95%.

The best phosphorus-binding chemical produces a precipitate that makes the P insoluble over a large pH range. Aluminum phosphate is very insoluble from pH 2 to >9. Neither aluminum nor phosphorus is released back into the environment under normal soil or water conditions.

Iron is a suitable P binding chemical and its presence in soil or sediment is largely responsible for much of the "background" P binding. Ferric phosphate is also quite insoluble, being about one order of magnitude more soluble than aluminum phosphate, but still very effective. Under anoxic conditions, the ferric phosphate will be reduced to ferrous phosphate, which is soluble thereby releasing the phosphorus back into the water or soil as a nutrient. The oxygen content of the soil or water does not effect aluminum compounds.

Calcium binds phosphate compounds best at high pH (>10). At pH values normally found in soil and water (<8.5), they are soluble and used as fertilizers and feed additives. Calcium phosphate compounds are several orders of magnitude more soluble than iron and aluminum phosphates and are not as efficient forms in which to bind phosphorus.

AGRONOMIC CONSIDERATIONS

Control of phosphorus runoff will increase the cost of doing business for the livestock producer. Each of the runoff control strategies involves an aberration from the status quo. The use of aluminum sulfate as a litter additive to control soluble phosphorus runoff has a payback associated with its use.

Reports from the application of alum to houses raising millions of birds confirm improvements in bird health and performance. Some of the benefits of litter amendment with alum are:

- Reduced mortality allows the farmer to sell more birds, and fewer to dispose of
- Reduced condemnations due to healthier birds give the grower a larger payment for birds accepted to the processing plants and saves money at the processing plant in rejected carcass disposal
- Improved feed conversion means the bird gains weight faster and consumed less feed
- Higher nitrogen content of the litter adds value as fertilizer
- Lower ammonia levels in poultry houses safer for animals

LAKE PRESERVATION AND REHABILITATION

Mitigating phosphorus runoff is a part of long term environmental protection. For those waters that are eutrophic due to excessive inputs of phosphorus, in-lake nutrient inactivation is an option. It can rehabilitate the lake to lower trophic states and improve the water quality while non-point source pollution remediation and Best Management Practices kick in.

The US EPA conducted the earliest whole lake nutrient inactivation program in the United Sates in 1970. Most lake rehabilitation programs using chemical nutrient inactivation are supervised by a federal or state agency. Since 1970, dozens of lakes from ponds less than one acre in size to lakes of thousand of acres have been successfully restored.

The principle is identical to the phosphorus binding concepts in animal waste management—tie up the phosphorus into a form that algae cannot rapidly assimilate. Algae have no roots and must rely on soluble nutrients—particulate forms of phosphorus must chemically or biologically solubilize. In lakes with a substantial input of suspended solids, the burial rate of the particulate P may exceed the rates at which the P is resolubilized. Thus, the binding and interception of soluble P can be the major influence in restoring the ecological balance in the lake.

Aluminum compounds have the most widespread use but iron and calcium compounds for in-lake treatment have also been used effectively. Iron use is best when accompanied by an aeration system to prevent the release of ferrous phosphates. Calcium salts typically raise the pH of the lake too high and are not used except for some specialty applications like calcium nitrite for sediment treatment. Both iron sulfate and aluminum sulfate will consume alkalinity in the water via hydrolysis. In low pH or poorly buffered water, care must be taken to avoid depressing the pH and shocking the biota. In these instances, 2:1v/v alum to sodium aluminate addition rate provides excellent P binding and maintains circumneutral pH values in the receiving water (Eberhardt 1997).

The application of the precipitants is straightforward. Specialized applicators utilize Global Positioning Systems to ensure minimal overlap or missed spots. New technology allows the operator to navigate an application vessel to within a fraction of a meter to where they left off. This important feature ensures that enough precipitant is used but not overused. Newer vessels have two distinct chemical storage and addition systems so that chemicals for buffering or other treatments can be simultaneously injected minimizing the interruption of normal lake activity. The common products, alum, ferric sulfate and sodium aluminate are liquid chemicals that react essentially instantaneously. Normal lake activity often continues around the application boat.

Table 3 offers the stoichiometric requirements on a weight basis to remove one unit of phosphorus and the typical commercial products used as phosphorus binding agents.

TABLE 3
CHEMICALS USED IN PHOSPHORUS INACTIVATION
THEORETICAL METAL: PHOSPHORUS REQUIREMENTS

Metal	Metal : P Requirement	Chemical Forms Available
Aluminum (Al^{3+})	0.87:1	Alum, Aluminum Chloride, Sodium Aluminate, PACl, ACH
Ferric Iron (Fe^{3+})	1.8:1	Ferric Sulfate, Ferric Chloride
Ferrous Iron (Fe^{2+})	3.2:1	Ferrous Sulfate, Ferrous Chloride Pickle Liquor, Copperas
Calcium (Ca^{2+})	1.93:1	Lime, Quicklime, Calcium Oxide Calcium Chloride, Calcium Sulfate

STORMWATER TREATMENT

Another technology for lake rehabilitation is continuous injection of alum to stormwater in flow. Urban and suburban runoff is every bit as nutrient laden as agricultural runoff. In this technology, flow sensors dose alum to the stormwater in proportion to the water volume. In poorly buffered waters pH sensors adjust the pH with caustic soda. This has been successfully employed in Florida, New Hampshire, and elsewhere for over ten years. Florida has over 30 such installations.

Aside from the benefit of fewer algae choking the lakes and an improvement in water quality, the rate of sedimentation is dramatically reduced. The addition of alum created aluminum hydroxide and aluminum phosphate precipitates that settle as solids on the bottom of the lake. This thin layer acts to seal soluble phosphorus into the sediments keeping it from resuspending as a nutrient. The layer of solids works its way into the bottom mud becoming an integral part of the sediment. Lakes not receiving treated stormwater have massive amounts of algae growth that deposits as thick layers of smelly sediment.

The cost of these systems varies based on water quality, volume to be treated, cost of land and construction. Lake Ella, Florida was one of the first such systems. The cost, including sewers to collect the runoff, was around $200,000. Alum costs were less than $40 per million gallons treated (Harper and Herr (1999).

SUMMARY

Since 1970 shallow lakes, deep lakes, mixed lakes and stratified lakes have all been treated for water column and sediment nutrient inactivation. Not a panacea by itself, nutrient binding by aluminum sulfate is an effective component of lake and river rehabilitation. These components include:

- Nutrient diversion and interception
- Non-point source nutrient management
- Animal waste management
- Urban stormwater treatment
- Macrophyte management
- Fisheries management
- Nutrient inactivation

Phosphorus binding and nutrient inactivation of animal wastes can be an integral part of watershed management and TMDL compliance. It is simple and utilizes familiar chemistry and chemicals that have been used in water clarification, wastewater treatment, pharmaceuticals, food additives, and dozens of other applications. Controlling the influx of soluble phosphorus and inactivating the nutrients already in the sediments and water column can be effective in rehabilitating eutrophic lakes and rivers.

REFERENCES

Bugbee G.J and Frink, C.R. 1985. *Alum Sludge as a Soil Amendment: Effects on Soil Properties and Plant Growth*. Connecticut Agriculture Experiment Station Bulletin No. 827.

Eberhardt, Thomas E. 1997. *Aluminum Dose Calculation*, Sweetwater Technology, Aitkin Minnesota. Technical Brochure.

Feedstuffs. 2000. *2000 Feedstuffs Reference Issue,* v 72. No. 29. July 13, 2000.

Harper, H.H., and J.L. Herr. 1999. *Stormwater Treatment Using Alum,*) Public Works. September 1999.

Haustein, G.K., Daniel, T.C., Miller, D.M., Moore, P.A. Jr., and R.W. McNew. 1998. *Effect of Aluminum Containing Biosolids on Soil and Runoff Water Quality from High P Soils*. University of Arkansas Crop Soil and Environmental Sciences Department, Fayetteville, AR 72701. Ph.D. Thesis.

Lind, C.B. 1997. *Water Treatment Residuals Used to Treat Eutrophic Soil*. WEF/AWWA Joint Residuals management Conference. Philadelphia, PA.

Moore, P.A. Jr., and Miller, D.M. 1994. *Decreasing Phosphorus Solubility in Poultry Litter with Aluminum Calcium and Iron Amendments*. J. Environmental Quality 23:325-330.

Moore, P.A., Jr., P.B. DeLaune, D.E. Carman. T.C. Daniel and A.N. Sharpley. 2000. *Development of a Phosphorus Index for Pastures,* National Poultry Waste Management Symposium Proceedings. Pp 158-165. J.P. Blake and P.H. Patterson Eds. Auburn Press, Auburn, AL.

Novak, J.T., Knocke W.R., Geertsma, W., Dove, D. Taylor, A. and R. Mutter. 1995. *An Assessment of Cropland Application of Water Treatment Residuals,*. American Water Works Association Research Foundation.

Peters, J.M. and Basta, N.T. 1996. *Reduction of Excessive Bioavailable Phosphorus in Soils by Using Municipal and Industrial Wastes.* J. Environmental Quality 25:1236-1241.

Shreve, B.R., Moore. P.A. Jr., Daniel, T.C. Edwards, D.R. and Miller, D.M. 1995. *Reduction of Phosphorus in Runoff From Field Applied Poultry Litter Using Chemical Amendments.* J. Environmental Quality 24:106-111.

Stumm, W and J.J. Morgan. 1981. *Aquatic Chemistry. An Introduction Emphasizing Chemical Precipitation in Natural Waters.*, Wiley Interscience, John Wiley and Sons, NY

United States EPA Mineql+.

Worley, J.W., L.M. Risse, and M.L. Cabrera. *Reduced Levels of Alum to Amend Broiler Litter* (2000) Applied Engineering in Agriculture v 16 No. 4 pp. 441-444. American Society of Agricultural Engineers.

Worley, J.W., L.M. Risse, M.L. Cabrera and M.P. Nolan, Jr. *Bedding for Broiler Chickens: Two Alternative Systems* (1999) Applied Engineering in Agriculture v 15 No. 6 pp 687-693. American Society of Agricultural Engineers.

Zublena, J.P., Barker, J.C. and Carter, T.A. 1996. *Poultry Manure as a Fertilizer Source*. North Carolina Cooperative Extension Service. Water Quality and waste management. Publication AG-439.

NUTRIENT MANAGEMENT PLANNING FOR VIRGINIA ORNAMENTAL NURSERIES.

Gregory K. Eaton
Joyce G. Latimer
Robert D. Wright
Department of Horticulture
Virginia Tech
Blacksburg, VA 24061
geaton@vt.edu

KEYWORDS: fertilizer, irrigation, modeling

ABSTRACT

Virginia greenhouse and nursery operations are presented with ever more choices in nutrient formulations and protocols and ever more refined irrigation technology. These industries are challenged from within to use these technologies to develop new production strategies that maximize marginal returns of resource inputs in crop production. These industries are also challenged by external pressure from government regulatory and service agencies, and the environmentally concerned public, to minimize nutrient and water use, particularly as it relates to loading of surface and ground water. The technologies that can maximize economic return are the same technologies that can minimize environmental impacts of nursery operations, but growers are faced with the considerable complexities of managing the needs of hundreds of different plant species at once, each of different production stages, each species and production stage requiring its own intensive cultural requirements. The models of nutrient and water planning designed for forage, feed and other, mostly monocultural, agronomic crops are inadequate for ornamental nurseries. Research in Best Management Practices (BMPs) for greenhouse and nursery operations have yielded promising new general strategies in nutrient and water planning in ornamental crop production, but detailed recommendations to growers are still lacking. Here we report on several aspects of an integrated effort to revise BMPs for Virginia greenhouses and nurseries by developing comprehensive Nutrient Management Plans (NMPs) that include specific nutrient and water recommendations based on specific production facilities and goals. We used the best available data on crop production programs, specific crop nutrient requirements, nutrient release rates, and BMPs of irrigation delivery to develop spreadsheet models that allow recommendations for NMPs for growers given their production practices, growing season, and types of crops. These models were tested in several commercial operations and revised to meet Virginia Department of Conservation and Recreation criteria for NMPs. User-friendly versions of the models were developed to assist county extension agents, nutrient management planners and other consultants in advising clients on nutrient management programs and developing NMPs for application toward tax credits and BMP cost-sharing.

THE MAJOR DETERRENT TO RECYCLING IRRIGATION WATER IN NURSERY AND GREENHOUSE OPERATIONS DESPITE THE LACK OF ALTERNATIVES FOR LIMITING NONPOINT SOURCE POLLUTION

C.X.Hong
E.A.Bush
P.A.Richardson
Hampton Roads Agricultural Research and Extension Center
Virginia Tech
Diamond Springs Road
Virginia Beach, VA 23455
chhong2@vt.edu

E.L.Stromberg
Virginia Tech
Department of Plant Pathology, Physiology, and Weed Science
Blacksburg, VA 24061

KEYWORDS: non-point source pollution, nursery and greenhouse production, *Phytophthora*, water recycling

ABSTRACT

The capture and reuse of irrigation runoff is critically important to limit pollutants associated with nursery and greenhouse production. However, recycling irrigation has been adopted in few nursery and greenhouse operations due to the fear of spreading water-borne plant pathogens. The primary objective of this research was characterization of *Phytophthora* species in irrigation water, a group of very common and destructive pathogens attacking numerous ornamental plant species. Starting from January 2000 until June 2001, water was collected monthly from the discharge points of both the irrigation water and runoff in two commercial nurseries. Samples were then filtered to concentrate pathogen propagules. Propagules were then re-suspended and spread on a selective media. The resulting colonies were counted and the representative isolates identified to species. Ten species of *Phytophthora* have been identified among the isolates recovered from the irrigation water over the past 18 months. These species include *P. cactorum, P. capsici, P. citricola, P. citrophthora, P. cryptogea, P. drechsleri, P. hibernalis, P. megasperma, P. nicotianae,* and *P. syringae*. Many of these *Phytophthora* species attack a wide range of ornamental crop species. The serious disease problems associated with these water-borne plant pathogens is the major reason for the limited adoption of water recycling systems, despite the lack of reasonable alternatives to attain compliance with pollution-control mandates. Additional investigations targeting improvements in waterborne plant pathogen detection methods and disease management practices are essential for growers to comply with the mandate while maintaining the economic viability of these horticultural operations.

The capture and reuse of runoff water is of critical importance to limit pollutants associated with nursery and greenhouse production of ornamental plants. However, recycling irrigation has been adopted in few nursery and greenhouse operations due to the fear of spreading the water-borne plant pathogens. Pathogens of economic significance isolated from irrigation water included bacteria (Lacy et al. 1981; Thompson, 1965), fungi (Easton et al. 1969; Gill 1970; Neher and Duniway 1992; Pettitt et al. 1998; Pittis and Colhoun 1984; Sanogo and Moorman 1993; Shokes and McCarter 1979; Steadman et a., 1975; Thomson and Allen 1974), nematodes (Faulkner and Bolander 1970; Schuster 1959) and viruses (Runia et al. 1996). Recycled water serves as a principal source and is a powerful vehicle for the dissemination of primary and/or secondary inoculum in many plant disease epidemics (Faulkner and Bolander 1970; Lacy et al. 1981; Thompson 1965; van Kuik 1992; Whiteside and Oswalt 1973).

Among water-borne pathogens, *Phytophthora* species are most the common and destructive in nursery production and many other crop production systems, and have attracted the greatest amount of attention from plant pathologists. *Phytophthora* species were recovered from water recycled in orchards of citrus (Ali-Shtayeh and MacDonald 1991; Klotz, et al. 1959; Thomson and Allen 1974) and apple (McIntosh 1966), fields of cranberry (Oudemanns, 1999), vegetables (Shokes and McCarter 1979), tobacco (Dukes, et al. 1977), and in nurseries and greenhouses of ornamental crops. For example, seven species of *Phytophthora* were recovered from nursery effluents in California (MacDonald, et al. 1994), five species were isolated from both nursery irrigation water and runoff in Oklahoma (von Broembsen and Wilson 1998), and three species were recovered from runoff water holding ponds in North Carolina (Lauderdale and Jones 1997). But no comparable research has been done in Virginia. The primary objective of this research was to characterize the major species of *Phytophthora* in recycled irrigation water in Virginia, and to assess the epidemiological and economic significance of these waterborne pathogens in nursery and greenhouse production of ornamental plants.

MATERIALS AND METHODS

Water samples were taken at two commercial nurseries monthly starting in January 2000. The nursery in eastern Virginia is designated as Nursery A and the other in western Virginia is designated as Nursery B. At each nursery, water samples were taken at three locations: 1) runoff entering the holding pond and the irrigation risers of both, 2) chlorinated, and 3) non-chlorinated water. An aliquot from water samples of 50 or 100 milliliters was passed through a membrane filter, depending on the type of water sample (runoff or irrigation water) and the location. Filters were transferred to test tubes containing 6 milliliters of 0.09% sterile water agar. Fungal propagules trapped on filters were re-suspended by vortexing the test tube for 30 seconds. Subsequently, an aliquot of 0.1 to 1 milliliter of resulting suspension was spread in 9-cm Petri dishes containing media PARP selective for Phytophthora and Pythium and PARPH for Phytophthora only (Ferguson and Jeffers 1999). The isolation dishes were incubated in the dark at 23^{o}C, and examined daily for mycelial growth for 6 days. Phytophthora-like colonies were counted. Subsequently, a portion of these colonies was purified. The species of individual isolates were identified by performing standard procedures (usually taking 1 to 6 weeks or longer) and the use of keys (Erwin and Ribeiro 1996; Stamps et al. 1990). The abundance of Phytophthora species was expressed as colony forming units (cfu) per liter of water and the relative abundance of individual species was computed by dividing by the total cfu of the Phytophthora species recovered.

RESULTS

Ten species of *Phytophthora* have been identified among the isolates recovered from the recycled irrigation water in these two nurseries over the past 18 months (January 2000 to June 2001). These identified species include *P. cactorum* (Leb. and Cohn) Schroeter, *P. capsici* Leonian, *P. citricola* Sawada, *P. citrophthora* (Smith and Smith) Leonian, *P. cryptogea* Pethybridge and Lafferty, *P. drechsleri* Tucker, *P. hibernalis* Carne, *P. megasperma* Drechsler, *P. nicotianae* Breda de Haan, and *P. syringae* Klebahn. Identification of some *Phytophthora* isolates are still pending.

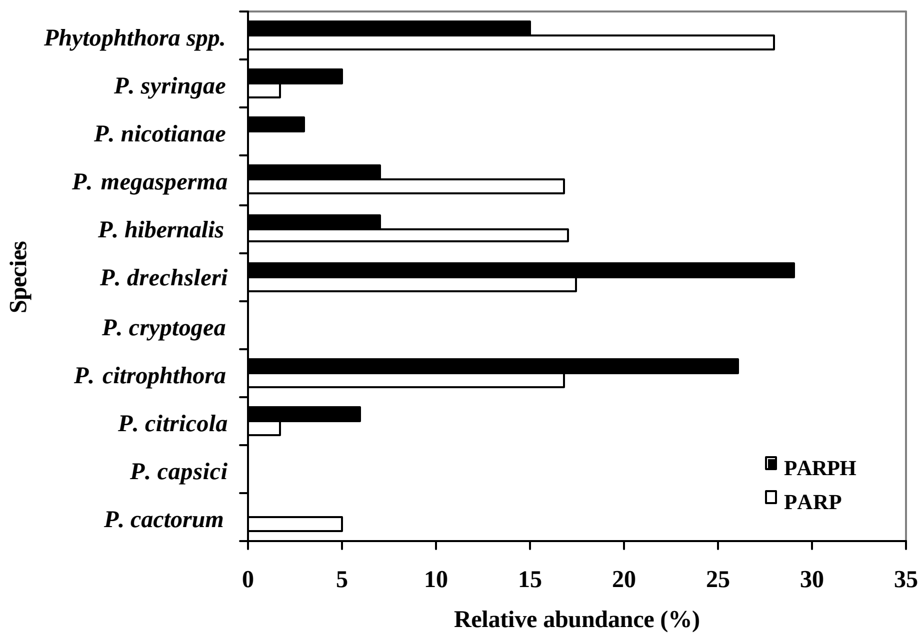


Figure 1. Relative abundance of *Phytophthora* species recovered from recycled irrigation water at Nursery A in eastern Virginia from January 2000 to June 2001.

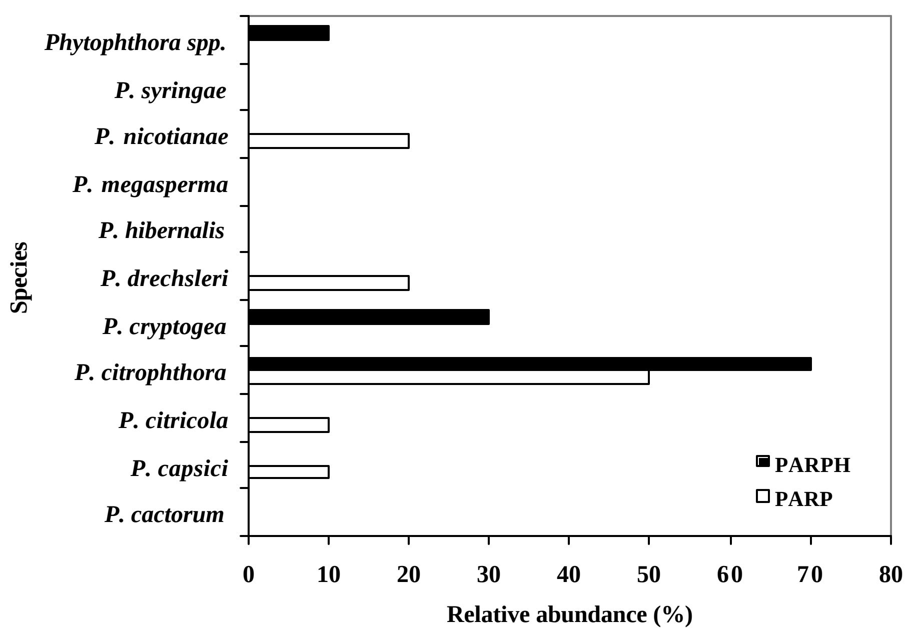


Figure 2. Relative abundance of *Phytophthora* species recovered from recycled irrigation water at Nursery B in western Virginia from January 2000 to June 2001.

The most dominant species of *Phytophthora* recovered from the recycled water in these two nurseries were *P. citrophthora* and *P. drechsleri* (Figures 1 and 2). Additional dominant species include *P. hibernalis* and *P. megasperma* in Nursery A (Figure 1) and *P. cryptogea* and *P. nicotianae* in Nursery B (Figure 2). Five of these six species (except *P. hibernalis*) have a wide host range, each attacking numerous ornamental plants. For example, *P. citrophthora* is a serious pathogen of annual vinca (*Catharanthus roseus* L.), carnation (*Dianthus caryophyllus* L.), cedar (*Cedrus deodora* (D. Don) G.

Don.), chestnut (*Castanea* spp.), eucalyptus (*Eucalyptus* sp.), ivy (*Hedera helix* L.), Japanese holly (*Ilex crenata* Thunb.), Persian violet (*Cyclamen* sp.), pines (*Pinus* spp.), rose (*Rosa* spp.), spindle trees (*Euonymus* spp.), many ornamental citrus (*Citrus* spp.), and prunus (*Prunus* spp.). *P. drechsleri* attacks azalea (*Azalea indica* L.), bottlebrush (*Callistemon* spp.), cedar (*Chamaecyparis* spp.), crape myrtle (*Lagerstroemia indica* L.), cypress pine (*Callitris pressei* Miq.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco, geranium (*Pelargonium zonale* (L.) L'Her ex Ait., poinsettia (*Euphorbia pulcherrima* Willd. Ex Klotzsch, pine (*Pinus* spp.), viburnum (*Viburnum tinus* L.), and many other plants (Erwin and Ribeiro, 1996). *P. drechsleri* and *P. nicotianae* are active in the summer (30^oC and above), while *P. hibernalis* is active in the winter (20^oC and below). The other three species are active in the spring and fall (20 to 30^oC).

The quantities of *Phytophthora* species recovered ranged from 80 to 250 cfu/liter in non-chlorinated water during 6 of the 14 months from April 2000 to June 2001 and in chlorinated water during one month at Nursery A. One cfu is equivalent to 4 to 12 propagules. Therefore, *Phytophthora* populations in the irrigation water assayed in this project can be extrapolated to 240 to 3000 propagules/liter during most of the year. Levels in this range of *Phytophthora* species in irrigation water are sufficient to cause serious disease damage on annual vinca (Hong and Epelman 2001).

DISCUSSION

This research identified ten species of *Phytophthora* present in recycled nursery irrigation water in Virginia. The most dominant species were *P. citrophthora*, *P. drechsleri*, *P. megasperma*, *P.cryptogea* and *P. nicotianae*. All these species can attack numerous ornamental plant species. The recovered population levels of these dominant species were sufficient to cause serious damage to nursery crops. The devastating disease problems associated with these water-borne plant pathogens is the major reason that adoption of water recycling systems has been slow, despite the lack of reasonable alternatives to attain compliance with pollution-control mandates. Thus, our data have significant implications in practice reducing the risks of non-point source pollution.

Growers should be informed that water disinfestation is warranted while planning for the capture and recycling of runoff to limit nitrate and pesticide pollutants. Chlorination is an option for water disinfestation to remove water-borne plant pathogens. Maintaining 2 ppm of free chlorine at discharge points is required to achieve adequate control of *P. nicotianae* in irrigation water (Hong 2001). Additional promising water disinfestation technologies include ultraviolet irradiation, ozonation, and water settling, although their effectiveness remains to be determined.

Rapid detection technology and innovative strategies for managing *Phytophthora* species in irrigation water is urgently needed in order to minimize the risk of severe crop losses caused by waterborne pathogens and encourage more growers to recycle runoff water. *Phytophthora* species are very destructive pathogens and can cause severe damage to nursery crops at very low levels through irrigation water (Hong and Epelman 2001). It will be extremely difficult to keep Phytophthora-incited diseases under control once the nursery production system becomes contaminated. Current detection techniques include baiting, filtration, plating, or a combination of the above. All of these techniques take at least several days to generate information and are normally too slow to assist growers in making disease management decisions. Consequently, fungicides are applied routinely for pathogens that cannot be detected quickly and efficiently. Additional investigations targeting improvements in water-borne plant pathogen detection methods and in making disease management practices are essential to maintain the economic viability of these horticultural operations during a compliance mandated by the Virginia Department of Conservation and Recreation. The agency would like to have an increase of 30% participation in recycling irrigation water by production facilities by the year 2004.

ACKNOWLEDGEMENTS

This project was supported in part by the Virginia Agricultural Council, Riverbend Nursery, Inc. and the Virginia Nursery and Landscape Association.

REFERENCES

Ali-Shtayeh, M.S., J.D. MacDonald. 1991. Occurrence of *Phytophthora* species in irrigation water in the Nablus area (West Bank of Jordan). Phytopath. Medit. 30:143-150.

Dukes, P.D., Jenkins, S.F.Jr., S.S. Jr Thompson. 1977. Detection and some observations of *Phytophthora parasitica* var. *nicotianae* in ponds used for irrigation of tobacco. Tob. Sci. 2:97-100.

Easton, G.D., Nagle, M.E., D.L. Bailey. 1969. A method of estimating *Verticillium albo-altram* propagules in field soil and irrigation waste water. Phytopathology 59:1171-1172.

Erwin, D.C., O.K. Ribeiro. 1996. Phytophthora Diseases Worldwide. APS Press. St. Paul, MN. 562 pp.

Faulkner, L.R., W.J. Bolander. 1970. Agriculturally-polluted irrigation water as a source of plant-parasitic nematode infestation. J. Nematol. 2:368-374.

Ferguson, A.J., S.N. Jeffers. 1999. Detecting multiple species of *Phytophthora* in container mixes from ornamental crop nurseries. Plant Dis. 83:1129-1136.

Gill, D.L. 1970. Pathogenic *Pythium* from irrigation ponds. Plant Dis. Rep. 54:1077-1079.

Hong, C.X. 2001. Effect of chlorine concentration and contact time on zoospore survival of *Phytophthora nicotianae*. Proc. South. Nur. Asspc. Res. Conf. (In press).

Hong, C.X., G. Epelman. 2001. Effect of pathogen concentration and exposure frequency on annual vinca blight by *Phythophthora nicotianae*. Phytopathology 91:S40.

Klotz, L.J., Wong, P.P., T.A. DeWolfe. 1959. Survey of irrigation water for the presence of *Phytophthora* spp. pathogenic to citrus. Plant Dis. Rep. 43:830-832.

Lacy, G.H., Lambe, R.C., C.M. Berg. 1981. Iris soft rot caused by Erwinia chrysanthemi, associated with overhead irrigation and its control by chlorination. International Plant Propagators Society Combined Proceedings. 31:624-634.

Lauderdale, C.C., R.K Jones. 1997. Monitoring irrigation ponds for *Phytophthora* sp. Proc. SNA Res. Conf, 42:225-226.

MacDonald, J.D., Ali-Shtayeh, M.S., Kabashima, J., J. Stites. 1994. Occurrence of *Phytophthora* species in recirculated nursery irrigation effluents. Plant Dis. 78:607-611.

McIntosh, D.L. 1966. The occurrence of *Phytophthora* spp. in irrigation systems in British Columbia. Can. J. Bot. 44:1591-1596.

Neher, D., J.M. Duniway. 1992. Dispersal of *Phytophthora parasitica* in tomato fields by furrow irrigation. Plant Dis. 76:582-586.

Oudemans, P.V. 1999. *Phytophthora* species associated with cranberry root rot and surface irrigation water in New Jersey. Plant Dis. 83:251-258.

Pettitt, T.R., Finlay, A.R., Scott, M.A., E.M. Davies. 1998. Development of a system simulating commercial production conditions for assessing the potential spread of *Phytophthora cryptogea* root rot of hardy nursery stock in recirculating irrigation water. Appl. Biol. 132:61-75.

Pittis, J.E., J. Colhoun. 1984. Isolation and identification of Pythiaceous fungi from irrigation water and their pathogenicity to *Antirrhinum*, tomato, and *Chamaecyparis lawsoniana*. Phytopath. Z. 110:301-318.

Runia, W.T., Michielson, J.M.G.P., van Kuik, A.J., E.A. van Os. 1996. Elimination of root infecting pathogens in recirculation water by slow sand filtration. ISOSC Proc. 395:407.

Sanogo, S., G.W. Moorman. 1993. Transmission and control of *Pythium aphanidermatum* in an ebb-and flow subirrigation system. Plant Dis. 77:287-290.

Schuster, M. 1959. Relation of root-knot nematodes and irrigation water to the incidence and dissemination of bacterial wilt of bean. Plant Dis. Rep. 43:27-32.

Shokes, F.M., S.M. McCarter. 1979. Occurrence, dissemination, and survival of plant pathogens in surface irrigation ponds in Southern Georgia. Phytopathology 69:510-516.

Stamps, D.J., Waterhouse, G.M., Newhook, F.J., G.S. Hall. 1990. Revised Tabular Key to the Species of *Phytophthora*. CAB Mycological Papers No. 162. 28pp.

Steadman, J.R., Maier, C.R., Schwartz, H.F., E.D. Kerr. 1975. Pollution of surface irrigation waters by plant pathogenic organisms. Water Resour. Bull. 11:796-804.

Thompson, D.L. 1965. Control of bacterial stalk rot of corn by chlorination of water in sprinkler irrigation. Crop Sci. 5:369-370.

Thomson, S.V., R.M. Allen. 1974. Occurrence of *Phytophthora* species and other potential plant pathogens in recycled irrigation water. Plant Dis. Rep. 58:945-949.

van Kuik, A.J. 1992. Spread of *Phytophthora cinnamomi* Rands in a recycling system. Med. Fac. Landbouww. Univ. Gent. 57:139-143.

von Broembsen, S.L., S.K. Wilson. 1998. Occurrence of *Phytophthora* spp. in nursery runoff and recycled irrigation water. Phytopathology 88:S92.

Whiteside, J.O., T.W. Oswalt. 1973. An unusual brown rot outbreak in a Florida citrus grove following sprinkler irrigation with *Phytophthora*-infested water. Plant Dis. Rep. 57:391-393.

BACTERIA SOURCE TRACKING TO IMPROVE TMDL DEVELOPMENT IN BACTERIA-IMPAIRED STREAMS

Kenneth E. Hyer and Douglas L. Moyer
U.S. Geological Survey
1730 East Parham Road
Richmond, VA 23228
kenhyer@usgs.gov
dlmoyer@usgs.gov

KEYWORDS: Bacteria Source Tracking, TMDL, HSPF

ABSTRACT

Surface-water impairment by fecal coliform bacteria is a water-quality issue of national scope and significance. In Virginia, more than 175 stream segments are on the Commonwealth's 303d list of impaired waters because of fecal coliform bacteria. The development of scientifically based fecal coliform management plans can benefit greatly from reliable information on sources of these bacteria and the incorporation of this information into an appropriate watershed model. In a demonstration of bacteria source tracking (BST) technology and improved total maximum daily load (TMDL) development, three watersheds (included on the Commonwealth's 303d list) with diverse land-use characteristics and potential bacteria sources were studied. Accotink Creek is dominated by urban land uses, Christians Creek by agricultural land uses, and Blacks Run is influenced by both urban and agricultural land uses. During the 18-month field component of this study, water samples were collected from each stream during a range of flow conditions and seasons. Fecal coliform concentrations of each water sample were enumerated using membrane filtration. Next, *Escherichia coli* were isolated from the fecal coliform bacteria and their sources were identified using ribotyping (a form of "genetic fingerprinting"). Fecal coliform concentrations were lowest during periods of base flow (typically 200–2,000 colonies/100 mL) and increased by several orders of magnitude during storm events (as high as 700,000 colonies/100mL). BST identified (and permitted quantification of) bacterial contributions from diverse sources that included humans, domestic livestock, pets, and wildlife. These data identified seasonal patterns in the distribution of bacterial sources, strong relations to land use within each watershed, and only minor differences in the distribution of bacterial sources between periods of base flow and storm flow. Watershed modeling was performed using HSPF (Hydrological Simulation Program-Fortran). The hydrological component of the watershed models was calibrated and verified using historical streamflow data; the fecal coliform transport component was initially calibrated using estimated fecal coliform loading rates based solely on animal population estimates. Results from the initial fecal coliform model calibration were then compared to the observed BST data and several major discrepancies were observed. The models were then recalibrated to the BST data; more scientifically rigorous watershed models and more defendable waste-load allocations were developed to support the TMDL plans.

DEVELOPING A RESERVOIR EUTROPHICATION MODEL FOR TMDL

Wu-Seng Lung
Rui Zou
D209 Thornton Hall
Department of Civil Engineering
University of Virginia 22904-4742
WL@virginia.edu

KEYWORDS: TMDL, eutrophication, nutrients, dissolved oxygen

ABSTRACT

A eutrophication model has been developed for the Loch Raven and Pretty Boy Reservoirs with the support from Maryland Department of the Environment. The Army Corps of Engineers' CE-QUAL-W2 modeling framework is used to generate the hydrodynamic file for input to the eutrophication model, configured with the EPA's WASP/EUTRO5 model. Such an indirect linkage between the hydrodynamic and water quality models offers an efficient way to calibrate the water quality model once the hydrodynamic model is run and its results are saved. In addition, nonpoint flow and nutrient loads to the reservoirs are generated by a watershed model and are incorporated into the water quality model. Receiving water data collected in 1992 are used in model calibration. Conductivity results from the CE-QUAL-W2 and WASP models are compared with the data throughout the entire year of 1992 to confirm a correct linkage between the two models. The calibrated water quality model produces results matching the data in the water column for both reservoirs.

USE OF EXISTING DATABASES TO DEVELOP A PREDICTIVE MODEL OF MACROINVERTEBRATE-STRESSOR RELATIONSHIPS FOR VIRGINIA STREAMS

R. Christian Jones
Gary R. Long
Environmental Science and Public Policy Program
George Mason University
4400 University Dr. MSN 5F2
Fairfax, VA 22030.
rcjones@gmu.edu

KEYWORDS: macroinvertebrates, stressors, TMDL's, Virginia, multivariate analysis

ABSTRACT

The Clean Water Act requires that waterbodies be managed to maintain and restore biotic integrity, yet many systems have impaired biological communities and will require TMDL's. Current protocols and procedures are not adequate for deducing critical stressors from macroinvertebrate data. However, recent studies suggest that with sufficient consistently collected data, relationships between individual stressors and macroinvertebrate community characteristics can be established. We have assembled recently collected extensive data sets with joint measurements of stressors and macroinvertebrate communities from Virginia's ecoregions. Principle component analysis was used to categorize stressor groups. Then multiple discriminant analysis was employed to determine which macroinvertebrate community characteristics could be used to predict individual stressors and groups of stressors within an ecoregion. Our work with three large datasets, Virginia DEQ, EPA Environmental Monitoring and Assessment, and USGS Potomac National Water Quality Assessment Program, suggested several problems related to ranges of stressors measured, range of sites represented, and taxonomic discrimination and consistency. We were able to develop a model for predicting stressors from macroinvertebrate data with the Virginia DEQ data. This model was then applied to a northern Virginia watershed experiencing suburban development. This application was only partially successful possibly due to differences in the range of conditions under which the model was constructed vs. the range of conditions in which it was applied. We are continuing to explore new data sets and variations in model approaches.

CHALLENGES IN PREPARING TMDL REPORTS FOR STREAM SEGMENTS IMPAIRED BY TROUT FARM EFFLUENT

Jane L. Walker
Tamim Younos
Jason L. Anderson
Kimberly R. Porter
Virginia Water Resources Research Center
10 Sandy Hall (0444)
Virginia Tech
Blacksburg, VA 24060
janewalk@vt.edu
tyounos@vt.edu

KEYWORDS. Aquaculture, Benthic, Macroinvertebrates, TMDL, Trout farms

ABSTRACT

Benthic impairments are unlike other types of impairments (such as fecal coliforms) and require a different approach when developing TMDL plans. First, the benthic condition is not the cause of a problem but merely an indicator of problems. Other stream impairments such as nutrient and sediment impairments are the direct cause of the degradation. Nutrients and sediment loads can be determined if concentrations and flow conditions are known. For benthic impairments, anthropogenic stressors that negatively impact the benthic organisms must be identified. Few studies have attempted to establish a relationship between stressors and benthic conditions, and results for those studies are either inconclusive or indicate high uncertainty in the relationship (Frondorf 2000, Jones 2001). Predicting stressor impacts on the benthic condition requires a 2-step process. In step 1, the pollutant impact on the stream water quality and stream habitat should be evaluated. In step 2, the model should be calibrated using long-term monitoring data. Lack of long-term data to develop and verify the model makes the evaluation of stressor effects on benthics impractical and uncertain. Furthermore, literature indicates that steam water quality and water temperature (and consequently the benthic condition) is more critically affected by the conditions of the riparian zone such as canopy and vegetation rather than impacts from other areas in the watershed (Tufford et al. 1998).

In addition to the above argument, three other issues specifically relevant to the trout farm TMDLS need to be considered.

First, the affected six stream segments are shallow (mostly less than 2 feet deep) and very short (0.02-0.8 miles) and watershed areas range from 10 acres (the smallest) to over 14,000 acres (the largest). The models incorporated in BASINS, such as HSPF, are not applicable to these small watersheds.

The second issue, and perhaps more critical, encompasses the selection of the target (reference) water condition. The water sources for the study trout farms are spring waters. The geologic formation from which a spring emerges influences its water chemistry and natural water quality. It is rather difficult to locate reference conditions (springs) of similar water chemistry, flows, and watershed size and characteristics that are minimally influenced by human activities.

The third issue is the point source characteristics. In aquaculture facilities, the effluent concentrations change with the various activities that occur on a daily or weekly and monthly timetable: fish feeding, fish harvesting, and settling basin cleaning. Likewise, the different amounts of feed provided throughout the year, as required to meet the changing needs of fish, influence the characteristics of the effluent. Also, the type of fish feed used affects the effluent because some feeds have higher residual content than others. Fish feeding, fish harvesting, and settling basin cleaning disturb the settled solid wastes and change the effluent characteristics.

In general, the effluent nature is highly diluted, but pollutant concentrations could be variable over time. Because trout farms do not operate in a consistent manner, intensive, year-long monitoring of each specific facility is needed to have a better grasp of the pollutant loads. However, unlike municipal treatment facilities, year-round and continuous monitoring of small aquaculture facilities are not practical and are cost prohibitive (at least for the duration and resources of the TMDL study). Therefore, limited intensive monitoring for cycles of activities is performed and the results are extrapolated to determine the total pollutant loads to the receiving stream.

Our preliminary background research that included field observations and literature research concluded that a conventional modeling approach applied to other TMDLs is not applicable to this particular benthic TMDL. This benthic TMDL should be based on alternative approaches, simple models, and professional judgment. We follow the nine steps outlined below to address the issue and develop benthic TMDL reports. The results of Steps 1 to 3 may indicate that the waterbody should be delisted. A full TMDL report should be developed if the results these three steps indicate impairment.

1. Check the validity of the reference condition. Is the impaired segment compatible with the reference condition in terms of water source (water chemistry) and other characteristics? If the original biosurvey did not use a compatible reference condition, the status of the impairment should be reevaluated using a compatible reference condition.

2. The original DEQ assessment used the RBPII protocol to classify impairments. We redid the bioassessment for each impaired segment using a combination of quantitative sampling and RBP III methodology. The quantitative sampling includes a series of replicate samples at each station, with five samples per sampling site, to allow for statistical analysis. The RBP III method, which identifies organisms to the genus/species level, is being used because family level sampling (as utilized in the RBP II method) does not provide enough information to allow a critical analysis of the stream conditions. If RBPIII protocols reconfirm the status as impaired, we will proceed with developing the TMDL. Additionally, the results of the RBP III analysis are likely to serve as a better indicator of the potential stressors and pollutant sources.

3. Establish a relationship between benthic macroinvertebrates and their predators. For example, some fish are predators of benthic organisms, and their increased presence in the impaired segment relative to the reference condition may have contributed to lower or different populations of benthics in the stream.

4. Conduct a comprehensive stream corridor survey for the riparian zone and landuse assessment for both the impaired segment and the reference condition watersheds to pinpoint potential sources of contamination.

5. Perform intensive water sampling (and analysis) during cycles of activities on the trout farm to catch critical point source contributions from which monthly and annual loads can be approximated.

6. Identify stressors for both the impaired segment and the reference condition using data from Steps 4 and 5.

7. Compute stressor loads (point and nonpoint sources) for both the impaired segment and the reference condition. The riparian zone should be considered as the critical zone in terms of nonpoint source contribution.

8. Make recommendations to reduce pollutants loads in the impaired segment to loads equivalent in the target condition.

9. Make recommendations for pollutant load allocations and management practices that could achieve the objective of Step 8.

REFERNCES

Frondorf, L. 2001. An Investigation of the Relationship Between Stream Benthic Macroinvertebrate Assemblage Conditions and Their Stressors. Unpublished M.S. Thesis. Virginia Polytechnic Institute and State University, Blacksburg, Virginia. 169 pp.

Jones, C. R. 2001. Determination of Environmental Stressors Influencing Benthic Invertebrate Community Structure: A Multivariate Statistical Approach. Draft Final Report Submitted to the Virginia Water Resources Research Center (Contact: R Christian Jones [rcjones@gmu.edu]), George Mason University, Fairfax, Virginia. 87 pp.

Tufford, D. L., H. N. McKellar, Jr., and J. R. Hussey. 1998. In-Stream Nonpoint Source Nutrient Prediction with Land-Use Proximity and Seasonality. J. Environ. Quality 27:100-111.

HYDROLOGICAL AND GEOCHEMICAL CONTROLS ON EPISODIC ACIDIFICATION OF STREAMS IN SHENANDOAH NATIONAL PARK, VIRGINIA

Karen C. Rice
U.S. Geological Survey
P.O. Box B
Charlottesville, VA 22903
kcrice@usgs.gov

Jeffrey G. Chanat
George M. Hornberger
James R. Webb
Department of Environmental Sciences
Clark Hall
University of Virginia
Charlottesville, VA 22903

KEYWORDS: concentration-discharge plots, catchment hydrochemistry, episodic acidification, Shenandoah National Park

ABSTRACT

Episodic stream acidification because of acid precipitation has been shown to have a deleterious effect on aquatic biota in streams in the Shenandoah National Park (SNP). Although the acid-neutralizing capacity (ANC) of a stream during baseflow is dependent on the underlying lithology, the role of hydrologic processes in buffering episodic acidification during stormflow is unclear. The objective of this study was to contrast the hydrologic and hydrochemical response of three catchments in SNP, and to develop a conceptual model of runoff generation that accounts for observed variation in ANC during storms.

The three study catchments are Paine Run, Piney River, and Staunton River. The catchments have areas of 10-12 square kilometers, with average stream gradients of 9-10 percent. Paine Run is underlain predominately by siliciclastic bedrock, which yields poorly buffered soils; Piney River is underlain by basaltic rock and has well-buffered soils; and Staunton River is underlain by granitic bedrock and has soils with intermediate buffering capacity. Discharge and ANC data have been collected at the three catchments at least weekly, and hourly during selected storms, from 1992 to the present by the Shenandoah Watershed Acidification Study of the University of Virginia.

In all three catchments, ANC is inversely related to stream discharge, and the data show a typical dilution response throughout all seasons. However, some scatter is observed in the points on a concentration-discharge (c-Q) curve indicating that simple dilution does not account for the full range of variability. The c-Q looping patterns suggest dynamic contributions from different hydrologic components of the catchment. The percentage of clockwise rotation patterns increased in the three catchments, moving from most acidic to least acidic, indicating that the surface-event component becomes less important in the catchments that have better buffered soils. Discriminant analysis indicates that pre-storm stream ANC is an important predictor for clockwise or counterclockwise rotation during a storm. The results also indicate that a conservative three-component (surface-event water, soil water, ground water) mixing model with a constant hydrograph template does not adequately represent observed episodic variation in ANC in these catchments.

SEAWATER EFFECTS ON THE AQUEOUS SOLUBILITY AND POLYMERIZATION OF STYRENE MONOMER: ENVIRONMENTAL DATA FOR EMERGENCY RESPONSE

Eric J. Miller
James R. Reed, Jr.
Department of Biology, Chemistry & Environmental Science
Christopher Newport University
1 University Place
Newport News, Virginia 23606
reed@cnu.edu

KEYWORDS: Styrene, Polymerization, Solubility, Aquatic Environments

ABSTRACT

Styrene monomer, a toxic mono-substituted aromatic hydrocarbon that is widely used to make plastic products, has received limited attention in regards to degradation reactions after large spills. In this study, styrene monomer was mixed with deionized lab water, artificial seawater, and natural seawater to determine what effects these materials would have on the polymerization and aqueous solubility characteristics of the chemical. The natural and artificial seawaters used were of a range of salinities representing fresh, brackish, and marine systems characteristic of the port of Hampton Roads in early spring.

In the polymerization studies, styrene monomer was mixed with artificial and natural seawaters with a salinity of 26‰ and incubated in darkness at approximately 25°C. After 192 hours, there was a significant difference in the kinematic viscosity of the samples on a small scale. However, the results suggest that seawater salts alone are not effective polymerization initiators for large spills of styrene monomer.

For the solubility measurements, styrene monomer mixed with artificial and natural seawaters were shaken for 24 hours and allowed to settle for 48 hours in a darkened cabinet at approximately 20°C. Dissolved styrene was extracted with hexane solvent, and its absorbance values were analyzed using a UV-spectrophotometer scanning at 291 nm. A significant salting out effect was observed between styrene samples of deionized lab water with a salinity of 0‰ and samples of artificial seawater with salinities up to 34‰. However, there was no significant styrene solubility difference between artificial and natural seawater samples with identical salinities.

INTRODUCTION

In the past three decades, environmental degradation mechanisms for many volatile organic compounds (VOCs) in marine waters have been thoroughly investigated. Aromatic hydrocarbons in particular have been examined in various laboratory mesocosms and at on-site monitoring stations in order to model the solubility and volatility of the compounds in seawater (Rossi and Thomas 1981; Gschwend et al. 1982; Hashimoto et al. 1982 and 1984; Whitehouse 1984; McDonald et al. 1988; Xie et al. 1997). Many of these studies focused on some of the most commonly used and toxic aromatic compounds, including benzene, toluene, and ethyl benzene. Despite this wide-ranging research, styrene monomer, another aromatic hydrocarbon used for making plastic, fiberglass, and styrofoam products, has not been heavily studied. No published material could be found concerning the solubility and polymerization characteristics of spilled styrene in seawater. This is unfortunate considering the widespread use of this important industrial chemical. U.S. production of styrene more than doubled from 2.0 million t in 1970 to 5.0 million t in 1995 (Chen 1997). The monomer is shipped in bulk quantities via tank truck on land, or tank barge by sea, to supply several operations around the world. Such an arrangement is located at the Nova Chemicals, Ltd. terminal in Chesapeake, Virginia, which receives an 80,000-barrel shipment of styrene monomer from Texas approximately once a month via tank barge (Beale 1998).

Most research on styrene releases has focused on health effects or small-scale environmental fates. For example, Fu and Alexander (1992 and 1996) examined styrene interactions with some marsh soil and aquatic systems. However, a few large spills in recent years indicate that additional environmental interaction information is still needed for styrene spills in ground and surface water systems (Desmond and Pittman 1992; Government of Canada et al. 1993; Crawford and Ulmer 1994; Lockheed-Martin 2001).

The acute toxicity of a bulk cargo of styrene monomer carried on a barge may significantly impact coastal or estuarine wildlife and commercial interests if it is accidentally spilled. However, the ecological severity of a spill is difficult to accurately predict based on the scarcity of information available about the interaction between styrene and marine ecosystems. The various dissolved salts in seawater may influence styrene volatility, solubility, and polymerization rates. The small number of toxicity studies conducted with the chemical shows that relatively minor concentrations of styrene in the water column is lethal to some freshwater fish and invertebrates (Pickering and Henderson 1966; LeBlanc 1980).

Styrene possesses several characteristics that can complicate cleanup efforts in large spills. Polymerization reactions are normally controlled in large-scale industrial processes, but can also occur accidentally when styrene monomer is exposed to certain contaminants, excessive heat, or ultraviolet light. Some industrial guidelines indicate that various salts and trace contaminants present during production, storage, or cleanup operations involving styrene may trigger unintended polymerization reactions (Chen 1997; Huntsman Chemical Corp. 1991). Uncontrolled polymerization reactions may clog the piping and machinery of pumping systems or, if confined, lead to an explosion. Other problems associated with the chemical include noxious and flammable vapors. In a 60,000 bbl freshwater spill, the chemical dissolved the oleophatic belts of oil skimming equipment (Desmond and Pittman 1992).

Polymerization rates and solubility are important parameters to understand for the cleanup of a major spill. Aqueous solubility influences the acute toxicity of the chemical to aquatic life and polymerization affects physical cleanup processes. Consequently, the two processes were considered important to measure when styrene is mixed with water from the lower Chesapeake Bay, Elizabeth River, and laboratory deionized water in order to observe whether solubility and polymerization reactions are influenced by dissolved salts. Results from this study will be useful to emergency responders if a styrene spill were to occur in or near one of the busiest waterways in the United States.

METHODS AND MATERIALS

Reagent-grade styrene (99% purity factor; inhibited with 10-15 ppm of p-tert-butylcatechol) was obtained from Aldrich Chemical Company and used as received. HPLC-grade toluene (99.9% purity factor), acetone, and A.C.S. spectranalyzed hexanes (99.9% purity factor; sum of 5 isomers total hexanes plus methylcyclopentane) were purchased from Fisher Scientific. Tap water was passed through a Virginia Water Systems Ultrapure Deionization System to provide deionized lab water for the appropriate samples and preparation of artificial seawater mixtures in both experiments. The filtering system produced deionized water with an 18,000,000-ohm resistance quality. Instant Ocean® artificial seasalt (Aquarium Systems) was used for artificial seawater mixtures. Water salinities were measured with a Salt Refractometer from Sper Scientific, Ltd. during the polymerization experiment and with an Orion Model 142 Conductivity/Salinity Temperature Meter during the solubility experiment. Incubation temperatures for both experiments were monitored using a StowAway Tidbit Temperature Logger (Onset Computer Corporation).

Three sites were chosen for sampling along the transport route of loaded barges bound for the Chesapeake processing terminal. These sites included the fishing pier of the Chesapeake Bridge Tunnel, a small pier on the Elizabeth River adjacent to Town Point Park in Norfolk, and a site beneath the steel bridge crossing the southern branch of the Elizabeth River in Chesapeake. The samples collected from these sites were designated Raw Thimble Shoals Channel (RTS), Raw Town Point Park (RTP), and Raw Steel Bridge (RSB), respectively. Solubility experiments were run with water from all three sites, while styrene polymerization experiments were run only in RTS samples. Raw water samples were collected in 4-liter amber glass bottles and used within 6 hours of collection. Prior to use, the collected water was filtered through layers of Marineland bonded filter pad from Aquaria, Inc. to remove coarse suspended material.

Polymerization Experiment. Polymerization of styrene monomer can be deduced from increases in the kinematic viscosity of a sample. Viscosity equipment and measurements were prepared and conducted based on the guidelines recommended in the ASTM Method D 445-97 (1998) and ASTM Method D 446-97 (1998). Three water classes, Deionized Water (DW), Artificial Thimble Shoals Water (ATS), and RTS were used to measure viscosity changes in spilled styrene over time. Consequently, samples were prepared in the three water classes to be measured after elapsed times of 12, 24, 48, 96, and 192 hours. Five samples were prepared for each of these time classes in each of the three water classes by adding 25 mL of styrene monomer to 250 mL of the appropriate water class in 500-mL Boston round amber glass bottles with polypropylene Teflon-lined lids. Once sealed, each bottle was vigorously hand-shaken for one minute before being placed in a darkened incubator set with an average temperature of 25.35°C (S.D. 0.94).

After the appropriate incubation period, the contents of a bottle were poured through a separatory flask to isolate the organic layer. A portion of the aged styrene was then extracted and weighed before being mixed with enough toluene to produce a final solution that was 0.5 mg styrene per mL of toluene. At least 11 mL of the solution were poured into a calibrated Ubbelohde viscometer warmed to 25.00 +/- 0.01°C in a Model CT 500 Constant Temperature Water Bath (Cannon Instrument Co.). Three measurements were made on each sample and averaged to produce one mean flow time. This value was then used to calculate the kinematic viscosity of the solution according to the formula in ASTM Method D 445-97 (1998):

$$v = C*t$$

where:

v = kinematic viscosity, mm^2/s (or 1 mm^2/s = 1 centistoke, cSt),

C = viscometer calibration constant $(mm^2/s)/s$, and

t = mean flow time, s.

Solubility Experiment. For the solubility studies, styrene monomer was mixed with water in three natural and six artificial water classes. The natural samples, RSB, RTP, and RTS, had artificial counterparts of a matching salinity labeled ASB, ATP, and ATS accordingly. The remaining artificial samples represented fresh water, DW, brackish water, ABW, and open seawater, ASW. Six experimental samples were created for each water type containing a mixture of approximately 2 mL of styrene monomer to 250 mL of water in 500-mL Boston round amber glass bottles with polypropylene Teflon-lined lids. Three control samples were also prepared in each class without styrene to correct for interfering UV-absorbing materials at the wavelengths scanned. Once prepared, the bottles were placed on an orbital shaker for 24 hours at lab room temperature (average 19.71°C, S.D. 0.40). The bottles were then stored inverted for a 48-hour settling period in a darkened cabinet.

After the equilibration period, a syringe was carefully inserted through a silicon-sealed hole that had been predrilled in each bottle's lid. Carefully, 10 mL of water were withdrawn from below the floating styrene layer and placed in a separatory flask. The 10 mL of water were mixed with two separate 5-mL washes of fresh n-hexanes solvent to extract the dissolved styrene. The hexane extracts were carefully collected and analyzed in a Helios Alpha Double Beam Scanning UV Spectrophotometer (Spectronic Instruments, Inc). Absorbance measurements recorded at 291 nm were used to calculate sample concentrations with a Beers Law Plot of known styrene standard solutions.

RESULTS AND DISCUSSION

Polymerization Experiment. The results of the experiment indicate that seawater alone will not initiate high rates of polymerization of inhibited styrene monomer over several days (Table 1). Using Two-way Analysis of Variance at the 95% C.I., there was a significant change in kinematic viscosity for the styrene monomer extractions over time and by water class (Table 2). However, the significant changes were on a very small scale of measurement. In terms of effects on potential spill cleanups, the styrene monomer phase essentially remained unchanged over the eight-day duration of the experiment. The ASTM Method D 445-97 (1998) states that the kinematic viscosity should be calculated by multiplying the efflux time in seconds by the viscometer calibration constant and recording the answer to four significant digits. The fourth significant digit appears to cause most of the minor variation observed in the results.

Table 1. Mean Kinematic Viscosities (cSt) with Standard Deviations of Styrene Samples (n=4) Listed According to Time class (hours) and Water Type Incubated and Measured at 25°C.

Time Class	Water Type		
	DW	ATS	RTS
0	0.6928 (0.0006)	0.6928 (0.0006)	0.6928 (0.0006)
12	0.6931 (0.0003)	0.6930 (0.0005)	0.6924 (0.0009)
24	0.6933 (0.0004)	0.6932 (0.0007)	0.6921 (0.0012)
48	0.6940 (0.0011)	0.6932 (0.0004)	0.6934 (0.0013)
96	0.6927 (0.0006)	0.6935 (0.0004)	0.6936 (0.0004)
192	0.6938 (0.0008)	0.6935 (0.0003)	0.6936 (0.0003)

Yaws (1999) reported his viscosity data to 3 significant digits. If the experimental measurements are reduced by one or two significant figures, the kinematic viscosities are almost identical between the water classes and over time. Upon comparing the kinematic viscosities of the 0.5-g/mL styrene solutions in Table 1 and the kinematic viscosities of pure styrene and toluene (0.900 and 0.865 cSt, respectively, Yaws 1999), it becomes evident that little polymerization has occurred in the experimental samples. The kinematic viscosities of the styrene solutions hover in the range expected for a mixture of pure toluene and styrene. Had significant polymerization occurred, the kinematic viscosities of the samples should have approached or exceeded the kinematic viscosity of pure styrene. In regard to the effects of polymerizing styrene on cleanup equipment, variations in the fourth, third, and possibly second significant figures of the measurements will be inconsequential. From a cleanup perspective, major changes in the first significant figure will reflect a predominant thickening of the styrene.

Table 2. ANOVA Two-way Without Replication Results for Kinematic Viscosities of Styrene Samples.

Source of variation	Degrees of freedom	F-value	P-value	F-critical value
Time class	11	2.081667	0.037341	1.967546
Water type	5	3.601282	0.006881	2.382826

Intuitively, the styrene should thicken over time as it is exposed for a longer period to radical initiators in the environment and as the inhibitor breaks down. In this case, however, the significant variation in kinematic viscosity for the samples over time and by water type does not necessarily mean that polymerization was the primary factor involved. The varied results over time on such a small scale may have been a result of contaminants in the extracted styrene, human error in the measurements, temperature effects, or slightly different styrene concentrations in the prepared toluene solutions. Qualitative observations provided the first hints that the styrene was not polymerizing on a large scale. Fresh styrene from the reagent bottles was relatively colorless. The styrene in the various samples remained transparent over the duration of the experiment. Polymerization would have been indicated by the styrene layer taking on a cloudy color or by residue sticking to the sides and bottom of the bottles.

The absence of widespread polymerization in this experiment may not be completely due to a lack of initiating radicals in the water samples. Oxygen, a known polymerization inhibitor present in approximately 200 cm^3 of headspaces in the sample bottles, may have had a neutralizing effect on any initiating radicals present in the water (Vollmert 1973). In addition, the p-tert-butyl catechol originally present in the styrene may have played a large role in reducing polymerization in the small volume of the sample bottles. Yaws (1999) stated that p-tert-butyl catechol is extremely hydrophobic with a solubility of 2.0000×10^{-7} ppm at 25°C. If this is the case, then the inhibitor should not readily wash out of the styrene phase and will heavily influence the chemical reactions in the organic layer.

These results are for styrene aged in the dark. Although the seawater appeared not to contain the necessary radicals that would initiate significant polymerization, this does not mean that polymerization may not be a factor in a spill. As Elias (1977) pointed out, polymerization can also be initiated by ultraviolet light. The energy associated with full sunlight might have the following effects on a large styrene spill:

(1) Provide enough energy to transform some monomer molecules into radical initiators in high enough concentrations to overcome the inhibiting effects of oxygen or p-tert-butyl catechol;

(2) Activate initiating radicals that may already be present in the water; and
(3) Degrade polymerization inhibiting substances through photolysis.

Solubility Experiment. The chemical phenomenon known as the salting-out-effect was clearly evidenced in this experiment. The effect is a linear relationship between solubility and typical natural conditions of salinity and temperature (Fig. 1). This is particularly evident in the artificial seawater measurements where a regression yielded a R^2 factor of 0.9845 for the best-fitting line through the data points. There were significant differences at the 95% C.I. in styrene solubility in the waters possessing different salinities (Table 3). However, there was not a significant difference in styrene solubility between artificial and raw waters containing identical salinities. Consequently, the results suggest that solubility is primarily dependent on the salinity content. Styrene solubility decreases as the salinity of the water increases.

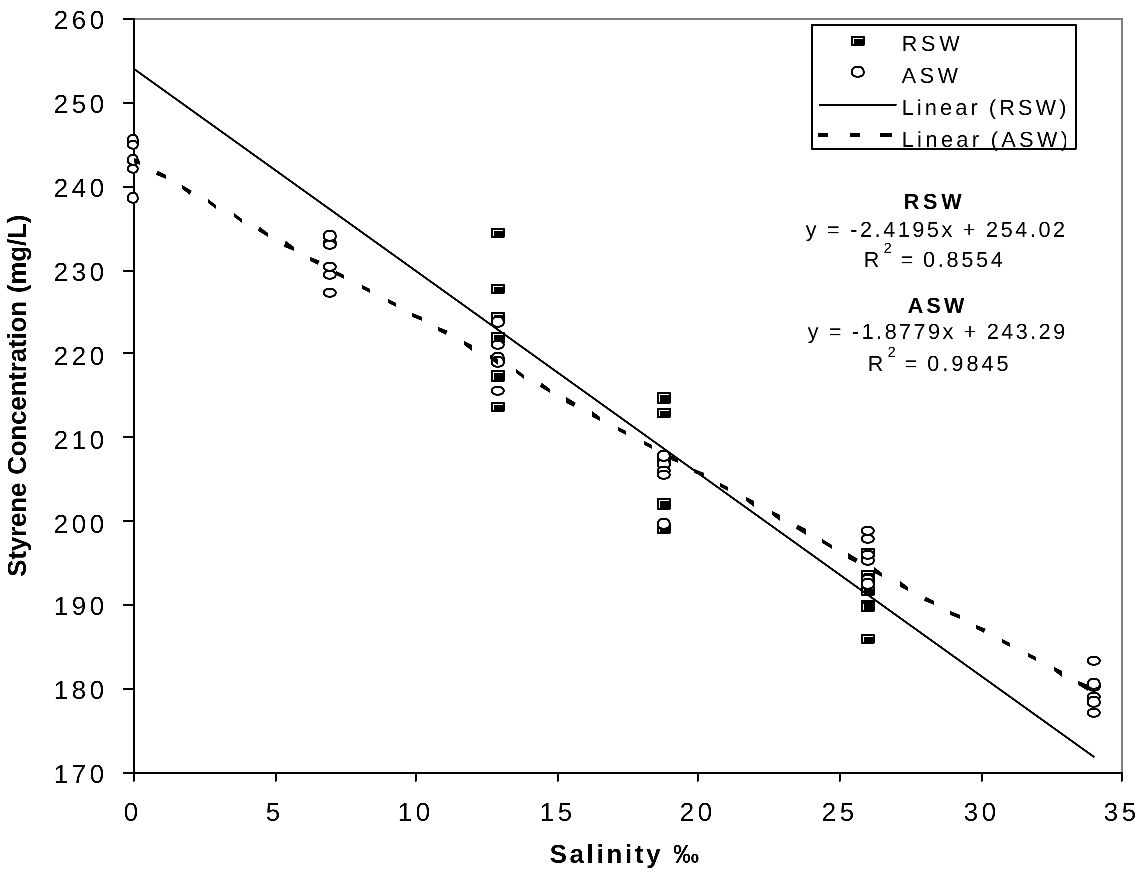


Fig. 1. Artificial (ASW) and Natural (RSW) Seawater Solubilities with Matching Salinities.

Regarding organic chemical solubilities, Schwarzenbach et al (1993) wrote that many organic chemicals dissolve from 10 to 50% less in seawater versus pure water. In this experiment, the average solubility of styrene ranged from 243.1 mg/L (S.D. 2.6) in deionized lab water to 179.7 mg/L (S.D. 2.2) in 34.0‰ artificial seawater. This is approximately a 26% drop in solubility for styrene in freshwater to seawater. The percentage of styrene that is salted out is determined by the following formula (Whitehouse 1984) using the average solubility calculated for each water type, both artificial and raw:

% Salting-out = [(DW – SW) / DW] X 100
where DW = Deionized water styrene concentration and SW = Seawater styrene concentration.

Table 3. ANOVA Two-way Without Replication Results for Solubilities Performed on Block Design of Salinity vs. Water Type for Natural and Artificial Stations.

Source of variation	Degrees of freedom	F-value	P-value	F-critical value
Artificial vs. raw seawater type	11	0.7223028	0.706306	2.258517
Salinity	2	90.45173	2.43E-11	3.443361

The salting out effect is an important chemical phenomenon that may have a significant ecological effect in a major marine spill. A confined spill in a brackish or freshwater area such as the upper Elizabeth River may be more toxic to local organisms than a spill in the saltier waters of Thimble Shoals Channel or near Old Point Comfort. The increased solubility in fresh water would allow the spill to diffuse faster through the water column, thereby impacting benthic as well as pelagic communities.

However, waters of a well-stratified nature, i.e., denser saltwater along the bottom and fresher water near the surface, would experience mixed toxic results from the solubility of styrene during a spill. The lower saltwater layer may provide a shielding effect for benthic communities from the downward chemical cascade of spilled styrene. However, Xie et al. (1997) provide a different view towards this situation. They suggest that an increased salinity may actually lead to larger risks for aquatic organisms. Dissolved organic molecules that are competing with dissolved salts for cavity space may readily sorb to other particulate matter, organic tissue, and other substances. These sorptions may be more energetically favorable.

The solubility results for the raw water classes are very similar to their artificial counterparts. Although not significantly different, the raw water styrene solubilities exhibited a larger spread of results for a particular salinity when compared to the artificial samples. The increased spread may be due to interactions with other dissolved organic and inorganic constituents in the raw water that were not present in the artificial solutions. Interestingly, the precision of the raw water samples appears to increase in stations with a higher salinity.

ACKNOWLEDGEMENTS

Our thanks go to Mr. Steve Miller and SJM Enterprises Inc., California, for providing funding for this research. Without their help, this project may not have been possible.

REFERENCES

American Society for Testing and Materials (ASTM). 1998a. Standard test method for kinematic viscosity of transparent and opaque liquids (the calculation of dynamic viscosity. Designation D 445-97. New York: 9pp.

American Society for Testing and Materials (ASTM). 1998b. Standard specifications and operating instructions for glass capillary kinematic viscometers. Designation D 446-97, New York: 23pp.

Beale, A. March, 1998. Private communication at Huntsman Chemical Company, Chesapeake, VA. .
Chen, S. Styrene. in Howe-Grant, M., (editor) 1997. Encyclopedia of Chemical Technology. 4th ed. Vol. 22. New York: John Wiley & Sons: 956-994.

Crawford, N. C., and C. S. Ulmer. 1994. Hydrogeologic investigations of contaminant movement in karst aquifers in the vicinity of a train derailment near Lewisburg, Tennessee. Environmental Geology. 12: 41-52.

Desmond, C. T. and W. M. Pittman. 1992. Teamwork makes quick work of styrene spill clean-up. Proceedings of Marine Safety Council. 49(5): 61-65.

Elias, H. 1977. Macromolecules, Volume 2 Synthesis and Materials. New York: Plenum Press: 535-1131pp.

Fu, M. H. and M. Alexander. 1992. Biodegradation of styrene in samples of natural environments. Environmental Science and Technology. 26(8): 1540-1543.

Fu, M. H. and M. Alexander. 1996. Biodegradation of styrene in waterlogged soils and aquifer solids. Soil Science. 161(12): 846-851.

Government of Canada, Environment Canada, Health Canada. 1993. Styrene. Priority Substances List Assessment Report. Minister of Supply and Services Canada: 47pp.

Gschwend, P. M., O. C. Zafiriou, R. R. C. Mantoura, R. P. Schwarzenbach, and R. B. Gagosian. 1982. Volatile organic compounds at a coastal site. 1. seasonal variations." Environmental Science and Technology. 16(1): 31-38.

Hashimoto, Y., K. Tokura, K. Ozaki, and W. M. J. Strachan. 1982. A comparison of water solubilities by the flask and micro-column methods. Chemosphere. 11(10): 991-1002.

Hashimoto, Y., K. Tokura, H. Kishi, and W. M. J. Strachan. 1984. Prediction of seawater solubility of aromatic compounds. Chemosphere. 13(8): 881-888.

Huntsman Chemical Corporation. Material Safety Data Sheet – 9000 Styrene. July 22, 1991: 3pp.
LeBlanc, G. A. 1980. Acute toxicity of priority pollutants to water flea (Daphnia magna). Bull. Environ. Contam. Toxicol. 24: 684-691.

Lockheed Martin Energy Systems. Lessons Learned Database. Fish Kill Resulting from Styrene Resin Spill. Identifier Y-1995-OR-LMESY12-0801. Available: 15 February 2001. <http://www.tis.eh.doe.gov/ll/listdb.html>

McDonald, T. J., M. C. Kennicutt II, and J. M. Brooks. 1988. Volatile organic compounds at a coastal Gulf of Mexico site. Chemosphere. 17(1): 123-136.

Pickering, Q. H. and C. Henderson. 1966. Acute toxicity of some important petrochemicals to fish. J. Water Pollution Control Federation. 38(9): 1419-1429.
Rossi, S. S. and W. H. Thomas. 1981. Solubility behavior of three aromatic hydrocarbons in distilled water and natural seawater. Environmental Science and Technology. 15(6): 715-716.

Schwarzenbach, R. P., P. M. Gschewend, and D. M. Imboden. 1993. Environmental Organic Chemistry. New York: John Wiley and Sons: 681pp.

Vollmert, B. 1973. Polymer Chemistry. New York: Springer-Verlag: 652pp.

Whitehouse, B. G. 1984. The effects of temperature and salinity on the aqueous solubility of polynuclear aromatic hydrocarbons. Marine Chemistry. 14: 319-332.

Xie, W., W. Shiu, and D. Mackay. 1997. A review of the effect of salts on the solubility of organic compounds in seawater. Marine Environmental Research. 44(4): 429-444.

Yaws, C. L. 1999. Chemical Properties Handbook. New York: McGraw-Hill: 779pp.

PREDICTING RELATIVE METAL TOXICITY WITH QUANTITATIVE ION CHARACTER-ACTIVITY RELATIONSHIPS (QICAR'S): SELECTING THE BEST ION CHARACTERS TO REFLECT BINDING TENDENCIES

Brian W. Moores
Department of Chemistry and Environmental Studies Program
Randolph-Macon College
Ashland, VA 23005
bmoores@rmc.edu

Michael C. Newman
School of Marine Science
Virginia Institute of Marine Science
Gloucester Point, VA 23062
newman@vims.edu

KEYWORDS: metal toxicity, ligand binding, QICAR, risk assessment

ABSTRACT

Intermetal trends in toxicity of metals have been established for a wide range of complexes between the free metal ion and the various ligands present in natural waters, and can be a useful tool in assessing the risk associated with metal species in aquatic environments. The toxic effect of a metal is predicted from metal-ligand binding tendencies, including quantitative measure of metal softness, bond strength with soft or intermediate ligands, and electrostatic bond strength with hard ligands. Although statistical models allow general predictions of toxicity, the usefulness of the resulting models is currently restricted by uncertainty in the selected ion properties used to compute binding tendency metrics. Many have not been carefully assessed for accuracy and, consequently, are a source of uncertainty in published QICAR models. We will present a careful re-examination of published ion properties in order to allow the generation of improved QICAR's for monovalent, divalent, and trivalent metals.

A THERMAL ADAPTATION OF BACTERIA IN AN ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL SYSTEM

Ufuk G. Erdal
Zeynep K. Erdal
Clifford W. Randall
Virginia Tech Department of Civil and Environmental Engineering
418 NEB
Blacksburg VA, 24061
uerdal@vt.edu
zkisoglu@vt.edu
cliff@vt.edu

KEYWORDS: activated sludge, cold temperatures, homeoviscous adaptation

ABSTRACT

Temperature is one of the key parameters that affects the reaction kinetics and performance of enhanced biological phosphorus removal systems (EBPRs). Although studies agree regarding the effect of temperature on kinetic reaction rates, there are contradictory results in the literature regarding the effect of temperature on the EBPR system performance. Early investigators reported better performance with lower temperatures (Sell 1981; Ekama, *et. al*. 1984), but others have reported that the EBPR functions "wash out" before other heterotrophic functions at low temperatures and the SRTs (McClintock, *et. al.* 1991; Mamais and Jenkins 1992). One speculation is that deterioration in the EBPR system performance at cold temperatures can be attributed to the rigid-like behavior of the cell membranes. The physical state of the membrane is an important characteristic to determine because, if the bacterial cell membrane is in a gel-state, solute transport and the electrochemical gradient mechanisms will shut down. The purpose of this investigation was to determine if phosphate accumulating organisms (PAOs) lose their ability to take-up substrate at low temperatures or if they can adapt. The increased unsaturation index suggests that the EBPR microbial community have the ability to change their membrane fatty acid compositions and hence regulate their membrane fluidity under cold temperatures.

INTRODUCTION

Excess biological phosphorus removal (EBPR) is the most effective and economical way to remove phosphorus from wastewater. During the past two decades, the mechanisms of the EBPR have been investigated by numerous researchers, and different biochemical models have been developed, e.g., by Wentzel *et al.* (1986), Mino *et. al. (1987,)* and Smolders *et. al. (*1994), to explain the mechanisms of EBPR. In addition, new models and new mechanisms have been developed in light of these models (Pereira *et al*. 1996; Louie, *et. al.* 2000). Basically, the EBPR systems utilize the alteration of anaerobic and aerobic cycles to favor the growth of phosphorus accumulating organisms (PAOs), while providing them with the required substrates. PAOs can store inorganic phosphorus as intracellular ploy-phosphate to a greater extent than is needed for growth metabolism. They do this as an energy-storing mechanism. In anaerobic zones, short chain fatty acids (VFAs) are taken into the cells, polymerized and stored as intracellular polymers known as poly-hydroxy-alkanoates (PHAs). The energy in polyphosphate bonds is used to drive these reactions, and orthophosphorus that is simultaneously released to the medium as Poly-P is de-polymerized. In some of the models, it is also believed that glycogen and other intracellular carbohydrates serve as essential electron donors and are degraded for the EBPR's purposes in the anaerobic stage (Mino *et. al.* 1987; Smolders *et. al.;* 1994; Pereira *et.al.* 1996). Then, in the aerobic stage, the PHA is broken down to synthesize new cells and produce the reducing equivalents (NADH) needed for ATP production. NADH is generated through either the TCA or other glyoxylate cycles. The newly generated ATP is used by the cells for energy or to store poly-phosphates, which are later used as an energy source for PHA storage in the anaerobic zone. The cations, potassium, and magnesium are essential for EBPR, and are released with phosphorus in the anaerobic zone and taken-up in the aerobic zone. In addition to the released phosphorus, some of the phosphorus initially present in the wastewater is removed, resulting in net removal when sludge is wasted from the system. The overall process is known as excess biological phosphorus removal (EBPR).

Most microorganisms must accommodate to a variety of changing conditions and stresses in their surrounding environment in order to survive and grow (Brock 1999). Adaptations to fluctuations in temperature are possibly the most common because of the impact of temperature on the biochemical reactions of the cell (Grout and Morris 1983). Membrane fluidity changes with temperature, generally decreasing as temperature drops and increasing as it rises. Every lipid bilayer of organisms has a characteristic transition temperature below which it freezes (gels) when cooled and becomes fluid again when warmed. The change in the state of the membrane is called a phase transition (Becker et.al. 1996). The fluidity of the membrane mainly depends on the length of the fatty acid present and the degree of unsaturation of their side chains (number of double bonds present). The membrane lipids with saturated fatty acids pack together very tightly, whereas lipids with unsaturated fatty acids do not fit together well because the cis double bonds cause bends in the chains that interfere with packing. This cis formation reduces the van Der Walls interactions and lowers the transition temperature. Most prokaryotic organisms are able to compensate for temperature changes by altering the lipid composition of their membranes, thereby regulating membrane fluidity. This ability is called homeoviscous adaptation because the main goal of such regulation is to keep the fluidity of the membrane approximately the same despite the change in temperature (Becker et.al.1996). As a result, this, this ability can provide a unique advantage for microorganisms to keep their membrane in a fluid state as the temperature changed. Homoeviscous adaptation is carried out in two different ways. Either the length of the hydrocarbon tails or the degree of unsaturation is adjusted according to temperature. A decrease in the temperature in E.coli, for instance, triggers the synthesis of a desaturase enzyme that introduces double bonds into the hydrocarbon chains of fatty acids (Okuyama et.al. 1986). The preservation of the membrane fluidity at 10^{o} and $0^{o}C$ in pyscrophilic bacteria, Vibrio Strain ABE-1, was attributed to the bacteria having an extremely high content of hexadecanoic acid (16:1, 16 carbon-number with one double bond) in the membrane phospholipids. Fodor et.al. (1997) investigated the lipid compositions of two symbiotic photosynthetic bacteria, Xenorhabdus nematophilus and Photorhadbus liminescens, at 28^{o} and $18^{o}C$. Lipid fatty acid composition from primary and secondary cultures of both bacterial species grown at $18^{o}C$ were more ordered (i.e., less fluid) than those grown at $28^{o}C$. This suggested that these particular bacterial species were unable to make homeoviscous adaptation. In light of the given information, it is clear that this unique ability, if it exists, can bring a very special advantage to bacteria to keep their membrane fluid under varying temperature conditions. It is also clear that some bacteria, unfortunately, cannot make such adjustments. Reduced EBPR performance under cold temperature conditions may be related to the inability of the EBPR bacteria to make homeoviscous adaptation. However, no study has been done to investigate this paradoxical case.

METHODS AND MATERIALS

Lab-scale EBPR system operation

A lab scale modified University of Cape Town (UCT) system containing two anaerobic (2L of each), two anoxic (2L of each), and three aerobic (3.5 L of each) reactors in series and fed with synthetic wastewater, was placed in operation during the early 1999s. The system schematic is illustrated by Figure 1. Feed water was deoxygenated by purging with N_2 to achieve a DO of <1 mg/L as the influent enters the system through the first anaerobic reactor. Synthetic feed was prepared daily to contain acetate as the sole COD and VFA source (400 mg/L, $(NH4)_2SO_4$ 30 mgN/L, K_2HPO_4 25 mg/L, 125 mg/L alkalinity, 210 mg/L $MgSO_4$, 44.4 mg/L $CaCl_2$, 1.11 mg/L $FeCl_3$, 0.66 mg/L $MnCl_2$. $6H_2O$, 0.44 mg/L $ZnSO_4.7H_2O$, 0.14 mg/L $CuSO_4.5H_2O$, 0.14 mg/L $CoCl_2.6H_2O$, 0.05 mg/L KI, and 0.12 mg/L H_3BO_4, 0.05 mg/L EDTA). After it was placed into operation, the system ran for three months before starting to collect steady state data. The seed for the EBPR system was obtained from the Roanoke wastewater treatment plant, which achieves partially P removal by the EBPR processes. The system was housed in a constant temperature room maintained at 20 ±0.5^oC and operated at a constant SRT for 10 days. System performance was monitored for six months through the measurement of SCOD, MLSS, MLVSS, NO_3^--N, NO_2^--N, NH_4^+-N, PO_4^{-3}-P and fatty acid methyl esters (FAMEs). The cation and anion analyses of filtered samples were performed using a DIONEX Ion Chromatograph according to APHA (1995). SCOD, MLSS, and MLVSS were also analyzed as outlined in APHA (1995). The temperature was then dropped to 5^oC in a week. The system was exposed to intermediate temperatures of 18^o, 15^o, and 10^oC for two days each as the temperature was dropped. Both the system performance and cellular membrane fluidity changes were determined at each temperature, and the determinations were continued to determine acclimated conditions**.**

Determination of membrane fatty acids composition:

Membrane fatty acid composition was determined according to the direct transesterification method developed by Lepage and Roy (1986). The following is a description of this method:

A 0.2 mL aliquot of an activated sludge sample from the aerobic reactor was precisely measured and poured into a glass tube. Due to the absence of tridecanoic acid in the bacterial cells, an internal standard consisting of 1 mg to 10 mg of tridecanoic acid (C13: 0) was dissolved in 50 mL of methanol-toluene 4:1 (v/v), and 4 mL of this solvent mixture was added to the activated sludge samples. A small magnetic bar placed into each tube provided stirring while 0.4 mL of acetyl chloride was slowly added to each tube. Tubes were tightly closed with teflon-lined caps and subjected to methanolysis at 100^oC for 1 hr. Tubes were weighted before and after heating as a check for leakage. After the tubes cooled in water, 10 mL of 6% K_2CO_3 solution was slowly added to neutralize the mixture. Then the tubes were shaken and centrifuged, and an aliquot of the upper phase was injected into a GC. Before injection, the samples were dried and dissolved in 1 mL of hexane.

VFA standards purchased from Sigma were used though GC runs as external standards. These standards are myristic acid (C14: 0), palmitic acis (C16:0), stearic acid (C18:0), palmitoleic acid (C16: 1), oleic acid (C18: 1), linoleic acid (C18: 2), and linolenic acid (C18: 3). A VG 7070 organic spectrometer furnished with a mass spectrophotometer, located in the Biochemistry Department of Virginia Tech, was used throughout the GC/MS runs.

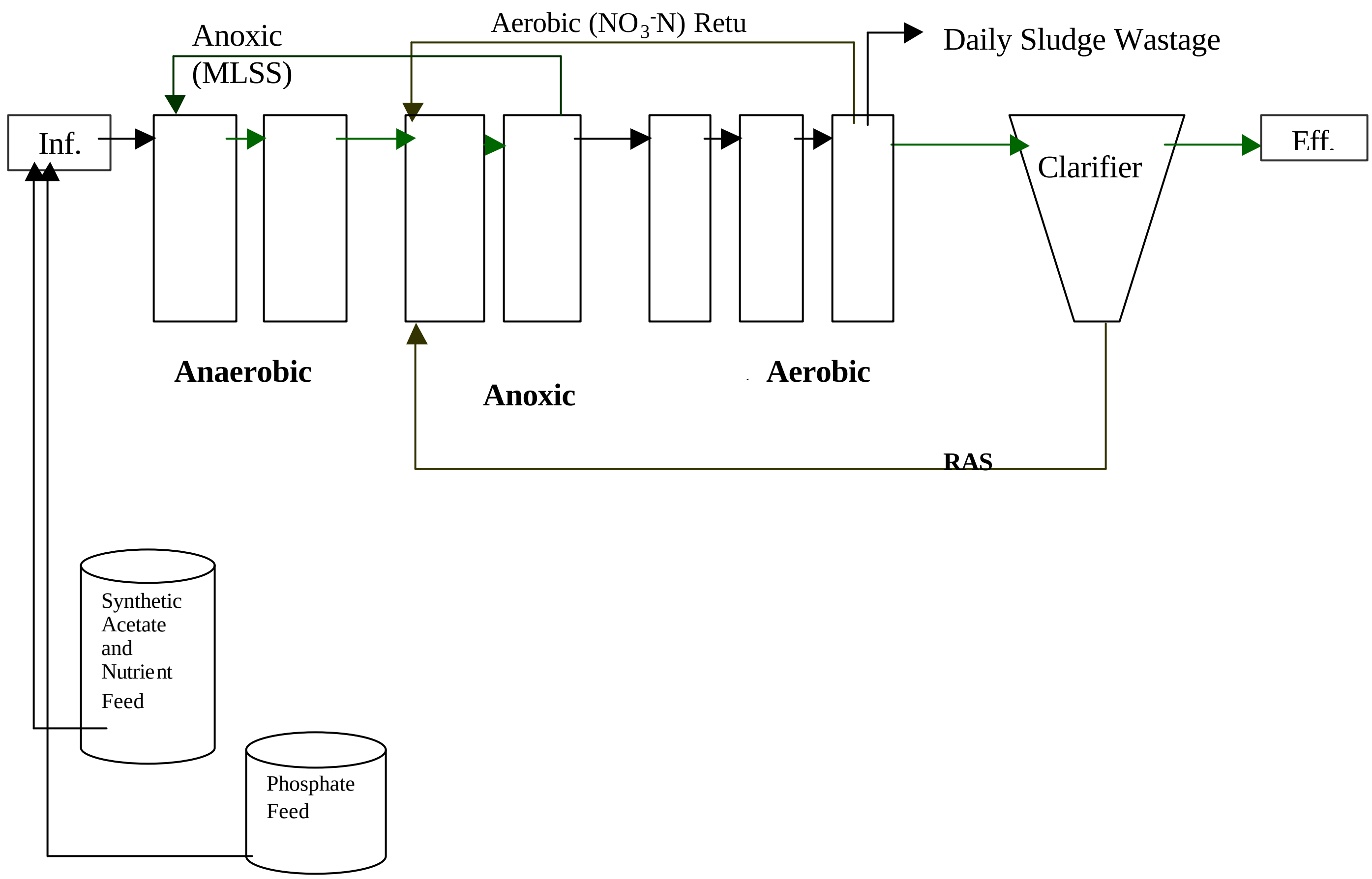


Figure 1: The schematic of EBPR plant.

RESULTS AND DISCUSSION

The results of the membrane fatty acids analysis of samples taken from the aerobic stage of the EBPR system at 20°, 18°, 15°, 10°, and 5°C are given in Table 1. The relationship between the temperature and the fatty acid unsaturated/saturated ratio is illustrated in Figure 2. Figure 2 shows that the unsaturation to saturation ratio increases as temperature decreases. The results of the study suggest that the membrane fatty acids were composed mainly of C16:1 (33.8%), C16:0 (27.5%) and C18:1 (21.2%) and the unsaturated to saturated fatty acid ratio was 1.31 at 20°C. The unsaturated to saturated fatty acid ratios were: 1.40, 1.55, and 2.31 at 18, 15, 10°C, respectively (Table 1). The composition of the major fatty acids was C16:1 (49.8%), C16:0 (13.2%), C18:1 (25.3%) and the unsaturated to saturated ratio was 3.61 at 5°C. An increased unsaturated fatty acid content at low temperatures and a complete acetate uptake rate (Figure 3) suggest the presence of homeoviscous adaptation. On the other hand, suggesting the membrane to be in fluid state in our EBPR sludge seems to be non-supportive in the absence of membrane fluidity measurements. Due to the complexity of such determinations and low accuracy in mixed cultures, no attempt was made to determine the membrane viscosity of samples at cold temperatures. Despite the lack of this information, a complete acetate uptake and very good P removal observed at 5°C, suggests that we have strong evidence to conclude that the membrane of the EBPR bacterial community is in a fluid state.

It was reported that homeoviscous adaptation is generally achieved in a short time period (Becker et.al. 1996; Grout and Morris 1987; deMendoza and Cronan 1983). The increased synthesis of phospholipids containing 18:1 was observed within 15 seconds of a temperature reduction from 42^o to 24^{o}C by deMendoza and Cronan (1983). The protozoan Tetrahymena pyriformis cell was chilled from 39^o to 15^{o}C by Ramesha and Thompson Jr. (1982). The result of the study clearly showed that the fatty acid acyl group rearrangement by deacylation referring to a homeoviscous adaptation was complete within the first hour of the temperature exposure, although experiments were extended to 15 hours at 15^{o}C. In our study, samples for the membrane fatty acid analysis were taken following a 24-hr period of the temperature shift. The t-test result (not shown in the text) at a value of 0.05 showed that there is no significance difference in membrane fatty acid compositions at short (24 hr) and long temperature conditions (steady state) for 5^{o}C. Therefore, it was concluded that a 24-hour period was enough to achieve homeoviscous adaptation in this particular sludge sample.

Table 1: Percent abundance of membrane fatty acids at different temperatures

	Percent abundance of fatty acids					
IUPAC name	# of Carbon	20^{o}C	18^{o}C	15^{o}C	10^{o}C	5^{o}C
n-dodecanoic	C12:(0)	1.94±0.42	2.97	1.18±0.11	1.0±0.52	0.83±0.31
n-tetradecanoic	C14:(0)	2.53±1.55	3.78	2.57±0.07	1.8±0.79	0.8±0.23
three decanoic acid	C15:(0)*	3.58±0.64	3.93	3.83±1.80	3.86±0.27	3.04±0.12
cis,cis -9,12 hexadecanoic	C16:(2)	0.65±0.35	1.35	1.18±0.09	0.67±0.38	1.63±0.48
cis-9-hexadecanoic	C16:(1)	33.8±4.14	33.31	34.7±1.83	40.51±5.86	49.82±2.36
n-hexadecanoic	C16:(0)	27.5±3.65	25.37	24.9±0.69	20.26±1.57	13.25±1.59
cis,cis-9,12 octadecadienoic	C18:(2)	0.92±0.58	1.08	0.99±0.8	2±0.05	1.02±0.08
cis-9-octadecanoic	C18:(1)	21.2±2.65	22.54	23.9±0.76	26.6±1.66	25.26±1.96
n-octadecanoic	C18:(0)	7.89±2.4	4.30	4.9±0.36	3.06±0.41	3.31±0.69

*three decanoic acid was used as an internal standard.

( ) Number in parenthesis refers to number of double bond(s) in fatty acid carbon chain.

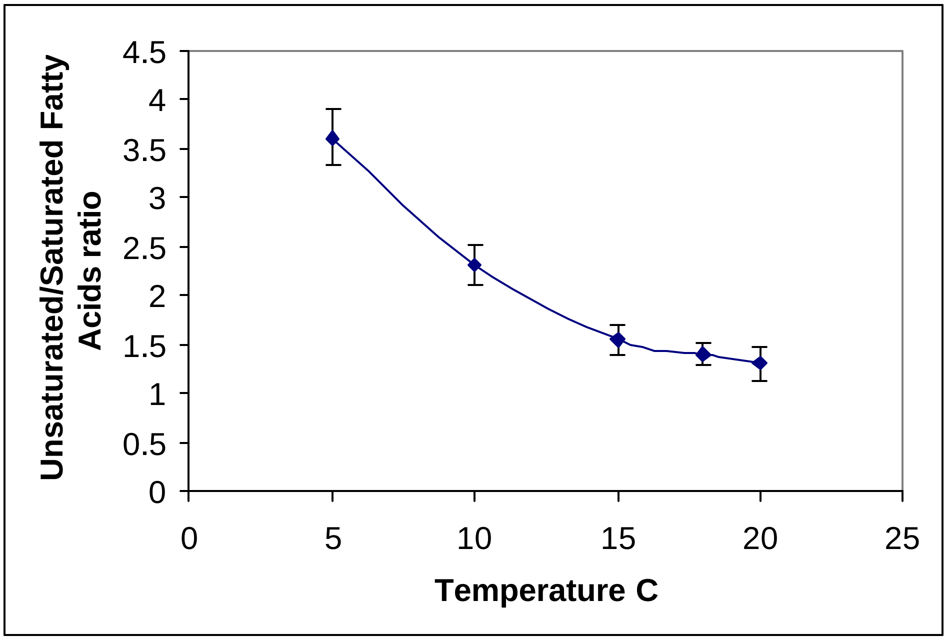


Figure 2: Fatty acid unsaturated/saturated ratio vs. temperature

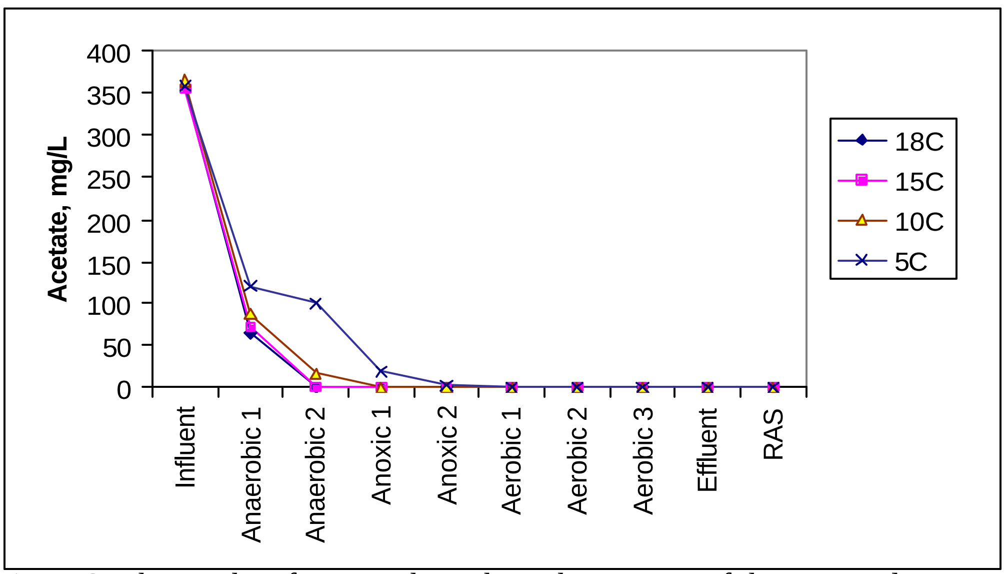


Figure 3: The uptake of acetate throughout the reactors of the EBPR plant.

CONCLUSION

- The EBPR bacterial community can achieve a homeoviscous adaptation at cold temperatures by simply increasing the unsaturated fatty acid ratio in their fatty acid side chains.

- The decreased EBPR efficiency reported at cold temperatures may be related to the application of unsuitable operational conditions (low SRT, low anaerobic detention time, non-acclimated sludge etc.).

REFERENCES

APHA. 1985. Standard Methods for the Examination of Water and Wastewater. 16th Edition, American Public Health Association, Washington D.C.

Brdjanovic, D., Slamet, A., van Loodsdrecht, M.C.M., Hooijmans, C.M., Alaerts, G.J. and J.J. Heijnen, 1998. Influence of Temperature on BPR: Process and Molecular Ecological Studies. Wat. Res. 32(4) 1035-1048.

Brock Biology of Microorganisms. 2000. Madigon, Martinko, Parker. 9th Ed. Prentice-Hall International UK.

The Effects of Low Temperature on Biological Systems. 1987. Grout B.W.W. and Morris G.J., Edward Arnold Ltd, UK.

Ekama, G., G. Marais, and I. Siebritz. 1984. "Biological Excess Phosphorus Removal", in Theory, Design and Operation of Nutrient Removal Activated Sludge Processes, Water Research Commission, Pretoria, South Africa.

Lepage G. and Roy C.C. 1986. Direct transesterification of all classes of lipids in a one-step reaction. Journal of Lipid Research 27 114-120.

Mamais, D. and D. Jenkins. 1992. "The Effects of MCRT and Temperature on Enhanced Biological Phosphorus Removal", Wat.Sci. and Tech., 26, (5-6), 955-965.

McClintock, S and C.W. Randall and V. Pattarkine. 1991. "The Effects of Temperature and Mean Cell Residence Time on Enhanced Biological Phosphorus Removal", Environmental Engineering, the Proceedings of the 1991 Specialty Conference on Environmental Engineering, ASCE. 319-324.

Mino, T., Arun, V., Tsuzuki, Y. and Matsuo, T. 1987. Effect of phosphorus accumulation on acetate metabolism in the biological phosphorus removal process. Proc. of IAWPRC Specialized Conference, 28-30 Sept. 1987. Rome. Italy. 27-38.

Okuyama H. 1986. Homeo-viscous adaptation in psychrophilic bacterium, Vibrio sp. Strain ABE-1 Journal of General and Applied Microbiology 32(6) 473-482.

Pereira, H., Lemos, P.C., Reis, M.A.M., Crespo, J.P.S.G., Carrondo, M.J.T. and Santos, H. 1996. Model for carbon metabolism in biological phophorus removal processes based on in vivo ^{13}C-NMR labeling experiments. Wat. Res. 30(9) 2128-2138.

Ramesha C.S. and Thompson G.A. Jr. 1982. Changes in the Lipid Composition and Physical Properties of Tetrahymena Ciliary Membranes following Low-Temperature Acclimation. Biochemistry 21, 3612-3617.

Sell, R. 1981. "Low Temperature Biological Phosphorus Removal". 54th Annual Conference Water Pollution Control Federation, Detroit, MI, Air Products and Chemicals, Inc, Allentown, PA.

The World of the Cell (1996) 3rd Edition. Becker, Reece and Poenie. The Benjamin Cummings Publishing Company. Menlo Park CA.