Conference Proceedings

2009 Virginia Water Research Conference

Water Resources *in* Changing Climates

October 15-16, 2009

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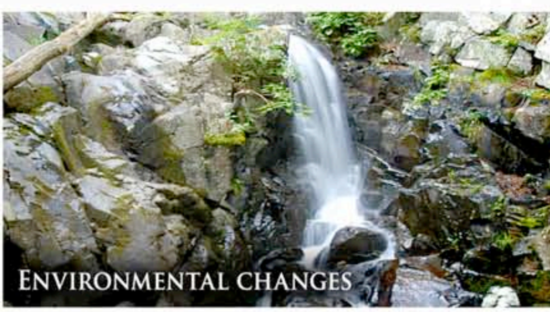

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Via Department of Civil and Environmental Engineering

Edited by:
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Table of Contents

Back to Table of Contents

2009 VIRGINIA WATER RESEARCH CONFERENCE

Plenary Session

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GOVERNOR KANE'S COMMISSION ON CLIMATE CHANGE: SCIENCE, ECONOMICS & POLITICS

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[No abstract provided]

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MEETING THE CHALLENGES OF CLIMATE CHANGE

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CHANGING CLIMATE AND INSTITUTIONS: IMPACT ON PUBLIC WATER SUPPLY ADEQUACY

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KEY WORDS: water supply, climate change, institutions, environmental protection, governmental regulation

ABSTRACT

Maintaining water supply adequacy is a basic social need that confronts varying challenges as the many factors affecting water availability and water uses evolve. The potential for changing climatic conditions is a major concern in maintenance of supply adequacy over time. Climate determines the amount of precipitation and its distribution, spatially and temporally, thereby setting limits on available water supply, and climate also affects water demand. Maintaining supply adequacy also depends on the social and political environment that reflects society's priorities and establishes the policy and regulatory framework governing water use and development. The most dramatic change in the social environment is the development of the threat of terrorism to water supply operations. Another significant social change in the United States has been the increasing restrictiveness in federal water management institutions. This trend is illustrated by the Clean Water Act section 404 permit program that uses a one-dimensional decision criterion providing for denial of permits for water facilities on environmental grounds without consideration of project need or availability of alternative water supplies. These changes in the social environment and the potential for more adverse climatic conditions in some areas create additional challenges for water supply managers as they attempt to provide an appropriately reliable supply to an increasing population. The combined effects of increasing physical scarcity, greater uncertainty associated with terrorism threats, and a more restrictive institutional environment will require reconsideration of the definition of supply adequacy and continuing innovation in all aspects of water supply management.

INTRODUCTION

Confronting change is a continuous feature of water resources management. Water management operates at the interface between complex natural systems that determine water availability on the one hand and human social systems that influence water use on the other. Change is a frequent occurrence in both of these dynamic systems. The natural hydrologic system that provides the foundation for water management is notable for its variability, including substantial fluctuation in precipitation, streamflow, and most of the other basic parameters. Social systems also undergo frequent change as values shift and social priorities change. Change is therefore not a new development for water managers.

But recent developments and trends within both natural and social systems create concern that changes of a more radical nature are occurring that will have greater disruptive impact and pose greater challenges for water managers in the future. In the case of natural systems, the prospect of climate change has potential for significant impact since it may establish new patterns of variation for hydrologic events such as precipitation. Over most of recorded history, such variation has occurred largely within the boundaries of established patterns. These patterns, while not completely defined and understood, set limits on variability that will not apply within new patterns resulting from climate change.

Major changes in the social environment of water management have also been underway. The most dramatic of these is the prospect of terrorism that targets water supply. The increasing willingness of some to inflict death and destruction on civilian populations in an attempt to advance their causes has impacted most human activities, including water management operations. Less dramatic changes in the social environment of water management are more pervasive and therefore important due to their widespread nature. One of the most significant of these social-change impacts in the United States arises from changes in water management institutions that have substantially modified long-standing priorities among alternative water uses. For example, the status of traditional water supply development has been substantially reduced with the ascendency of environmental values. One prominent decision process in current federal law allows water development proposals to be rejected for environmental-protection reasons without consideration of the need for the project in question or the availability of alternatives. This provision and other institutional modifications create a fundamentally different context for current and future decision making about water use and development. Impacts of these changes in the physical and social contexts of water management are far-reaching and encompass both those programs that focus on managing excess water such as flood damage reduction as well as those water programs that manage water shortage. One of the water uses in this latter category likely to see significant impact from changes in the managerial climate is public water supply, which is of special concern since water supply has such a direct relationship with human welfare. The likely impacts of climate and social change on efforts to maintain public water supply adequacy are the focus of the remainder of this paper.

CLIMATE CHANGE AND INCREASING WATER SUPPLY SCARCITY

Climate change has potential to strike at the heart of the water supply enterprise by altering natural inputs to water supply systems. While some areas may receive additional water due to altered precipitation patterns, other areas will be adversely affected as a consequence of reduced inputs. A basic goal of water suppliers is to maintain an appropriate balance between water demand and available supplies so that customer expectations are met. Over much of history, meeting this goal involved expanding supply to satisfy whatever demand was projected to occur. Supply was expected to meet demand not only under normal operating conditions but also during predictable periods of natural shortage and times of greater than normal demand. This managerial philosophy often required substantial interventions in hydrologic systems, usually in the form of reservoir construction to store water for augmentation of naturally available supply during periods of natural water scarcity.

More recently, this managerial approach has been altered by implementation of demand reduction measures as part of the process of balancing demand and supply. Such measures can be implemented for all uses (or certain types of use) on a continuous basis in order to reduce overall system demand, or they can be employed on a more limited basis such as during peak usage hours or designated periods of shortage in supply. Willingness to impose temporary restrictions during shortages on an increasingly frequent basis as system use increases over time can postpone the need for system expansion.

Whatever management strategy is employed at a given location, the existing balance between demand and supply can be upset by changes in natural inputs to the supply system. Adverse changes could take the form of reduced average flows in source waters or changes in supply patterns that reduce the dependable yield of supply facilities (such as change to a pattern involving greater floods accompanied by more intense drought periods). Both types of change could make an existing supply system inadequate sooner than anticipated and accelerate the need for additional supply development or increased demand reduction measures. Water suppliers historically have noted the difficulty of meeting increasing demand with a constant supply. Recognition that the useable supply at a given location may not remain constant but may actually decrease over time has interjected a new concern and suggested that maintaining supply adequacy in some areas may be more difficult than previously thought.

These climate change impacts that reduce water supply inputs to existing water supply systems and potential water supply sources are the most readily identifiable impact of climate change, but other impacts are possible. For example, sea level rise may adversely affect the operation of low-lying impoundments or other water infrastructure. In addition, higher sea levels may increase salt-water intrusion into coastal rivers or aquifers in coastal regions that serve as sources of public supply. All these reductions in water supply potential of hydrologic systems in some geographic areas will place additional constraints on water supply managers as they continue the basic challenge of maintaining an appropriate balance between supply and demand. With fewer management options, such areas may have to rely more heavily on demand management or turn to non-traditional alternatives such as desalination or importation of water from other areas.

WATER SUPPLIES AND THE TERRORISM THREAT

Expansion in the use of terrorism against the general population as a means to advance political causes has added a new dimension to maintenance of adequate public water supplies. The essential nature of water supply and the direct connection to human health and welfare make such supplies and related facilities obvious targets for anyone desiring to disrupt and harm a particular society. This threat has several aspects. One of the most direct is the contamination of supplies, an event that historically was limited to accidental occurrences. Viewing contamination as an intentional act requires a new approach to designing preventive measures previously limited to control of accidental releases of contaminating substances.

Other aspects of the terrorism threat include destruction of water management infrastructure and the potential loss of life and property that could arise from damage to facilities such as reservoirs. The initial response to this threat has been restriction of access and increased monitoring. The potential for destruction of facilities and other loss of water supply to terrorism increases water supply uncertainty and may involve catastrophic events in some situations, but the typical water supply operation is more likely to be directly affected by other, more pervasive changes in the social environment such as policies and institutions affecting water supply development.

INSTITUTIONAL CHALLENGES TO WATER SUPPLY DEVELOPMENT

Maintenance of adequate water supply is closely related to institutional arrangements affecting water use and development within a particular society. Even with demand reduction measures included in the overall management approach, supply development continues to be a basic option for maintaining adequate supply as populations and human activities increase over time. Recent institutional change in the United States has created new challenges by placing additional constraints on traditional practices for expanding supply as a basic management option. Although public water supply is one of the most basic of human water uses, human interactions with water are multi-dimensional and encompass many water uses and values in conflict with water supply. The institutions that establish priorities among water uses and provide decision processes for resolving conflict have undergone long evolution. Public policy and underlying public attitudes over much of U.S. history accorded the highest water-use priority to public water supply, and the governance system controlling water use was generally sympathetic to water supply proposals. Many large-scale projects, often based on generous assumptions about future water demand, were approved with limited opposition. This favorable climate for water supply facilitated the maintenance of adequate and highly dependable supplies but also resulted in excessive development and significant environmental damage in some cases.

The institutional framework within which water supply is currently implemented is considerably more restrictive. These changes have primarily been the result of the greater standing given to environmental values in public perception and governmental policies and regulatory programs. The ascendancy of environmental values has involved a variety of developments. One of the earliest and the most symbolic was passage of the National Environmental Policy Act (NEPA, 2009). NEPA declared environmental protection to be a federal responsibility and established requirements for environmental assessments, including preparation of environmental impact statements under certain conditions. It is perhaps significant to note that maintenance of public water supply adequacy is not a declared federal responsibility, and no federal water supply programs exist on par with such purposes as flood damage reduction, navigation enhancement, or, more recently, protection of environmental values. Facilitative programs exist such as the Water Supply Act of 1958 (WSA 2009), which authorizes inclusion if water supply in federal project being undertaken for other purposes, but the secondary status of water supply is evident. The Act views water supply as an add-on to projects with other primary purposes and requires that additional costs of its inclusion be paid by parties requesting the water supply storage; thus, it does not elevate water supply to a project purpose of equal standing to other traditional purposes.

The restrictive perspective of the federal government toward water supply relative to environmental protection is most evident in regulatory programs that provide direct controls over water supply and other development activities. One of the most significant of these with respect to water supply is the Clean Water Act section 404 permit program for controlling the “discharge of dredged or fill material" (CWA 2009, sec. 1344). Most water supply projects are within the scope of section 404 since it has broad coverage of surface waters and water development activities that potentially affect such waters. The jurisdictional coverage of the program has seen both expansion and contraction at its margins as a result of litigation and remains a subject of intense debate, but coverage of water supply facilities at present is broad.

The section 404 permit program goes considerably beyond the requirement of NEPA for consideration of environmental values in decision making; it establishes priority for such values over competing activities such as water supply. This effect can be seen in the criterion for final decision making on a permit application. Unlike most permit actions, a final section 404 decision involves the actions of two federal agencies. The U.S. Army Corps of Engineers makes the initial section 404 permit decision under guidelines developed by the U.S. Environmental Protection Agency, but EPA has authority to veto permit issuance upon specified findings. Corps' regulations provide that its permit decisions include a public interest review in which expected benefits of a proposed action are weighed against its foreseeable detriments, with the decision reflecting concern for both protection and utilization of important resources (USACE 2009). In the case of section 404 permits, however, the balancing process to determine the public interest is subjected to the constraint that a permit cannot be issued if the proposal is not consistent with EPA guidelines for such permits. These guidelines prohibit permit issuance if a "practicable alternative" to the proposed project exists that would have less adverse impact on the aquatic environment or if the proposed action would "cause or contribute to significant degradation" of the waters covered by CWA (USEPA 2009a). These prohibitions place substantial constraints on the flexibility to define the public interest as part of the Corps' review and requires the denial of certain section 404 permits that otherwise would be issued based on the broad balancing approach.

If these special constraints on section 404 permit issuance leave any doubt as to the reduced standing of water supply and other development projects relative to environmental protection in current federal law, it is dispelled by the principles that define EPA's veto power over Corps' permits that are issued. This decision is based on a single criterion: whether the environmental impact is acceptable (CWA 2009 sec. 1344 (c)). EPA maintains that it does not have to consider either the need for the permit-applicant's project or the availability of alternatives to the project (USEPA 2009b). The federal courts have upheld EPA's position in a case involving an EPA veto of a permit for a local government water supply impoundment in Virginia (JCC 1993). The fact that this principle appears well established indicates complete reversal of the historic approach to project approval. While some water projects once were approved without consideration of costs in the form of environmental values to be destroyed, such projects now can be rejected without consideration of their merits in the form of the values associated with water supply or other water development. (For a more detailed analysis of the CWA section 404 permit program, see Shabman and Cox 2004.)

In addition to CWA section 404 requirements, several other federal laws restrict water supply and other development projects in conflict with specifically designated environmental values. Included are other potentially applicable permit programs that require consideration of environmental impacts (such as the Federal Water Power Act (FWPA 2009) and the Rivers and Harbors Appropriation Act of 1899 (RHAA 2009)) and additional protective measures that serve as constraints on issuance of section 404 and other permits. Examples of these additional measures include the Endangered Species Act (ESA 2009), the Wild and Scenic Rivers Act (WSRA 2009), the Coastal Zone Management Act (CZMA 2009), and the National Historic Preservation Act (NHPA 2009). These acts generally operate by restricting federal activity, including the issuance of permits for private projects, and may prohibit issuance of a federal permit where proposed actions would be detrimental to protected environmental values. For example, the Wild and Scenic Rivers Act prohibits issuance of federal permits for dam construction and other adverse activities on streams designated as part of the Wild and Scenic Rivers System. Similarly, the Endangered Species Act prohibits permit issuance where proposed projects threaten the continued existence of animal and plant species designated for protection under the act. The restrictions illustrated by these particular examples do not apply to all proposed projects since WSRA and ESA requirements apply only within areas where designated environmental resources are located.

Each of these specialized environmental measures is intended to protect a recognized societal value and was created to address the previous tendency to give inadequate consideration to these values, but their cumulative impact may be considerably greater than the sum of their individual restrictions. This effect arises because they apply in a largely uncoordinated, sequential manner providing opportunities for redundant debate of essentially the same issues in multiple forums. As a result of the sequential nature of these proceedings, opponents of water supply proposals have several opportunities to voice the same objections, multiple environmental impact assessments may be required, and multiple opportunities for judicial challenge of any decision favorable to a proposed project may arise. (See Cox 2007 for an example of the repetitive nature of the individual regulatory decisions applicable to the project to divert water from Lake Gaston on the Virginia/North Carolina border to Virginia Beach, Virginia.)

The sequential nature of these independent proceedings creates a situation with general similarities to the criminal-law concept of "double jeopardy." Any given regulatory decision related to a proposed project is likely to be followed by another decision process where many of the same issues will again be debated. This fragmented, sequential process appears to maximize the weight given to the interests of project opponents, who often include local groups supported by national organizations who oppose most development projects without regard to their positive contributions. Federal participation will likely be limited to opposition from federal agencies with mandates for environmental protection since water supply is not a federal water management responsibility. Within this chain of decisions, any negative outcome will nullify multiple positive outcomes at other decision points. But the most fundamental flaw in the fragmented decision making environment created by these diverse federal programs is its failure to provide a forum for holistic consideration of the full range of public interest issues involved with respect to the adequacy of water supply. The narrow focus of the individual decisions limits the opportunity for broad consideration of the best overall approach to maintenance of adequate water supply.

CONCLUSION

The challenges confronting those responsible for maintaining adequate water supply are decidedly greater than at previous times in history. Supply and demand must continue to be balanced as population increases, but development of scarcity may be accelerated by the new threat of climate change. The threat of terrorism increases uncertainty and complicates operations, as concern for security must be incorporated. All necessary management activities relating to additional supply development must be accomplished in an institutional environment considerably more hostile to water supply than in the past, primarily due to the greater weight given to protection of environmental values and the associated restrictions placed on water supply expansion.

Most of the heightened challenges confronting water suppliers are the result of trends not likely to be reversed in the near term. Action to address the underlying causes of new challenges such as climate change and terrorism must be undertaken, but quick solutions do not appear likely. Measures to address climate change are still being debated, but no agreement has been reached on such basic issues as the extent of the human role in the process, what actions are necessary to control adverse impacts, and how to apportion responsibilities for implementing such actions. Resolution of the terrorism concern also appears remote and illustrates the extent to which water managers are affected by issues beyond their areas of influence.

Major adjustments to the hostile institutional framework for water supply development appear unlikely. The ascendancy of environmental values through institutional evolution reflects a shift in public values and a corresponding modification of decision processes that historically had largely ignored environmental consequences. The additional challenges these new arrangements impose can be seen as an adjustment to previously flawed decision processes no longer consistent with public values and expectations.

But current institutions appear to have gone beyond addressing previous institutional deficiencies and established decision processes with a different set of deficiencies. This outcome can be explained by the pendulum theory of public policy that seems to be in effect (which suggests that any movement to achieve a new balance between two opposing objectives will not likely stop at a neutral position but will, like the pendulum, first swing to the other extreme). This theory makes it likely that the shift to greater attention to environmental values will be accompanied by loss of adequate recognition of competing values such as those embedded in utilitarian water uses such as public supply.

The most direct example of current imbalance in current decision processes is the CWA section 404 permit process, which does not provide a neutral forum for holistic evaluation of society's conflicting interests in water but has an inherent bias against water resource development. In the program's current form, a permit for a proposed water supply project can be denied on the basis of unacceptability of the associated environmental impacts without consideration of the need for the project in question or the availability of alternatives. The need for a mechanism to prohibit specific projects on environmental grounds is clear, but there is need for a more comprehensive forum for evaluating all the public interest considerations associated with such determinations.

Another flaw in current decision processes consists of the uncoordinated, duplicative manner in which a variety of independent environmental protection measures are implemented. Each of these protective measures represents important societal values and appears to be necessary, but better coordination to replace the multitude of independent, repetitive, and narrowly focused procedures with a coordinated, more comprehensive evaluation process would add a needed measure of rationality absent from the current process.

Addressing these institutional flaws may be possible over time, but, as in the case of the challenges posed by climate change and terrorism, substantive change is difficult and does not appear likely in the near term; therefore, the current challenges faced by water suppliers represent the new reality for the predictable future. Meeting these challenges is changing the water supply industry and in turn will impact the average water system customer. Traditional water user expectations of low-cost water and unrestricted supply will continue to fade. Increasing scarcity will require use of more costly supply options such as desalination, and more intrusive demand reduction measures will likely become more common. The basic concept of water supply adequacy may change. For example, the expectation that a dependable supply involves almost no probability of inadequate service under reasonably anticipated conditions may have to be exchanged for the view that a dependable supply has an expected frequency of service disruptions (or scheduled prohibitions on certain water uses as a means to avoid system failure). At the least, maintaining a high level of dependability will involve greater costs. To some extent, these trends have been underway for a long time, but changes in climate and social processes increase their rate of development. Ultimately, the public's long tradition of taking for granted a low-cost, dependable water supply may be in jeopardy. To maintain this tradition, those responsible for water supply will have to be ever more innovative as they operate in this more challenging environment.

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DOMINION: NEW DIRECTION IN ENERGY

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CLIMATE CHANGE ADAPTATION AND WATER RESOURCES IN VIRGINA

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Back to Table of Contents

Concurrent Session I

(A) Understanding Climate Change Effects on Water Resources
(B) Modeling Water Quantity and Quality
(C) Connecting Nutrient Cycling and Water Quality (Part 1)

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I-A Understanding Climate Change Effects on Water Resources

**(1) The Impact of Climatic Change in Population and Economic Activities in Costa Rica -- ** Freddy Araya Rodríguez, *Instituto Tecnológico de Costa Rica*

(2) Water in Mind: Investigating the Cultural Implications of Climate Change in Siberia -- Susan Crate, *Environmental Science & Policy, George Mason University* (Presented by Vivek Prasad, *Environmental Science & Policy, George Mason University)*

(3) Population Dynamics of American Horseshoe Crabs: A Story of Historic Climatic Events and Recent Anthropogenic Pressures -- Eric Hallerman, *Department of Fisheries and Wildlife Sciences, Virginia Tech*

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THE IMPACT OF CLIMATIC CHANGE IN POPULATION AND ECONOMIC ACTIVITIES IN COSTA RICA

Freddy Araya Rodríguez
Daniel Pérez Murillo
Cristian Moreira Segura
Alfonso Navarro Garro
Jorge Chaves Arce
Instituto Tecnológico de Costa Rica

KEY WORDS: climatic change, interdisciplinary, global warming

ABSTRACT

Experts in climatic change have agreed that developing countries show a limited adaptative capacity, related to the long term effects of increasing world temperature. In the particular case of Central America, this region produces less than 0.5% of the carbon in the planet. Yet, it is one of the most vulnerable places on earth to climatic change effects. In Costa Rica public universities have assumed a challenge and a responsibility related to water use and conservation at all levels. This is the case of the Instituto Tecnólogico de Costa Rica, which has developed numerous projects in these fields with interdisciplinary groups. Those attempts have collided in one idea, which attempts to studying the global warming problem in the context of Costa Rica by designing a strategy that focus them from different angles and with contributions from professionals of different areas. This proposal consists on an integral approach to sensitize target

population about causes, effects and possible solutions to this current issue. The educational component remains as the main element from where all the other elements depart as an answer to a multifactor problem. This paper illustrates the necessary steps to be followed when trying to fulfill such endeavor, with the view point of a public university.

INTRODUCTION

According to experts in climatic change developing countries show a significantly reduced long-term adaptative capacity in relation to the effects of increasing of temperature. This situation has to do with a number of related factors: low levels of economical wealth; lack of social and physical infrastructure, especially health and education; insufficient access to technology; low level of trust in public institutions and the services they offer to society; lack of information and knowledge; and finally social inequity and poverty that avoids an even distribution of social benefits (Gutiérrez 2007).

It is undisputable that climatic change affects everybody without any distinction of social status or the geographic region where we live. In the particular case of Central America, the United Nations Economic Commission for Latin America and the Caribbean (ECLAC) stated that this region produces less than 0.5% of the carbon in the planet. Yet, it is one of the most vulnerable places on earth to climatic change effects (CEPAL 2009). On the other hand, the rise of atmospheric and ocean temperature, the reduction and instability of rain cycles and the increase of ocean levels have a direct impact on production, infrastructure, living styles, and general population's health.

Research conducted in Costa Rica shows that even when climatic variables are impossible to control; it is possible to take action to control and reduce vulnerability of population to precipitation and provide some corrective measures. Vega and Vega (2007) suggest that an adequate urban planning, construction and improvement in rain sewer and sanitary sewer systems, increasing the wellbeing of habitants, element that affects in a better cost/benefit relationship.

An attempt to quantify the impact of climatic change on economic activities present a first scenery known as *base climatic scenery*, and it considers the repercussions climatic change has on goods on the market—that is, it takes into account only those sectors where prices are explicit and predetermined such agriculture, energy consumption, forestry utilization, *etc*. (Gutiérrez 2007).

Economic implications and social problems generated due to disasters caused by hydrometeorologic events: drought, floods, heat waves, sudden gales, landslides, accidents caused by rain, in Costa Rican economy in the last ten years this represented 84% of the total of natural disasters registered.

JUSTIFICATION

Climatic variability has affected many different productive sectors of the country, even though the particular characteristics Costa Rica has in the agriculture sector, where most of the economic activity is centered, keeps facing emergencies, due to a lack of prevention. As a result of this situation, the losses related to agro industry are greater and the recovery process of the affected area and social groups become slower. Conditions affecting families which lost their homes and crops influence negatively the development of the community, for instance, children stop attending school, which worsen low educational levels in agricultural areas.

As a consequence of diverse impacts, the government intends to develop Strategies and Policies with a regional point of view though which different sectors, including the private one, define and execute mitigation, compensation and adaptation actions to face climatic change. A particular strategy applied to the Productive Sector refers to Carbon Neutral that helps generate competitive advantages to agricultural products that get that norm.

In constant change scenario, information and education continue to be key factors to make this sector stronger and to develop innovative ideas to improve economical condition for agriculture workers and making the planting of necessary crops more stimulating to fulfill Costa Ricans´ needs to contribute with food independence of the country.

MAIN CROPS AND EVOLUTION OF PRODUCTIVE

In the year 2007, agriculture sector, silviculture, fishing obtained the sixth place in relative participation in the Gross Internal Product (GIP) according the type of activity, being banana, pineapple, and coffee the most important in terms of agricultural added value.

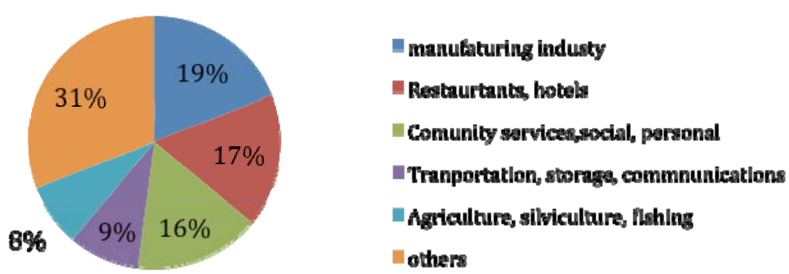

Figure 1.Gross Domestic Product: Relavtive Particiapation According to Economic Activity 2007

Agriculture sector as well as livestock sector, fishing industry and food industry grew in the last years. Sectors like pineapple doubled their production in the last two years with a very high environmental cost. There was also an increasing in the sales, element that indicates the growing of a structurally healthy sector (Barquero 2007).

Extreme climatic events that threaten human health country´s economy, production and biodiversity become more common in the country every day. During 2007 rains damaged 80% of the coffee production in Acosta, causing losses about ¢ 350 million due to the wastage of 5.000 bushels of grain and an increase in a disease named " Ojo de Gallo" (*Mycena citricolor*) (Hernández 2007). A month before, in Guanacaste, floods affected 20% of sugar cane plantations in Hacienda el Viejo. In this part of the country, producers possess more than 7000 hectares (Arguedas 2007).

Table 1. Agriculture Sector: Total Stimate of Losses Caused By Extreme Climatic Events in 2007 (Thousands of Colones)

Item	Losses
Amount of damages	11,368,271,365.00
Agriculture and Livestock	9,819,487,389.00
Fishing (Chorotega Region)	35,000,000.00
Irrigation infrastructure	1,519,258,978.00
Others (apiculture and aquaculture)	65,475,000.00

Source: SEPSA 2008

Heavy rains that affected the country in October caused damages in paved and ballast roads in 2005. The last three hurricanes: Stan, Rita and Katrina provoked losses near ¢5000 million in road infrastructure. Preliminary numbers made by the Ministry of Public Transportation (MOPT) indicate that urgent repairs to open roads, remove landslides, set provisional bridges bear ¢22000 million. It is necessary to add to this amount ¢45000 million to build permanent bridges, install new sewers and drainages and improve pavement and ballast coverage (Loaiza 2008).

According to SEPSA (Secretaría Ejecutiva de Planificación Sectorial Agropecuaria 2008), a technical unit, the reduction in the sowing areas of 111,978.53 hectares – moving from 511,326.77 in 2006 to 399,348.24 in 2007 – is due to abnormal conditions (high rainfall levels, strong winds, floods, low temperatures) in the Eastern Central and Western Regions. Estimations made by the Ministry of Agriculture (MAG) indicate that "La Niña" affected more than 255,853.8 hectares of diverse crops affecting more than 6,380 farmers mainly in the Chorotega Region (Guanacaste) where 2,844 of them suffered from rainfall effects. A number of crops were damaged: sugar cane, rice, beans, coffee, vegetables, plantain, palm trees, melon and water melon (Barquero 2007). A total of ¢13,046,203.74 million colones are required to recover affected areas.

Table 2. Area Affected by Niña According to Agricultural Activity (Hectares)

Region	Total	Agriculture	Livestock	Activity
Chorotega	252,787	20,875	231,912	Sugar, rice, beans, corn, vegetables
Brunca	858.8	848.8	10	Rice, coffee, vegetables, sugar, beans, pasture
South Central	465.5	401.5	64	Tomato, onion, green, beans, plantain, mango, palm, papaya, coffee
Pacific Central	1,143	1,143	ND	Rice, melon, water, melon, vegetable, coffee, corn, beans, milk
West Central	343.5	343.5	0	Vegetables, coffee, tomato
East Central	256	256		Potato, vegetables, fruits, flowers
Total	**255,854**	**23,867.8**	**231,986**	

Source: SEPSA 2008

Water systems, considered the base of community development, are vulnerable to climatic conditions since their origins correspond to rainfall. Rainfall is influenced in its spatial and time distribution by climatic elements like rain, evaporation and wind. Alteration in climatic patterns reverberates in the water supply of the system varying the hydrological cycle and the activities related to it. Climatic change, shows as a real threat. It models climate, nevertheless, its short term implications are still uncertain and discussed. Recently, models of future scenarios incorporate past effects of climate extremes produced by the registered variability. These registers are used as starting points to analyze effects on short and medium term basis. For instance, alterations in the rain periods as a result of El Niño can produce high-risk scenarios to superficial water uptake facilities and nearby sources of water supply (OPS 1998).

According to Solera (2000), experiences in Costa Rica with EL Niño show variations in rain patterns and the vulnerability of the water system to these atmospheric disturbances. The irregular way in which rain season appears in the whole country affects drinkable water and sanitary sewer services in either way, excess of deficit of rainfall. Rainfall deficit causes drought that affects superficial and underground water intakes as a result of pollution or reduction of the absorption and purification capacity and the concentration of agrochemicals, dead fish caused by an oxygen level reduction or dead animals near riverbeds (OPS 1998). Excess of rainfall provokes an increase in river and stream discharges, sediment load that make the drinkable water supply impossible because of the suspended solids, turbidity, color, *etc*. (Solera 2000).

The impact of climatic change on water systems goes beyond damages caused on physical conditions of water paths. It is not just the riverbed, the water well or the aqueduct, the social implication, more than the economical moves to the cultural, patrimonial and political in regions where migration and the trade of goods are ways to survive in the affected community. According to this point of view, prevailing conditions of vulnerability in management and disaster risk reduction associated to hydrometeorologic events involve a physical, social, cultural, economic and political frame of a country (EIRD/UN 2004).

PROJECT TO BE DEVELOPED IN RIVER BASINS IMPACTED BY CLIMATIC CHANGE CIRCUMSCRIBED BY SUSTAINABLE DEVELOPMENT AND ENVIRONMENT

As a reference element, sustainable development is defined. Economic growth, social development, and environmental protection are interdependent and reinforce one another. The need of finding equilibrium among these three elements is recognized under a wider concept: *sustainable development*. This proposal was articulated in 1987 in the document “Our Common Future,” created by the World Commission on Environment and Development. This document was followed up in the 1992 United Nations Conference about Environment and Development, the Las Americas Summit about Sustainable Development in 1996 and the United Nations World Summit in 2002.

DESCRIPTION OF THE AREA OF STUDY

A comparative study of two river basins in Costa Rica located in different areas: Humid Tropic and Dry Tropic.

Characteristics of the River Basin Located in Humid Tropic

San Carlos River Basin is located in the northeast region of Costa Rica, specifically among North Lambert Coordinates 425683 – 519405 and 307315 – 236810 approximately, consisting of an area of 3122.1 Km^2 (Chaves 2002). This river basin represents a good example of recent climatic change problems that can reach high levels of deterioration and its recovery would imply a disproportionate cost to the nearby population and the country in general. The greater part of the population of the North Zone of the country is located inside the limits of the river basin.

Physiography and Relief

The following figure shows a Digital Elevation Model and the drainage network of the river basin where it is possible to appreciate its irregular escarpment.

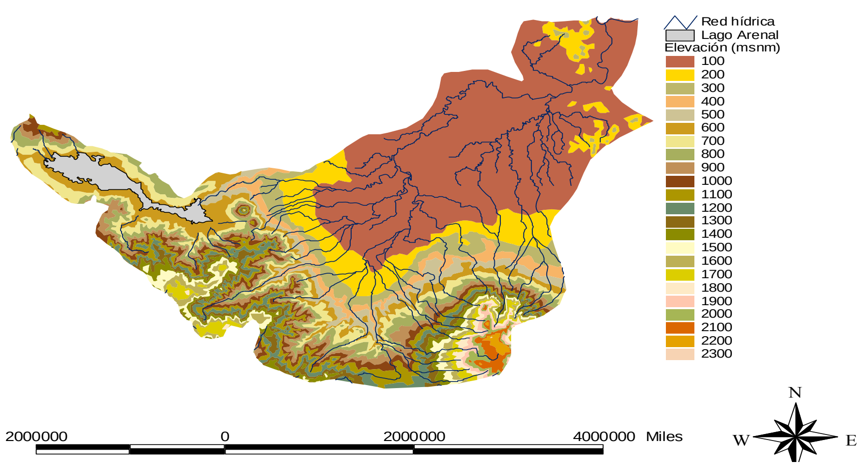

Figure 2. Digital Elevation Model and the drainage network.

Since the slope indicator correspond to 11% and the values in Table 3, it is possible to state that topography of ground through the River Basin is curvilinear. Such conditions in basins with high rainfalls favor the loss of soils with the consequent sediment load to the riverbed (Kiely 1999). These conditions have privileged the creation of nearly sixteen hydro electrical projects, which make this river basin one of the most important in terms of electricity production in Costa Rica.

Table 3. Morphological Characteristics of San Carlos River Basin.

Characteristic	Value
Surface	3122.1Km^2
Perimeter	333.4 KM
Length of main channel	141.2Km
Maximum height	2320 m.a.s.l
Minimum height	20 m.a.s.l
Average Height	366.8 m.a.s.l
Compactness index	1.67
Slope indicator	0.11
Average gradient of the river	1.63%
Drainage density	1.05 (Km/km^2)

Information contained in Table 3 confirms the existence of a notable slope since the riverbed of 141.2 km has variations in height ranging from 2320 to 20 meters above sea level, factor that causes intense turbulence in water especially in the high and medium beds of the river. San Carlos River basin is characterized by heavy rainfalls with a yearly average of 3,961 mm with an annual rainfall runoff of 3,143 mm (PROCUENCA 2004).

Main Agricultural Activities

Cattle production is one of the most relevant activities of the region mainly in San Carlos where it occupies 67% of the territory. It is also a perfect place to locate farms devoted to citrus fruits, sugar cane, forestry, ornamental plants, root and tuber.

To vividly characterize the activities taken place in the region, some pictures illustrate them. These pictures reflect the use of superficial water, the view from the upper part of the river basin where mainly milk cattle is grown.

Figure 3. General characterization of representative areas in the San Carlos River Basin

In the next pictures, it is possible to observe some samples of livestock activity in the Río San Carlos Basin. An important number of dairy farm facilities are located along the river of a natural water stream with the purpose of tossing waste into the river the moment the milking process is finalized. With this procedure countless quantities of water are wasted. This water supply comes mostly from water devoted to human consumption.

Figure 4. Characterization of livestock activity in the San Carlos River Basin

Dry Tropic Characterization

The Tempisque River Basin is located in the Northeast of Costa Rica, in the province of Guanacaste. It has an area of 3,407 km^2; in this basin 24,000 hectares of sugarcane are planted; an important amount of local consumption rice is produced here, about 25%; it is the biggest producer of water melon to export with an approximately 5,300 hectares dedicated to plant his crop.

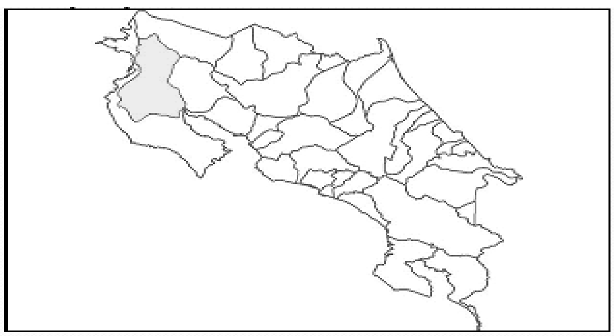

Figure 5. Location of Tempisque River Basin

Important ecosystems are also found, Bolsón, Riberino, Zapandi, Palo Verde Wetlands and some habitats like low level dry forests, plains with trees, ever green forests, and some of these areas correspond to national parks and reserves.

Hydro geologically, the Tempisque River is formed by the joint of two rivers: Tempisquito and Ahogados. With the confluence of Colorado River, the alluvial valley of Tempisque River.

The river basin presents slopes above 7% in the high lands and less than 2% in low lands. The highest elevation this area possesses is 1,916 m.a.s.l in Santa Marta Volcano (Alpizar *et al*. 2004). The average rainfall is approximately 1,833 mm (Oreanmuno 2004).

Meanwhile this river basin shows excess of water during rainy season – that shows what they need for recurrent floods – in the dry season the availability of the resource is significantly reduced with a delay of 6 months.

The steadiness of the riverbed is combined with the fact that Rio Tempisque waters and all superficial waters flow freely. It means that there is not any work of regulation and river stream that facilitate its storage in the wet season to use it in the dry one.

MAIN OBJECTIVE

Develop a methodology to relieve the impact in the activities of economic development in urban areas due to the modification of water systems in the basins as a result of climatic change.

SPECIFIC OBJECTIVES

- Collect data in, rainfall cycle, riverbed status, and economical activities of population centers in the river basins and the population centers in the entire basin
- Develop risks and vulnerability indexes required to determine the impact in the river basins as a result of climatic change.
- Generate models of prevention of risk and vulnerability of human populations and diverse economical populations in the basins.
- Develop an early warning monitoring network to prevent natural disasters in the area with low cost to maintain a permanent control to ease the decision making process.
- Apply a proper methodology to mitigate the impact of climatic change in rainfall y beds of rivers in the basins.

EXPECTED IMPACT OF THE PROJECT

There are numerous studies that appraise climatic change from many areas, nevertheless, it is inevitable that without integrating the economic effects, efforts are washed away and lack of expected impact since they try to guide another example.

Generating a Risk Map that defines areas that are vulnerable and where hydrometeorologic extremes and the future tendencies of elements such as temperature and rainfall can strongly impact the system.

Impacts that have been identified in this study as a consequence of extreme climatic scenarios, not only have value for their qualified magnitude, but also for their risk analysis and the proper strategy to reduce it. That is to say, areas with high risk (high vulnerability, high threat) with documented negative impacts can be converted in examples to design an adaptation strategy.

The degree of affectation of an impact consists on one of the most important to define methodology. Policies and legal framework set the route to be followed by proposed measures and they constitute the milestone for strategies to adapt to condition of a future climate.

METHODOLOGY

I Stage: Risk and Vulnerability

Diagnostic analyses of the selected areas become the first step of the process. A characterization of the analysis of risk and vulnerability to climatic change is a priority. More populated areas have the tendency of capturing heat, creating more vulnerable areas to atmospheric variation which reduces the capacity of the system to provide basic water service. Besides, the collected data will be stored in Geographical Information Systems. The selected river basins were defined as a geographic unit recommended analyzing impacts on hydrologic systems.

II Stage: Risk and Vulnerability analysis

Analysis of risk and vulnerability according to Risk= "(threat, vulnerability)" will constitute the second stage. Recollecting socio-economical information help to construct indicators to detail activities in the micro basins.

III Stage: Construction of indicators

A statistical analysis with the different events and the proper indicators will guide this stage.

IV Stage: Prevention Models

Developing models becomes a representative element of the process since it will permit recreate event before the happen and reconstruct them for analysis.

V Stage: Remote Sensor network

Monitoring different variables throughout the river basin will provide data and criteria to take actions and reorient processes in different levels.

VI Stage: Transferring Technology

In this stage, data analysis helps guide the process of transferring information and technology to people, institutions and organization related to the river basin in order to transfer generated knowledge to be applied in real settings.

EXPECTED OUTCOMES

- Designing of production scenarios to measure according to Costa Rican conditions.
- Sampling and analyzing procedures of rainfall and riverbeds.
- Designing a report about quantification of rainfall and riverbed that are beneficial to river basin activities.
- Establishing of indexes of risk and vulnerability due to climatic change.
- Application of new methodologies to get a better use of water resource.
- Installation of a remote sensor network to measure different variables.

- Identification of sensitive amphibious to climatic change.
- Generating a proposal of variation in the productive areas to reduce climatic change effects.
- Training to implement environmental management to increase competitivity.

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WATER IN MIND: INVESTIGATING THE CULTURAL IMPLICATIONS OF CLIMATE CHANGE IN SIBERIA

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KEY WORDS: native Siberian communities, global climate change, altered water regimes, cultural implications, policy implications

ABSTRACT

This talk explores the cultural implications of the uncertain water regimes brought about by global climate change for Viliui Sakha, native horse and cattle breeders of northeastern Siberia, Russia. 90% of 2004 survey participants confirmed that climate change is causing unprecedented change in their local areas, threatening to undermine their subsistence economy, their health and culture. In response, the author is conducting a three-year NSF-funded research project, entitled: Assessing Knowledge, Resilience & Adaptation and Policy Needs in Viliui Sakha Villages of Northeastern Siberia, Russia Facing Unprecedented Climate Change. After providing project context, the paper focuses on water issues. Local perceptions of and responses to changes in water regimes brought about by global climate change (GCC) are framed by a culture's past and evolving narratives of water. Similarly new narratives are imported to a culture by media, researchers, local and regional policy efforts, *etc*. 2008 fieldwork revealed that one of the main effects of climate change for these communities in increasing water on the land. Inhabitants expressed not only concern about their future but also common fear that they would 'go under water.' Effective adaptation and policy interventions need to address not only the physical realities of altered water regimes but also the cultural implications. To investigate this need, our 2009 field season looks in more depth at communities' perceptions of water, using cultural consensus methods. This paper will present our initial findings and make suggestions on how these findings can be used to inform local adaptation and regional policy.

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POPULATION DYNAMICS OF AMERICAN HORSESHOE CRABS: A STORY OF HISTORIC CLIMATIC EVENTS AND RECENT ANTHROPOGENIC PRESSURES

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Tim L. King, Leetown Science Center, U.S. Geological Survey
Matthias Obst, Sven Lovén Center for Marine Sciences Kristineberg, University of Gothenburg
Eric M. Hallerman, Department of Fisheries and Wildlife Sciences, Virginia Tech
Cino Pertoldi and Peter Funch, Department of Biological Sciences, Aarhus University

The American horseshoe crab, *Limulus polyphemus*, has declined in population size but neither the causes not the magnitude are fully understood. In order to evaluate historic demography, variation at 13 microsatellite DNA loci surveyed in 1218 American horseshoe crabs sampled from 28 localities was analyzed with Bayesian coalescent-based methods. The analysis showed strong declines in population sizes throughout the species' distribution except in the geographically isolated southernmost population in Mexico, where a strong increase in population size was observed. Analyses suggested that demographic changes in the core of the distribution occurred within the last 150 years and likely were caused by anthropogenic effects. Declines of the peripheral northern and southern populations occurred during the "Little Ice Age" and are more likely to have been climatically driven. This study highlights the importance of considering both climatic changes and anthropogenic effects in efforts to understand population dynamics – a topic which is highly relevant in the ongoing assessment of the effects of climate change.

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Back to Table of Contents

I-B Modeling Water Quantity and Quality

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DEFINE HYDROCLIMATIC PROVINCES AND REGIONAL FACTORS IN PRECIPITATION DYNAMICS FOR WATER RESOURCE ENGINEERING IN CONTIGUOUS UNITED STATES

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ABSTRACT

Water resources adaptation is a risk management approach against adverse effects of climate change. Future precipitation projections are its fundamental technical basis. This subject is at the center of the EPA's water resources adaptation program with the objectives to support water utilities and other stakeholders in adaptation engineering and management. In this paper, we describe the development of a novel methodology in precipitation projections that begins with delineation of hydroclimatic provinces in the contiguous U.S. Through a comprehensive wavelet temporal and GIS spatial analysis of historical precipitation records, in a total of 129,000 station-years for 1207 climatic stations across the U.S., it is found that prominent climate change and variability signals can be grouped into six hydroclimatic provinces and their transitional zones: (1) Western Coast, (2) Ranges and Basins, (3) Great Plains and Midwest, (4) Lower Mississippi – Ohio River valley – New England region, (5) Florida and Southeast coast, and (6) Great Lakes. These provinces have their own distinctive wavelet time-frequency spectra reflecting regional

precipitation regimes. Their boundaries coincide with major topographic features indicating the effects of topographic forcing and land boundary feedbacks on continental precipitation. Within each province, the precipitation variations are relatively uniform with quantifiable periodicities. These properties, when used in conjunction with atmosphere-ocean general climate model (AOGCM) simulation outputs of future climate scenarios, provide a basis for precipitation projections in the next 30-50 years, a time frame that is useful for general water resources master planning.

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INCORPORATING UNCERTAINTY AND VARIABILITY WHEN DETERMINING GROUND WATER CONTAMINATION SOURCE REDUCTIONS

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KEY WORDS: 2nd order Monte Carlo models, simulation, decontamination, uncertainty

ABSTRACT

Contaminant source reduction is a technique that, when coupled with natural attenuation of a plume, can be a cost-effective method for remediating ground water pollution. In many situations, however, site characteristics and chemical properties are not fully known, and often vary in space and time. This makes determining the needed level of source reduction difficult.

Risk assessment models currently distinguish between uncertainty and variability. Variability represents the natural heterogeneity of the system, while uncertainty represents the lack of knowledge about the system. Uncertainty can be reduced by further study, but variability is part of the natural process and cannot normally be changed. Both are represented as probability distributions in risk assessment models, and these distributions can be combined through the use of an overall 2nd order Monte Carlo model.

This work illustrates the application of a 2nd order Monte Carlo model for determining source level reduction using a simple advection-dispersion steady state model to simulate contaminant transport. The model first determines the degree of reduction necessary to meet a user-defined concentration limit at the property boundary at a user-defined level of confidence generated from the Monte Carlo method. Then the model calculates how long from when remediation is completed before the concentration actually meets the limit. This approach allows for better

resource allocation and less wasted spending when removing ground water pollution or determining whether decontamination is even necessary.

INTRODUCTION

Contamination of groundwater sources poses severe health and environmental concerns. Source reduction of contaminant, combined with the natural attenuation of contaminants in groundwater, is one method for reducing contamination to a tolerable level. More and better methods for removing contaminant mass are continuously developed, and as a result their usage in the field has been growing considerably, accounting for approximately 50% of sites where remediation is necessary (USEPA 2004).

As computing power has risen at an exponential rate per Moore's Law, creating deterministic computer models to simulate the attenuation of contaminant plumes has become increasingly viable. Moreover, models can now account for uncertainty and variability in areas that were previously simplified for computational simplicity. Thus, the goal arose for this project to create a computer model capable of incorporating both the natural variability, which represents the natural heterogeneity of a system, as well as the inherent uncertainty within the system as a whole. For this assessment, a stochastic, deterministic model utilizing a 2nd order Monte Carlo method was created to simulate the attenuation of a plume and determine the necessary time of stabilization to reach regulatory maximums.

There are three central tenets to calculating the necessary amount of source contaminant reduction for a plume:

1. Time of Stabilization (ToS) - This is the time it takes for a plume currently in a steady state to reach a new steady state once the source contaminant has been reduced. It measures the delay between the reduction and its effects on the plume.

2. Point of Compliance (PoC) - The length of the plume that is allowed to be at or exceed regulatory maximums for the contaminant. Beyond this point in the plume, all contaminants should comply with the existing regulations.

3. Maximum Contaminant Level (MCL) - The regulation specified maximum concentration for a contaminant in the water supply.

The ultimate objective of this project is to determine the necessary amount of source reduction to meet the MCL at the POC and then to determine the time it would take to reach this MCL. Thus, the end result will be a degree of contaminant reduction that meets environmental and health regulations within a desired timeframe, as well as uncertainty estimates around these values that can help risk managers is setting appropriate levels of protection.

MATERIALS AND METHODS

Modeling Uncertainty and Variability

Risk assessment models currently distinguish between uncertainty and variability. Variability represents the natural heterogeneity of the system, while uncertainty represents the lack of knowledge about the system. Uncertainty can be reduced by further study, but variability is part of the natural process and cannot normally be changed (Cullen and Frey 1999, Vose 2008). Both are represented as probability distributions in risk assessment models, and these distributions can be combined through the use of an overall 2nd order Monte Carlo model.

The model was developed as a 2nd order Monte Carlo model, as conceptualized in Figure 1. This is an extension to the standard or 1st order Monte Carlo modeling approach which allows input parameters to be treated as stochastic. In the 2nd order approach, input parameters may be deterministic, variable and therefore described as a probability distribution, or uncertain in which case the probability distribution itself is not known. The variable parameters are treated in a fashion similar to variables in a 1st order model. For the uncertain parameters, the parameters of the distribution (*e.g.* the mean and standard deviation of a normal distribution) are treated as probability distributions. For each uncertainty iteration, these distribution parameters are randomly generated and the resulting probability distribution for that uncertainty iteration is generated. Then a typical Monte Carlo simulation is undertaken and a resulting probability distribution for the output variables generated. The process is repeated for each uncertainty iteration.

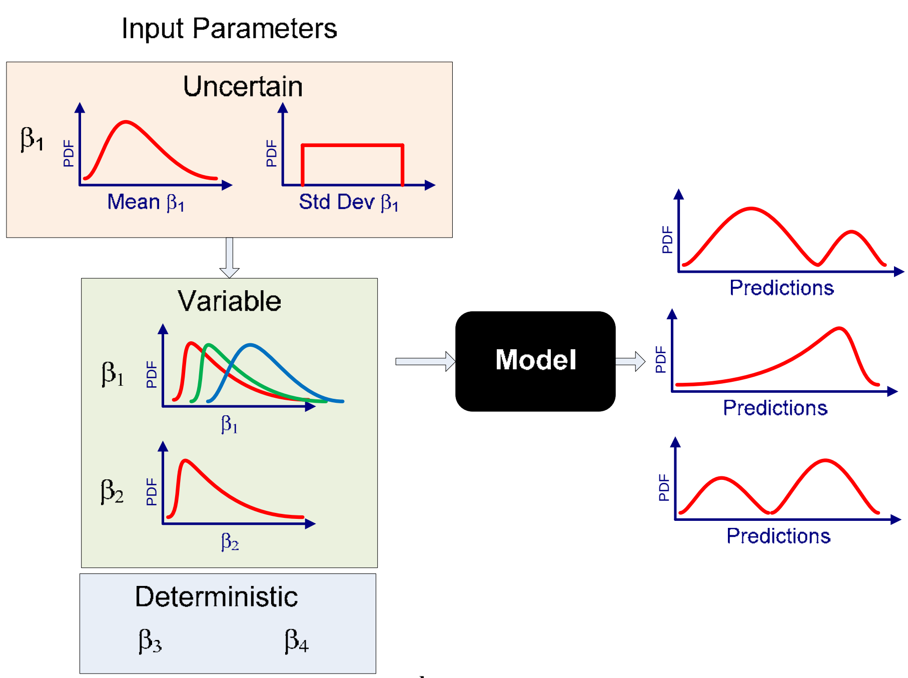


Figure 1. Conceptual Model of a 2nd Order Monte Carlo Approach Depicting Deterministic, Variable, and Uncertain Model Inputs.

Comparisons of variability and uncertainty are usually based on the cumulative density function plots from each uncertainty iteration. If these are clustered together, variability dominates. If these are spread out, uncertainty dominates. The process will be illustrated below. In addition, the histograms of a particular quantile of the uncertainty distributions can be evaluated.

Ground Water Model Theory

The fundamental equation governing contaminant behavior is noted in Equation 1:

$$D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} - v_x \frac{\partial C}{\partial x} - \lambda C = R \frac{\partial C}{\partial t} \qquad \text{Eq. 1}$$

In this equation, x and y represent the distances from the source contamination, C represents contaminant concentration, λ is the first order contaminant decay rate, R is the retardation factor (units: dimensionless), v_x represents the velocity of the source groundwater, and D_x and D_y represent the hydrodynamic dispersion coefficients in the x and y domains, respectively (Mendez 2008).

While numerical solutions to this differential equation are often needed for site-specific remediation design, useful analytical models can sometimes be obtained with simplifying assumptions. Assuming study state, homogeneous conditions, with complete mixing in the vertical direction (and thus a 2-dimensional model) and a rectangular source region, the resulting steady state equation for a given time t and distance along the centerline can be determined. Assuming a source remediation to a specified concentration, superposition can be used to solve for the concentration profile along the plume centerline after source remediation. The result is shown in Equation 2:

$$C(x,0,t^*) = C_o \exp\{-(NAC)x\}\left\{ erf\left[\frac{Y}{4(\alpha_y x)^{0.5}}\right]\right\}$$

$$-\frac{\Delta C_o}{2}\left(\begin{array}{l} \exp\left\{\left(\frac{x}{2\alpha_x}\right)\left[1-\left(1+\frac{4\lambda\alpha_x}{v_x}\right)^{0.5}\right]\right\} erfc\left[\frac{x - v_c t^*(1+4\lambda\alpha_x / v_x)^{0.5}}{2\sqrt{\alpha_x v_c t^*}}\right] \\ + \exp\left\{\left(\frac{x}{2\alpha_x}\right)\left[1+\left(1+\frac{4\lambda\alpha_x}{v_x}\right)^{0.5}\right]\right\} erfc\left[\frac{x + v_c t^*(1+4\lambda\alpha_x / v_x)^{0.5}}{2\sqrt{\alpha_x v_c t^*}}\right] \end{array}\right)$$

$$\left\{ erf\left[\frac{Y}{4(\alpha_y x)^{0.5}}\right]\right\} \qquad \text{Eq. 2}$$

Where Y is the width of the source region (length), α_x and α_y are the dispersivities (length) in the x and y direction respectively, t* is the time since the source remediation, and NAC is the natural attenuation capacity.

$$NAC = \frac{-v_x + \sqrt{v_x^2 + 4D_x\lambda}}{2D_x} \qquad \text{Eq. 3}$$

Once steady state is reached after the source reduction, we can use Equation 2 to solve for the needed reduction in source concentration ΔC that meets the MCL at the PoC. Thus, we also need to introduce the following equation in Equation 4 for x = L, the target point of compliance along the centerline of the plume:

$$C(L,0) = C_o^{\mathrm{Rem}} f(L) = MCL \qquad \text{Eq. 4}$$

$$\text{Where} \quad f(L) = \exp\{-(NAC)L\}\left\{erf\left[\frac{Y}{4(\alpha_y L)^{0.5}}\right]\right\} \text{ and}$$

C_0^{Rem} is the remediated source concentration.

Solving this equation for ΔC_0, that is, the change in contaminant at the source, we have:

$$\Delta C_o = C_o - (MCL) f(L)^{-1} \qquad \text{Eq. 5}$$

Thus, we now have an equation for the distance of compliance (represented as x = L in the above two equations) for a target MCL. That is, for a given distance of separation, we can now calculate the necessary reduction in contaminant to comply with the MCL.

Once the source reduction has been solved for, we next need to calculate the ToS, that is, the time it will take for the plume to reach its new steady-state at the PoC. Solving equation 1 for the time component yields the equation presented in equation 6:

$$t_s = \frac{\left(2\beta_1 + Z^2\beta_2^2\right) + \sqrt{\left(2\beta_1 + Z^2\beta_2^2\right)^2 - 4\beta_1^2}}{2\beta_1^2}\left(\frac{L}{v_c}\right) \qquad \text{Eq. 6}$$

$$\text{Where} \quad \beta_1 = \sqrt{1 + \frac{4\lambda\left(L/v_c\right)}{R}\frac{\alpha_x}{L}}, \quad \beta_2 = \sqrt{4\frac{\alpha_x}{L}}$$

Z is usually taken to be approximately -1.8. Thus, we now have the fundamental underpinnings of the model, the ability to calculate both the time of stabilization for a given plume, t_s, and the necessary contaminant source reduction, ΔC_0, to meet the MCL along the centerline at a specific distance from the contaminant source, the PoC. With this, we can simulate any given plume with the given data, and solve it with for our constraints in time and space. This model development is more fully described in Mendez (2008).

The second element of the model is incorporating the inherent variability within a system, and the uncertainty for the data used as inputs. To deal with these aspects, we implement a second order Monte Carlo framework. We first make an assumption about the uncertain parameters. These decisions will vary by site, but for this example the decay rate and the original source concentration were treated as uncertain. (See Table 1 below for a complete description of each variable type and its corresponding distribution.)

Site Example

To illustrate the process of a second order Monte Carlo, the Old Camden County Landfill in Georgia was selected. The site and ground water remediation has been described in Chapelle *et al.* (2005) and Mendez (2008). Unregulated tetrachloroethene (PCE) was disposed at the site, and a plume of chlorinate ethylene compounds resulting from microbial degradation of the PCE resulted, as shown in Figure 2. The plume developed in a permeable sand layer of the surficial aquifer located 10-13 m below land surface. When first discovered, the plume was approximately 200 m long and extended in the northwest direction.

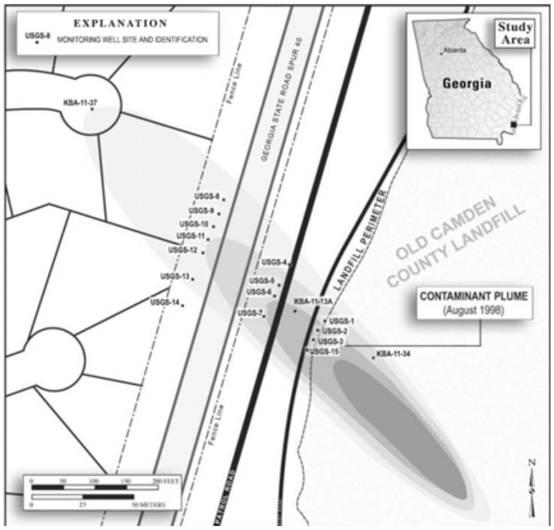


Figure 2. Old Camden County Landfill and Resultant Total Chlorinated Ethene plume. From USGS 2003.

The property boundary was 49 m from the region of highest concentration, near Well KBA-11-13A. This location served as the point of compliance. Other data used for the model are given in Table 1. Two parameters were treated as uncertain: the contaminant decay rate and the original source concentration. For both variable and uncertain parameters, the distributions were chosen to approximately match field data. However, the goal is to illustrate the integration of 2nd order Monte Carlo models and site remediation requirements, so these parameter values should be thought of as illustrative rather than exact site-specific values.

Table 1. Input Parameter Values and Distributions Used for Groundwater Model

Parameter	Classification	Distribution & Range	Comment	Units
Point of Compliance	Defined by User	Fixed – 49 m	Distance from the source to the PoC	Meters along x axis
Source Width	Defined by User	Fixed – 20 m	The width of the source	Meters along y axis
Maximum Contaminant Level	Defined by User	Fixed – 5 µg/L	MCL –Concentration to be met at PoC	µg/L
Groundwater Velocity	Variable	Lognormal, mean = -1.25 StdDev = 0.2	Velocity of groundwater from source to PoC	m/s
Retardation Factor	Variable	Uniform, Min = 1.86 Max = 2.90	Retardation factor for contaminant velocity compared to groundwater velocity	Dimensionless
Dispersivity in x	Variable	Normal, Mean = 7 StdDev = 1	Contaminant dispersivity in the x direction	m^2/s
Ratio of Dispersivities	Variable	Uniform, Min = 0.04 Max = 0.06	Ratio of dispersivities in the y to x directions	Dimensionless
Decay Factor Mean	Uncertain	Normal, Mean = 0.0039 StdDev = 0.00039	Mean of contaminant decay rate distribution	1/day
Decay Factor Standard Deviation	Uncertain	Uniform, Min = 0.08 Max = 0.12	Standard deviation of contaminant decay rate distribution	1/day
Decay Factor Probability Distribution	Uncertain	Lognormal, using above parameters	Distribution for decay factor in variable runs	1/day
Source Contaminant Mean	Uncertain	Normal, Mean = 6200 StdDev = 620	Mean of contaminant concentration distribution at source	µg/L
Source Contaminant Standard Deviation	Uncertain	Uniform, Min = 500 Max = 1000	Standard deviation of contaminant concentration distribution at source	µg/L
Source concentration probability distribution	Uncertain	Normal, using above parameters	Distribution for source concentration in variable runs	µg/L

Two thousand uncertainty iterations of one million variability runs each were modeled for both TOS and for the required source concentration after remediation.

Software Used

The model is written in R version 2.9.1 (R Core Development Team 2007). Each run is based on 2000 uncertainty iterations and 1,000,000 variability iterations implying a total of 2 billion different simulated plumes. For each uncertainty iteration, the model stores the 101 quantiles from 0 to 100. This is for ease of analysis, as it breaks down all the data from the variable runs into distinct percentiles, allowing the end user to merely specify what level of confidence they require, and select that subset of the data. Run times were on the order of 2 hours for a 3 GHz Intel Core 2 Duo desktop computer.

RESULTS

Source Contaminant Reduction

The first result of interest is the target amount of contaminant reduction at the source to meet the MCL at the PoC. Figure 3 illustrates three different histograms, each for different percentiles of the uncertainty distributions.

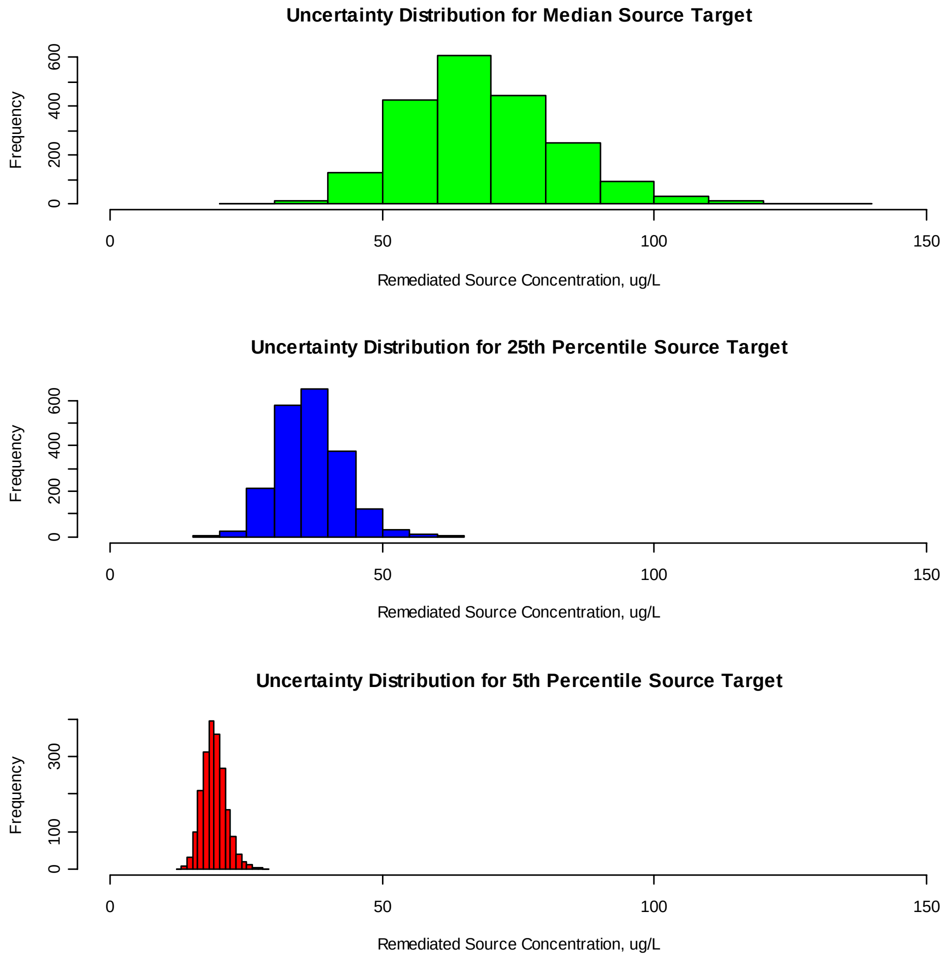


Figure 3. Histograms of contaminant reduction across the different uncertainty runs. Different graphs represent percentiles of the uncertainty distributions.

What is interesting to note is the rough order of the results. While the 5th percentile is obviously lower than that of the 25th and median, it is not significantly so. In fact, there is less than a full order of magnitude between them. The median of the median distribution was calculated to be 66 μg/L, and the median of the 25% and 5% quantiles 36 and 19 μg/L respectively. Note that higher margins of safety imply using the lower quantiles, *i.e.*, the left portion of the concentration distribution where the required concentrations are lower.

Especially in terms of the original quantity of contaminant (mean of 6200 μg/L), the target quantities are of the same order. Thus, the confidence that the MCL is met at the PoC can be greatly increased with relatively small further decreases in the source concentration.

This is of particular import to regulatory authorities, as it means that, should this property hold to be consistent across multiple plume structures, regulations can be strict even in the face of large amounts of uncertainty, as the additional cost in the reduction could be relatively minimal relative to the amount of contaminant reduction that is required anyway. Thus, regulators should be at least willing and preferably proactive in setting tight regulations to meet their specified goals, rather than err on the side of caution as not to burden a party or industry guilty of creating a source contaminant plume.

Time of Stabilization

The second area of interest for this paper was the time of stabilization to reach the new steady state. The results of this data are outlined in Figure 4.

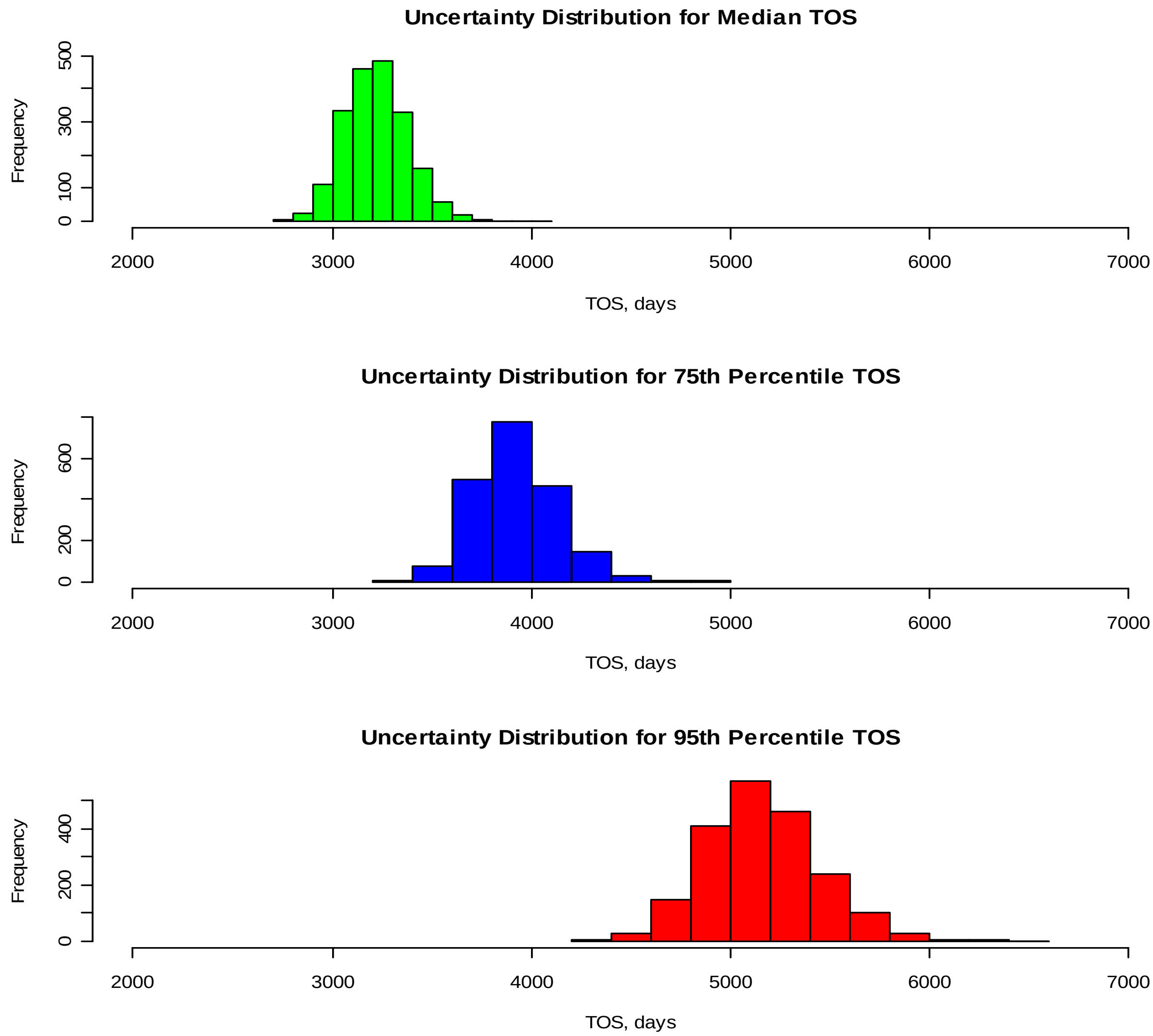


Figure 4. Histograms of the Time of Stabilization across the uncertainty runs. Different graphs represent different percentiles of the uncertainty distributions.

The median of the median distribution was calculated to be 3200 days, but even for the median the ToS ranged from approximately 2900 to 3600 days. For higher margins of safety, *e.g.*, the distributions for the 75% and 95% quantiles, the ToS was longer. The median TOS for the 75% and 95% distributions were 3900 and 5100 days respectively.

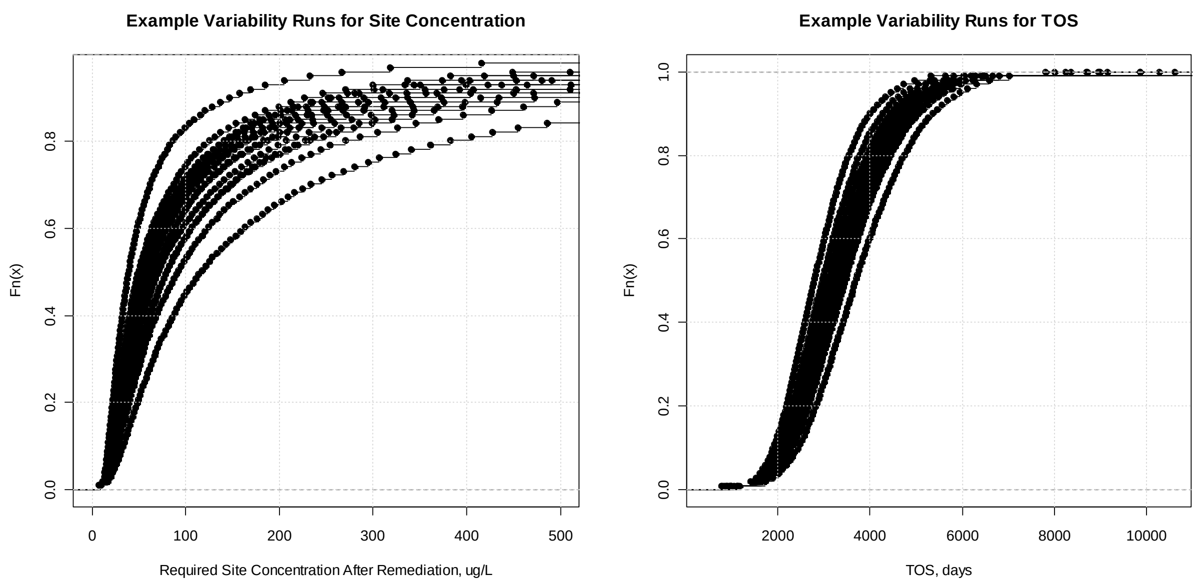
Again, we see that there is relatively little variation between the different levels of confidence, roughly an order of two between them. This suggests that, for the specific plume in the model, there was relatively consistent behavior across both the uncertainty and variability iterations, such that neither of them created a particularly wide range. Note that these results are and always will be plume specific, and the model must be rerun with different parameters to make judgments about any other plumes.

However, there is also cause for concern, in that the stabilization time is relatively long - almost 8 years between when the plume reaches its steady state from the initial source reduction.

Uncertainty vs. Variability

An important element of risk analysis is determining the critical parameters that dominate within the model. As applied to this model, the priority was to ascertain whether the variable sets of parameters (that is, in intrinsic, irreducible heterogeneity of the system) or the uncertain parameters (that which reflects our lack of knowledge of the system) dominate. The answer to this would indicate the utility gained by better studying of the system, and thus having more accurate data. A sampling of 15 different uncertainty runs for ToS and contaminant reduction are outlined in Figures 5 and 6.

A word on reading the graphs: The following two figures will illustrate the 100 quantiles of source remediation for 10 different uncertainty runs. Thus, each individual line represents a single uncertainty run, and the variation within that line represents the influence of variability. The impact of uncertainty is measured by looking at the difference between starting and ending points. If uncertainty has a dominating influence, the lines will begin and end at very different points on the graph.



Figures 5 and 6 (left and right, respectively). Several sample uncertainty runs, illustrating the difference in variability for both the source remediation and time of stabilization.

From this, we can see that there is little impact from uncertainty (all of the runs start right around the same level). Variability appears to have a larger impact upon the system, suggesting that uncertainty is not a significant concern when attempting to reduce groundwater contamination. This is evidenced by the significant differences in the slopes of each line. While they all begin around the same area, the slope and curve of each line is significantly different, indicating that the inherent variability of the system may be a problem in source remediation.

The other element in which uncertainty and variability could manifest would be in determining the time of stabilization. Figure 6 illustrates the same concept as Figure 5, except with ToS rather than source remediation as the variable.

In this case, we see less of an impact due to the variable elements (that is, the lines are much steeper, implying that variability has less of an influence on the results). However, uncertainty also appears to have little impact (all of the distribution lines are in nearly the same place). The conclusion to be drawn here is that the time of stabilization appears to be intrinsic to parameters in the plume not included in either variability or uncertainty, though their impact exists. This may be of some use when attempting to meet a contaminant level within a certain timeframe, as it to be a relatively simple calculation for a plume.

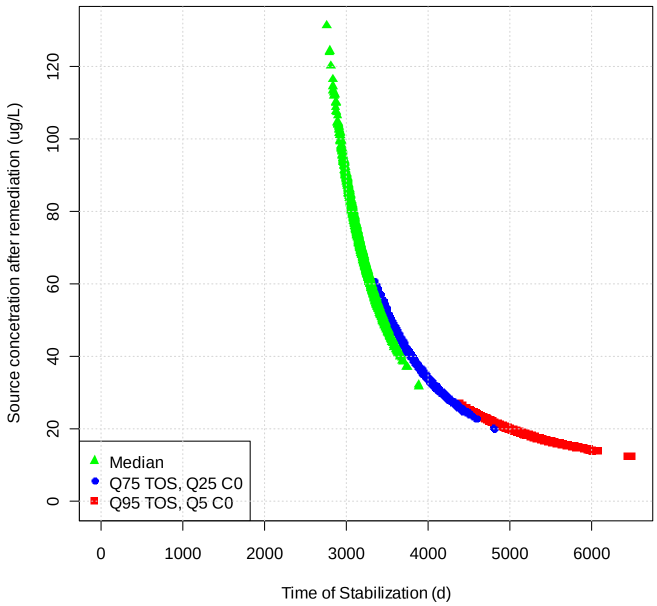


Figure 7. Tradeoffs between ToS and Target Site Contamination.

Lastly, it is of some interest to compare the source remediation with the time of stabilization, which is outlined in Figure 7. The median required source concentration has a very broad range, but a fairly narrow ToS. As the required safety factor increases, the concentrations drop to about 20 μg/L with a fairly narrow range, while the ToS becomes much broader. This outlines the fact that, despite the best efforts at source remediation, the quantity of contaminant already in the plume has a significant impact on the overall contaminant level.

CONCLUSIONS

Second order Monte Carlo models allow for the formal distinction between variability and uncertainty, and as such allows for better informed decision making, in particular it aids in assessing if additional data to reduce variability would be helpful. The approach can be used for any level of model complexity, from simple analytical screening models to complex dynamic multidimensional numerical models.

The only significant disadvantage of this approach is the training required for risk managers to evaluate and use such model results. The models are slightly more data intensive than traditional Monte Carlo models, and can require substantially longer computer run times even for simple analytical models. This simple analytical model analysis required about 2 hours of run time. In practice, parallel processing is needed. Because multicore desktop computers are common, and many computer languages now incorporate parallel processing capabilities, this is not a serious limitation.

With regard to the results of the model, we can see that there are significant gains from modeling prior to engaging in source reduction to establish target levels of contaminant. The model outlines clear numerical targets for a given plume to any level of confidence. Additionally, we can see that, for minimal additional reduction (given the original level of contamination), there are significant gains to be had in the level of confidence. Regulators should take advantage of the additional computing power now available to model and enhance regulations for source contaminant reduction.

ACKNOWLEDGEMENTS

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MODELING FRAMEWORK FOR BALANCING WATER SUPPLY, WATER QUALITY, AND ENVIRONMENTAL OBJECTIVES

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KEY WORDS: water resources modeling, optimization, water quality, long-term planning, system reliability

ABSTRACT

This presentation will describe an innovative modeling framework for use in developing solutions to complex, multi-objective water supply planning problems. The reservoir system model (OASIS, HydroLogics, Inc.) is a robust platform that allows managers and operators to simulate the routing of water through a reservoir system and efficiently run "what if" scenarios to examine how operating decisions and system changes could impact future system status. Applications include long-term infrastructure planning, short-term decision-making, climate change impacts analysis, drought reliability planning, and enhancing stakeholder negotiations.

An important aspect of the OASIS system model is the capability to link to other models, including reservoir water quality models. In one application, an OASIS model for the New York City water supply system was linked with 2-D temperature/turbidity models for key reservoirs in order to evaluate the potential water quality benefits and water supply impacts of a range of operational and infrastructure alternatives for controlling turbidity transport within the system. The linked tool was used to evaluate turbidity control performance under a wide range of environmental forcing conditions, providing a robust analysis of long-term performance while accounting for the dynamic interaction between how a reservoir is operated and the resulting water quality available for withdrawal. In this case, the linked water supply and water quality model will be further upgraded to develop a near real-time operations support tool that will assist operators in making daily and long-term decisions that seek to balance water supply reliability, water quality objectives, and regulatory requirements.

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USING PROBABILISTIC AND PROCESS-BASED MODELS TO CHARACTERIZE WATER FLOWS IN VIRGINIA STREAMS AND THE POTENTIAL INFLUENCES OF CLIMATE CHANGE.

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KEY WORDS: hydrology, 1Q30, 7Q10, probabilistic, process-based, modeling, HSPF

ABSTRACT

Characterizing the magnitude, frequency, and duration of water flows is essential to water supply planning and management of water resources. Accurate prediction of these flows is important to management of adequate flow for both off and on-stream beneficial uses. An understanding of the potential influences of climate change on water flows is critical to anticipating and planning for water needs across the Commonwealth.

The U.S. Geological Survey (USGS) and the Virginia Department of Environmental Quality (VADEQ) are combining the predictive abilities of a process-based model, with the correlative ability of probabilistic models. The probabilistic models include functions describing flow regimes at gaged stations, and equations to predict water flows using basin characteristics. These models will be combined with the Chesapeake Bay Program's Phase 5 watershed hydrology model for use in predicting the impacts of climate change in both gaged and ungaged basins.

Process-based models are especially valuable for evaluating the effects of varying climatic conditions, however, they require long-term flow records for calibration, and involve a lumping of physical parameters which homogenize the flow regime in smaller basins where land form and subsurface features may control flows. Probabilistic models are effective at utilizing small, discontinuous flow records in conjunction with continuous flow records to represent the often non-linear relationships amongst flows within a single, non-homogeneous region.

By combining these two types of models, we will use the outputs of the process based models as inputs to the probabilistic models, gaining a greater understanding of the full spectrum of effects that may occur when future meteorology interacts with physiography.

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Back to Table of Contents

I-C Connecting Nutrient Cycling and Water Quality (Part 1)

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ASSESSMENT OF NITROGEN RETENTION IN A TIDAL FRESHWATER STREAM FOLLOWING RESTORATION

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KEY WORDS: nutrients, nitrogen, stream, wetland

ABSTRACT

Nutrient retention in aquatic ecosystems is governed by the interplay between physical processes that control the throughput of water and materials (*i.e*., water residence time), and by biological processes that govern transformation and uptake (*e.g*., microbial denitrification). A partial breach of the dam located on Kimages Creek (VA) re-established its' historical (pre-1920) connection to the James River and provided a well-defined channel to gauge tidal exchange. Tidal volumes and solute concentrations were used to assess retention within the restored stream-wetland complex. Retention was determined from a comparison of predicted and observed outflow concentrations where predicted values were derived from discharge and concentration of the inflow and observed values were measured outflow concentrations. The mixing model accurately predicted outflow concentrations of conservative solutes (Cl) to within 10%. For dissolved inorganic nitrogen (DIN), data suggest that the tidal segment was a net source during winter months but a sink in spring and fall. Rates of N retention in the newly formed wetland were comparable to values reported for long-established sites. Retention (as a proportion of inputs) was governed in part by seasonally changing nitrogen concentrations in the James River as well as seasonal variation in river stage. A hydrologic-mass flux model is being constructed

to assess the net movement of N between the wetland and river to take into account divergent seasonal patterns in these two systems. The model is being developed to quantify rates of N removal during transport from catchments to the estuarine environment.

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WASTEWATER TREATMENT DERIVED EFFLUENT ORGANIC NITROGEN: BIOAVAILABILITY IN THE ENVIRONMENT

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KEY WORDS: organic nitrogen, wastewater treatment plant effluent

ABSTRACT

Coastal eutrophication resulting from point and non-point source nutrient loading continues to be a problem despite years of targeted efforts to reduce nutrient loads to the environment. As loads of total N are reduced in response to more stringent regulations, and because dissolved inorganic nitrogen (DIN) is easier to remove in conventional wastewater treatment than dissolved organic nitrogen (DON), the proportion of DON released to the environment in treated wastewater is likely to increase as total N loads are further reduced. Although studies have examined the bioavailability of DON from a variety of sources, few have targeted the bioavailability of

wastewater-derived DON that enters rivers and estuaries. To investigate the effects that effluent-derived DON (EON) may have on natural waters as it is transported and altered by both abiotic and biotic processes along a salinity gradient, we conducted several bioassay experiments wherein we amended natural waters collected from lower part of the Chesapeake Bay watershed with concentrated EON. Results from bioassay experiments suggest that DIN is released from organic compounds as a result of salt effects. An additional pool of EON appears to be bioavailable and is translated into growth of resident microbes (including phytoplankton). Another part of the EON pool appears to be transformed during incubations while some chemical structures appear to be recalcitrant in the environment. It is important that we understand the lability and impact of EON in the environment as the nutrient landscape changes and N loads become increasingly dominated by DON compounds.

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BIOMANIPULATION EFFECTS ON NUTRIENT RELEASE BY GIZZARD SHAD IN CENTRAL FLORIDA LAKES.

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KEY WORDS: *Dorosoma cepedianum,* biomanipulation, phosphorus, excretion

ABSTRACT

Although fish removals have been conducted in a number of systems, it is less well understood how biomanipulations impact lake nutrient cycles. To better understand the nutrient effects of fish removals, we measured nutrient excretion rates of gizzard shad from four central Florida lakes (2005-2006) and combined these measures with gillnet harvest data (2002-2007) to estimate system-wide effects. We also examined the effects of different mesh sizes on length-frequency distributions of the catch and subsequent effects on nutrient cycling.

Regressions were developed to predict phosphorus excretion in lakes where extensive fish removals were conducted. The amount of phosphorus cycling prevented per kg of fish removed was somewhat higher in Lakes Apopka and Griffin than in Lake Dora, due to the harvest of larger fish in Lake Dora, which have lower mass-specific excretion rates. Phosphorus effects of

harvest in these systems ranged from 3.6-13.0 x 10^3 kg P $year^{-1}$ for Lake Apopka, 1.5-1.9 x 10^3 kg P $year^{-1}$ for Lake Dora and 2.1-8.9 x 10^3 kg P $year^{-1}$ for Lake Griffin. The per hectare effect on phosphorus cycling ranged from 0.29-2.35 kg P ha^{-1} yr^{-1}. Smaller mesh sizes typically harvested smaller size classes of fish, indicating that 4" stretch mesh nets leave a substantial portion of the biomass unharvested. In Lake Apopka, the shift from 10.2 cm stretch mesh nets (2002-2006) to 8.9 cm stretch mesh nets (2007) increased the nutrient based effect by 9.8%, presuming an equivalent harvest.

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NITRATE LEACHING IN NO-TILLAGE VERSUS TILLED FIELDS

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KEY WORDS: PCAPS, leaching, nitrate, no-tillage

ABSTRACT

In order to compare nitrate (NO_3-N) leaching losses between tillage treatments, four long-term no-tillage sites paired with four conventional tillage (rotational tillage) sites across four soil series (Bojac, Altavista, Emporia, and Slagle) are being monitored for NO_3-N leaching losses. Sites are on two commercial farms. Three passive capillary samplers (PCAPS) were installed at each site. Leachate volume is measured and analyzed for NO_3-N. In all sites the crop rotation has been conducted with winter small grain-double crop soybean in one year and corn in the other year. Volume of water leached through soil profiles was the same between tillage treatments, even when analyzing the data for a specific phase of the crop rotation in the field. Volume of water leached was significantly different only when comparing between phases of the crop rotation and summarizing leaching data from both tillage managements together. The highest volume leached was found during the fallow period, followed by small grains and corn, and then soybean. Tillage had no effect on NO_3-N leaching losses when analyzed for the whole period of study or within each phase of the rotation as well. Amounts of NO_3-N leaching losses were significantly different between the phases of the crop rotation. Highest amounts of NO_3-N leaching losses were found during the fallow and corn phases. Soybean showed the lowest amount of NO3-N leaching losses. These results indicate the need for solutions to better manage nitrogen during the fallow and corn phases of the crop rotation to minimize NO_3-N leaching losses.

INTRODUCTION

No-till (NT) management has been implemented on a significant portion of the USA and South America (mainly Brazil and Argentina) croplands (Agrosoft Brasil 2008). Some of the reasons for implementation of NT are that it generates benefits to crop production systems by improving soil fertility, soil structure, water holding capacity, reducing erosion, and reducing cost of production due to lower machinery and labor costs. In addition, the improvement of technologies such as weed and pest control and equipment has made the transition from conventional till (CT) to NT easer. Most of the soil-associated benefits of NT are obtained due to increased levels of soil organic matter (SOM) with long-term continuous NT. The increment of SOM levels is thus one of the major benefits of adopting NT systems since it improves soil quality indices (*e.g.*, soil structure) and may increase yield potential. Farmer observations and scientific studies (Daniel *et al*. 1999, Diza-Zorita *et al*. 2002) have reported that yields obtained with continuous NT systems are similar or even higher than those obtained with CT systems.

No-till systems usually have increased macroporosity compared to CT systems on the same soil. This feature suggests that a preferential water flow (infiltration) may occur in NT compared to CT, which may be accompanied by an increase in NO3-N leaching to the ground water (Shipitalo *et al*. 2000, Zhu *et al*. 2003). In addition, SOM is around 5% N (Stevenson 1994), with this organic form of N representing about 95% of total N in surface soils (Havlin *et al*. 2005). Thus, any increase of SOM levels by adopting NT can significantly change the soil N cycle. This means that NO_3-N may be increased in NT due to higher levels of organic N in surface soil. Therefore, NO_3-N coming from both manufactured fertilizers and/or SOM may be subject to increased leaching losses due to NT implementation. As a result, the possible increase in NO_3-N leaching losses under NT systems has become a concern for groundwater quality.

The Passive Capillary Sampler (PCAPS) is a device being used to obtain pore-water and solute samples from saturated and unsaturated soils in groundwater quality monitoring (Holder *et al*. 1991, Knutson *et al*. 1993). The PCAPS are installed *in situ* with minimal disturbance to the native flow regime and passively use the natural capillarity developed by its fiberglass wick, rather than applied potentials, to draw representative pore-water samples from soils (Boll *et al*. 1992, Knutson *et al*. 1993). The wetted fiberglass wick acts as a hanging water column, making it possible to draw samples from saturated and unsaturated soil without external application of suction. PCAPS can collect both macropore flow and soil matrix water held at potential between 1 to -6 kPa (Holder *et al*. 1991). These lysimeters have given superior results compared to existing samplers such as suction cup and pan lysimeters in terms of mass balance of water and chemical loading. Zhu *et al*. (2002) found that the average annual leachate volumes collected by PCAPS over 5 years were 2.7 times greater than those collected by pan lysimeters. On average, pan lysimeters collected about 40% of the percolation water and PCAPS collected approximately 100%.

The objective of this study is to quantify the potential leaching losses of NO_3-N from crop production soils of the Coastal Plain of Virginia and determine if leaching differs between no-till versus fields managed with tillage.

MATERIAL AND METHODS

Four long-term no-till sites paired with four conventional tillage sites across four soil series were selected for N leachate monitoring. All sites are on commercial farms. Two of the paired sites are on a farm located in New Kent County and two are on a farm in King William County. The soil series at the two paired sites on the farm in New Kent County are Bojac loamy sand (Coarse-loamy, mixed, semiactive, thermic Typic Hapludults) and Altavista sandy loam (Fine-loamy, mixed semiactive, thermic Aquic Hapludults) and on the farm in King William County are Emporia sandy loam (Fine-loamy, siliceous, subactive, thermic Typic Hapludults) and Slagle sandy loam (Fine-loamy, siliceous, subactive, thermic Aquic Hapludults). Tillage treatments within the same soil series are located within ~300 m of each other.

For the PCAPS installation, a vertical shaft 1.2 m in diameter and 1.8 m deep was excavated with a hydraulic auger and lined with corrugated polyethylene pipe. From the vertical shaft, a horizontal access shaft 60 cm in diameter and 100 cm deep was hand excavated and lined with 60 cm diameter pipe. The PCAPS were installed in the soil profile at the end of the tunnel 110 cm below the surface. The PCAPS design was adapted from that of Holder *et al*. (1991) and Zhu *et al*. (2002). A 30 cm x 30 cm x 1.9 cm thick plexiglass plate with a 3.8 cm diameter hole in the center was attached to another 30 cm x 30 cm x 0.95 cm thick plexiglass support platform with 15 cm turnbuckles at each corner. Fiberglass wicks were threaded through the center hole in the plexiglass plate and the individual strands unbraided and evenly spread over the surface. Between the wick support structure and the collection vessel, the wick was enclosed in an opaque, flexible drainage hose to prevent evaporation and exclude light. Collection vessels were constructed from 10 cm diameter PVC pipe extending the length of the horizontal access shaft with a PVC valve attached to the end for sample collection. The PVC collection vessel has a volume of ~10 L allowing for the collection of up to ~10 cm of leachate. Three PCAPS were installed at each site by the end of September 2005.

No-till and conventionally tilled sites within the same farm have been managed by the same producer. This will ensure that, with the exception of tillage, sites within the same soil series are managed the same. Standard farming practices, including fertilization, have been used at all eight sites. The crop rotation at all sites is corn (*Zea mays*) - small grain - double crop soybean (*Glysine max*). Small grain grown in the rotation is either wheat (*Triticum aestivum*) or barley (*Hordeum vulgare*). Seasonal crop rotation and yield potential of each soil series is summarized in tables 2 and 3. The tillage history of each location is summarized in Table 1.

Table 1. Tillage history of each site used in the study.

		Last year tillage was used prior to planting		
Soil Series	**Treatment**	Corn	Small Grain	Soybean
Bojac loamy sand	No-till	1982	1996	1974
	Tillage	1982	2007	1974
Altavista sandy loam	No-till	1982	1996	1974
	Tillage	1982	2007	1974
Emporia sandy loam	No-till	1976	1992	1975
	Tillage	1976	2008	1975
Slagle sandy loam	No-till	1976	1992	1975
	Tillage	1976	2008	1975

Leachate sampling began in November 2005 from each PCAPS on a monthly basis or as needed when large rainfall events occur. Samples will be collected until November 2010. The amount of leached is determined volumetrically and a subsample analyzed for NO_3-N concentration with a QuickChem Automated Ion Analyzer (Lachat Instruments). The data are presented on an area basis (kg ha^{-1}). The samples are also analyzed for ammonium (NH_4-N) but these data are not going to be presented here due to its extreme low value (~zero). Rainfall is monitored using a WatchDog data-logging rain gauge located adjacent to each set of PCAPS.

Soil samples are collected annually at the end of the growth season from 0-15 cm depth adjacent to each set of PCAPS and analyzed for pH (soil/ water ratio of 1:1) and Mehlich 1 extractable P, K, Ca, and Mg. In addition, soil cores have been collected annually adjacent to each PCAPS from 0-15 cm depth. Soil cores are separated into 0-2.5, 2.5-7.5, and 7.5-15 cm and analyzed for C and N by dry combustion at 900^{o}C (Vario Max CNS-Analyzer). Crop yield is determined at each location for each crop.

Before statistical analysis, the data was normalized by dividing the volume of water and amount of NO_3-N captured in each phase of the crop rotation per the number of months of the crop rotation phase in the field. Using soil series as the blocking factor and either tillage or crop rotation as the treatment factor, analysis of variance and means separation of the data were performed using the PROC GLM procedure of SAS (SAS Institute 2002). The least significant difference (LSD) procedure, with a probability level of 0.05, was used to determine significant differences between treatment means.

RESULTS AND DISCUSSION

Figure 1 presents summarized precipitation data for the period 11/30/2005 to 7/1/2009. Precipitation in New Kent and King William counties were similarly distributed during this period except for precipitation of 23.4 cm in King William County in 9/5/2006 due to a localized thunderstorm.

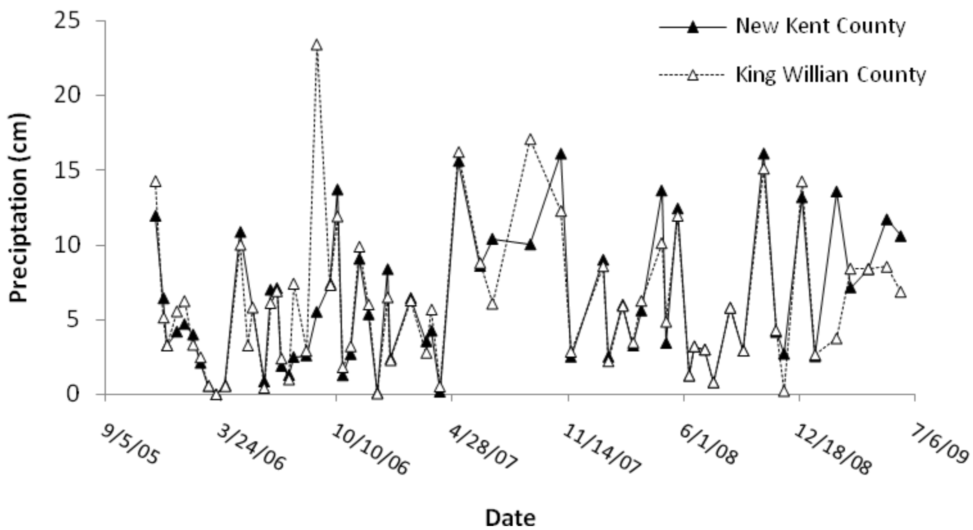

Figure 1. Average precipitation in New Kent and King William Counties field experiments from November 2005 to July 2009

The data analysis shows that the average volume of water leached during the whole period of study did not show any significant difference between tillage treatments (Table 2). Furthermore, the data was analyzed between the different phases of the crop rotation in the field (small grain, soybean, corn, and fallow) to eliminate the potential variability due to these phases of the rotation. This additional approach of analysis did not show any significant difference between tillage treatments for any phase of the rotation (Table 2). The lack of difference between tillage treatments for the volume of water leached found in the present study supports the conclusion of Shipitalo *et al*. (2000) and Zhu *et al*. (2003) that tillage has no major effect on the volume of water percolation.

Table 2. Average volume of water leached through tilled and no-till systems during the whole period of study (November 2005 - July 2009) and under different phases of the crop rotation.

	Conventional Till	No-till
	------------------------------cm month^{-1}------------------------------	
Whole Period	4.3a*	3.2a
Small Grain	3.9a	2.8a
Corn	4.9a	3.5a
Soybean	0.5a	0.7a
Fallow	6.8a	4.9a

* Means in a row with the same letter are not significantly different by LSD test ($P = 0.05$).

Assuming no difference between tillage treatments (data from NT and CT analyzed together without distinction), the data were further analyzed with the phase of the rotation as the treatment factor. The result of this analysis is presented in Figure 2. This analysis approach showed significant differences of volume of water leached between the phases with fallow having the highest volume leached, soybean having the lowest levels, and small grain and corn together in the middle position. Zhu *et al*. (2003) also using PCAPS found that the greater volume of water was leached during the fallow period compared to the growing season in both CT and NT systems. The fallow period shows the highest volume of water leached due to low evaporation (low temperature) and lack of transpiration (no crop in the field) during this period. On the other hand, the lower volume of water leached during the soybean period is justified due to a relative lower precipitation and higher evapotranspiration for these double-crop soybeans that grow during July through October.

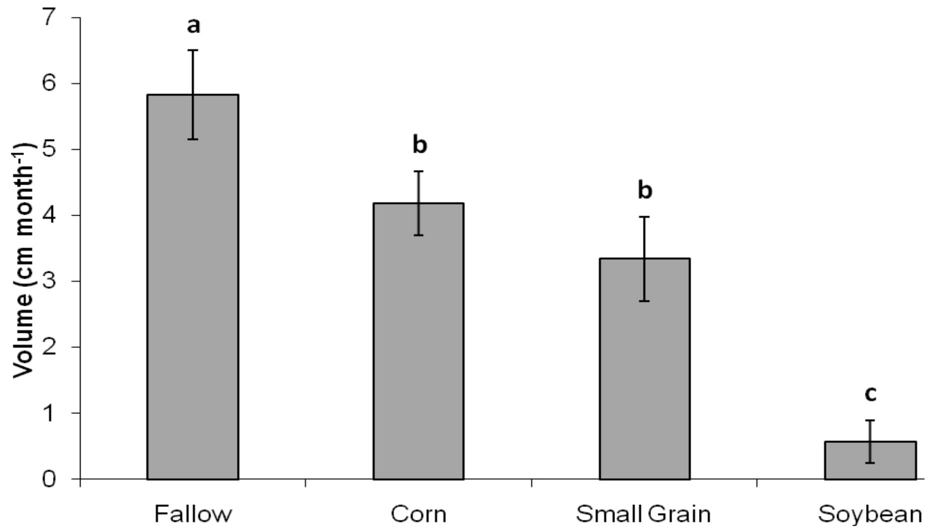

Figure 2. Volume of water leached through soils under different phases of crop rotation from November 2005 to July 2009. Means with the same letter are not significantly different by LSD test (*P* = 0.05). Vertical bars represent standard errors.

Amounts of NO_3-N leaching losses (kg ha^{-1} $month^{-1}$) showed no significant difference between tillage treatments when analyzing the data for the whole period of study, or even within each phase of the crop rotation (Table 3). Zhu *et al*. (2003) had similar results as they found no significant difference in NO_3-N leaching losses (kg ha^{-1}) between NT and CT treatments during 6 years of experiment. Also, these researchers found no significant difference when comparing tillage treatments during each phase of the rotation (corn and soybean).

Significant differences in NO_3-N leaching losses were found when comparing the different phases of the rotations (Figure 3). Here data from NT and CT analyzed together without distinction. Highest amounts of NO_3-N leaching losses occurred during fallow and corn phases, and the lowest losses were observed during the soybean phase. These results are similar to those found for the volume of water leached (Figure 2) since the NO_3-N downward movement in soils is water dependent. In addition, the lowest amounts of NO_3-N leaching losses found for soybean are supported by the fact that no fertilizer N is applied during this phase of the crop rotation. Results like these indicate the potential value of cover crops during the fallow period, and working to better manage fertilizer N during the corn period of the rotation.

Table 3. Average amount of NO_3-N leached through tilled and no-till systems during the whole period of study (November 2005 - July 2009) and under different phases of the crop rotation.

	Conventional Till	No-till
	------------------------ kg NO_3-N ha^{-1} $month^{-1}$---------------------	
Whole Period	4.7a*	3.4a
Small Grain	3.9a	3.0a
Corn	5.9a	4.4a
Soybean	0.2a	0.2a
Fallow	7.2a	4.9a

* Means in a row with the same letter are not significantly different by LSD test (*P* = 0.05).

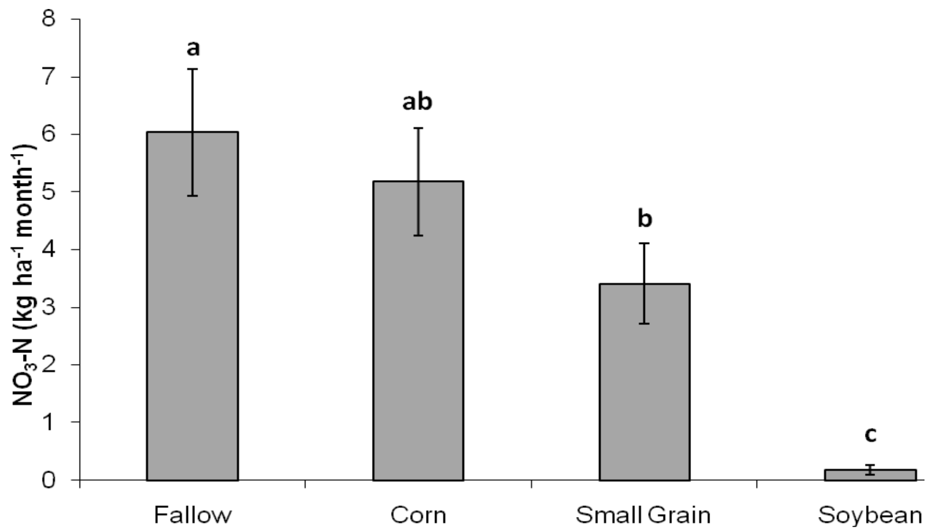

Figure 3. Amount of NO_3-N leached through soils under different phases of crops rotation from November 2005 to July 2009. Means with the same letter are not significantly different by LSD test (*P* = 0.05). Vertical bars represent standard errors.

CONCLUSIONS

The major findings in these data are that no significant differences were measured in leaching losses of NO_3-N between tilled and no-tilled treatments for 3.5 years of a small grain, double-crop soybean, and corn cropping system in 4 major soil series used for crop production in the Virginia Coastal plain. Significant differences for NO_3-N leaching losses are found when comparing between the phases of the crop rotation. The NO_3-N leaching losses range between 0.2 and 6.0 kg ha^{-1} $month^{-1}$ with highest amounts being lost during the fallow and corn phases of the crop rotation, and the lowest during the double-crop soybean phase.

The data show that a cover crop in the field during the fallow phase could be useful to reduce NO_3-N leaching loss since most of the leachate happens during this time due to low evapotranspiration. Also, the great NO_3-N leaching losses during the corn period indicate the need of better N fertilizer management in the Virginia Coastal Plain region.

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Back to Table of Contents

Concurrent Session II

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II-A Assessing Stream Flows in a Changing Climate

♦ ♦ ♦ ♦ ♦

USING FIELD MEASUREMENTS OF VELOCITY TO STUDY EROSION PROCESSES IN A RIVER

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KEY WORDS: erosion, velocity profiles, secondary currents, acoustic Doppler current profiler

ABSTRACT

The spatial distribution of velocity in a river influences both the channel morphology and ecology. Velocity characteristics, specifically secondary currents, in meander bends have been shown to have a strong effect on bank erosion. This study describes the use of field measurements of velocity to study erosion processes. The acoustic Doppler current profiler (ADCP) represents an important new technology for measuring three-dimensional velocity profiles in rivers. While typically used for measuring discharge, time-averaged velocity profiles and turbulence statistics obtained with ADCPs have recently been reported. The fixed-vessel

approach to obtaining velocity time series with an ADCP is reviewed here and data analysis techniques are presented. Some potential uses of ADCP data are discussed and include determination of boundary shear stress and calibration of computational fluid dynamics models. Field measurements from two sites on the lower Roanoke River are used as examples. These measurements were obtained for two different discharges; one close to the mean annual flow and the second during typical flood control operations. The relationship between the velocity characteristics and observed erosion at the sites is discussed.

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INVESTIGATE RELATIONSHIP BETWEEN WATER QUALITY VIOLATIONS AND STREAMFLOW CHANGES

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KEY WORDS: water quality, stream flow, impairment, TMDL.

ABSTRACT

The capacity of the earth's atmosphere to trap solar radiation and increase global temperature has now become the topic of intense concern to agriculture and water resource communities. The belief that global warming will continue is now widely recognized by scientists and policy makers. Precipitation has been found to increase in U.S. by 5 to 10% over the 20th century (Intergovernmental Panel on Climate Change, IPCC 2001a), and is predicted to continue to increase in many regions. Few studies have predicted specific precipitation changes across the U.S. These include 25% increase in the Northeast and 10 to 30% increase in Midwest and Pacific Northwest.

Water quality impairment is predicted to increase under climate changes (IPCC 2001a). Specifically, precipitation is expected to occur more frequently through high intensity rainfall events, causing increased surface runoff and erosion. Sediment and nonpoint source pollutants will be transported into stream and groundwater systems, resulting in deteriorated water quality. Water quality will also be affected in areas receiving less precipitation, as pollutants become more concentrated. Studies have shown that the majority of water quality violations (*i.e.*, bacteria), including extreme violations, are related to extreme runoff events, specifically the high and low flow conditions. Thus, it is essential to understand the impacts of various flow condition changes on water quality impairment, as well as develop mechanisms to address those impacts. The present study investigates the impact of flow conditions on potential changes in maximum value of water quality violation parameter (*i.e.*, bacteria) and discusses these impacts for a few impaired stream segments within Commonwealth of Virginia. How these scenarios might be integrated with water quality improvement plans needs further investigations.

INTRODUCTION

Various scientists and researchers have widely and conclusively determined that global climate change is real and happening world-wide. The intensity and frequency of recent extreme weather conditions such as hurricanes and droughts, and rising temperatures observed globally over the past decade has raised concerns that fundamental climate shift may be occurring in North America and elsewhere (Adams and Peck 2006). Several climatic models have predicted U.S. average annual temperature to rise 5 to 9 degree F over the next 100 years (National Assessment Synthesis Team, NAST 2001). Precipitation which has increased in the U.S. by 5 to 10% over 20th century (IPCC 2001a), is predicted to continue to increase in many regions. A few studies have projected specific precipitation change across the U.S. – 25% increase in Northeast, 10 to 30% increase in the Midwest, 20% increase in the Pacific Northwest, and up to 25% decline in Oklahoma panhandle, north Texas, eastern Colorado and western Kansas (NAST 2000). This study indicates that the potential impact of the assumed climate change scenarios on low flow standards is substantial. A 25% decrease in mean precipitation results in a 63% reduction in design flow (Wayland, Wildermuth and Herricks 2000).

Climate change has the potential to impact practically all aspects of water resource development and management. Five keys water resources issues where impacts could occur more significantly include: ecosystem vulnerability; heavy precipitation and droughts; groundwater quality and quantity; competition for water supplies; and surface water quality (NAST 2001). All of these issues are inter-connected, and significantly affect hydrological behavior of a watershed.

A range of potential effects of global climate change on water resources and agriculture has been suggested – increased surface temperature and evaporation rates, increased global precipitation received as rain (rather than snow), earlier and shorter runoff seasons, and decreased water quality (IPCC 2001b).

Water Quality Impairment

Surface water quality is impacted by climate change through a combination of physical, biochemical and hydrological processes involving changes in precipitation and air temperatures. For example, increased temperature and precipitation may increase and/or decrease streamflow and associated pollutant concentrations and loads. Precipitation is the primary driving force affecting hydrological behavior. *Therefore, surface runoff quantity impacts surface water quality.*

Water quality impairment is also predicted to increase under climate change (Gleick 2000, NAST 2000, IPCC 2001b). Specifically, precipitation is expected to occur more frequently through high-intensity rainfall events, causing increased runoff and erosion. Sediments and pollutants, such as nitrogen and phosphorous, will be transported into streams and groundwater systems, decreasing water quality. Water quality will also be impaired in areas receiving less precipitation, as nutrients and contaminants become more concentrated in low runoff volume (Gleick 2000, IPCC 2001b).

Most of the impaired water bodies within the Commonwealth of Virginia are impaired due to bacteria pollution (fecal coliform and *E. coli*). A water body is considered impaired, or unsuitable to meet its designated use, if bacteria concentration violates the State's water quality standard (235 colony forming units/100 ml). If violations exceed in 10.5% of the samples, then the water body is listed as the impaired water. This study investigates the potential impact of varied hydrological regimes (stream flow) in relation to violation of fecal coliform concentration.

The development of Total Maximum Daily Loads (TMDLs) in the United States is mandated by U.S. Environmental Protection Agency (EPA) rules and guidance (National Research Council 2001). As required by section 303(d) of the Clean Water Act (Kovalic 1987), each state must identify the waters which are not in attainment of water quality standards or not supporting their designated use. All water bodies in which bacteria concentration exceeds more than 10.5% of the samples collected are placed on the impaired water listing. For those impaired waters, each state must establish a TMDL containing the point and nonpoint source loadings which will bring the impaired water body into compliance with water quality standards. For many primary pollutants, such as bacteria, critical loads are computed based on the most conservative values of bacteria concentration, *i.e.*, a single, maximum concentration value.

METHODOLOGY

The Virginia Department of Environmental Quality has primarily developed TMDLs for bacteria and benthic impaired water bodies (http://www.deq.virginia.gov/tmdl/homepage.html). A TMDL development report contains various key elements, such as existing and TMDL allocated pollutant loadings, and reductions required from all point and nonpoint sources to meet water quality standards. Many bacteria TMDL reports have been developed based on load-duration methodology. For these TMDLs, flow-duration curves are developed for the impaired stream. A flow-duration curve is a plot showing the flow magnitude (cubic feet per second, cfs) along the "y" axis and the frequency of daily average stream flow (%) along the "x" axis. The flow duration interval values plotted against the corresponding flow values yielded a log-normal flow duration curve. The curve shows the flow value corresponding to its percentage for which the historic record exceeds. For example, the flow value corresponding to 1% is the stream flow that has been exceeded only 1% of the time of the historic record. Such a curve for Tuckahoe Creek is shown in Figure 1 (Bacteria TMDL for Tuckahoe Creek, Little Tuckahoe Creek, Anderson, Board, Georges and Readers Branches and Deep Run 2004; http://www.deq.virginia.gov/tmdl/apptmdls/jamesrvr/tuckcr.pdf).

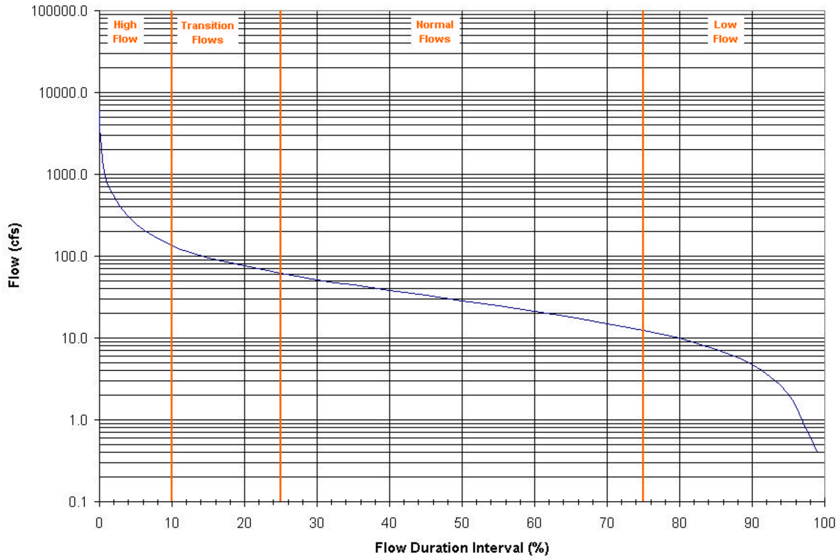

Figure 1. Flow-duration curve for Tuckahoe Creek at Tuckahoe Village, VA.

Based on flow-duration curve, the load-duration curves are developed for existing conditions and also for the condition with maximum exceedance (*i.e.*, condition having maximum load). These two load-duration curves (Figure 2) are then utilized to compute load reductions required to meet bacteria water quality standard (Bacteria TMDL for Tuckahoe Creek, Little Tuckahoe Creek, Anderson, Board, Georges and Readers Branches and Deep Run 2004; http://www.deq.virginia.gov/tmdl/apptmdls/jamesrvr/tuckcr.pdf).

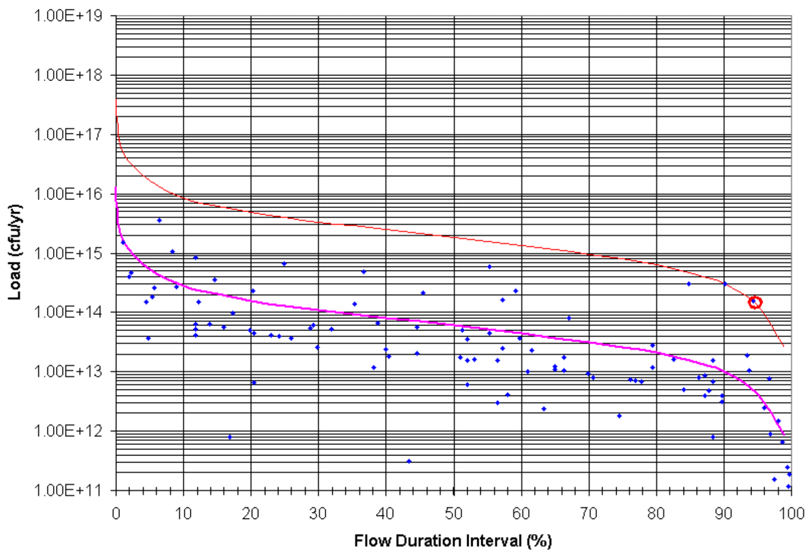

Figure 2. Load duration curve with maximum exceedance curve for Tuckahoe Creek at Tuckahoe Village, VA.

The flow duration curve thus obtained was divided into four sections to help describe the flow conditions. These sections are: “High Flows”, “Transient Flows”, “Normal Flows”, and “Low Flows”. Low flows can be roughly equated to near-drought or drought flows. High flows are near-flood or flood flows. Normal flows are flows under average conditions, and transition flows are, as implied, neither normal nor high flows. Bacteria violation rates were determined for each of the flow conditions. The TMDL development report includes this flow analysis and corresponding bacteria violation rates. The analysis indicates potential effect of flow conditions on bacteria violation rates.

For the purpose of this study, TMDL development reports on a few creeks – Fourmile Creek, White Oak Creek, Piney Run Creek, Flat Creek and Matadequin Creek were reviewed, and the data on flow conditions under which all bacteria violations occurred, including maximum violation rate, were compared.

RESULT AND DISCUSSION

Various TMDLs development studies suggest that with few exceptions, about 60% to 100% of the fecal coliform violations could be related to surface runoff events. This suggests that a large majority of the *E. coli* violations may be caused by nonpoint source runoff events. Additional information may be derived from these studies regarding the nature of the violations in relation to the stream flow conditions under which violations occur. The details of impaired segments, bacteria violation rates, and number of violations under different flow conditions (high, normal and low) are provided in Table 1.

Tuckahoe Creek and its adjoining impaired streams located in Henrico and Goochland Counties have about 30.2 miles listed as impaired segments. Based on data collected for a period from 1992 until 2003, flow analysis presented in the TMDL development report indicated that 100% of the fecal coliform violations could be related to surface runoff events. This suggests that a large majority of the *E. coli* violations may be caused by nonpoint source runoff events. Further, six of the violations occur during high or transitional flow conditions. Seven of the violations occur in normal flow conditions. Eight violations occur in low flow conditions. The study further suggests that maximum violation resulting in 97% *E. coli* load reduction falls under low flow conditions (Table 1).

Fourmile Creek located in Henrico County has about 31 miles listed as impaired segment. Based on data collected for a period from 1994 until 2003, flow analysis included in the TMDL development report indicated that 80% of the fecal coliform violations could be related to surface runoff events. This suggests that a large majority of the *E. coli* violations may be caused by nonpoint source runoff events. Further, four of the violations occur during high or transitional flow, including the maximum violation resulting in the 95% *E. coli* load reduction. Five of the violations occur in normal flows, and six violations occur in low flow conditions (http://www.deq.virginia.gov/tmdl/apptmdls/jamesrvr/4mileck.pdf).

White Oak Creek located in Henrico County has about 6.51 miles listed as impaired segment. Based on data collected for a period from 1996 until 2003, flow analysis presented in the TMDL report indicated that 86% of the fecal coliform violations could be related to surface runoff events. This suggests that a large majority of the *E. coli* violations may be caused by nonpoint source runoff events. Further, nine of the violations occur during high or transitional flows. Sixteen of the violations occur in normal flow. Nine violations occur in low flow, including the maximum violation resulting in the 97% *E. coli* reduction (http://www.deq.virginia.gov/tmdl/apptmdls/jamesrvr/whiteoak.pdf).

Piney Run Creek located in Loudoun County has about 3.52 miles listed as impaired segment. Based on data collected for a period from 1992 until 2003, flow analysis presented in the TMDL development report indicated that 67% of violations could be related to surface runoff events. This suggests that a large majority of the *E. coli* violations were caused by nonpoint source runoff events. Further, six of the exceedances occurred during high or transitional flows, including the violation requiring the highest load reduction. Eleven exceedances occurred during normal flows. Only one exceedance occurred in the range of low flows (http://www.deq.virginia.gov/tmdl/apptmdls/potrvr/pineyrun.pdf).

Flat Creek located in Mecklenburg County has about 8.95 miles of impaired segment. Based on data collected for a period from 1991 until 2003, flow analysis provided in the TMDL development report indicated that 59% of violations could be related to surface runoff events. Further, four of the exceedances occurred during high or transitional flows. Twenty-six exceedances, including the violation requiring the highest load reduction, occurred during normal flows. Ten exceedances occurred during low flow conditions (http://www.deq.virginia.gov/tmdl/apptmdls/roankrvr/flatfc.pdf).

Matadequin Creek located in Hanover County has about 5.01 miles listed as impaired segment. Based on data collected for a period from 1991 until 2003, flow analysis presented in TMDL report indicated that 87% of the fecal coliform violations could be related to surface runoff events, suggesting that a large majority of the *E. coli* violations were caused by nonpoint source runoff events. Further, seven of the violations occur during high or transitional flows. Twelve of the violations occur in normal flows, and four violations, including the maximum violation resulting in the 97% *E. coli* load reduction, occurred in low flow conditions (http://www.deq.virginia.gov/tmdl/apptmdls/yorkrvr/matadeq.pdf).

TMDLs for all impaired stream segments are developed for the worst case scenarios, in other words, these are developed for the maximum value violating water quality standard. This maximum violating value leads to reduction in nonpoint source loadings to their maximum extent possible (mostly 95 to 100%). The requirement of maximum reduction leads to a large scale implementation of control measures to achieve desired load reductions and to attain water quality standard. This ultimately drives cost of the implementation projects high.

The changes in precipitation due to climate changes will affect runoff patterns, and may also affect occurrence of maximum bacteria concentration value based on which TMDLs are developed. It is not yet clear what specific impact it would have. There may be three distinct possibilities: (1) The occurrence of maximum violation values remains the same as present - under low and high flow conditions; (2) The occurrence of maximum violation value currently falling under low flow conditions might shift towards the normal flow condition. Due to dilution effects, this shift would result into reduced maximum values, and may not require extensive implementation of control measures; and (3) the occurrence of maximum violation value currently falling under high flow conditions might shift towards normal flow. This scenario would result in reduced maximum value and/or occurrence of higher violating values more frequently, resulting in higher violation rates. Many water bodies not showing any impairment now may start showing higher pollutant loading in the stream, leading to higher number of impaired water bodies. In either case, change in global climate will impact water quality impairments and also the methodology based on which TMDLs are developed.

In addition, the TMDL development time is comparable to the near-future climate change time period. Therefore, in the time lag between identifying a water as impaired and TMDL development and implementation, climate change could alter the meteorological assumptions employed in the TMDL models. However, TMDL development and implementation are costly and time-consuming, and the cost of adding climate scenarios may outweigh the benefit of preventing re-assessment of a developed TMDL, especially given the uncertainty in climate change parameters. But, it is worthwhile to consider the potential impact of climate changes in TMDL development and implementation planning process. Lacking any specific data, further studies are required to quantify the impact of runoff changes on maximum value of a pollutant concentrations and their violation rates over a wide range of flow conditions.

CONCLUSIONS

Various studies have established significant impacts of climate change on global temperature and precipitation. A number of changes in weather and climate extremes observed in various part of the world have shown decreased temperature range and increased rainfall intensity, suggesting that upper limit of rainfall intensities could increase. The changes in rainfall amounts and intensities affect surface runoff significantly. The changes in surface runoff have been related to few possible impacts on bacteria concentration values. The potential impacts of change of flow conditions on the bacteria violations could have implications on future TMDL development and implementation studies.

In addition, the time lag between identifying a water as impaired and TMDL development and implementation, climate change could alter the meteorological assumptions employed in the TMDL models. However, TMDL development and implementation are costly and time-consuming, and the cost of adding climate scenarios may outweigh the benefit, especially given the uncertainty in climate change parameters. But, it is worthwhile to consider the potential impact of climate changes in TMDL development and implementation planning process. Lacking any specific data, further studies are required to quantify the impact of runoff changes on maximum value of pollutant concentrations and their violation rates over a wide range of flow conditions.

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EVALUATING THE ERODIBILITY OF COHESIVE RIVERBANKS WITH THE JET EROSION TEST

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KEY WORDS: cohesive soil, erosion, jet erosion test, *in situ* tests

ABSTRACT

Erosion rates for natural cohesive soils depend on both the complex inter-particle forces within the soil and the applied shear stress by the moving fluid. Due to the difficulty in describing these parameters theoretically, empirical methods are typically used to determine soil erodibility. To analyze erosion of cohesive riverbanks on the lower Roanoke River in North Carolina, jet erosion tests were performed at field sites. The jet erosion test scours the soil by applying a constant headwater jet and the measured scour depth and time period provide empirical estimates of soil erodibility parameters. The erodibility parameters assume an excess shear stress model with a linear relationship between erosion rate and applied shear stress. The advantages of the test are (1) it is performed at the site, negating the need for sample removal, (2) it can be performed on steep slopes such as those typical of many riverbanks, and (3) the results are easy to interpret with a spreadsheet program. The general testing procedure and analysis is reviewed and the implications of the underlying model discussed. The results from the Roanoke River are presented and erosion rates are compared with soil properties determined from other *in situ* and laboratory tests. Integration of jet erosion test results with numerical modeling of river flows is also discussed.

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Back to Table of Contents

II-B Monitoring Watershed Characteristics and Changes

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ANALYSIS OF CONTINUOUS WATER QUALITY MONITORING DATA FROM THE TIDAL FRESHWATER POTOMAC RIVER

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KEY WORDS: water quality, continuous monitoring, tidal, Potomac, Occoquan

ABSTRACT

Recent advances in water quality monitoring have facilitated “continuous monitoring”--the acquisition of basic water quality variables at fixed locations at short intervals over extended periods. Several fixed monitors have been sited in the tidal freshwater Potomac River over the past few years. We focus our analysis on a monitor on the tidal Occoquan River at the Belmont Bay development in Woodbridge, Virginia. Temperature, conductivity, dissolved oxygen, and pH were collected at 15 minute intervals during the summer and early fall of 2009 using a YSI 6600 extended deployment sonde. Results of time series analysis indicate that, on a short term basis, conductivity shows a semidiel pattern, presumably driven by tidal excursion. On the other hand, dissolved oxygen, pH, and temperature exhibited a simple diel pattern driven by the daily light and temperature cycle attributable to photosynthesis by abundant phytoplankton and submersed aquatic vegetation in the area. Longer term patterns were related to longer term climatic factors such as a dry summer with low freshwater inputs and seasonal progressions of light and temperature. Results from this site were compared with data from other continuous monitoring studies to illustrate the value of continuous monitoring data in answering questions

about temporal patterns in water quality data, relationship to driving variables at various scales, and impacts on aquatic resources and other beneficial uses.

INTRODUCTION

Recent advances in water quality monitoring have facilitated "continuous monitoring"--the acquisition of basic water quality variables at fixed locations at short intervals over extended periods. The data sets derived from these deployments facilitate and enhance our understanding of the effect of driving variables like light, freshwater inflows, and temperature on water quality dynamics as well as the interplay among water quality parameters. In addition, these temporally rich and continuous data sets allow more rigorous testing of the extent to which tidal systems satisfy water quality criteria supportive of aquatic life and other beneficial uses.

Notable implementations of continuous monitoring in the mid-Atlantic area include the Chesapeake Bay National Estuarine Research Reserve System (NERRS) which has reserves in Virginia and Maryland (Moore and Reay 2009) as well as Maryland's "Eyes on the Bay" program which includes continuous monitors at more that 30 sites in the Bay region (http://mddnr.chesapeakebay.net/eyesonthebay/index.cfm). Data from these and other similar sites nationwide have been used to help address a variety of basic and applied research questions.

One set of questions involves determining the patterns of water quality variability at various scales ranging from subdiel through interannual. Wenner and Geist (2001) conducted time series spectral analysis on 30 minute interval data from nine NERRS sites along the Atlantic and Gulf coast. They found a strong tidal effect on conductivity at all sites. Dissolved oxygen exhibited a much stronger diel effect than tidal effect at most sites. However, at those sites with a tidal amplitude greater than 1 m, tidal effects were equal or greater than diel effects. Buzzelli *et al*. (2007) compared two tidal creeks in South Carolina finding that the creek with the stronger diel dissolved oxygen signal also had higher phytoplankton and benthic production. In addition, this creek also had a greater storage volume and a wider marsh. Edwards *et al*. (2004) applied a novel nonparametric harmonic analysis to data from two continuous monitoring sites and found a seasonal difference in diel effects on dissolved oxygen and pH.

A second set of questions relates to the assessment of water quality drivers and impacts on habitat suitability for living resources. Necaise *et al*. (2005) used continuous monitoring of temperature, dissolved oxygen, salinity, and pH during *in situ* exposure of winter flounder in cages to assess effects on fish growth. Ringwood and Kepler (2002) used continuous monitoring to establish a negative effect of pH on the growth of clams in a South Carolina estuary even at pH's near neutral. Wenner *et al*. (2004) examined data from 55 NERRS sites for incidence and duration of hypoxia, a lethal condition for many aquatic organisms. They found that hypoxia generally lasted less than 12 hours and, in the absence of continuous monitoring, many anoxic and hypoxic events would have been missed. Buchanan (2009) analyzed data from 20 continuous monitoring sites on the tidal Potomac River in Virginia and Maryland over the period 2004-2008. A suite of water quality parameters including temperature, salinity, dissolved oxygen, pH, turbidity, and chlorophyll a were logged at 15-minute intervals for one to five years at each site. These data sets were then compared with a set of threshold values for various parameters, which included both formal water quality criteria (for example, instantaneous minimum dissolved oxygen criterion) and parameter values indicative of certain processes (for example, supersaturated dissolved oxygen).

METHODS

We focused our analysis on a monitor on the tidal Occoquan River at the Belmont Bay development in Woodbridge, Virginia (38.6558°N, 77.2321°W). The tidal Potomac River is essentially fresh water (<0.5 ppt salinity) from the head of tide to near Quantico, Virginia about 10 km downstream of where the tidal Occoquan opens into the Potomac mainstem and about 16 km downstream of the study site. Temperature, conductivity, dissolved oxygen, and pH were collected at 15 minute intervals during the fall of 2008 and the spring and summer of 2009 using a YSI 6600 extended deployment sondes. The sondes were equipped with copper coated probe cover, wiping brush parts were copper coated, and individual probes were wrapped in copper impregnated tape to minimize fouling. The sonde was moored to a floating dock at a constant depth of about 0.6 m immediately adjacent to the main channel of the tidal Occoquan. There is little or no depth stratification in this area. Data were transmitted to a dedicated web site maintained by YSI and at weekly intervals were emailed to the investigators. Two sondes were rotated at the deployment site at 4-6 week intervals at which time sondes were crosschecked for comparability. In addition to the original 15-minute temporal scale, data were compiled at daily and weekly scales. Weekly compilations were made from Sunday through Saturday. Weather data (temperature and photosynthetically active radiation) were collected at the deployment site using a Hobo weather station from Onset Computer. Occoquan River flow data were obtained from the web site of the Occoquan Watershed Monitoring Laboratory. Graphing was done using SigmaGraph and statistical analyses were done with Systat. Correlation analysis utilized the nonparametric Spearman coefficient.

Water quality indicator analysis was conducted using Microsoft Excel as described by Buchanan (2009). Water quality indicators used as metrics included:

- Percent of instantaneous minimum dissolved oxygen < criterion value (criterion value was 3.2 mg/L at temperatures less than 29°C and 4.6 at temperatures greater than or equal to 29°C)
- 7-day mean dissolved oxygen in mg/L
- Percent of dissolved oxygen values with >100% saturation
- Median magnitude of diel dissolved oxygen change in percent saturation
- Percent of instantaneous pH > 9

Indicator values were compiled for the entire period in aggregate as well as for each week separately.

RESULTS

Overall Patterns from Weekly Averages

Patterns in climatic and hydrologic forcing variables are shown in Figure 1 using weekly averages. From an initial value of about 22.5°C, water temperature climbed rapidly during June and then increased more gradually, but steadily through mid August to a maximum of just over

29°C. In late August a marked decline was observed in water temperature reaching about 22.5°C by mid September. Photosynthetically active radiation (PAR) was available starting in mid July. It remained above an average of 440 µmoles•m^{-2}•sec^{-1} through August, but declined substantially in September. Occoquan River flow was relatively high in mid June averaging over 1000 cfs, but declined strongly in late June and was virtually absent for the rest of the summer. This was partially attributable to low precipitation during the summer months of 2009. Then stream flow that did reach the upstream Occoquan River was detained by the reservoir just upstream of tidewater. Water withdrawals for drinking water and evaporation combined to offset the meager streamflows resulting in very limited discharge from the reservoir during the summer months.

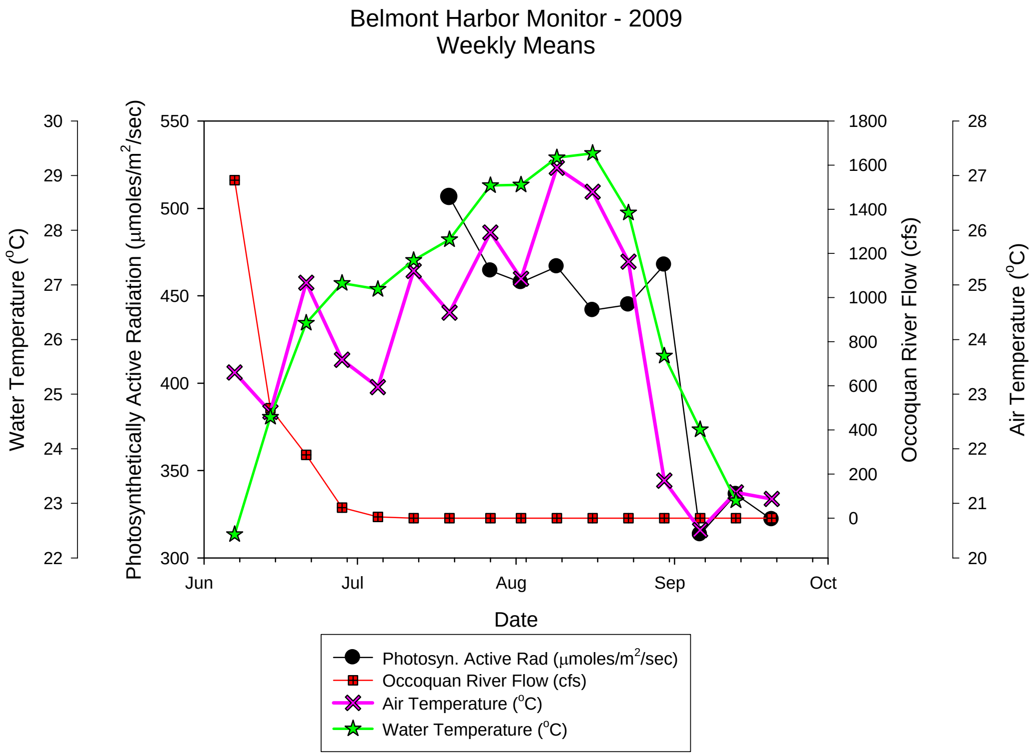

Figure 1. Patterns in climatic and hydrologic forcing variables on a weekly basis.

Specific conductance started in early June at relatively low values of about 0.17 mS/cm, but increased steadily through the summer attaining a value of about 0.34 mS/cm by mid September (Figure 2). This reflected the low river flow conditions, which meant no low ion freshwater dilution, which allowed slightly brackish water to gradually mix into the existing freshwater mass and raise its conductivity. Dissolved oxygen percent saturation averaged between 90 and 110% on a weekly basis. Average DO values as percent saturation showed a general increase from June to mid July and a general decline through the remainder of the year. Average weekly pH exhibited a range from 7.3 to 8.1. The general seasonal pattern of pH was similar to that in DO. pH was available for two additional weeks in early June and these suggested a steady decline throughout June. Overall, week-to-week patterns in DO closely tracked those in pH and also showed a relationship to PAR.

Correlation analysis was conducted to determine which climatic and water quality parameters were related on a weekly basis. As the weeks progressed, PAR showed a significant negative trend (r=-0.733, n=10), while specific conductance exhibited a strong positive correlation (r=0.989, n=15). Average water temperature was not significantly correlated with the average of any water quality parameter. Both pH and dissolved oxygen were highly correlated with PAR (r=0.900, n=9 and r=0.867, n=9, respectively). Among water quality parameters, the strongest correlation was between DO percent saturation and pH (r=0.780, n=13).

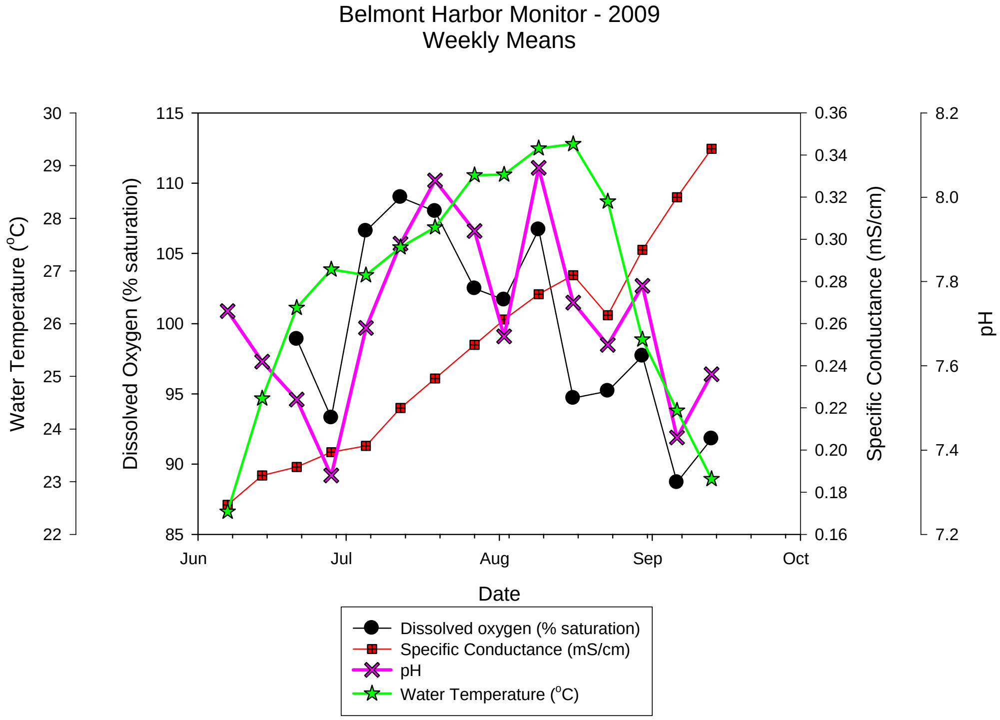

Figure 2. Patterns in water quality variables on a weekly basis.

Overall Patterns from Daily Averages

Correlation analysis was used to test for relationships among variables at the daily time scale. PAR was negatively correlated with date (r=-0.435, n=66) and specific conductance exhibited a strong positive correlation (r=0.967, n=91). Average barometric pressure was correlated with date (r=0.607, n=91) consistent with the paucity of storms that occurred during the period. Dissolved oxygen saturation and pH were correlated with average PAR (r=0.497, n=66 and r=0.443, n=66, respectively) consistent with a photosynthesis effect. Interestingly, specific conductance also exhibited a PAR correlation (r=-0.467, n=66). Among water quality variables the main correlation between daily means was between dissolved oxygen saturation and pH (r=0.809, n=91), again consistent with photosynthetic effects. Interestingly, there was also a correlation between mean temperature and the standard deviation of all three water quality variables (pH: r=0.541, n=91; dissolved oxygen saturation: r=0.461, n=01; specific conductance: r=0.486, n=91).

Multiday patterns were examined using time series analysis. Average air temperature showed evidence of a cyclical pattern with local maxima in autocorrelation occurring at about 7-8 and 16 days suggesting a relationship to frontal passages (Figure 3). Interestingly, water temperature did not reflect that pattern, but showed a decreasing correlation with increasing lag over the shorter term 25-day period. However, the correlation increased at longer intervals consistent with multimonth seasonal pattern. Specific conductance exhibited no cyclical pattern over either the 25-day period or the 100-day period. pH exhibited a multiday pattern that was similar to that in temperature, with local maxima in autocorrelation occurring at 8 and 13 days (Figure 4). This was similar to the pattern in DO saturation, which peaked at 7 days and exhibited a shoulder at 12 days. A cross-correlation plot showed that pH and DO correlated best at 0 lag, but also very strongly at a lag of -7 days. Cross correlation of pH and DO with PAR was maximal at 10 and 9 days, respectively.

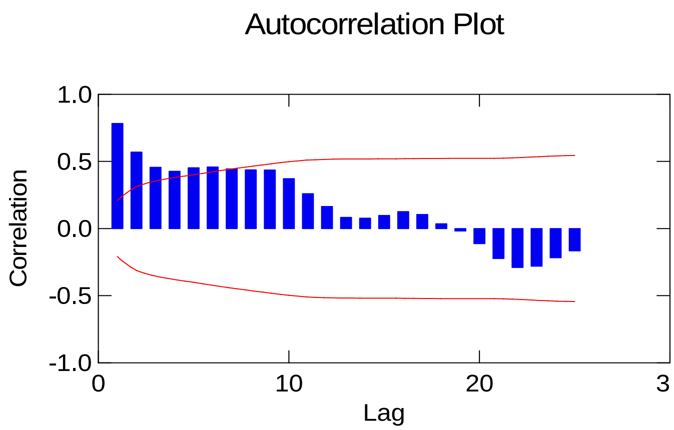

Figure 3. Autocorrelation plot for average daily air temperature. Correlation coefficients related values at time 0 to values a given number of time units later (lag value). Time units here are days.

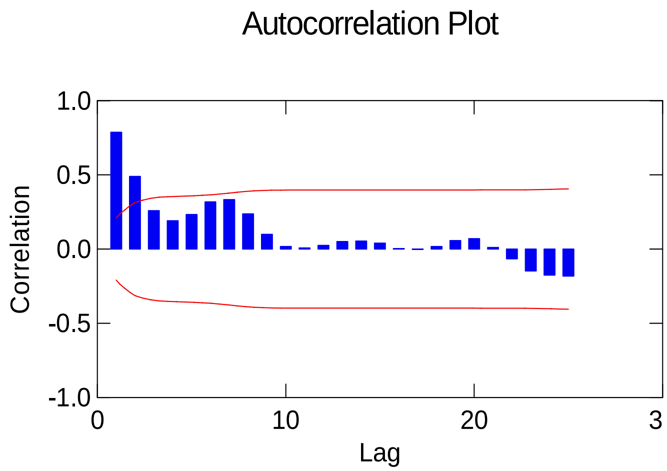

Figure 4. Autocorrelation plot for average daily pH. Correlation coefficients related values at time 0 to values a given number of time units later (lag value). Time units here are days.

Overall Patterns from Individual 15-minute Readings

Diel patterns were probed using time series analysis. The data collected at 15 minute intervals for water temperature, specific conductance, dissolved oxygen and pH were used in this analysis. In this case the lag interval would be 15 minutes so that a 24-hour diel period would consist of 96 lag units. Temperature exhibited a clear cyclical diel pattern (Figure 5) with a single maximum and minimum per 24 hour period this was reflected in a minimum correlation occurring at 48 lag units followed by a peak at 96 lag units. This would correspond to the daily pattern of heating and cooling of the water body related to the daily solar cycle. The general overall trend was down indicating decreasing correlation with the reference day as days went by. Specific conductance exhibited a distinctly different pattern with two maxima and minima per 24-hour period (Figure 6). This type of pattern relates to the tidal cycle, which on the east coast of North America is semidiurnal. Specific conductance of water coming in at high tide from the main Potomac channel has slightly higher ion content than that coming down from upriver at low tide resulting in the pattern. Note that all values remain well within the freshwater range. Dissolved oxygen and pH displayed extremely strong diel patterns with correlations dropping to very low levels at 12 hours, but increasing to 0.7 or 0.8 after 24 hours (Figure 7). This pattern corresponds with the daily cycle in PAR and reinforces the role of photosynthesis and respiration in controlling dissolved oxygen and pH in this system.

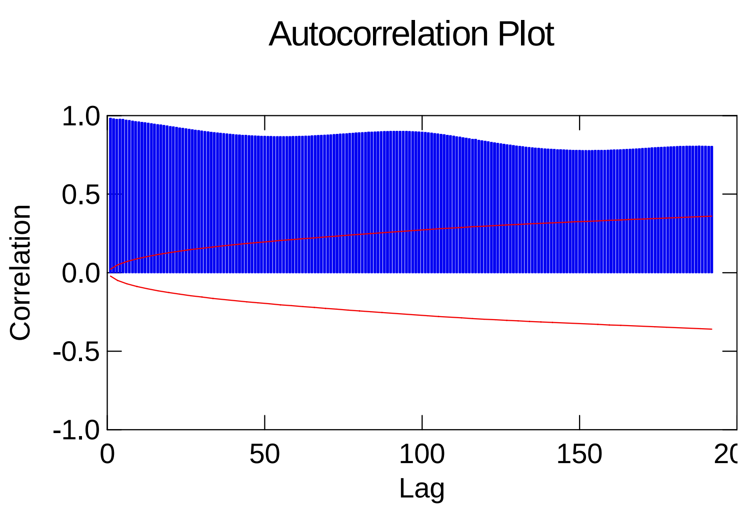

Figure 5. Autocorrelation plot for 15-minute water temperature data. Correlation coefficients related values at time 0 to values a given number of time units later (lag value). Time units here are 15 minutes.

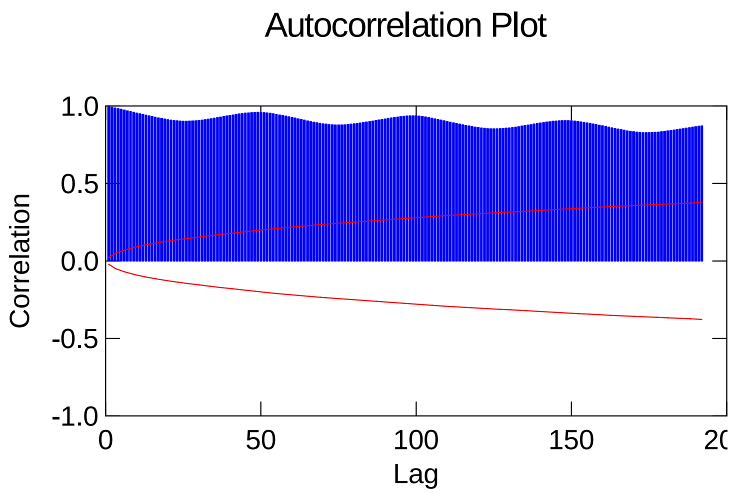

Figure 6. Autocorrelation plot for 15-minute specific conductance data. Correlation coefficients related values at time 0 to values a given number of time units later (lag value). Time units here are 15 minutes.

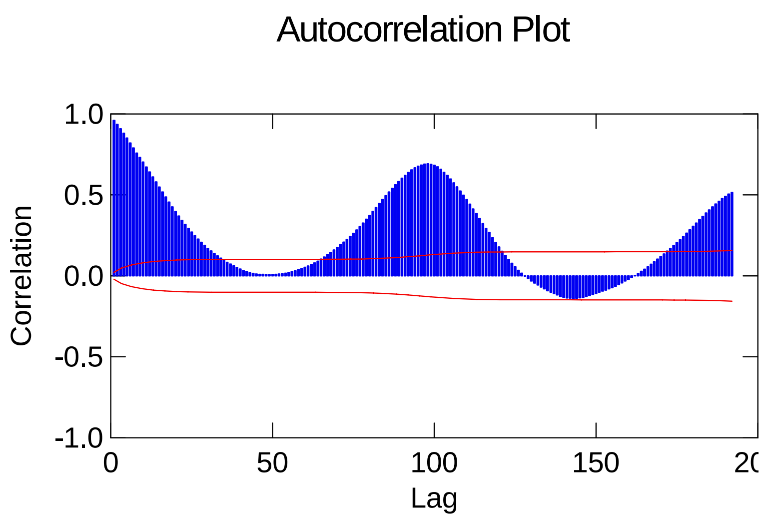

Figure 7. Autocorrelation plot for 15-minute dissolved oxygen data. Correlation coefficients related values at time 0 to values a given number of time units later (lag value). Time units here are 15 minutes.

Water Quality Indicator Analysis

When all weeks were taken in aggregate, a general pattern in dissolved oxygen metrics suggested that supersaturated values were very common (41.5% of all values) and that diel swings in dissolved oxygen were very marked (median diel swing was 43.7% in percent saturation units). The high values for these two dissolved oxygen metrics suggests a dominant role for photosynthesis over respiration in this system. Despite these large diel fluctuations dissolved oxygen was almost never below the lower threshold value (only 0.1% of all observations). Average dissolved oxygen over the entire period was 7.90 mg/L. The high pH indicator (percent of pH above 9) had a frequency of less than 1% suggesting that while photosynthesis was strong, it was generally not excessive.

Metric values did show some obvious variation on a weekly basis. Percent of supersaturated values ranged from 7.7% to 66.5%, while diel swing in percent dissolved oxygen ranged from 22.5% to 72.4%. Those weeks with higher values of these two indicators demonstrated strong photosynthesis effects, but the weeks with lower values were representative of a much reduced photosynthetic impact. Interestingly, the week with the highest incidence of low dissolved oxygen metric values (week 33) had among the highest indicators of strong photosynthetic activity.

Table 1. Indicator Metrics. Dates are shown for each week along with week number in parentheses. Column abbreviations: %SatDO, percent of dissolved oxygen values with % saturation greater than 100%; DM%Sat, seasonal median of the diel magnitude of change in dissolved oxygen % saturation; %DO<Min, percent of values less than the instantaneous minimum dissolved oxygen criteria; 7-day mean, 7-day mean of dissolved oxygen (mg/liter); %pH>9, percent of pH values greater than 9.0 criterion.

			METRIC		
TIME PERIOD	%SatDO	DM%Sat	%DO<Min	7-day mean	%pH>9
All Weeks	41.5%	43.7%	0.1%	7.90	0.8%
6/7-6/13 (24)					0.0%
6/14-6/20 (25)					0.1%
6/21-6/27 (26)	37.4%	44.6%	0.0%	7.97	0.0%
6/28-7/4 (27)	24.6%	46.3%	0.0%	7.42	0.0%
7/5-7/11 (28)	61.9%	51.5%	0.0%	8.49	0.1%
7/12-7/18 (29)	66.4%	57.2%	0.0%	8.60	2.2%
7/19-7/25 (30)	66.5%	47.4%	0.0%	8.47	0.1%
7/26-8/1 (31)	45.9%	52.2%	0.0%	7.89	4.3%
8/2-8/8 (32)	50.8%	65.9%	0.3%	7.84	0.0%
8/9-8/15 (33)	60.0%	72.4%	1.2%	8.15	6.0%
8/16-8/22 (34)	30.1%	36.9%	0.0%	7.23	0.7%
8/23-8/29 (35)	31.1%	59.6%	0.0%	7.40	1.9%
8/30-9/5 (36)	43.5%	25.8%	0.0%	7.97	0.0%
9/6-9/12 (37)	7.7%	22.5%	0.0%	7.42	0.0%
9/13-9/19 (38)	20.4%	27.3%	0.0%	7.85	0.0%

DISCUSSION

The first objective of this analysis was to determine patterns of water quality variability over a range of temporal scales and relate these to patterns in forcing functions. When the entire period of study (about 3.5 months) was examined distinct seasonal patterns were observed temperature and PAR with highest values of PAR in the early weeks of summer and highest temperatures in the later weeks of summer corresponding with typical seasonal patterns in the north temperate region. While freshwater inflow from the Occoquan watershed was relatively robust in spring of 2009 before the study period, it had declined substantially by the initiation of data collection and essentially ceased after the first few weeks. In the absence of direct freshwater inflow, conductivity gradually and consistently increased during the study period nearly doubling over the 14 week study period. pH and dissolved oxygen, on the other hand, exhibited a general increase in the early weeks, peaked in July and August and declined in the early fall. This pattern was probably related to the seasonal growth of phytoplankton and submersed aquatic vegetation (SAV) in the river.

Autocorrelation analysis on daily averages confirmed and further amplified these relationships. Consistent with a linear decline through time, autocorrelation of conductivity values consistently decreased with time over all lag periods. Autocorrelation analysis of daily pH and dissolved oxygen averages suggested a cyclical component of about 7-8 days which would be consistent with average time between weather changes associated with frontal zone passage. This conclusion is consistent with the observation that daily air temperature showed a similar cycle. This would suggest that frontal zone passages alter factors controlling photosynthesis and respiration by phytoplankton and SAV in the river yielding a change in dissolved oxygen and pH that repeats itself with each frontal passage.

Diel patterns in water quality were examined using autocorrelation analysis of the 15-minute data series. Specific conductance was found to exhibit a clear semidiel pattern consistent with a tidal effect. Higher tides brought in water with slightly more ionic content. However, values remained well within the freshwater range. This tidal effect on specific conductance was consistent with the findings of Wenner and Geist (2001) at a range of NERRS sites. Water temperature, dissolved oxygen saturation, and pH all exhibited a strong diel pattern related to the solar cycle. Very strong autocorrelations were found at a lag of 24 and 48 hours for pH and dissolved oxygen saturation. There was no evidence for a tidal effect on these parameters. While not present in the immediate area of the monitor due to its water depth, the tidal Occoquan contains large beds of SAV both immediately upriver and across the channel from the study site. Phytoplanktons are also very abundant during the summer in the tidal fresh Potomac. It was not possible to discriminate the relative importance of these two groups in the current study. The strong diel dissolved oxygen signal observed here is consistent with the findings of Buzzelli *et al*. (2007) for a creek which had robust phytoplankton and a large marsh upstream. Given the tidal range of about 0.6 m in the tidal Occoquan, the dominance of the diel signal for dissolved oxygen is consistent with the findings of Wenner and Geist (2001) at a range of NERRS sites with lower tidal amplitudes.

The findings from the water quality indicator analysis can be compared with those of Buchanan (2009) for multiple sites in the tidal Potomac. In the current study failure of the instantaneous DO minimum criteria (indicating hypoxia) occurred in only 0.1% of readings compared with rates as high as 31.5% at sites which she examined from 2004-2008. However, our results were similar those of the 2004-2008 study for other sites in Occoquan Bay. Our median range in diel oxygen and average dissolved oxygen saturation values were also similar to those from the earlier years for Occoquan. Values for the pH>9 metric showed a lower incidence in the 2009 data than in previous years for Occoquan.

ACKNOWLEDGEMENTS

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AN ANALYSIS OF THE UPPER STROUBLES CREEK WATERSHED CHARACTERISTICS USING GEOSPATIAL TECHNOLOGIES

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KEY WORDS: urbanization, watersheds, Stroubles Creek, geospatial technologies

ABSTRACT

Urbanization alters physical characteristics of watersheds and, in many cases, changes the stream's natural flow direction and intensity and impacts the stream quality. The alterations are multifaceted and range from changing the size and slope of the watershed to changing the stream habitat. Understanding how changes affect the health of the watershed is important in determining how to correct the detrimental effects of urbanization. Changes to watersheds are established in many ways and the goal of this research is to investigate the changes in watershed characteristics using geospatial technologies.

An NSF REU research project, conducted during the summer of 2009, evaluated the changes caused by urbanization in the Upper Stroubles Creek Watershed in Blacksburg, Virginia. Technology used to compare these characteristics included GIS, LiDAR, GPS measurements and aerial photos. Physical characteristics analyzed included channel length, width and depth, stream source, watershed elevations, slopes, area and perimeter.

This paper will review the techniques used in the lab and in the field for the delineation of the various watershed characteristics. It will then review the results of the comparative analysis between the field data and the data delineated from the electronic and archival sources.

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RAINFALL INTERCEPTION IN TROPICAL FOREST ECOSYSTEMS: TREE PLANTATIONS AND SECONDARY FOREST

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KEY WORDS: rainfall interception, throughfall, stemflow, *Vochysia ferruginea*, *Vochysia guatemalensis*, tropical secondary forest.

ABSTRACT

A study was conducted in the tropical lowlands of Costa Rica, at La Selva Biological Station, to evaluate the rainfall interception of two forest plantations of *Vochysia guatemalensis* Donn. Sm. *Vochysia ferruginea* Mart. and one secondary forest. Daily measurements of gross rainfall, throughfall and stemflow were taken during the peak of the rainy seasons of 2004 and 2005 (August to November). The estimated throughfall expressed in percentage of the total gross rainfall for the secondary forest, Botarrama plantation and Cebo plantation were: 76%; 87.6% and 92.1% respectively. The estimated stem flow in percentage of gross rainfall was of 3% for *Vochysia ferruginea* and of 3.4% for *Vochysia guatemalensis.* Streamflow for the secondary forest was omitted due to the forest structure, composition and high density of palms trees that makes stemflow measurements a difficult task. This study shows that forest structure and composition of studied ecosystems have different degrees of influence in rainfall interception losses. Complex forest structure and composition such as tropical secondary forest intercept more rainfall than forest plantations. This information is important for selection of reforestation species in watershed managements programs as well as in evaluating the hydrological environmental service of these ecosystems.

INTRODUCTION

Given the reported the strong dynamic of land cover change and the Scheme of Payment for Environmental Services in Costa Rica (Calvo-Alvarado *et al*. 2009), a good quantification of the impact of forest ecosystems on water fluxes is essential for the correct evaluation of these ecosystem services.

Rainfall interception (RI) is affected by: precipitation amount, intensity and frequency, and by forest age, structure and composition like: the canopy density, leaf area index and vertical strata distribution (Casey 1996, Cavelier and Vargas 2002). RI processes affect the net rain deposition on the soil surface and hence the soil water storage (Fallas 1996).

In a wide range of rainfall interception studies, the water fluxes inside the forest ecosystem have been divided traditionally into throughfall, stemflow, total interception and losses by evapotranspiration (Filoso *et al*. 1999, Marín *et al*. 2000, Cavelier and Vargas 2002, Staelens *et al*. 2003). RI has been studied in few tropical forest ecosystems, where the throughfall averages had ranged between 75% to 86% and the stemflow had oscillated around 2% of the total gross rainfall (Cavelier and Vargas 2002).

METHODS

Study Site

The study was carried out at La Selva Biological Station (N 10°26', W 83°59') of the Organization for Tropical Studies (OTS) Heredia, Costa Rica. Mean annual temperature is 25°C and annual precipitation for the last 13 years average is 4,194 mm, with all months receiving more than 130 mm (Figure 1). According to the Holdridge's (1967) vegetation classification the Life Zones is Tropical Wet, which is the second most extensive in Costa Rica (Hartshorn and Hammel 1994). More information about this region is available in McDade *et al*. (1994).

Three plots were established in two forest plantations and one secondary forest. The 11 year old forest plantations of *Vochysia guatemalensis* Donn. Sm. (Cebo) and *Vochysia ferruginea* Mart. (Botarrama) were located in La Flaminea sector at La Selva. In each forest plantation a plot of 600 m^2 (20m x 30m) was established (Figure 2). The dbh (cm) and tree height (m) for all trees were measured in each plot (Carvajal-Vanegas 2004, Jiménez-Rodríguez 2005). The secondary forest had an estimated age of 25-30 years and it was located in the flood plains of Puerto Viejo river (Figure 2). In the secondary forest a plot of 1200m^2 was established (30 m x 40 m). The dbh and canopy height of all trees above 5 cm dbh in the secondary forest were measured (Jiménez-Rodríguez *et al*. 2006).

Experimental Design

<u>Forest Plantations</u>

The gross rainfall was collected by two 103.87cm^2 (diameter = 11.5 cm) rain gauges placed in two nearest open areas (Figure 2). To measure throughfall 40 rain gauges of 122.7cm^2 (diameter = 12.5cm) were placed randomly within each plot. After every 10 rain events, all the rain gauges were relocated randomly to decrease the variation after suggestions made by Skau (1964), Marín *et al*. (2000), and Fleischbein *et al*. (2005). Five trees in each forest plantation were selected to measure stemflow. The trees were chosen to represent the complete tree plot diametric range. A plastic open pipe was placed in each of the chosen trees and sealed to the stem at dbh, with nails and silicon. At the end of each pipe, a plastic collector of 40 gallons was placed (Carvajal-Vanegas 2004).

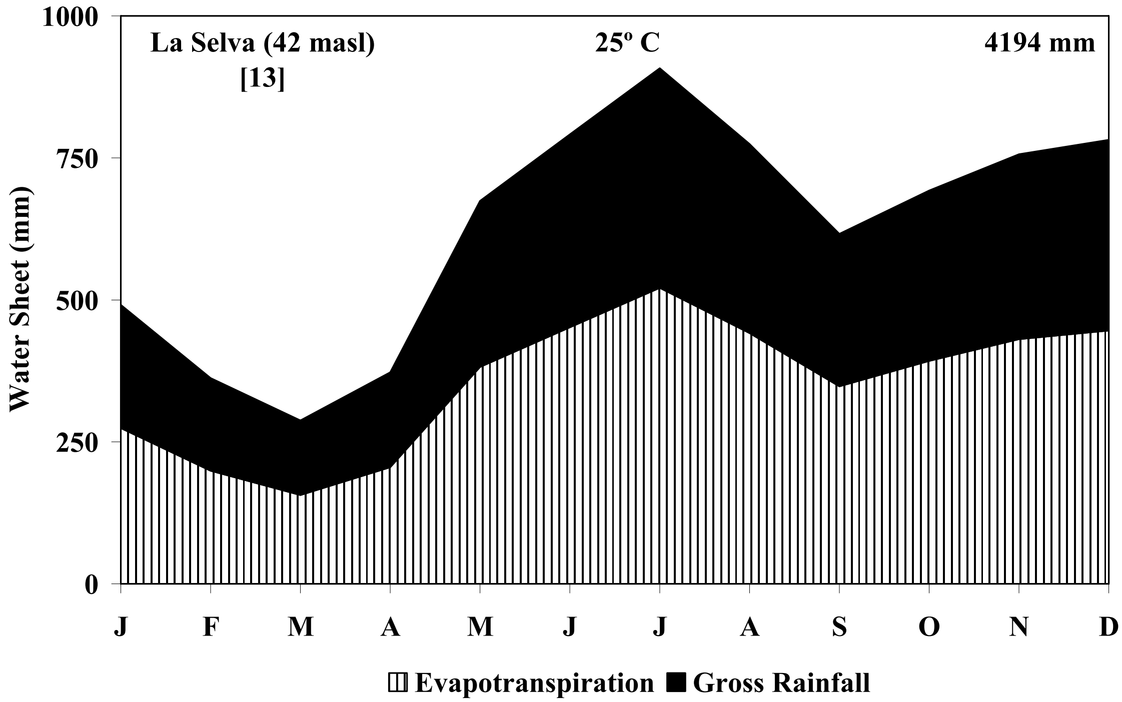


Figure 1. Climate diagram for La Selva Biological Station, Costa Rica. Based on meteorological data for the last 13 years, La Selva Meteorological Station. The monthly precipitation (solid black) and potential evapotranspiration (vertical lines) are scaled. (Adapted from: Jiménez-Rodríguez 2005).

Secondary Forest

To measure gross rainfall one rain gauge of 314.16cm^2 (diameter = 10cm) was placed in the nearest canopy gap attached to a pole of 10m height. Three extra rain gauges of 103.87cm^2 (diameter = 11.5cm) were placed in the nearest open area to compare the collected gross rainfall at the canopy gap (Figure 1). To measure throughfall we followed the same procedures described above for the forest plantations. Knowing the forest species richness and complex structure of the selected secondary forest, we decided to omit the stemflow evaluation in this study because of the outstanding differences among species (Jiménez-Rodríguez 2005).

Data Collection

This study compiled information of two trials executed by the authors in two different years. The rainfall interception study for the forest plantations took place between August to November 2004 while the rainfall interception study for the secondary forest took place between August to October 2006. For both studies, daily measurements were taken for the gross rainfall, throughfall and stemflow every day between 5 to 6 am. Few events were discarded during the two studies because of flooding or wind damages.

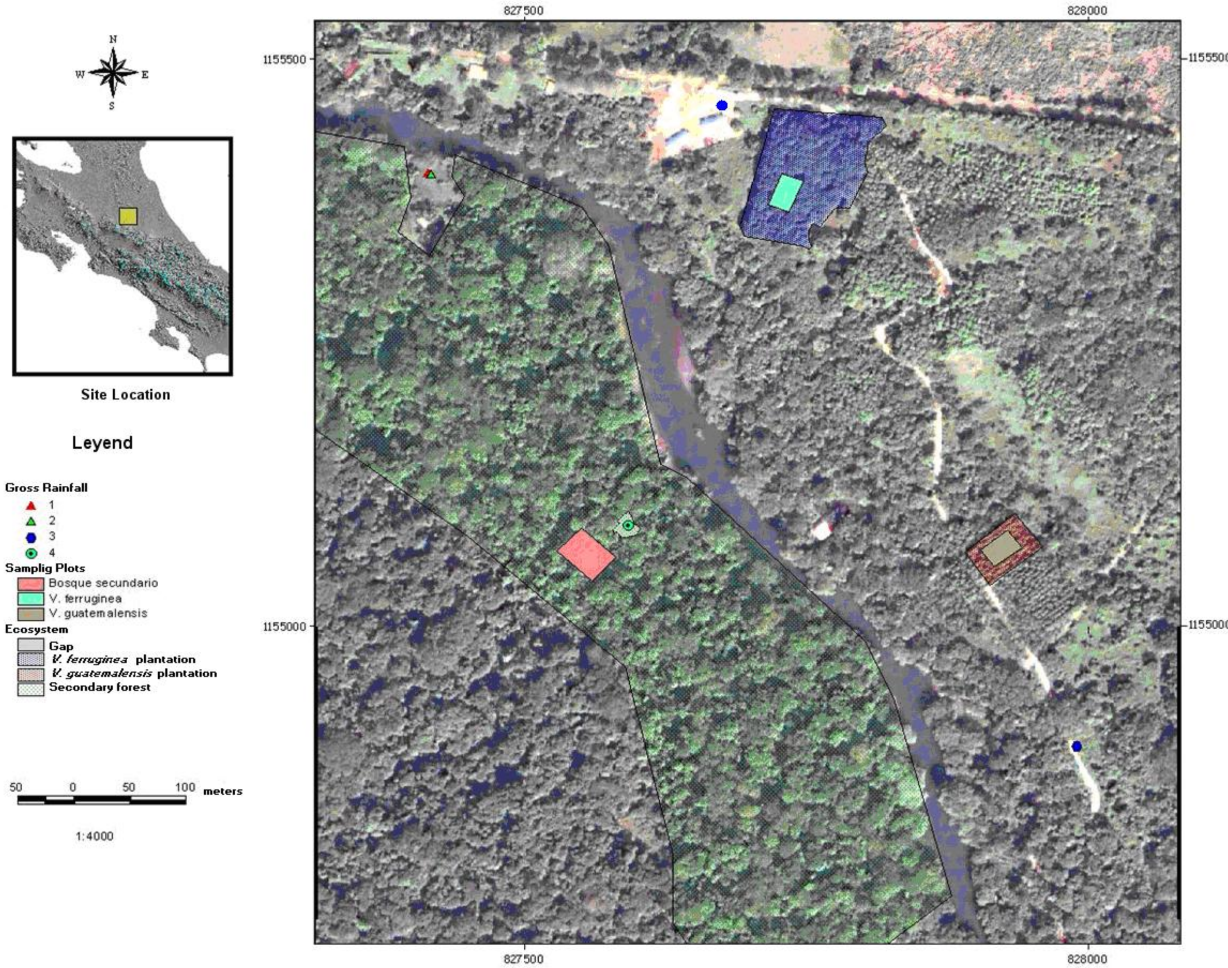


Figure 2. Location of studied plots and rain gauges at La Selva Biological Station, Puerto Viejo, Sarapiquí, Costa Rica (Adapted from Jiménez-Rodríguez *et al*. 2006).

Data Analysis

Gross rainfall, throughfall and stemflow were measured in ml in the field and then the data was transformed into mm of water. For the stemflow, the tree rainfall collecting area was estimated as the projected horizontal tree canopy area measured by six radiuses. This value was used to transform the collected stemflow volume into sheet of water in mm. The average throughfall from the 40 rain gauges was considered as the best estimation of the total throughfall for each event. In the same manner the average stemflow collected for the five selected trees was considered as the total stemflow value for each event. Both, stemflow and throughfall were compared with gross rainfall to estimate total rainfall interception.

The forest structure for the secondary forest and tree plantations was evaluated using the Holdridge complexity index (C_{HCI}) (Holdridge 1967, Holdridge *et al*. 1971): C_{HCI}= (HGDS/1000), where H is the mean tree plot height in m, D is stem density, G is plot basal area in m^2 and S is the number of species in the plot. All the values were expressed in relation to 0.1 ha plot area. This index provides an idea of the relation between the species composition and the forest structure. To compare the effect of ecosystem type in rainfall interception we used

ANCOVA (p = 0.05) and the homogeneous grouping by Fisher LSD (p = 0.05). The statistical analysis was performed using STATISTICA 6.0 (StatSoft, Inc. 2003).

RESULTS AND DISCUSSION

Forest Structure, Composition and Complexity

As expected the forest structures and species composition among the three selected ecosystems showed great differences (Table 1). The secondary forest had 36 species with three vertical strata. The palm *Prestoea decurrens* was a dominant specie in the first two vertical strata; while the trees *Castilla elastica*, *Bursera simarouba* y *Virola koschnyii* were the dominant species for the canopy strata. Contrasting this feature the two forest plantations had only one vertical stratum dominated by the planted tree species. The forest floor for the *V. guatemalensis* plot had more shrub species (dominated by *Musa* sp. and *Piper* sp.) than the *V. ferruginea* plot that almost was free shrubs. *V. ferruginea* plantation resulted with the lower basal area than the other two plots; while its tree height was similar to *V. guatemalensis* plot. As expected tree density and species composition increased in the secondary forest. Consequently the less complex ecosystems were the two forest plantations and the most complex ecosystem was the secondary forest, as depicted by the Holdridge complexity index (Table 1).

Table 1. Forest structure, species composition and Holdridge complexity index for three forest ecosystems at La Selva Biological Station, Sarapiquí, Costa Rica. Information based in woody species greater than 5 cm dbh.

Site	Species Number	Trees Density (n/ha)	Basal Area (m^2/ha)	Canopy Height (m)	HCI
V. ferruginea	1	483	26.9	19	2.47
V. guatemalensis	1	617	36.6	18	4.06
Secondary forest	36	1058	36.5	25	289.63

Rainfall Interception

Gross rainfall

The sampled gross rainfall events for both studies represented very well the natural daily rainfall distribution for this site. We were able to sample rainfall events as high as 105 mm/day in the secondary forest study and 78 mm/day in the forest plantations study. In total we measured 30 rainfall events in each study.

Throughfall

The total estimated throughfall for *V. ferruginea* plantation was 87.65 % while for *V. guatemalensis* was 92.12 % of the total collected gross rainfall. These values contrasted dramatically with the secondary forest value of 75.89 %. These results were obtained by totalizing all throughfall and gross rainfall events. Another way to estimate throughfall was by considering the slope of the regression line between gross rainfall (x axis) and throughfall (y axis) as showed in Figure 3 and suggested by Marín *et al*. (2000). In this case the throughfall estimates were: 90% for *V. ferruginea*, 95% for *V. guatemalensis* and 76.5 % for the secondary forest. The R^2 values for all regressions were higher than 0.99, which indicated good regressions results.

The ANCOVA applied for the daily throughfall showed significant differences among ecosystems ($p_{value} = 0.000080$) and a significant effect of gross rainfall as a covariable in the three sites ($p_{value} = 0.000008$). Among the three ecosystems, the *V. guatemalensis* had the less canopy interception, while the secondary forest has the highest value. The throughfall order was:

$$\frac{92.12\%}{Vg} \triangleright \frac{87.65\%}{Vf} \triangleright \frac{75.89\%}{Sf}$$

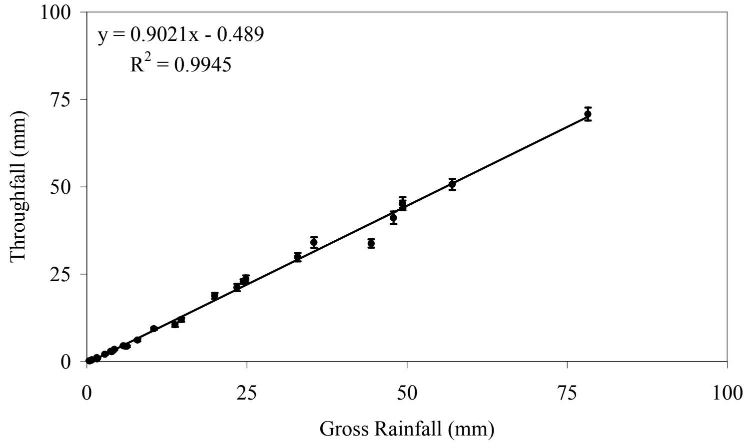
Stemflow

As indicated in the Methods section only the tree plantations were sampled to estimate the stemflow values. In total we were able to sample 30 events for the tree plantations and for the secondary forest to estimate stem flows. The total estimated stemflow in relation to gross rainfall in percentage was 2.98% for *Vochysia ferruginea* and 3.39% for *Vochysia guatemalensis*. The ANCOVA applied using daily mean stem flows did not show significant differences among ecosystems ($p_{value} = 0.38477$) but showed a significant effect of gross rainfall as a covariable in all the two sites ($p_{value} = 0.000000$).

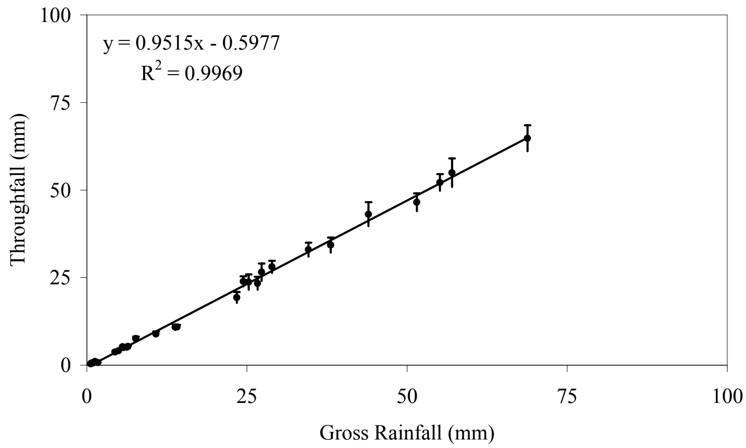
Total Rainfall Interception

Considering the throughfall and stemflow values estimated for both plantations, the total rainfall interception in percentage in relation to gross rainfall were: 8.9% for *V. ferruginea* and 4.9% for *V. guatemalensis* (Fig. 4).

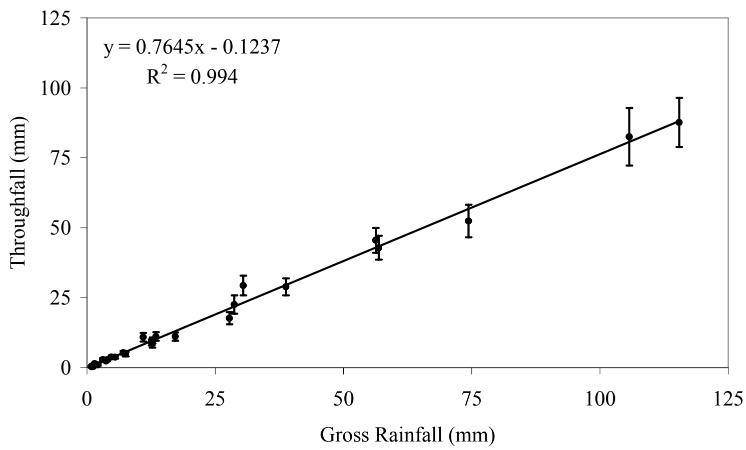
Costa Rica has a lack of information about RI in secondary forest and other ecosystems forest ecosystems such as tree plantations, but some studies in other life zones and latitudes are available. The secondary forest of this study resulted in a RI of 24.1%, which is almost the same value for tropical cloud forest in Costa Rica (Fallas 1996), which reported RI of 24% of the gross rainfall; while Marín *et al.* (2000) reported a RI of 18% for flooded tropical forest. This information shows the secondary forest had higher RI values than forest plantations (Figure 4).



Vochysia ferruginea plantation



Vochysia guatemalensis plantation



Tropical secondary forest

Figure 3. Canopy throughfall and open rainfall for three forest ecosystems in La Selva Biological Station, Sarapiquí, Costa Rica.

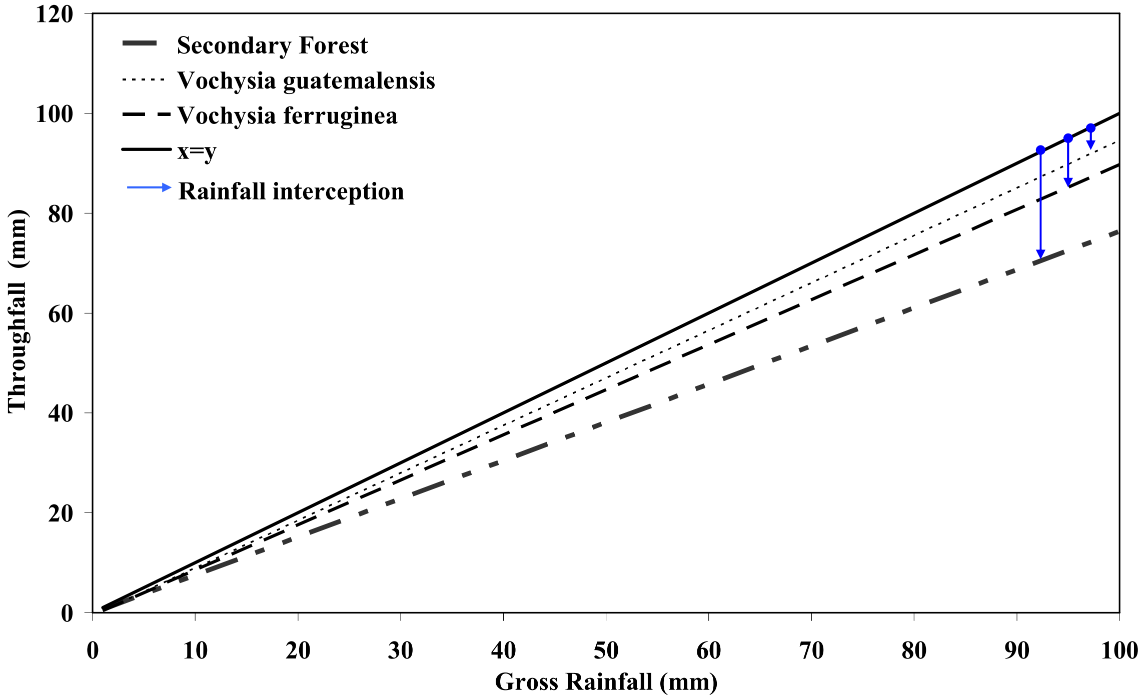


Figure 4. Canopy throughfall and open rainfall (blue arrows) in three forest ecosystems at La Selva Biological Station, Sarapiquí, Costa Rica.

CONCLUSIONS

Plantations of same age of two species growing under same environmental conditions resulted in significant different rainfall interception losses due probably to differences in tree architectural characteristics, leaf area, bark and leaf surface type. Secondary forest rainfall interception was higher due to the complex forest structure, number of strata and species composition.

This study proves the importance to evaluate the effect of different forest ecosystems and ages in water fluxes. This information is important to consider in watershed management plans. Also, knowledge of this information can lead to better approaches for reforestation programs and Payment for Environmental Services, especially in the scenarios of regulating watershed water fluxes.

More studies are required to complete a good set of data to estimate the impact of all reforestation species used in the tropics in watershed water fluxes. These suggested studies must cover all possible ages and environmental conditions. The same can be said about natural forests in its different successional stages in different Life Zones.

This study was of exploratory nature and was conducted to generate information to calibrate the methodology for further applications in similar studies. We concluded that we achieved our main objectives and generated additional information that so far had not been produced.

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Back to Table of Contents

II-C Connecting Nutrient Cycling and Water Quality (Part 2)

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STREAMSIDE MANAGEMENT ZONES MINIMIZE NUTRIENT FLUXES FROM FOREST FERTILIZATION IN PIEDMONT STREAMS

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KEY WORDS: streamside management zones, forestry best management practices, forest fertilization, water quality

ABSTRACT

State Forestry Best Management Practices (BMP) recommend Streamside Management Zone (SMZ) of varying widths based on limited data with regard to nutrient fluxes from silvicultural activities. Studies in Agricultural environs show increases of nitrogen (N) and phosphorus (P) in streams following fertilization. However, little information exists regarding the effectiveness of recommended SMZ widths for controlling nutrient fluxes following forest fertilizer application. We hypothesized that N and P levels would decrease on the soil surface, forest floor, and soil subsurface in forested SMZs as distance from the harvest boundary to the stream increased. Furthermore, we hypothesized that wider, unthinned SMZ's would better prevent nutrients from reaching the stream than narrower and/or thinned SMZ's. Diammonium Phosphate (DAP) and UREA were applied to subwatersheds of 2-3yr old loblolly pine (*Pinus taeda*) upslope from SMZ study areas in Buckingham Co., VA. Three replications of four SMZ treatments (30.5m, 15.2m unthinned, 15.2m thinned, and 7.6m) were studied using surface water collectors, cation/anion exchange membranes, lysimeters, and stream grab-samples. Measurement stations were spaced symmetrically across the SMZ from the uphill SMZ edge to streamside with grab

samples being collected approximately 20m upstream and downstream of the fertilized area. Results show that stream water quality is basically unaffected by fertilization at all SMZ width treatments. However, we caution that these results were collected during a relative dry period and that other studies on the same sites indicate that 7.6m wide SMZs may be too narrow to fully provide other riparian functions, such as sediment trapping.

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THE SOIL NITROGEN SOURCE TO STREAMFLOW DURING SNOWMELT IS AFFECTED BY SOIL FREEZING

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KEY WORDS: nitrate, nitrogen, climate change, soil freezing, N mineralization, nitrification, source waters

ABSTRACT

Although climatic models of north temperate ecosystems predict greater amounts of winter precipitation in the future, reductions in snowpack are likely to occur due to the increased importance of thaws, sleet, and rain-on-snow events. Without an insulating snowpack, more frequent freeze-thaw cycles will occur and could affect nutrient cycling. Changes in snowpack dynamics, may affect soil and ground water sources in watersheds and the amount and timing of nutrient transport during spring snowmelt. We examined nitrogen (N) dynamics during late winter and spring snowmelt in the 696 ha Point Peter Brook watershed (PPBW), in western, N.Y. during 2007 and 2008. Contrary to what has been observed during late summer/early fall hydrologic events, in this watershed, near-surface soil water was an important source of nitrate during spring melt. To test the effects of soil freezing on *in situ* rates of soil nitrate production (nitrification), a snowpack manipulation study was conducted in winter 2007-2008. We established reference and snow manipulation treatment plots. One pair of treatment and reference plots was located in the riparian zone of PPBW while another pair was located on the hillslope. The treatment plots at both landscape positions had significantly greater N mineralization than reference plots. No treatment effect was observed for nitrification in the riparian plots while the hillslope treatment plot had a smaller nitrification rate than the reference

hillslope plot. As climate change alters temperate forested ecosystems, especially during winter, the effect of soil freezing should be considered when evaluating changes in sources and export of N during spring snowmelt.

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THE USE OF FLOATING AQUATIC PLANTS FOR PHYTOREMEDIATION OF EUTROPHIC WATERS

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KEY WORDS: aquatic plants, phytoremediation, eutrophic, macrophytes

ABSTRACT

Over the last 40 years a great deal of research has been published on the use of floating aquatic macrophytes to treat wastewater both from point sources (feedlots, food processing plants) and non-point sources. These plants can recover nutrients such as nitrogen and phosphorus from eutrophic surface waters. They can also remove or accumulate metals, radionuclides and other pollutants in their tissues. Examples of floating aquatic macrophytes include *Eichhornia crassipes* (water hyacinth), duckweed (*Lemnaceae* family), *Azolla caroliniana* (water fern), *Pistia stratiotes)*, (water lettuce), *Hydrocotyle umbellate, (*pennywort) and *Salvinia molesta* (giant salvinia).

Considerable research has been carried out in recent years on the use of these floating aquatic macrophytes to treat wastewater by recovering nutrients present in these waters while at the same time providing a useful product in return. This article will discuss various types of floating aquatic macrophytes and the uses that have been found for their harvested biomass. These floating aquatic plants often act as invasive species and can reproduce asexually as well as sexually. This review will summarize some of the published work done using these plants to phytoremediate natural, domestic and agricultural wastewaters.

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Back to Table of Contents

Concurrent Session III

(A) All About Algae
(B) Managing Wastewater

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III-A All About Algae

(1) Factors Contributing to Persistent Algal Blooms in the James River -- Paul Bukaveckas, *Department of Biology, Virginia Commonwealth University*

(2) Factors Limiting Benthic Algal Abundance in Virginia Streams of the Coastal Plain -- Michael Patrick Brandt, *Center for Environmental Studies, Virginia Commonwealth University*

(3) Increasing Occurrence and Development of Potentially Harmful Algal Blooms in Virginia Tidal Rivers -- Harold Marshall, *Department of Biological Sciences, Old Dominion University*

(4) Controls on the Formation and Transport of *Cochlodinium polykrikoides* Blooms in Lower Chesapeake Bay -- Ryan Morse, *Department of Ocean, Earth, and Atmospheric Sciences, Old Dominion University*

(5) Molecular Identification and Detection of *Alexandrium monilatum* in Chesapeake Bay Water and Sediment -- Kim Reece, *Virginia Institute of Marine Science, The College of William and Mary*

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FACTORS CONTRIBUTING TO PERSISTENT ALGAL BLOOMS IN THE JAMES RIVER

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KEY WORDS: eutrophication, algal blooms, nutrients, rivers impairment

ABSTRACT

Algae are important components of riverine food webs and are used in biomonitoring to assess nutrient enrichment. Their abundance is regulated by factors affecting growth rates (light, nutrients and temperature) and by losses associated with grazing, washout and sedimentation. Monitoring by the VA DEQ for the Chesapeake Bay Program has documented consistently high

algal abundances in the tidal freshwater segment of the James River (proximal to the VCU Rice Center). Chlorophyll concentrations at this location are typically two- or three- fold higher than those observed in the upper (riverine) or lower (estuarine) segments of the James. We investigated phytoplankton growth and loss processes in this segment of the river to better understand the mechanisms that contribute to persistent algal blooms. Our findings suggest that the location of the blooms is due in part to natural features of the channel and to the proximity of anthropogenic nutrient inputs. At this location, the geomorphology of the James transitions from a riverine (narrow, deep) to a more estuarine (broad, shallow) channel form resulting in greater light exposure for phytoplankton. More favorable light conditions enable phytoplankton to exploit available nutrients. On an annual basis, nutrient inputs from the upper watershed (principally non-point sources) dominate. Point source inputs associated with wastewater treatment facilities likely act to maintain high nutrient levels during summer, low-discharge conditions. Grazing rates by zooplankton were low and suggest that little of the algal production is directly passed to higher trophic levels.

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FACTORS LIMITING BENTHIC ALGAL ABUNDANCE IN VIRGINIA STREAMS OF THE COASTAL PLAIN

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KEY WORDS: streams, algae, nutrients, impairment, biomonitoring

ABSTRACT

Algae are important components of stream food webs and often used in biomonitoring assessments. Little is known regarding the factors that limit their abundance in streams of the VA Coastal Plain. The surficial geology of the Coastal Plain is predominately sandy deposits, which comprise the dominant substrate in streams of this region. In a comparative study of five streams located near the VCU Rice Center, we quantified substrate composition, light availability, and nutrient concentrations to assess their relative importance in determining benthic algal abundance. The proportion of stream area comprised of hard substrates was found to be a significant predictor of variation in benthic algal abundance (r^2=0.66). An experimental component comparing algal colonization on artificial hard substrates (tile) to the natural substrate reinforced the importance of substrate stability. Hard substrates, which included gravel and aggregated clay likely provided greater stability for algal colonization relative to sand and silt deposits, resulting in lower mortality from scouring and sedimentation. Incident solar radiation was found to be a secondary factor affecting algal abundance with shaded streams exhibiting

lower benthic chlorophyll. Where substrate and light conditions were favorable, relationships between benthic algal abundance and dissolved phosphorus concentrations were observed. Results from this study highlight the challenges of using benthic algal abundance as an indicator of nutrient impairment in streams of the Coastal Plain. Our findings suggest that nutrient enrichment is likely to enhance algal production only in streams where substrate and light conditions are favorable.

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INCREASING OCCURRENCE AND DEVELOPMENT OF POTENTIALLY HARMFUL ALGAL BLOOMS IN VIRGINIA TIDAL RIVERS

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KEY WORDS: algal blooms, Virginia rivers

ABSTRACT

Algal blooms are natural phenomena that are common occurrences in Virginia tidal tributaries. Their bloom threshold levels are species specific, with dinoflagellates the most common bloom producers in Virginia tidal waters. The historical records and present status of the bloom producing species are presented. These taxa include the dinoflagellates *Akashiwo sanguinea, Alexandrium monilatum, Cochlodinium polykrikoides, Dinophysis acuminata, Heterocapsa rotundata, H. triquetra, Karlodinium veneficum, Noctiluca scintillans,* and *Prorocentrum minimum,* plus the cyanobacterium *Microcystis aeruginosa* and the ciliate *Myrionecta rubra*. Several of these species produce toxins, and others cysts that become the source of subsequent populations in these waters. Within recent decades many of these algae have increased their bloom producing status, including several potentially harmful species.

INTRODUCTION

The phytoplankton in Virginia's tidal tributaries undergoes significant seasonal changes in their composition and abundance (Marshall *et al*. 2005a). Within this dynamic series of events there frequently occurs a larger growth response from one or more algal species resulting in a bloom where cell numbers increase rapidly to high concentrations (Marshall 2008a). Smayda and Reynolds (2001) describe this as a stochastic response by the species, and their ability to take advantage of prevailing conditions within the water more efficiently than others present. Most of these blooms will produce a visible color signature in the water column (*e.g.*, a red or mahogany tide) due to the pigments contained in the cells of the blooming species.

Marshall (1989) reviewed reports of blooms in the Chesapeake Bay estuarine complex occurring 1960-1989 and reported they occurred more frequently in the tributaries entering the Bay (67%), with their highest incidence (54%) during summer. Their bloom concentrations were generally at 10^3 to 10^4 cells mL^{-1}. In comparison, present blooms in these tributaries are still common during summer, with several having increased abundance levels, duration and scope. There is additional concern that these taxa include several potential toxin bloom producers (Marshall *et al*. 2005b, 2008a). Long-term studies (ca. 20 years) in these waters have also identified significant increases in total phytoplankton abundance and biomass, in addition to several increasing station trends in total nitrogen and total phosphorus levels (Marshall *et al*. 2003a, 2009). Increasing biomass trends of diatoms, chlorophytes, and cyanobacteria were also indicated. Our monitoring records indicate peak diatom development occurred during periods of increased river discharge, whereas, chlorophytes, cyanobacteria, autotrophic picoplankton, and euglenophyte development was more closely related to reduced flow and more stable water conditions (Marshall and Burchardt 1998, 2003, 2004, 2005). The most active time for dinoflagellate blooms ranged from early spring through autumn, and frequently following prior days of rainfall. In general, dinoflagellate blooms often were associated with rising temperatures, increased residency time, and reduced flow within these rivers. The occurrences of these blooms have been previously addressed by Marshall (1995, 1996, 2003a) and Marshall *et al*. (2008a, 2009). The objectives of this paper are to identify major bloom producing algae in these Virginia tributaries, to establish bloom threshold levels for these taxa, and provide information regarding their current status in these waters.

METHODS

The Old Dominion University Phytoplankton Analysis Laboratory has been monitoring algal blooms within Virginia Rivers and the Chesapeake Bay since 1985, as a component of the Chesapeake Bay Monitoring Program. The majority of these bloom samples have been provided by the Virginia Department of Health Shellfish Sanitation Division and the Virginia Department of Environmental Quality. Additional water samples have been taken by our laboratory. Collections were centered in the Elizabeth, James, York, Rappahannock, and Potomac rivers, plus their associated sub-estuaries. Approximately 440 samples were examined annually over this time period from 50-80 estuarine sites (Fig. 1) where salinities ranged from tidal freshwater to polyhaline locations. The water samples (0.5 or 1.0 L) were taken at the surface (< 1m) and fixed on station with Lugol's solution (2-3 mL). Examination followed using a modified Utermöhl procedure at 300X and 600X magnification for species identification and cell counts (Marshall *et al.* 2009). This protocol was often supplemented with scanning electron microscopy, and more recently using PCR analysis to verify the presence of several potentially harmful taxa (Tang *et al*. 2008). Numerous changes have been made in the nomenclature of the species discussed here from those originally reported in earlier studies. To address these changes, the currently accepted species name is given, followed in parentheses by previously referenced names for these taxa.

RESULTS

Within recent decades several bloom-producing algae have become more established in Virginia tidal waters (Marshall *et al*. 2008a). These include several potentially toxic species that represent a specific threat to regional shellfish and fish populations, with others contributing to the degradation of the water quality within these river systems. A common water quality impact during or following a major bloom event is reduced oxygen concentrations within the water column resulting in stress or deaths among the local biota. To discuss these bloom producing agents further they have been divided into 3 categories regarding their presence in Virginia tidal waters. These are: A) the historical bloom producers gaining in abundance, B) more recently established species having an expanding range of development, and C) algae considered periodically invasive species to this region.

A. Prevalence of historical bloom producers: This category includes those species noted in earlier studies that have developed into major bloom producers that characterize the dominant algal flora in these tidal waters. They are generally indicative of species found in fertile estuaries that are capable of extended periods of development, or as common background species to other species and occur generally as bloom producers from spring through autumn.

1. *Prorocentrum minimum* (Pavillard) Schiller (*Prorocentrum triangulatum, Exuviaella mariae-lebourae*) (Fig. 2A). Early records of this species were reported for the Patuxent (Morse 1947) and James (Marshall 1967a) rivers, and possibly this is the smaller *Prorocentrum* mentioned by Wolfe and Cunningham (1926) in their Bay study that resembled *Exuviaella*. Bloom levels were reported for *P. minimum* in the Potomac, Rappahannock, and York rivers by Mackiernan (1968), Zubkoff and Warinner (1975), and Zubkoff *et al*. (1979), and by Patten *et al*. (1963) in the lower Bay. Tyler and Seliger (1978) discuss further its seasonal transport and broad distribution for bloom development within Chesapeake Bay. *P. minimum* continues to be a major bloom producing species within the Bay and these tidal tributaries, in addition to maintaining its presence in sub-bloom levels throughout the year (Marshall *et al*. 2005a). Over the past 2 decades peak concentrations, have occurred within these rivers in spring (10^4 cells mL^{-1}), with years (2000, 2001) of higher abundance levels reaching 10^5 cells mL^{-1}. Blooms are brownish/red in coloration. Bloom threshold levels began at $>10^3$ cells mL^{-1} and occurred most frequently at temperatures 18-28 ^oC, salinities 8-14, and Secchi depth readings <1.0 m. These concentrations are considerably higher than those reported 5 decades ago for Chesapeake Bay by Wolfe and Cunningham (1926) which were 10^2-10^3 cells mL^{-1}. This same relationship of increased presence within the Bay tributaries is also likely since current Bay concentrations are also at these higher levels. A typical bloom of *P. minimum* over an extended time period would contribute to degraded water quality conditions, especially in the shallow sub-estuaries of these rivers (*e.g*., reduced oxygen concentrations). Although not associated with toxic events in this region to date, strains of this species have been identified as potential toxin producers, and associated with shellfish poisoning and human illness (Steidinger 1993, Heil *et al*. 2005).

2. *Heterocapsa triquetra* (Ehrenberg) Stein (*Peridinium triqueta*, *P. triquetrum*). Early records of this species are from the Patuxent River (MD) by Morse (1947) and as a bloom producing species in several Virginia tributaries reported by Zubkoff and Warinner (1975), and also recorded in the James River (Marshall 1967), and lower Chesapeake Bay (Patten *et al*. 1963. Marshall 1980). This is a common spring bloomer in these rivers with increased abundance occurring in early spring, *e.g*., March through May (10^2 to 10^3 cells mL^{-1}). Lowest mean monthly concentrations occurred during summer with an increasing presence in autumn and continuing into spring. Bloom threshold levels begin at 10^3 cells mL^{-1} with the highest

concentrations noted in these rivers in 1993 at ca. 2,500 cells mL^{-1}. This is one of the most common dinoflagellates that characterize the flora of these rivers. It is non-toxic, and is a cyst producer, with these cysts very common in the sediment of these rivers, and they would provide a source of cells for these waters throughout the year (Seaborn and Marshall 2008).

3. *Akashiwo sanguinea* (*Gymnodinium sanquineum* Hiraasaka, *G. splendens*, *G. nelsonii*) (Fig. 2B). This species is noted by Morse 1947 in the Patuxent River, and is one of the bloom producers mentioned by Mackiernan (1968) and Zubkoff and Warinner (1975) in the York River and other tributaries of the Bay. Its presence in the lower Bay was noted by Patten *et al*. (1963) and Marshall (1980). This is a large deeply pigmented species that is common in the lower reaches of these tidal rivers. Its development, often to bloom levels occurred most frequently between April and September. Over the past 20 years *A. sanguinea* had variable and inconsistent abundance levels, and often is a background species during blooms of other dinoflagellates. Mean annual concentrations were <10 cells mL^{-1} and bloom maxima ca. 80-180 cells mL^{-1}, often producing a brownish discoloration to the water due to pigments within these cells. Bloom threshold levels would begin at >10 cells mL^{-1}. This species has been reported to produce toxic substances (Steidinger 1993), but to date has not been associated with toxic events in these rivers. It is presently in a low level category as a bloom producer, but continues to be a common floral component at sub-bloom concentrations.

4. *Heterocapsa rotundata* (Lohmann) Hansen (*Karlodinium rotundatum*, *Massartia rotundata*). Patten *et al*. (1963) reported this species producing "red water" in the York River. Marshall (1994) described it as one of the most common species in Chesapeake Bay, appearing in 60.6 % of the water samples analyzed within a 7-year monitoring period. This same high representation among the algal flora also occurred in the tributaries. It had a year round presence, with repeated seasonal periods of maximum development occurring throughout the year. This is a non-toxic species, with mean high monthly concentrations at 200 – 700 cells mL^{-1}, and representing its bloom threshold level. If not the dominant component, it is frequently a prominent background species to the dominant bloom producers. It has not been associated with detrimental impacts to the biota or water quality.

5. *Myrionecta rubra* Jankowsky (*Mesodinium rubrum*). This is a red pigmented ciliate that contains a cryptophyte symbiont that with bloom concentrations produces "red tides". It is a frequent bloom producer in Chesapeake Bay and Virginia tributaries that includes the Potomac, Rappahannock, York, and James rivers. Bloom thresholds begin at $>10^2$ cells mL^{-1}, with the blooms occurring generally from spring into autumn, and are considered non-toxic. These blooms have occurred sporadically and typically localized within these rivers and have been short lived. An exception to this pattern occurred in October 1995 when a major bloom of *M. rubra* developed over a large section of the lower Chesapeake Bay with concentrations of ca. 500 cells mL^{-1} (Marshall 1996). Other more extensive blooms of *M. rubra* have probably occurred within these waters, but were not documented, and would be expected to occur in the future.

B. Expanded development of bloom producers: This category includes species whose prominence in these waters has increased significantly in recent years, and specifically includes taxa with strains known to be toxin producers of world wide significance.

1. *Cochlodinium polykrikoides* Margalef (*Cochlodinium heterolobatum*) (Fig. 2C). Several species are mentioned in the early references in these waters. From net tows taken in 1943-45 Morse (1947) reported the rare presence of *Cochlodinium* sp. and *C. schuetti* in the Patuxent River (MD). Griffith (1961) noted a species in the Chesapeake Bay that appeared to be *C. catenatum.* Patten *et al*. (1963) detected possibly *C. vinctum* in the lower Chesapeake Bay, and noted patches of red tide in the lower Potomac and York rivers. Later, Wood (1966) indicated *C. helicoids* as seasonally appearing in the York River. These earlier reports did not indicate chain formation present among these observations and further documentation of their identification is lacking. The presence of *Cochlodinium polykrikoides* (*C. heterolobatum*), a chain-forming dinoflagellate was later described by Mackiernan (1968), Zubkoff and Warinner (1975), and Zubkoff *et al*. (1979) as a bloom producer in the lower York River, along with several other dinoflagellates. They surmised these cells may have come from benthic cysts, or entered the region by sub-surface transport, and predicted more blooms if favorable conditions would prevail. In support of this prediction, *Cochlodinium* was initially detected in our sub-pycnocline water samples at several Bay and tributary stations beginning in 1986. Also, Seaborn and Marshall (2008) reported *Cochlodinium* cysts in several of these tributaries as "seed" populations for its future development. During September 1987, a major *Cochlodiniu*m bloom occurred along the Virginia Beach shoreline that extended out of Chesapeake Bay and along the Atlantic coastal waters of Virginia. In September 1992, another major bloom moved southward from the Rappahannock and York rivers, entering many of the tributaries and inlets along the western shoreline of the lower Chesapeake Bay, and then moved out of the Bay, maintaining bloom concentration along the North Carolina coast (Marshall 1995b). Since 1992 annual blooms of *C. polykrikoides* have been regular occurrences in the Lafayette, Elizabeth, and Warwick rivers, including their smaller tributaries. Prior to this period *Cochlodinium* was not noted in an earlier seasonal study at the James River entrance, or in the Elizabeth River (Marshall 1967a, 1967b). The 1992 bloom may have been instrumental in "seeding" many of these lower Bay tributaries with *Cochlodinium* cysts. Over the past 2 decades the earliest development of *Cochlodinium* has been noted in a small residentially located tributary (Knitting Mill Creek) of the Lafayette River. Massive blooms began to appear here annually following 1992 in late summer and appeared subsequently to enter the Lafayette, Elizabeth, and lower James Rivers. These blooms were associated with a dense brownish coloration of the water due to the cell's pigments, and often a noxious odor upon their decomposition. Tidal flow above and below the pycnocline would be able to transport these cells throughout the Bay ecosystem and the Virginia coastal waters. Bloom thresholds begin at 10^2 cells mL^{-1} with the highest concentrations noted to date occurred in Knitting Mill Creek (August 29, 2008) at 115 X 10^3 cells mL^{-1}. In 2007 an extended bloom (5 weeks) of *Cochlodinium* occurred in the Lafayette/Elizabeth river complex at concentrations of 10^2 to 10^3 cell mL^{-1}. Chain lengths of this species often include a series of 4, 8, or 16 cells, in addition to solitary cells. Strains of this taxon are known to be highly toxic to finfish and shellfish at concentrations beginning at 10^2 cells mL^{-1} (Tang and Gobler 2009).

2. *Karlodinium veneficum* (Ballantine) J. Larsen (*Gymnodinium galatheanum*, *Gyrodinium galatheanum*, *Karlodinium micrum*) (Fig. 2D). Li *et al*. (2000) have identified this species as a common bloom producer (>4 X 10^3 cells mL^{-1}) within Chesapeake Bay, and it is known to produce toxins that kill fish (Goshorn *et al*. 2004). In recent years it has been associated with spring blooms in the Potomac River, in addition to numerous inlets and streams along the river's shoreline in Virginia and Maryland. A major *Karlodinium* bloom developed in the Potomac

River from June through August in 2007, with concentrations ranging from 10-33.7 X 10^4 cells mL^{-1}. Blooms of this taxon are often accompanied by increased abundance of other dinoflagellates, *e.g*., *A. sanguinea* and *H. rotundata*. The bloom threshold for this species would begin at ca. 10^3 mL^{-1}. Deeds *et al*. (2002) and Gorshorn *et al*. (2004) describe the toxicity of *K. veneficum* within an aquaculture facility and a Bay estuary, with associated fish kills. Toxin production is associated with bloom concentrations. In addition to its presence in the Potomac River, this species has been identified (PCR) at sub-bloom concentrations in the James and York rivers.

3. *Microcystis aeruginosa* (Kützing) Kützing. This cyanobacteria taxon is usually associated with freshwater habitats. Cells occur in colonial formations within a gelatinous matrix, and are most abundant in nutrient rich waters. It has been a common component within the tidal freshwater regions of these rivers, but also occurs in regions of low salinity (*e.g*., <5 ppt), with its concentrations decreasing into the higher saline regions of these rivers. Re-occurring annual blooms of this species have been common events in the lower saline regions of the Potomac River and the adjacent tributaries and inlets along its shoreline (Tango and Butler 2008). Concentrations of ca. 10^6 cells mL^{-1} have frequently occurred during June to August in the tidal fresh and oligohaline waters of this river system. These Potomac bloom events were associated with periods of rising water temperatures and increased residency time producing a dark greenish coloration to the water. Microcystin toxins have also been detected with these blooms in the Potomac and other Chesapeake Bay tributaries (Tango and Butler 2008, Marshall *et al*. 2005b, 2008a). These extensive and long lasting blooms in the Potomac River were not common in the tidal James, York, Rappahannock, or Pamunkey rivers. The Commonwealth of Virginia established a chlorophyll level of 27.5 µg L^{-1} (27.5 mg Chl m^{-3}) and 50,000 cells mL^{-1} as bloom criteria and levels of concern for the potential toxin producing *M. aeruginosa*. In general long term monitoring (1985-2005) over the past 2 decades has indicated significant trends of increased cyanobacteria biomass within regions of the Bay and these tidal rivers (Marshall *et al*. 2005b).

C. Invasive or exotic species that produce blooms. This category includes species that are new to the region as a bloom producer, or those that periodically may enter or develop in this region.

1. *Dinophysis acuminata* Claparede & Lachmann (Fig. 2E). Morse (1947) identified this species as rare in the Patuxent River with Patten *et al*. (1963) and Marshall (1980) indicating it once in the lower Chesapeake Bay. It is a common oceanic coastal species and its occurrence in the lower Bay is now frequently noted in our monitoring in sub-pycnocline waters in the lower Bay, but major bloom events for this species in the Bay tributaries have been rare. A major bloom did occur within several sub-estuaries far north in the Bay in the Potomac River that lasted from February to April 2002 (Marshall *et al*. 2003b). Peak cell concentration during this period reached 235 cells mL^{-1}. Bloom thresholds for this species would be 10-100 cells mL^{-1}. Since its presence was noted in our sub-pycnocline records prior to this bloom it was suggested this was the conduit for reaching the Potomac waters (Marshall *et al*. 2003b). Tyler and Seliger (1978) have previously identified this pathway for the re-population of *Prorocentrum minimum* into the northern regions of Chesapeake Bay. *D. acuminata* is a potential producer of okadaic acid, the toxin resulting in diarrhetic shellfish poisoning (Marcaillou *et al*. 2005). Low

concentrations of okadaic acid were detected during the 2002 bloom event within the Potomac River.

2. *Alexandrium monilatum* (Howell) Taylor (*Gonyaulax monilata*) (Fig. 2F). This is a deeply pigmented chain forming species, often represented by lengths of 4, 8, 16, or more cells. It produces an ichthyotoxin and is associated with fish kills (Gates and Wilson 1960). Bloom thresholds begin at 10^2 cells mL^{-1}. This species was first reported by Marshall *et al*. (2008a) as a co-dominant during a bloom of *C. polykrikoides* in the York River, Sarah's Creek, and Chesapeake Bay in September 2007. Concentrations in the York River ranged from 240 to 4,270 cells mL^{-1} and Sarah's Creek 1,880 cells mL^{-1}. The Bay sample was < 1 cell mL^{-1}. This species was also observed in September 2008 in the James and York rivers at concentrations of 0.5 and 40 cells mL^{-1} respectively, and September 2009 in the York River at concentrations of < 1 cell mL^{-1}. When dense, the cells will discolor the water with a brownish red appearance. It is a cyst producer, so if the recent populations produced adequate numbers of cysts in these waters, *A. monilatium* will continue to occur in these waters and pose a future threat to regional fisheries.

3. *Noctiluca scintillans* (Marcartney) Kofoid & Swezy (*N. miliaris*). This is one of the largest dinoflagellates that may be found in the Bay and its tributaries having a size range between 200µ to ca. 1 mm. This was a common species in the Bay during cruises in 1915-1916 with peak concentrations at 2-3 cells mL^{-1} (Wolfe and Cunningham 1926, Cowles 1930), but it has become less common in recent decades. It is also mentioned by Morse (1947) and included in the Bay flora by Marshall (1994). There have been 2 autumn blooms of *N. scintillans* occurring in both 1987 and 2000 within these tributaries, and a single bloom in the lower Bay in 2002. Each were short lived with bloom thresholds established at >1 cell mL^{-1}.

Several other bloom producing species in these tributaries have been discussed elsewhere (Marshall 1994, Marshall *et al*. 2005a, Tang *et al*. 2008). These include the potential toxin producers *Pfiesteria piscicida* Steidinger and Burkhold and *P. shumwayae* Glasgow and Burkholder. Their presence continues to be sporadically detected in these tributaries, but in low concentrations. Another dinoflagellate common to the Bay, but rarely at bloom levels in these rivers is *Ceratium furca* (Ehrenberg) Claparede and Lachman (Marshall 1995).

SUMMARY

1. Dinoflagellate blooms are common occurrences in the tidal waters of the Chesapeake Bay tributaries and they occur mainly from spring through autumn.
2. Comparing their present status to that recorded from earlier studies, many of the bloom producing species have increased in their distribution and abundance levels.
3. In 2007, we identified the ichthyotoxic *Alexandrium monilatum* in the York River, and subsequently in 2008 and 2009 in the York and James rivers. Its ability to form cysts may lead to its continual presence in this region as an annual bloom producer.
4. Cyst formation has apparently been successful in the range expansion of *Cochlodinium polykrikoides* and possibly *Alexandrium monilatum*. *Heterocapsa triquetra* has remained a dominant species within these rivers aided by seeding these rivers with cyst stages of its life cycle.

5. The ichthyotoxic *Karlodinium veneficum* has become a common bloomer in the Potomac River and various Maryland locations. Presently it has also been recorded in Virginia rivers at sub-bloom concentrations, but should be considered as having the potential of produce major blooms at these sites.
6. The environmental conditions within Virginia Rivers are receptive to continued bloom development from flora presently in these waters, as well as, others that may enter these river systems.

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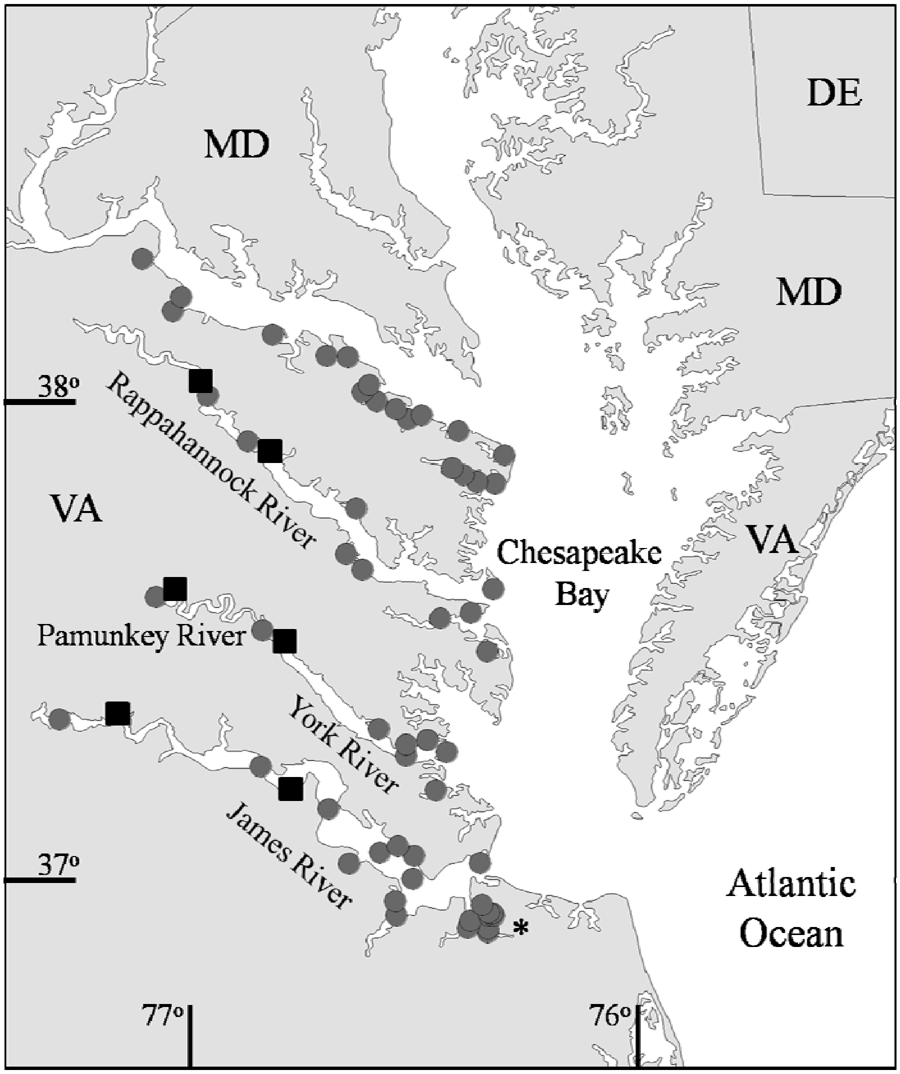

Figure 1. Representative station locations monitored 1985-2009 for algal blooms. Samples taken by the Virginia Department of Environmental Quality (■) and Virginia Department of Health Sanitation Division (●). * = location of Elizabeth and Lafayette rivers. VA = Virginia, MD = Maryland, DE = Delaware.

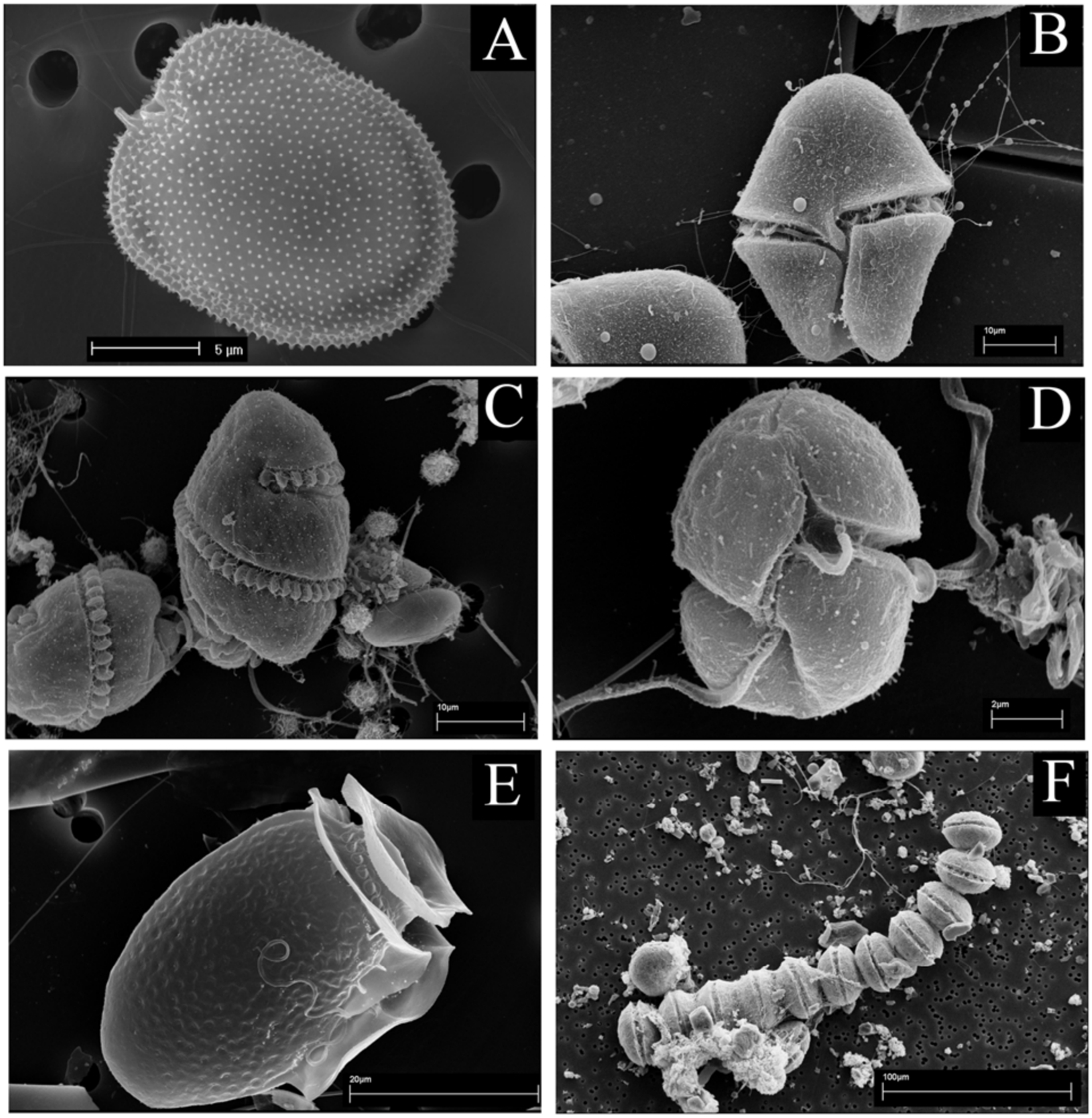

Figure 2. Scanning electron micrographs of dinoflagellate bloom species. A. *Prorocentrum minimum*, B. *Akashiwo sanguinea*, C. *Cochlodinium polykrikoides*, D. *Karlodinium veneficum*, E. *Dinophysis acuminata*, and F. *Alexandrium monilatum.*

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CONTROLS ON THE FORMATION AND TRANSPORT OF *COCHLODINIUM POLYKRIKOIDES* BLOOMS IN LOWER CHESAPEAKE BAY

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KEY WORDS: algal blooms, eutrophication, climate change

ABSTRACT

Massive blooms of the harmful alga *Cochlodinium polykrikoides* Margalef occurred in lower Chesapeake Bay and its tributaries from August to late September of 2007 and from late July through early September 2008. The Lafayette and Elizabeth Rivers appear to act as the initiation grounds for *Cochlodinium* bloom formation. Bloom initiation appears to be correlated with intense, highly localized rainfall events, and the increase in algal abundance is greatest during neap tides. During rainfall events, stratification increases and nutrient loading is high, promoting rapid bloom development. *Cochlodinium* can take up a wide range of nitrogenous compounds, thus no single nitrogen (N) species can be linked to bloom formation. Spring tides increase tidal flushing and transport of the bloom organism from the Lafayette and Elizabeth Rivers into the lower James River. Tidally driven eddy formation and passive injection of particles into a frontal zone in the lower James River facilitates upriver transport of bloom organisms once they enter the James River. Bloom organisms become entrained in deep water, and are transported upriver by typical estuarine net flow. Because this phenomenon is tidally controlled and the system is nutrient replete, once *Cochlodinium* blooms manifest in the Lafayette River, physical forcing controls the extent and duration of the bloom in the James River and lower Chesapeake Bay. A confluence of physical controls including seasonal rainfall patterns, increased stratification and nutrient loading, spring-neap modulation, and complex estuarine mixing and circulation allows *Cochlodinium* to form massive blooms in the lower Chesapeake Bay and its tributaries.

INTRODUCTION

Over the last 20 years, sections of the lower Chesapeake Bay and its tributaries have experienced a decrease in phytoplankton diversity and an increase in the abundance of potentially harmful algal taxa (Dauer *et al*. 2005, Marshall *et al*. 2003). Worldwide, algal blooms appear to be increasing in frequency due to cultural eutrophication (Anderson *et al*. 2002, Glibert *et al*. 2006, Paerl 1988, Pinckney *et al*. 2001, Smayda 1990).

During the summers of 2007, 2008, and 2009, massive blooms of the harmful alga *Cochlodinium polykrikoides* Margalef occurred in lower Chesapeake Bay and its tributaries. These blooms extended for more than 30 nautical miles from the mouth of Chesapeake Bay into the James River and further into the Elizabeth and Lafayette River basins (see Figure 1 for map of the region). The 2007 bloom forced beach closures as the bloom penetrated into the Atlantic Ocean and was transported south along the coast toward the Outer Banks. During the 2008 bloom, surface dissolved oxygen concentrations decreased to hypoxic or near-anoxic levels following the collapse of the bloom, resulting in widespread fish and invertebrate mortality in the Elizabeth and Lafayette Rivers.

Cochlodinium polykrikoides has a very flexible metabolism and is capable of utilizing a variety of nitrogenous compounds to support its growth (Mulholland *et al*. 2009). Mulholland *et al*. (2009) demonstrated that communities dominated by *Cochlodinium polykrikoides* took up every nitrogen (N) species offered, suggesting that no single N species is necessary to promote bloom growth. Nutrient concentrations in the Lafayette River, where the 2008 and 2009 blooms first initiated, are typically high and the system is highly eutrophied throughout the year (Morse *et al*. in preparation), providing an ideal location for bloom development.

Cochlodinium polykrikoides is a regular component of the phytoplankton community in the lower Chesapeake Bay region (Marshall 1995), and is often abundant in the Lafayette River during the summer months (Mulholland unpublished data). In a study by Seaborn and Marshall (2008), *Cochlodinium* cysts were the second most predominant dinocysts present in sediments from the James River, and cyst abundance increased near the mouth of the Elizabeth River (Seaborn and Marshall 2008). These authors did not sample in the Lafayette and Elizabeth Rivers however, and their study was conducted in 1996, well before the blooms reported on here. *Cochlodinium* cysts are likely to have accumulated in the Lafayette and Elizabeth Rivers, providing a seedbed for subsequent blooms.

We used weekly underway mapping of chlorophyll *a* (chl *a*), salinity, and dissolved oxygen from surface waters in the James, Elizabeth, and Lafayette Rivers from June through September 2008, when *Cochlodinium* blooms typically manifest, in addition to hydrological and meteorological data, to better understand the triggers and factors controlling the formation of these massive blooms of *Cochlodinium polykrikoides* in the lower Chesapeake Bay region.

METHODS

The Hampton Roads Sanitation District collects DataFlow data using an underway-sampling system during weekly cruises in the lower James River and Elizabeth Rivers between March and September. The James River cruises are partitioned into a mesohaline (JMSMH shown in the red oval) and polyhaline (JMSPH shown in the blue oval) region that are sampled on consecutive days (Figure 1). A third weekly cruise was added in 2008 to provide coverage in the Elizabeth and Lafayette Rivers (ER-LAF, shown in the green oval) (Figure 1). During these cruises, water is pumped continuously while underway from 1m depth into a flow through system containing an YSI 6600 datasonde, which measures temperature, salinity, pH, dissolved oxygen, turbidity and fluorescence. These parameters are measured continuously during the cruise and spatial and temporal data are added to the data set via GPS. The resulting datasets were interpolated and mapped to give a spatial 'snapshot' of surface chlorophyll (measured as fluorescence), which provides a picture of bloom extent. When viewed as a timeseries, these maps allow a visualization of the initiation and transport of blooms throughout the lower Bay. Further details of the DataFlow system and data visualization can be found at http://www2.vims.edu/vecos.

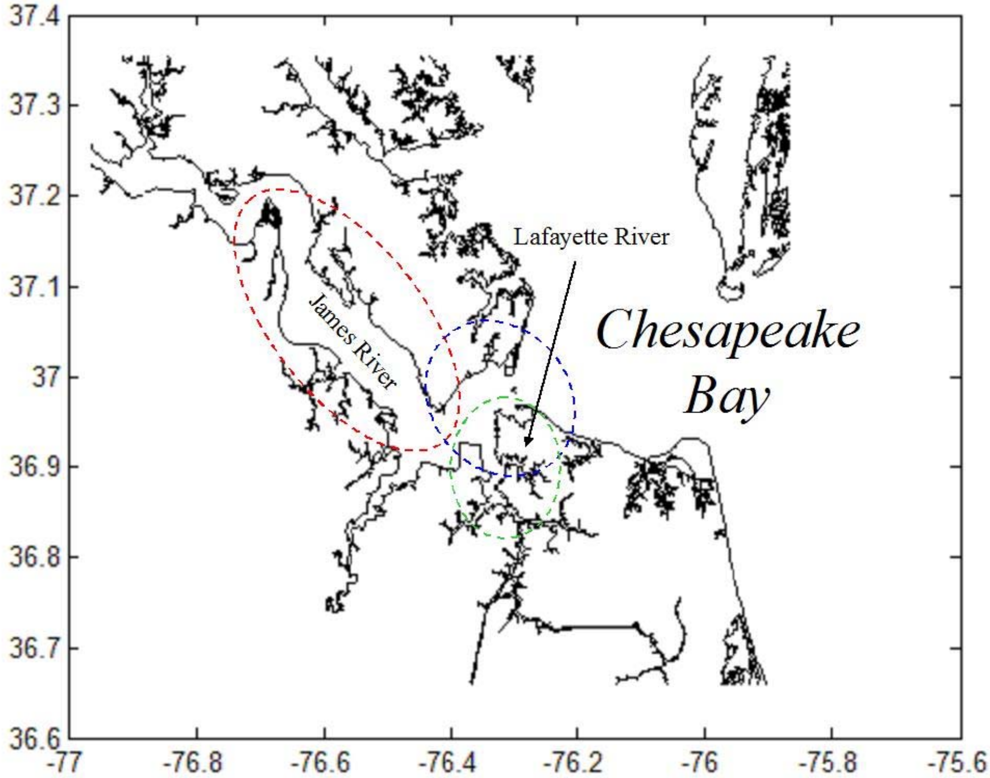

Figure 1. Map of the study area including the James River (red and blue ovals, JMSMH and JMSPH cruises, respectively) and Elizabeth River basin, including the Lafayette River (green oval, ER-LAF cruise)

In addition to the DataFlow system, A CTD equipped with sensors to measure pressure, temperature, fluorescence, and salinity was deployed at regular stations to give vertical profiles. This allowed the determination of the degree of stratification and the location of *Cochlodinium* in the water column over time. *Cochlodinium* exhibits strong vertical migration toward the surface during the daytime and often returns to the deeper waters during the night.

Routine phytoplankton samples were collected from bloom sites to identify and confirm that the dominant species was *Cochlodinium polykrikoides*. Data for precipitation and wind speed were taken from the Norfolk Naval Air Station (NAS-Norfolk), and tidal predictions and tidal height data were obtained from the National Oceanic and Atmospheric Administration's Physical Oceanography Real Time Series (NOAA PORTs) station at Sewell's Point in Norfolk, VA.

RESULTS

The 2008 *Cochlodinium polykrikoides* bloom initiated in the Lafayette River in early July (Figure 2, top row). Chlorophyll *a* concentrations increased in the Lafayette River in response to brief but intense precipitation events (Figure 3) in early to mid-July, primarily due to the increasing abundance of vegetative *Cochlodinium polykrikoides* cells in the upper reaches of the Lafayette River. Salinity decreases in the headwaters of the Lafayette River in response to these precipitation events (Figure 2, bottom row), as the Lafayette drains much of urban Norfolk, Virginia. Heavy precipitation occurred on July 6 and 23, 2008 (Figure 3), just as the *Cochlodinium* bloom was forming (Figure 2).

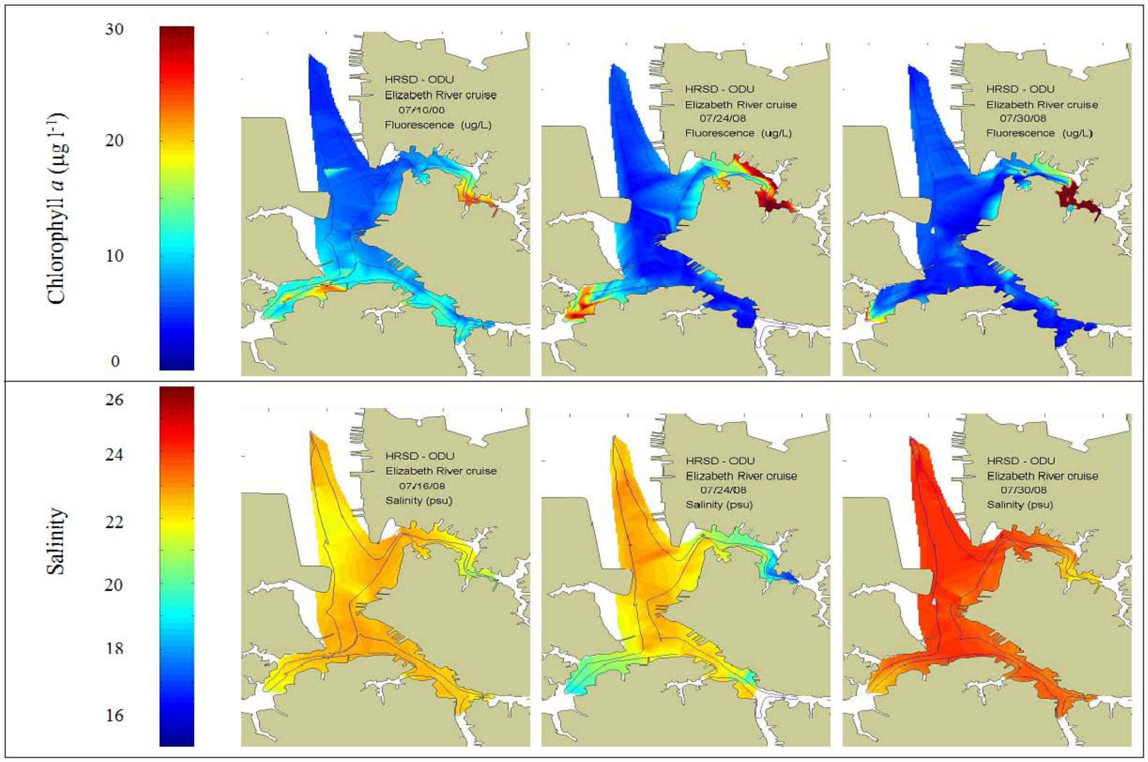

Figure 2. Surface chlorophyll *a* (μg l^{-1}, top row) and salinity (bottom row) timeseries showing bloom initiation in the Lafayette River in mid July during the ER-LAF cruises on July 16, 24, and 30, 2008. Chlorophyll *a* levels increase in response to freshwater input via rainfall, shown as decreased salinity in the headwaters of the Lafayette River.

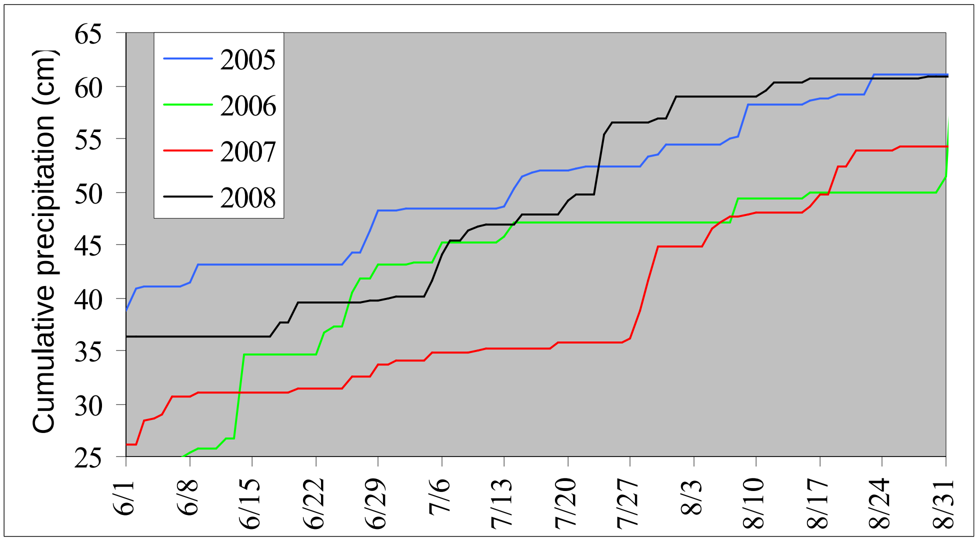

Figure 3. Cumulative precipitation measured at NAS-Norfolk, VA from June through August during 2005-2008.

Spring-neap cycling and tidal forcing has been shown to influence bloom formation, with blooms typically occurring during neap tides, and dissipating during spring tides (Cloern 1991). This was observed in the Lafayette River as well, with bloom formation occurring in early July during neap tides (Figure 4) between July 6-20, with increased transport from the Lafayette River into the Elizabeth River occurring during spring tides between July 30 and August 5 (Figures 4, 5).

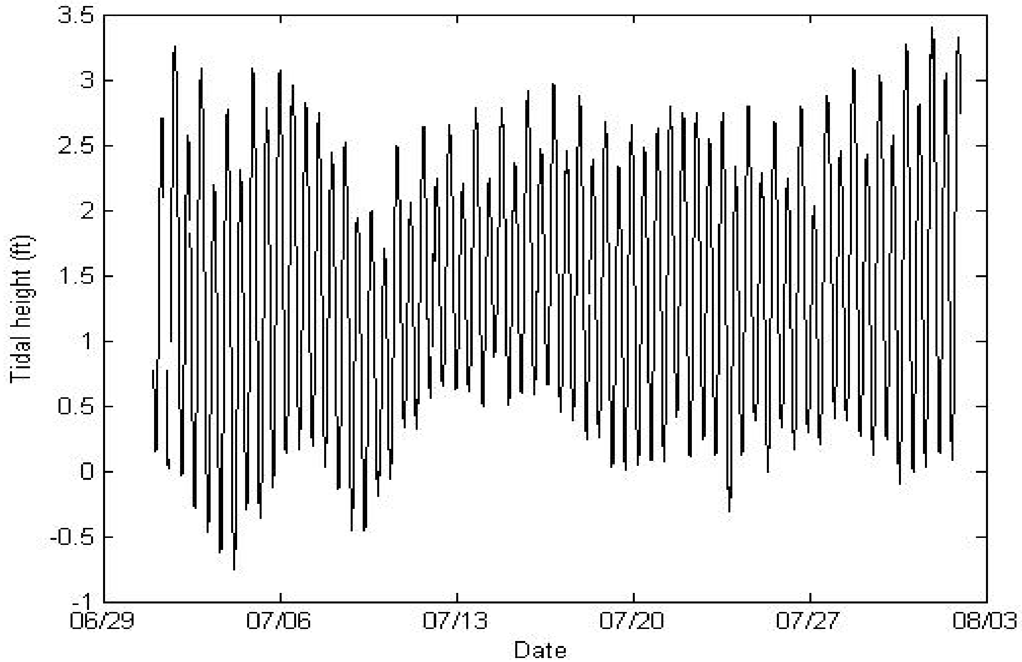

Figure 4. Tidal height measured at Sewell's Point in Norfolk, VA on the Elizabeth River during July 2008.

Transport of the *Cochlodinium* bloom from the initiation grounds in the Lafayette River into the Elizabeth River occurred as a result of increased flushing during spring tides due to tidal forcing in late July (Figures 3, 4, 5). The bloom was transported from the Elizabeth River into the lower James River between August 5 and 6 (Figure 5). One week later, the bloom was prevalent in the mesohaline portion of the James River (JMSMH, 8/13 Figure 5), upriver from Newport News Point, and was present in the polyhaline portion of the James River (JMSPH, 8/12, Figure 5) in the area of Hampton Flats, where a counterclockwise flowing eddy forms on ebb tides.

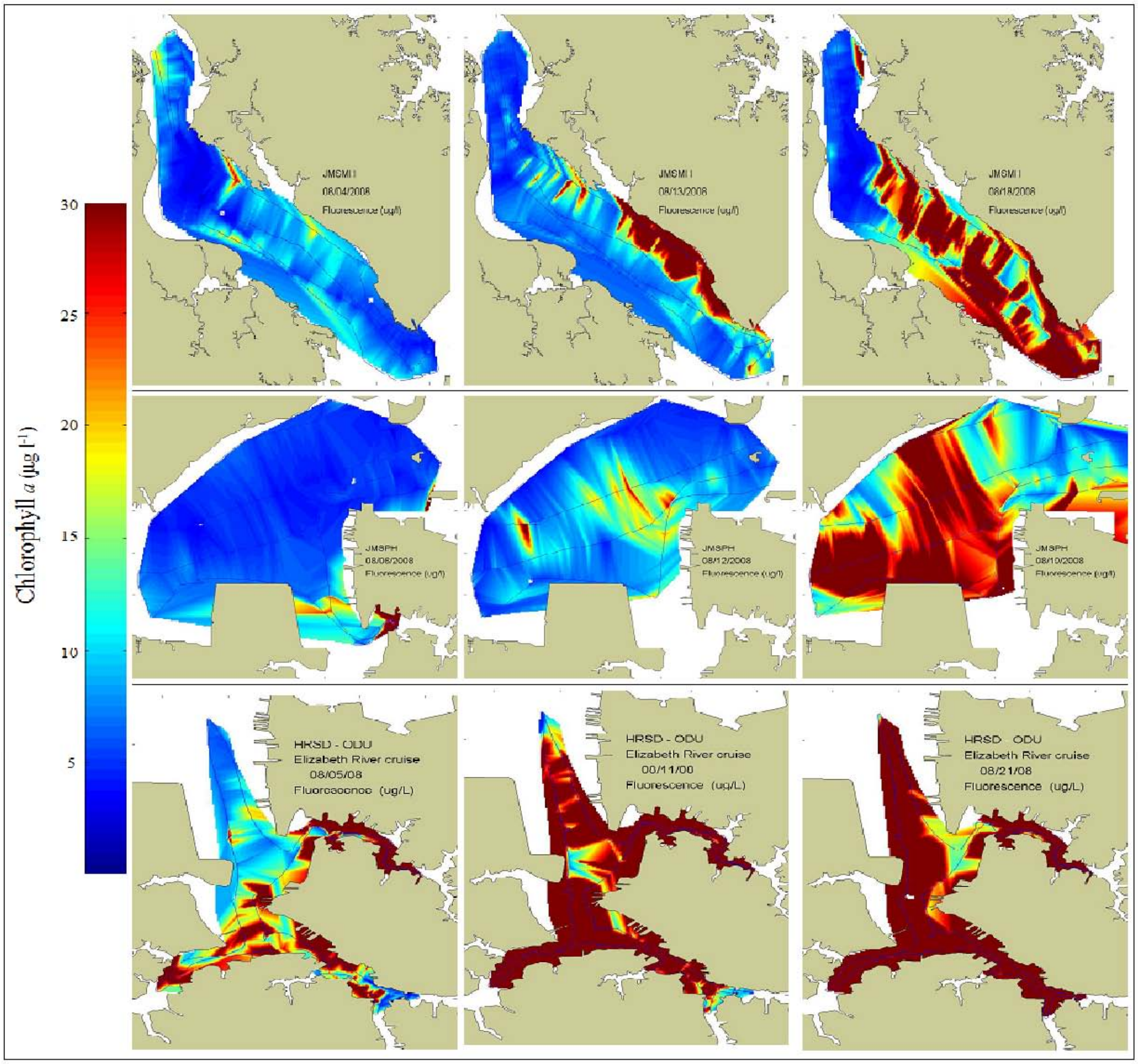

Figure 5. Surface chlorophyll *a* (µg l^{-1}) timeseries showing transport of the *Cochlodinium* bloom from the Elizabeth and Lafayette Rivers into the James River and lower Chesapeake Bay during 2008. The top row are JMSMH cruises on 08/04, 08/13, and 08/18, the middle row are JMSPH cruises on 08/06, 08/12, and 08/19, and the bottom row are ER-LAF cruises on 08/05, 08/11, and 08/21.

By August 19, the bloom was fully developed and extended over 20 nautical miles from the Elizabeth River into the James River and out into the Chesapeake Bay proper (data not shown). The bloom persisted in the JMSMH and ER-LAF through August 26, when a high-pressure system passed through the region bringing high winds (not shown). From the formation of the bloom in the Lafayette in early July to the bloom dissipation following high winds on August 26, the 2008 *Cochlodinium polykrikoides* bloom persisted for more than seven weeks, and affected more than 20 nautical miles of the lower Chesapeake Bay region from mid-Bay to the Ghost Fleet in the James River and nearly 10 nautical miles into the Southern branch of the Elizabeth River past downtown Norfolk and Portsmouth.

DISCUSSION

The Lafayette River is a shallow, well mixed sub-estuary to Chesapeake Bay. It drains much of urban Norfolk, Virginia, but has no freshwater end-member. As such, tidal influences, evaporation, and precipitation are the primary controls on salinity within the Lafayette River. Because of it's urban setting, nutrient concentrations in the Lafayette River are typically high, with dissolved inorganic nitrogen concentrations often above 30 µM (Mulholland unpublished data), and is classified as a highly eutrophied system. Summer precipitation characterized by highly localized brief but intense rainfall result in increased nutrient loading and increased stratification, conditions favorable for the formation of dinoflagellate blooms (Margalef 1978, Sellner *et al*. 2001).

These precipitation events appeared to be correlated with the timing of *Cochlodinium* bloom formation in 2007 (Mulholland *et al*. 2009), and also during the 2008 bloom, as salinity decreases in the Lafayette following precipitation and chlorophyll *a* increases in response to the freshwater pulse (Figure 2), presumably due to increased stratification and nutrient loading. Figure 6 shows salinity profiles in the Lafayette River between July 10 and July 30, during the time of bloom formation. The Lafayette River is typically well mixed (as shown in Figure 6), except following heavy precipitation in the summer months, when the surface waters become stratified, as was the case on July 24 (Figure 6). The effects of precipitation on July 6 (Figure 3) can be seen in the salinity profile from July 10, where the water column was well mixed several days after the precipitation event, but still showed a lower average salinity than normal for this time of year.

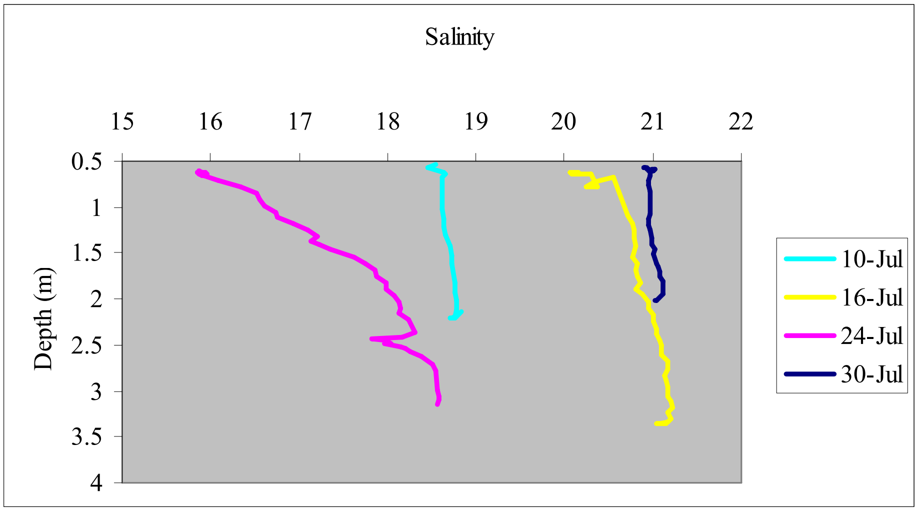

Figure 6. Salinity profiles in the Lafayette River at the Granby Street Bridge during ER-LAF cruise on July 10, 16, 24, and 30, 2008.

Increased stratification and nutrient pulsing from the precipitation events in late July, in conjunction with the favorable growth conditions caused by decreased vertical mixing during neap tides (Cloern 1991), resulted in the rapid growth of *Cochlodinium polykrikoides* in the Lafayette River.

Once a *Cochlodinium polykrikoides* bloom forms in the Lafayette River, a combination of tidal transport of the bloom organism into the Elizabeth and James Rivers, and the typical circulation pattern in the lower James River appear to control the duration and extent of the bloom throughout the James River and lower Chesapeake Bay region. A counterclockwise flowing eddy regularly develops on ebb tides on the opposite shore across from the mouth of the Elizabeth River (Shen *et al*. 1999). This eddy circulation brings saltier, denser water from the Bay into an area where a strong tidal front exists off Newport News Point. The result of this eddy flow is that the saltier, denser water subducts below the fresher less dense water at the tidal front and becomes entrained in the bottom waters, where typical net estuarine flow transports the bottom water upriver. A portion of the surface water transported out of the Elizabeth River due to tidal transport likely becomes entrained in this counterclockwise flowing eddy and is transported upriver in the James River. The timing of bloom formation in the upper James River mesohaline portion is consistent with this theory, and the bloom manifests along the eastern shoreline of the mesohaline portion of the James River, where upwelling of the bottom waters due to changes in local bathymetry is known to occur (Valle-Levinson *et al*. 2000).

Ruzecki and Hargis (1989) estimate that only 40% of any suspended particles within the area of eddy circulation around Hampton Flats will be retained within the James River, and of that 40%, a smaller subset will actually be transported up-estuary. This suggests that timing of the transport of *Cochlodinium* cells in the surface waters from the Elizabeth River into the James River is an important control on whether the bloom will manifest in the upper reaches of the mesohaline portion of the James River. As the eddy formation at Hampton Flats is subject to regulation by spring-neap cycling (Shen *et al*. 1999, Valle-Levinson *et al*. 2000), the export of *Cochlodinium* from the Elizabeth into the James during neap tides will likely have the greatest effect on upriver transport in the James River (Shen *et al*. 1999, Valle-Levinson *et al*. 2000).

The 2008 *Cochlodinium polykrikoides* bloom initiated in the Lafayette River, and was subsequently transported by tidal flushing into the Elizabeth River, where it continued to bloom until through August (Figures 2, 5). Tidal transport from the Elizabeth River into the James River occurred between August 6 and August 12 (Figure 5), corresponding with the timing of a neap tidal cycle, which increases the strength of the eddy flow around Hampton Flats and enhances upriver transport in the James River (Shen *et al*. 1999). Since *Cochlodinium* was present in high abundance in the Elizabeth River throughout the month of August, it is likely that the *Cochlodinium* was continually transported by tidal flushing into the area of Hampton Flats and injected into the frontal zone to continually repopulate the mesohaline portion of the James River. Tidal transport of surface waters from the mesohaline portion of the James River would bring the bloom water downriver into the polyhaline portion of the James, and the process would repeat itself until the bloom could no longer sustain its growth or until other factors, such as increased mixing due to storm activity, create conditions unfavorable for growth. Spring tides, which occurred in late August as the bloom came to an end, increase flushing, destabilize the water column (Cloern 1991), and stop the development of the eddy formation around Hampton

Flats (Shen *et al*. 1999), effectively stopping any further upriver transport of the Cochlodinium in the James River.

Mulholland *et al*. (2009) reported on the direct effects of the presence of *Cochlodinium polykrikoides* cells in contact with fish larvae and juvenile oysters in bioassay experiments, noting that 100% mortality of fish larvae occurred within 15 hours of exposure to the cells, and 80% mortality occurred within 5 hours. Filtered bloom water did not cause mortality over the duration of the experiment, suggesting that direct contact with the cells is responsible for the observed mortality (Mulholland *et al*. 2009). Mortality rates among the juvenile oysters were lower, but still approached 20% mortality over 15 hours (Mulholland *et al*. 2009). This has implications for climate change and overall estuarine health, as climate change may result in longer bloom durations and bloom formation at earlier than usual dates, perhaps even coinciding with mass larval recruitment into the Bay (Mulholland *et al*. 2009).

Cochlodinium blooms affect aquatic organisms in indirect ways as well. A strong front following an atmospheric high-pressure system passed through the region following August 26, 2008. Increased wind driven mixing disrupted the bloom and destabilized the water column, marking the demise of the bloom throughout much of the region. As the bloom dissipated, the *Cochlodinium* cells clumped together forming dense aggregates, which sank to the bottom of the estuary. As bacterial degradation of the dead cell aggregates commenced, the dissolved oxygen concentration in the surface waters of the Elizabeth and Lafayette Rivers fell to hypoxic and near-anoxic levels (Figure 7). Fish and invertebrate kills, mostly of gizzard shad and blue crabs, were reported in the Lafayette and Elizabeth Rivers by the local papers for several days following the collapse of the bloom, with surface dissolved oxygen concentrations bottoming out around 2 mg l^{-1} on September 4 (Figure 7). Since the *Cochlodinium* cell aggregates sank, it is possible that dissolved oxygen concentrations near the bottom were much lower than that observed at the surface, leading to increased mortality of benthic infauna, which likely goes unreported.

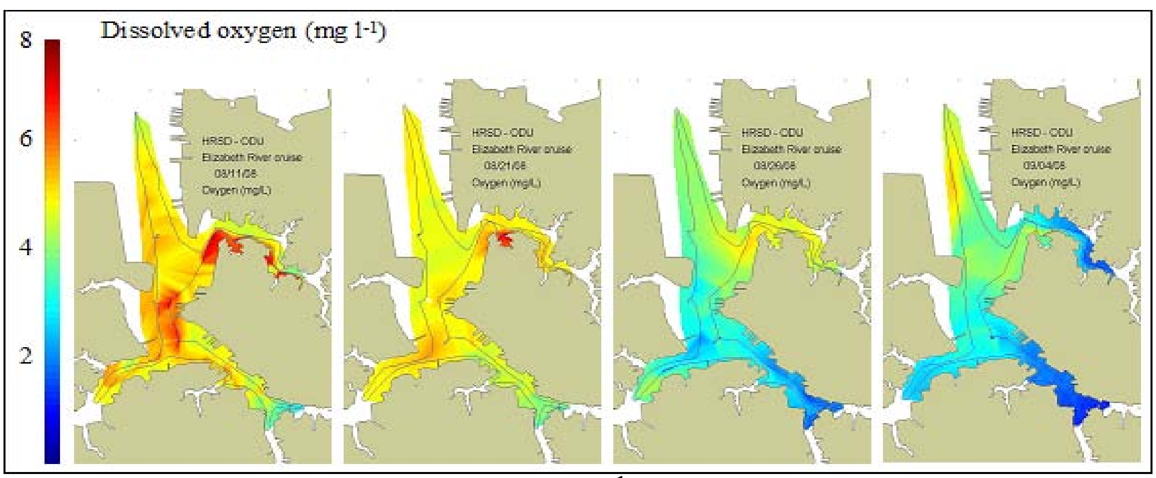

Figure 7. Dissolved oxygen concentrations (mg l^{-1}) measured during the ER-LAF cruises on 08/11, 08/21, 08/26, and 09/04

Here we demonstrate that physical forcing is a key factor affecting the extent and duration of *Cochlodinium* blooms in the Lower Chesapeake Bay and its tributaries. The Lafayette and

Elizabeth Rivers appear to act as seedbeds wherein blooms initiate and develop before being flushed out into the Lower James River and Chesapeake Bay. The timing of bloom initiation with respect to the local meteorology and climatology may be an important factor in determining the impacts of blooms during particular years. These results have important implications for managing blooms of this organism in the Lower Chesapeake Bay. For example, it may be possible to prevent and control blooms by targeting management actions at sites of bloom initiation or to undertake measures to control the impact of stormwater at sensitive sites in the estuary.

ACKNOWLEDGEMENTS

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MOLECULAR IDENTIFICATION AND DETECTION OF *ALEXANDRIUM MONILATUM* IN CHESAPEAKE BAY WATER AND SEDIMENT

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KEY WORDS: *Alexandrium monilatum,* harmful algal blooms, Chesapeake Bay, environmental water, sediment

ABSTRACT

Recent increases in the frequency, severity and distribution of harmful algal blooms (HABs) have occurred worldwide and the threats posed by these blooms are predicted to increase. In Virginia's estuarine and marine waters several potentially harmful species, including *Alexandrium monilatum, Cochlodinium polykrikoides*, *Karlodinium veneficum, Microcystis* spp. and *Prorocentrum* spp. have produced significant and more frequent blooms over the last few years. While the human and animal health impacts of these organisms have not been adequately assessed, *Alexandrium monilatum* blooms have reportedly caused fish kills along the southern Atlantic and Gulf coasts of the USA. In Sept. 2007 and 2008 *A. monilatum* was identified using microscopic and molecular methods as the dominant species of bloom events persisting for several weeks in the York River. DNA-based molecular assays were developed for detecting *A. monilatum* in environmental samples. York River water samples collected during the 2007 bloom event were estimated to have cell concentrations as high as ~40,000 cells/ml. During the 2008 event counts were as high as ~3,000 cells/ml for the York, with positive samples also observed from the Rappahannock and Potomac Rivers. DNA from sediment samples taken from the York River in the spring of 2008, as well as archived DNA from 2005 and 2006 water samples, were screened and low levels of *A. monilatum* were detected. Human exposure with minor health effects, as well as animal deaths were strongly suspected to result from these recent Chesapeake Bay blooms.

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Back to Table of Contents

III-B Managing Wastewater

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MOLECULAR TECHNIQUES FOR ASSESSING PATHOGENIC ORGANISMS IN DAIRY MANURE

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Pathogen contamination of water resource is a risk to human health. This contamination originates from various sources including animal manure when applied to cropland as fertilizer. Currently, land application is the predominant method of using manure on livestock and poultry farms. The 2002 National Animal Health Monitoring System (NAHMS) survey indicated that 38.5% of farms had at least one cow infected with *E. coli* O157; this number was 24.2% in 1996. Overall, 4.3% of cows were culture positive for *E. coli* O157 in 2002, up from 1.2% in the 1996 survey.

The objective of this study was to determine the sources, fate, and transport of pathogens in dairy manure during an anaerobic digestion treatment processes. Both the culture and DNA-based methods were used to detect and enumerate *E. coli*. For the culture based measurements, modified mTEC agar plates were employed. For DNA-based methods, *Quantitative PCR* was adopted, where *gadA* and *gadB* genes were the targets. An *E. coli* mutant strain lacking *gadA* and *gadB* genes was constructed and was added to each sample prior to processing as an internal control to quantify the DNA extraction efficiency during the Q-PCR analyses; a kanamycin resistance gene cassette that was inserted in place of the *gadA* gene was the target for enumeration of the control strain. The results indicated that DNA-based methods could detect and quantify pathogen more precisely than culture based method.

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ECOLOGY OF PATHOGENIC MYCOBACTERIA IN CHESAPEAKE BAY

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KEY WORDS: *Mycobacterium* spp., ecology, striped bass

ABSTRACT

The striped bass (*Morone saxatilis*) is an economically and ecologically important finfish along the U.S. Atlantic coast. Recent research by our group indicates that disease due to infection by *Mycobacterium* spp. is associated with mortality of this fish in Chesapeake Bay. This potentially fatal disease creates considerable concern about the continuing health of striped bass. A variety of slow-growing mycobacteria have been cultured from diseased striped bass in Chesapeake Bay, dominated by two new species, *M. pseudoshottsii* and *M. shottsii*. The biology of these mycobacteria outside their striped bass hosts has been completely unknown until recently, including whether *M. pseudoshottsii* and *M. shottsii* are environmental mycobacteria as is typical of mycobacterial pathogens of fishes, or if they may be obligate pathogens. We have developed species-specific quantitative PCR assays for detection of *M. pseudoshottsii* and *M. shottsii* in environmental matrices, as well as in fish tissues. We have demonstrated that *M. pseudoshottsii* is ubiquitous in water and sediments of the mainstem Chesapeake Bay, while *M. shottsii* is not found in water or sediments. *M. pseudoshottsii* is also found with high prevalence, and in some cases high density, in Atlantic menhaden, whereas *M. shottsii* has not been detected in menhaden. Here, we will present data from a high-density qPCR-based survey of *M. pseudoshottsii* and *M. shottsii* in water and sediments of the Rappahannock River, which serves as a major spawning and nursery ground for the striped bass. Supported by VA Sea Grant, NOAA Chesapeake Bay Office, and Virginia Water Resources Research Council.

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THE EFFECTS OF AQUATIC ESTROGEN POLLUTION ON THE DEVELOPMENT OF *RANA SLYVATICA*

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ABSTRACT

The significance of this study is to examine the effects of aquatic pharmaceutical pollution on the development of marine organisms. This research determines developmental changes in representative marine species, frogs, *Rana slyvatica* exposed to an estrogen polluted environment. The major source of pharmaceutical pollution is city sewage systems, waste containing birth control pills, antidepressants, painkillers and other residual compounds that enter into our waterways. According to the EPA these pollutants are referred to as PPCPs, Pharmaceuticals and Personal Care Products**,** bioactive chemicals substances that have an effect on living tissue. These microconstituents of the environment have potential effects on organismal development and human health. Previous studies have evaluated the impact of estrogen pollution in water, altered the gender of marine organisms and developmental patterns. Additional studies have evaluated the consequences of pharmaceutical pollution of pesticides and prescription medications in drinking water that can have adverse effects on humans.

This study examines the rate of *Rana slyvatica* development in an estrogen-polluted environment. Rana *slyvatica* eggs were placed a polluted aquatic environment containing Beta Estradiol, a by-product of estrogen, and eggs were placed in an unpolluted aquatic environment on April 18, 2008. The aquatic environments were evaluated daily and the developmental stages of the frogs were recorded. This study determined that estrogen pollution had a dependent effect on the rate of growth and development of *Rana slyvatica* by acting as a developmental disrupter. This investigation illustrated a decline in growth and an alteration of developmental rate in *Rana slyvatica*. A developmental disrupter or endocrine disrupter affects organisms by altering normal growth and development. This research emphasizes the importance of understanding the potential dangers of developmental disrupters on marine organisms caused by aquatic pharmaceutical pollution.

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WASTEWATER STABILIZATION PONDS: WATER QUALITY ASSESSMENT

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ABSTRACT

Municipal wastewater samples from the University of Dar es Salaam's Waste Stabilization Ponds (WSPs) were analyzed, using standard water quality testing procedures, to determine the environmental and public health impact to the local population. The levels of total phosphorous, chloride, sulfate, Chemical Oxygen Demand (COD), Zn, Fe, Mn, Cu, Cr, MG, Cd, Pb and Ni were measured at different sampling points along the wastewater treatment course. The results showed a 20%-50% decrease in Zn, Fe, Mn and Mg levels, a 90% decrease in COD, and a 5%, 18% and 65% increase in chloride, sulfate, and total phosphorous, respectively. The results show some compliance with World Health Organization (WHO) wastewater discharge standards as well as the U.S. Environmental Protection Agency (EPA) National Recommended Water Criteria (EPA 2002).

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METHODS FOR DETECTING FAILING SEPTIC SYSTEMS AND ASSESSING THEIR RELATIVE IMPACT

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ABSTRACT

Significant portions of receiving water impairments have been attributed to nonpoint source pollution. Failing septic systems (FSS) can contribute to a downstream impairments and cause significant impacts from both nutrient load and fecal contamination. Properly designed, sited, installed, and maintained septic systems can provide sufficient treatment for many years. However it is estimated by the U.S. EPA that between 10 and 20% of septic systems may fail to provide adequate treatment. Septic system failures occur for a variety of reasons, including age, poor soils, inadequate design, and/or excessive hydraulic loading. Many municipalities are required under their Stormwater NPDES permits to conduct illicit discharge detection surveys. FSS, as illicit discharges are included in this class. Finding FSS is a difficult technical issue due to their dispersed nature and a lack of available records. Implementing corrective action is a vexing policy challenge for many municipal agencies, due to the expense and potential direct impact on residents. The problem can be particularly acute in tidal waters of the Chesapeake Bay watershed because of the proximity of many aging septic systems to tributary waters. Locating FSS could result in reductions in loadings and associated downstream impacts from

these systems. A case study watershed will be evaluated with a simplified model to estimate the relative loads of FSS within the watershed and then assess the effect on receiving water quality. A review of both standardized protocols and advanced sensor technologies for finding FSS is provided. Suggestions are provided for improving both detection systems and corrective action policies.

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Back to Table of Contents

Concurrent Session IV

(A) Planning for Water Uses and Water Impacts
(B) Stormwater (Part 1): Developing Management Policies and Practices

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IV-A Planning for Water Uses and Water Impacts

(1) Regional Water Supply Alternatives for the City of Richmond and Its Neighboring Jurisdictions -- Robert Steidel, *City of Richmond Department of Public Utilities;* Yuan Fang, *Greeley and Hansen*
(2) Water Resources Element, Cecil County, MD -- Maggie Cawley, *Environmental Resources Management*
(3) A Longitudinal Analysis of the Impact of Urbanization on Stroubles Creek: Historical Perspective -- Stephanie DiBetitto, *University of Vermont*
(4) The Taste and Economics of Desalinated Water -- Andrew Snyder-Beattie, *Department of Economics, University of Mary Washington*

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REGIONAL WATER SUPPLY ALTERNATIVES FOR THE CITY OF RICHMOND AND ITS NEIGHBORING JURISDICTIONS

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KEY WORDS: regional water supply alternatives, water demand, water source, water supply, water treatment capacity

ABSTRACT

The *City of Richmond Virginia Water Supply Plan* (WSP) was submitted to the Virginia Department of Environmental Quality (DEQ) in October 2008 documenting that the City has sufficient water source and treatment capacity to satisfy its citizen and wholesale customers' needs through 2060. However, the region has shown unprecedented growth and is projected to

experience a water deficit. Based on growth prior to the economic crisis, by the year 2060, the region may reach a peak day water supply shortage of 191 MGD.

To overcome challenges caused by water supply shortage, the City developed several iterative regional water supply alternatives that will increase the supply of treated water for future demand in a cost effectively way. The three selected alternatives were developed to increase water treatment capacity paced with water demand in the region and also to meet the needs of each individual jurisdiction. Programs to implement the selected alternatives are detailed in this study. All three alternatives address the problem of regional water treatment capacity deficit. However, they point to the severe water source deficit anticipated in the near future.

The wise use of water advocated by the EPA WaterSense program must be promoted to reduce future water demands. Water harvesting techniques for stormwater, reuse and brackish water desalinization could also become potential alternative water sources. These measures, together with integrated water resource planning in the central Virginia area watershed, will reduce the stress on the region's water supply.

INTRODUCTION

The City submitted the *Richmond Water Supply Plan* (WSP) to the Virginia Department of Environmental Quality (DEQ) in October 2008 in accordance with the Code of Virginia (amended by Senate Bill 1221). The Plan predicts water demands for the City and the region including Henrico County, Chesterfield County and other Appomattox River Water Authority (ARWA) members, Hanover County, Goochland County, New Kent County, Powhatan County, and Charles City County. It is found that the region as a whole will have a severe water supply shortage in the near future. As a vital water supplier in the region, the City of Richmond is committed to serving the region's water need and to working cooperatively with neighboring jurisdictions to overcome the challenges caused by the growing water supply shortage.

WATER DEMAND AND SUPPLY ANALYSIS

According to the WSP, water demand of the City will not change significantly in future years because the population in the City is projected to decline slightly and stabilize around 187,066 in 2020. However, most of its neighboring counties are anticipated to experience significant water demand increases due to rapid population growth projected by the Virginia Employment Commission. Table 1 shows peak day water demand projections for the region from 2010 to 2060. It is estimated that regional peak day water demand in 2060 is 492 MGD.

There are six water treatment facilities in the region with a total treatment capacity of 301 MGD (Table 2). Figure 1 shows the region's water treatment capacity versus water demand projection, it is likely that the peak day demand will exceed the existing water treatment capacity in 2025. The region is anticipated to have a peak day water deficit of 191 MGD in 2060.

Table 1. Regional peak day water demand prediction 2010-2060 (MGD)

Jurisdictions	Year					
	2010	2020	2030	2040	2050	2060
Richmond and Neighboring Counties						
City of Richmond (1)	39.8	41	43	45	46	47.7
Henrico County (1)	74	100	130	148	159	186
Chesterfield County (2)	64	78	92	106	120	134
Hanover County (3)	20	26	31	37	42	48
Goochland County (1)	1	3	7	13	15	19
Powhatan County (4)	0.44	1.31	2.46	4.41	6.7	10.4
New Kent County (1)	1	3.2	5.4	7.6	9.8	12
Charles City County (1)	0.7	0.8	0.9	0.9	1.0	1.1
Other ARWA Members Except Chesterfield (2)						
Prince George	3.3	4.1	4.9	5.9	7.0	8.3
City of Colonial Heights	3.9	4.3	4.6	4.6	4.6	4.6
Dinwiddie County	3.1	3.8	4.7	5.6	6.7	8.4
City of Petersburg	9	9.6	10.1	10.7	11.3	12.4
Total Regional Peak Day Demand	**220**	**276**	**336**	**388**	**429**	**492**

(1) Based on population growth and area development
(2) Draft Regional Water Supply Plan, Appomattox River Water Authority. June 2007.
(3) Long-Range Water Resources Planning Study, Hanover County. May 2002.
(4) Water and Wastewater Capacity Study, County of Powhatan. December 2004

Table 2. Water source and treatment capacity for the WTPs in the Region

Jurisdiction	Facility Name	Supplies Water to	Treatment Capacity (MGD)	Water Source
City of Richmond	Richmond WTP	- Richmond - Henrico - Chesterfield - Hanover - New Kent - Goochland	132	James River
Henrico County	Henrico WTP	- Henrico - Hanover	55	James River
ARWA (1)	ARWA WTP	- ARWA members	96	Lake Chesdin (Appomattox River)
Chesterfield County	Swift Creek WTP	- Chesterfield	12	Swift Creek Reservoir (Swift Creek)
Hanover County	Ashland WTP	- Hanover	2	South Anna River
	Doswell WTP		4	North Anna River
		Total Capacity	**301**	

(1) ARWA: Appomattox River Water Authority, members include the Cities of Petersburg and Colonial Heights and the Counties of Chesterfield, Dinwiddie, and Prince George.

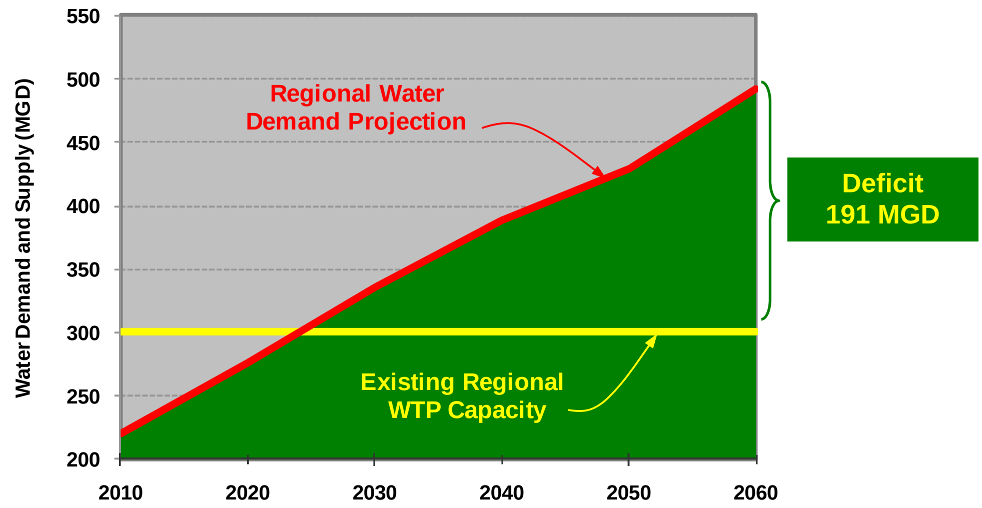


Figure 1. Regional water treatment capacity and water demand projection

WATER SUPPLY ALTERNATIVE DEVELOPMENT

In order to overcome the challenges caused by the growing water supply shortage in the region, the City of Richmond proactively developed several regional water supply alternatives to increase water supply paced with regional water needs in a cost-effective manner. Figure 2 shows the geographical locations of the City of Richmond and neighboring jurisdictions, with their water treatment facilities, in the James River watershed in the Commonwealth of Virginia.

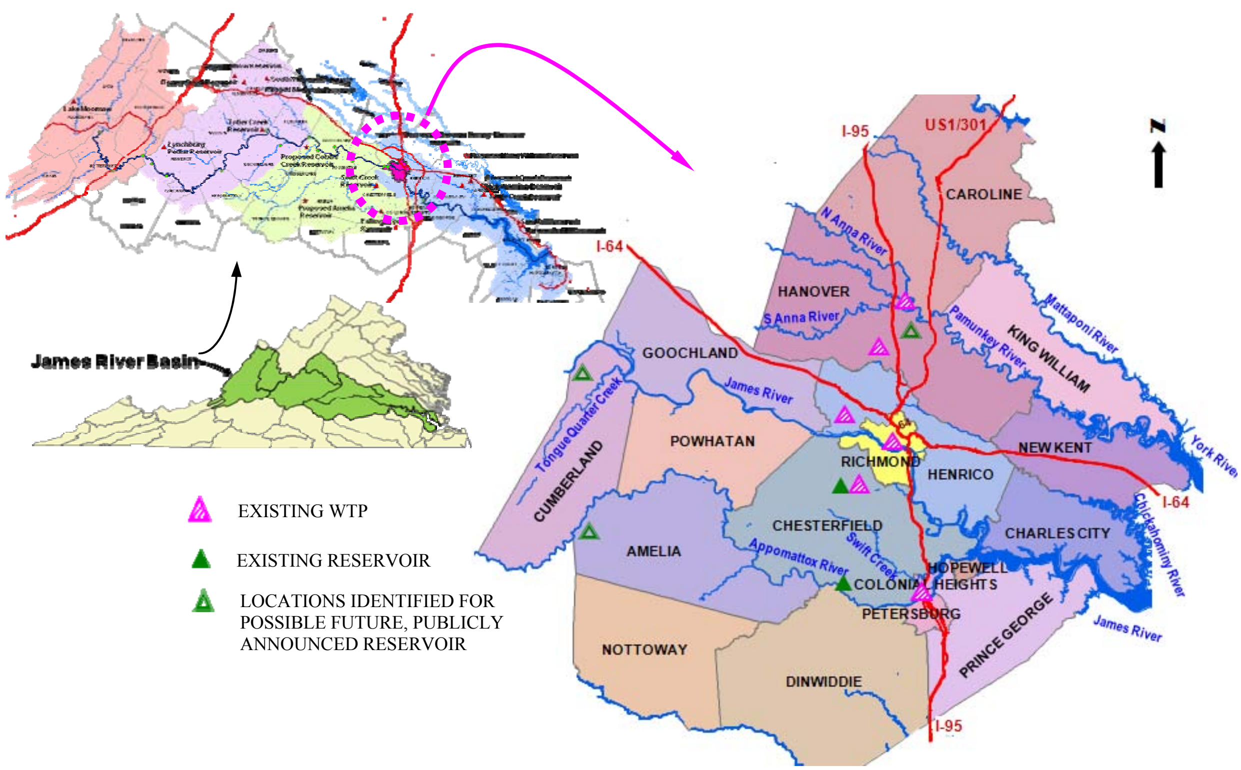


Figure 2. Geographical location of the City of Richmond and neighboring jurisdictions

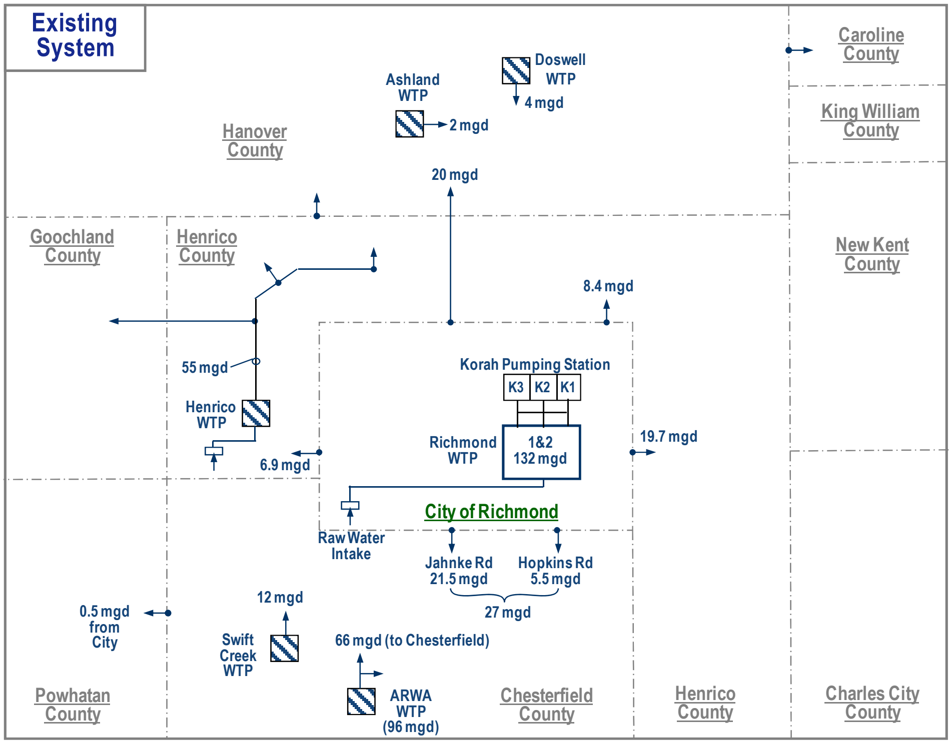


Figure 3. Schematic of the existing water supply system in the region

A schematic of the existing water supply system in the region is shown in Figure 3. Elements shown include relative geographical location of each jurisdiction, water treatment facilities, and water supply within and between jurisdictions. The City has a water treatment plant of design capacity 132 MGD and three finished water-pumping stations (K1, K2, and K3). In addition to its own citizens, the City provides 35 MGD finished water to the Henrico County (6.9 MGD to west, 8.4 MGD to north and 19.7 MGD to east), 27 MGD to the Chesterfield County (21.5 MGD through Jahnke Road and 5.5 MGD through Hopkins Road), and 20 MGD to the Hanover County.

Chesterfield owns the 12 MGD Swift Creek WTP and has an allocation of 69.31% (66 MGD) from the ARWA WTP. The ARWA WTP needs significant upgrades to reach its maximum design capacity of 96 MGD. Considering limited available supply capacity from ARWA WTP and its fast growth in the north, the Chesterfield County has requested extra 5 MGD water supply from the City of Richmond.

Henrico owns a 55 MGD WTP and provides 2 MGD to Hanover.

Hanover owns the 4 MGD Doswell WTP and 2 MGD Ashland WTP. The Ashland WTP is currently not in service and would require substantial upgrades to return to service.

Individual Jurisdiction's Water Demand and Supply

In the existing water agreement between the City and the Chesterfield County, Chesterfield is required to provide certain amount of treated water to the Powhatan County. It is expected that

Powhatan continue to receive increasing amounts of water for its future needs from Chesterfield or from the City of Richmond via the Chesterfield water transmission system. The Goochland County receives part of its water supply from Henrico County. It is assumed that Goochland will receive increasing amounts of water for its future needs from Henrico County or from the City of Richmond via the Henrico water transmission system.

Based upon publicly available information and growth patterns prior to the economic down-turn, it would appear that water demands from Chesterfield and Powhatan Counties may exceed the existing supply capacity of 110 MGD by approximately 2040, water demands from Henrico and Goochland Counties may exceed the existing supply capacity of 90 MGD by approximately 2015, and water demand of Hanover County may exceed the existing supply capacity of 28 MGD by approximately 2024. Confirmation of these data would need to be provided by these jurisdictions.

Regional Water Supply Alternative Development

Region water supply alternatives are developed by adding new water treatment and transmission facilities to the existing regional water system according to the following criteria: (1) water treatment capacity shall meet water demands in a timely manner; (2) water transmission system shall satisfy both short-term and long-term water needs; (3) water treatment and supply capacity shall meet each jurisdiction's water needs shown in Table 1. Originally seven alternatives were developed for screening and three are selected for further consideration. Table 3 shows the selected three alternatives and the phases of water treatment capacity increments required in each alternative.

Table 3. Regional water supply alternatives 1, 2, and 3

Alt	WTP	WTP Capacity and Capacity Increment											
		Existing	2012	2018	2020	2032	2036	2040	2042	2044	2052	2054	2060
1	Richmond	132		+18					+40				190
	Henrico	55	+25		+20	+30							130
	Hanover	6		+10			+10					+10	36
	West (new)	0						+40					40
2	Richmond	132		+18					+40				190
	Henrico	55	+25		+20	+30							130
	Hanover	6		+10			+10					+10	36
	East (new)	0						+40					40
3	Richmond	132		+18					+40				190
	Henrico	55	+25		+20								100
	Hanover	6											6
	East (new)	0			+50					+25	+25		100

<u>**Alternative 1**</u> was developed assuming future growth is more substantial in the west. Figure 4 shows water demands for individual jurisdictions and for the entire region. Figure 4 also shows the proposed water supply increments. In addition to the planned capacity upgrades for the existing water facilities, it is proposed to build a new WTP in the west end of the region.

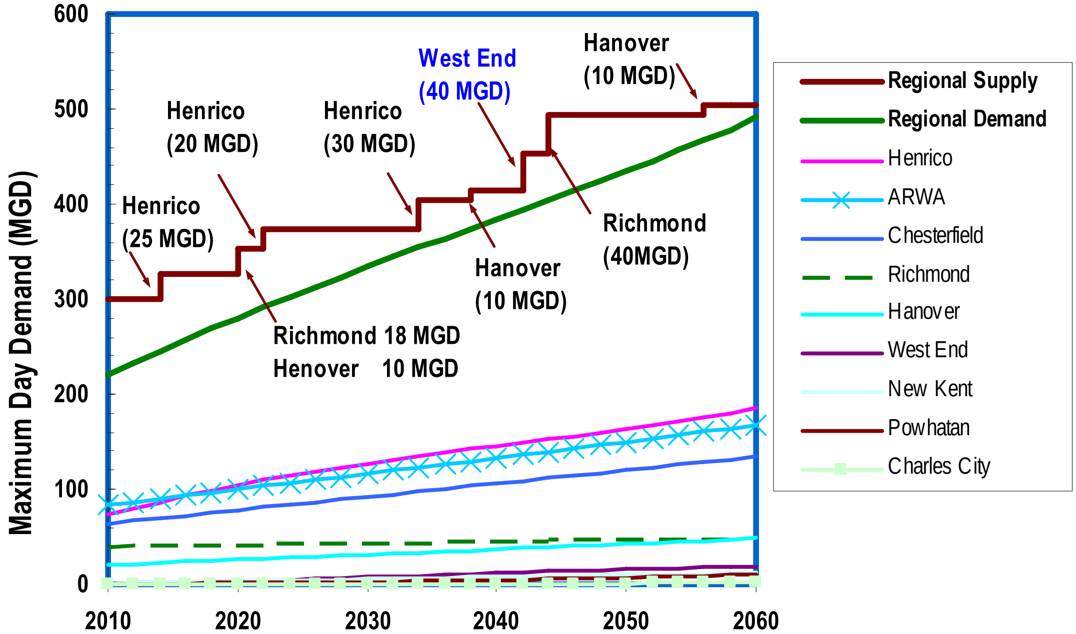


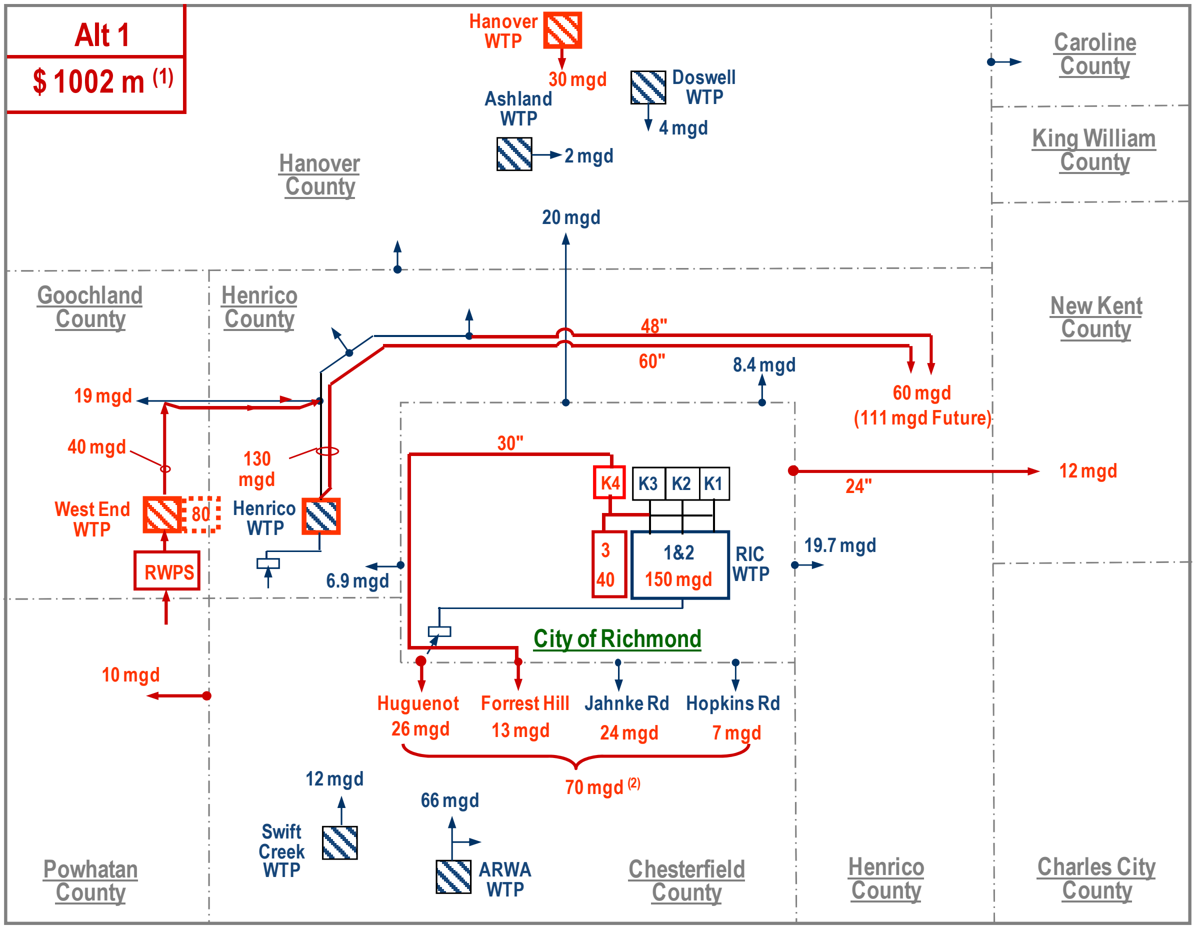
Figure 4. Regional water demand and supply, Water Supply Alternative 1

To provide the water needs of the Chesterfield and Powhatan Counties beyond 2040, the City of Richmond WTP will reach its capacity and need a capacity increase by 40 MGD in 2046. The water supply strategy for Chesterfield and Powhatan is the same for all three water supply alternatives developed in this study.

To provide the water needs of Henrico and Goochland Counties up to 2040, the Henrico WTP treatment capacity will increase by 25 MGD in 2012, and an additional 20 MGD in 2020 and 30 MGD in 2032. Extra water needs of Henrico and Goochland beyond 2040 will be provided by the new West End WTP.

To meet the water needs of the Hanover County, the County plans to build its own water treatment system, using a quarry for raw water storage. This new WTP has a final capacity of 30 MGD, with 10 MGD increment in year 2018, 2036, and 2054. The water supply strategy for the Hanover County is the same for Alternative 1 and Alternative 2.

To meet the water needs of the New Kent County and other counties with small water demands, the City of Richmond WTP will need a capacity upgrade by 18 MGD in 2018.



(1) Comparative Planning Level Project Costs (+50%/-30%)
(2) Include 4 mgd for the other ARWA members.
(3) Dash line for builtd-out condition

Figure 5. Schematic of regional Water Supply Alternative 1

The implementation of Alternative 1 in year 2060 is shown in Figure 5. For the Richmond WTP, in addition to capacity upgrade from 132 MGD to 150 MGD, a new 40 MGD plant and a new finish water-pumping station (Korah 4) will be built, together with a 24" transmission main to the New Kent County and a 30" transmission main to the Chesterfield County. For the Hanover WTP, a 30 MGD water treatment plant will be built with 10 MGD increments. For the Henrico WTP, plant capacity will be upgraded from 55 MGD to 130 MGD, with a 60" transmission main. For the new West End WTP, plant capacity of 40 MGD may be built in the Goochland County, with a raw water intake from the James River, together with a 48" transmission main to provide water to the Goochland County and to eastern Henrico County.

Alternative 2 was developed assuming future growth is more substantial in the east. Figure 6 shows water demands for individual jurisdictions and for the entire region. Figure 6 also shows the proposed water supply increments. In addition to the planned capacity upgrades for the existing water facilities, it is proposed to build a new WTP in the east end of the region.

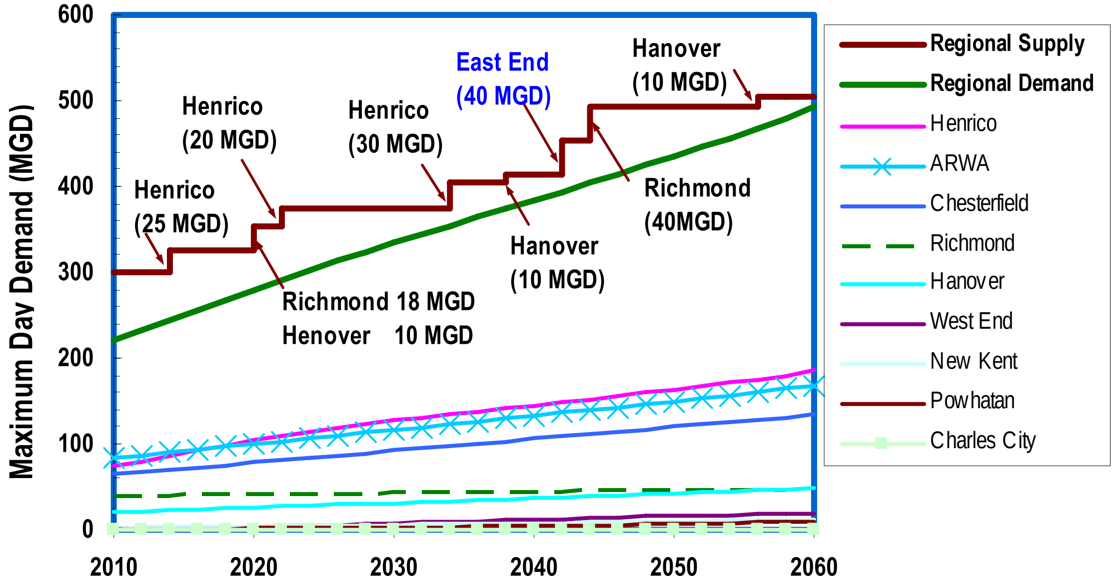
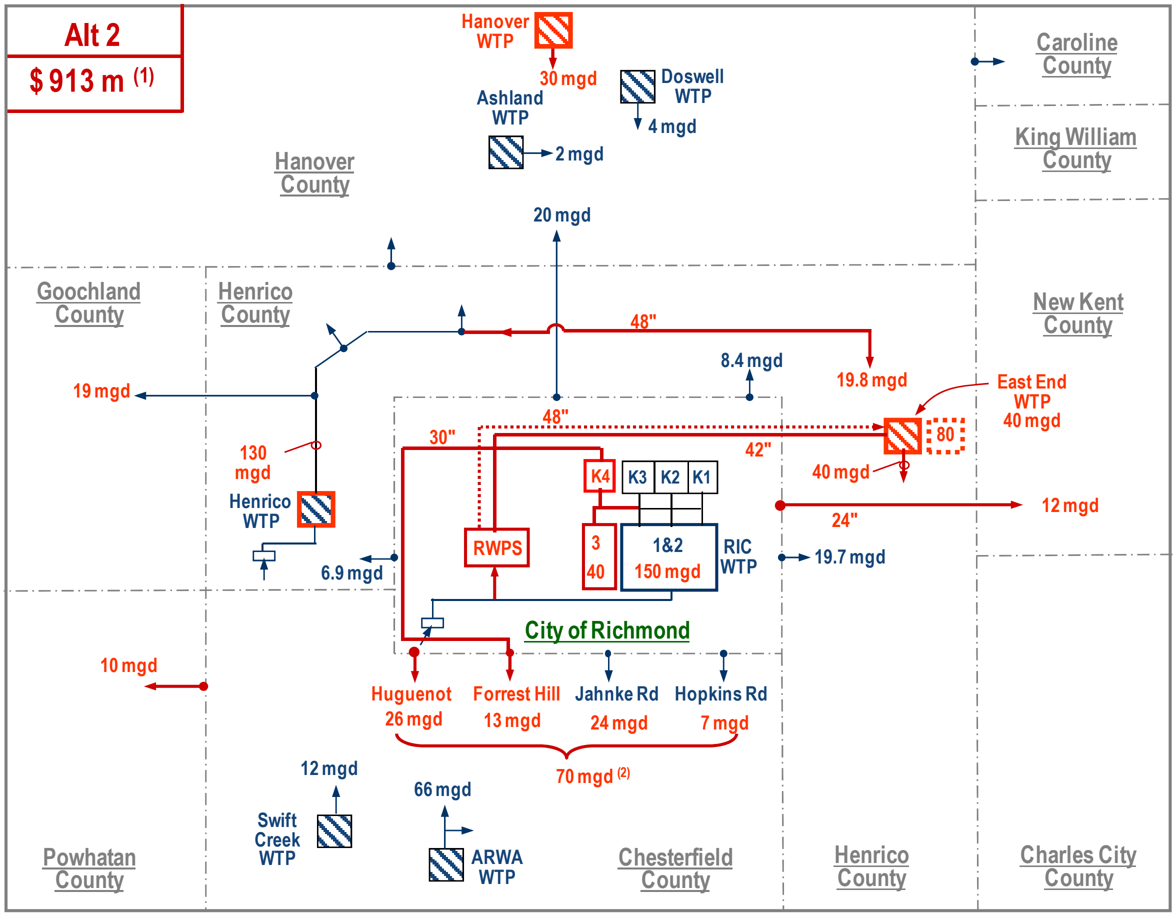


Figure 6. Regional water demand and supply, Water Supply Alternative 2

The water supply strategies in Alternative 2 are similar to those in Alternative 1, except that the new 40 MGD water treatment plant is to be built in the east end instead of the west end.

The implementation of Alternative 2 in year 2060 is shown in Figure 7. Facility upgrades are the same for the Richmond WTP the Hanover WTP as shown in Alternative 1. For the Henrico WTP, plant capacity will be upgraded from 55 MGD to 130 MGD, with a 48" transmission main. For the new East End WTP, plant capacity of 40 MGD may be built in the Henrico County, with a raw water intake from the James River from the City of Richmond via a 42" force main, to provide water to eastern Henrico County.



(1) Comparative Planning Level Project Costs (+50%/-30%)
(2) Include 4 mgd for the other ARWA members.
(3) Dash line for buiildt-out condition

Figure 7. Schematic of regional Water Supply Alternative 2

Alternative 3 was developed assuming future growth is more substantial in the east and assuming Hanover will not build its water treatment plant. Figure 8 shows water demands for both individual jurisdictions and the whole region. Figure 8 also shows the proposed water supply increments. In addition to the planned capacity upgrades for the existing water facilities, it is proposed to build a new WTP in the east end of the region.

The water supply strategies in Alternative 3 are similar to those in Alternative 1, except the following:

To provide the water needs of Henrico and Goochland Counties up to 2030, the Henrico WTP treatment capacity will increase by 25 MGD in 2012, and an additional 20 MGD in 2020. The extra water needs beyond 2040 will be provided by the new East End WTP.

To provide the water needs of the Hanover County, the City of Richmond will provide additional 2 MGD due to its capacity upgrade from 132 MGD to 150 MGD based on the water agreement between the City and the County. The extra water needs of the Hanover County beyond 2020 will be provided by the new East End Plant.

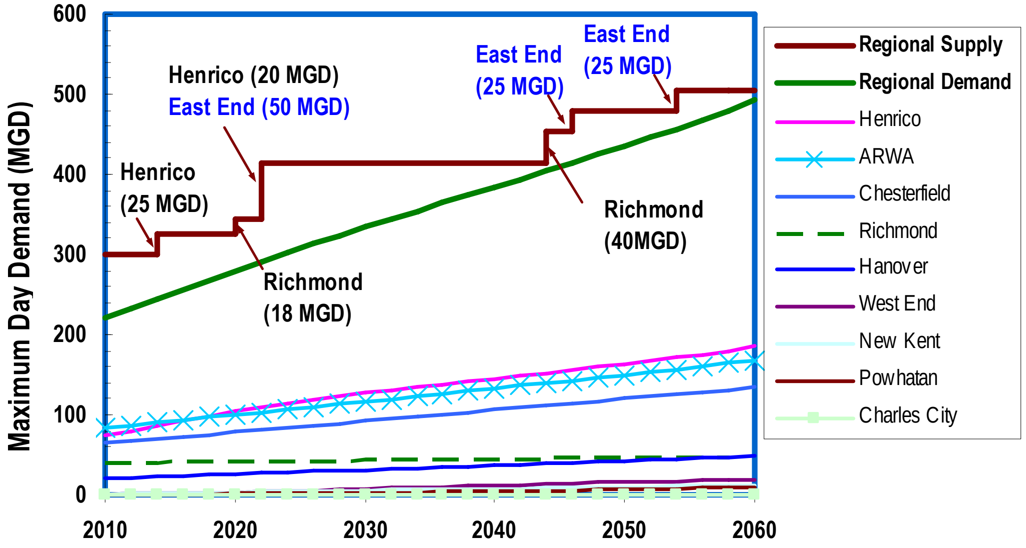
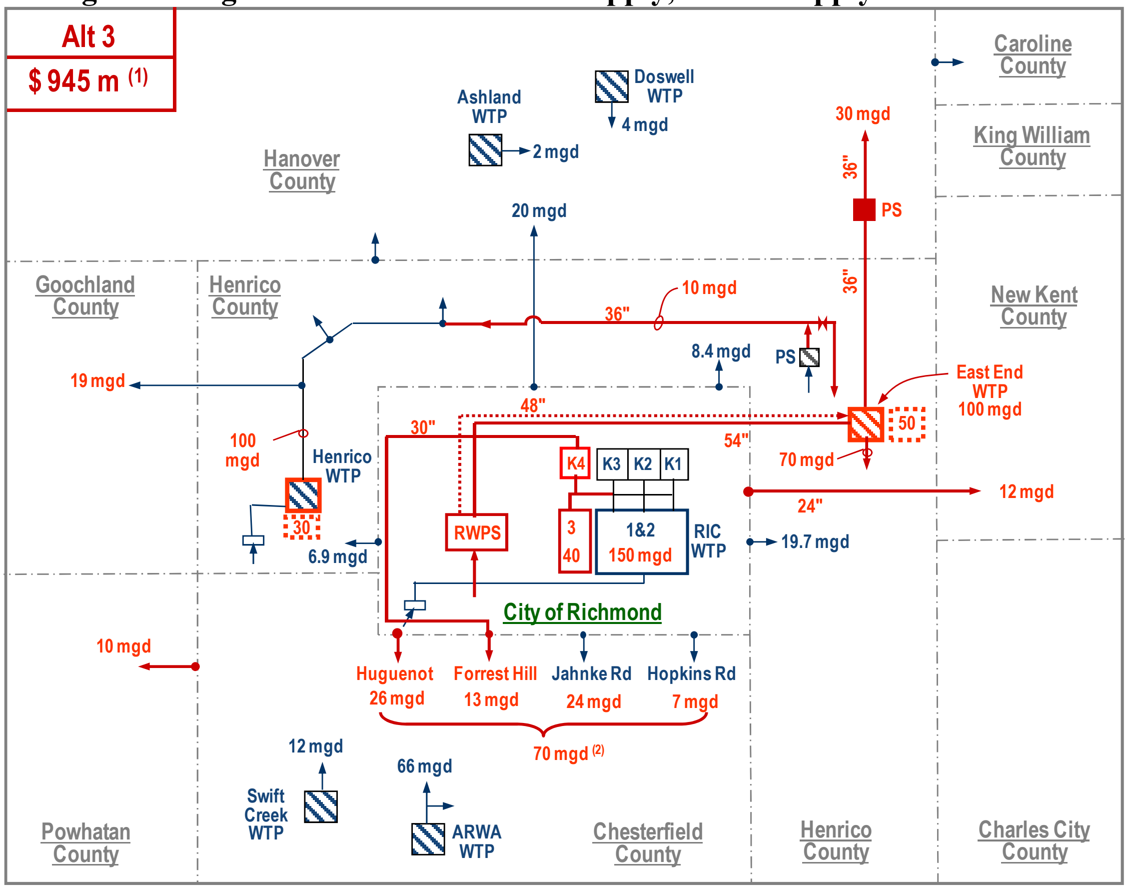


Figure 8. Regional water demand and supply, Water Supply Alternative 3



(1) Comparative Planning Level Project Costs (+50%/-30%)
(2) Include 4 mgd for the other ARWA members.
(3) Dash line for builtd-out condition

Figure 9. Schematic of regional Water Supply Alternative 3

The implementation of Alternative 3 in year 2060 is shown in Figure 9. Facility upgrades are the same for the Richmond WTP as shown in Alternative 1&2. For the Henrico WTP, plant capacity will be upgraded from 55 MGD to 100 MGD, with a 36" transmission main. For the new East End WTP, plant capacity of 100 MGD may be built in the Henrico County, with a raw water intake from the James River from the City of Richmond via a 54" force main, to provide water to eastern/western Henrico County and the Hanover County.

Cost Comparison

A preliminary cost estimation for all three water supply alternatives is shown in Table 4. Also, shown in the table are treatment capacities for each water treatment facility in 2060.

Table 4. Treatment capacity and cost estimation for all water supply alternatives

	Alternative 1	Alternative 2	Alternative 3
Total WTP Capacity (MGD)	**390**	**390**	**390**
Richmond WTP (MGD)	190	190	190
Henrico WTP (MGD)	130	130	100
Hanover WTP (MGD)	30	30	
New West End WTP (MGD)	40		
New East End WTP (MGD)		40	100
Estimated Project Cost (1)(2)(M$)	**$ 1002**	**$ 913**	**$ 945**

1. Costs are for relative comparison only, and do not include costs for flow augmentation.
2. Comparative planning level project costs in 2008 dollars (+50%/-30%).

It should be noted that at this stage of the development the three alternatives are within the Project Costs estimation range (+50%/-30%). Thus, implementation of the alternatives should be guided by the geographic location of future demands in the region.

REGIONAL WATER SUPPLY CHALLENGES

The existing James River Management Plan documents that for compliance with Minimum in-stream flow (MIF) requirements the total withdrawal from the James River by Richmond and Henrico is 230 MGD. However, the region will need 390 MGD raw water to meet its peak day water demand in 2060. Thus, additional water required from the James River is estimated to be 160 MGD for all proposed alternatives.

Seeking additional water source is critical to alleviate the challenge of water source deficit in the region. Options to augment the region's water sources may include: (1) comprehensive watershed management in the James River Basin for a more efficient usage of all the reservoirs in the basin, including Lake Moomaw (Gathright Dam) and other existing or new proposed reservoirs; (2) pump WWTPs effluent to downstream of Williams Island Dam to augment MIFs. Reclaimable WWTP effluents from Richmond, Henrico, Hanover, Chesterfield, and South Central Plant could amount to 184 MGD; (3) modification of MIF to increase allowable withdrawal from the James River from 230 MGD to 280 MGD. This would require long lead-time for regulatory approval. Water reuse and brackish water desalinization could also be considered as potential alternative water sources.

Promoting efficient water use advocated by the EPA WaterSense program must be promoted to reduce future water demand. WaterSense launched in 2006 is a partnership program sponsored by the U.S. EPA to encourage water efficiency in the United States through the use of a special label on consumer products (EPA 2006). Products that display the WaterSense label must meet two requirements: first, products must perform as well as or better than their competitors; second, products must be water efficient, using at least 20 percent less water than their inefficient competitors. WaterSense-labeled products available to customers include high-efficiency toilets, bathroom sink faucets, and landscape irrigation services, *etc*.

Assuming water savings of 15 percent by efficient water use from year 2020 on, the region's water demand in year 2060 would be 418 MGD, which is 74 MGD less than the original projection of 492 MGD. This water demand drop will enable the region to reduce or postpone the needs of water facility upgrades/constructions, alleviate stress in seeking new water sources, and decrease residential water bill.

Efficient use of water and water re-use together with integrated water resource planning in the James River watershed, will reduce the stress on the region's water supply.

CONCLUSIONS

Water demand is expected to grow significantly in the near future in the greater Richmond region, the City of Richmond has developed three cost-effective water supply alternatives to overcome the foreseeable water deficit facing the region. The proposed alternatives allow the region to adjust the geographic locations of new water treatment capacity and transmission lines to pace the growth and water needs. It is important for all jurisdictions in the region to work together to finalize and implement the most cost-effective water supply plan.
For all proposed water supply alternatives, seeking additional water source is essential and critical to alleviate the challenge of water source deficit in the region.

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WATER RESOURCES ELEMENT, CECIL COUNTY, MD

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KEY WORDS: water resources element, point source pollution, wastewater treatment capacity

ABSTRACT

The Water Resources Element (WRE) was created in 2006 when the Maryland General Assembly passed House Bill 1141, which modified Article 66B of the Annotated Code of Maryland. The purpose of this WRE plan[1] is to recommend growth areas and strategies that will utilize the Cecil County's resources in an efficient and sustainable manner. Cecil County is projected to grow by nearly 50 percent over the next 30 years. The majority of future growth should be confined to areas that can be served by water and sewer infrastructure, while the remainder should be directed to areas where development will result in the lowest possible discharge of nutrients to the County's rivers and streams. This report first analyzes the current opportunities and limitations presented by Cecil County's local and regional water resources and wastewater treatment facilities. An alternative land use plan for the County is then presented that will maximize use of existing and future water and sewer infrastructure. Objectives, strategies, and suggestions for implementation support the County's efforts to reach these goals, by pursuing a land use plan that emphasizes town-centers and conservation of natural areas.

INTRODUCTION

The WRE was created in 2006 when the Maryland General Assembly passed House Bill 1141 (HB 1141), which modified Article 66B of the Annotated Code of Maryland (the local planning and zoning enabling statute). The WRE is one of two new comprehensive plan elements, and must be adopted (either as part of a full comprehensive plan update, or as an amendment to the existing comprehensive plan) by "all counties and municipalities that exercise planning and zoning authority," by October 1, 2009 (Maryland Department of Planning 2007).

The catalysts for the WRE portion of HB 1141 include the following:

- Limits on nutrient (nitrogen and phosphorus) discharge resulting from Maryland's participation in the Chesapeake Bay Agreement
- The need for greater coordination of growth management efforts with the availability of drinking water and wastewater resources to serve new growth
- The need to consider the non-point source pollution (*i.e.*, stormwater) impacts of growth.

[1] This project was originally completed to fulfill a Masters Degree thesis requirement, and served only as a basis for the 2010 Comprehensive Plan Water Resources Element. The data and policy recommendations presented in this document differ from the WRE that will be adopted by Cecil County. The original document has been condensed from 70 pages including appendices.

In the years preceding HB 1141, some local governments were forced to issue building moratoria while new water supplies were secured. The purpose of the WRE is to avoid such problems in the future by ensuring that all future comprehensive plans reflect the opportunities and limitations presented by local and regional water resources, and to link future growth with the available resources to serve that growth.

Cecil County has undertaken numerous studies of water quality and supply, as well as of wastewater system capacity. This WRE plan combines and elaborates on previous studies, while linking them to land use and other policy decisions.

BACKGROUND

Cecil County has historically been a largely rural county whose identity and economy were tied to a strong agricultural sector. Over the past twenty years, however, Cecil County has seen significant growth in population and urbanization due largely to its close proximity to the expanding Philadelphia/Wilmington and Baltimore metropolitan areas and the presence of the I-95/US 40 transportation corridor. Between 2000 and 2006 Cecil County's population grew by approximately 15 percent, compared to the state population which grew by approximately 6 percent over the same time period. This growth is predicted to not only continue but to escalate; the Maryland Department of Planning (MDP) projects that Cecil County will have nearly 160,000 residents by 2030. This equates to approximately 26,000 new households, of which approximately 80 percent are likely to occupy single family homes with an average lot size of one acre.

One major impact of projected growth is the rapid consumption of rural (particularly agricultural) land. To limit development in rural areas, the 1990 County Comprehensive Plan designated the I-95/US 40 corridor as the County's primary growth area. However, development since 1990 has not necessarily followed the County's desired plan. From 1990 to 2001, 87 percent of land developed in Cecil County (for residential, commercial, industrial, and similar land uses) was outside of Priority Funding Areas (PFAs), existing communities and places where the County wants to direct state investment to support future growth.

According to the Green Infrastructure Plan, only 17 percent of new development between 1997 and 2002 fell within town boundaries, and only 26 percent of new development occurred where there was existing sewer service. One estimate suggests that if current land development trends continue, projected development will consume another 25,000 acres of agricultural land, diminishing the rural character of the County and further degrading its waterways. Transportation investments in the growth area have been deficient due to the limits of central water and sewer in the growth areas. Development cannot take advantage of the higher densities/intensities permitted in the Zoning Ordinance, making major transportation investments in these areas cost-ineffective.

Drinking water and wastewater treatment plant capacities and projections indicate that the County-designated growth corridor currently does not have sufficient infrastructure to support the projected growth. This lack of infrastructure makes growth areas less attractive to developers, who often take advantage of lower land costs in the County's agricultural areas.

Split ownership of water and wastewater infrastructure between municipalities and the County also leads to inefficiencies.

DRINKING WATER ASSESSMENT

Approximately 14,356 dwelling units in Cecil County and its towns (41 percent of the County total) receive drinking water from public water systems, with the remaining 21,858 dwelling units reliant upon personal wells. Approximately 65 percent of the drinking water for public systems comes from surface water, while the remaining 35 percent is withdrawn from groundwater or purchased from private water companies. Public water supply systems currently treat approximately 2.8 MGD of surface water, with appropriation permits for up to 5.35 MGD. Private wells draw water from a variety of water-bearing formations in the County, but rely primarily on the Potomac formation.

An increase of 26,000 new households will create an overall need for approximately 13.6 MGD of drinking water from both private wells and public systems; an increase of 5.85 MGD. Several systems will reach their permitted withdrawal capacity by 2030, and will require expansions or other modifications to meet demand:

- Charlestown is expected to reach its permitted withdrawal capacity of 0.157 MGD by 2030, and should consider a connection to the North East system, which will have excess supply of 0.6 MGD after expansion to a 2 MGD system.
- Elkton will reach its permitted withdrawal capacity of 2.15 MGD by 2030. The County and Elkton should consider purchasing a larger amount from Artesian Water or adding wells to support a demand of approximately 3 MGD. A connection with the Meadowview system may also be attractive since it will have an unused supply of 0.757 MGD.
- Port Deposit will reach its permitted withdrawal capacity of 0.4 MGD by 2030 and should consider agreement with Perryville, which will be able to support projected growth due to a pending plant expansion to 2 MGD.

Potential future drinking water sources include groundwater, surface water, and purchase from private water suppliers. Cecil County is not generally known for high yielding wells, but groundwater resources could be tapped to provide some water in the future. In the Surface Water Study of 2004 Cecil County identified nine surface water bodies as potential sources for future water supply, many of which already are used as public water sources, including the Susquehanna River, Principio Creek, and Big Elk Creek. Maryland Department of the Environment (MDE) has indicated it will be unlikely to permit additional surface water supplies without reservoir backup due to past shortages in this region. Based on County studies, the most feasible water sources are the Susquehanna River and Principio Creek, although there are concerns about water quality in the Susquehanna due to the presence of sediments in the Conowingo Dam Pool and a reservoir would need to be constructed to utilize water from Principio Creek. Several water systems successfully utilize groundwater resources, but Cecil County is not generally known for high yielding wells.

Private water companies supply some water to individual Cecil County residents and to public water systems. There is a possibility of greater procurement from major private water suppliers, including United Water Company, Chester Water Authority (CWA), and the Artesian Water Company.

WASTEWATER ASSESSMENT

Approximately 16,296 dwelling units in Cecil County and its towns (45 percent of the County total) receive drinking water from public water systems, with the remaining 19,918 dwelling units reliant upon personal onsite sewage disposal systems (septic systems). As of 2007, 69 percent of new residential units were on private septic systems. There are three major wastewater treatment plants (WWTPs) and seventeen minor wastewater treatment plants in Cecil County, ranging in technology from septic tank to Enhanced Nutrient Removal (ENR) plants.

Most of the County's public sewer systems will not be able to accommodate projected residential and nonresidential growth through the year 2030. Some systems will require expansions or other modifications as follows:

- Cecilton: Projected to exceed capacity by approximately 0.007 MGD. After planned expansion to 0.1 MGD, the plant could serve approximately 173 more households and meet projected demand. Growth is expected mostly in the rural areas, adding about 439 more septic systems.
- Chesapeake City: Projected to exceed capacity by approximately 0.15 MGD. Currently there are no plans to expand the system but without expansion, this system could serve another 150 households.
- Elkton: Projected to exceed capacity by approximately 0.31 MGD. This area is expected to see a significant increase in growth and the County should pursue the expansion of the system's capacity and an increase in discharge limits to serve a 2030 need of 3.5 MGD.
- Meadowview: Projected to exceed capacity by approximately 0.46 MGD. Due to its proximity to Elkton and the I-95 corridor, the County should expand and upgrade this plant to support a majority of these new. Cherry Hill WWTP will have excess capacity and could be a source of nutrient credits or used as a backup in case of system overflows.
- Perryville: Projected to exceed capacity by approximately 0.39 MGD. If the Port Deposit WWTP expands to 0.7 MGD as planned, it will have excess capacity to accommodate and redirect some of Perryville's projected growth.
- Rising Sun: Projected to exceed capacity by approximately 0.11 MGD. The town of Rising Sun is surrounded by agricultural land, so the further upgrade and/or expansion of this plant may help to direct development away from agricultural and forest land, and into suburban and urban areas.

NUTRIENT DISCHARGES AND ASSIMILATIVE CAPACITY

Nitrogen and phosphorus from WWTPs and from stormwater and other "non-point sources" are the primary contributors to degraded water quality in the Chesapeake Bay and its tributaries. As a result of Maryland's participation in the Chesapeake Bay 2000 Agreement, and resulting state policies designed to help restore the Bay, water and sewer planning must take into account the "assimilative capacity" of a receiving body of water—the mass of nutrients that the stream can receive while still maintaining acceptable water quality. The majority of Cecil County is in the Chesapeake Bay Watershed.

To address nutrient loads from point sources (such as WWTPs), the state has established Chesapeake Bay Tributary Strategy point source caps[2]. These caps are numerical limits on the amount of nitrogen and phosphorus that WWTPs can discharge to the Bay and its tributaries (expressed as pounds per year of nitrogen and phosphorus). In the Chesapeake Bay area, eutrophication is a widespread problem that can be remedied by decreasing input rates of nitrogen and phosphorus into the water. Table 1 below shows the projected demand and nutrient loading overages for all of the treatment plants in the County that would result from an upgrade at each facility.

Table 1. Current and Projected Nutrient Discharge and Overages 2007 & 2030

		Load Cap (lbs/yr)		2007 Excess Nutrients (lbs/yr)		Projected Demand, 2030	2030 Excess Nutrient Discharge (lbs/yr)					
							Regular Treatment		BNR[2]		ENR[3]	
Watershed	System	N	P	N	P	(MGD)	N	P	N	P	N	P
Bohemia River	Cecilton	2,466	411	929	721	0.107	3,400	1,544	141	241	(1,162)	(313)
Big Elk Creek	Cherry Hill	7,881	1,314	(2,077)	621	0.228	4,623	2,854	(2,324)	75	(5,102)	(1,106)
Back Creek	Chesapeake City (N)	4,112	685	(115)	647	0.180	5,766	2,608	278	413	(1,917)	(520)
	Chesapeake City (S)	4,441	740	(1,320)	300	0.141	3,305	1,842	(999)	121	(2,720)	(611)
Upper Elk River	Elkton	37,156	2,787	2,267	7,069	3.511	N/A	N/A	N/A	N/A	5,570	417
Lower Elk River	Harbour View	460	77	1,237	489	0.054	2,503	911	857	252	199	(28)
Cristina River	Highlands[1]	3,039	152	(630)	651	0.000	N/A	N/A	N/A	N/A	N/A	N/A
	Meadowview	42,560	2,128	(31,706)	585	1.165	N/A	N/A	14,201	4,962	(28,381)	(1,065)
North East River	North East / Seneca Point	24,364	1,827	(12,744)	(955)	2.349	N/A	N/A	N/A	N/A	4,212	316
Lower Susquehanna River	Perryville	20,101	1,508	(2,799)	2,818	2.049	N/A	N/A	29,753	10,956	4,826	362
	Port Deposit	8,223	1,371	(1,433)	892	0.358	11,352	5,154	477	804	(3,873)	(1,045)
Octoraro Creek	Rising Sun	15,076	2,513	(1,990)	1,849	0.560	15,581	7,706	(1,451)	893	(8,263)	(2,002)

Existing nutrient caps place the Harbour View and Cecilton WWTPs over the limits for both nitrogen and phosphorous, and all plants except for North East River and Elkton are over the limit for phosphorous. If growth trends continue, all plants will reach nitrogen limits, with the exception of Meadowview WWTP. Existing wastewater treatment plants will reach nutrient caps for both nitrogen and phosphorous by 2030. Plants will have to upgrade to ENR technology, establish alternative disposal systems, or participate in nutrient trading to secure additional load credits in order to meet the legal limit.

2 Water quality goals for the Chesapeake Bay were set by the Chesapeake 2000 Agreement, which placed Maryland's statewide nutrient loading goals at 37.3 million pounds per year for nitrogen and 2.9 million pounds per year for phosphorous. Other states in the Chesapeake Bay watershed (Delaware, Pennsylvania, New York, Virginia, and West Virginia) have adopted similar goals. These goals are also caps, meaning once Maryland and the other States achieve the necessary reductions, they must maintain that level in order to maintain acceptable water quality in the Bay.

If all plants were upgraded to ENR by 2030, projected growth could be accommodated by most systems without exceeding nitrogen and phosphorous caps. The exceptions are in the Elkton and Seneca Point systems, which are already at the ENR treatment level, and would have to acquire nutrient credits or look into alternative treatment options to be able to meet projected demand. If capacity at Elkton and Seneca Point is not expanded via such methods, growth will be severely restricted in the North East and Elkton areas and will likely be deflected to other systems and rural areas outside of public sewer systems. If ENR upgrades are not achieved at other plants, then much of the projected growth in Cecil County will also be deflected to rural areas served by community or individual septic systems

NONPOINT SOURCE POLLUTION

A majority of Cecil County's primary water courses are also influenced by nonpoint source pollution. Nonpoint sources consist of agricultural run off, erosion and sediment from development, and stormwater runoff from roads, streets, and highways. Impervious surfaces and agriculture are significant contributors of nutrients and other pollutants to the County's waterways.

Impervious surfaces do not allow rainwater to enter the ground, which leads to runoff that causes stream bank erosion, sediment deposition into stream channels, increases in stream temperatures, and degradation to water quality and aquatic life. The amount of impervious surface in a watershed is a key indicator of water quality. According to the Conservation Fund, water quality in streams tends to decline as watersheds approach ten percent impervious coverage, and drops sharply when the watershed approaches 25 percent impervious coverage. Countywide about three percent of all land is impervious. Total nutrient discharge resulting from non-point sources is approximately 1.78 million pounds of nitrogen and 155,000 pounds of phosphorous per year.

As of 2002, Cecil County's 468 farms occupied 37 percent of the County's land (approximately 77,089 acres). Agriculture is important to the aesthetic and economic value of the County, but runoff from cropland, feedlots and pastures carries nutrients and pollutants from manure, fertilizers, ammonia, pesticides, livestock waste, oil, soil and sediment into waterways. Agricultural sources are the most significant contributor of nitrogen to waterways in Cecil County with 59 percent of total discharges coming from agricultural uses.

Table 2 summarizes existing impervious coverage and related nutrient loading as of 2002 for existing land use trends and the existing County future land use plan through 2030. A continuation of existing trends will reduce total nitrogen from non-point sources and increase nitrogen released from septic systems due to an increase in low-density rural development. Overall nutrient discharge levels would decrease as agricultural land is developed, since agriculture is currently the most significant contributor of non-point nutrients. However, land use decisions should not be made based solely on this finding as increased low-density development creates a need for roads, parking lots, and non-residential buildings, which increases impervious surfaces and runoff, and contributes to greater infrastructure costs for the County. Agriculture can be made more sustainable through best management practices and a reduction in nutrient discharge. If the County were to successfully implement the growth corridor land use plan as recommended in the 1990 Comprehensive Plan, nutrient levels would not diminish (Table 2).

Table 2. Non-Point Source Nutrient Loading

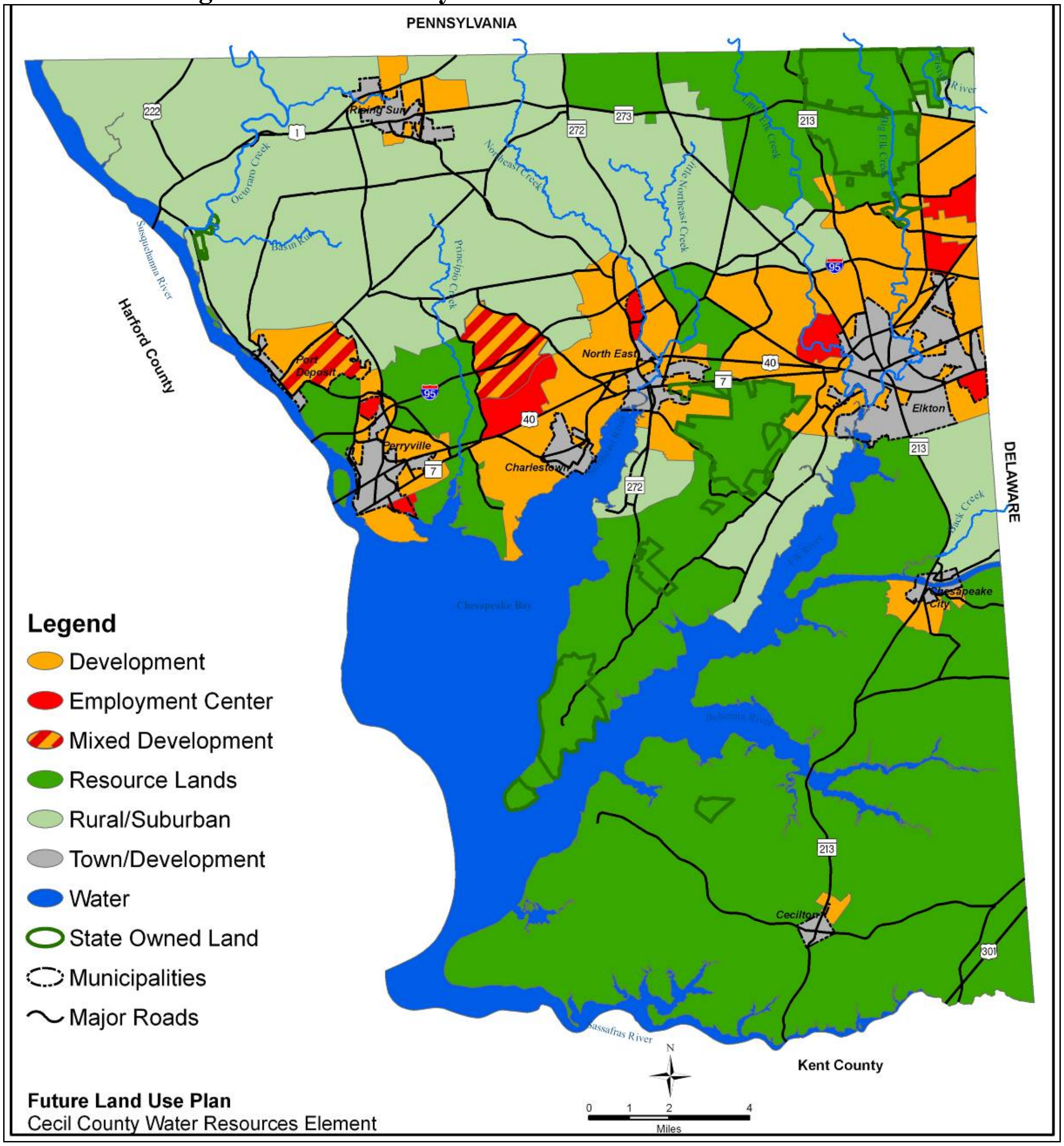
	Land Use 2002 (acres)	Land Use Trends 2030	Percent Change	Future Land Use Plan 2030	Percent Change
Impervious Cover (acres)	8,361	12,122	45%	14,706	76%
Impervious Cover (percent)	3.09%	4.48%	1%	5%	76%
Pervious Cover	261,998	258,237	-1%	255,653	-2%
P (lbs/yr) from Impervious cover	182,347	169,832	-7%	184,807	1%
N (lbs/yr) from Impervious Cover	2,038,626	1,931,096	-5%	2,061,036	1%
N from Septic Systems	154,420	248,424	61%	225,492	46%
Total Nitrogen	2,193,045	2,179,520	-1%	2,286,528	4%
1: Calculations are summary results from a model developed by Maryland Department of the Environment					

AN ALTERNATIVE FUTURE LAND USE PLAN

Limitations on wastewater treatment plant capacity will challenge Cecil County's ability to manage future growth. Unless capacities are expanded and nutrient discharges are offset without violating nutrient caps, new development will consume forest and farm land outside of growth areas. Such a pattern would result in a proliferation of septic systems and individual wells in rural areas, and an increase in the amount of nutrients discharged into the Chesapeake Bay and its tributaries, thereby defeating the purpose of the nutrient caps. If WWTPs can be expanded and upgraded, allowing growth to be channeled to the areas served by public water and sewer systems, the County will be able to maintain its rural character while strengthening the economies of its Towns and developed areas.

Figure 1 shows the recommended development areas based on water availability, wastewater treatment capacity, and nutrient loads (shown in orange). In particular, the County should direct growth to the Elkton area north to Meadowview, in and around the Town of North East, and Perryville north to Port Deposit. Growth is predominantly directed towards these communities because of the availability of water and ENR wastewater treatment plants. The intent of this plan is to create nodes of development that will be better served by transportation and water and sewer infrastructure, while conserving land around the towns. Conserved land will be especially important for maintaining water quality, potential future land application of treated wastewater, and for overall quality of life.

Figure 1. Cecil County Alternative Future Land Use Plan[3]



The purpose of a WRE plan is to recommend growth areas and strategies that will utilize the County's resources in an efficient and sustainable manner. The majority of future growth should be confined to areas that can be served by public infrastructure (specifically water and sewer), while the remainder should be directed to areas where development will result in the lowest possible discharge of nutrients to the County's rivers and streams. Table 3 identifies five major goals and supporting objectives to help the County realize a more sustainable future land use pattern

[3] This alternative land use plan differs from the Future Land Use plan as adopted by Cecil County, and was based on the Author's preferences and recommendations.

Table 3. Goals, Objectives, and Implementation Strategies

Goal 1: Locate water sources that will support high quality development at appropriate densities in growth areas, while protecting the natural environment.		
	Objective 1.A: Ensure that existing and planned public water systems meet projected demand.	
		Strategy 1.A.1: The County, working cooperatively with the Towns, should update and coordinate its Master Water and Sewerage Plan and its Water and Sewer Action Plans based on the information contained in this WRE.
		Strategy 1.A.2: Require zoning, plat approval, and development approval to be contingent upon a demonstration that water supplies are adequate to meet requested demands.
		Strategy 1.A.3: Continue to monitor water levels in streams and aquifers to ensure that they remain at safe and sustainable levels.
		Strategy 1.A.4: Further evaluate the use of sites in Mineral Extraction areas as future reservoir sites.
		Strategy 1.A.5: Evaluate increased water purchases from private suppliers.
	Objective 1.B: Identify strategies to channel development away from agricultural and forest land and towards designated growth areas.	
		Strategy 1.B.1: Define growth areas that can absorb the majority of future development and growth.
		Strategy 1.B.2: Require new development to pay for the cost of expanded public drinking water systems that serve such development.
		Strategy 1.B.3: Identify Transfer of Development Rights (TDR) receiving areas with public water service and provide incentives for TDR.
		Strategy 1.B.4: Limit or phase growth in a way that allows sufficient time to develop additional drinking water resources and infrastructure.
Goal 2: Conserve water in all public and private systems		
	Objective 2.A: Increase the role of re-use in meeting the water supply needs of both urban and rural users	
		Strategy 2.A.1: Require that development and redevelopment projects, where feasible, retain stormwater for on-site use to offset the use of other water.
		Strategy 2.A.2: Encourage the reuse of treated wastewater for landscaping, parks, public facilities, and other appropriate uses.
		Strategy 2.A.3: Revise building codes to encourage wastewater reuse systems, roof catchments, rain barrels, and other methods to minimizing the groundwater use.
	Objective 2.B: Promote and encourage the efficient use of water by all water users	
		Strategy 2.B.1: Monitor and encourage the existing flow reduction program
		Strategy 2.B.2: Design and implement a rigorous water conservation program for existing development, including pricing measures and incentives
		Strategy 2.B.3: Promote the use of shared water systems between multiple housing units in rural areas by encouraging cluster development
		Strategy 2.B.5: Require County-operated water systems to minimize water loss and waste
Goal 3: Protect and restore water quality, and meet water quality regulatory requirements in the County's rivers and streams.		
	Objective 3.A: Pursue land use patterns that limit adverse impacts on water quality.	
		Strategy 3.A.1: Establish source water protection areas and associated protection measures around existing and future water supply sources
		Strategy 3.A.2: Define growth areas so they will absorb a majority of development and decrease development on rural lands.
		Strategy 3.A.3: Minimize conversion of open space, especially forest which has the lowest nutrient export rate.
		Strategy 3.A.4: Develop incentives for infill development with the Towns and other developed areas.

	Objective 3.B: Reduce pollution from nonpoint sources	
		Strategy 3.B.1: Amend the building code to allow and encourage green roofs on new and renovated buildings to reduce peak stormwater runoff and reduce the urban heat island effect.
		Strategy 3.B.2: Design, construct, and maintain County buildings, roads, bridges, drainage and other facilities to minimize sediment, nutrients, and other pollutants in stormwater flows.
		Strategy 3.B.3: Continue to promote recycling of oil, antifreeze, batteries, fertilizer, pesticides and other chemicals and materials
		Strategy 3.B.4: Promote the use of pervious pavement in appropriate locations.
		Strategy 3.B.5: Use fertilizers sparingly and don't fertilize before a rain storm, or use organic.
		Strategy 3.B.6: Fence livestock out of streams and their buffers.
		Strategy 3.B.7: Reduce phosphorus and protein in animal feed.
		Strategy 3.B.8: Promote the use of alternative water sources over the use of groundwater or surface water. Sources could include rainwater collection or wastewater reuse.
	Objective 3.C: Maintain and expand existing riparian forest and wetlands, and restore areas important to water quality (Figures 24 & 25)	
		Strategy 3.C.1: Restore riparian forest along streams supplying drinking water and on eroding stream banks and hill slopes.
		Strategy 3.C.2.: Identify and protect highly permeable soils, especially in the Coastal Plain, to ensure effective groundwater recharge and minimize pollution.
Goal 4: Improve regional cooperation between the County, municipalities, and the State.		
	Objective 4.A: Pursue formal and permanent cooperation and collaboration between municipalities and the County for development and maintenance of water and sewer infrastructure.	
		Strategy 4.A.1: Identify sources and methods for countywide infrastructure financing.
		Strategy 4.A.2: Develop long-term agreements to spell out the goals and organizational contributions involved in implementing a common County vision.
Goal 5: Upgrade and expand capacity at existing WWTPs		
	Objective 5.A: Ensure that existing and planned public wastewater collection and treatment systems meet projected demand without exceeding their permitted capacity and nutrient caps.	
		Strategy 5.A.1: Require proposed developments to meet verified assimilative capacity requirements prior to final approval.
		Strategy 5.A.2: Identify and eliminate sources of inflow and infiltration (I/I) to free up additional capacity for treatment plants.
	Objective 5.B: Utilize MDE's Point Source Nutrient Trading Policy and identify nutrient reduction strategies that could provide credits to WWTPs.	
		Strategy 5.B.1: Upgrade existing WWTPs to BNR or ENR treatment technology
		Strategy 5.B.2: Retire existing minor WWTPs (such as Cherry Hill) and connect their flows to a BNR or ENR facility.
		Strategy 5.B.3: Examine options for land application of pre-treated wastewater (*e.g.*, spray irrigation and rapid infiltration basins) as a way to increase wastewater treatment plant capacity without increasing nutrient discharges.
	Objective 5.C: Identify opportunities to use innovative and alternative methods of on-site collection, treatment, and disposal of wastewater, particularly in areas where nutrient loading is high.	
		Strategy 5.C.1: Initiate the development and use of spray irrigation systems in addition to current WWTP surface discharges3 where feasible, particularly for the Elkton system.
		Strategy 5.C.2: Develop or expand community wastewater treatment systems in areas with widespread septic system problems that are a health concern and cannot be addressed by on-site maintenance and management programs.

The majority of strategies outlined above will require significant funding. Maryland has many different programs that provide funding for environmental projects and infrastructure. Cecil County's public facilities cannot rely on only one technique; a combination of methods should be employed. Potential funding resources include but are not limited to:

- Impact Fees: Financial contributions imposed by communities on developers or builders within a designated geographic area. Revenues can only be used to pay for capital improvements associated with new development in that area. The County must obtain the authority to levy impact fees from the Maryland General Assembly. Once such authority is obtained, Cecil County should create a differential fee structure in which costs would be higher in rural areas and lower in the desired growth areas.

- Excise Taxes: Taxes on specific goods or activities such as gasoline, tobacco, real estate transactions, or new development. Excise taxes can be collected and applied countywide, or within a designated taxing area. The authority to levy an excise tax must be expressly granted by the Maryland General Assembly. Cecil County has no local transfer tax but the State of Maryland collects a 0.5% Program Open Space transfer tax. Excise taxes could be used for local land protection and restoration throughout Cecil County.

- Program Open Space (POS): POS is a state initiative that is funded through a 0.5% real estate transfer tax and provides up to 100% of a project's cost for the acquisition of open space areas throughout Maryland, and up to 90% for development of local outdoor recreation areas. Cecil County's share of POS funds in 2007 was $1.9 million, or 1.4% of the total allocated to local Maryland governments.

- Maryland Environmental Trust (MET): MET is a statewide land trust, established by the Maryland General Assembly, and administered through the Department of Natural Resources. MET accepts donated development easements in return for eligibility for a 100% property tax credit on the unimproved portion of the subject property. Other state and federal tax mechanisms, such as income tax deductions and estate tax reductions or exclusions, provide additional incentives for easement donations.

- MDE's Drinking Water State Revolving Fund (DWSRF): The purpose of the DWSRF is to make low-interest loans to community water systems and non-profit non-community systems for drinking water infrastructure projects. Systems applying for DWSRF loans must develop a plan for future financial stability and must meet capacity requirements.

CONCLUSION

Funding of conservation programs to improve water quality will be a significant challenge for Cecil County over the next few decades. However, the County has the rare opportunity to preserve large, contiguous areas of open space between two major metropolitan areas (Baltimore and Philadelphia). Doing so will not only improve the quality of life for people living in and visiting Cecil County, but it will protect the County's water supply and sustain the County's vulnerable ecosystems.

This WRE is just the first step in creating a vision and a Comprehensive Plan for the County that will satisfy its broader land use, and economic goals. Long-term thinking and investment will be necessary to accommodate growth, but near-term action will also be important in protecting lands and preparing for the future. Water resources and treatment capacity can and should be made available to channel development away from rural lands, and maintaining the County's agricultural and tourism sectors. If Cecil County is willing to make significant investments in coordination with its municipalities and the State, it will be able to accommodate growth in a sustainable manner.

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A LONGITUDINAL ANALYSIS OF THE IMPACT OF URBANIZATION ON STROUBLES CREEK: HISTORICAL PERSPECTIVE

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KEY WORDS: urbanization, watersheds, archival research

ABSTRACT

Watersheds are often studied for alterations resulting from urbanization. Research is usually conducted to understand urbanization impacts and if these impacts are beneficial or adverse. Research goal and approach varies by researcher, varies in location within the watershed and varies in parameter selection. In most cases, these analyses are independent of each other but reference each other to show time period and parameter gaps and methodology differences. Documenting urbanization's impacts on watersheds overtime is an important step in understanding these impacts.

The goal of this research is to analyze urbanization of the Upper Stroubles Creek watershed using historical records and data from the early 20th century to the present. The watershed encompasses the main campus of Virginia Tech and a portion of the Town of Blacksburg, Virginia. During the summer of 2009, a complete archival search was conducted on the watershed. The methodology consisted of library research and stakeholder and researcher interviews. Library research was conducted for all forms of documentation including historic maps, aerial photographs and research reports. Records were reviewed for type of research performed, water quality data and development changes. Interviews were accomplished with stakeholders involved in the watershed, including town officials, local environmental organizations, local conservation organizations, university researchers, and teachers from the local schools who conduct activities within the watershed.

This paper will present the results of this longitudinal analysis in conjunction with the watershed changes resulting from long-term development.

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THE TASTE AND ECONOMICS OF DESALINATED WATER

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KEY WORDS: aesthetics, calcium, hardness, water taste, desalination

ABSTRACT

Advances in technology and increasing population pressure have resulted in shifts on both the supply and demand sides of the market for desalinated water, leading to an increase in equilibrium quantity. While desalination removes nearly all the minerals, re-mineralization is necessary to make water potable and to minimize corrosion to the distribution system. To make desalinated water drinkable and desirable to consumers, an improved understanding of sensory perception of minerals in drinking water is needed.

This study investigated if people can identify different concentrations of calcium hardness in drinking water. Test concentrations started at 10 mg/L Ca (25 mg/L Hardness as $CaCO_3$) and consecutively doubled until the sixth concentration of 320 mg/L Ca (800 mg/L Hardness as $CaCO_3$). No statistically significant differences were found in taste between the calcium concentrations of 10, 20, and 40 mg/L Ca (equivalent to 25-100 mg/L Hardness as $CaCO_3$) or between 80 and 160 mg/L Ca. The 320 mg/L Ca solution was readily identified as different and described as “bitter,” “nasty,” and “undesirable.”

These findings provide guidance to desalination utilities on concentrations of hardness that are acceptable to consumers. Consumers often complain when they detect a change in the flavor of their water. That consumers cannot detect a change in taste between 10-40 mg/L Ca provides utilities with a flexible range for adding or removing calcium without altering taste.

INTRODUCTION

With exponential population growth and a limited freshwater supply, the drinking water industry is evaluating desalination technology to alleviate a looming crisis. Many forms of desalination are evolving, including experimental designs of freezing, solar evaporation, or hybrid reverse osmosis and multi-stage flash plants, but there are currently only two economically competitive methods for desalinating water. The first is thermal processes, which use heat and low pressure to boil water. This method is extremely energy intensive, which is why reverse osmosis (RO) is emerging as the cheaper and more efficient desalination technology (Karagiannis and Soldatos 2008). RO works by forcing water through a membrane against osmotic pressure. The membrane removes almost all the salt content, leaving pure water.

The future of desalination will ultimately be decided on how economical methods are compared to conventional treatment. While average current costs for conventional treatment are below those of desalination ($0.45 plus or minus $0.23/m^3 (Wittholz *et al*. 2008)), many factors including technology, innovation, regulation, and population are encouraging a shift to desalination.

Economists represent growth of beneficial technology by an increase in supply. The typical result of increased technology is more output at a cheaper price. A good example of technology increasing the supply is widespread computer and cell phone use, something that could hardly be imagined 50 years ago.

Desalinated water is undergoing a similar revolution. Technology has improved rapidly on a number of fronts. First and foremost, the RO membranes are becoming more advanced. Membranes that can withstand higher pressure and resist chemical corrosion reduce maintenance costs and allow desalination plants to run at higher capacity. Pretreatment technologies are being tailored to fit the needs of RO membranes, ensuring that microorganisms and other potential dangers to the membrane are eliminated. Capital costs can be decreased by converting a conventional treatment plant to a pretreatment plant for desalination (Younos 2005). While pumping the water against osmotic pressure has high energy requirements, advances in energy recovery devices are improving the ability to maintain pressure while reducing costs (Glueckstern 1999). In the past 40 years, the cost of desalination has dropped 5.3% annually (Zhou and Tou 2004). Creating desalinated water is becoming more widespread and more affordable.

When economists use the term demand, they are referring to both the willingness and ability to pay for a good or service. Since water is essential for human life, both in regards to direct consumption and agriculture, the willingness to pay for water could potentially reach astronomical levels. Population projections indicate that by 2025 we could have 8 billion people living on our planet (Frioui and Oumeddour 2007). In fact, the sheer rate of population growth dictates that we will soon have no choice but to start desalinating water on a larger scale (Frioui and Oumeddour 2007).

As desalination and membrane technologies grow in prevalence, the remineralization of deionized water is vital to make healthy, palatable, and minimally corrosive water (Hasson & Bendrihem 2006). The high purity processes necessary to remove unwanted salts also remove minerals which are experimentally linked to good taste and good health in drinking water. In addition, the supplementation of minerals to deionized water is essential to prevent the corrosion of distribution systems.

Unlike conventionally treated water, the mineral content of desalinated water may be honed to optimal cation and anion concentrations for a balance of aesthetics, health benefits, corrosion reduction, and cost effectiveness. Finding this level is a difficult task, so a better understanding of water hardness, one of many constituents, will help to better characterize water quality as a whole.

Water hardness is the concentration of polyvalent cations, which highly correlates to the concentration of calcium and magnesium cations (Klevay & Combs 2004). The most notable effect of water hardness is scaling on pipes and dishes and an inability to form soapsuds. However, research within the last several decades, beginning with a study by Kobayashi in 1957, has produced evidence of beneficial effects of hardness on health (Kozisek 2003). In addition, significant experimentation has been done on the taste and corrosion potential of drinking water hardness. The ideal levels are a current area of research and the main focus of this paper.

Table 1. Classification of Water Hardness

Classification	mg/l as $CaCO_3$	grains/gal
Soft	0 - 17.1	0 - 1
Slightly hard	17.1 - 60	1 - 3.5
Moderately hard	60 - 120	3.5 - 7.0
Hard	120 - 180	7.0 - 10.5

Calcium is the most abundant mineral found in the human body, and sufficient dietary intake of calcium is necessary to maintain and replenish its essential functionality. Nearly all of the calcium (99%) is found in the bones and teeth, but calcium is also vital for muscle contraction, hormone and enzyme secretion, and message sending in the nervous system (Abrams *et al*. 2009). The dietary intake of calcium has been epidemiologically linked to an inverse relation with the occurrence of osteoporosis in aging women (Azouly *et al*. 2001). However, nutritional surveys have revealed that more than half of North Americans do not intake the recommended daily amount (RDA) of calcium.

The three most vital sources of naturally bioavailable calcium are milk, dairy products, and water (Azouly *et al*. 2001). Actually, drinking water can provide significant amounts (several % of RDA) of calcium, but extreme values may adversely affect the flavor and acceptability of the water. High levels of calcium create a bitter or salty taste and a slimy mouth feel, depending on the associated anion concentrations (Lawless *et al*. 2003). The presence of calcium has a 0.96 correlation with water hardness and primarily originates from limestone, dolomite, gypsum, and other minerals (Klevay & Combs 2004).

Drinking water, whether it is tap water or bottled water, describes a consumer product with expectations not only for safety and sanitation but also for aesthetics and tastiness. Consumers desire consistency in their products. Humans can readily detect differences and usually do not like changes in their daily beverages, be it water, coffee, tea, or colas (Dietrich 2006). In fact, producing an acceptable and consistent product is a large determiner of public trust and confidence in a drinking water utility (Burlingame *et al*. 2007). For this reason, it is important to understand the sensory perception of drinking water to determine what composes a desirable taste versus an unacceptable taste. Several regulatory organizations, including the USEPA, have already placed some aesthetic standards on a number of drinking water constituents but there have been no values set for hardness, though it is often constrained by total dissolved solids (TDS) limits. Within the last century the science of sensory testing has evolved, searching for qualitative laws of human perception (Moskowitz 1983). However, that research has not expanded much into the drinking water industry.

When evaluating the taste of water hardness the concentration of cations is the major determinant of taste. Taste is stimulated when molecules interact with chemoreceptors in the taste buds (Fox 2008). However, the taste of divalent cations such as in calcium and magnesium salts has proven to be a complex science. Conversely, the tastes of monovalent salts follow trends correlated with the corresponding atomic masses (Lawless *et al*. 2003). Therefore, the taste of divalent salts needs more descriptive studies to search for qualitative relationships with perceived sensation. Good tasting waters have been found to have a hardness between 10 to 100 mg/L due largely to calcium hardness (Burlingame *et al*. 2007). The growing importance of the taste of tap water is evidenced by the budding bottled water industry, which primarily seeks to fill the market niche of a quality consistent aesthetic product.

The objectives of this research were to evaluate human sensory perception of different calcium concentrations that are possible in drinking water and to determine the sensitivity of humans toward detecting different calcium concentrations.

MATERIALS AND METHODS

The primary means of data collection for the sensory perception of drinking water hardness were human panelists. The taste testing sessions were held with individual panelists or in separated groups to attain subject isolation. All test subjects were Blacksburg residents or affiliated with Virginia Tech. The testing procedure was approved by the Internal Review Board (IRB) at Virginia Tech. Each test subject signed a written consent form and completed a demographics questionnaire before testing began. No subjects were below 18 as it is the minimum age for consent.

Panel Description: The 41 panelists who participated had a mean age of 35.9, with a standard deviation of 15.5 and a median of 33. The age of panelists ranged from 19 to 60 years of age. Of the panel, 58.5% were female. All subjects were healthy individuals with varied drinking water preferences and were regular consumers of varied hardness drinking waters.

Solution Preparation: A stock solution of calcium chloride was produced at 1600 mg/L hardness as $CaCO_3$ to be diluted for desired concentrations. The reagent water was deionized water from an Aries column unit and a Barnstead Mega-pure organic removal system with a chemical resistivity of above 16 $M\Omega/cm^3$ and a pH of approximately 5.45. This water was mixed with Fisher Chemical calcium chloride dihydrate to prepare the stock solution. Six separate solutions were prepared at concentrations of 10, 20, 40, 80, 160, and 320 mg/L Ca, equivalent to 25, 50, 100, 200, 400 and 800 mg/L hardness as $CaCO_3$. These solutions were tested using atomic absorbance spectroscopy or inductively coupled plasma mass spectroscopy (ICP-MS).

Taste Testing Procedure: The taste testing panels were given a simple ranking test- randomized complete block design in which the six different concentrations of solution were presented to the panelist in a balanced, random order. After the panelists rinsed their mouths with taste free (nanopure) water, they tasted a moderate concentration of the calcium solution to train or calibrate their sensory perception. The panelist then rinsed with taste free water again and began tasting the six different solution concentrations. Each panelist attempted to place the samples in order from least intense flavor to most intense. The panelists were asked to wait 15-30 seconds between samples to avoid aftertaste effects and highly encouraged to retest samples as needed. The panelists then recorded their answers when confident. Each white 3 oz. sample cup had a three digit code so as to limit preference bias in ranking selections.

Table 2. Concentrations Tested

Test Solution	1	2	3	4	5	6	STOCK
Moles/L	0.00025	0.0005	0.001	0.002	0.004	0.008	0.016
Hardness*	25	50	100	200	400	800	1600
mg/L Calcium	10	20	40	80	160	320	640

* As mg/L Ca as equivalent $CaCO_3$

The simple ranking test was used to compare the samples according to a single attribute, which was "mineral content" in this study (Meilgaard *et al*. 2007). The test is well suited to provide a large amount of data about a sample set using a relatively small sample size.

DATA ANALYSIS

Analysis of the collected data was carried out using a Friedman-type statistic and a multiple comparison procedure. The Friedman's test assigns a T-value (equation 1) to the data which must be greater than the table chi-squared value for the prescribed confidence interval (0.95) and the degrees of freedom (5) in order for the null hypothesis (no significant differences or type I error) to be rejected. If the null hypothesis is rejected, a multiple comparisons test assigns a least significant difference between samples based on the parameters of the data. The difference is assigned using a non-parametric equivalent of the Fisher's least significant difference for rank sums (equation 2) (Meilgaard *et al*. 2007):

$$T = \frac{12}{bt(t+1)} \sum_{j=1}^{t} x_{,j}^{2} - 3b(t+1) \quad (1)$$

$$LSDrank = z(\alpha/2) \sqrt{\frac{bt(t+1)}{6}} \quad (2)$$

Equations 1 & 2: minimum T-value and least significant difference (LSD).
b = number of panelists; t = number of samples; z = z score of α; x term = sum of squared rank-sums.

The difference between the rank sums, the total sums of ranks assigned to each concentration by the panelists, must be greater than the least significant difference to considered statistically different. This difference can then be used to detect statistically significant differences between the concentrations tasted in the rank test. The least significant difference describes a statistical value valid for the population that may or may not be correct on an individual basis.

The type II error or false negative (false perceived similarity between samples) was tested with a post hoc power analysis using a bootstrapping method on the statistical software, R version 2.9.1, comparing each concentration to each other for each test. The powers between the first and second concentrations were low, but this confirms the sensory perception of "no difference" though there is a known physical disparity in concentrations. The powers between the lower and higher concentrations were high enough to confidently reject a type II error (greater than a power of 0.8). Therefore, enough panelists were used to produce statistically significant results.

RESULTS AND DISCUSSION

At higher concentrations, the calcium taste was most commonly described as bitter, salty, astringent, and tongue coating. At lower concentrations, there was little taste but some mouthfeel. The results indicate that the first three concentrations showed no significant difference for the population. However, the fourth and fifth concentrations were both significantly different from all of the first three concentrations but not significantly different from each other as shown in Figure 5. The highest concentration was significantly different from all of the other concentrations. The bars underneath the concentration boxes signify a statistical equivalence between concentrations as determined by the difference between concentration rank sums (the numbers below the boxes).

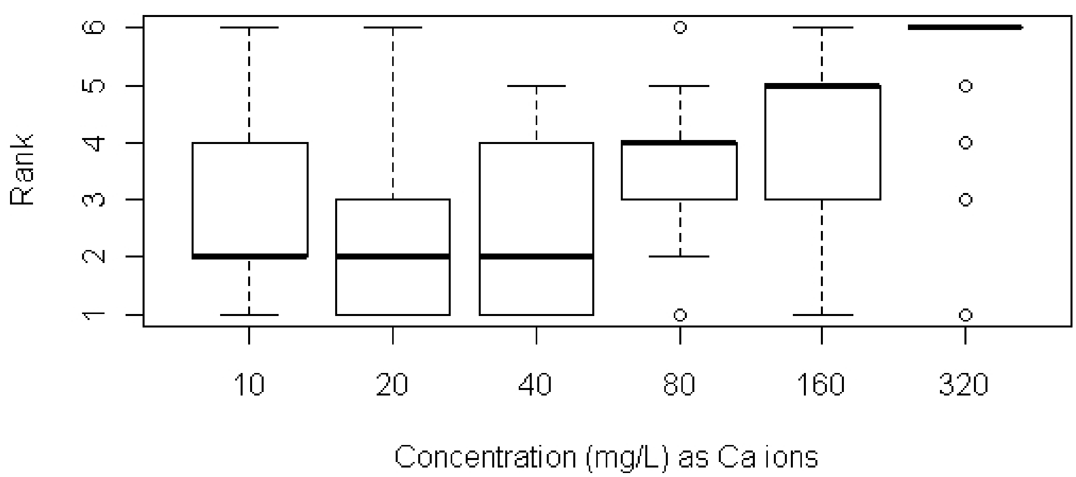
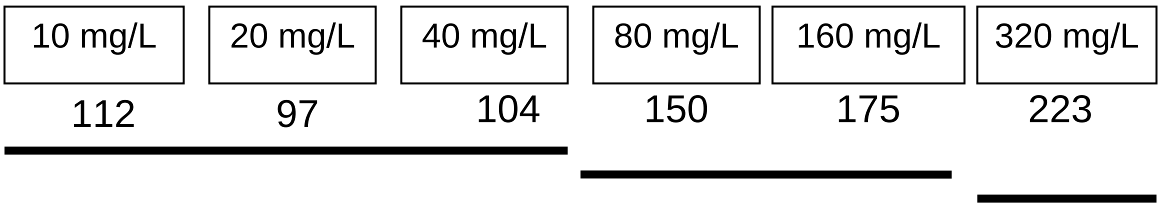


Figure 3. Boxplot summary of assigned ranks.



n = 41   p-value = < 2.2e-16   LSD = 33.2

Figure 4. Statistically significant differences for calcium; values under the boxes represent the rank sum; a difference of 33.2 (least significant difference) is required between calcium concentration in order to have a statistically significant difference.

The taste threshold for chloride is 200-300 mg/L, depending on the associated cation, while the taste threshold for calcium is between 100-300 mg/L (WHO 2005). Therefore, the ranking tests results are consistent with threshold values published by the World Health Organization (WHO) and complementary to the taste intensity results found by Lawless in a study on the taste of calcium and magnesium (Lawless *et al*. 2003). Though the primary focus of Lawless' study was food-typical levels of calcium, the lowest concentration (0.01 M) was close to the highest concentration (0.008 M) for the ranking test. At these levels, the taste intensity of calcium was about equivalent for the sensations of salty and bitter, but differences came at levels (>0.06M) above typical drinking water concentrations (Lawless *et al*. 2003).

CONCLUSION AND FUTURE WORK

The population as a whole could not distinguish calcium concentrations between 10 and 40 mg/L, or 25 and 100 mg/L hardness as $CaCO_3$. Therefore, the necessary remineralization of desalinized water should focus on the corrosion potential and cost of the treated water, as there is evidence that the population as fluctuations in taste between 25 and 100 mg/L hardness will not significantly affect the taste for most people. In addition, these findings provide evidence for easier quality control for utilities with highly variant source water and/or need for softening.

More research is necessary to better characterize the taste of divalent cations such as calcium and magnesium. The taste of water hardness will be especially important as desalination and remineralization become more prevalent. Therefore the tastes of different ratios of magnesium to calcium should be explored as well as the taste effects of the associated anions at different concentrations of hardness. Also, the effect of personal drinking water habits on the perception of drinking water hardness could be explored. In addition, remineralization techniques should be explored for solution preparation to better simulate municipal drinking water.

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Back to Table of Contents

IV-B Stormwater (Part 1): Developing Management Policies and Practices

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SOME CHALLENGES CONFRONTING STORMWATER POLICY IN VIRGINIA

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KEY WORDS: stormwater, costs, benefits, watershed, regulation

ABSTRACT

A comprehensive revision of stormwater regulations is currently underway in Virginia. The proposed regulations place more stringent regulatory requirements on land development activities and establish local stormwater program administration requirements across the Commonwealth. The proposed regulation includes new requirements for the control of both stormwater quantity and quality. The proposed regulations places new emphasis on runoff reduction as a stormwater control practice. This extensive effort will, if successfully implemented, alter the land development practices throughout the state.

This presentation will illustrate some fundamental challenges to Virginia's evolving stormwater policy. Each challenge has important implications for both the economic and water quality outcomes of stormwater management. First, the proposed regulation increases site specific water quality requirements for redevelopment and high density urban development. Such requirements create disincentives for urban densification. Increasing urban development density has the potential to improve overall water quality in an entire watershed and reduce stormwater control costs. Second, state water policy should (but currently does not) recognize that some urbanizing areas may not be able to maintain ambient water quality conditions regardless of the amount of stormwater controls implemented. Overall watershed objectives may be advanced by acknowledging that specific areas (slated for high density development) may suffer lower local

water quality while enhancing water quality in other areas. Finally, the proposed regulations create stringent and uniform site-level water quality standards across the state. Such runoff standards will be costly to achieve, but produce minimal watershed benefits in some areas of the state.

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ASSESSING THE WATER QUALITY PERFORMANCE OF BMPS

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ABSTRACT

It has been long understood that the water quality characteristics of urban runoff vary widely, particularly for phosphorus. Historically, phosphorus has been the key nutrient of concern in Virginia. Treatment units or BMPs (Best Management Practices) must accommodate a wide range of flows, chemical conditions, and phosphorus influent concentrations. Assessing treatment performance can be difficult. Manufactured Treatment Devices (MTDs) typically exchange technology for space, so assessing their performance adds an additional layer of complexity. This paper presents a summary of the best available methods for assessing MTD performance, and factors that impact performance, such as maintenance. This paper is a summary of the initial work of an expert panel under contract with the Virginia Department of Conservation and Recreation (VDCR) to develop a phosphorus protocol for MTDs for treatment of stormwater. Because of the timing of this work, it may not be public by the time of the conference. Therefore, this paper will present the rationale behind the panel's recommendations, rather than the protocol itself.

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STORMWATER CODES AND ORDINANCES IN THE RIVANNA RIVER WATERSHED

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ABSTRACT

The Rivanna Conservation Society (RCS) and the Southern Environmental Law Center (SELC) supported by the UVA Environmental and Conservation Law Clinic have developed comprehensive recommendations relating to the stormwater codes and ordinances in communities throughout the Rivanna River Watershed.

Working together these groups have developed a comprehensive set of recommendations for the City of Charlottesville, the County of Albemarle, the County of Fluvanna and the County of Greene, with the expectation that each local government will incorporate the recommendations into their Comprehensive Plans and implementing Codes and Ordinances.

The Center for Watershed Protection (CWP) developed a Code and Ordinance Worksheet ("Worksheet") that was used as the starting point for our analysis. The Worksheet contains a number of benchmarks against which a locality's ordinances may be compared to determine how well they promote development practices and techniques that reduce stormwater runoff.

The RCS/SELC/UVA recommendations are the culmination of a three year effort to expand and refine the initial work of the CWP, and represent a manageable set of practical, common-sense steps the County could take to reduce the damage that polluted stormwater runoff is causing to our local waterways.

The recommendations are grouped into five broad categories, which are articulated in the individual reports:

1. Promote better design and layout of new development sites.
2. Actively encourage low-impact development techniques.
3. Limit sediment-laden runoff from construction sites.
4. Promote riparian protection on pasture land.
5. Increase protection of buffers.

INTRODUCTION

In 2006 the James River Association invited the Rivanna Conservation Society (RCS) to conduct a watershed wide review of the stormwater codes and ordinances in central Virginia. RCS contacted the University of Virginia Environmental Law and Conservation Clinic (UVA) to request pro-bono legal assistance.

RCS and UVA determined that an in-depth analysis of current development codes and ordinances for stormwater in the City of Charlottesville and the Counties of Albemarle, Fluvanna and Greene would be the focus of the project. The Southern Environmental Law Center (SELC) joined the team in 2007 as a part of its Charlottesville/Albemarle Project.

This project was conceived to be a follow up to a project initiated in 2006 by the James River Association using the Codes and Ordinance Worksheet (COW) created by the Center for Watershed Protection (CWP).

Specifically, the James River Association (JRA) focused on the forty-five major localities that make up the James River watershed. JRA used the Code and Ordinance Worksheet that contained a number of benchmarks used to measure how well a locality's ordinances promote development practices and techniques that reduce stormwater runoff (Center for Watershed Protection, "Code and Ordnance Worksheet"). We used the Worksheet as the starting point for our analysis to help identify City and County practices and Code provisions that could be modified to yield greater water protection.

This triad of environmental and conservation organizations has been working for 3 years to develop recommendations for the Rivanna Watershed, based on the Codes & Ordinance Worksheet (COW) developed by the Center for Watershed Protection (CWP).

The COW Model Ordinance included 28 principles in 4 areas:

- Residential Streets and Parking Lots
- Lot Development
- Conservation of Natural Areas
- Stormwater and Erosion Control

The team working on these reports then analyzed the Code in greater detail to identify specific areas for action and improvement. It then spent several months expanding and refining those preliminary findings based on discussions with local government staff members, interested citizens, as well as the collective experience and knowledge of our own organizations. The recommendations contained in the four reports are the culmination of this effort and represent a manageable set of common-sense steps the local governments can take to reduce the damage to our waterways caused by polluted stormwater runoff.

The Rivanna River Basin Allocation

- Albemarle – 65 %
- Charlottesville – 50 %

- Fluvanna – 40 %
- Greene – 36 %
- Fractional percentages of Louisa, Nelson and Orange Counties.

Aquatic life impairment:

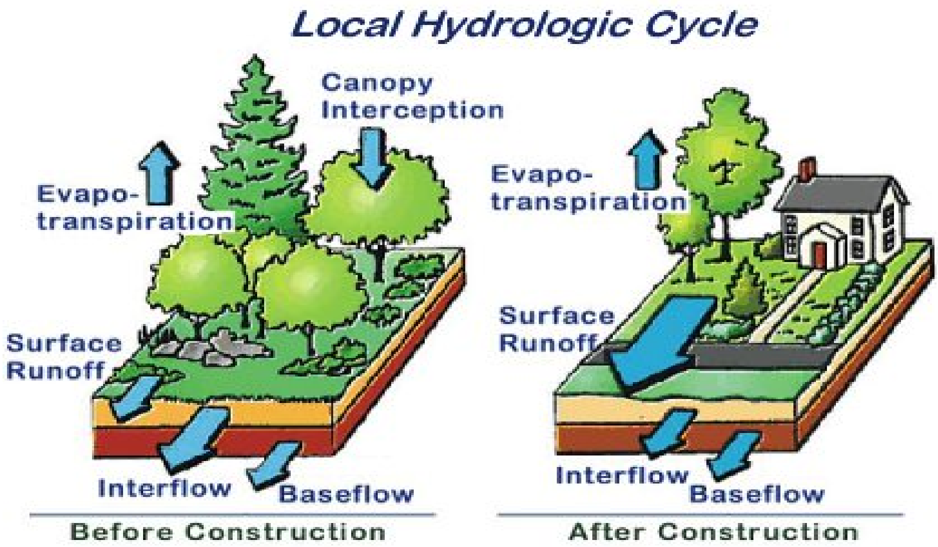
- An 11-mile stretch of the Rivanna River is impaired, beginning at confluence of North and South Forks.
- Sedimentation is the most likely cause of the impairment.
- Largest source of that sediment (44%) is from streambank erosion caused by higher stream flows.

In the Rivanna Basin, declining water quality is closely related to development and urbanization. Already, a number of rivers and streams flowing within or along the borders of Fluvanna County are listed by the Virginia Department of Environmental Quality (DEQ) as "impaired waters." Approximately fifteen miles of the Rivanna River itself are "impaired" under Virginia's aquatic life standard. Although DEQ has not yet identified the source of the pollution causing this impairment, violations of this standard are typically associated with sediment pollution, which, in turn, is frequently caused by stormwater runoff. For urbanized portions of the Rivanna, stormwater runoff has already been identified as an important cause of pollution (Information about impaired waters in Fluvanna County can most easily be retrieved by visiting http://gisweb.deq.virginia.gov/FactSheets2008/Choose.aspx and searching for impaired waters in Fluvanna County.) (DEQ 2008).

As outlined on the EPA website- stormwater runoff occurs when precipitation from rain or snowmelt flows over the ground. Impervious surfaces like driveways, sidewalks, and streets prevent stormwater runoff from naturally soaking into the ground. This is a problem because Stormwater can pick up debris, chemicals, dirt, and other pollutants and flow into a storm sewer system or directly to a lake, stream, river, wetland, or coastal water. Anything that enters a storm sewer system is discharged untreated into the waterbodies we use for swimming, fishing and providing drinking water. Polluted stormwater runoff can have many adverse effects on plants, fish, animals and people. *Sediment* can cloud the water and make it difficult or impossible for aquatic plants to grow. Sediment can also destroy aquatic habitats. *Excess nutrients* can cause algae blooms. When algae die, they sink to the bottom and decompose in a process that removes oxygen from the water. Fish and other aquatic organisms cannot exist in water with low dissolved oxygen levels. *Bacteria and other pathogens* can wash into swimming areas and create health hazards, often making beach closures necessary. Polluted stormwater often affects drinking water sources. This can affect human health and increase drinking water treatment costs.

In 2008, the volunteer water quality-monitoring group StreamWatch issued a report summarizing the biological health of the Rivanna River at thirty-one sites. The report rated the health of these sites on a scale of very good, good, fair, poor, or very poor. Only 23% of the sites monitored in the Rivanna basin received a good or better ranking (Murphy 2008, Fluvanna County 2009).

It is the hope of RCS, UVA and SELC that our recommendations will be implemented by all jurisdictions in the Rivanna Basin and that they will play an important role in reducing stormwater pollution from new development. By implementing our recommendations now the jurisdictions can help protect the quality of some of its most important natural resources – its rivers and streams.



The Challenges of Stormwater Runoff

Stormwater runoff occurs during rainstorms when precipitation that would normally soak into and infiltrate natural ground cover instead collects and flows over paved surfaces and construction sites. As the amount of developed land increases, less rain is absorbed into the ground, thus increasing the volume and speed of stormwater runoff. Scientific documentation clearly demonstrates that urban and agricultural runoff is dramatically affecting water quality throughout Virginia (DEQ 2006).

Stormwater causes pollution in two ways. First, as it grows in *quantity*, it can cause excessive erosion and sedimentation of the waterways into which it flows. In natural and forested conditions, much of the precipitation from rainstorms is absorbed back into the ground near where it falls, nourishing plant life and helping to recharge groundwater aquifers. It has been estimated that a one-acre parking lot creates 16 times more runoff than a meadow of the same size (Maurer 1996). Rain collects on compacted, impervious surfaces and creates fast-moving flows that gush directly into nearby waterways or get flushed into stormwater sewers which lead to the waterways.

Second, the *quality* of stormwater can be detrimental. Natural ground cover normally helps slow and filter stormwater runoff. However, as rainfall collects upon and washes over paved surfaces, construction sites, and manicured lawns and pastures, it picks up soil, sediment, fertilizers, and bacteria present on those surfaces (DCR 2009). The runoff sweeps those pollutants along as it flows into nearby waterways or drains into stormwater sewers that usually discharge directly into the waterways. This influx of pollutants can harm aquatic life and make rivers and streams unfit for recreation.

In general our recommendations are grouped into four broad categories:

1. Promote Better Design and Layout of New Development Sites
2. Promote On-Site Infiltration and Encourage Low-Impact Development Techniques
3. Limit Erosion from Construction Sites
4. Implement a Buffers Ordinance

Damage from stormwater runoff can be seen in a number of ways, including;

- Higher water treatment costs.
- Sediment in reservoirs, gradually reducing capacity.
- Using treated drinking water for every use.
- Depletion of groundwater supplies.
- Abnormal stream flows: flood or trickle.

Much of the runoff comes from streets and driveways;

- Streets typically account for roughly half of the impervious cover in the overall road network of traditional neighborhoods.
- Driveways generally account for another twenty to thirty percent, and cul-de-sacs and other turn-arounds represent approximately seven percent.

Reducing stormwater runoff can protect local streams and rivers from:

- Erosion of streams
- Influx of pollutants
- Reduce water treatment costs:
- Less sediment in reservoirs.
- More recycled rainwater instead of treated drinking water.
- Replenish groundwater supplies.
- Protect and restore stream flows.

Our analysis and recommendations address only stormwater from "new development," though we recognize that agricultural runoff and other pollution sources are important issues in the Rivanna River watershed. Recommendations were developed for Charlottesville, Albemarle, Fluvanna and Greene Counties.

PROJECT STATUS REPORT

Final reports for the City of Charlottesville and the County of Albemarle have been issued and presented to the governing officials, including the City Council, the Board of Supervisors and the Planning Commissions.

Charlottesville - We presented our report to the City of Charlottesville Planning Commission and City Council in the spring of 2008. The City Council asked that we work with City staff to draft ordinance language. Recommendations include:

1. Amend City Code provisions to reduce impervious surface.
2. Promote on-site infiltration and low impact development features.
3. Limit erosion from construction sites.
4. Update and expand City's stormwater manual.
5. Explore new initiatives to enhance stream buffers.

Albemarle County - We presented our report to the Albemarle County Board of Supervisors (BoS) in August 2008. We were invited by the BoS to work with County staff to draft ordinance language. 20 recommendations were cut down to 5 priorities. Of the 5 ordinances: One was unanimously adopted by the BoS; one was incorporated into the operating manual; and three are currently before the Planning Commission. Recommendations include:

1. Reduce minimum parking requirement for office buildings.
2. Require stronger stormwater protections when exceeding parking maximums.
3. Enhance landscaped areas in new parking lots.
4. Establish outer limit on how long construction sites may be left destabilized.
5. Augment agreements-in-lieu of Erosion & Sedimentation plans.

Final reports for the counties of Fluvanna and Greene are being drafted and we intend to have these reports printed and distributed to the municipalities by the end of December. We are planning to meet with the Fluvanna and Greene County Boards of Supervisors in February 2010 to present our recommendations. These recommendations will include buffer requirements that are already in place in the other jurisdictions.

Fluvanna County

1. Promote Better Design and Layout of New Development Sites
2. Promote On-Site Infiltration and Encourage Low-Impact Development Techniques
3. Limit Erosion from Construction Sites
4. Implement a Buffers Ordinance

Greene County

1. Promote better design and layout of new development sites.
2. Actively encourage low-impact development techniques.
3. Limit sediment-laden runoff from construction sites.
4. Promote riparian protection on pasture land.
5. Increase protection of buffers.

Parking Lots and Garages

Parking lots and garages are a huge contributor to stormwater runoff. For example, a 1-acre lot experiencing 1-inch rain produces 27,000 gallons runoff. The Codes and Ordinances reports recommend that the jurisdictions require that an appropriate percentage of parking spaces within large parking lots be designed to "compact" dimensions, which can reduce the size of the parking lot while accommodating the same number of vehicles. It can also increase the space available within the lot for LID stormwater management practices. The reports recommend:

- Lower mandated minimum number of spaces for offices (Albemarle County)
- Combine shorter parking spaces with more landscaping and LID (Albemarle County)
- If exceed maximum number spaces, use more landscaping and LID (City of Charlottesville, Albemarle County)

Re – vegetation of Denuded Area

A loophole in the Virginia state statute has allowed construction sites to be clear cut and left destabilized for extended periods. This can result in significant erosion and sedimentation. Specifically, this legislative language provides that - "[S]tabilization shall be applied… within seven days after final grade is reached… Temporary soil stabilization shall be applied…to denuded areas that…will remain dormant for longer than 30 days. Permanent stabilization shall be applied to areas that are to be left dormant for more than one year." 4 Va. Admin. Code 50-30-40(1)

SUMMARY

Each of the jurisdictions was provided with recommendations tailored to each community. Some areas within the Rivanna River watershed are urbanized and others are rural and experiencing rapid growth. Some segments of the watershed are relatively healthy (Fluvanna and Greene) while large portions of the Rivanna River system in the urbanized areas of Albemarle County and Charlottesville are impaired by stormwater runoff.

Our collective efforts highlight a number of ways in which ordinances and policies can be refined to foster management and development decisions that help protect local waterways. By removing unnecessary regulatory obstacles to smarter development patterns, strengthening water protections where loopholes currently exist, and providing stronger incentives for more sensitive land stewardship, we can ensure cleaner and healthier rivers and streams throughout the Rivanna Watershed.

All reports and recommendations will be issued by the end of 2009. In 2008 and 2009 formal presentations have been made before the County of Albemarle and the City of Charlottesville. RCS, SELC and the UVA Environmental Law and Conservation Clinic will be meeting with the new members of the Boards of Supervisors and City Council in 2010. Meetings with staff and elected officials continue to assure successful implementation. Formal presentations before the Fluvanna and Greene County Board of Supervisors are planned for February 2010.

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STORMWATER MANAGEMENT IN VIRGINIA: PROPOSED AMENDMENTS TO PARTS I, II, III, AND XIII OF THE VIRGINIA STORMWATER MANAGEMENT PROGRAM REGULATIONS

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[No abstract provided]

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Back to Table of Contents

Concurrent Session V

(A) Conserving Water and Exploring Alternative Water Supplies
(B) Stormwater (Part 2): Using Tools for Better Management

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V-A Conserving Water and Exploring Alternative Water Supplies

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MODERN RAINWATER COLLECTION PROVIDES ADDITIONAL POTABLE WATER FOR POOR VIRGINIA COMMUNITY

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KEY WORDS: family home rehabilitations; rain waster harvesting; poor soils

INTRODUCTION OF PROJECT DETAILS AND BACKGROUND

- Southeast Rural Community Assistance Project, Inc. (SERCAP became involved through Jack Naylor of Skyline Community Action Program (CAP)), a piedmont area community housing agency. He requested SERCAP provide engineering and field construction help in a substandard housing area for onsite water and wastewater needs.
- This, in turn enabled them to meet their family home rehabilitation funding requirements for water and wastewater with the Albemarle Housing and Improvement Program (A.H.I.P.).
- This housing rehabilitation package included approximately 11 people in 3 different houses. The project area is in the central piedmont are of Virginia, about 30 miles north of Charlottesville and is in the northeastern region of Appalachia

- 6/26/06 SERCAP makes a total allocation of $50,000 to Rainwater Management System, Inc. (RMS) for installation of an alternative water system consisting of a potable rainwater harvesting source.

Community Partners involved. AHIP; SERCAP; Skyline CAP; RMS; Tractor Works (excavating); Nationwide Homes; and Mr. Jerome Jefferson

The residents. Maxine Morton and her relatives, previously had access only to a shared pit privy for their cluster of mobile homes. They have never had any sewage disposal system or running water in their substandard dwellings. One shared, community well was drilled about 15 years ago but had insufficient supply, and is not fully piped to the houses.

Population Data. The Residents are all poverty level; all are minority race; and some are disabled or retarded.

Water needs. One shared community well was drilled about 15 years ago but its production was insufficient for all of Morton Lane. This led to SERCAP TAP Phillips involving Rainwater Management Solutions, Inc. (RMS) of Salem, Virginia in an innovative rainwater harvesting project using a modern roof washing; filtering; and disinfection processes.

Wastewater needs. Because of very poor soil properties, many alternative onsite schemes were evaluated including mounds, drip disposal, and constructed wetlands. Working through Greene County Health Dept. specialists Hogge and Mazurowski, TAP then did a full engineering design with specifications for a dual-septic tank, pumped effluent and treatment field.

Soils on this 3-acre area were extremely bad; the following list is a history of soils evaluations done on site:

- Auger testing by Greene County Health Dept specialists Hogge & Phillips 2002;
- Jefferson Health District augering w/ me in 3/04;
- AOSE augering by Tom Ashton of American Manufacturing, 6/04;
- Evaluation of data by phone w/ AOSE Houston 7/04;
- Virginia Tech's technician Cobb confirmed insufficient soil profile 8/04;
- SERCAP standard PERC testing by TAP Phillips, 10/04;
- Cobb Amooz meter testing w/ me, 12/2004

Wastewater Solution/Resolution: Skyline CAP and SERCAP were then successful in negotiating an easement with neighboring landowner for a mass drain field location with suitable soils. Phillips then did both preliminary and final engineering design with specifications for a dual-septic tank, pumped effluent and mass drain field disposal. An onsite permit was issued in 11/2006.

Community and state rolls. Greene County Health Department's environmental specialist Alan Mazurowski has overseen the onsite permit approval. The county inspections office has assisted in erosion control guidance.

Water Resolution: A SERCAP community grant allowed for installation of a potable rainwater harvesting capability and common pump house for the combination well and rainwater supply. Rainwater harvesting normally yields 0.62 gallons per square foot of roof area, or 620 gallons collected in one inch of rainfall on a 1,000 square foot roof area. Concrete, clay, and asphalt shingled roofs usually have about a 10 per cent loss due to insufficient flow or evaporation.

The contracting company, RMS, designed the collection system consists of roof washers; filtering components; underground storage tanks; and valves for blending the water from the well. The system is further constructed so that it is "sustainable". This means the system will operate indefinitely without tank drainage, for cleaning or regular replacement of parts and filters.

Basic Components of a Rainwater Harvesting System:

- Catchment Surface – (roof material)
- Conveyance System: Gutters and Downspouts – Channeling of water from the roof to the tank

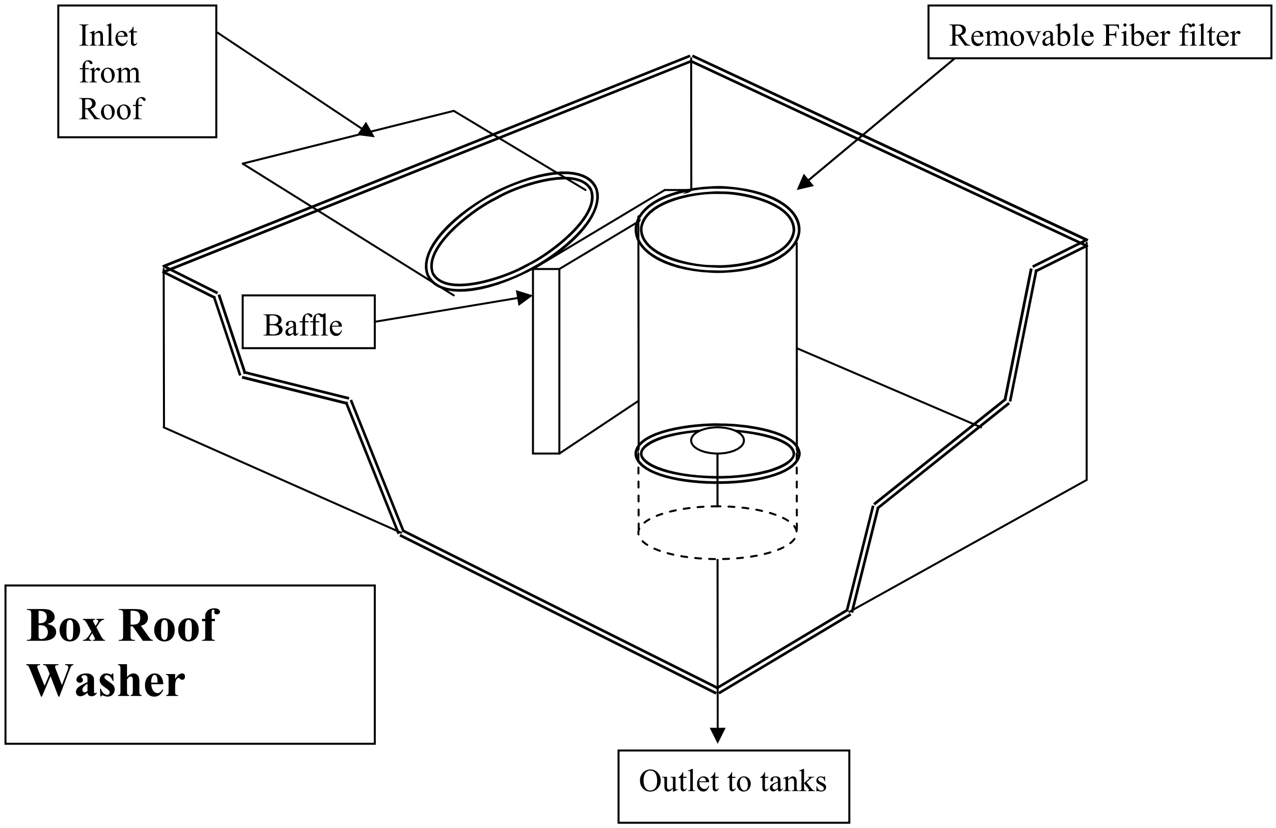
Leaf Screens; Roof Washers; and First-Flush diverters (Standpipes) – These can be in the form of leaf guards; funnel-type downspout filters; Strainer baskets; cylinders of rolled screens; or filter socks

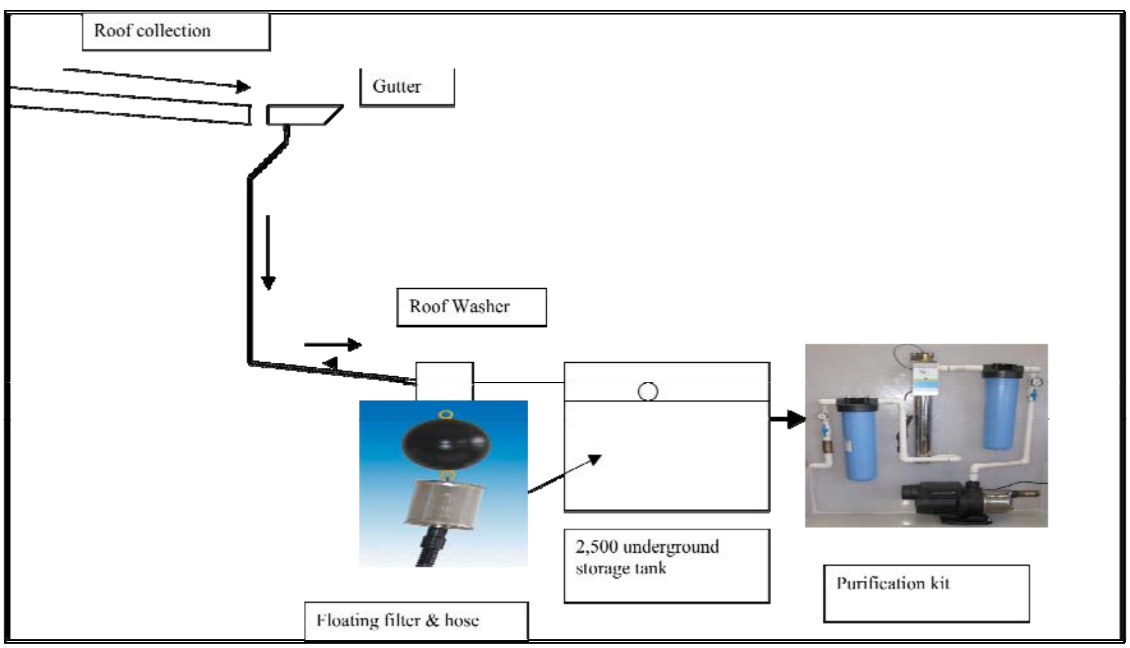
- Storage Tanks: Need to be opaque to inhibit algae growth. Use of screened vents; accessible for cleaning
- Delivery System and pressure tanks
- Treatment / Purification

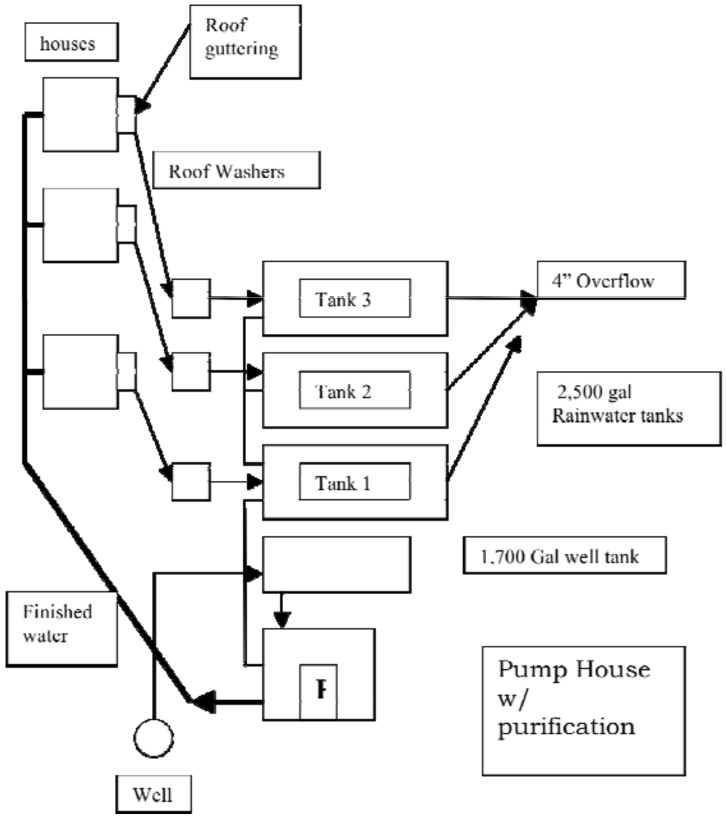
All four tanks are polyethylene underground storage tanks.

The delivery system for Morton Lane consists of parallel SSHM-2 Berkeley booster pumps, one for the well side and one for the rainwater side of the of the pump house.

Following this are the disinfection tranes, which consist of parallel sets of sediment filters: A 5-micron fiber cartridge filter followed by a 3-micron activated charcoal cartridge filter. These are then followed by an ultraviolet light


Inlet from Roof
Removable Fiber filter
Baffle
Box Roof Washer
Outlet to tanks


Roof collection
Gutter
Roof Washer
2,500 underground storage tank
Purification kit
Floating filter & hose



There is a float switch in Tank 1 to protect the rainwater delivery pump. The float opens a solenoid. A similar float switch is in the well tank to protect the well side delivery pump. A float here opens a solenoid to recharge the tank.

Southeast RCAP Board of Directors member Cabell Brand has been instrumental in promoting the use of rainwater harvesting as a responsible conservation method. He promotes the use of this technology as a viable answer to the problem of eliminating homes lacking complete plumbing.

OPERATION & MAINTENANCE

Appropriately designed rainwater harvesting systems require very little maintenance. However, like any household component, it should be checked periodically to ensure an efficiently and appropriately operating system. The following comes from the *Virginia Rainwater Harvesting Manual*, Cabell Brand Center.

- Gutters: Periodically flush to clear organic matter and eliminate clogs.
- Downspouts: Checked occasionally and remove debris, especially at connection to the gutter.
- Roof Washer filters: Periodic cleaning. Replacement yearly of cartridge.
- Tanks: If a first flush filter is not used, clean annually to remove organic debris.
- UV light: Manually cleaning the quartz sleeve.

SERCAP, Inc. & Rainwater Mgmt Solutions, Inc. (RMS) recently established detailed Operating and Maintenance Standard Operating Procedures (SOPs) to educate homeowners on Basic Use of the onsite combination well and rainwater potable water system. These step-by-step procedures for both wastewater pump operation and water system operation were posted in the pump house.

Quote from Skyline CAP's Director Kim Smith to SERCAP, Inc.: *"We are so thankful that you all have worked on this project, and that you have worked hard at the site as well."*

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RAINWATER HARVESTING AS A WATER CONSERVATION TOOL IN COASTAL TOURISM AREAS: PUNTA CANA, DOMINICAN REPUBLIC

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KEY WORDS: rainwater harvesting, water conservation, saltwater intrusion, coastal aquifers

ABSTRACT

Most of the world's population is concentrated in coastal areas. Freshwater scarcities and saltwater intrusion into coastal aquifers are two of the problems that plague many coastal systems around the world. The island nation of the Dominican Republic builds much of its economy on the tourism sector throughout the northern and eastern coastlines. The need to preserve natural resources and study the impact of water demand in coastal areas is crucial to tourism economy and social welfare in the Dominican Republic. While tourism industry for this small island is booming, availability of adequate, water resources are now coming into question. There is a significant need for developing water supply management plans and accountability for water use or water consumption. Punta Cana, the study site for this research, is one of the several resort areas developed along the coastline and totally depends on groundwater to meet its increasing water demand. The goal of this study is to investigate the feasibility of rainwater harvesting as an alternative water source that will complement traditional centralized and groundwater supplies in Punta Cana. An analysis of decentralized rainwater harvesting and the potential benefits in terms of water conservation and preventing saltwater intrusion will be discussed. Also, this study will explore the potential benefits of water savings on energy conservation that influences the carbon emission and climate change.

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INVESTIGATING THE RELATIONSHIP BETWEEN EDUCATION AND WATER CONSERVATION IN UNIVERSITY RESIDENCE HALLS

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KEY WORDS: natural resource conservation, environmentally relevant behavior, university residence halls

ABSTRACT

Universities and colleges are major consumers of natural resources. A U.S. Department of Energy study (1993) revealed that while buildings at the nation's colleges and universities represent only 5% of the nation's multi-building facilities, they consume 18.6% of their total energy use. Energy usage in university residence halls includes heating and cooling, heating water, and electricity for various uses by students. Water usage impacts energy use as electricity is used to treat, deliver and heat/cool water.

The objective of this research is to determine the relationship between education and environmentally relevant behavior in college students related to water and energy conservation. The results of the different strategies used in residence halls to redirect students' behavior from egocentric to altruistic and eco-centric, and the resultant effects on the water and electricity usage are examined. The research outcomes will reveal the various strategies' successes and can be used as a model by other universities for promoting water and energy conservation and behavior change.

INTRODUCTION

With the world human population estimated to reach 9.2 billion people by 2050 (United Nations 2007), the challenge is how to preserve the earth's resources to sustain and meet the needs of the world's rising population. Human actions and consumption have brought the world to its current state of environmental distress (Martin 1990, Abrahamse *et al*. 2005), but changing environmentally relevant behavior is difficult in a society based on high consumption rates (McKenzie-Mohr 2000). Environmental sustainability is a priority of the United Nations and the U.N. challenges higher education to assume a leadership role in sustainability and conservation education (United Nations Agenda 21, 1992). Universities are leaders in the community and can take responsibility for this education (Boyer 1990) by providing opportunities for students to learn and implement pro-environmental behaviors (Geiser 2006, Kagawa 2007).

Universities and colleges are major consumers of natural resources. A U.S. Department of Energy study (1993) revealed that buildings at colleges and universities represented 5% (77,000 out of 1,497,000) of total buildings at multi-building facilities in the United States. Of this, 20% of university buildings (or 1% of the total) are residential buildings. Yet despite this low percent, colleges and universities consume 18.6% (541 trillion BTU out of 2,901 trillion BTU) of the total energy use for all multi-building facilities in the U.S. (U.S. Department of Energy 1993). Virginia Polytechnic Institute and State University's (Virginia Tech) central campus, located in Blacksburg, Virginia, contains 170 buildings, of which 49 buildings (29%) are residence halls; a slightly higher percent than the national average (Figure 1).

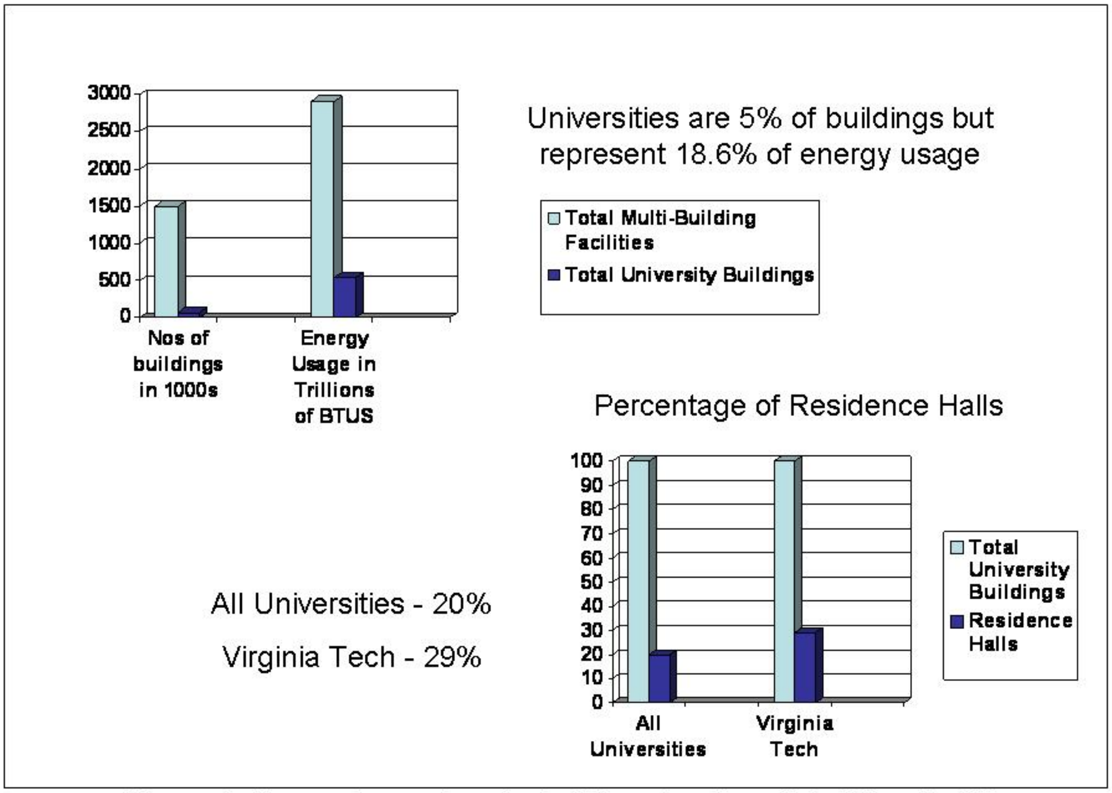

Figure 1. Comparing university buildings to all multi-building facilities (U.S. Dept of Energy, 1993; Virginia Tech Department of Facilities, 2008).

Energy usage in residence halls includes heating and cooling, heating water, and electricity for various uses by students. Water usage impacts energy use as electricity is used to treat and deliver water. Yet the students living in residence halls do not see a direct impact of their consumption behavior on natural resources as they pay a lump sum housing fee prior to the beginning of the school year. They are then able to consume as much or as little electricity and water as they desire. The challenge is how to promote conservation behaviors in people who have no immediate financial incentive to reduce their use of water and electricity.

Water supply and delivery infrastructure is energy intensive. Energy is used to treat and deliver water. Conventional/centralized water supply systems are estimated to use about 75 billion kWh per year of electricity (Oliver & Putnam 1997). The range of U.S. energy use for water treatment and delivery is reported as between 0.25 – 3.5 kWh/1,000 gallons (AWWARF 2007). The U.S. Department of Energy estimated energy consumption for water treatment and distribution as 1.45 kWh/1,000 gallons (cited in Kloss 2008). Commercial buildings consume significant amounts of the water supplied through public water systems. The electricity use for water treatment and delivery to Virginia Tech and the Town of Blacksburg was estimated as 1.67 kWh/1,000 gallons (Younos *et al*. 2009).

A daunting question is how to promote environmentally relevant behavior in college students who exhibit egocentric behavior. The objective of this research is to promote environmentally relevant behavior in students residing in Virginia Tech residence halls by implementing different information strategies.

The research began in January 2009 and was conducted over the entire Spring 2009 semester. The research continues throughout the Fall 2009 semester, with an interruption over the summer period. The research concludes with the end of the semester in December 2009. This paper reviews only the methodology used over the course of the Spring 2009 semester. Similar methodologies are being used for the Fall 2009 semester.

METHODS

Residence halls on Virginia Tech's central campus include two types of halls – dormitories and the Oak Lane Community (hereinafter referred to as "Greek houses"). The halls were stratified into these two types and then characteristics within these two stratifications were compared to eliminate variability in the study halls. Variability parameters considered include building characteristics and demographics. Building characteristics are design, renovation and remodeling history, heating and cooling methods, age, information on kitchen, laundry and bathroom facilities, structural characteristics including square footage and room composition (residential only, classrooms plus residential, or classrooms plus offices and residential), and resident demographic information such as population relative to course of study - checking for homogeneity in any particular dorm; and education level – freshman, sophomore, upper classmen or graduate student.

Once homogeneity was established, a random numbers table was used to distribute the halls into five study groups. Each group contains two dormitories and two Greek houses and each group received different educational strategies to promote environmentally relevant behavior. Each educational strategy was partially based on the antecedent behavior and consequence model (ABC Model) (Lehman & Geller 2004). Table 1 details the different information strategies used for each study group in the randomly chosen residence halls.

Table 1. Study groups and strategies

<table>
<tr><th></th><th>Control Group</th><th>Group - Information Only</th><th>Group – Feedback</th><th>Group - Comparative Feedback</th><th>Group – Team Leaders</th></tr>
<tr><td rowspan="5">Antecedent Strategies</td><td rowspan="5">Initial email advising of study</td><td>Initial email</td><td>Initial email</td><td>Initial email</td><td>Initial email</td></tr>
<tr><td>Educational information</td><td>Educational information</td><td>Educational information</td><td>Educational information</td></tr>
<tr><td>Prompts</td><td>Prompts</td><td>Prompts</td><td>Prompts</td></tr>
<tr><td>Posters</td><td>Posters</td><td>Posters</td><td>Posters</td></tr>
<tr><td>Periodic follow up emails providing educational information</td><td>Periodic follow up emails providing educational information</td><td>Periodic follow up emails providing educational information</td><td>Periodic follow up emails providing educational information</td></tr>
<tr><td rowspan="2">Consequence Strategies</td><td rowspan="2">None</td><td rowspan="2">None</td><td rowspan="2">Monthly feedback on their residence hall's results</td><td>Monthly feedback on their residence hall's results</td><td>Monthly feedback to team leaders on their residence hall's results</td></tr>
<tr><td>Monthly Feedback on how their residence hall's results compares to others halls in the study</td><td>Leaders within the halls to act as a coach to remind students of techniques to reduce consumption</td></tr>
</table>

Prompts and posters promoting conservation behaviors were placed in the halls prior to the start of the semester and the halls' residents were notified of the study via email when the semester started. The initial emails advised the residents of their participation in the study and provided a list of conservation behaviors. In late January 2009, separate meetings were held with the residence hall advisors in one study group (group leaders) to engage their assistance in placing posters and modeling conservation behavior for the students living in their halls.

In early February, March and April, follow-up emails (as outlined in Table 1 above) were sent to the designated residence halls providing the results of their conservation activities. These emails also provided a list of conservation behaviors. In March, prior to the students departing the university for spring break, an email was sent to the halls asking the students to be sure all electrical appliances were turned off and/or disconnected prior to their departure. A second email was sent on the Monday of their return to remind them of the ongoing study. Three informational/question and answer seminars were provided in three of the halls at the request of their residents.

Data Collection

The university provided historical water and electrical usage data categorized by hall and by month. Average per student electricity usage over the past four years and average per student water usage over the past seven years were calculated as the baseline with which to compare usage during the study period. Water and electricity data were collected monthly during the 2009 spring semester. However, metered water data for each individual Greek house was not available, so the study only focused on electricity conservation in the Greek houses.

Changes in electricity and water use were calculated as a percent change over baseline. Electricity and water use in the study residence halls do not include heating and cooling. Heating is accomplished with steam heat and a different system is used to document consumption. As such water consumption was limited to showers, toilets and water fountains; and electricity usage was limited to lights and other electrical devices under the control of students.

Table 2 and Figure 2 reflect the per student historical water usage by dormitory, January through May's seven year average. Table 2 is listed by strategy used. Figure 2 demonstrates the per student usage in each dormitory, lowest to highest. With the exception of Miles, historical usage is higher in dormitories with either partial or full female occupancy.

Table 2. Per Student Historical Water Consumption

Control Group	Information Only	Individual Feedback	Comparative Feedback	Group Leaders
Ambler Johnston	Johnson	Eggleston Main	O'Shaughnessy	Campbell East
498.68	807.73	871.77	623.51	743.96
Barringer	Vawter	Eggleston West	Miles	Pritchard
264.80	599.09	760.60	769.32	319.48

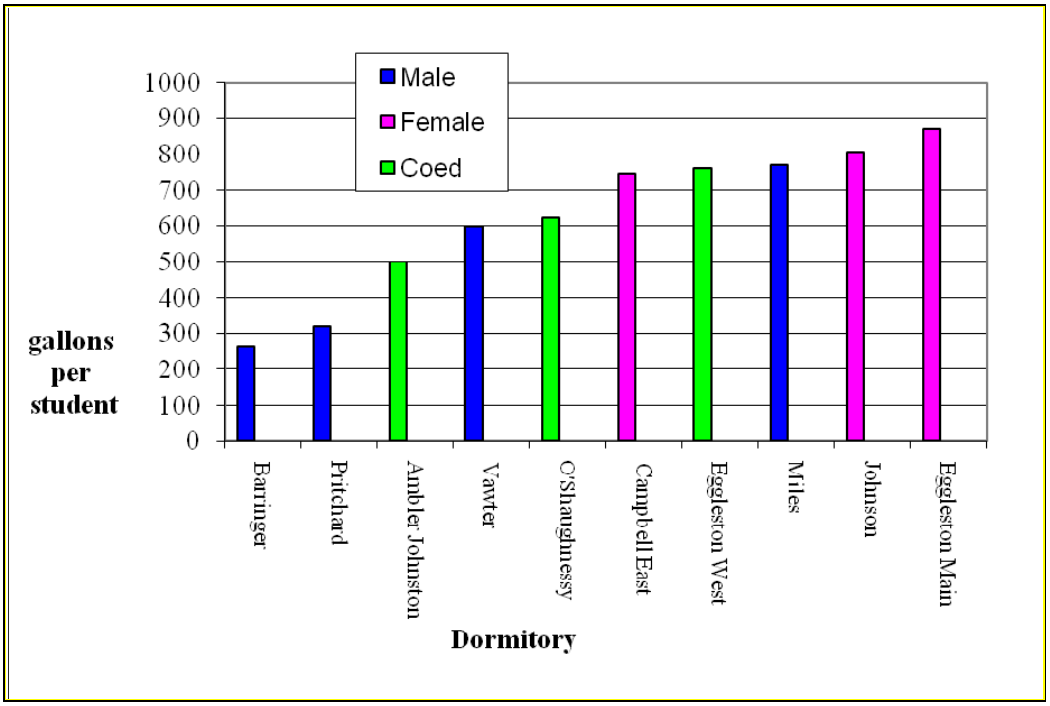

Figure 2. Per Student Historical Water Consumption

Figure 3 demonstrates the per student historical electricity usage, January through May's four year average. Unlike water consumption, no trends were documented with regards to gender differences. However, historical usage was generally higher in the Greek houses than the dormitories.

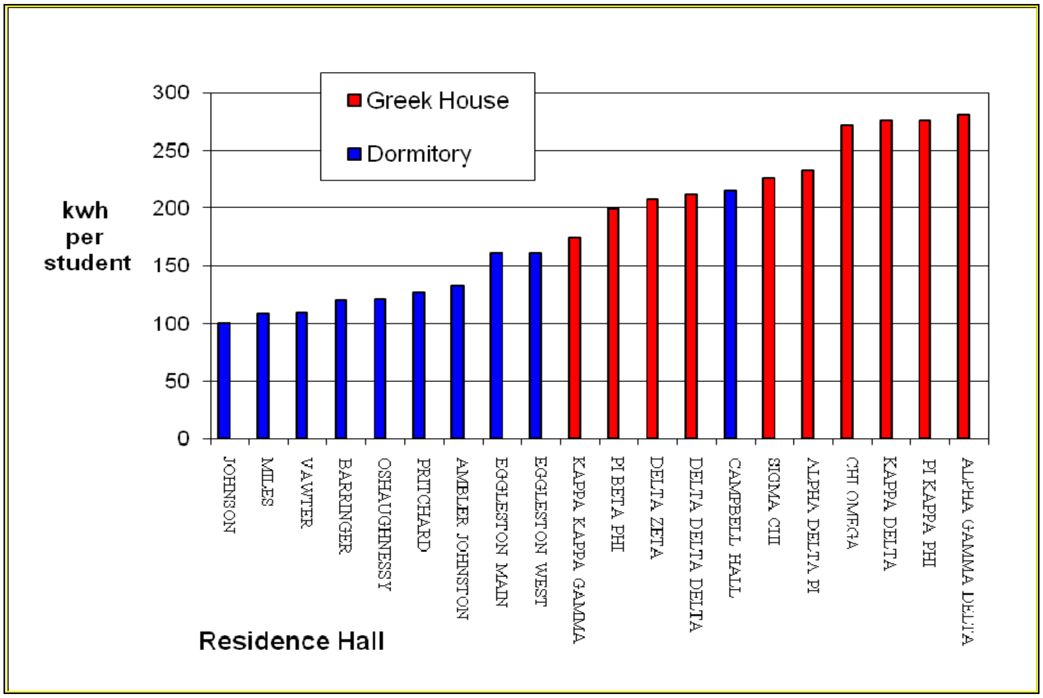

Figure 3. Per Student Historical Electricty Consumption

RESULTS

2009 Spring Semester Results -Water Consumption

Figure 4 demonstrates the 2009 Spring Semester per student water usage from lowest to highest. Consistent with the historical average, partial or full female occupied dorms have higher usage.

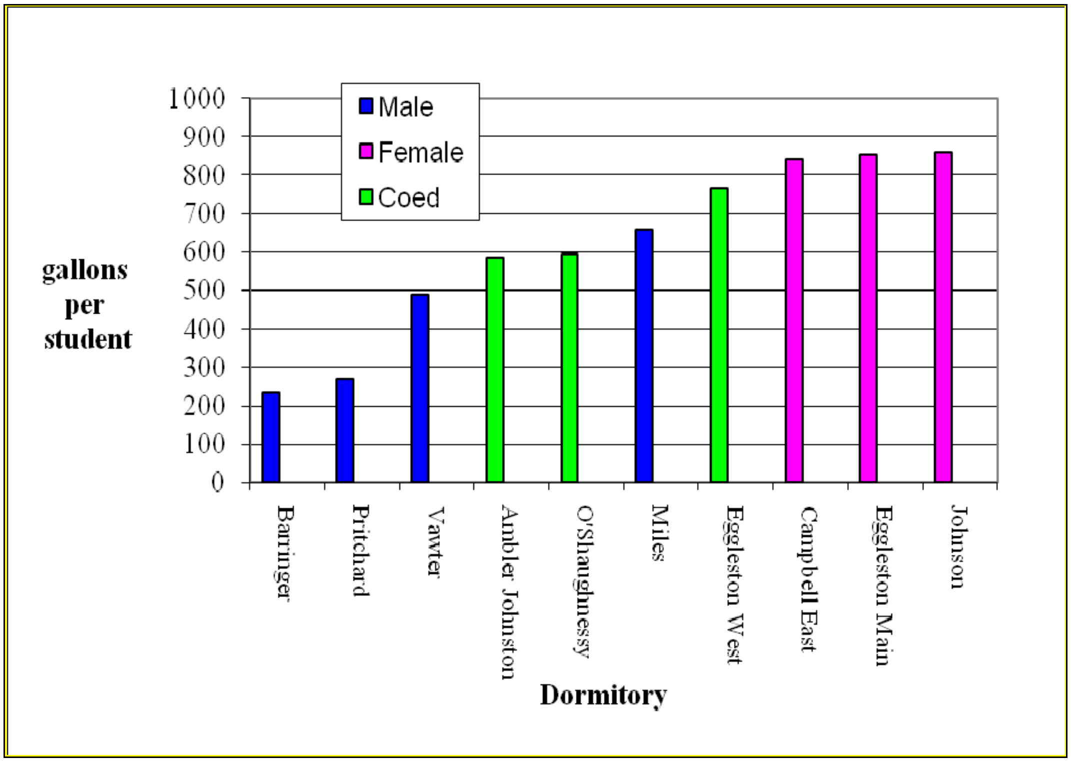

Figure 4. 2009 Spring Semester Dormitory Water Consumption

Table 3 documents the percent change in per student water usage, 2009 Spring Semester versus historical. The dorms with partial or full female occupancy achieved either minimal reductions or increases in their consumption, and as a result the full female occupancy dorms now represent the three highest consumption rates (Figure 4). All four male dorms achieved reductions in excess of 10% (Table 3) and as a result, three of the male dorms now represent the lowest usage and the fourth male dorm, Miles, moved into a lower usage ranking (see Figure 4).

Table 3. Water Conservation Study Spring Semester 2009 Results
Percentage change in per student usage 2009 versus historical

Control Group	Information Only	Individual Feedback	Comparative Feedback	Group Leaders
Ambler Johnston	Johnson	Eggleston Main	O'Shaughnessy	Campbell East
17.5%	6.3%	-2.3%	-4.7%	12.7%
Barringer	Vawter	Eggleston West	Miles	Pritchard
-11.2%	-18.1%	0.7%	-14.5%	-15.9%

2009 Spring Semester Results - Electricity Consumption Results

Table 4 documents the percent change in electricity usage, 2009 Spring Semester versus historical. With the exception of three Greek houses, consumption reduction was achieved in all residence halls, even the control group. This result is not surprising. By the end of January, general campus knowledge existed that a conservation study was being conducted in the residence halls, and the residence hall advisors across campus contacted the researcher asking for assistance in tracking their efforts to promote electricity consumption reduction. In addition, the Virginia Tech Collegiate Times published an article on the study in early February. To date, various parties across campus are still contacting the researcher for study information and questioning how to continue the efforts after the study's conclusion in December.

Table 4. Electricity Conservation Study Spring 2009 Results
Percentage change in per student usage over 4 years historical data

Control Group	Information Only	Individual Feedback	Comparative Feedback	Group Leaders
Ambler Johnston	Johnson	Eggleston Main	O'Shaughnessy	Campbell East
-14.68%	-2.50%	-9.46%	-11.15%	-9.12%
Barringer	Vawter	Eggleston West	Miles	Pritchard
-13.04%	-8.93%	-9.46%	-11.90%	-8.04%
Pi Kappa Phi	Kappa Kappa Gamma	Delta Delta Delta	Pi Beta Phi	Sigma Chi
-5.40%	-11.37%	-11.71%	16.59%	-11.92%
Delta Zeta	Alpha Gamma Delta	Chi Omega	Alpha Delta Pi	Kappa Delta
3.15%	-26.47%	-12.76%	5.80%	-5.40%

Alpha Gamma Delta, a Greek house, had the largest historical per student usage (Figure 3) and achieved the highest percent reduction (Table 4). However, even with the electricity reductions achieved during the study period, the usage in the Greek houses continues to be higher than the usage in the dormitories (see Figure 5).

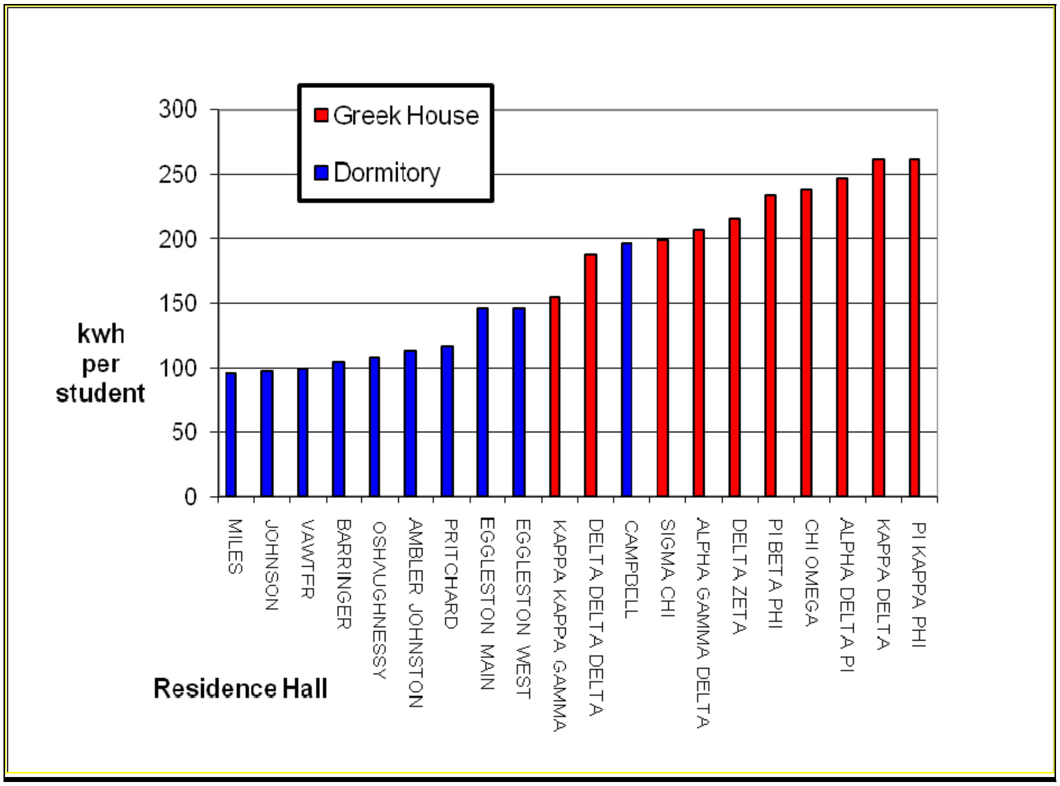

Figure 5. Spring 2009 Residence Hall Electricity Consumption

End of Semester Survey

During the last week of April 2009, an email was sent to the residence halls' students requesting that they take a short survey to report their conservation activities. Based on the residence hall population figures provided by the university, this survey invitation was sent out to 2,828 students. 559 students accepted the invitation and participated in the survey. 77% of the students (431 out of 559) responding to the survey stated they participated in conservation activities. Consistent with our higher achievements in electricity consumption reduction, reported activities were more prevalent in electricity conservation. Table 5 documents the survey questions and student responses.

Table 5. Spring 2009 Survey

Question	Answer	Number of Responses
Were you aware that your residence hall was participating in a study on conserving water and electricity?	Yes	528
	No	30
How did you find out about the study? Check all that apply	Received an email	479
	Saw the notices posted in my residence hall	288
	Attended a seminar held in my residence hall	8
	Did not know about the study	19
Did you actively participate in this study?	Yes	431
	No	126
If you answered yes to question 3, please indicate which of the following actions you took? (check all that apply)	Turned off lights in unoccupied rooms	420
	Turned off my computer when not in use	202
	Turned off all power strips when not in use	40
	Used task lights when available and not overhead lighting	207
	Only washed full loads of laundry	387
	Did not overload clothes dryers	240
	Washed clothes in cold water	156
	Turned off the water while brushing my teeth	379
	Turned off water while shaving.	184
	Took a shorter shower	142
	Took a shower instead of a bath	154
	Reported any water leaks or running toilets immediately to maintenance	44
	Turned off all electronics when gone for the weekend	241
	Turned off all electronics when gone for spring-break	391
	Took no action	30
Will you continue your conservation related activities when you leave the residence hall and move off-campus?	Yes	503
	No	55
If you are in a university residence hall during the Fall 2009 Semester, will you participate in conservation activities	Yes	348
	No	112

DISCUSSION

Electricity consumption reductions were achieved in all residence halls, with the exception of three Greek houses. One Greek house was in the control group and the other two were in the comparative feedback group. Water consumption reductions were achieved in the male residence halls, but the female occupied halls increased water consumption. The most significant achievements from our study are the high percent of student participation in conservation activities and the increased general campus awareness surrounding natural resource consumption. The research strategies, data collection and analysis continue throughout the Fall 2009 semester.

ACKNOWLEDGEMENTS

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CARBON FOOTPRINT OF WATER CONSUMPTION: CASE STUDY

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KEY WORDS: water conservation, energy conservation, carbon footprint, rainwater harvesting

ABSTRACT

Water consumption has an indirect carbon footprint because energy is used to treat water and deliver it to the point of consumption. In the United States, 3-4% of total energy use is attributed to municipal water/wastewater treatment and distribution/discharge. Interest in reducing the carbon footprint of water consumption includes coping with carbon emissions and climate change and preserving water resources. This article addresses the potential of water and energy conservation in a single building to mitigate climate change impact. Results show the estimated carbon footprint for current water consumption in a case study building and estimated carbon footprint if a water conservation measure such as rainwater harvesting is implemented.

INTRODUCTION

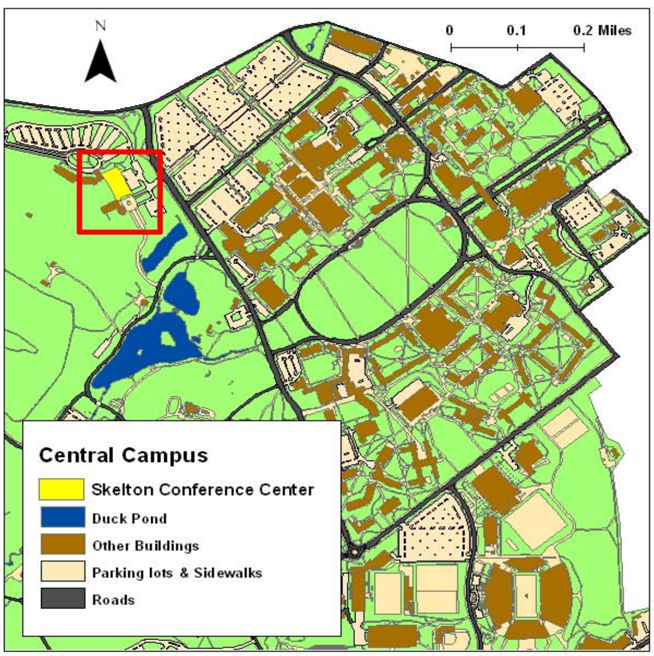
Climate change and its potential impacts are global and pose significant threat to the United States' national security. Beyond understanding the basic science of climate change, is how to mitigate its impacts and encourage informed decision making in the arena of energy conservation in all aspects of life in our modern society. More than 60,000 water supply plants and 15,000 wastewater treatment plants operate in the United States and the demand for electricity at these facilities is 75 billion kWh per year – about 4% of total energy consumption in the U.S. (Oliver and Putnam 1997). In the U.S., energy use for water treatment and delivery is reported in the range of 0.25 – 3.5 kWh/1,000 gallons (AWWARF 2007). The U.S. Department of Energy estimated energy consumption for water treatment and distribution as 1.45 kWh/1,000 gallons (cited in Kloss 2008). Chen *et al*. (2007) estimated energy use for water treatment and distribution as 1.67 kWh/1,000 gallons of water in Blacksburg, Virginia. Griffiths-Sattenspiel and Wilson (2009) provide an analysis of energy use and water carbon footprint for various uses of water. Younos *et al*. (2009) estimated carbon footprint for conventional potable water infrastructure in Blacksburg, Virginia. These studies indicate that energy efficiency in the water management sector provide an opportunity for lower energy consumption and consequently lower carbon footprint.

The overall goal of this research is to address climate change mitigation education and decision making related to water infrastructure. Specifically, this article addresses the potential of water and energy conservation to mitigate climate change impact in a single building.

RESEARCH METHODS

The Study Site

The study site is The Inn at Virginia Tech and the Skelton Conference Center located in Blacksburg, Virginia (Figure 1). The Skelton Complex opened in 2005 and occupies a total of 193,020 ft^2 that includes three separate buildings: The Inn, the Skelton Conference Center, and the Holtzman Alumni Center. The Inn portion of the Skelton Complex includes 147 guest rooms, 99 double/double rooms, 48 king rooms, and 6 suites. The Skelton Complex also provides 23,705 ft^2 of flexible meeting space, an 8,832 square-foot Ballroom with 22 foot high ceilings, 2,193 ft^2 of pre-function space, outdoor function space and eleven conference rooms. The Skelton Center holds many events including weddings, dinner ceremonies, and conferences (The Inn at Virginia Tech 2009).



GIS Layers Courtesy of Virginia Tech Facilities Information System.
Map completed by Tammy E. Parece, Graduate Student - Department of Geography

Photo of Skelton Conference Center
available at
http://www.vt.edu/about/buildings/skelton-conference-center.html

Figure 1. The Skelton Complex

Water Consumption at the Skelton Complex

The Skelton Complex receives potable water from the Blacksburg-Christiansburg-VPI Water Authority (Blacksburg Christiansburg VPI Water Authority). Currently, six water meters service the Skelton Complex. Table 1 shows annual water consumption at the Skelton Complex (Compton 2009).

Table 1. Annual Meter Water Use at the Skelton Complex

Meter name	Year 2006 Water Use (Gallons/Year)	Year 2007 Water Use (Gallons/Year)	Year 2008 Water Use (Gallons/Year)
ALUMNI CTR	5103800	6866500	9245700
ALUMNI CTR COLD WTR	78000	85500	85800
ALUMNI CTR COOL WTR	163800	219000	279100
ALUMNI CTR FOUNTAIN	1371800	187700	1892800
ALUMNI CTR CHILL WTR	30	130	180
ALUMNI CTR IRRIGATION	0	1791300	2737700
TOTAL	6717430	9150130	14241280

Estimating Electricity Use for Water Consumption

Energy is required to treat and deliver water to the point of use. Previous research estimated the energy required to treat and deliver water to Blacksburg and Virginia Tech as 1.67 kWh/1,000 gallons (Chen *et al*. 2007). This figure is used to estimate electricity use attributed to water consumption in the Skelton Complex using the water use data shown in Table 1.

Estimating the Carbon Footprint of Water Consumption

The carbon footprint can be estimated from carbon emissions attributed to electricity using an energy conversion coefficient. The carbon footprint of electricity for a coal-fired power plant has a coefficient of 2.249 lbs CO_2 because there are 2.249 lbs of CO_2 equivalent greenhouse gasses per kWh. According to Randolph *et al*. (2008), in the Town of Blacksburg, 88.3% of the electricity received from the local grid originates from coal-fired power plants. The remaining electricity comes from nuclear and hydro-electric facilities that generate no greenhouse gas emissions. Thus Blacksburg's energy coefficient is adjusted to 1.985867 lbs CO_2/kWh (2.249 x 0.883). This energy coefficient (1.985867 lbs CO_2/kWh) is used to calculate the Skelton Complex's carbon footprint for water consumption from electricity use (1.67 kWh/1,000 gallons). As an example, one of the Skelton Complex's water meters, Alumni Center, consumed 5,103,800 gallons of water in 2006. The Alumni Center's annual carbon footprint of water is calculated as follows:

$$5{,}103{,}800 \text{ gal} \times \frac{1.67 \text{ kWh}}{1{,}000 \text{ gal}} \times \frac{1.985867 \text{ lbs } CO_2}{\text{kWh}} = \mathbf{\frac{1.6926.23 \text{ lbs } CO_2}{\text{Year}}}$$

Water Conservation Measure - Rainwater Harvesting

Water conservation (less potable water use) will lead to less electricity use and thus lower the carbon footprint due to water consumption. Several ways of conserving water in the Skelton Complex, such as installing low water use fixtures, are already implemented to some degree. In this research, rooftop rainwater harvesting and use is proposed as a water conservation measure to reduce electricity use. Basic components of a rainwater harvesting system include a collection surface (rooftop area), conveyance system, pre-tank treatment, water storage tanks and water distribution pipes. Harvested rainwater can be used indoors (*e.g.*, toilet flushing) and outdoors for landscape irrigation and the water fountain.

The harvestable rainwater can be estimated using the following equation (Virginia Rainwater Harvesting Manual 200):

URV (gallons/month) = Roof Area (sq ft) x Avg Rainfall (inch/month) x C x 0.6233 (Eq. 1)

URV is usable rainwater volume, C is collection efficiency (approximately 0.8 due to splash and evaporation resulting in loss of water), and 0.6233 is the conversion factor to estimate water volume in gallons. Long-term average monthly rainfall data is used to estimate harvestable rainwater (Table 2).

Table 2. Thirty-Year Average Monthly Precipitation in Blacksburg, Virginia

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (inches)	3.37	3.02	3.83	3.83	4.39	3.93	4.17	3.68	3.39	3.19	2.96	2.87

Source: National Weather Service Total Annual Rainfall: 42.63
www.idcide.com/weather/va/blacksburg.htm

The rooftop areas for the three buildings were obtained from Thomas Tucker, the Building Information Manager of the University Planning, Design and Construction.

Table 3. Roof Top Area of the Skelton Complex

Building Name	Roof Top Area (sq ft)
THE INN	21,644
SKELTON CONFERENCE CENTER	37,106
HOLTZMAN ALUMNI CENTER	11,993
Total Roof Top Area	70,743

Source: Tucker 2009

The total amount of indoor and outdoor water use attributed to harvested rainwater on a building is equivalent to potable water savings in theory. With the rainwater harvesting systems capture and use, energy is conserved because less energy is used to supply, treat, and distribute water. Savings can be estimated as seen in the following equation:

Energy Conservation (kWh/1,000 gal) = (Potable Water Saving (gal) x Estimated Energy Use (kWh/1,000 gal)) – (Indoor/Outdoor Pump Energy Need (kWh)) (Eq. 2)

RESULTS AND DISCUSSION

Carbon Footprint of Water Meters

Tables 4 – 7 show each water meter's carbon footprint of water for 2006, 2007, and 2008 and the total annual carbon footprint for the facility due to water consumption.

Table 4. Year 2006 Meter Water Use and Carbon Footprint of Water at the Skelton Complex

Meter Name	Annual Water Consumption (Gallons/Year) (seen in Table 1)	Estimated Electricity Use attributed to Water use (kWh) (x 1.67 kWh/ 1,000 gal)	Estimated CO2 output (lbs CO2/Year) (x 1.985867 lb CO_2 / kWh)
ALUMNI CTR	5103800	8523.35	16926.23
ALUMNI CTR COLD WTR	78000	130.26	258.68
ALUMNI CTR COOL WTR	163800	273.55	543.23
ALUMNI CTR FOUNTAIN	1371800	2290.90	4549.43
ALUMNI CTR CHILL TWR	30	0.05	0.10
ALUMNI CTR IRRIGATION	0	0	0.00
TOTAL	671740	11218.11	22277.67

Table 5. Year 2007 Meter Water Use and Carbon Footprint of Water at the Skelton Complex

Meter Name	Annual Water Consumption (Gallons/Year) (see Table 1)	Estimated Electricity Use attributed to Water use (kWh)	Estimated CO_2 output (lbs CO2/Year) (x 1.985867 lb CO_2 / kWh)
ALUMNI CTR	6866500	11467.06	22772.05
ALUMNI CTR COLD WTR	85500	142.79	283.55
ALUMNI CTR COOL TWR	279000	365.73	726.29
ALUMNI CTR FOUNTAIN	187700	313.46	622.49
ALUMNI CTR CHILL TWR	130	0.22	0.43
ALUMNI CTR IRRIGATION	1791300	2991.47	5940.66
TOTAL	9150130	15280.73	3045.47

Table 6. Year 2008 Meter Water Use and Carbon Footprint of Water at the Skelton Complex

Meter Name	Annual Water Consumption (Gallons/Year) (see Table 1)	Estimated Electricity Use attributed to Water use (kWh) (x 1.67 kWh/ 1,000 gal)	Estimated CO_2 output (lbs CO2/Year) (x 1.985867 lb CO_2) kWh
ALUMNI CTR	9245700	154403.32	30662.42
ALUMNI CTR COLD WTR	85800	143.29	284.55
ALUMNI CTR COOL WTR	279100	466.10	925.61
ALUMNI CTR FOUNTAIN	1892800	3160.98	6277.28
ALUMNI CTR CHILL TWR	180	0.30	0.60
ALUMNI CTR IRRIGATION	2737700	4571.96	9079.30
TOTAL	14241280	162745.95	47229.75

Table 7. Total Water Use and Total Carbon Footprint of Water at the Skelton Complex (Meters Combined)

Year	Total Gallons (Meters combined)	Total lbs CO_2 (Meters combined)	lbs CO_2 difference	% CO_2 Increase
2006	6717430	22277.67 (11.14 Tons CO_2)		0.0%
2007	9150130	30345.47 (15.17 Tons CO_2)	8067.80	36%
2008	14241280	47229.75 (23.61 Tons CO_2)	24952.08	112%

Total Carbon Footprint of Water: 99852.59 lbs CO_2 (49.92 Tons CO_2)

From 2006 to 2008, an increase in water consumption from total water meter consumption at the Skelton Complex is seen in Tables 4, 5 and 6. As water consumption increases, carbon emissions increase creating a larger carbon footprint of water. As seen in Table 7, there is a 112% increase in CO_2 output from 2006 to 2008. Figures 2a and 2b exhibit the relationship between water use and CO_2 output. As the Skelton Complex uses more water, carbon emissions increase.

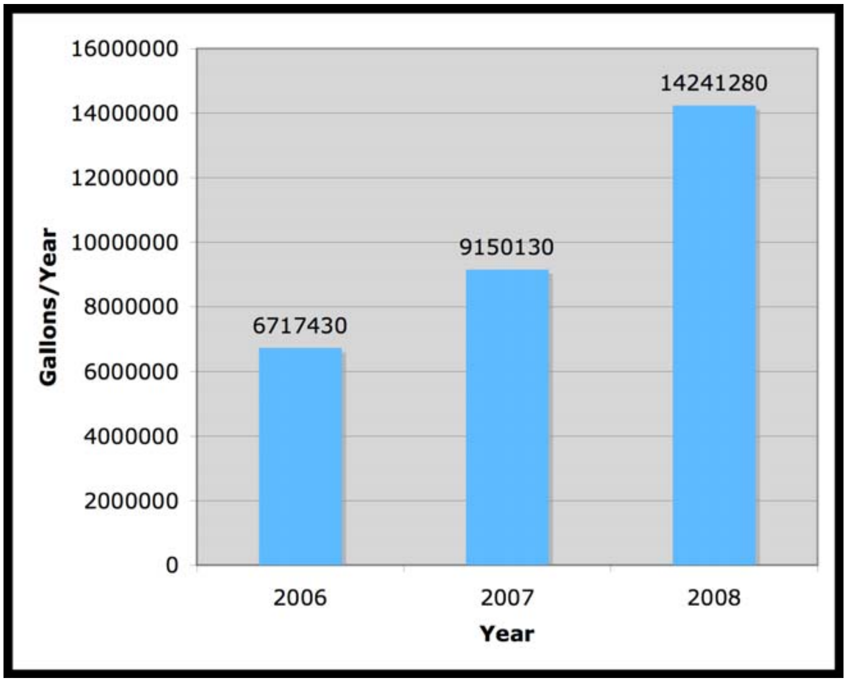


Figure 2a. Total Water Use at the Skelton Complex (Meters Combined)

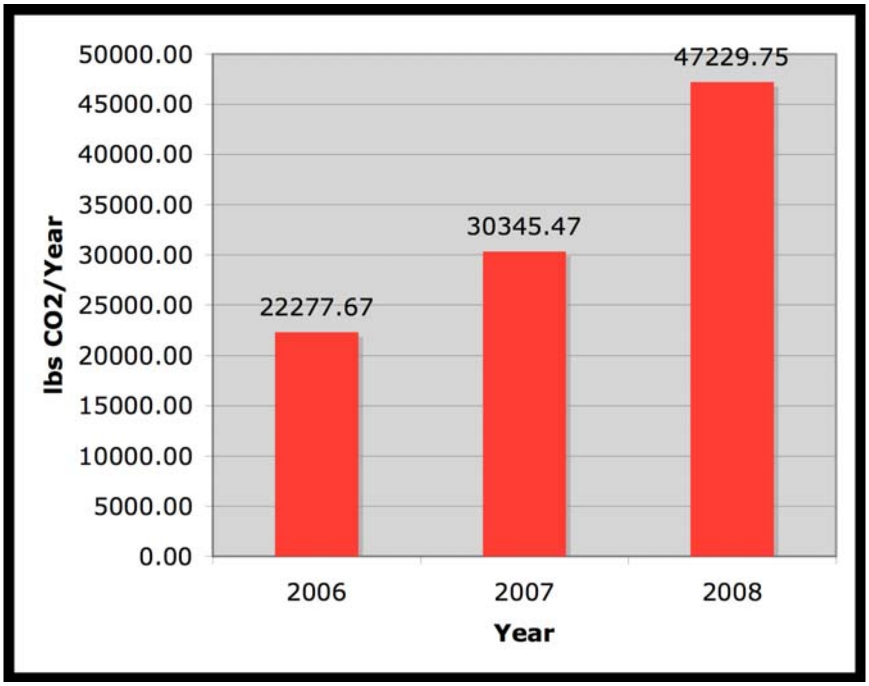


Figure 2b. Total Carbon Footprint of Water at the Skelton Complex (Meters Combined)

Rainwater Harvesting: Estimating Potable Water Savings

If methods to save water are taken into account, energy is conserved while decreasing carbon output to the environment, which will mitigate climate change. Rainwater harvesting methods are looked at in this case study as a way to conserve water. Table 8 shows The Skelton Complex broken down into its three separate buildings and the amount of water in gallons/ year saved for each building if rainwater harvesting is used.

Table 8. Rainwater Harvesting Use Potential at the Skelton Complex

Building Name	Rainwater Harvesting/ use potential (Eq. 1) (gallons/year)
THE INN	517,598
SKELTON CONFERENCE CENTER	887,358
HOLTZMAN ALUMNI CENTER	283,169

To see if enough rainwater is available to make up for water used from ALUMNI CTR IRRIGATION and the ALUMNI CTR FOUNTAIN, the gallons from the three buildings were totaled to account for rainwater harvested from the entire Skelton Complex and compared to the water used from the ALUMNI CTR IRRIGATION and ALUMNI CTR FOUNTAIN combined. Figure 3 shows this comparison.

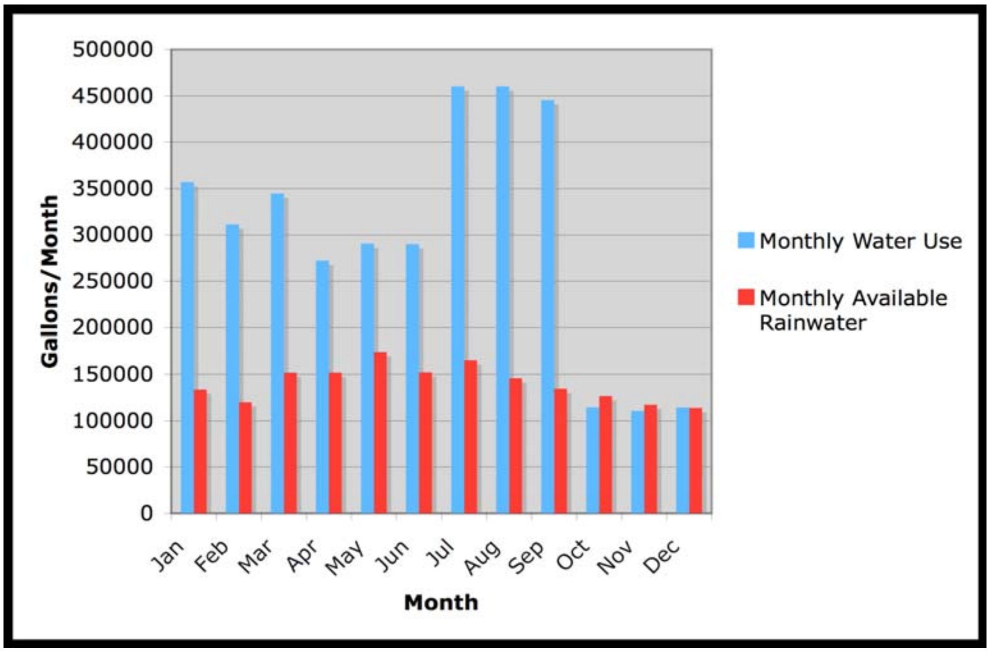


Figure 3. Monthly Water Use 2008 vs. Monthly Available Rainwater

Table 9. Water Use vs. Available Rainwater at the Skelton Complex

Month	ALUMNI CTR FOUNTAIN and ALUMNI CTR IRRIGATION combined Water Use (Gallons/Month)	Skelton Complex Available Rainwater (buildings combined) (Gallons/Month)
Jan	356953	133737
Feb	311369	119848
Mar	344731	151992
Apr	272215	151992
May	290480	174216
Jun	290005	152328
Jul	460283	165485
Aug	460283	146039
Sep	445434	134531
Oct	114363	126594
Nov	110674	117467
Dec	114363	113895
Total	3571153	1688124

As seen in Table 9, if captured rainwater is stored, it will provide 47% of water needed for landscape irrigation and the fountain. If captured rainwater is used only for landscape irrigation, it will compensate for 69% of irrigation water demand.

The total capture rainwater, 1688124 gallons/year, if used outdoors will translate to the amount of potable water saved. Below, the annual reduction of carbon footprint of water consumption due to rainwater harvesting is estimated:

$$\frac{1688124 \text{ gallons}}{\text{year}} \times \frac{1.67 \text{ kWh}}{1{,}000 \text{ gal}} \times \frac{1.985867 \text{ lb } CO_2}{\text{kWh}} = \mathbf{5598 \text{ lb } CO_2 \text{ reduced}}$$

$$\frac{5598 \text{ lbs } CO_2}{427320 \text{ lbs } CO_2} = \mathbf{11\% \; CO_2 \text{ reduced}} \text{ (from Skelton Complex's carbon footprint of water)}$$

In a previous study, switching to florescent lights reduced the Complex's carbon footprint by 1.5% (Poole and Younos 2009). The total amount of carbon emitted into the atmosphere in 2008 from the Skelton Complex's water use was 47230 lbs CO_2/year. Rainwater harvesting reduces the Skelton Complex's carbon footprint of water by 11% (5598 lb CO_2/ 47230 lb CO_2). Reduction in the Skelton Complex's total carbon footprint can be calculated as well (electricity, natural gas, and water use combined).

The carbon footprint of water from 2008, 23 tons CO_2/year (47230 lbs CO_2 x 1 ton/2000 lbs) is added to the carbon footprint of the Skelton Complex due to direct energy use (natural gas and electricity), 5870.42 tons CO_2/year (Poole and Younos 2009). Including the reduction in CO_2 emissions, 2.7 tons CO_2 (5598 lbs CO_2 x 1 ton/2000 lbs), rainwater harvesting further reduces the total carbon footprint of the building by 0.05%. The total carbon footprint reduction is 1.55%.

Table 10. Skelton Complex's Total Carbon Footprint % Reduction

Year	Skelton Complex's Carbon Footprint (natural gas and electricity) % reduction	Skelton Complex's Total Carbon Footprint % reduction (natural gas, electricity, water conservation combined)
2008	1.5% (Poole and Younos 2009)	1.55%

The reduction of carbon footprint due to water conservation for a single building does not appear to be significant. However, in an urban environment, if rainwater harvesting or other water conservation practices are implemented in multiple buildings, the process will result in significant water and energy conservation and mitigating the impact of climate change.

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Acknowledgement is due to Chris Compton, the Chief Engineer of the Inn at Virginia Tech and Skelton Conference center, who provided water meter data as well as electricity usage and natural gas usage of the Skelton Complex. Thomas Tucker, the Building Information Manager for Virginia Tech's University Planning, Design, and Construction, provided roof top area for the Skelton Complex. Also, thank you to Tammy Parece for providing the map and figure for the Skelton Complex.

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Back to Table of Contents

V-B Stormwater (Part 2): Using Tools for Better Management

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TRUE LOW IMPACT DEVELOPMENT: FROM SINGLE FAMILY HOME TO THE ENTIRE DEVELOPMENT, REAL LID

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INTRODUCTION

Low Impact Development (LID) has been around for many centuries under many different names and disguises. Most notably have been Backyard Conservation (NRCS), Permaculture (1960's) and yet is turning into Better Site Designs as well as Green Development. No matter what title it is, the principal is still the same: the conservation of resources.

When we have used the conservation of natural resources title in workshops and group meetings the glazed over look of the audience is a true sign that they do not want to hear anything else that could be misinterpreted as a political discussion or a mandate. The uses of innovative, ear catching phrases are used to spark interests and get people to understand the same practices just with a different title.

This document is to help understand the true principals of LID from the home all the way to the entire development. Localities can require the developer to put in a certain percentage of LID practices however the major problem occurs when the developer has completed the project and the homeowners do not understand the value of LID practices. Then when you add the misconception that LID is something that has to be engineered the homeowners shy away from it because they usually do not have any money available for an engineer to design plans.

When looking at LID it is very apparent that we have only focused on the development end of the problem and we have forgotten the one place to start at is the home. Then you need to ask the major question how much is enough or where do we stop. In your thoughts and planning you should not stop and you need to research everything. If you see a design by an engineer find out what is its end results and see if you can get the same results somewhere else but cheaper and easier for anyone to do.

Do not look at LID as only for developers and only for municipalities or local governments to do. Look at it for everyone. Then do not stop with the stormwater or pollution that can be generated but take it further and ask if there is an energy efficient product out there that can help my site out. Take the next step and dream a little. Figure out what you can do to keep all impacts onsite and design for it. Plan every little detail before you present it. Then when you look at it with the "Design Professionals" as they begin to knock off items that seem impractical in their minds ask them why and have them prove to you it will not work.

There are two things that must be kept in mind at all times

1. LID is truly the ability to infiltrate or re-infiltrate the water as it had been doing before any form of disturbance occurred.
2. There is no site in the world that will not support some form of LID. (If there was then we would not have invented the aqueducts as well as rain barrels and cisterns.)

LID with Green development or True LID

A comprehensive approach to LID is not just to use the manufactured BMPs but to also incorporate landscaping as well as the potential evapotranspiration of the plants to be used within traditional landscaping practices.

Spotsylvania County is seeing an increase in plans that design using the landscape to its fullest potential. As Thomas Jefferson had done in the past, as well as many landscape professionals over the centuries, the proper placement of certain trees plants and grasses can address many of the stormwater management problems that have been highlighted through the years.

Several of these sites from the calculations have been able to establish a conservative rate of "0" offsite discharge in the 2 yr, 10 yr, and 50 yr, storm events. In fact if installed properly they will not allow stormwater discharge until a 100, year storm event.

Can this be enhanced or improved upon? YES! By introducing several manufactured products as well as many practices that have been around and used for other practices you can produce a finished project that will lower if not eliminate stormwater runoff all together.

Consider if there was no in crease in discharge then there would be no increase in pollution transport and no potential sediment movement after the site has been stabilized. These are all items that were considered far fetch because they could not place a true number or calculation for many of the practices that have been instinct for years if not centuries.

The next step or LID on Steroids

There are no limits to what can be achieved if you just put your mind to it. This phrase has echoed the halls of institutes and universities for many years and it is still true with LID and green development.

Looking at any site that is being proposed for any form of development a design concept can be produced to provide for total electrical needs being met without the use of local utilities and coops. In fact if done properly each structure could produce enough electricity they can sell it back or create their own coop and generate revenue.

When looking at the entire site we can produce a development that would host several LID practices and principals that would create a complete development. From a house that would not even generate trash to go to a landfill but also design with no stormwater basins. In fact the only visible water would be in amenities that could be used as recreational facilities and will also help to regulate as well as generate power.

METHODS

Look at every site the same way… There are no limits!

To achieve this design concept the methods that should be considered are as follows:

1. Porous pavement and sidewalks
2. Underground cisterns
3. Solar Shingles
4. Mini hydro electric generators
5. Trash burning generators
6. Wind turbine generators
7. Concrete homes
8. Grass pave
9. Hydro Batteries
10. Electric vehicles
11. Landscaping to handle drainage

RESULTS

As you drive into the project you will still see pavement, curb and gutter nothing will change dramatically on what you first see when you enter the community. You will begin to notice no curb slot inlets and no (traditional) storm drain system. This thought pattern is a new proposal for a development that is being designed now that features no traditional storm drain system. The piping would be eliminated. Basins would be for extreme events and all water would be filtered before it would even venture into a basin pond or structure.

All impervious surfaces will have no sheet flow during any storm event so the hazard of standing water as well as potential icing during the winter. The se hazards even though will not be eliminated they will be dramatically reduced.

The underground piping will be replaced with infiltration type conduits that will allow the water to filter through the sand to these conduits and then transport to underground cistern systems. The overflow of the underground cisterns will go directly in to the water features being green pools, ponds or full lakes as amenities.

The driveways will have no water runoff and will not produce the traditional maintenance nightmare of concentrated flows that have usually been produced over time and consistent rain events.

Sidewalks, paths and trails will be made of materials that would be ridged enough for handicapped accessibility. These trails even if in the flood plain and Resource Protection Areas would only need to be swept and will have no erosion produced from its use.

The structures both commercial and residential will be built with concrete and feature solar shingles. Building types and styles will vary and do not need to look futuristic. They can look Victorian, Georgian, Ranch, *etc*. there is no limits to the types and uses of these structures.

Supplemental power can be used by trash burning generators still being produced and tested or they can use current mini hydroelectric generators. The use of supplemental wind power along with new batteries that generate electricity while sitting in water can all be used to supplement any solar shingle type system. The generation potential could even warrant the need to develop a new regional electric coop to sell power back to the neighboring community. All generated by nature.

The potential of using new electric cars that will go from 0-60mph in a few seconds and will go up to 100 miles on a single charge will also enhance the developments potential. The recent introduction and improvements of solar shingles could also provide an answer for recharging electric vehicles while traveling. The new solar shingles can actually look like the ornamental canvas tops featured on many cars now. This will produce an invisible energy generator that would become standard on all electric vehicles.

Some of the most recent developments in the electric cars that have begun to catch everyone's attention are SUV's, SUT's, Sports cars and many more. The technology is finally meeting the demand and we just need to take it the next step.

As with LID the use of multiple practices can produce a true Low Impact Development that has reduced the water quality as well as quantity impacts and has dramatically reduced the carbon footprint for any development or community. The added bonus when looking at the entire site is the addition of electrical generating practices that until now have been hobbies for many. Bring them to the forefront and we can eliminate our need for foreign energy supplies. We can do as we had done in the past rely on nature and our own innovation.

DISCUSSION

Do not take my word for it, do the research for yourself. Just keep in mind that each of these items in one form or another has been seen within many developments on many different sites. It is just that we need to bring them together. Low Impact Development has morphed into something that by using multiple practices will provide for better water quality and quantity reduction. True LID is the complete package and provide for alternative energy as well as recycling to better use/preserve our resources. While reducing it why do we not just take it the next step and provide for a better site with many LID and green development practices put together?

ACKNOWLEDGEMENTS

To all who believe that there is a better way to skin a cat and for the ones who kept telling me to always look deeper and keep it simple. There are many who have influenced this and I must acknowledge those who always told me to ask one question and that is WHY?

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Pervious Pavement using asphalt and concrete will be used to create the same infrastructure in any subdivision and development that has been built for the last 50 years. The use of porous materials will eliminate or greatly reduce the need for Drop inlets in any form. The use of complex underground pipe systems at varying depths will yield to innovative infiltration techniques to transport water.	
	http://www.perviouspavement.org/design.htm
 Solar Shingles will be used to provide the largest % of energy needs for any building or dwelling unit with full batter storage as well as some regeneration abilities to keep the batteries fully charged.	
http://www.solar-components.com/pvshingl.htm http://www.uni-solar.com/interior.asp?id=102	
Small Hydroelectric generators will be used to supplement the solar batteries in times where there is little UV or at night.	
	http://www.absak.com/library/hydro-power#

	The diversity of reinforced concrete with insulated foam exterior will provide any house or structure plan to become super insulated and meet any façade requirements of any community
http://www.mid-atlanticfoam.com/	
Grass pave will be used in many forms but to create a safe lawn that will be allowed to trap and store water underground in raintank cistern system.	
	http://www.acfenvironmental.com/index.php
	The use of trash burning generators will help supplement the electricity needs of the planned community as well as potentially create a coop to provide the excess to be used by neighbors.
http://news.uns.purdue.edu/x/2007a/070201LadischBio.html	
Tankless hot water heaters will provide on demand hot water. The water user will no longer need to waste water while it heats up at their remote faucet(s) away from the traditional hot water heater.	
http://www.foreverhotwater.com/	

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MUNICIPAL INCENTIVE PROGRAMS FOR STORMWATER BMP INSTALLATION ON PRIVATE PROPERTY

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KEY WORDS: stormwater, decentralized, BMP, incentive

ABSTRACT

Localities across the United States are facing escalating costs as existing stormwater infrastructure ages and surface water quality standards are more strictly enforced. One set of techniques to augment conventional municipal stormwater systems are broadly categorized as decentralized stormwater BMPs. These BMPs include rain gardens/bioretention cells, rainwater harvesting, constructed wetlands, pervious pavers/pavement, and increased canopy cover among others. Decentralized BMPs have benefits beyond stormwater management, including aesthetic enhancement, habitat creation, environmental education, community development, and increased property values. This paper examines several incentive programs that target private landowners, community groups, and neighborhood groups as incentive recipients for the installation of decentralized stormwater BMPs on private property. The aspects addressed for each program include: structure, allowable BMPs, supporting legislation, program budget, funding, individual reward structure, and rules dictating BMP installation.

INTRODUCTION

Aging infrastructure is a top concern of the federal government as well as state and local governments across the United States. Transportation and water infrastructure are considered to be in a state of crisis. According to the Congressional Budget Office, spending on transportation and water related infrastructure has steadily increased since the 1950's (CBO 2007). However, infrastructure spending has not kept pace with maintenance needs according to American Society of Civil Engineers, who estimate that $1.6 trillion is needed over the next five years to ensure that the nation's transportation and water infrastructure is in good condition (ASCE 2009). The health of a specific system is dependent upon the level of maintenance carried out by the responsible authority. Many localities will be forced to expand and upgrade existing stormwater infrastructure over the coming decades to accommodate stormwater flow, prevent overflows and meet water quality standards. While centralized systems will continue to play the principle role in the stormwater management strategies of most US localities, decentralized BMPs may prove to be a cost effective way to reduce stormwater flow through centralized systems. By treating stormwater at the parcel level the required storm sewer volume capacity is reduced. The expected long-term results of BMP installation on private property include smaller conventional stormwater system needs, reduced costs for sewer maintenance and fewer system upgrades. Additionally, decentralized BMPs will reduce polluted water flow to receiving waterways, an integral part of watershed management.

INCENTIVE PROGRAMS

Overview

This paper looks at four incentive programs in the United States. Each program was chosen based on disparate attributes to provide a broad overview of program structure, types of incentives, and program costs. The four case studies are:

1. Clean River Rewards, Portland, Oregon
2. RiverSmart Homes, Washington, D.C.
3. RainScapes Rewards, Montgomery County, Maryland
4. Mt. Airy Rain Catchers, Shepherd Creek Watershed, Cincinnati, Ohio

The programs were created to promote installation of small scale stormwater best management practices (BMPs) on private property. Reasons cited for the creation of an incentive program included: a storm sewer system with inadequate capacity, sewer overflows during rainfall events, old or failing infrastructure, Municipal Separate Storm Sewer System (MS4) permit requirements, green infrastructure initiative, overall water quality protection, city beautification, and groundwater recharge.

The incentive programs are a small piece of comprehensive conventional and alternative stormwater management programs. The District of Columbia has a Green Roof Subsidy Program, schoolyard greening initiatives, targeted watershed restoration projects, and open space projects all of which augment the City's stormwater management efforts (DDOE 2009). Montgomery County, Maryland has an extensive Stormwater Facility Maintenance Program, which oversees stormwater facilities on public and private property, as well as a rain barrel program (Montgomery DEP 2009). The City of Portland has developed an extensive collection of stormwater programs, some of which utilize coordination across multiple agencies such as the Grey to Green Initiative and the Green Streets Program (Portland BES 2009). The Shepherd Creek Watershed Pilot Program (Mt. Airy Rain Catchers) is an exception because it is an EPA sponsored study rather than a program sponsored by a municipality.

Each program included outreach to local residents and potential program participants. Program outreach to the community utilized fliers, direct mailings, community meetings, utility bill inserts, web-based information, or a combination of several outreach strategies. Program incentives included: lump sum payout, cost share, utility fee discount, or cost reimbursement. Stormwater BMPs included in the incentive programs varied, however all case study programs included rain gardens and rain barrels. Table 1 shows BMPs employed by the incentive programs listed above.

Table 1. Locality BMP Matrix

		Program Location			
		Portland	Washington, D.C.	Montgomery County	Shepherd Creek
Program Best Management Practices	Bioretention Cell or Rain Garden	♦	♦	♦	♦
	Rain Barrel	♦	♦	♦	♦
	Green Roof or Ecoroof	♦		♦	
	Conservation Landscaping (BayScaping)		♦	♦	
	Tree Canopy	♦	♦	♦	
	Engineered or Contained Planters	♦			
	Porous Pavement or Pavers	♦	♦	♦	
	Oil-water Separator	♦			
	Dry Well	♦		♦	
	Rainwater Reuse System	♦		♦	
	Ponds and Wetlands	♦			
	Detention Tank	♦			
	Pollution Reduction Facility	♦			
	Swale	♦			

Clean River Rewards Program
Portland, Oregon

<u>Background</u>

The Clean River Rewards Program was created to encourage stormwater utility ratepayers to retain a portion of stormwater onsite in return for a reduced utility fee. The desired result was to reduce stormwater volume entering the City's sewer system. The program was developed to mitigate the financial impact on ratepayers attributable to the City's stormwater utility fee and to promote environmental stewardship among residents (Clayton 2009).

Portland initiated a stormwater utility fee in 1977 to help fund flood control. That fee now funds stormwater management programs including Clean River Rewards. Following MS4 Phase I initiation in the early 1990's Portland created a discount program for industrial sites required to adhere to MS4 permitting regulations. Because the sites allocated resources to onsite stormwater management, the additional cost of the onsite stormwater utility fee was considered unnecessary by the City. The original discount program was dismantled in 1995 because it proved to be financially unsustainable. Ratepayers receiving a discount under the original system advocated for a new discount program. The Clean River Rewards, which is cost neutral to the City of Portland, is the culmination of these efforts (Clayton 2009).

Incentives and Organization

Clean River Rewards is managed by the Portland Bureau of Environmental Services (BES). The program allows stormwater utility ratepayers (land owners or renters that live within the City limits) to qualify for a discount on the City's stormwater utility fee. Ratepayers receive one water bill for all water related services provided by the City. The bill includes a stormwater utility fee based on land use: residential (single family or duplex) or other (commercial, industrial, institutional, and multi-family). The stormwater utility fee is further separated into onsite and offsite assessments. Clean River Rewards allows ratepayers to receive a discount of up to 100 percent for the onsite portion of the stormwater utility fee. This portion reflects roof area for residential properties and a combination of roof and paved areas for other properties (Portland BES 2006). Fees are split between onsite and offsite assessments to ensure that ratepayers are contributing to the stormwater management fund (Clayton 2009).

The discount offered by Clean River Rewards is based on the portion of stormwater that is retained onsite (Portland BES 2006). Many properties qualify for at least a partial discount already, due to existing trees or swales. Initially, discounts are rewarded based on the honor system because of the large number of ratepayers who apply. As time and resources permit, BES employees conduct audits of properties to ensure that the appropriate discount has been applied (Clayton 2009).

Stormwater utility discounts for residential properties are based on the amount of stormwater retained from the roof area. Residential discounts are broken down into four general categories. If all roof rainwater is retained onsite, or the roof is covered by an eco-roof, then the ratepayer qualifies for a 100 percent discount. Partial retention of rainwater from the roof area yields a 67 percent discount. If the total impervious area is less than 1,000 square feet, then the property qualifies for a 25 percent discount. Supplemental discounts of eight percent are awarded when there are four or more trees that are taller than 15 feet on the property (Portland BES 2006). Stormwater utility discounts for other properties are calculated based on the extent and effectiveness of onsite stormwater retention or treatment. Analysis takes into account pollution control, flow rate, and stormwater volume reduction. The following BMPs qualify for a stormwater utility discount: direct release to a river or slough, permitted release to City sanitary sewer system, ecoroof, contained planter, pervious pavement, pond and wetland, detention tank or vault, manufactured pollution reduction facility, oil-water separator, dry well, other approved source controls, and approved rainwater re-use system. The discount is assigned on a case-by-case basis, and is more closely examined by BES staff than the discounts received by residential ratepayers (Portland BES 2006).

When the program was initiated in 2006, the City hired approximately 16 temporary staff to assist with added administrative, customer service, technical assistance, and permitting needs. The added staff was funded, in part, by a stormwater utility rate increase of 18 percent. This substantial rate increase provided the financial incentive, particularly for the larger properties, to participate in the Rewards Program. After two years, the temporary staff was reduced to two permanent technical assistants who are responsible for helping property owners to assess stormwater management needs and complete the application process (Clayton 2009).

Ratepayers may apply online, over the telephone, or using a paper form. BES initially estimated that 112,000 stormwater utility rate payers would apply for the program and be approved to receive the discount. The current number of participants is approximately 33,000 residential properties and 1,000 commercial, multifamily or industrial properties (Clayton 2009).

Funding and Budgeting

Clean River Rewards is funded by the City's stormwater utility fee. The program's initial budget included $10 million for discounted user fees, $9.2 million for retroactive credits, and about $2 million for accounting systems and customer support services (Portland BES 2009). The program is currently supported by two full time technical assistants as well as several other BES staff who provide program management and support. Approximate administrative costs to BES for the two full time employees are $160,000 per year, including benefits (Clayton 2009). The 2009 stormwater utility rates are: $7.73/month flat fee for residential (Portland BES 2008) and $8.43/1,000 square feet impervious area/month for all other properties (Portland BES 2009).

Outreach

When Clean River Rewards was launched, BES coordinated an educational outreach blitz that included radio ads, newspaper inserts, workshops, resident surveys, and neighborhood meetings (Clayton 2009). Currently, BES offers educational opportunities to residents through online and published resources as well as workshops. BES provides an online calculator which allows a ratepayer to estimate the stormwater utility discount for a property by entering information such as lot size, building footprint, vegetation, and BMPs (Portland BES 2009). BES has promoted and funded demonstration projects throughout the city, at locations including: schools, government buildings, and neighborhood anchors. Demonstration sites incorporate prominent signage and educational placards.

RiverSmart Homes Program
Washington, D.C.

Background

RiverSmart Homes was created to reduce stormwater flow into the City's sewer system and to protect stream integrity while both educating and engaging the public in environmental stewardship and City beautification. RiverSmart Homes was initiated as a pilot program in 2007 and expanded to citywide implementation in the spring of 2009. The District began the program to address nonpoint source pollution from residential development and has incorporated the program into the City's MS4 program (Karimi 2008). Previous attempts to reduce stormwater through voluntary BMP implementation met with mixed success, leading the City to develop an incentive based approach (US EPA 2008).

Incentives and Organization

RiverSmart Homes is managed by the Watershed Protection Division of the District Department of Environment (DDOE). It is a cost-sharing program in which residential property owners apply to have stormwater BMPs installed on their property. The program is linked to the City's Municipal Separate Storm Sewer (MS4) program, which addresses tree canopy, low impact development (LID), rain barrel, and rain garden installation goals (DDOE 2007). Projects are funded on a first-come, first-serve basis. Each project begins with an onsite audit by a city employee, followed by installation of the BMP by a city-approved contractor, and ends with a final inspection of the site by city staff. Projects are scheduled annually, after the application deadline has passed and project applications have been processed (US EPA 2008).

The program provides funds for the following BMPs: large shade trees, above ground cisterns or rain barrels (downspout disconnect), rain gardens or bioretention cells (downspout disconnect), BayScaping (conservation landscaping specific to the Chesapeake Bay terrestrial ecosystems), pervious pavers or other pervious substrate (DDOE 2009). Recipients of RiverSmart Homes funding are entitled to up to $1,200 for landscaping and property improvements. However, the program requires that the project manager or property owner pay approximately 10 percent of the cost. The cost for the manager or owner is roughly, $50 per shade tree, $30 per rain barrel, $75 and up for BayScaping projects, $100 and up for each rain garden, and the cost above $1,200 for pervious pavers (DDOE 2009).

The RiverSmart Homes Program began in the Pope Branch watershed as a pilot project in the fall of 2007. At the time of writing, 60 projects have been approved and 11 projects have been installed in the pilot watershed. DDOE plans to install a total of at least 100 projects in the pilot watershed by the fall of 2009. The program has successfully spiked interest among homeowners. DDOE has received over 600 applications from homeowners throughout the City as of March 2009. Currently, one of the greatest constraints is the lack of contractors who are qualified to install stormwater BMPs. As green infrastructure becomes more commonplace in the District, the number of qualified contractors is expected to increase, allowing the number of installed projects per year to grow (Saari 2009).

Funding and Budgeting

Initial funding for RiverSmart Homes was obtained from a Clean Water Act 319 grant from the EPA, which allowed the City to install 9 demonstration sites and begin outreach to residents. As the CWA 319 grant money is depleted, RiverSmart Homes funding will be sourced from a new stormwater utility fee based on impervious cover and the City's general fund (US EPA 2008, DDOE 2009). The current annual budget for RiverSmart Homes is approximately $450,000; enough to fund about 375 residential projects per year (Saari 2009).

Outreach

Interested residents have access to basic information about the program online at the DDOE website http://ddoe.dc.gov/. The website includes an online application that asks for basic information such as BMP preference, resident address, and contact information. Additional outreach to residents takes place through information sessions, educational signage, and demonstration sites (DDOE 2009).

RainScapes Rewards Program
Montgomery County, Maryland

Background

RainScapes Rewards was created to enhance groundwater recharge as well as to reduce sediment, nutrient infusion, and stormwater volume which impact local waterways. It began in January 2008 as a reimbursement program for landowners and property managers who install stormwater management facilities on privately owned property. Prior to launching the RainScapes Rewards Program, the County commissioned a report on watershed protection project case studies and a community workshop series to engage residents in the program design process (RESOLVE 2007). The program does not target a particular region of the county; rather the program managers strive to fulfill 250-300 applications per year regardless of the property location (Curtis 2009).

Incentives and Organization

RainScapes Rewards is managed by the Montgomery County Department of Environmental Protection (DEP), Division of Environmental Policy and Compliance. The program has two full-time and one-part time staff (Curtis 2009). Reimbursement to program applicants is limited to $1,200 per residential lot and $.50 per square foot of impervious surface (up to $5,000) for multi-family, commercial, and private institutional properties. Reimbursement does not cover taxes paid on supplies nor labor expenses. Reimbursements may not be applied to installation of projects associated with new building construction, additions or renovations (Montgomery DEP 2009).

Each reimbursement request requires that the land owner or project manager submit an initial application specific to the BMP to be installed including pictures, materials needs, location specifications, cost estimates, and requested rebate amount. If the application is approved, a DEP employee will conduct a site inspection and verify that the project is eligible. The initial inspection must occur before the BMP project has physically begun. If construction starts before the initial inspection, the project no longer qualifies for a rebate. Final inspection and verification by County staff and a review of itemized receipts and/or invoices are the final steps in the process (Montgomery DEP 2009).

The program will reimburse for the following BMPs: rain gardens, rain barrels, dry wells, cisterns, replacement of turf grass with native plant conservation landscaping (BayScaping), replacement of impervious surfaces with permeable pavers, creation of new tree canopy in urban areas, and installment of green roofs (Montgomery DEP 2009). In the 18 months since program initiation, RainScapes has received 112 applications, 51 of which have been approved. The 51 projects break out as follows: 35 rain barrel projects, six conservation landscaping projects, four rain gardens, four urban tree canopy projects, one green roof and one permeable paver project. These projects have received a combined rebate of $15,114. Over the course of the program, DEP will document the following project information: location, BMP size and type, square footage of impervious surface treated, total project cost, and whether the project was self-installed or installed by a contractor. At the time of writing, follow up procedures have not been finalized; however, procedures are expected to include electronic surveys and a one-year inspection, followed by a five-year inspection (Curtis 2009).

Funding and Budgeting

RainScapes is funded out of the County's general fund. In FY2008, the initial year of the RainScapes Rewards Program, the budget was $500,000.The proposed budget for FY2009 was $500,000; however the amount was reduced to $434,910 due to budget constraints. At the time of writing, the FY2010 budget is also $434,910 (Curtis 2009).

Outreach

Montgomery County DEP conducts outreach to residents through participation in public events, workshops for residents, and web content at www.montgomerycountymd.gov/rainscapes. The program website includes an application packet that contains separate applications specific to the allowable BMPs.

Mt. Airy Rain Catchers & Shepherd Creek Watershed Study
Cincinnati, Ohio

Background

The Shepherd Creek Watershed Pilot Project, also known as the Mt. Airy Rain Catchers Project is part of a larger effort by the EPA to quantify the water quality impact of decentralized BMPs on a watershed scale and to test the effectiveness of market-based mechanisms (Thurston *et al*. 2008). The Shepherd Creek watershed is located in a predominantly residential area of Cincinnati, Ohio. The watershed is approximately 2 km^2 (247 acres) within and around Mt. Airy Forest Park. The watershed has a mix of land uses, including forested parkland, commercial, and residential. The upper portion of the Shepherd Creek watershed is densely developed, dominated by single family residential development and scattered commercial sites. The lower portion of the watershed is preserved as a forested park. At the beginning of the study, the EPA calculated that just over half of all impervious cover in the watershed was connected to the stormwater system (Thurston *et al*. 2008, Wilson n.d.).

The Mt. Airy Rain Catchers Project is a watershed scale experiment led by the National Risk Management Research Laboratory (NRMRL), Sustainable Technology Division, of the US EPA Sustainable Environments Branch. The study was designed to evaluate two factors, one of which was a market-based mechanism to encourage participation. The mechanism utilized in this study was a reverse auction in which homeowners submitted a bid for monetary compensation to be paid to the homeowner in return for permission to install an owner specified BMP(s) on their property. Bids were awarded based on the property's location in the watershed and the monetary award requested. The BMPs used in the study were limited to storage using rain barrels and infiltration using rain gardens (US EPA 2009, Thurston *et al*. 2008).

The second factor evaluated in the study was water quality in receiving streams before and after the installation of the BMPs. The water quality testing will not be completed until 2010. Water quality parameters included nutrients, suspended solids, organic carbon, chloride, trace metals including copper and zinc, and stream biota. Researchers have completed initial studies comparing flow and water quality of a nearby undeveloped headwaters stream to that of Shepherd Creek prior to BMP installation. Their analysis found stream impairment in Shepherd Creek caused by silt embedding in the stream substrate, high levels of fecal coliform bacteria, and high peak flows (US EPA 2009, Wilson n.d.).

At the time of completion, the EPA study will include detailed water quality testing results before and after BMP installation as well as detailed records of community outreach and the reverse auction. Initial results of the auction and community outreach were published in 2008. Water quality and biological monitoring results will be collected through the summer of 2010, to be published in 2011 (Thurston 2009).

<u>Incentives and Organization</u>

Rain barrels and rain gardens were chosen as the study BMPs due to the high percentage (50 to 72) of rooftops and driveways that made up the impervious surface in the watershed, as well as the ease of installation. Participation in the program was determined by reverse auction bids and a rating system that weighed the property location in the watershed as well as the payment bid made by the homeowner. The first round of auctions resulted in 100 rain barrels and 50 rain gardens, which were installed in 2007 at 68 residential properties. A second round of auctions the following year led to the installation of 76 rain barrels and 35 rain gardens at 49 properties. Over the two years, the study installed 176 rain barrels and 85 rain gardens on approximately one third of the 350 residential properties in the watershed (US EPA 2009, Thurston *et al*. 2008, Wilson n.d.).

The EPA contracted a private firm, Tetra Tech, to carry out the reverse auction, BMP installation, BMP monitoring, and water quality monitoring. Prior to program initiation, Tetra Tech and NRMRL separated the Shepherd Creek project area into five sub watersheds. Researchers compared impervious surface coverage in the sub watersheds to stream conditions and found that higher impervious coverage resulted in greater stream impairment. Impervious cover ranged from 12 to 20 percent with an average of 13 percent among the subwatersheds (US EPA NRMRL 2009, Tetra Tech n.d., Wilson n.d.).

Tetra Tech will continue to monitor selected individual BMPs until a period of three years after installation has passed. Rain garden monitoring assesses hydrology, soils, and water quality; rain barrel monitoring assesses water quality and water level in select barrels. Final analysis will compare watershed health of five sub watersheds in the Shepherd Creek watershed to baseline data. Time from baseline to final analysis of water quality data is 2004-2010, or seven years (Thurston *et al*. 2008, H. Thurston 2009).

<u>Funding and Budgeting</u>

The Mt. Airy Rain Catchers program was funded by the US EPA as a short-term study. Project managers estimate that the cost of the seven-year study, excluding overhead and biological monitoring, totaled about $500,000 to $600,000. Exact figures are not yet available. However, the approximate cost for each task was: $10,000 for the demonstration site, $50,000 for the auction, $350,000 for materials, and $100,000 for BMP installation labor (H. Thurston 2009). Costs beyond the auction and BMP installation included approximately $250,000 for water quality and biological monitoring (Shuster 2009). Each home was eligible for up to four rain barrels and one rain garden. Because project costs varied based on homeowner bids, project costs varied from year to year. Bids ranged from $0 to $500. Bid payout to homeowners was $5,347 in 2007, and payout for 2008 is not available (Wilson n.d.).

Outreach

Homeowners were contacted by two direct mailings that explained the project, how the BMPs function, and the auction process. The second mailing package encouraged homeowners to apply and included an auction form with a business return envelope for easy submittal, as well as an extra $5 to peak interest. Demonstration rain barrels and rain gardens were installed at a public park area in the Shepherd Creek watershed to augment the direct mailings (Thurston *et al*. 2008).

DISCUSSION

Stormwater BMP incentive programs may prove to be a low cost component of comprehensive stormwater management plans. Decentralized stormwater management at the parcel level has the potential to reduce stormwater sewer system capacity needs, and in turn, reduce the cost to local governments for system installation and maintenance. As discussed in the previous examples, incentives may take the form of lump sum payouts, cost shares, cost reimbursement, or utility fee discounts. Other incentives such as the reduced cost of materials, tax credits, project financing, and recognition awards have been implemented in similar programs (US EPA 2009).

One of the greatest challenges to localities interested in an incentive program is securing funding. Federal grants, loans, or new fees and taxes are the most common strategies for green infrastructure funding. In instances where the local government is unable to initiate a new program, officials and residents may consider a public-private partnership. Nonprofit watershed associations may be prepared to address the need for decentralized BMPs when public programs are not an option.

Stormwater BMP incentive programs are in their infancy. Over the coming decade, research is needed to compare program cost and stormwater volume retained by BMPs on private property to the cost of conventional stormwater management for equivalent volumes. Any comparison between management strategies needs to include environmental costs associated with conventional discharge of stormwater into receiving waters as well as environmental benefits of green infrastructure, including urban wildlife habitat and reduction in heat island effect. Results from the EPA's Shepherd Creek Watershed Study will be helpful in quantifying water quality improvements resulting from dollars spent on decentralized BMPs.

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EFFECT OF SPATIAL RAINFALL DATA ON THE PERFORMANCE OF HYDROLOGIC MODELS

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ABSTRACT

Rain gage measurements have traditionally been used as input to hydrologic models. In most watersheds, the spatial density of rain gages is very low, meaning little detail about the spatial characteristics of rainfall events are used in the models. In general, rain gage data are not adequate to develop unit hydrographs (UHs) or to reconstruct a storm response, especially for nonhomogeneous watersheds. The spatial and temporal characteristics of a storm will influence the watershed response, while storm movement, direction, and velocity will influence the hydrologic response. Therefore, spatial data about rainfall could improve hydrological models. The possibility of using spatial radar rainfall data, rather than point rain gage data, as input to UH development was investigated. The goal of this research was to determine whether knowledge of spatial characteristics of rainfall events could improve model predictions of hydrologic and watershed response. Variation in UHs derived using different rain gages in the same watershed was assessed and found to be significant. Spatially averaged rainfall hyetographs, including the Thiessen average rainfall and radar rainfall, were found to be more representative of the rainfall over the watershed and, therefore, the watershed response, than hyetographs developed from an individual rain gage. To evaluate the true impact of UH variation on design, peak flow rates were calculated and compared for UHs based on both point rainfall data and spatially averaged rainfall. The variation found in individual UHs was observed to carry over into designs made using those UHs.

INTRODUCTION

Unit hydrographs (UHs) are frequently used in hydrologic design. The definition of a UH is a runoff hydrograph that results from one inch of precipitation excess (PE) that falls uniformly in time over the storm duration. The PE must have a uniform spatial distribution over the watershed. This condition rarely occurs, so this portion of the definition must often be applied loosely in order to use the UH procedure. Several assumptions about the rainfall distribution must be made in order to calculate a UH. The extent to which these assumptions are met, either in analysis or design, has not received the attention that it deserves, given the extent to which UHs are used, such as in the HEC and USDA computer programs. Unit hydrographs are often fitted using rainfall data from a single rain gage, which does not have the ability to reflect spatial variability in the rainfall. Therefore, the uncertainty of spatial variation of rainfall over the watershed on the fitted UH needs to be investigated.

The intent of this research was to better understand factors that influence UH accuracy, especially the spatial characteristics of rainfall. This is important if UHs are to be improved. To meet this goal three objectives were evaluated. First, the uncertainty in UHs due to both storm-to-storm and within-pixel variation was investigated. Second, the potential effects of transmission losses on UHs derived for arid regions were also investigated. Finally, the potential for spatial data, such as radar or Thiessen average rainfall data, for use in the UH procedure was evaluated.

UNIT HYDROGRAPH ANALYSES

Derivation of UHs

Given a rainfall hyetograph and a total runoff hydrograph for a complex storm, development of a UH requires the following: (1) elimination of baseflow to produce the direct runoff (DRO) hydrograph; (2) elimination of initial abstraction; (3) separation of losses to produce the rainfall excess (PE) hyetograph; (4) a unit hydrograph model; and (5) a method of fitting the parameters of the UH model.

First, baseflow was separated from the total runoff. Because Walnut Gulch is located in an arid region and the streams are ephemeral (Stone *et al.* 2008), it was assumed that baseflow did not exist. Therefore, all of the runoff measured at the flow gages was considered DRO. Next, losses were separated from the rainfall hyetograph to determine the PE hyetograph. All rainfall prior to the start of runoff was assumed to be lost as initial abstraction. After this was removed the constant percentage method (McCuen 2005) was used to separate losses from the rainfall hyetograph, with losses assumed to be proportional to the rainfall rate such that the volumes of PE and DRO are equal.

The PE hyetograph and the DRO hydrograph were used in a nonlinear least squares analysis to determine the optimum Weibull UH parameters for each storm event. The nonlinear least squares analysis determined the best-fit values of the Weibull shape (c) and scale (b) parameters. Then the UH and PE(t) were convolved to generate a predicted DRO hydrograph. Goodness-of-fit statistics including the standard error ratio (Se/Sy), the correlation coefficient (R), and the coefficient of determination (R^2) were evaluated using the computed and measured DRO hydrographs.

UHs Derived Using Rain Gage Rainfall Data

In the first analysis, UHs were derived using rainfall hyetographs from each individual rain gage located within the boundaries of one radar pixel along with the nearest downstream flow gage hydrograph. This allowed the variability existing in UHs derived for different rain gages located fairly close together to be assessed. Using this procedure to analyze several storm events allowed conclusions to be drawn about the effects of storm-to-storm variation.

Data for these analyses were obtained from rain gages and flow gages located within the Walnut Gulch Experimental Watershed. This watershed, located near Tucson, Arizona, is operated by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) Southwest Watershed Research Center (http://www.tucson.ars.ag.gov/dap/). The climate in this region is semi-arid and most of the rainfall occurs during the summer monsoon season (Goodrich *et al.* 2008). Streams within the watershed are ephemeral, flowing only in response to a storm event (Stone *et al.* 2008). Based on work done by the Stone *et al.* (2008), it was known that runoff in Walnut Gulch peaked very quickly after the runoff began. This could result in UHs that differed somewhat in shape from the commonly seen hydrograph shape. Aridlands hydrographs with steep rising limbs and shorter than normal recessions have been reported elsewhere (Peebles *et al.* 1981, Sen 2007, 2008). Peebles *et al.* (1981) attribute these particular characteristics to transmission losses in the channel.

UHs Derived for Rain Gages Within One Pixel

Table 1 provides the Weibull shape (*c*) and scale (*b*) parameters determined for each of the individual rain gages in pixel 12, as well as goodness-of-fit statistics, during the storm event on August 13, 2006. Figure 1 shows these UHs for comparison. Significant variation is obviously possible in UHs derived using different rain gages, as the scale parameters vary from 3.5 to 29.3 and the shape parameters vary from 0.33 to 1.46. Differences in scale are evident from Figure 1, where the UH peak values range from approximately 10 to 40 cms/mm. Differences in shape are also visible, as several of the UHs have a typical shape with a rising limb, peak value, and a receding limb, while several others have exponential shapes with no rising limbs. Osborn (1983) also found that the location of the storm within a watershed significantly influenced the response. The differences in UH parameters obtained for each of the individual rain gages is caused by spatial variation in the rainfall hyetographs. The important observations from these two analyses are: (1) the spatial uniformity of rainfall influences the uniformity of computed UHs and (2) the temporal variations of rain experienced even at nearby gages influence the variation between fitted UHs for the same storm.

Table 1. Rain Gage UH Parameter and Goodness of Fit Statistics for Storm on 8/13/06
Pixel 12

	b	c	Se/Sy	R	R^2
RG 53	15.5	0.77	0.37	0.93	0.86
RG 57	22.5	1.05	0.45	0.90	0.80
RG 58	28.5	1.43	0.44	0.90	0.81
RG 59	29.3	1.46	0.43	0.90	0.82
RG 61	3.5	0.33	0.27	0.96	0.93
RG 63	12.7	0.53	0.42	0.91	0.82
RG 72	13.1	0.59	0.32	0.95	0.90
Thiessen	19.2	0.85	0.40	0.92	0.84

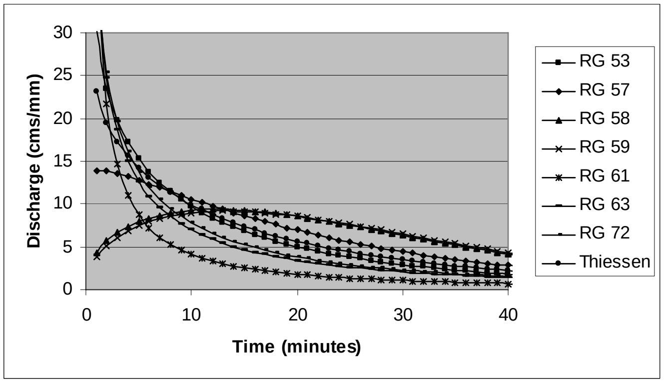

Figure 1. UHs Derived from Rain Gages and Thiessen Rainfall for Storm on 8/13/06 Pixel 12

The exponentially-shaped UHs observed in Figure 1 result from distinct values of the Weibull shape parameter. Shape parameters less than 1.0 cause exponential UHs, while shape parameters greater than one result in more typically-shaped UHs. The variations in the *c* values and the variation between UHs derived from different rain gages appear to be related to the length of time between the center of mass (CM) of the DRO and the CM of the PE. For the storm event on August 13, 2006, the rain gage-to-rain gage differences in time of CMs of the PE varied, and the time between the PEs and CMs of the DRO were fairly short. A short difference in the time between the CM of the DRO and the CM of the PE causes the Weibull *c* values to be small.

Transmission loss (TL), which is the infiltration of streamflow into the channel bed, is believed to be a physical cause of the exponential UHs. In arid regions such as Walnut Gulch, transmission losses have been found to be a significant factor in hydrologic modeling. One result of TL is a decrease in both flow volume and peak discharge as the flood wave moves downstream (Jordan 1977). Transmission losses cause the DRO hydrographs to have a steeper rise and the initial abstraction to occur over a longer period of time. These two factors cause the CM of PE to be delayed and the CM of runoff to occur closer to the start of DRO, which often resulted in the rise of the DRO hydrograph occurring near peak rainfall intensities. The result is less time between the two CMs and a steep rise on the UH and, therefore, lower Weibull *c* values. In a previous analysis, transmission losses were proven to result in UHs with steeper rising limbs and lower Weibull shape parameters. Based on this evidence, it was concluded that transmission losses were responsible for the exponential UHs observed in Figure 1.

UHs Derived Using Thiessen Rainfall Data

Individual rain gages, which are commonly used to derive UHs, provide only point rainfall measurements. The Thiessen polygon averaging method can be used to derive a spatially averaged rainfall hyetograph based on point rainfall data at several gages. Thiessen average hyetographs were calculated for each of the pixels examined for the four storm events evaluated in the previous analysis. Thiessen weights for each rain gage were obtained using planimeter measurements. These weights were applied to the rain gage hyetographs, resulting in a spatially-weighted average rainfall hyetograph for each storm event. These hyetographs and the nearest downstream flow gage hydrographs were used to determine the optimum Weibull UH parameters, which were then compared to the rain gage UHs.

Comparison of Individual Rain Gage and Thiessen Rainfall UHs

Table 1 and Figure 1 compare the UH derived using the Thiessen average hyetograph for the storm event on August 13, 2006, over pixel 12 to those derived using the individual rain gages. Both the *b* and *c* values for the Thiessen averaged rainfall and the goodness-of-fit statistics fall well into the ranges provided by the values for the individual rain gages. The resulting Thiessen UH is centrally positioned within the UHs from the individual rain gages. The goodness-of-fit statistics should also be examined to determine the ability of the UH to accurately predict storm runoff. The standard error ratio calculated for the Thiessen UH is 0.40, the correlation coefficient is 0.92, and the coefficient of determination is 0.84. The statistics indicate that the UH derived using the Thiessen hyetograph is able to make acceptably accurate runoff predictions.

UHs Derived Using Radar Rainfall Data

After evaluating the benefits of using Thiessen averaged rainfall data in deriving UHs, another spatially averaged data set, radar rainfall data, were used in deriving UHs. To evaluate the ability of radar data to be used in deriving UHs, radar data from the area of Walnut Gulch was first obtained from Hydro-NEXRAD, an online service for downloading radar data (http://www.hydro-nexrad.net). The computed radar rainfall hyetograph was developed for each of the storm events used in the previous analyses. This hyetograph and the nearest downstream flow gage hydrograph were used to determine the optimum Weibull UH parameters. The UHs derived in this analysis were compared to those derived using Thiessen hyetographs. If the two UHs derived for each pixel and storm event were observed to be comparable, it would indicate that radar data could be a satisfactory rainfall data source for UHs.

Comparison of Thiessen and Radar Rainfall UHs

Table 2 and Figure 2 present the Weibull shape and scale parameters and goodness-of-fit statistics for UHs derived using the Thiessen and radar rainfall hyetographs for the storm on August 13, 2006, over pixel 12. The purpose of comparison was to assess whether or not spatially averaged radar rainfall data would better reflect the watershed response than individual point rainfall data in the UH procedure. Reasonable agreement is observed between the Thiessen average and radar UHs, though differences in scale are visible. Specifically, the radar rainfall UH is slightly steeper than the Thiessen averaged rainfall UH.

The differences between the Thiessen and radar UHs should be compared to the differences between the individual rain gage UHs. The Weibull *b* value varies only from 12.1 to 19.2 between the Thiessen and the radar UHs, which is far less than the range from 3.5 to 29.3 seen between the individual rain gages reported in Table 1. Similarly, the Weibull *c* values range from 0.57 to 0.85 between the Thiessen and radar UHs, as compared to a range of 0.33 to 1.46 for the individual rain gages. The lower *c* value derived for the radar UH explains the difference in steepness between the UHs observed in Figure 2. The goodness-of-fit statistics calculated for the Thiessen and radar UHs should also be compared. Based on these statistics, the radar UH appears to be slightly more accurate than the Thiessen UH.

Table 2. Comparison of Thiessen and Radar Rainfall UH Parameters and Goodness-of-Fit Statistics for 8/13/06 Storm Event Pixel 12

Storm Date	Method	b	c	Se/Sy	R	R^2
8/13/06	Thiessen	19.2	0.85	0.40	0.92	0.84
8/13/06	Radar	12.1	0.57	0.26	0.97	0.93

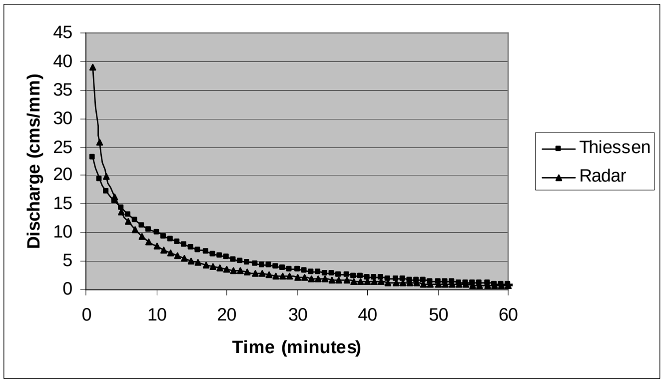

Figure 2. Thiessen and Radar UHs for the Storm on 8/13/06 Pixel 12

IMPLICATIONS OF UH VARIATION ON DESIGN

In examining the variation in UHs derived using different rainfall hyetographs potentially significant variation was seen. Ultimately, the effect of this variation on an engineering design is the criterion used to judge the significance of the variation. From the results of the UH analyses, it appears that the rain gage used in deriving a UH could significantly impact the result. These results suggest that it could be difficult to obtain a UH that is representative of the watershed using just a single rain gage. Because the ultimate goal of the UH procedure is to predict runoff from given storm events, in order to properly design storage facilities, conduits, levees, *etc*., a UH that is not actually representative of the watershed could cause significant design error. The purpose of this part of the study was to show the potential impact of the variations in UHs derived using individual rain gages on calculations of predicted runoff peak discharge. The same procedure was also followed using the Thiessen average rainfall and the radar rainfall, for comparison.

Methods of Analysis

The Weibull UH parameters calculated for each of the rain gages located within pixel 12, the Thiessen rainfall, and the radar rainfall, were convolved with a 24-hour Type II design storm to obtain a predicted runoff hydrograph. The NRCS (SCS) method was used in this process. Data from Walnut Gulch pixel 12 for the storm on August 13, 2006, and the storm on July 20, 2007, were used. A generic watershed of 64 acres and a curve number of 75 were used for this analysis. The analysis was repeated three times for each unit hydrograph, for a 2-year design storm (3.2 inches of rainfall), for a 10-year design storm (4.8 inches of rainfall), and for a 100-year design storm (7.2 inches of rainfall).

To more closely evaluate the differences in peak flows a frequency analysis was conducted. Using logarithms of the discharges, frequency curves were plotted for each of the rain gages located within a given radar pixel for each return period, the Thiessen average rainfall, and the radar rainfall. This visualized the variation possible in designs made based on varying UHs.

Peak Discharge Analysis for August 13, 2006, Storm Event

For the storm event occurring on August 13, 2006, the UHs derived for pixel 12 were used in a peak discharge analysis. The plot developed from the frequency analysis is presented in Figure 3. For this storm event the spread between the lowest and highest rain gages in the frequency analysis was nearly a half of a log cycle, resulting in differences of nearly 20 cfs for a 2-year storm and 345 cfs for a 100-year storm. The peak discharges and the ratios of rain gage or radar peak discharge to the Thiessen peak discharge calculated for this pixel are presented in Table 3. The 2-year peak discharges ranged from a low value of 8.1 cfs to a high value of 27.8 cfs, while the 100-year peak discharges ranged from 136 cfs to 481 cfs. An increase in peak discharge of nearly 350 cfs could significantly overwhelm a facility designed using one of the lower rain gage UHs. Serious flooding could be a problem in a case such as this. This indicates that the use of a UH that is not representative of the watershed in design work could have significant safety and risk consequences.

Table 3. Peak Discharge Rates (cfs) Calculated for 2 (Q_2)-, 10 (Q_{10})-, and 100 (Q_{100})-year return periods (T) Using UHs Derived for Storm Event 8/13/06 Pixel 12

	Q_2	Q_p/Q_{pT}	Q_{10}	Q_p/Q_{pT}	Q_{100}	Q_p/Q_{pT}
RG 53	14.68	1.258	71.36	1.251	268.11	1.240
RG 57	9.50	0.814	44.47	0.780	165.53	0.766
RG 58	8.22	0.704	37.68	0.661	138.31	0.640
RG 59	8.12	0.696	37.17	0.652	136.16	0.630
RG 61	27.84	2.386	131.18	2.300	481.48	2.228
RG 63	19.87	1.703	94.89	1.664	351.85	1.628
RG 72	18.81	1.612	90.15	1.580	335.11	1.550
Thiessen	11.67	---	57.04	---	216.14	---
Radar	19.69	1.687	94.20	1.651	349.65	1.618

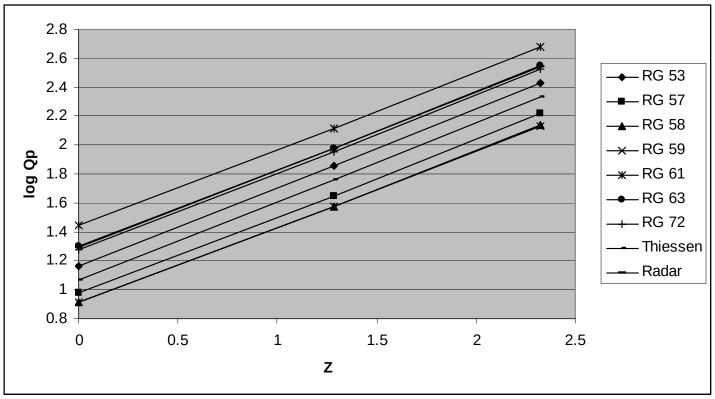

Figure 3. Log Frequency Curve for Storm on 8/13/06 Pixel 12 based on 2-year (Z=0), 10-year (Z-1.282), and 100-year (Z=2.327), where Z is the standard normal deviate

The calculated Thiessen rainfall hyetograph appears to be fairly representative of the rainfall over the watershed, and it resulted in an accurate UH. The frequency analysis illustrates that the peak discharges calculated using the Thiessen average UH fall in the middle of the range of peak discharges calculated using the individual rain gages. Therefore, using the Thiessen average rainfall hyetograph rather than one of the individual rain gage hyetographs should produce a more adequate engineering design.

The Thiessen average rainfall peak discharge and the radar rainfall (presented in Table 3) peak discharge were again compared. Unfortunately, a lack of similarity between the two designs can be observed between the peak discharges reported in Table 3 and the frequency analysis plots in Figure 3. Based on differences in the UH parameters for each, the radar peak discharge was seen to be 0.2 log cycles above the Thiessen average peak discharge. For the 2-year event the peak discharge calculated using the Thiessen rainfall was 11.7 cfs vs. 19.7 cfs calculated using the radar rainfall. For the 100-year storm the peak discharges were 216 cfs using the Thiessen rainfall vs. 350 cfs using the radar rainfall. These differences would require significantly different designs. Because the Thiessen average rainfall UH and peak discharge calculation seem accurate based on the individual rain gage results, this casts some doubt on the radar rainfall data. However, the possibility of an error in the radar data should be considered as a possible explanation, due to the fact that Thiessen rainfall results seem appropriate. There are still many possible sources of inaccuracy in radar measurements, such as attenuation of the radar beam, blockage of the radar beam, and improper conversion of the actual radar measurements to rainfall intensity readings.

Peak Discharge Analysis for July 20, 2007 Storm Event

To confirm the findings of the analysis of the storm event on August 13, 2006, a peak discharge analysis was also completed for the storm event on July 20, 2007, over pixel 12. The results of this analysis are presented in Figure 4 and Table 4. The differences observed between the peak flows calculated using the individual rain gage UHs was nearly 0.4 log cycles, as seen in Figure 4, with a minimum peak flow of 5.5 cfs for the 2-year storm and a maximum peak flow of 17.5 cfs. For the 100-year storm the peak flows ranged from 395 cfs to 939 cfs. The peak discharges and ratios of rain gage or radar peak discharges to Thiessen peak discharges calculated for the storm event on July 20, 2007, for pixel 12 are presented in Table 4. The differences in peak discharge caused by UH variations are clearly significant in this case. Differences of more than 500 cfs are observed between the rain gages for a 100-year storm event. If a UH that was not representative of the watershed were used in this case, a significant possibility of risk to health and safety exists.

Table 4. Peak Discharge Rates (cfs) Calculated for 2 (Q2)-, 10 (Q10)-, and 100 (Q100)-year return periods (T) Using UHs Derived for Storm Event 7/20/07 Pixel 12

	Q_2	Q_p/Q_{pT}	Q_{10}	Q_p/Q_{pT}	Q_{100}	Q_p/Q_{pT}
RG 53	54.76	1.148	255.15	1.140	927.53	1.136
RG 57	55.63	1.166	258.58	1.156	938.63	1.150
RG 58	50.32	1.054	235.95	1.055	860.95	1.054
RG 59	22.45	0.470	106.95	0.478	395.26	0.484
RG 61	22.76	0.477	108.38	0.484	400.41	0.490
RG 63	35.08	0.735	167.44	0.748	617.98	0.757
RG 72	42.59	0.892	201.34	0.900	738.47	0.904
Thiessen	47.72	---	223.74	---	816.53	---
Radar	34.37	0.720	163.29	0.730	601.38	0.737

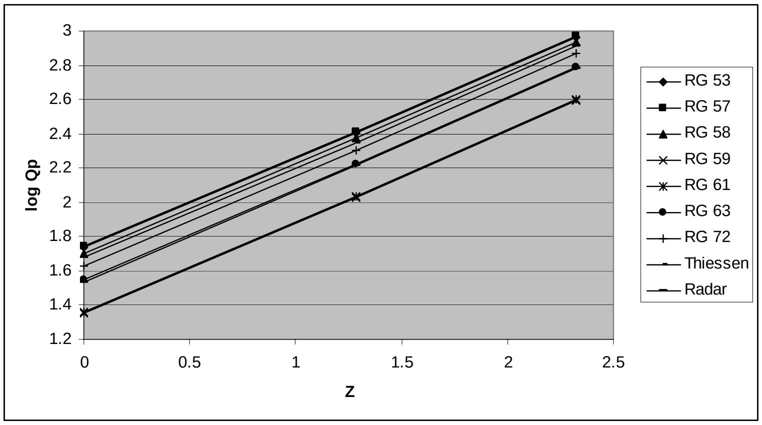

Figure 4. Log Frequency Curve Developed for Storm on 7/20/07 Pixel 12 based on 2-year (Z=0), 10-year (Z=1.282), and 100-year (Z=2.327), where Z is the standard normal deviate

The Thiessen average UH again resulted in calculated peak flows that fell within the range of values calculated using the rain gages. The Thiessen peak discharges calculated for the 2-year storm event was 47.7 cfs and for the 100-year storm the peak flow was 817 cfs. The Thiessen design calculations are overall comparable to the individual rain gage calculations, indicating that the Thiessen average UH could be successful in calculating a reasonable peak discharge for storm runoff in the watershed. The Thiessen hyetograph should be more representative of the rainfall being experienced over the watershed than any one of the individual rain gage hyetographs, so the facility being designed (*e.g.*, pipe system, levee) is more likely to adequately manage the storm runoff if designed using the Thiessen average UH than one of the rain gage UHs.

The peak discharges calculated using the Thiessen average hyetograph are also moderately close to the radar to the peak flows calculated using the radar rainfall (34.4 cfs for a 2-year storm event and 601 cfs for a 100-year storm event). Based on the reasonable similarity between the Thiessen peak discharges and the radar rainfall peak discharges, it would appear that the radar hyetograph may ultimately be able to provide a reasonably accurate UH that can be safely used in design calculations. This is further reinforced by the fact that the frequency analysis results indicate that the radar rainfall provided a better average than the Thiessen average. In this scenario, the radar rainfall UH produces peak flows that fall closer to the average of the rain gages than the Thiessen average hyetograph does. The conclusion to be drawn from this is that radar rainfall may provide a viable method of calculating and using unit hydrographs, which is good news for watersheds without rain gage networks able to provide a representative picture of the rainfall.

CONCLUSIONS

The objective of this research was to evaluate the level of variation that existed between UHs derived using different rain gages, and to determine whether spatial data sources, such as Thiessen average rainfall or radar rainfall data, could be used to derive UHs. Another purpose was to assess the degree to which the variation in UHs affected design calculations based on the UHs. Significant variation was seen in UHs derived using different rain gages located within the boundaries of one radar pixel. This indicates that, even when two rain gages are located close to each other, they may result in much different UHs due to spatial variation in the rainfall hyetographs.

Two spatial data sets, Thiessen average rainfall and radar rainfall data, were evaluated for potential use in UH development. The Thiessen UH was first compared to the UHs developed from individual rain gages. The Thiessen UH was observed to perform comparably to the rain gage UHs, and in fact the goodness-of-fit statistics calculated for the predicted runoff provided assurance that the Thiessen UH was accurate. Then the radar rainfall UH was compared to the Thiessen UH, and the two were seen to compare favorably. Minor differences of course existed, but these differences were only a fraction of the differences observed between the individual rain gage UHs. The conclusion to be made from these results is that spatial rainfall data can be used to calculate an acceptably accurate UH. Rarely does a watershed have enough rain gage data to calculate a Thiessen hyetograph, so this finding that radar data can be used to develop UHs is quite beneficial.

Several conclusions can also be drawn from the peak discharge analysis conducted using the UHs previously derived. First, significant variation in runoff peak flow rate is possible depending on the UH used in calculations. Unit hydrographs are typically derived using only one rain gage hyetograph. If several rain gages are available for use within a watershed, the rain gage used to derive the UH may make a difference in ultimate designs. Depending on the level of variation seen in the individual rain gage hyetographs, these differences can be quite significant.

Second, the Thiessen average UH, which typically is based on a more representative rainfall hyetograph than a UH derived from one rain gage, can also produce designs more likely to be sufficient to handle the runoff from a storm event. The variation in UHs from different rain gages leaves much room for errors in design, which can be minimized by using the more representative Thiessen UH.

Third, radar rainfall data can be used to make reasonable design calculations. The radar rainfall UH showed promise in producing designs that were similar to the Thiessen average design or otherwise representative of the individual rain gage designs. Radar rainfall data could be used when sufficient rain gages are not available to calculate a representative Thiessen average hyetograph, if it is found to be accurate and representative. This research has taken the first step in finding that radar data can be representative of the Thiessen average rainfall and the individual rain gage rainfalls, in both derivation of the UH and design work using the rain gage.

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SPATIO-TEMPORAL EFFECTS OF LOW IMPACT DEVELOPMENT PRACTICES

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ABSTRACT

Land development and urbanization in the U.S. and worldwide is causing environmental degradation. Traditional off-site stormwater management does not protect small streams. To mitigate the negative effects of land development, best management practices (BMPs) are being implemented into stormwater management policies for the purposes of controlling minor flooding and improving water quality. Unfortunately, the effectiveness of BMPs has not been extensively studied. The purpose of this research was to analyze the effects of location of two types of BMPs: cisterns and bioretention pits. A spatio-temporal model of a microwatershed was developed to determine the effects of BMPs on peak runoff rates and volumes for residential and commercial lots compared to predevelopment conditions. The results show that cisterns alone are capable of controlling rooftop runoff for small storms. The spatial location of BMP storage on a microwatershed influences the effectiveness of BMPs. The location is a factor in the peak reduction and a maximum volume of effective BMP storage exists for both hydrologic metrics. In regards to water quality, BMPs were effective in reducing small stream scour up to 98% for single storm events. These results provide guidelines for developing stormwater management policies that can potentially reduce degradation of first-order streams, lower the cost and maintenance of stormwater management requirements, enhance aesthetics, and increase safety.

INTRODUCTION

As America adopts a greener philosophy, hydrologists are developing practices to control poor water quality from developed areas. One hope is that these new methods will be effective in reducing flooding as well as simultaneously improving water quality. The methods are an integral part of what the public refers to as *smart growth* (Davis and McCuen 2005). Unfortunately, localities are adopting these "best management practices", or BMPs, even though they have not been extensively tested for effectiveness. It appears that cost-effectiveness is a primary metric used in selecting among alternative best management practices (Strubble *et al*. 1997).

With the growth in land development and urbanization, impervious surfaces prevent water from infiltrating. Preventing infiltration decreases the volume of ground water recharge, lowers water tables, increases surface runoff volumes and peak discharges, and decreases base flows during dry periods. These factors contribute to an increase in the transport of pollutants and the degradation of stream channels (Arnold and Gibbons 1996, Gove *et al*. 2001, Bartone and Uchrin 1999, Pennington *et al*. 2001). For example, higher runoff rates increase the scouring of channel bottoms. Uncontrolled channel erosion results in increased sedimentation, which causes many additional problems. Suspended sediment in streams negatively affects aquatic habitat, such as the fish population as well as the macro invertebrates on which fish feed. Other environmental consequences of channel erosion include the washouts at bridges or highways, topsoil maintenance for productivity, channel stability, and delta formations. Channel erosion can also cause sediment accumulation in rivers used to provide drinking water. This has economic effects as sediment filtration is needed at water purification plants. The cost of cleaning the water of suspended soil particles can be substantial, and alternative practices can have benefits above that of conventional systems (Larson 1996).

Advancements in storm water management include low impact development (LID) methods that aim to control rainfall on-site such that post-development characteristics of lot runoff do not differ significantly from pre-development conditions (PGCo. 1999). This improves water quality by limiting the transfer of pollutants as well as scour from increased runoff. In theory, these methods are an improvement to solving the storm water management problem. However, factors that influence the effectiveness of LID technologies have not been conclusively determined. Factors such as the optimal location and quantity of BMPs as well as the effects of land use types and return period need investigation. Until the effects of these factors have been established, BMPs that are arbitrarily sized and located may be unable to achieve optimal effectiveness.

This study provides spatio-temporal analyses of the effects of low impact development (LID) practices on runoff rates and volumes from microwatersheds as well as erosion depths in first-order streams over time. A spatio-temporal model of a microwatershed was formulated that can be used to simulate runoff for either natural or urban/suburban conditions and the resulting channel erosion of a nearby first-order stream. The study consisted of two parts: (1) The effects of storage and location of LIDs on on-site flood characteristics and (2) the effects of LIDs on channel erosion were evaluated for various land use types and return periods. The sensitivity of BMP effectiveness to the location and volume of BMPs will assist in achieving optimal effectiveness and will be useful in establishing drainage policies.

SPATIO-TEMPORAL MODEL OF A MICROWATERSHED

A model was developed in the Matlab language to simulate both the temporal and spatial characteristics of the rainfall, runoff, and infiltration processes for any return period on lot-sized watersheds. Analyses were conducted for 1- and 2-yr return periods. For the first part of the analysis, three watershed layouts were simulated, one forested and two developed. The spatial distribution of land use for each of the developed watershed layouts was designed to represent a residential and commercial lot. The percent of impervious land cover for the residential and commercial lots were 32.5 and 72%, respectively. For the developed lots, the model replicated multiple LID plans consisting of cisterns and bioretention cells to determine their effects on stormwater runoff volumes and peak discharge rates. The bioretention cells allow for infiltration while the cisterns were above-surface storage aimed at limiting flow rates from rooftops.

Each lot was assumed to be roughly 0.1 ha (0.25 acre). The model spatially separated the lots into a grid of cells; Figure 1a and 1b show the layouts for residential and commercial lots with typical flowpaths for stormwater runoff. Each cell is assigned an elevation to reflect the topography of the lot, an infiltration rate, and the following roughness coefficients (n) associated with the land cover type: forest: 0.4; lawn: 0.25; and roadway, driveway, and parking lot: 0.012. The topography was held constant for both the pre-developed and developed lots with an average slope of 3%. Infiltration rates of 3.8, 3.2, and 5.1 cm/hr were used for the wooded, grass covered, and bioretention cells, respectively. The elevations were assigned so that the entire lot drained to the southeast corner. The only variation was for the roadways in the residential lot. This lot was designed so that runoff drained directly from the roadway onto grass. The roadway runoff then followed a swale along the roadway to the outlet at the southeast corner of the microwatershed.

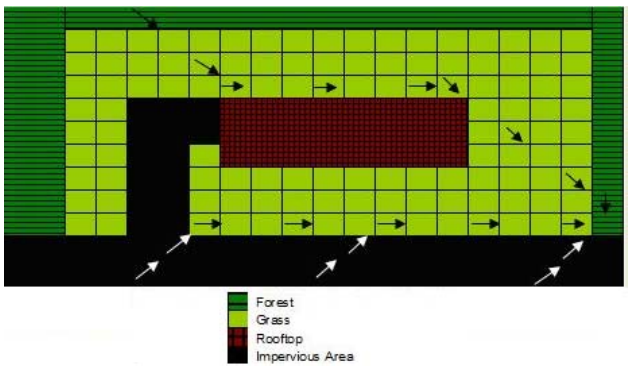

Figure 1a. Residential Lot

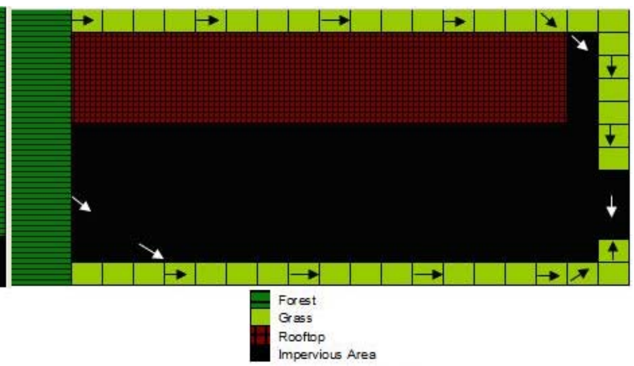

Figure 2a. Commercial Lot

For the second part of the analysis, the model was modified to simulate flood runoff from a small housing development on a single roadway. The model represented an area of 7956 m^2 and enclosed eight quarter-acre residential lots consistent with the design in Figure 1a. The roadway was located down the center of the watershed, with the flood runoff from the eight lots draining along side of the roadway to watershed outlet where the watershed drains into a small stream.

The 1-year and 2-year rainfall events with depths of 2.2 cm and 3.6 cm, respectively, were simulated based on the IDF curve for Baltimore, Maryland, and represented by a center-loaded, triangular hyetograph. Calabro (2004) showed that triangular storms provided the best discrimination for water quality control simulations. For the first part, 1-hour storm durations were used, as local rain gage records indicated that this would cover approximately 50% of actual storms. For the second part, the storm duration varied. The 1- and 2-yr events were studied, as they are likely the upper limit for small BMP control of pollution. Larger events are less frequent, while smaller events would be controlled by designs based on the 2-yr event. A study of 14 long-term precipitation records in the Middle Atlantic region indicated that more than 50% of the events were of the 2-yr depth or less and 1-hour storms. This would likely cause a significant portion of the annual pollution load. Preliminary analyses showed that changes in BMP effectiveness were most noticeable between the 1-yr and 2-yr events, whereas for smaller events, *i.e.*, the 6-month storm, BMP effectiveness was invariant to factors such as the return period of the storm. Therefore, BMPs will have little effect for large storms, but the effectiveness may be invariant to return period for small and more frequent storms.

For both parts of the study, the model computes the depth of rainfall to each cell within each 1-minute time increment. The surface runoff from each cell was calculated differently for cells that contained a bioretention facility, cells that contained a cistern, and cells that did not contain a BMP. The cisterns were located only to intercept rooftop runoff, with each rooftop corner cell draining directly to a cistern. Outflow from a cistern drained through an orifice. When the storage capacity of the cistern was reached, all of the excess water overflowed and was added immediately to the outflow through the orifice for that time increment. Each cell designated as a bioretention facility has a depth of 15 cm below the ground surface, which yields a storage volume of 0.6 m^3. Overflow occurs when runoff from higher gradient cells enters the bioretention facility at a faster rate than the water is infiltrated or overflowed. Runoff was calculated for each cell based on Manning's equation. The model output a total runoff value for each time increment in the form of a hydrograph.

To estimate erosion rates in headwater streams, a stream erosion model was developed, which uses the runoff hydrograph generated from the eight-lot residential watershed microwatershed model as input. The erosion model calculated the total depth of soil scoured from the stream bottom for a specific storm. This model consisted of a series of calculations that required, as inputs, the hydrograph ordinates Q from the runoff model as well as the mean soil particle diameter and the slope of the channel. The following equation for sediment discharge per unit width q_s (m^2/s) was derived from Julien (2002):

Equation 1:

$$Q_s = 1.1Q^{1.1}\ d_s^{-0.27}\ S^{1.44}$$

Where Q_s =sediment discharge rate (m^3/s), Q= hydrograph input, d_s=soil partical diameter (m), and S = slope (m/m). The sediment concentration is calculated by the relationship between concentration load (L_s) and the water discharge rate (Q):

Equation 2:

$$C = L_s / (KQ)$$

Where C is the concentration (mg/L), L_s is the sediment load (g/s), and K is a constant 1. To determine the concentration, the sediment discharge rate Q_s must be converted into the sediment load L_s using the specific weight of soil (25.986 kN/m^3) along with conversion factors. L_s is found to be:

Equation 3:

$$L_s = (2.91*10^6)\ Q^{1.1}\ d_s^{-0.27}\ S^{1.44}$$

Substituting equation (3) into equation (2) yields the actual sediment concentration equation:

Equation 4:

$$C = (2.91*10^6)\ Q^{0.1}\ d_s^{-0.27}\ S^{1.44}$$

The theoretical concentration [C] (mg/L) of sediment is determined by the amount of sediment in the volume of water, with the final equation for the theoretical concentration is given by:

Equation 5:

$$[C] = (2648.92\ D) / h$$

Where D is the depth of scour (m) and h is the depth of water (m). Equations (4) and (5) are then set equal to each other to provide an estimate of the depth of scour D:

Equation 6:

$$D = k\ Q^{0.1}\ d_s^{-0.27}\ S^{1.44}\ h$$

Where k is a constant that is later determined through model calibration. The intent here is to estimate the relative effect of BMPs on erosion of small streams. The annual depth of erosion is computed by accumulating the scour depth over all storms in one year, with the depth of scour varying depending upon the storm.

Scour model calibration was necessary for tailoring the model to this specific project. Because Julien's equations were intended to apply to relatively large watersheds, the derived scour depth equation (6) required a value for the constant k to make it relevant to small watersheds. By using known theoretical values of scour depths for several types of storms and substituting them into equation (6), k was iteratively determined to be 0.07.

PART 1 RESULTS

On-Site Effects of Development

Land development increases both the volume of stormwater runoff and the peak discharge. Therefore, these were used as the metrics for comparison. The forested lot represents the pre-development land cover condition. For the 1-year storm, the forested lot completely infiltrates the rainfall. The 1-year storm produced a peak discharge rate and total runoff volume of 0.16 m^3/min. and 4.33 m^3, respectively, for the residential lot and 0.35 m^3/min. and 11.03 m^3 for the commercial lot. The developed lots had lower infiltration rates because construction activities were assumed to decrease the potential capacity and the lots were partially covered by impervious surfaces.

For the 2-year storm, the forested lot produced surface runoff with a total runoff volume of 5.70 m^3 and a peak discharge of 0.31 m^3/min. Compared to the forested lot, the single-family lot increased the total volume of runoff by 196 percent and the peak discharge by 86 percent, with values of 16.90 m^3 and 0.58 m^3/min., respectively. For the 2-year storm on the commercial lot, the total volume increased by 369 percent and the peak discharge by 157 percent, with values of 26.75 m^3 and 0.80 m^3/min., respectively. These increases are similar to increases suggested by both the Rational method and the NRCS curve number approach. Based on these results, it is apparent that storm water management is necessary to counteract the effects of development. Ideally the storm water control measures would totally mitigate the effects of the land development on the two hydrologic metrics. These developments without any stormwater management are designated as scenario A in Table 1.

Table 1. Percent Decrease of Peak Discharge Rate (Q) and Total Runoff Volume (V) on the Residential (R) and Commercial (C) Lots for the 1 and 2-Yr Storm based on Scenario (S) of Cisterns and Varying the Number (N) and Location of Bioretention Facilities.

S	N	Description	Q		V		Q		V	
			1-Yr Storm				2-Yr Storm			
			R	C	R	C	R	C	R	C
A	0	No BMPS	0	0	0	0	0	0	0	0
B	0	4 Cisterns	30	9	32	14	6	0	10	6
C	5	Combined near Outlet	47	18	78	44	8	3	27	**20**
D	5	Intercepting Cisterns	31	**38**	37	40	**25**	**14**	28	19
E	5	Intercepting Impervious Area	**92**	15	**92**	**45**	8	0	**30**	19
F	5	Divided Among Impervious Area and Cistern	38	37	67	43	12	3	28	20

Effectiveness of Cisterns

Spatio-temporal analyses were made where four cisterns were implemented as shown in Figures 2a and 2b. The percentage decreases from post development values without BMPS in both peak discharge and flow volume were computed (Scenario B in Table 2). The effectiveness of cisterns in controlling flood runoff lessens as the size of the storm increases. For the 1-year storm, cisterns reduced the peak rate and volume by 30% and 32%, respectively, for the single-family lot. For the 2-year storm, however, the cisterns reduced both the peak and volume by less than 10%. The total storage volume of the cisterns was too small to effectively control the rooftop runoff caused by the 2-year storm. For the 2-year event, the cistern storage was essentially filled at the time the peak rainfall intensity occurred. Thus, when used as the only on-site BMP, the cisterns were minimally effective for the 2-year storm. However, for smaller storms, cisterns alone provide some control.

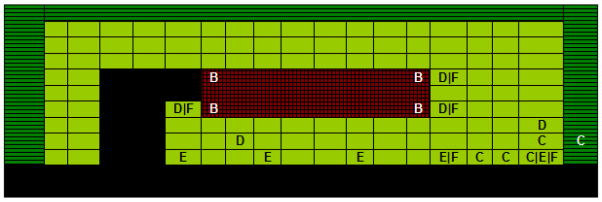

Figure 2a. BMP Scenarios for Residential.

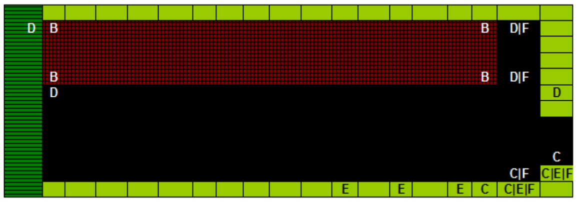

Figure 2b. BMP Scenarios for Commercial.

The effectiveness of cisterns also varies with land use. For the 1-year storm, cisterns reduced the peak and volume by 30% and 32%, respectively, for the single-family lot and 10% and 14%, respectively, for the commercial lot. The effects vary with land use because the ratio of the cistern volume to the rooftop area was much less for the commercial lot than for the residential lot and the commercial lot contains a higher percentage of impervious area. An equal volume of cistern storage will be less effective in controlling the rooftop runoff in the commercial lot than on the residential lot. This is partly due to the amount of available storage and partly that the cistern storage is filled when the peak rainfall intensity occurs.

In summary, the effectiveness of cisterns as a BMP for on-site control varies considerably with the volume of storage relative to the volume and time distribution of the runoff. For maximum effectiveness, the volume of storage needs to be coordinated with the volume of runoff at the time of the maximum rainfall intensities. Excess cistern storage may be unnecessary to control peak discharges, while less than adequate storage may have little effect on reducing peak discharges.

Effects of Bioretention Storage Location.

On large watersheds, the spatial distribution of storage reservoirs is known to influence the overall effectiveness of the flood control systems (McMahon and Adeloye 2005). Therefore, it is reasonable to study the effect of the location of hydrologic storage on the response of a microwatershed. The issue here is the effect of the location of BMP storage on watershed discharge rates and volumes. The most effective location of bioretention facilities was expected to vary depending on the land use, the return period of the storm, and the purpose of implementing the BMP (*i.e.*, peak or volume reduction).

To determine the effects of location of bioretention facilities on stormwater runoff, multiple analyses for a combination of four cisterns and multiple bioretention facilities were conducted for each landuse and the two storm sizes. For the location analyses, five bioretention facilities were modeled in various locations. First, the location in regards to which portion of the watershed is intercepted was tested in four scenarios: (1) Bioretention facilities were sited surrounding the outlet of the lot to intercept runoff from all portions of the microwatershed (scenario C in Table 2); (2) Bioretention facilities were sited to intercept water cistern overflow (scenario D); (3) Bioretention facilities were sited along the roadway for the residential lots and along the south side of the parking lot for the commercial lots to intercept runoff from impervious areas (scenario E); and (4) Bioretention facilities were sited with two intercepting impervious areas and three intercepting the cistern outflow (scenario F). Figures 2a and 2b provide a visual explanation of each scenario for the residential and commercial, respectively. The effects of each scenario on the two metrics are shown in Table 2.

<u>Residential Lot</u>

For a residential lot, varying the location of bioretention facilities influenced the amount by which the peak rates and runoff volumes decreased compared to values for residential lots without BMPs. To have the greatest effect on runoff volumes, bioretention pits should be located to intercept runoff from impervious areas such as the roadway. Roadway runoff has the least opportunity to infiltrate as it drains towards the outlet. Thus, when sited near impervious surfaces that are directly connected to the outlet, such as a roadway, all of the available storage volume of the facilities will be used, which will encourage infiltration over a longer portion of the storm. Because the rooftop runoff passes across the lawn, which provides some opportunity for infiltration, the impact of siting the facilities within the lawn area is less than optimal for decreasing the total runoff volume. Therefore, providing additional infiltration for the roadway runoff through bioretention facilities maximizes the reduction of the total volume of runoff for the residential lot.

To illustrate the effect for the residential-lot layout, bioretention facilities were located to intercept the runoff from the roadway while cisterns intercepted the rooftop runoff (scenario E in

Table 2). This configuration reduced the runoff volume for the single-family lot by 92% for the 1-year storm and 30% for the 2-year storm. In comparison to siting the facilities to intercept runoff from the cisterns (scenario D), locating the facilities to intercept runoff from the roadways reduced an additional 55% and 5% of the total runoff volume for the 1- and 2-year storm, respectively. These results show that for the small, more frequent storms, more effective control of runoff rates and volumes will be achieved when the cisterns and bioretention facilities are located on the lot in a way that they are hydrologically independent of each other.

In terms of peak discharge reduction, the most effective BMP location varies with the design return period. For the 2-year storm, bioretention facilities located to intercept cistern outflow resulted in the greatest reduction in peak discharge (Scenario D in Table 2). The peaks were reduced by 25%. Cisterns store the rooftop runoff from the early portion of the storm, but reach their storage capacity before the most intense portion of the storm. When the storm intensities are highest, storage in the bioretention facilities is still available to store the rooftop runoff that exceeds the cistern capacity. Therefore, bioretention facilities that intercept the cistern runoff are effective in reducing the peak discharge for the 2-year storm. Again, this result shows that matching the BMP storage volume to the time distribution of runoff is an important factor in determining the effectiveness of the BMPs.

For the 1-year storm, overflow from the cisterns that drains to the lawn can infiltrate at a rate that significantly decreases discharge rates from the grassy portion of the lot. Thus, for the 1-year storm, the combination of cistern and ground water storage is sufficient to control the rooftop runoff. Placing bioretention facilities to intercept the cistern runoff reduced the peak by 31% while cisterns alone reduced the peak by 30% (Scenario B and D in Table 2). Therefore, locating the bioretention facilities to intercept cistern runoff during the small storms had very little impact on their effectiveness to reduce peak discharge. For the 1-yr storm, the bioretention facilities are most effective when they intercept runoff from the street and roadway (Scenario E), reducing the peak by 92%. In summary, the benefits for peak discharge control of placing cisterns and facilities in series rather than being spatially independent varies with the size of the storm, with little effect on runoff for the smaller, more frequent storms.

Commercial Lots

While location was important for the residential lots, the location of bioretention facilities had little effect on the total storm runoff volume from the commercial lot. For the 1-year storm, varying the location of the bioretention facilities changed the percentage of volume reduction by only 5 percentage points (Scenarios C-F in Table 2). For the 2-year storm, the percent volume reduction changed by only 1 percentage point (Scenarios C-F). This result is because of the greater impervious area in the commercial lot compared to the residential lots. The potential of the BMPs to store and infiltrate runoff was small and of little consequence to the total runoff volume. The bioretention facilities were the primary source of infiltration regardless of where they were located and the storage availability was not synchronized with the temporal storage requirement. Therefore, the maximum volume of runoff that the bioretention facilities will be able to intercept equals the volume of water that can infiltrate from the facilities during the storm plus the volume stored. In this case, the storage volume was inadequate for the facilities to be effective.

The peak discharge from the commercial lot was affected by the location of the BMPs for both the 1-year and 2-year storm. Bioretention facilities located to intercept the cistern runoff (Scenario D in Table 2) reduced the peak by 38% for the 1-year storm and 14% for the 2-year storm. For both storms, this location decreased the peak by at least 11 percentage points more than for other locations. The cisterns were able to store much of the rooftop runoff before the most intense part of the storm occurred. Therefore, storage in the bioretention facilities was still available during the middle of the storm, which enabled the facilities to be effective in reducing the peak flow. When the cisterns and facilities are located so that they function independently of each other, their storage reaches capacity during the initial part of the storm, so they have minimal impact when the peak storm intensities occur. In summary, when locating BMPs on small commercial lots, their storage volumes must be sized with consideration of the type of storm that they are intended to control and locating BMPs in series may be most effective.

Varying Effects on Hydrologic Metrics

Control of peak rates and total storm volumes are two metrics that can be used to judge the effectiveness of a low impact development plan (McCuen 2003); however, it should not be assumed that effectively controlling one metric will necessarily lead to a similar control of the other metric. Figure 3 shows the variation of the two metrics for the case where the residential site includes four cisterns and a variable number of bioretention facilities. The total storage shown includes both the cistern storage and the storage in the facilities. Adding bioretention facility storage beyond that of the cistern storage increases the reduction in the volume of runoff at an almost linear rate up to the point where only uncontrolled parts of the lot are contributing runoff. However, the second metric, peak discharge, shows a different trend. Adding BMP storage beyond the cistern storage reduces the runoff volume in the early part of the storm event but not at the time of the maximum storm intensity. Therefore, the peak reduction does not initially change. However, when the facility storage is of sufficient quantity, it then is effective for controlling the peak discharge during the time of maximum storm intensity and the rise in peak reduction is rapid for small changes in storage volume. When the facility storage is used up, then the peak does not show additional reduction because the peak is controlled by the parts of the drainage area not controlled by the cisterns or facilities. Also, a maximum effective storage exists when dealing with a specific design storm as shown for the 1-year storm. Therefore, design objectives should be considered when implementing BMPs.

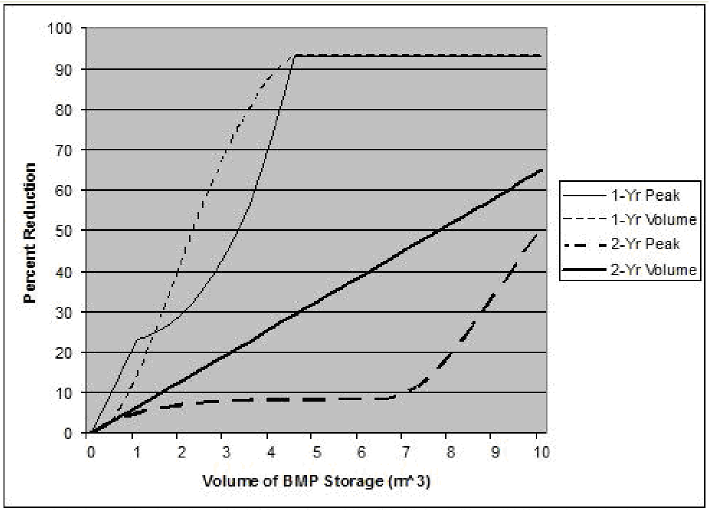

Figure 3. Effects of Varying Storage on Peak and Runoff Volume for the Residential Lot.

PART 2 RESULTS

Analysis of Annual Scour Depths on Pre-Developed Land

Scour from runoff for a forested lot was calculated to show the advantages of using BMPs on developed land. Storms varying in duration and rainfall depth were applied to the models. The total scour was computed using the average number of storms for each storm type over the course of one year. The total annual depth of scour was very low, 0.507 mm, indicating the environmental advantage associated with undeveloped areas. The majority of the scour was caused by the short duration storms. For example, 30-minute and 90-minute storms generated 0.327 mm and 0.16 mm of scour annually, respectively. The larger 24- and 9-hour storms did not generate any significant scour. The scour from the short duration storms occurred because of the increased rainfall intensities for each time increment. Longer storms spread the same rainfall depths over a longer time period, allowing more time for infiltration and therefore, less runoff.

Analysis of Annual Scour Depth on Post-Developed Land with and without BMPs

To analyze the effects of development, the annual depths of scour for the post-developed microwatershed with and without bioretention facilities were calculated. For post-developed land without BMPs, the total annual scour depth for all storms equaled 5.54 mm. For the post-developed land with BMPs with five bioretention facilities implemented, the total annual depth of scour was 1.22 mm. Therefore, BMPs reduced the annual scour depth for all storms by 79% relative to the post-developed scenario without BMPs. The majority of scour is caused by short duration storms because the BMPs do not have enough time to infiltrate the rainfall volumes as opposed to long duration storms, which spread rainfall over a longer time period.

Analysis of Single Storm Scour Depths on Post-Developed Land without BMPs

An analysis was conducted to determine the effects of rainfall depth and duration on scour. First, developed land without BMPs was analyzed as the standard of comparison for developed land with BMPs. Table 2 shows scour depths per specific storm on the developed watershed without bioretention facilities present. Based on these results, the scour depth increases as the storm depth increases for a set storm duration. For a given duration, the peak of the hydrograph and, therefore, the depth of flow in the channel, will increase as the total storm depth increases. As a result, a greater shear stress is exerted on the soil particles in the channel bed, which causes the particles to be detached and transported down the stream. Liu and Singh (2004) discussed the effects of factors that influence shear stress on soil particles.

For a given storm depth, the scour rate will also vary with storm duration. For small storms (1.27 and 4.45 mm), scour depth generally increases with increasing duration (see Table 2). This occurs because the depth of flow for low volume storms is so low that the scour is almost the same in each minute. Therefore, the only factor that affects scouring for a nearly constant depth of runoff is the duration of the storm. With larger storms *i.e.*, 19.1 and 38.1 mm, the flow depth in the stream causes greater variation in the minute-by-minute scour. Generally, scour depth decreases for the most part as storm duration increases because as the storm duration lengthens, the rainfall is spread across a longer period of time, resulting in lower stream depths and less scour. However, some storms do not follow this general trend. Nine- and 24-hour storms with depths of 19.1 mm and 38.10 mm experience an increase in scour depth. This is due to the much longer duration of scouring flows that the channel bottom endures.

Table 2. Scour Depth per Single Storm (mm) for Developed Land without BMPs

Duration	Storm Depth (mm)				
(hr)	1.27	4.45	9.53	19.05	38.1
0.5	0.00578	0.0212	0.2171	0.8401	1.891
1.5	0.00787	0.0188	0.0472	0.3481	1.481
2.5	0.00912	0.0218	0.0371	0.1891	1.041
4.5	0.01081	0.0261	0.0442	0.0717	0.584
9	0.01331	0.0319	0.0543	0.0882	0.143
24	0.01781	0.0427	0.0729	0.1181	0.192

Analysis of Scour Depths on Post-Developed Land for a Single Storm with BMPs

Analyses for single storm scour depths were also conducted for developed watersheds with bioretention facilities. The percentage decrease in scour depth per specific storm for the BMP scenarios was calculated (see Table 3). The percent reduction ranges from 0.02% to 98.4% relative to the situation without BMPs. The general trend shown in Table 3 is seen vertically through each of the columns. The percentage decrease due to bioretention increases as storm duration increases because the facilities are more effective for longer duration storms. This is because when storms occur over longer periods of time and retain the same rainfall depth, the rainfall is spread out more, becomes less intense, and can infiltrate at a faster rate.

Table 3. Percentage Decrease in Scour Depth per Storm with BMPs

Duration	Storm Depth (mm)				
(hr)	1.27	4.45	9.53	19.05	38.1
0.5	0.02	35.8	81.7	61.4	20.7
1.5	0.88	0.53	32.6	98.4	37.3
2.5	19.9	18.3	17.8	73.7	81.3
4.5	66.5	65.7	65.1	64.8	92.9
9	90.2	89.7	89.5	89.4	89.2
24	98.4	98.2	98.1	98.1	98.1

GUIDELINES FOR LOCATING BMPs

While an almost infinite number of scenarios for locating BMPs could be investigated, the scenarios reported herein suggest general trends. As shown herein, the location of a BMP is critical to its effectiveness. Based on these analyses, guidelines for locating BMPs to effectively control peak discharge rates and runoff volumes were developed. The guidelines are as follows:

- The effectiveness of cisterns in controlling peak discharge rates requires the cistern volume to be sufficient to store the runoff through the time of the peak intensities of the rainfall.
- Siting bioretention facilities in areas that drain pervious rather than impervious surface runoff is less effective because the grassy areas partially reduce the runoff rates and volumes.
- BMPs may be unnecessary for very small storm events on microwatersheds with high levels of pervious surfaces but analyses will need to be made for each case to determine the size of the storm at which the critical level is reached.
- The effectiveness of a BMP is very dependent on the return period of the storm.
- For small, frequent storms, bioretention pits should be located independently of cisterns to increase the available storage to intercept runoff at the peak of the storm.
- For larger storms (*i.e.*, approximately 2-yr events) on high impervious lots, cisterns and bioretention pits may need to be placed in series to increase the available storage volume that would be available during the more intense part of the storms and, therefore, control the volumes of runoff and peak discharge rates.
- The effect on peak discharge rates due to the volume and location of BMP storage will be different than the effect on runoff volumes, which means that BMP designs should be selected based on the objective, which could be either peak or volume control.
- When locating BMPs in a watershed, peak discharge rates heavily depend on the portions of the watershed not controlled by a BMP facility.
- The effectiveness of BMPs in decreasing scour depth increases as the duration of a storm increases for a set storm depth.
- Scour depths in receiving small channels decreased with additional facilities per lot; however, significant reductions will not be observed until effective volumes of BMPs are implemented. Analyses must be made to determine this volume, which in this study were five bioretention facilities to reduce the scour by approximately 78%.

CONCLUSIONS AND IMPLICATIONS

BMPs can be effective control measures, but if not properly sited, the positive effects can be limited. The non-optimum location of bioretention facilities will diminish the positive effects that the facilities can have on controlling peak rates and runoff volumes. The less effective a bioretention facility, the greater storage volumes of facilities required to achieve the desired reduction in peak rate and stormwater runoff. Knowledge of the most effective location of BMPs can influence the cost, maintenance, aesthetics, and safety of a development design. Additionally, knowledge of the effects of BMPs on scour is important to control water quality in first order streams. The results of this study showed that BMPs are effective in decreasing scour for small storms; however, the effectiveness varies with storm characteristics.

The reported analyses focused on examining the effect of BMP location rather than on a wide array of watershed characteristics such as slope, roughness, or infiltration rates. The effects of these factors are generally acknowledged. BMPs are currently being installed without a full understanding of the effect of location, so the reported work centered on this factor. While the results may not apply to extreme conditions, such as 25% or greater slopes or clay soils, the reported effects of location should be applicable over a wide range of watershed conditions because the relative effects were the focus of the evaluations.

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USING LANDSCAPE PLANTS FOR PHYTOREMEDIATION

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ABSTRACT

Phytoremediation is an emerging technology that uses plants to degrade, extract, contain, or immobilize contaminants such as metals, pesticides, explosives, oil, excess nutrients, and pathogens from soil and water. Phytoremediation has been identified as a more cost effective, noninvasive, and publicly acceptable method of removing environmental contaminants than most chemical and physical methods.

Two nutrients commonly found in stormwater runoff are nitrogen (N) and phosphorus (P). Both of these pollutants are also macronutrients needed for agronomic and horticultural plant growth, and are components of all complete fertilizers. Fertilizer application to residential, commercial, and municipal lawns and landscapes is a major non-point source of pollution with potential for reduction via phytoremediation.

The majority of plants currently used in phytoremediation applications, including stormwater ponds (BMPs), riparian buffers, rain gardens, green roofs, constructed wetlands, *etc*., are herbaceous or non-woody. New stormwater runoff systems, that incorporate woody landscape plants into the systems, are being designed for streetscapes and landscapes. Two research projects are currently being conducted at Virginia Tech to identify woody landscape plants with nutrient and heavy metal hyperaccumulation or phytoremediation potential. One project involves a nutrient uptake screening protocol for landscape trees and shrubs. The other project involves screening landscape plants *in situ* and in Filterra stormwater management units to compare nutrient and heavy metal accumulation from landscape soil vs. the Filterra unit

substrate. Results from both projects are beginning to identify both native and non-native landscape plants that are hyperaccumulators with phytoremediation potential.

INTRODUCTION

The Clean Water Act (CWA) is the cornerstone of surface water quality protection in the United States. Passed in 1972, and amended in 1997, this statue employs a variety of tools to, in part, manage polluted runoff. While initially focused primarily on "point source" (direct pollutant discharge) facilities (municipal sewage plants, industrial facilities), starting in the late 1980's efforts increased to address "non-point" runoff sources such as streets, parking areas, construction sites, farms, landscapes, and other "wet-weather" sources (EPA 2008).

The pollutant loading found in urban runoff can have detrimental effects on water quality and water body ecosystems (Hsieh and Davis 2005). Pollutants are a major concern in stormwater runoff since these parameters are harder to control as a nonpoint source pollutant. Pollutant effects can include oxygen depletion, eutrophication, species stress and toxicity (Hsieh *et al*. 2007). The impact of nutrients, mainly phosphorus and nitrogen, on water quality is of particular concern, because nutrients in runoff can cause eutrophication where algal blooms grow excessively and deplete dissolved oxygen levels and increase turbidity. This can then result in poor water quality and low biodiversity. Fertilizers, atmospheric deposition, soil erosion, animal wastes and detergents can contribute to the nutrients in runoff. Phosphorus can exist as both dissolved and particulate forms in runoff and include organic and inorganic components (Hsieh *et al*. 2007). Nitrogen can exist as both organic forms and inorganic forms such as ammonia, nitrate and nitrite.

Heavy metals such as copper, lead, zinc, and cadmium are carried in stormwater runoff and can bioaccumulate in aquatic systems because they cannot be broken down into less toxic forms. Sources of heavy metals are present almost everywhere and include car brake pads, building siding and roofs, tires, and atmospheric deposition. As these heavy metals bioaccumulate, the levels can become too toxic for aquatic life to tolerate and may lead to death (Davis *et al*. 2001).

Stormwater best management practices (BMPs) are used to lessen the impact of urban runoff on water quality, flooding, and erosion (Hsieh and Davis 2005). The use of plants to remediate contaminated soils and wastewater has been practiced internationally for some time, but new research is being conducted to determine how effective plants are at removing contamination from polluted waters due to both stormwater and wastewater discharges (Wang *et al*. 2002). Phytoremediation is an emerging technology that uses plants to degrade, extract, contain, or immobilize contaminants such as metals, pesticides, explosives, oil, excess nutrients, and pathogens from soil and water (EPA 2000). Phytoremediation has been identified as a more cost effective, noninvasive, natural, and publicly acceptable method of removing environmental contaminants than most chemical and physical methods (Arthur *et al*. 2005).

Both nitrogen (N) and phosphorus (P) are macronutrients needed for agronomic and horticultural plant growth, and are components of all complete fertilizers. Fertilizer application to residential, commercial, and municipal lawns and landscapes is a major non-point source of pollution with potential for reduction via phytoremediation. Though run-off from farms is generally decreasing due to nutrient management, run-off control techniques, and an overall decline in farmland, run-off from urban and suburban areas continues to increase as more land is developed, more native filtering plants are removed, and more hardscaped areas are installed.

The heavy metals copper (Cu) and zinc (Zn) are micronutrients for plants, and accumulate in the plant tissue in higher concentrations than other metals such as cadmium and lead that accumulate in the plant roots since they are not as mobile. A variety of research studies have been conducted to determine what plant species, both aquatic and terrestrial, can best accumulate heavy metals without toxic effects to the plant, and are identified as metal hyperaccumulators. Metal uptake is dependent upon plant species and availability of dissolved metals in the water. Dissolved metals available for plant uptake can depend on the amount of organics in the system, retention time, pH, redox likelihood, and particle bound metals. Plants also affect dissolved metal availability due to their effect on soil pH and oxygenation (Fritioff and Greger 2003).

The majority of plants currently used in phytoremediation applications, including stormwater ponds (BMPs), riparian buffers, rain gardens, green roofs, constructed wetlands, *etc*., are herbaceous or non-woody. New stormwater runoff systems that incorporate woody landscape plants into the systems, such as the Filterra® Bioretention System (Americast 2009), are being designed for streetscapes and landscapes. If commonly used landscape trees could be used for stormwater (and soil) phytoremediation our trees would have an added environmental value. It is therefore important to screen commonly available landscape trees for their potential use in these systems.

Phytoremediation research with woody trees and shrubs has been more limited, with the willows (*Salix* sp.) having been identified as significant hyperaccumulators. Pollutant bioavailability and uptake by plants is very much dependent upon the rhizosphere processes. A major part of the rhizosphere microbial community is mycorrhizal fungi, which form a symbiotic relationship with plant roots. Because they help transfer nutrients and metals to plant roots these associations play an important role in mediating plant uptake. Microorganisms in the rhizosphere will biologically transform pollutants into less toxic forms through enzymatic detoxification, thus making them available for plant uptake via the mycorrhiza (Arthur *et al*. 2005). Willows do form mycorrhizal associations, and preliminary research has indicated a potentially significant contribution of mycorrhizas to accumulator willow heavy metal uptake (Wenzel 2005). A study by Wenzel (2003) found that the willow species accumulated the most metals in their leaves, with concentrations highest just before leaf fall. Wenzel's study showed that willow, a fast growing species, is most suitable for phytoextraction of metal-contaminated soils. According to Arthur *et al*. (2005), hyperaccumulator species are able to tolerate high metal concentrations in their biomass through the use of phytochelatins, which are sulfur-rich proteins.

The objectives of our initial research were to: 1. Use a nutrient uptake screening protocol for landscape trees and shrubs that was originally designed using water hyacinths as the remediation plant. This will determine what plants currently in nursery production have phytoremediation capabilities, or what plants not common in the industry need to be produced for phytoremediation use; 2. Screen landscape plants *in situ* and in Filterra® Bioretention Systems stormwater management units to compare nutrient and heavy metal accumulation from landscape soil vs. the Filterra® system substrate. For both objectives both native and non-native landscape plants were used to determine which might be hyperaccumulators with phytoremediation potential.

METHODS

Modified Hyproponic Screening

In 2007 and 2008, using a protocol developed for phytoremediation screening with water hyacinths (Fox *et al*. 2008), several species of woody shrubs, including redtwig or redosier dogwood (*Cornus sericia*), buttonbush (*Cephalanthus occidentalis*), and deciduous holly or winterberry (*Ilex verticillata*) were subjected to increasing levels of N and P (Figure 1). Whole plants were harvested and dried, and leaves were weighed and subjected to N and P analysis using the method described for the water hyacinths.

Figure 1. The modified hydroponic system used to evaluate woody shrub accumulation of N and P. (In the foreground are the water hyacinths used to develop the protocol.)

Landscape Screening

In 2007 and 2008, to begin to compare the accumulation of N, P, Cu, and Zn accumulation, woody shrubs were planted in landscape sites adjacent to Filterra® units. A unique feature of the Filterra® unit is that it holds a substrate into which a shrub or tree is planted. These units have been field evaluated for their removal efficiency of N and P, along with suspended solids and some heavy metals (Figure 2). Several sites in Norfolk, VA and the Richmond, VA area were selected for evaluation. For statistical purposes, a requirement of each site was a minimum of three same sized Filterra® units planted with the same shrub. That shrub was then planted into landscape soil a few feet from the Filterra® unit. The major species used for this evaluation were several hollies (*Ilex* sp,), crape myrtle and redtwig dogwood. Each fall, mature leaves evenly distributed around the shrubs were harvested, dried, and weighed, and then subjected to N, P, Cu, and Zn analysis again using the method described for the water hyacinths (Figure 3).

Figure 2. Hollies planted in Filterra® units installed in a parking lot with replicate landscape holly in background.

Figure 3. Collection of leaves from a holly for N and P analysis.

RESULTS

Modified Hydroponic Screening

There was a definite trend for all species used in the modified hydroponic system to grow larger and accumulate more N and P in their tissue as the rate of N and P in the water increased, with no signs of excessive nutrients (no marginal necrosis, *etc*.). These evaluations will be repeated in 2009, possibly using higher levels of N and P. Several species of willow were started in a nursery at HRAREC in 2006 to evaluate both their phytoremediation potential and their landscape suitability (size, growth rate, color, *etc*.).

Landscape Screening

One of the most important components of the Filterra® Bioretention System is the plant since it plays a critical role in pollutant uptake. Release of nutrients from substrate absorption sites makes this a sustainable system. Though a range of N, P, and heavy metal percents is available generically for deciduous and evergreen trees and shrubs, there are few ranges known for individual species and/or cultivars. The leaves of the shrubs planted in the landscape soil were used as a baseline nutrient content against which the shrubs in the Filterra® units could be compared. With a few exceptions and regardless of shrub species, there was more N, P, Ca, Cu, Ni and Zn in the leaves of the plants in the Filterra® units than in the landscape plants. This suggests that these shrubs may be able to "luxury feed" or act as hyperaccumulators.

Results to date are preliminary since collection has only occurred over two years. Stormwater pollutants of concern that were included in the analysis comprise Cu, Pb, Ni, Zn, Cr, N and P. Nutrients were only included in the first year of analysis and heavy metals and other micronutrients were added for the second year of analysis. Of the statistically valid locations, Cu, Ni and Zn showed the greatest uptake in the Filterra® system in comparison to the landscape plants with 95% confidence limits. The plants in the Filterra® systems took up 53% more Cu, 55% more Ni and 58% more Zn than the landscape plants (Tables 1, 2 and 3). Cr and Pb were below detection limits. Results over the two years at the statistically valid locations show there is no correlation between year and location. Thus the locations were pooled and from 2007 to 2008 there is a statistically significant increase in phosphorus uptake with 98% confidence limits. The results also show a statistically significant increase in phosphorus uptake between the Filterra® and the landscape plants with 97% confidence limits. Based on the statistically valid locations, the plants in the Filterra system took up 24% more total phosphorus than the landscape plants. Nitrogen was reported as two different types of nitrogen by the laboratory for each year and could not be compared across years. However, the plants in the Filterra system took up 38% more total nitrogen than the landscape plants in 2008. Upcoming data for 2009 will provide a larger data set.

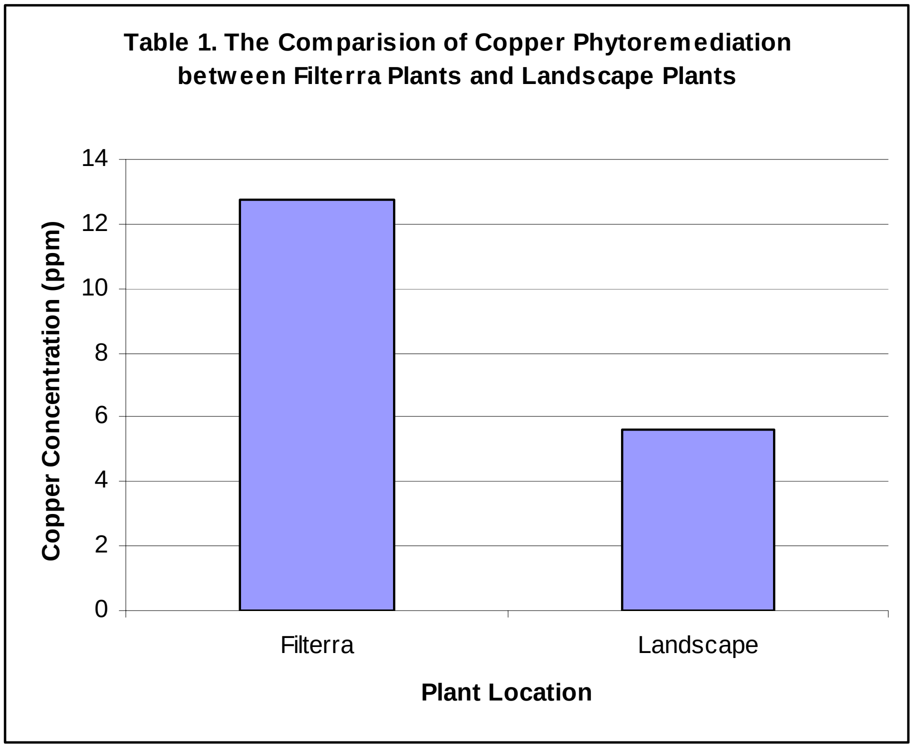


Table 1. The Comparision of Copper Phytoremediation between Filterra Plants and Landscape Plants
Copper Concentration (ppm)
14
12
10
8
6
4
2
0
Filterra
Landscape
Plant Location

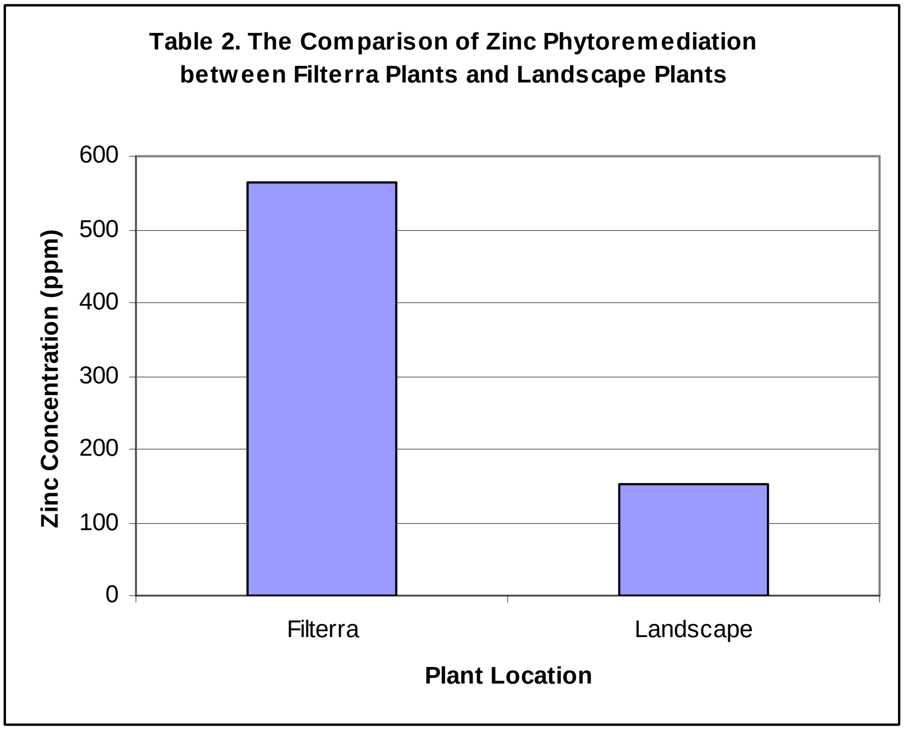
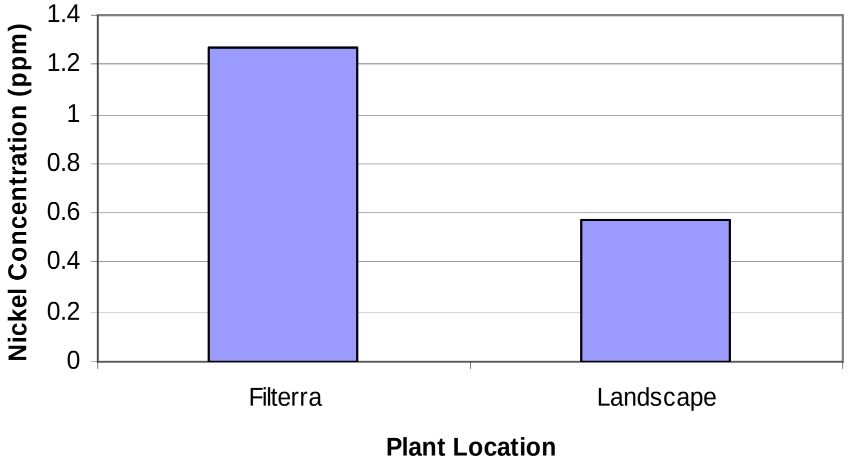


Table 2. The Comparison of Zinc Phytoremediation between Filterra Plants and Landscape Plants
Zinc Concentration (ppm)
600
500
400
300
200
100
0
Filterra
Landscape
Plant Location

Table 3. The Comparison of Nickel Phytoremediation between Filterra Plants and Landscape Plants



DISCUSSION

Identifying trees and shrubs that can be used for phytoremediation would increase the perceived and real value of landscape plants, and would be an additional marketing tool available to nurseries. Incorporation of these plants into streetscapes and landscapes, or nursery buffers, could improve water quality and the image of the green industry that is seen as a contributor to water pollution. Many of these plants might be appropriate to use not only in specific stormwater treatment systems such as Filterra®, but also in bioretention cells, riparian buffers, constructed wetlands and other landscape-based stormwater treatment features to increase the use of plants for phytoremediation. These hyperaccumulators could be available nationwide from nurseries and could thus be used by the green industry, governments, private businesses, non-profits, and communities.

It is hoped that once results are disseminated, nurseries will begin to produce effective plants and members of the landscape design and installation industries will begin to specify and install said plants. Future extensions of this study will evaluate additional tree and shrub species in future Filterra® installations. Several other commercial landscape species (and their cultivars), including the shrubs abelia (*Abelia* x *grandiflora*), inkberry (*Ilex glabra*), anise (*Illicium floridanum*), cherrylaurel (*Prunus laurocerasus*), Scarlet Curls willow (*Salix* x 'Scarlet Curls'), and vitex (*Vitex agnus-castus*), and the trees Amur maple (*Acer ginnala*), Little Gem magnolia (*Magnolia grandiflora* 'Little Gem'), and corkscrew willow (*Salix matsudana* 'Tortuosa'), have a size, configuration, and environmental tolerance that should make them good plants for Filterra® systems. Evaluation would follow the same protocol of testing them in both Filterra® systems and adjacent landscape sites at new installations. In selecting plants for hydroponic screening and landscape planting, choosing plants with fibrous root systems would allow for more adsorption sites for pollutant uptake.

Future investigations may look at protocols to include harvesting roots and shoots since different metals accumulate in different parts of the plant based on a study by Fritioff and Greger (2003). Plant heavy metal and nutrient concentrations may vary based on collection area due to different runoff concentrations, and may be due to uptake ability and uptake sites among the plants. Fritioff and Greger's study could not identify pH or organic matter content in sediments having an effect on metal uptake. The study did demonstrate that metals are available for plant uptake at a pH near 6.0.

High accumulation of metals in terrestrial and emergent plant roots could stabilize the soil and prevent leaching of heavy metals according to Fritioff and Greger. Terrestrial plants show good uptake of cadmium and zinc in the root system. Certain plant species have storage organs in their rhizomes that also store heavy metals, and thus have potential to be used as phytoremediators, especially in a percolation system for stormwater treatment.

The preliminary research is encouraging that the identification of specific plants for bioaccumulation of pollutants seems possible. Future research is still needed for advancing phytoremediation as a technology. This includes studying how to screen and harvest plants, choosing an assortment of plants for particular pollutants of concern, understanding mechanisms for nutrient and heavy metal removal, and ideal environments for maximum plant uptake.

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Back to Table of Contents

Poster Session

- **Contamination & Climate Change: Examining the Relationship Between Virginia's Hazardous Waste Sites & Public Health --** Emily Russell, *Environmental Stewardship Concepts* and Martha Ellen Wingfield, *Environmental Stewardship Concepts*
- **Adsorption of Fluorine on Limestone-derived Apatite: Equilibrium and Kinetics --** Cyprian Murutu, *Department of Chemical and Metallurgical Engineering, Tshwane University of Technology*
- **The Impact of Environmental Water Pollution on Pre-metamorphic Tadpole Development --** Cherelle J. Johnson, *Department of Biology, Norfolk State University* and Lawrence O. Garnett, *Department of Biology, Norfolk State University*
- **Bacterial Community Diversity and Metabolic Activity in the James River --** Catherine M. Luria, *Virginia Commonwealth University*
- **Perchlorate Concentrations in Commercially Available Sparklers and Post Burn Residues --** Jennifer L. Gundersen, *U.S. Environmental Protection Agency - Region 3*
- **Application of Molecular Techniques for Assessment of Marine Recreational Waters --** Corinne Audemard, *Department of Environmental and Aquatic Animal Health, VIMS, College of William and Mary*
- **Dye Tracing to Fay and Sempeles Springs in Winchester, Virginia --** Nathaniel C. Farrar, *Department of Environmental Science, University of Virginia*
- **Interim Measures of Water Quality Change: A Standardized Non-parametric Characterization --** Roger E. Stewart, *Virginia Department of Environmental Quality*
- **Using a GIS Approach to Analyze Blue-green Interactions --** Jennifer Ciminelli, *Center for Environmental Studies, Virginia Commonwealth University*
- **Using *Galdieria sulphuraria* Oxidative Enzymes as a Water Quality Biosensor --** Camellia M. Okpodu, *Department of Biology, Norfolk State University*
- **Saltwater Intrusion Effects on Soil Organic Carbon in Tidal Freshwater Wetland Soils --** Lindsey M. Koren, *Virginia Commonwealth University*
- **Plant Community and Soil Saturation Effects on the Structure and Function of Microbial Communities in an Emerging Freshwater Wetland --** Christine E. Prasse, *Virginia Commonwealth University*
- **Seasonal Dynamics of Microbial Communities in an Emergent Freshwater Marsh --** Amy Jenkins, *Virginia Commonwealth University*
- **Reedy Creek: A Prime Example of Urbanization's Detrimental Effects on Streams and Watersheds --** Tammy E. Parece, *Department of Geography, Virginia Tech*
- **Challenging Assumptions: Physical Contributions to Water Quality Variation in Stormwater Retention Ponds --** Melissa Montagna, *Keck Environmental Lab, College of William and Mary*
- **Effectiveness of Amendments in Reducing Nutrients and Mercury Release from Green Roofs --** Lan M. Tran, *Virginia Wesleyan College*
- **Impact of Heated Runoff from Parking Lots During Summer Storms on Stream and Wetland Temperatures --** Kalen Bauman, *Department of Civil and Environmental Engineering, Virginia Tech*

- **Stormwater Management: Discharge, Turbidity, and Nutrient Concentrations During Storm Events --** Robert S. Arthur, *Department of Civil and Environmental Engineering, University of Virginia* and Kate E. Abshire, *Department of Environmental Sciences, University of Virginia*
- **Validating Water Quality and Quantity Outcomes for an Innovative Stormwater-management Design --** Michael J. Downey, *Department of Environmental Sciences, University of Virginia* and Kate E. Abshire, *Department of Environmental Sciences, University of Virginia*
- **Space-efficient Enhancement of Phosphorus Removal for Urban Stormwater Practices Through Supplemental Wetland Filtration --** Shawn Rosenquist, *Department of Biological Systems Engineering, Virginia Tech*
- **Reevaluating Irreducible Concentration Limits Based on Filterra® System Performance Monitoring in Washington State --** Mindy Ruby, *Filterra Bioretention Systems*
- **Advanced Bioretention Media for Enhanced Bacteria Removal from Stormwater Runoff --** Mindy Ruby, *Filterra Bioretention Systems*
- **Filterra® Advanced Bioretention System: Discussion of the Benefits, Mechanisms, and Efficiencies --** Glen Payton, *Filterra Bioretention Systems*

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CONTAMINATION & CLIMATE CHANGE: EXAMINING THE RELATIONSHIP BETWEEN VIRGINIA'S HAZARDOUS WASTE SITES & PUBLIC HEALTH

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ABSTRACT

Climate change presents a myriad of challenges to the maintenance of human and ecological health in the Commonwealth of Virginia. The loss of coastal and inland wetlands, an increased frequency of extreme weather events and precipitation, as well as a rise in sea levels all threaten the state's water resources. We will focus specifically on the effect of climate change on chemically contaminated sites and what that will mean to our water supply. We examined the EPA and DEQ databases to investigate the relationship between hazardous waste sites and water bodies. In addition, we reviewed federal and state investigations on anticipated changes in extreme weather events for Virginia.

Two-thirds of Virginia's hazardous waste sites named to the National Priorities List are located near or immediately on bodies of water. In the event of extreme storm surges and increased sea level rise, this translates into the possible spread of chemicals into surface and ground waters, leading to long-term economic and environmental damage. Heavy rainfall can compromise the efficiency and efficacy of treatment plants, meaning that contamination is likely to spread to drinking water. Communities near military bases, such as Hampton Roads, with groundwater

contamination have been shown in studies to have a greater frequency of negative health effects such as cancer and developmental problems.

We conclude that the solution to these threats lies in prioritizing the remediation of hazardous waste sites. Preparation for severe storm events is also key, including storm surge prediction and securing or relocation of sites that contain these threats. By doing so, the water resources that are so dear to communities throughout Virginia will be protected in the face of our changing climate.

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ADSORPTION OF FLUORIDE ON LIMESTONE-DERIVED APATITE: EQUILIBRIUM AND KINETICS

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ABSTRACT

Fluoride in drinking water above permissible levels is responsible for human dental and skeletal fluorosis. Adsorptive based defluoridation is probably the most popular technique with several end-user applications. Consequently, the current study describes the fluoride removal potential of a novel sorbent, limestone-derived apatite from drinking water. The adsorbent was prepared by calcining limestone followed by reacting with orthophosphoric acid. Batch sorption studies were performed as a function of contact time, pH, initial fluoride concentration, particle size, temperature and adsorbent dose. Sorption of fluoride was found to be pH dependent with a maximum occurring in the pH range of 5-9. It was also observed that the material had a buffering effect on the same pH range. Meanwhile, the adsorption capacity was found to increase with temperature, depicting the endothermic nature of the adsorption process and decreases in adsorbent mass and particle size. The equilibrium data was well described by the conventional Langmuir isotherm, from which isotherm the maximum adsorption capacity was determined as 22.2 mg/g. From the kinetic perspective, the fluoride adsorptive reaction followed the pusedo-second order mechanism.

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THE IMPACT OF ENVIRONMENTAL WATER POLLUTION ON PRE-METAMORPHIC TADPOLE DEVELOPMENT

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ABSTRACT

Environmental water pollution has devastating effects on the development and vitality of marine organisms. The importance of this study is to investigate the influence of pharmaceutical and agricultural water pollutants acting as developmental disrupters of premorphogenic tadpoles. This research determines morphological disruptions in the development of marine species, frogs, *Rana sylvatica* and *Rana pipiens* exposed to an estrogen and nitrate polluted environment. A leading source of pharmaceutical water pollution is waste containing birth control pills, antidepressants and other compounds that are finding their way into the nation's water ways. A major source of agricultural water pollution is artificial fertilizers, pesticides and farmyard waste polluting water through cultivation runoff. Previous studies have examined the impact of estrogen and ammonium nitrate pollution on the developmental patterns of marine organisms. It is vital to understand the potential dangers of developmental disruptors on marine organisms caused by environmental pollutants.

This is a continuous study of the effects of environmental water pollution. *Rana pipiens* tadpoles were placed in a polluted ammonium nitrate environment and an unpolluted environment on April 19, 2009. A similar study was conducted April 18, 2008 in the same laboratory using estrogen as the pollutant. *Rana sylvatica* tadpoles were placed in an estrogen polluted water environment and an unpolluted environment. The aquatic environments were monitored daily and the developmental stages were recorded. The amount of beta estradiol and ammonium nitrate used in this study was based on the Environmental Protection Agency standards for human water consumption and toxicity reports for marine species. The effects of estrogen and ammonium nitrate water pollution were studied independently and the data was correlated in this investigation. This research determined ammonium nitrate and estrogen water pollution act as developmental disruptors of *Rana sylvatica* and *Rana pipiens* during the pre metamorphosis stages of tadpole to frog development. This research establishes the effects of pharmaceutical and agricultural water pollution as developmental disruptors on the metamorphosis of amphibians.

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BACTERIAL COMMUNITY DIVERSITY AND METABOLIC ACTIVITY IN THE JAMES RIVER

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KEY WORDS: bacteria, phytoplankton, river and estuaries, eutophication

ABSTRACT

Bacterial communities are diverse assemblages comprised of thousands of species that differ in their physiological capacities, levels of metabolic activity and preferred growing conditions. Because they play an essential role in material and energy cycles, a deeper understanding of these communities, and particularly of how they function, may provide valuable insights into ecosystem processes. This project aims to describe how bacterial communities in the James River respond to key environmental gradients including light, nutrient, and dissolved organic carbon (DOC) availability. Toward this goal, water samples were collected on a monthly basis from the tidal freshwater segment of the James River (between Richmond and Hopewell). Measurement parameters included nutrients, DOC, phytoplankton biomass (as CHLa) and production, community respiration and bacterial abundance and metabolic activity. Experiments were performed wherein water from James River was incubated under varying light, nutrient and DOC (glucose) treatments: Preliminary results show a strong coupling between algal and bacterial activity with enhanced light and nutrient availability leading to increased bacterial abundance and metabolism. The conclusions from this research will enhance our understanding of factors that regulate bacterial diversity and function in river and estuarine environments.

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PERCHLORATE CONCENTRATIONS IN COMMERCIALLY AVAILABLE SPARKLERS AND POST BURN RESIDUES

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ABSTRACT

Perchlorate (ClO_4^-) is one of the most commonly used oxidizers in sparkler manufacturing where its use is not regulated, except in shipping. A review of labeling on several varieties of sparklers revealed that some claimed to contain no perchlorates while others made no statement regarding perchlorate content. Perchlorate is believed to interfere with thyroid hormone

function. It is highly water soluble and mobile in groundwater. Most occurrences in the environment are from rocket fuel, fireworks, road flares and explosives. While not a regulated pollutant, EPA recently issued an interim health advisory level of 15 ppb for drinking water.

Given the widespread use of sparklers throughout the country, and the solubility and mobility of ClO4-, there is a potential for sparklers to be a source of ClO4- contamination in groundwater. In this study, burned and unburned sparklers from various sources were analyzed for ClO4- by HPLC/MS (EPA Method 6850). Concentrations varied from non-detectable to several mg in unburned sparklers. Perchlorate concentrations in the residues from burned, perchlorate-containing sparklers were much lower than the corresponding unburned sparkler, but ClO4- was never completely consumed. In this sample set, product labeling was not an accurate indicator of perchlorate content.

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APPLICATION OF MOLECULAR TECHNIQUES FOR ASSESSMENT OF MARINE RECREATIONAL WATERS

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KEY WORDS: rapid molecular methods, fecal indicators, marine recreational waters

ABSTRACT

A variety of cultural and molecular-based methods for detection and quantification of selected indicators of enteric pollution were applied to samples collected at Fairview Beach, a recreational bathing beach on the Potomac River in Virginia. Currently, assessment of health risk for closure of marine bathing waters is based on the 1986 USEPA enterococcus criterion that uses a 24 hour culture technique. We developed, evaluated and validated molecular-based methods for rapid detection and quantification of the enterococci that could provide more timely information for managers. Evaluation of different DNA extraction methods for enterococci-spiked samples revealed maximum recovery using a bead beating method described by Haugland *et al*. (2005). Using genus-specific enterococcus primers, spiked water samples yielded a sensitivity of 100 enterococci 100 ml^{-1}. qPCR results of water samples tracked closely with enterococci enumerated by both IDEXX and membrane filtration on mEI agar. Shallow bathing area sediments (0.25-0.5m) analyzed using a cultural method were determined not to be potential reservoirs of enterococci at the study site. The enterococcal *esp* gene, proposed as a specific indicator of human fecal pollution, was detected in mEI enrichments from beach waters as well as in dog feces and stormwater samples. In addition to enterococci, beach samples were also tested for male-specific FRNA coliphage by culture and qPCR using genogroup-specific primers. Although FRNA coliphage densities were below the detection limit of the qPCR method (>1000 coliphages per sample), the primers were used to genotype FRNA coliphages recovered by

culture and results supported the presence of human fecal inputs to beach waters. Our results demonstrate the potential use of the enterococcal qPCR assay in the rapid assessment of beach water quality and discrimination of human fecal contributions using phage genotyping.

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DYE TRACING TO FAY AND SEMPELES SPRINGS IN WINCHESTER, VIRGINIA

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KEY WORDS: spring, dye trace, groundwater, Winchester

ABSTRACT

Fay Spring and Sempeles Spring are located within the karst of the Great Valley physiographic province in northern Virginia. In this region, surface water and groundwater interactions are complex and largely influenced by local geologic structures. Fay Spring is owned by the city of Winchester; although the spring was once used as a water supply for the city, it is no longer within the supply line. The springs are 300 m apart and lie along a common fault. A quantitative dye trace was conducted from a sink point along Sunnyside Run located approximately 1 km west of Fay and Sempeles Springs in an attempt to understand the degree of impact of sinking stormwater runoff on these springs.

Two kg of Rhodamine WT dye was injected on June 30, 2009 at 4 pm. The dye breakthrough occurred at both springs less than 3 days after injection. The dye was more concentrated at Sempeles Spring than at Fay Spring, reaching a peak value of 0.35 ppb at Sempeles compared to 0.24 ppb at Fay. An estimate of mass recovery indicated approximately 34 g of the dye was recovered at the two springs within the first two weeks, or 1.7% of the amount injected. A lesser amount of dye was also positively recovered within Redbud Run, a surface stream that receives groundwater discharge, however mass recovery estimation is not possible. Subsequent rainfall events caused peaks in dye concentrations more than 2 weeks after injection, indicating that dye is retained within more stagnant zones of the groundwater system.

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INTERIM MEASURES OF WATER QUALITY CHANGE: A STANDARDIZED NON PARAMETRIC CHARACTERIZATION

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ABSTRACT

A novel methodology, "interim measures" has been developed to track annual changes in key water quality parameters. Using the interim measures approach we are able to evaluate water quality trends over broad geographic regions which may include data from numerous collecting organizations, projects, and testing laboratories. Furthermore we will present a comparison between our interim measures results and our formal Kendall test for trends. We have introduced a scoring system to the interim measures similar to an index of biological integrity (IBI) to summarize each annual water quality distribution. Individual observed values in the most desirable water quality quartile receive a score of 5, those in the least desirable quartile receive a score of 1, and values in the intermediate (inter quartile range - moderate) water quality class receive a score of three. The Integrated Water Quality score (IWQ score) for the year consists of the average of the individual scores for that year. A linear regression line is included only to indicate the general trend. Any effort to estimate the statistical significance of the regression line, or to estimate confidence intervals, would be inappropriate since it is based on integrated, non-parametric ordinal scale measures.

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USING A GIS APPROACH TO ANALYZE BLUE-GREEN INTERACTIONS.

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KEY WORDS: Geographic Informations Systems (GIS), INSTAR, watershed integrity, blue-green interaction, Virginia

ABSTRACT

GIS (Geographic Information Systems) and statistical analyses were used to determine the presence of blue-green relationships by analyzing terrestrial and aquatic models at different spatial scales. The VA Department of Conservation Division of Natural Heritage, in collaboration with VCU Center for Environmental Studies, VA Department of Forestry and VA DEQ Coastal Zone Management Program developed a geospatial model of important terrestrial

areas that contribute to watershed integrity as part of the Virginia Conservation Lands Needs Assessment, an approach for mapping green infrastructure in Virginia. VCU Center for Environmental Studies, in collaboration with the VA Department of Conservation and Recreation and VA DEQ Coastal Zone Management Program have developed a dynamic and interactive mapping and data visualization application called INSTAR ***(IN**teractive **ST**ream **A**ssessment **R**esource*). INSTAR allows users to access and manipulate a comprehensive (and growing) database representing over 2,000 aquatic (stream and river) collections statewide. Data represent fish and macroinvertebrate assemblages, instream habitat, and stream health assessment, based on integrative, multimetric indices at the watershed scale and a stream reach scale and serves as the blue infrastructure component of the study. The watershed integrity model and INSTAR data were analyzed to assess if "blue-green" relationships could be determined using GIS techniques; and, the limitations associated with the spatial scale of the approach.

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USING *GALDIERIA SULPHURARIA* OXIDATIVE ENZYMES AS A WATER QUALITY BIOSENSOR

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KEY WORDS: water quality, algae, antioxidants, biosensors

ABSTRACT

Galdieria sulphuraria, a thermoacidophile red alga, is fast becoming a model system for understanding the process of eukaryotic organelle genesis and evolution. Its bio-complexity makes it a preferred model that can be studied from a number of perspectives, which could provide a better understanding of the genetics and biochemistry of eukaryotic organisms.

G. sulphuraria can survive at temperatures above 50^{o}C and very low pH's (less than 2) – conditions under which most eukaryotic cellular proteins become denatured. *Galdieria* can grow in complete darkness on a wide variety of organic compounds, including sorbitol, glycerol and mannitol. These polyols have to be converted to sugars or sugar phosphate in order to be useful to metabolism. *G. sulphuraria* grows on most of these substrates by having very active hydrogenases that convert these intermediates to highly active and useful biologically active metabolites. The high adaptability of this organism to extreme environments (*i.e*., elevated temperature and extremes with pH) that causes oxidative stress makes it an interesting organism to study the regulation of the active oxygen species (AOS) and antioxidant scavenging systems.

G. sulphuraria has been shown to have enzymes and products of the inositol signaling pathway, which change after stress. Although our long-term objective is to understand the antioxidant mechanism in this alga, because high concentrations of AOS generated in oxidative burst have direct cytotoxic effects in defense mechanisms, we are interested to investigate what role *G. sulphuraria* oxidative enzymes can be us biosensor to detect contaminants in the environment, specifically in aquatic systems.

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SALTWATER INTRUSION EFFECTS ON SOIL ORGANIC CARBON IN TIDAL FRESHWATER WETLAND SOILS

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KEY WORDS: tidal freshwater wetlands, soil organic carbon, saltwater intrusion, carbon lability

ABSTRACT

Tidal freshwater wetlands (TFWs) are unique ecosystems that bridge the gap between terrestrial and aquatic ecosystems and are important in the sequestration of soil organic carbon. With the ever changing global climate, TFWs are left vulnerable to downstream effects of rising sea level and saltwater intrusion due to increase in precipitation and flooding. These changes often act over large spatial scales, but the scale can vary over local and regional scales resulting in significant impacts. This multidisciplinary study assessed the amount, lability and optical characteristics of desorbed organic carbon in tidal freshwater wetland soils from the Waccamaw River, South Carolina ("organic" soils, 50-65% organic content) and Pamunkey River, Virginia, ("mineral" soils, 13% organic content). Soils from each TFW were extracted at salinities 0-35 and the dissolved organic carbon (DOC) concentration, carbon lability, and excitation-emission fluorescence spectroscopic signatures (EEM), of the leachates were measured. Based on the resulting parameters, the soil desorption shows an increase in the amount, rate and percentage of DOC in the organic soil in comparison to the mineral soil. These measurements also indicate as salinity increases, there is a positive correlation in respect to the amount, rate and percentage of DOC. EEM fluorescence spectra of the DOC was used to characterize the organic carbon into

autochthonous and allochthonous components. By understanding how saltwater intrusion affects desorption and lability of soil organic carbon, it can demonstrate how climate change will play on regional carbon storage and the global carbon cycle.

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PLANT COMMUNITY AND SOIL SATURATION EFFECTS ON THE STRUCTURE AND FUNCTION OF MICROBIAL COMMUNITES IN AN EMERGING FRESHWATER WETLAND

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KEY WORDS: microbial/bacterial communities, freshwater wetlands, community composition, biogeochemical cycling

ABSTRACT

Wetlands are ecologically important habitats that are responsible for a variety of functions including cleansing polluted water, ameliorating floods, and recharging groundwater aquifers. More notably, the characteristic wetting/drying cycles of wetlands sustain a diverse population of microorganisms responsible for mobilizing and recycling nutrients. This project aims to describe how plant communities and soil saturation contribute to the maintenance and selection of bacterial function and diversity. To achieve this goal, soil cores were collected from two treatments (vegetated and de-vegetated plots) within three different hydrological regimes. Data collected from the early growing season has confirmed differences in soil physiochemical properties (pH, redox, organic matter content, C:N), microbial community function (assessed as extracellular enzyme activity), and microbial community composition (T-RFLP) between the three hydrological regimes and soil depth profiles. As of yet, there is little evidence that the presence/absence of vegetation is significant; however it may take several months for the effects of manipulation to develop in the treatment plots. As we collect further into the growing season, we expect to see extreme differences in microbial community composition and function between the two vegetation treatments since soil saturation, organic matter content, and oxygen availability are all influenced by the presence/absence of plants. The conclusions presented from this research will enhance our understanding of factors that regulate bacterial diversity, function, and soil quality in dynamic environments.

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SEASONAL DYNAMICS OF MICROBIAL COMMUNITIES IN AN EMERGENT FRESHWATER MARSH

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KEY WORDS: freshwater marsh, microbial communities, temporal patterns

ABSTRACT

Sediment microbial communities are important contributors to biogeochemical processes in freshwater marshes, though relatively little research has been conducted to determine the environmental parameters that constrain the distribution and function of these organisms. This long-term study examined temporal patterns in microbial community structure, function, and soil environment in a freshwater marsh along the James River (USA), and considered the effects of sampling depth, moisture availability, and plant community composition and biomass on the bacterial communities. Strong seasonal patterns were observed for both the environmental parameters (soil pH, redox, and moisture) and the wetland vegetation, and both types of data correlated with successional changes in the soil microbial community. However, depending on sampling depth and location within the marsh, this relationship differed. For example, at the wettest site, microbial community composition was strongly correlated to changes in the diversity of the aboveground vegetation, while the microbial community at the drier sites seems to vary primarily in response to soil moisture and redox status. This study reinforces the importance of understanding temporal patterns and environmental controls on microbial community structure and function, which are essential to preservation of overall ecosystem function in marsh habitats.

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REEDY CREEK: A PRIME EXAMPLE OF URBANIZATION'S DETRIMENTAL EFFECTS ON STREAMS AND WATERSHEDS

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KEY WORDS: urbanization, sedimentation, improvement projects, Reedy Creek

ABSTRACT

The Reedy Creek watershed is a watershed located entirely within the political boundaries of the City of Richmond, Virginia. From its headwaters, the stream flows 3.68 miles through residential areas, commercial areas, Forest Hill Park and then the James River Park where it empties into the James River. The James River Watershed is one of the major watersheds composing the Chesapeake Bay Watershed and, as such urbanization's influences on Reedy Creek affect the Chesapeake Bay Watershed.

Reedy Creek and its watershed are prime examples of urbanization's detrimental effects on streams and watersheds. These effects include sedimentation, channel degradation, stream bank erosion, pollution and changing physical parameters. Reedy Creek was placed on the TMDL list in 2002 due to high levels of *E. coli*. Macro-invertebrates present in the stream represent pollution tolerant species. The City has undertaken sixteen separate improvement projects to correct flooding issues in various parts of the watershed. Reedy Creek continues to degrade. This poster presentation will demonstrate urbanization's effects on Reedy Creek and its watershed.

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CHALLENGING ASSUMPTION: PHYSICAL CONTRIBUTIONS TO WATER QUALITY VARIATION IN STORMWATER RETENTION PONDS

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KEY WORDS: water quality, stormwater retention pond, nutrients, BMP

ABSTRACT

Retention ponds are widely used as management structures (BMPs) to control the volume of water discharged during storms, but they may also retain sediment and nutrients draining into larger bodies of water. This "water quality enhancement" function is based largely on the assumption that greater retention time leads to better water quality, but no research to date has determined which, if any, physical characteristics of these ponds contribute to the quality of water released. To address this information gap, we sampled and measured water quality in 96 stormwater retention ponds in James City County, VA. Using ArcGIS software, the James City County code of each BMP was identified and available physical data on the ponds and surrounding watersheds were extracted; additional data are being generated from direct measurements. Once complete, we will run separate factor analyses on water quality and physical data to generate eigenvalues and then discern how variation in water quality correlates with variation in physical characteristics. Ultimately, we hope the relationships we identify can then be used to help developers, planners, and managers design stormwater control structures that also enhance water quality.

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EFFECTIVENESS OF AMENDMENTS IN REDUCING NUTRIENTS AND MERCURY RELEASE FROM GREEN ROOFS

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KEY WORDS: green roof, nitrogen, phosphorus, mercury

ABSTRACT

Vegetated green roofs are effective in reducing storm water runoff. However, recent literature and experiments at Virginia Wesleyan College have found that green roofs leach higher concentrations of nutrients and mercury than typical gravel roofs due to added fertilizer or compost in the growing media, which can impact eutrophication and human health. Preliminary laboratory studies indicated that alum and Ultra-Phos Filter showed promise at reducing nutrient runoff. Fifteen experimental green roof plots and two real green roofs were used to evaluate 1) the difference in nutrient and mercury runoff from green versus traditional gravel roofs, and 2) the effectiveness of alum and Ultra-Phos Filter in reducing nutrients and mercury in the runoff. The experimental plots were divided among the following treatments: standard green roof, green roof plus alum, green roof plus Ultra-Phos Filter, and standard gravel roof. A dormitory roof was divided into four sections: green with slow release fertilizer, green with no fertilizer, green with fertilizer and Ultra-Phos Filter, and gravel. The roof of a commercial building in downtown Portsmouth, VA, was divided into two sections: green with Ultra-Phos Filter and gravel. Two to three rainstorms were sampled for each of the roof types. These initial results indicate that the green roofs continued to leach higher concentrations of nutrients than the gravel roofs, even three years after installation. The mean concentrations of nitrogen and phosphorus were not significantly lower in the treatments with added alum or Ultra-Phos Filter. Plans for ongoing studies to confirm these results will be discussed.

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IMPACT OF HEATED RUNOFF FROM PARKING LOTS DURING SUMMER STORMS ON STREAM AND WETLAND TEMPERATURES

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ABSTRACT

Runoff from hot parking lots during summer thunderstorms injects pulses of hot water into receiving water bodies. If the magnitude of these thermal perturbations is sufficiently large,

aquatic organisms downstream can be impacted. Such concerns are heightened because aquatic organisms are particularly sensitive above their thermal optima, and climate change will likely both raise the temperature and reduce the magnitude of baseflow in aquatic systems. While previous studies have determined that the impact of summer storm thermal pulses on stream temperatures can be significant, none have fully resolved the spatial extent and magnitude of these impacts in space or time in receiving streams nor evaluated impacts in other types of water bodies (*e.g.*, wetlands). Here we present preliminary temperature timeseries data collected using arrays of wireless temperature sensors in two example waterbodies (a stream with directional flow and a wetland with minimal current) immediately downstream of the outlet of storm sewers draining large nearby parking lots on the Virginia Tech campus in Blacksburg, VA. These data are useful to quantify the magnitude, duration, and evolution of thermal perturbations from individual storms and how these vary with current velocity, weather conditions, and time of year. We will compare the magnitude, extent and frequency of measured perturbations in the receiving water body to thermal tolerance data for both representative and sensitive species to evaluate the expected ecological impacts. We also outline future research planned on this topic.

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STORMWATER MANAGEMENT: DISCHARGE, TURBIDITY, AND NUTRIENT CONCENTRATIONS DURING STORM EVENTS

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KEY WORDS: stormwater, monitoring, sampling, turbidity, nutrients

ABSTRACT

The dynamic interaction of precipitation, runoff, streamflow, and Pond residence determines the outcome of the stormwater management structures designed and constructed at University of Virginia in 2004. Time-course sampling during and following storms in which 0.2-1.0 inches of rain were received over the course of several hours determined discharge, turbidity, and nutrient concentrations at locations (1) upstream of the engineered channel, (2) at the end of the vegetated, sinuous channel with reconstructed floodplain, and (3) at the outlet of the Pond. A sharp peak in discharge, turbidity, and phosphate upstream of the stormwater-management system occurs with every rainfall. Peak storm turbidity can reach 800 NTU. High discharge is

maintained, but turbidity drops quickly during flow along the vegetated channel, so that water entering the Pond is rarely greater than 50 NTU. The Pond acts to dampen the flood peak, and retention time is adequate to reduce the turbidity to values of 5-8 NTU. Approximately 2 feet of loose sediment has already accumulated on the bottom of the 6-foot deep forebay of the Pond. Upstream phosphate levels reach 3 mg/L at peak turbidity and range 0.05-0.1 mg/L at the Pond outfall. Upstream nitrate concentrations are 0.4-0.6 mg/L as N, and the Pond outfall is commonly 0.2-0.3 mg/L as N. The decrease in phosphate levels mirrors the turbidity decrease, but the nitrate concentrations are lowered to a lesser degree. The greatest water quality improvement is seen in the turbidity, and distribution on reconstructed floodplain and deposition in the Pond are critical factors in determining what is passed further downstream.

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VALIDATING WATER QUALITY AND QUANTITY OUTCOMES FOR AN INNOVATIVE STORMWATER-MANAGEMENT DESIGN

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KEY WORDS: stormwater, design, daylighted, engineered, assessment

ABSTRACT

University of Virginia is set at the headwaters of Meadow Creek, an impaired tributary of the Rivanna River. Urban development provides significant coverage by impervious surfaces in this small watershed, resulting in high peak runoff with elevated turbidity and nutrient content. In 2004, 1100 feet of Meadow Creek were daylighted into an engineered channel, reconstructed flood plain, and detention basin (Dell Pond). Assessment of stormwater quantity and quality provided data to determine regulatory compliance and to validate the success of the design. Measurements were made (1) upstream of the engineered channel, (2) at the end of the vegetated, sinuous channel, (3) at the outlet of the Pond, (4) at the entrance to the new John Paul Jones Arena, and (5) at the exit from University property. Large reductions in turbidity and phosphate concentration are achieved as water flows along the vegetated channel and is detained in the Dell Pond. The Pond further acts to dampen peak discharge, and turbidity is reduced to

nearly baseline levels by retention in the Pond. The decrease in phosphate levels mirrors the turbidity decrease, but retention in the Pond is too short to significantly reduce the nitrate concentrations. The outlet of the Pond is water of good quality, but further inputs of stormwater occur downstream. The final construction of the stormwater-management features at the Arena did not follow the original design. The result is a missed opportunity to positively influence stormwater quality and quantity derived from large expanses of parking areas and arena roof at the downstream terminus of University property.

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SPACE-EFFICIENT ENHANCEMENT OF PHOSPHORUS REMOVAL FOR URBAN STORMWATER PRACTICES THROUGH SUPPLEMENTAL WETLAND FILTRATION

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ABSTRACT

Anthropogenic eutrophication of surface waters caused by excess nutrient loads is a major environmental and economic problem in the US. Phosphorous, typically the limiting nutrient for algal growth in freshwater, is often targeted to prevent eutrophication. While agricultural sources are often a primary target for phosphorus reduction, urban landscapes are also a major contributor of phosphorus and must be addressed. Constructed wetlands (CW) have demonstrated significant promise in reducing phosphorous in stormwater, but challenges exist for implementing traditional CW in urban areas, such as high land value and flashy storm events. The objective of this research is to investigate a novel approach to CW filtration in urban stormwater, which addresses the specific constraints of the urban setting. Land use and associated cost is decreased by regularly rejuvenating the removal capacity of a much smaller CW. Limitations associated with flashy storm events are overcome by pairing the CW with existing retention ponds, thereby utilizing existing infrastructure and further decreasing cost. This paired treatment strategy allows the CW to be optimized for removing dissolved phosphorus. Bench-scale studies have provided promising results, leading to validation at field-scale. Field-scale evaluation for the filtration and rejuvenation processes includes several 30L filters receiving source water from a eutrophic retention pond. The filters are scaled to limit sorption sites and accelerate the degradation in removal performance, allowing a much shorter study period. Results presented include the quantification under field conditions of filter performance, performance degradation, and the effectiveness of the rejuvenation process in regaining original removal performance.

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REEVALUATING IRREDUCIBLE CONCENTRATION LIMITS BASED ON FILTERRA® SYSTEM PERFORMANCE MONITORING IN WASHINGTON STATE

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KEY WORDS: bioretention, monitoring, water quality, performance, stormwater

ABSTRACT

A Technology Evaluation Report (TER) for the Filterra® Bioretention System was submitted to the Washington State Department of Ecology for approval through the Technology Assessment Protocol – Ecology (TAPE) in the summer of 2009. The Filterra® system was tested at the Port of Tacoma in Tacoma, Washington from May 2008 through May 2009. The Filterra® system is a self-contained stormwater bioretention treatment system manufactured by Americast, Inc. The Filterra® system is a flow-through stormwater treatment device intended for removal of suspended sediments, nutrients, heavy metals, and oil & grease from stormwater flows within small-scale catchments such as parking lots and streetscapes. During the 2008-2009 monitoring period, a total of 27 storm events were sampled to characterize the water quality treatment performance of two Filterra® test systems at the Port of Tacoma.

During the 2008-2009 monitoring period, the Filterra® test systems at the Port of Tacoma demonstrated significant reductions in total suspended solids (TSS), dissolved zinc, dissolved copper, and total petroleum hydrocarbons (TPH). TSS removal ranged from 79 to 90 percent for influent TSS concentrations 20 milligrams per liter (mg/L) or greater. The irreducible TSS concentration is commonly considered to be 20-40 mg/L TSS; however, the sampling conducted at the Port of Tacoma demonstrated that TSS reduction beyond this threshold are possible with effluent concentrations from the monitored systems ranging from 2.0 to 7.8 mg/L. This presentation will demonstrate how the Filterra® Bioretention System pushes the limit of typical stormwater effluent irreducible concentrations and raises the bar for stormwater treatment system performance.

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ADVANCED BIORETENTION MEDIA FOR ENHANCED BACTERIA REMOVAL FROM STORMWATER RUNOFF

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KEY WORDS: bioretention, bacteria, stormwater, pollutant removal

ABSTRACT

Bioretention filters stormwater runoff through a terrestrial aerobic plant / soil / microbe complex to remove pollutants through a variety of physical, chemical and biological processes. The goal of Filterra®, division of Americast Inc., is to advance and optimize bioretention media through the use of bioretention's physical, chemical and biological pollutant removal mechanisms.

With the growing concern about bacterial impairment of recreational waters associated with stormwater runoff, extensive laboratory and field studies were conducted by Filterra®, to determine an optimum blend for bacteria removal. The Filterra® bioretention BMP blend is currently designed to utilize pollutant mechanisms to remove typical stormwater pollutants such as TSS, phosphorus, nitrogen and heavy metals. Filterra® has developed a specialized treatment media to remove fecal coliform and other pathogens from urban stormwater runoff. This new media blend has been trade marked Bacterra.

Laboratory tests have shown bacteria removal rates between 77% and 99%, with field results showing removal between 93% and 99%. It is believed that the media goes through a maturation process where it develops a complex microbiological ecosystem that enhances predation, capture and destruction of fecal coliform. Physical, chemical and biological processes are all believed to contribute to the removal process, but sorption is believed to be the primary removal mechanism.

This study demonstrates that a high flow through rate can achieve high bacteria removal efficiencies. This presentation will summarize the history and advancements in bioretention and the research effort and findings of Filterra® in the development of their Bacterra™ high flow bioretention media treatment technology.

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FILTERRA® ADVANCED BIORETENTION SYSTEM: DISCUSSION OF THE BENEFITS, MECHANISMS AND EFFICIENCIES

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KEY WORDS: bioretention, low impact development, stormwater, water quality

ABSTRACT

Filterra® represents the latest advancement in bioretention technology for urban stormwater runoff treatment. Filterra's® bioretention plant / soil / microbe treatment complex utilizes physical, chemical and biological pollutant mechanisms to remove nutrients, heavy metals, TSS, bacteria and other constituents found in urban runoff. It is essentially "bioretention in a box" combining a high flow rate filter media, with an attractive tree or shrub, in a concrete container. Filterra® also provides many added values such as enhanced aesthetics, improved habitat, and easy safety inspection. Filterra can be designed as a filter and / or to infiltrate / recharge runoff and can be used for any type of develop (new or retrofit applications) in any soil conditions to achieve multiple stormwater management goals. Maintenance is easy, safe and the first year is free.

Filterra's® high pollutant removal efficiency is primarily due the multiple treatment systems inherent in a plant/soil/media filter system. This presentation will outline the wide array of pollutant removal mechanisms, design strategy and benefits provided by Filterra® that allow it to perform and operate in such an exceptional manner.