Operationalizing Scale in Watershed-based Stormwater Management

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Abstract

Watershed-based stormwater management (WSM) has been proposed as more effective for stormwater management than traditional methods of controlling stormwater, which are carried out based on jurisdictional lines at the parcel-scale. Because WSM considers the watershed as a total unit, this method is considered to be more effective in reducing problems associated with stormwater management including environmental degradation and flooding. However, larger watersheds encompass smaller watersheds, and therefore WSM can be implemented at a wide range of scales. There has been little research on what scale is most appropriate, and more specifically, only a modest amount of work has taken stakeholder opinion into account.

The specific objectives of this study are to determine: 1) if watershed scale is an important factor in WSM, 2) whether stakeholder opinion has an effect on the appropriate scale used in WSM, and 3) what scale is most appropriate for WSM, if scale is an important factor. To meet these objectives, we delineated sub-watersheds within a watershed in southwestern Virginia, surveyed stakeholders within the watershed on their opinions of stormwater management methods, and compared the results at both watershed scales using statistical tests and decisions support software. The results of this study have important implications for geographic scale in WSM as well as the use of qualitative data in determining appropriate geographic scale in matters of implementation in the field of planning.

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Attribution

Dr. Korine Kolivras was my committee chair and academic advisor for my thesis. She provided valuable guidance in carrying out the project, from helping me understand the basics of the research process to aiding me in the development of the survey questionnaire to guiding me through the writing process. Her background in geographic research and the survey process was vital to this project.

Dr. Stephen Prisley was a member of my thesis committee. His experience in physical geography, and specifically geographic information systems was vital in my initial collection of data and sub-watershed delineations.

Peter Sforza was a member of my thesis committee. His background in geographic information technology, web design, and the integration of the two fields was very important in aiding me to develop the website and online stakeholder survey.

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1. Introduction

1.1. Background

Watersheds are the earth's natural method for managing stormwater. According to the United States Environmental Protection Agency (EPA, 2003), a watershed is a geographical area where all water, or runoff, drains to the same body of water. The earth naturally removes stormwater runoff at a velocity and volume that is sustainable to the surrounding ecology. When humans began to develop land, it became necessary to deal with stormwater runoff, which became a growing issue as land was graded and developed, and impervious cover eventually came into use. Thus, the practice of stormwater management was born. Traditionally, stormwater management plans in the United States are based on property lines and minimizing short-term costs. However, as development amplifies, traditional stormwater control methods have an increasingly adverse effect on the surrounding environment (Chocat et al. 2001; NRC, 2008; Roy et al. 2008). Geographic factors, such as topography, have often been seen as constraints rather than opportunities, and traditional methods tend to favor quick removal of runoff over environmental protection. Traditional stormwater controls are typically pipes or swales that drain runoff into nearby streams as quickly as possible, which can cause pollution downstream, decreased groundwater regeneration, and if overrun, increased flooding. (NRC, 2008)

Now, traditional stormwater controls are often blamed for major environmental issues such as increasing water scarcity, environmental degradation, and flooding in urban and urbanizing areas. In attempts to mitigate these problems, local governments have implemented stormwater management plans as development expands in urban areas.

However, they often fail due to the parcel-level scale at which they are implemented as traditional stormwater controls become ineffective when overwhelmed during storm events. (Chocat et al., 2001; NRC, 2008; Roy et al., 2008). As researchers have become increasingly aware of the negative effects of traditional stormwater methods, new research recommends using the watershed as a model for future stormwater management (Chocat, 2001; EPA, 2003; Wu et al. 2006; NRC, 2008). Watershed-based stormwater management (WSM) has been put forth as a method to mitigate problems associated with traditional stormwater management methods (Chocat et al. 2001; NRC, 2008; Roy et al. 2008). This new approach takes geographic features, such as topography, slope, and land use into account at the watershed-scale to plan stormwater management, as opposed to planning stormwater controls with focus only at the property-scale.

WSM is effective because planning is carried out based on the watershed as a total unit (ASCE, 1998; EPA, 2003; Zhen, 2004). WSM uses the natural topography of the watershed to select and place stormwater controls that redirect runoff while providing environmental protection. Planning stormwater management according to the natural topography of the land allows stormwater runoff and the actual stormwater controls to have less impact on the natural environment because less soil and vegetation are displaced. This is possible because most stormwater controls used in WSM reduce the volume and velocity of runoff while fitting into the natural topography of the land, effectively causing runoff to have less impact on the environment and to be less likely to cause urban flooding. Stormwater controls often utilized in WSM include measures such as bio-retention, vegetated buffers and swales, green roofs, sand filters, and other sustainable controls.

1.2 Problem Statement

WSM offers improvements to the field of stormwater management, however research on the implementation of WSM has been fairly limited. One specific topic that could benefit from further study, addressed through the research presented here, is related to the appropriate implementation scale of WSM. Smaller watersheds are encompassed by larger watersheds, which are encompassed by even larger watersheds, so there are wide range of scales at which WSM could possibly be implemented. So, what scale is best? Working at a macro- scale, such as the Chesapeake Bay watershed, would be overwhelming since the main output of a WSM program is implementation of stormwater controls on a more local level. Important details could be missed at this scale. However, working at a micro-scale, such as the watershed of a temporary stream that results from a heavy storm event, would be extremely time-consuming and overwhelmingly tedious. It could result in missing effects of stormwater controls on the overall topography of the land.

On top of the geographic factors that play into stormwater management, people living on the land can be affected by the physical existence and effectiveness of stormwater controls. Given that people's opinions change over space based on individual and population characteristics, the scale at which WSM should be implemented could be affected as different people may have differing opinions as to what they prefer when it comes to stormwater management. For example, a household or group of households may want the highest level of environmental protection available with their stormwater management, which can be expensive, whereas another group of households may desire something more affordable, and another group just wants the stormwater control to be aesthetically pleasing. These preferences should be taken into account when designing WSM plans and could affect the scale at which a WSM plan is implemented.

Research often assumes a scale based on what is convenient for the study, as discussed in Chapter 2, but there is clearly debate about how to operationalize scale in WSM (NRC, 2008; Randhir and Tsvetkova, 2008; Roy et al. 2008), specifically whether a watershed can be too large or too small for this approach, and how people's opinions affect that. Scale is an important concept to understand in WSM, because the size of the watershed used can have a direct effect on two things: the level of environmental protection and runoff capture that the WSM plan can provide, both of which can have an effect on those using the watershed.

This study examines the importance of scale in WSM using a case study watershed, the Tom's Creek watershed in Montgomery County, Virginia. In the 1980s, the US Geological Survey (USGS) divided the entire United States into successively smaller hydrologic units (watersheds) and assigned each one a hydrologic unit code (HUC) based on its size (NRCS 2007). As this study is one of the first of its kind, this analysis of scale starts small, using a watershed in the smallest level of HUC and several sub-watersheds inside it. Should this research be non-conclusive, recommendations would be given to compare to the next larger HUC size to better determine appropriate scale. In this study's examination of scale, environmental factors, such as soil, topography, and land use, as well as stakeholder opinions were taken into consideration.

This research asks the question: what scale of watershed is appropriate for WSM in order to protect social and environmental resources? The basic research objectives include: assessing the importance of scale in WSM and the impact of stakeholder opinions on scale in WSM. The applied research objectives include: 1. Evaluate stakeholder preferences at two different scales (HUC12 and HUC14 equivalent) to determine if one scale is more appropriate for WSM, 2. Determine the appropriate stormwater management controls and methods to make a recommendation for implementation in Tom's Creek watershed. These objectives will be addressed as I answer the following questions:

- Is watershed scale an important factor in WSM?
- Does stakeholder opinion on issues of cost, aesthetics, environmental impact, and safety affect appropriate watershed scale in WSM?
- If scale is important in WSM-based planning, what scale is most appropriate?
- What stormwater controls are most appropriate for the case study watershed and its sub-watersheds when using WSM?

1.3. Significance of Study

The study results will add to the growing body of literature regarding the effectiveness of WSM and will be shared with the governing body and stakeholders of the case study watershed. Because this study is one of the first of its kind in WSM, the results have important implications for the importance and effectiveness of considering scale and stakeholder opinion in WSM. Understanding stakeholder preference and its effect on scale in a watershed could not only improve the effectiveness of stormwater management in a watershed, but could also improve the marketability of the area as the development is more catered to the needs of that population. Thus, the results of this research will help researchers, planners, and geographers make WSM more effective in long-term implementation.

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2. Literature Review

2.1 Introduction

The following literature review will identify several major gaps and debates surrounding the issue of scale in WSM that will be addressed through my research. First, I will consider how research in WSM is significant in the field of geography. Second, I will address debates in the literature about how to operationalize scale in WSM. Finally, I will consider the need for stakeholder involvement in WSM research.

2.2 Research Significance in Geography

Pattison (1964) described human-environment studies as one of the four traditions of geography, noting that geographers have been probing the relationships and interactions between humans and the natural environment throughout history (Robinson, 1976). However, the topic of stormwater management is understudied in the geographic literature, and specifically the body of literature that falls under the broad umbrella of human-environment studies, even though the main purpose of stormwater management relates to mitigating humans' impacts on the environment. Stormwater management was originally intended for the conveyance of runoff from human activity to a point of discharge (Ellis, 1995), the reduction of peak storm flow rates (NRC, 2008), and more recently the goal of ecosystem preservation has gained importance (Roy et al. 2008).

Additionally, Cutter, Golledge, and Graf (2002) identify this question: 'How is earth being transformed by human actions?' as one of the big questions in geography, and yet they fail to mention stormwater management as one of the topics in need of geographic research. I conjecture that this gap exists because stormwater management is often lumped into the field of urban planning; thus, it is typically studied from a planning perspective, not a geographic one. Consequently, traditional stormwater management programs have been carried out based on jurisdictional lines, with a focus on the quick transference of runoff and cost-effectiveness, rather than on geographic features (Chocat et al., 2001; NRC, 2008). According to research in the field in the past decade, traditional stormwater management methods contribute to environmental problems, including flooding, decreased water quality and quantity, destruction of ecosystems, and ultimately the loss of soil and the vegetation's ability to hold moisture (Chocat et al., 2001; NRC, 2008; Roy et al., 2008).

As research has called for it, the field of water resources management is shifting to a more holistic approach that requires the inclusion of environmental protection as a consideration of stormwater management (Cortner and Moote, 1994; Roy et al. 2008). This shift is highly suited to, and in many ways necessitates, the use of a geographic perspective in water resources management. In lieu of traditional stormwater management recent literature in the field of planning has suggested that watershed-based stormwater management is a more suitable way to plan for stormwater management. (Chocat, 2001; EPA, 2003; Wu et al. 2006; NRC, 2008). Because WSM is carried out based on the shape and geographic characteristics of the watershed, such as slope, soils, vegetation, landcover, and other features (ASCE, 1998; Zhen, 2004), the literature is indirectly charging researchers in both planning and geography to collaborate and explore stormwater management from a geographic perspective. Because this shift in water resources management is so recent, there is little research available on the topic, so there is a clear need for further geographic study of WSM.

Although stormwater management is under-researched in the field of geography, geographers have contributed more broadly to the field of water resources management, and more specifically to watershed management. The watershed as a unit is a strong focus in geography, as demonstrated by the major contributions listed here. Trimble (1993) links soil erosion with watershed analysis, while Marston (1994) and Trimble and Mendel (1995) specifically examine the effects of animals, such as beaver and cattle, on watershed geomorphology, finding that they affect the path of run-off. Wescoat (1999) looks at the effects of land use and land cover change on run-off, sedimentation, stream habitat, and water supply in watersheds. Yarnal (1992, 1997, 2000) links climate variability with multiple hydrologic aspects of river basin watersheds, finding that climate change has an effect on water supply, water quality, and flood protection. Finally, the National Research Council (1999) discusses important new physical, social, and environmental policy aspects of watershed management. The literature has clearly identified the watershed as an important unit in environmental management. Geographers have studied many dimensions of watersheds, and the research I am proposing would add to the growing body of watershed-related research in geography through the examination of issues related to scale in stormwater management.

2.3 Operationalizing Scale in WSM

The geographic concept of scale is one noticeable gap in the literature surrounding WSM. In the broad spectrum of topics in geography, scale can have different meanings and applications. For example, cartographic scale refers to the size an object or location is represented on a map as opposed to its actual size on the earth (Smelser and Baltes, 2001). Analysis scale refers to the scale at which phenomenon are studied, whereas phenomenon scale refers to the actual size at which phenomena exist (Smelser and Baltes, 2001). This study looks at analysis scale: what size watershed is appropriate for watershed-based stormwater management, since watersheds exist in differing sizes?

According to one broad definition, “scale refers to one or more levels of representation, experience, and organization of geographical events and processes,” (Johnston, 2000, p. 724). More specifically for the purposes of this study, scale refers to different sizes of watersheds: micro-scale refers to small order streams (usually temporary or seasonal), meso-scale refers medium order streams (perennial tributaries), and macro-scale refers to large order streams (typically rivers). The literature on scale emphasizes the importance of using the proper scale in research, however there is debate amongst researchers about how to operationalize scale in WSM because watersheds vary in shape and size. McCarty et al. (1956) observed that deductions and assumptions made at one scale do not automatically apply to data that is expressed at other scales. Researchers have expanded on McCarty’s work noting that observations documented at too great a scale could mask the big picture while working at too small a scale could cause important details to go unseen. (Cash and Moser, 2000; Mayhew, 2009) Furthermore, researchers have posited that the scale used should be dependent on the problem being studied (Schumm, 1991; Johnston et al., 2000).

There is debate in the literature about the appropriate scale at which WSM should occur. Some researchers arbitrarily select a watershed size, out of convenience of location and without justification, while other researchers do not address the issue of scale all together. For instance, Randhir and Tsvetkova (2008) use medium order streams (streams that flow into rivers) when researching WSM, while the National Research Council of the National Academies (NRC, 2008) identifies ‘watershed-scale’ as a watershed that has an area within a few square miles and is within one municipality. However, the NRC does not justify why this scale is appropriate or provide literature backing it. In contrast, Roy et al. (2008) suggests that 'watershed-scale implementation' does not require a specific scale but can take place at many scales and include one or multiple jurisdictions. When it comes to implementation of WSM scale is a major gap that needs to be addressed, specifically what size watershed is most appropriate for planning decisions.

2.4 Stakeholder Involvement in WSM

There is little analysis of stakeholder preference in the current body of literature surrounding WSM. The term, 'stakeholder,' refers to any person, organization, or agency that is concerned with or will be affected by the outcome of a proposed project. There are several major challenges to the implementation of WSM, including cost issues, long-term maintenance issues, urban sprawl, and safety and aesthetic concerns. (NRC, 2008) There is one specific gap that all of these challenges relate to in WSM: the inclusion of stakeholders' opinions in research and analysis. Each challenge relies on an understanding of the needs of the stakeholders involved, as well as quantitative environmental research. Duram and Brown (1998) assert that to have long-term success in any stormwater management plan, public participation and an open dialogue amongst all stakeholders is necessary. Including stakeholders in the planning process develops trust amongst the stakeholders and governing body, while building support for better stormwater management (Duram and Brown, 1998; Gregory and Wellman, 2001).

Most research put forth in WSM is quantitative: for example, Wu et al. (2006) assess WSM from a water quality perspective; Rhandhir and Tsvetkova (2009) identify tradeoffs between water quality and water quantity in WSM; and Zhen et al. (2004) investigate optimal stormwater basin size in WSM. However, these studies become less valuable at implementation if the support of the stakeholders is not present. Stakeholders decide whether to use or purchase land within a watershed. They are often even included in the decision-making process, so land becomes less appealing and in turn less marketable if factors such as stormwater controls are not acceptable to the prospective stakeholders. Several authors (Ellis, 1995; NRC, 2008; Roy et al. 2008) suggest the need for future research to involve the collaboration of stakeholders because their support is necessary in the effective implementation of WSM. In the field of watershed planning, data acquired from stakeholder interviews and meetings have been utilized and recommended in decision-making in addition to the Total Maximum Daily Loads and other analytical tools required by the federal government (Ellis, 1995; Roy et al. 2008, Floress et al. 2009). Stakeholder involvement is a key issue in WSM that is often ignored in the literature and thus will be addressed in this study.

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3. Manuscript:

Operationalizing Scale in Watershed-Based Stormwater Management*

*This chapter is a manuscript in preparation for submission to the Journal of the American Water Resources Association.

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Abstract
Watershed-based stormwater management (WSM) has been proposed as more effective for stormwater management than the traditional methods, which are carried out based on jurisdictional lines at the parcel-scale. Because WSM considers the watershed as a total unit, this method is considered to be more effective in reducing problems associated with stormwater management including environmental degradation and flooding. However, larger watersheds encompass smaller watersheds, and therefore WSM can be implemented at a wide range of scales. There has been little research on what scale is most appropriate, and more specifically, only a modest amount of work has taken stakeholder opinions into account. Our objectives are to determine: 1) if watershed scale is an important factor in WSM, 2) whether stakeholder opinion has an effect on the appropriate scale used in WSM, and 3) what scale is most appropriate for WSM, if scale is an important factor. To meet these objectives, we delineated sub-watersheds within the larger Tom's Creek watershed in southwestern Virginia, surveyed stakeholders within the watershed on their opinions of stormwater management methods, and compared the results at both watershed scales using statistical tests and decision support software. The results of this study have important implications for considerations of geographic scale in WSM as well as the incorporation of stakeholder opinion in stormwater management implementation.

Key Words: watershed-based stormwater management, scale, stakeholder

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3.1 Introduction

Increasing water scarcity, environmental degradation, and flooding are major problems that are often attributed to poor stormwater management in urban and urbanizing areas (NRC, 2008; Roy et al. 2008). Stormwater management plans, implemented by local governments as development expands, attempt to mitigate these problems, but often fail due to the parcel-level scale at which they are implemented; many stormwater controls are overwhelmed during storm events and thus rendered ineffective (Chocat et al., 2001; NRC, 2008; Roy et al., 2008). Traditionally, stormwater management plans in the United States are based on property lines and minimizing short-term costs rather than on geographic factors such as topography, favoring the quick removal of runoff over environmental protection and important eco-services. Recently, watershed-based stormwater management (WSM) has been proposed to mitigate problems caused by traditional methods (Chocat et al. 2001; NRC, 2008; Roy et al. 2008). This new approach uses geographic features and stakeholder opinions at the watershed-scale to plan stormwater management, as opposed to planning stormwater controls at the parcel-scale.

According to the Environmental Protection Agency (EPA, 2003), WSM is so effective because planning is carried out based on the watershed as a total unit, as opposed to being planned parcel by parcel as with traditional methods. WSM uses the natural topography of the watershed to select and place stormwater controls that reduce and redirect runoff while providing environmental protection. Using the natural topography of the watershed for planning allows implementation of stormwater controls to have less impact on the natural environment, because less soil and vegetation is polluted and/or displaced.

Although it is apparent that WSM offers improvements to stormwater management, there is much research to be done on the implementation of WSM. Larger watersheds encompass smaller watersheds, which include even smaller watersheds, and therefore watersheds have a wide range of scales at which WSM could possibly be implemented. There is debate about how to operationalize scale in WSM (NRC, 2008; Randhir and Tsvetkova, 2008; Roy et al. 2008), specifically whether a watershed can be too large or too small for this approach. It is important to understand scale in WSM, because the size of the watershed used can have an effect on the level of environmental protection and runoff capture that the WSM plan can provide, and in turn, those using the watershed.

This study examines the importance of scale in WSM using a case study watershed, the Tom's Creek watershed in Montgomery County, Virginia. Both environmental factors, such as soil, topography, and land cover, and stakeholder opinions will be taken into consideration in this examination of scale. This research asks the question: what scale of watershed is appropriate for WSM in order to protect social and environmental resources? Our basic research objectives are to assess the importance of scale in WSM and more specifically, the impact of stakeholder opinions on the appropriate scale to use in WSM. Our applied research objectives are to evaluate stakeholder preference at two scales (HUC12 and HUC14 equivalent) to determine which is more appropriate for implementation of WSM, and to determine appropriate stormwater management controls and methods to recommend for implementation in Tom's Creek watershed.

3.2 Background

3.2.1 Stormwater Management Practices

The original purpose of stormwater management was the conveyance of increased runoff from human activity to a point of discharge (Ellis, 1995). Traditionally stormwater management planning and research falls under the fields of urban planning and civil engineering. Consequently, traditional stormwater management programs have been carried out based on jurisdictional lines, with a focus on the quick transference of runoff and cost-effectiveness, rather than on geographic features (Chocat et al., 2001; NRC, 2008). Research suggests that these traditional stormwater management methods contribute to a wide range of environmental problems, including flooding, decreased water quality and quantity, destruction of ecosystems, and ultimately the loss of soil and the vegetation's ability to hold moisture (Chocat et al., 2001; NRC, 2008; Roy et al., 2008). Therefore, a greater emphasis was put on reducing peak storm flow rates in stormwater management (National Research Council of the National Academies (NRC), 2008), and more recently the goal of ecosystem preservation has gained importance (Roy et al. 2008).

A paradigm shift is occurring in water resources management to a more holistic approach, one that requires the inclusion of environmental protection as a consideration of stormwater management (Cortner and Moote, 1994; Roy et al. 2008). Recent literature in the field of planning has posited that WSM is a more appropriate way to plan for stormwater management, as compared to traditional methods (Chocat et al., 2001; EPA, 2003; Wu et al. 2006; NRC, 2008). WSM is carried out based on the shape and geographic characteristics of the watershed, such as slope, soils, vegetation, landcover, and other features (American Society of Civil Engineers and Water Environment Federation, 1998; Zhen, 2004). Due to the recent nature of this paradigm shift in water resources management, there has been only a modest amount of research conducted on the topic, so there is a clear need for further study of WSM.

3.2.2 Operationalizing Scale in WSM

One noticeable gap in the literature on WSM relates to the geographic concept of scale. According to one definition, "scale refers to one or more levels of representation, experience, and organization of geographical events and processes (Johnston, 2000, p. 724)." There is debate amongst researchers about how to operationalize scale in WSM because watersheds vary in shape and size, and the literature on scale stresses the importance of using the appropriate scale in research. McCarty et al. (1956) observed that conclusions made at one scale do not necessarily apply to data that is articulated at other scales. Later researchers expanded on McCarty's work noting that observations recorded at too large a scale could hide the big picture while too small a scale could conceal important details (Cash and Moser, 2000; Mayhew, 2009), and the scale used should be dependent on the problem being studied (Schumm, 1991; Johnston et al., 2000).

Therefore, a key question in WSM research is: what is the appropriate scale of watershed to use in WSM? In the literature, some researchers arbitrarily specify a watershed size in WSM, out of convenience of location and without justification, while other researchers ignore the issue of scale all together. For example, Rhandhir and Tsvetkova (2008) use medium order streams (streams that flow into rivers) when employing WSM in their research, while the National Research Council of the National Academies (NRC, 2008) identifies 'watershed-scale' as a small watershed within one municipality. However, the NRC provides no justification for why this scale is appropriate. In contrast, Roy et al. (2008) note that 'watershed-scale implementation' can take place at many scales and include one or multiple jurisdictions. There is clear debate in the literature about the appropriate scale at which WSM should occur. One gap that needs to be addressed is the issue of scale in the implementation of WSM to determine what size watershed is most appropriate for planning decisions, if in fact a certain scale is better.

3.2.3 Need for Stakeholder Involvement in WSM

The body of literature surrounding WSM fails to include data from stakeholder input in most analyses. The term, 'stakeholder,' refers to any person, organization, or agency that is concerned with or will be affected by the outcome of a proposed project. The NRC (2008) identified several major challenges to the implementation of WSM, including cost issues, long-term maintenance issues, urban sprawl, and safety and aesthetic concerns. All of these challenges relate to one major gap in the research surrounding WSM: the inclusion of stakeholders' opinions in research and analysis. Each challenge relies not only on the quantitative hydrologic and geographic data, but also on the support of the stakeholders involved. Duram and Brown (1998) assert that public participation and an open dialogue amongst all stakeholders is necessary for the long-term success of any watershed and stormwater management program. Including all affected agencies and landowners in the planning process develops trust amongst the stakeholders and local government, while building support for better stormwater management (Duram and Brown, 1998; Gregory and Wellman, 2001).

Research in WSM is almost entirely quantitative: for example, Zhen et al. (2004) investigate optimal stormwater basin size in WSM; Rhandhir and Tsvetkova (2009) compare tradeoffs between water quality and water quantity in WSM; and Wu et al. (2006) assess WSM from a water quality perspective. However, all of these studies become less valuable at implementation if the support of the stakeholders is not present. Ultimately, stakeholders decide whether to utilize or purchase land within a watershed. They are often even included in the decision-making process, so if factors such as stormwater controls are not acceptable to the prospective stakeholders, the land becomes less appealing and less marketable. Several authors (Ellis, 1995; NRC, 2008; Roy et al. 2008) suggest the need for future research to involve the collaboration of stakeholders because their support is necessary in the effective implementation of WSM. In the field of watershed planning, data acquired from stakeholder interviews and meetings have been utilized and recommended in decision-making in addition to the Total Maximum Daily Loads and other analytical tools required by the federal government (Ellis, 1995;

Roy et al. 2008, Floress et al. 2009). A key issue that is ignored in the literature surrounding WSM and will be addressed in the research presented here is the involvement of stakeholder input in the WSM process.

3.3 Study Area

The Tom's Creek watershed is a rural watershed located in the small town of Blacksburg and the surrounding unincorporated area of Montgomery County, VA (Tom's Creek Task Force, 2009). Demographically, the watershed is predominantly white and rural, with almost 70% of households with an income less than $50,000, and over 15% with an income below $15,000 (USCB, 2000). Approximately 75% of the adult population is over the age of forty (USCB, 2000). There is an interesting juxtaposition of middle-aged rural dwellers and young college students living in the watershed, as the watershed borders a large university.

Although its current land cover is composed mostly of forest (67%) and agricultural land (21%) as you can see in Figure 1 and Table 2, the watershed is under heavy pressure for development as the Blacksburg population grows (Pavlick, 2009). Tom's Creek Watershed is known for its rural character and, even with pressure for development, the Blacksburg Comprehensive Plan calls for the preservation of that rural character, of water quality, and of the creek's natural amenities (TOB, 2007). This should result in two major practices as development unfolds in this watershed: 1)Undeveloped areas and corridors will be planned into development as green infrastructure and 2) Stormwater best management practices (BMPs) will have to be utilized to control, slow, and filter increased runoff, or if possible, prevent increased runoff with development (EPA, 2003; TOB, 2007; NRRC, 2008).

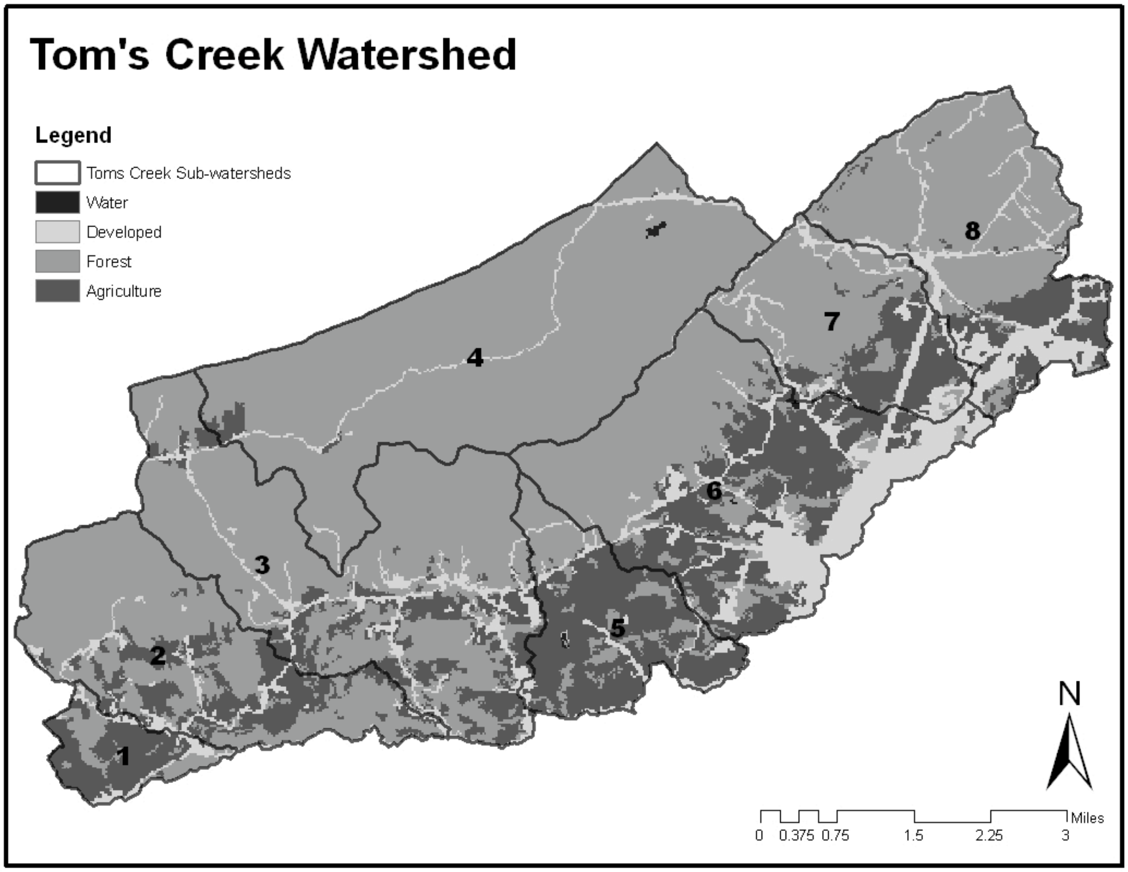

Figure 1. Land use of watershed mostly composed of forest and agriculture with urban pressure in the East. (NLCD adapted from: Homer et al. 1994)

Tom’s creek itself has a reputation of being a clean creek kept in good condition because of the lack of development around it; however, this is changing. In certain areas, the creek has already shown signs of increased sediment deposition and decreased biodiversity, due to residential development (Tom’s Creek Task Force, 2009). Although these changes have not been substantial enough to cause the stream to become impaired, they offer a warning for impacts of further development if stormwater is not handled appropriately. Tom’s Creek is an ideal watershed for this case study because good stormwater BMPs could maintain or improve its existing conditions with further development, and the watershed is under pressure for development and stormwater management controls will likely be implemented in the near future.

3.4 Methods

In order to meet the aforementioned objectives of this research, the following steps, further discussed in the subsections below, were completed within the case study area, the Tom's Creek watershed and its sub-watersheds:

Table 1. Methods

Step:	**Method Description:**
Spatial Data Preparation	1. Collect spatial elevation and land use data from USGS and Montgomery County. 2. Delineate sub-watersheds: ArcGIS hydrology tools including, the flow direction and watershed tools were utilized to divide the watershed into sub-watersheds 3. Spatially analyze the following geographic factors within sub-watersheds: drainage area size, soil type, geologic constraints, impervious surface fraction, land use
Survey Data Collection	Solicit opinions from stakeholders via online surveys advertised by postcard mailings.
Data Analysis: Stakeholder preference	Statistical analysis of preference variability at watershed and sub-watershed scales
Data Analysis: Determination of Recommended BMPs	Further Data Analysis: Use Stormwater BMP Decision Support Software (BMPDSS) developed at Virginia Tech (Young et al., 2008), to determine BMPs that would be implemented based on stakeholder preferences and environmental factors at the sub-watershed and full watershed scales

3.4.1 GIS data Preparation and Compilation

In order to prepare the spatial data, ArcGIS hydrology functions were used on a ten-meter Digital Elevation Model (DEM) to delineate eight sub-watersheds within the Tom's Creek watershed based on perennial tributaries. These sub-watersheds were used in this case study as the fine-scale sub-watersheds and are displayed in Figures 1 and 2.

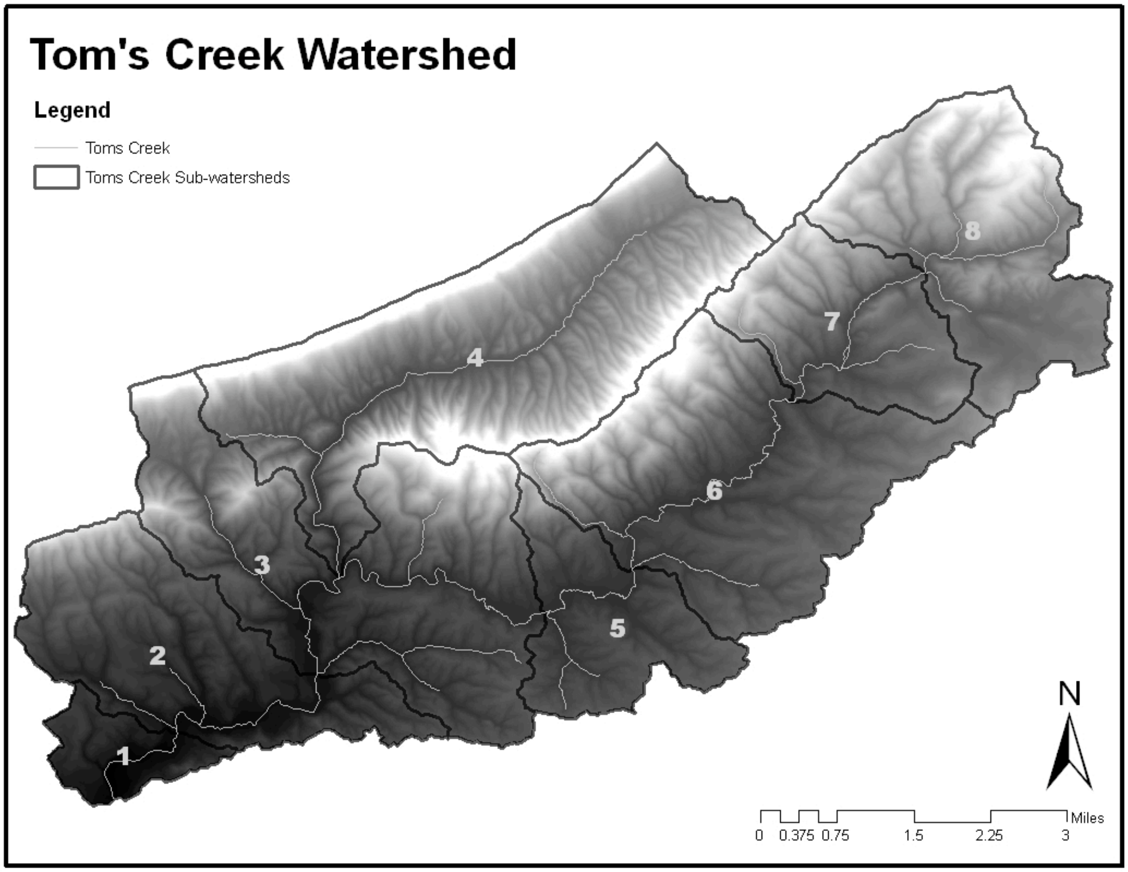

Figure 2. Eight sub-watersheds delineated based on tributaries of watershed.
(NHD adapted from: USGS-EPA, 1999; NED data adapted from: Gesch et al., 2002)

ArcGIS was used for gathering and compiling environmental data necessary for the analysis. Because this study is holistic, taking both environmental and human factors into consideration, it was necessary to gather spatial data on important environmental factors in the watershed. Geographic factors taken into account in this step include: drainage area size, slope, land use type, soils, and impervious surface fraction. These environmental factors are coupled with stakeholder opinions and used during the final phase of analysis. Table 2 summarizes the environmental conditions in the Tom's Creek Watershed.

Table 2. Geographic Factors of Sub-watersheds

Sub-watershed	Acres	Impervious Fraction (%)	Predominant Land Uses	Soil – Extreme Low/High runoff Potential
1	681	13.5	Rural	NO
2	3,037	5.9	Rural/Forest	NO
3	4,842	8.6	Suburban/Forest	NO
4	5,729	2.2	Forest	NO
5	1,742	8.4	Suburban/Rural	NO
6	4,467	23.3	Suburban/Forest	NO
7	1,981	16	Suburban/Rural/Forest	NO
8	3,157	17.5	Forest/Rural	NO
Tom's Creek Watershed	25,636	11.9	Forest/Rural/Suburban	NO

3.4.2 Data collection: Stakeholder Surveys

Although there are various stakeholders that could be affected by stormwater management practices, this study focuses on the preferences of residents within the watershed as they are most affected by the specific stormwater management controls implemented. Stakeholder address information was obtained from Montgomery County in the form of Geographic Information Systems parcels data (Mont. Co., 2010). Arc GIS was used to assign each household to its sub-watershed of residence (ID numbers 1-8 in Table 2 and Figures 1 and 2). At the time of data collection (October, 2010 –February 2011), there were approximately 5000 households in the Tom's Creek watershed. This data was sifted for missing information leaving approximately 4700 households for the sample, and the records were then imported into Microsoft Office Excel. An anonymous survey, which was advertised by postcards, was offered via the World Wide Web to a stratified random sample of approximately 55% of the watershed (Table 3). A stratified random sample was used to guarantee that the same percentage of households in each sub-watershed would have the opportunity to take the survey.

Table 3. Sampling Data by Sub-watershed

SUB-WATERSHED ID	TOTAL NUMBER OF HOUSEHOLDS	POSTCARDS SENT
1	143	78
2	399	218
3	627	343
4	72	40
5	202	111
6	2005	1097
7	553	302
8	1204	660
Tom's Creek Watershed	5205	2850

The survey webpage offered the user a map service where they typed in their address and a marker located their parcel in the sub-watershed group. Below this, a link was provided to direct the user to the survey where they input the sub-watershed in which they reside and answer the remaining questions. In that way, the participants' responses were assigned to individual sub-watersheds. The Google-based map service and survey were available to the users via filebox.vt.edu and survey.vt.edu.

This survey offered the residents an opportunity to express their preferences in relation to stormwater management techniques. The survey began with basic background on the research project and definitions associated with the different types of stormwater control methods, and it then asked stakeholders to rank the importance of specific aspects of stormwater management as it applies to them on a scale of one to five, one being of minimal importance and five being of maximum importance. Stakeholders were asked to rank their preferences regarding the importance of decision-making based on aesthetics, installation costs, maintenance costs, safety/nuisance/liability, and environmental protection. A summary of the survey questions is provided in Table 4. See Appendix A for a full copy of the survey.

Table 4. Summary of Survey Questions

Section	Questions
1	1. In what color sub-watershed are you located?
	2. How important are aesthetic benefits of stormwater controls to you?
	3. How important is safety/liability/nuisance of stormwater controls to you?
	4. How important are low initial installation costs of stormwater controls to you?
	5. How important are low ongoing maintenance costs of stormwater controls to you
	6. How important to you are pollutant removal and environmental protection capabilities in stormwater controls?
2	Rank the importance of the following stormwater management criteria against one another: aesthetics, safety/nuisance, low implementation costs, low maintenance costs, environmental protection
3	Select gender
	Select choice that applies to you: rent or own parcel
	Select Age Bracket
	Select Income Bracket

3.4.3 Data Analysis

For the first part of the analysis, stakeholder responses were compiled and prepared for statistical analysis in Microsoft Excel. To statistically analyze the distribution of preference in the sub-watersheds, the prepared survey responses were input into SAS JMP. This program was utilized to build contingency tables and mosaic plots of response distribution for each question. The data were then analyzed for statistical significance (α=0.05) of overall variation or similarity amongst the sub-watersheds. A p-value of 0.05 or lower would denote a significant difference between the sub-watersheds. A significant difference amongst the sub-watersheds would suggest that implementation of WSM at the finer scale would be more appropriate; whereas similarity amongst the sub-watersheds would suggest that the larger watershed scale is more appropriate.

The second part of the analysis uses the stakeholder data as input into a program designed to assist stakeholders and localities in the selection of BMPs for the treatment of stormwater runoff in order to examine how resident preference translates to actual implementation. Through this portion of the analysis, we specifically consider (1) how resident preference affects the scale as which stormwater management practices should be implemented, and (2) what implementation measures are recommended for the case study watershed or sub-watersheds.

The Virginia Tech BMPDSS was developed as part of Virginia's Stormwater Evaluation Project (Young 2009a, 2009b). The software was designed to assist stakeholders and localities in the selection of BMPs for the treatment of stormwater runoff. BMPDSS uses the Analytic Hierarchy Process as a selection tool because it is a multiple criteria decision-making tool that can take both subjective and objective criteria into account (Saaty, 1988; Schmoldt, 2001; Lopez et al., 2006). The BMPDSS was chosen for this research for several reasons. 1) It was built based on Virginia's stormwater regulations; 2) It takes both environmental data and desires of the user into account; 3) It boasts a comprehensive list of available stormwater BMPs; and 4) It offers an organized way to resolve conflict in stormwater management planning. The software offers fifteen selection criteria for the user to rank in importance. Some of the criteria are based on environmental data, such as soil type or impervious fraction, while other criteria are based on stakeholder opinion, like aesthetic benefits, environmental protection, implementation costs, operation and maintenance costs, and safety or nuisance concerns, which were the criteria used in the resident survey. See Table 2 for list of physical parameters used for this analysis, which were specific to Toms Creek Watershed. For further definition and review of the Analytic Hierarchy Process, see Appendix B.

The previously described resident survey was designed so that resident ranking of each criterion could be used as input data, and the software used those rankings in an algorithm to determine the most appropriate stormwater BMPs for each sub-watershed. For this project, the stakeholders' preference rankings will be averaged for each sub-watershed and the Tom's Creek watershed as a whole, then, along with the environmental data, the rankings will be entered into the BMPDSS for each sub-watershed and for the whole watershed. The software will compute the most appropriate stormwater BMPs for each sub-watershed. The output BMPs will be compared to find the differences when the system is employed at different scales. The possible output BMP recommendations are shown in Table 5.

Table 5. BMP alternatives BMP DSS

Dry Extended Detention Basins	Bio-retention
Extended Detention Basins- Enhanced	Sand Filters
Retention Basins	Grassed Swales
Constructed Wetlands	Vegetated Filter Strips
Infiltration Basins	Manufactured BMP Systems
Infiltration Trenches	Vegetated Roofs
Porous Pavement	Rainwater Harvesting Systems

All of the BMPs listed in Table 5 are recognized by the State of Virginia Stormwater Management Program with the exception of vegetated roofs and rainwater harvesting, which are in the process of being added to the program. Further definition and discussion of the BMPs can be found in the BMPDSS handbook (Young et al, 2009).

We compared the output of the BMPDSS program across sub-watersheds and when calculated over the entire watershed using environmental data and stakeholder preference as inputs. Variation amongst the sub-watersheds in the results of using this tool would show that WSM implementation at the finer scale would be more appropriate while similarity in results would support using the larger scale watershed. As many of the sub-watersheds carry similar environmental attributes, major differences in the BMP outputs would most likely be attributed to differences in the stakeholders' opinions, answering the major question of whether stakeholder opinions affect the appropriate scale at which to carry out WSM. Since this is a case study using quantitative data and actual stakeholder opinions from the Tom's Creek watershed, the BMPDSS outputs can be recommended as prospective stormwater controls to be assessed and possibly implemented in the watershed, answering the major question of which stormwater controls are most appropriate for the case study watershed. Because stakeholders in one watershed can have different opinions about stormwater management, it is important to consider that these differences can affect the scale at which WSM should be carried out.

3.5 Results and Discussion

3.5.1 Overall survey response rate

Out of 5205 addresses in the Tom's Creek watershed, 2835 (55%) were sent post cards advertising the online survey, and 190 complete survey responses were returned. The overall response rate was approximately 7%, meaning that of those who received the advertisement, approximately 7% responded. The breakdown of response rates by sub-watershed is shown in Table 6:

Table 6. Response Data by Sub-watershed

Sub-Watershed	Number of Responses	% of Total Responses Received	Overall Response Rate
1	2	1.1%	2.5%
2	8	4.2%	3.7%
3	18	9.5%	5.2%
4	3	1.6%	7.5%
5	2	1.1%	1.8%
6	88	46.3%	8.0%
7	29	15.3%	7.9%
8	40	21.1%	6.1%
Tom's Creek Watershed	190	100.0%	6.7%

In order for a sub-watershed's response to be considered statistically significant in this study, there needed to be a high enough response rate for statistical calculations. Four of the eight sub-watersheds (1, 2, 4, and 5) received too few responses for use in statistical analyses.

3.5.2 Breakdown of responses by survey criteria

In this section, we describe the results of the stakeholder survey. For each of the five criteria (aesthetics, safety/liability/nuisance, low installation costs, low maintenance costs, environmental protection), a contingency analysis breaks down how participants responded by sub-watershed and results are shown in Figure 3. P-values were computed for each criterion as well, shown in Table 7. A p-value at or below .05 would imply a significant difference amongst the data. However none of the p-values for the criteria in this dataset fell below .05, suggesting a lack of variability in stakeholder opinion across sub-watersheds in this study, which supports carrying out WSM at the broader-scale watershed level (Tom's Creek watershed).

Table 7. P-values for Criteria Evaluated

Criteria Evaluated	P-value
Aesthetics	.50
Safety/Nuisance Liability	.51
Low Installation Costs	.92
Low Maintenance Costs	.99
Environmental Protection	.82

Aesthetics of stormwater controls

Across the Tom's Creek watershed as a whole, 14.4% of participants found aesthetic benefits to be extremely important, 43.7% it to be very important, 28.7% of participants found it to be moderately important, 11.5% found it to be somewhat important, and 1.7% found it to be not important. Overall, the four sub-watersheds included in statistical analyses had similar responses, as shown by its high p-value of .50. The mosaic plot shown in Figure 3a displays the contingency analysis supporting the lack of significant difference in response in this sub-watershed.

Concerns related to safety, liability, and potential nuisances associated with stormwater controls

Across the Tom's Creek watershed as a whole, 35.% of participants found safety/liability/nuisance to be extremely important, 46.3% of participants found it to be very important, 10.3% found it to be moderately important, 6.3% found it to be somewhat important, and 1.7% found it to be not important. Sub-watersheds 3, 6, and 8 had more participants respond that safety/liability/nuisance was very important, and sub-watershed 7 had equal responses in extremely and very important. Sub-watershed 3 also had a higher percent respond that safety/liability/nuisance was somewhat or not important. Even still, overall the sub-watersheds show little variability in response and no significant difference as shown by the high p-value of .51. Safety/liability/nuisance is of high importance to most participants, as displayed in Figure 3b.

Importance of low initial installation costs of stormwater controls

The response pattern of this question, shown in Figure 3c, looks very different than the first two questions: Most participants found low implementation costs to be only somewhat to moderately important. Across the Tom's Creek watershed, 7.4% of participants found low installation costs to be extremely important, 18.9% of participants found it to be very important, 26.3% of participants found it to be moderately important, 25.7% of participants found it to be somewhat important, and 21.7% found it to be not important. A p-value of .91 shows that overall there is little variation between the four sub-watersheds.

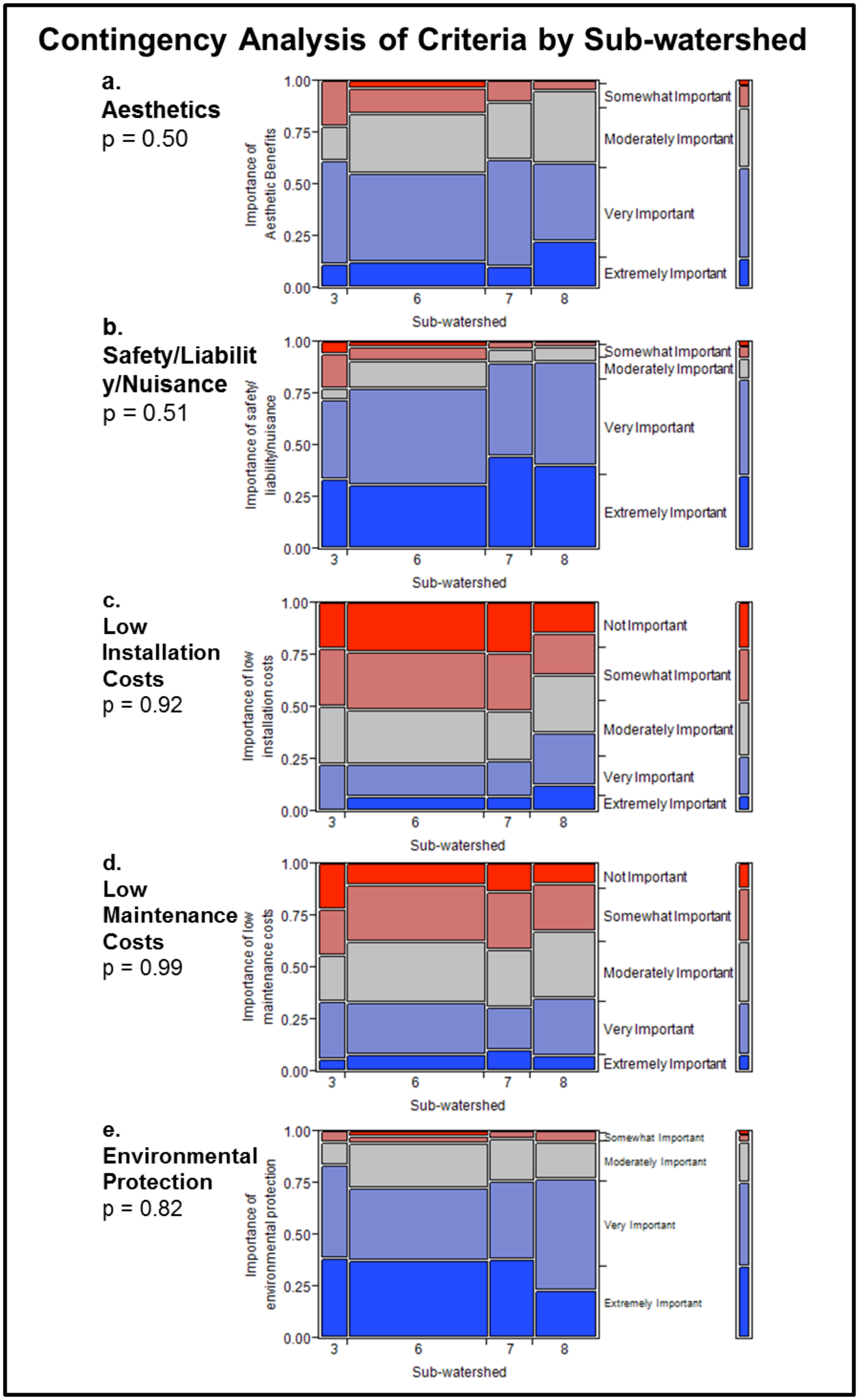

Figure 3. Plots show little variability (width of plot indicates response *n*)

Importance of ongoing maintenance costs of stormwater controls

Figure 3d displays the moderate response elicited when participants were asked to evaluate the importance of maintenance costs of stormwater controls. Across the Tom's Creek watershed, 8% found low maintenance costs to be extremely important, 25.1% found them to be very important, 29.1% of participants found them to be moderately important, 25.7% of participants found them to be somewhat important, and 12% found them to be not important. Overall, in preference on this criteria there was little variation and no variation of note, as supported by the very high p-value of .99, amongst the four sub-watersheds.

Importance of stormwater controls for pollutant removal and environmental protection

The responses to this question closely resemble that of the first and second questions in that most participants found environmental protection to be of high importance. Across the Tom's Creek watershed, 34.3% of participants found environmental protection to be extremely important, 40.6% of participants found it to be very important, 19.4% found it to be moderately important, 4% found it to be somewhat important, and 1.1% found it to be not important. However, Figure 3 supports the high p-value, 0.82, in showing that, overall, the four watersheds responded similarly to this question.

Results of ranking criteria against each other

In section 2 of the survey, participants were asked to rank the five criteria against each other from least important to most important. In this ranking scenario, no level of importance could be used twice. This part of the survey forced participants to choose a different level of importance for each criterion, whereas the first section allowed them to select different or equal levels of importance for each criterion. Of the 190 participants in the Tom's Creek Watershed, 151 of them answered this part correctly using only one level of importance for each criterion. Of the 151 correct responses environmental protection was most often ranked extremely important, safety/nuisance/liability – very important, aesthetics – moderately important, low maintenance costs – somewhat important, low implementation costs – not important.

Findings Interpreted

These initial findings suggest that stakeholders seem to be more concerned about environmental protection, safety/nuisance/liability and aesthetics, while they are less concerned about costs. When ranked against each other, the stakeholders show preferences consistent with their response in the initial individual ranking. Overall, the statistical results show that stakeholder preferences are very similar across the sub-watersheds, suggesting that working at the finer watershed scale is unnecessary to effectively carry out WSM.

The results of this study may have been affected by the demographics of the response. The watershed population as a whole is 47% male and 53% female (USCB, 2000), while the response showed 58% male and 42% female. Table 8 summarizes response by age from the watershed in comparison to the entire population in the watershed (USCB, 2000).

Table 8. Response by Age Bracket

Age Bracket	% Tom's Creek Watershed Population	% Tom's Creek Watershed Response
18 - 21	3.83	1.58
22 - 29	8.47	17.89
30 - 39	13.58	18.42
40 - 49	17.25	16.84
50 - 64	28.47	28.42
65+	28.40	16.84

Table 9 summarizes response by income from the watershed in comparison to the entire population (USCB, 2000). Most respondents came from the wealthier participants, which may have skewed the results, and could be the reason why costs were ranked with minimal importance. This higher response could be related to the positive correlation between internet access in the home and wealth.

Table 9. Response by Income

Annual Income	% Tom's Creek Watershed	% Tom's Creek Watershed Response
Less than $10,000	16.8	6.8
$10,000 - $14,999	8.3	1.6
$15,000 - $24,999	17.9	7.4
$25,000 - $34,999	11.0	4.2
$35,000 - 49,999	14.1	8.4
$50,000 - $74,999	15.8	11.6
$75,000 - $99,999	6.9	18.9
$100,000 - $149,999	5.5	17.4
$150,000 - $199,999	1.3	5.2
$200,000+	2.4	3.2

3.5.3 Analysis using BMPDSS

The final analysis in this study combines the geospatial environmental data for each sub-watershed with the collected stakeholder preferences in the Stormwater BMP Decision Support Software (Young, 2008) to determine what stormwater controls are best for the designated sub-watersheds, as well as the entire Tom's Creek watershed. This analysis extends the study beyond basic stakeholder opinions to provide a view of how those opinions could affect WSM implementation on the ground.

For this analysis, an average ranking for each of the five criteria was calculated within each of the four sub-watersheds for entry into the BMPDSS. It was possible to average the rankings as each response equated to a number that is used in the ranking system in the BMPDSS: Not important = 1, Somewhat Important = 3, Moderately Important = 5, Very Important = 7, and Extremely Important =9. As previously discussed, the output of the BMPDSS is a set of recommended BMPs ranked in order of appropriateness based on the environmental data entered and the stakeholder preferences. The results of this analysis are shown in Table 10.

Table 10. Recommended Ranked BMP outputs from BMPDSS

	Sub-watershed 8	**Sub-watershed 7**	**Sub-watershed 6**	**Sub-watershed 3**	**OVERALL TOM'S CREEK**
Rank 1	Rainwater Harvesting	Rainwater Harvesting	Rainwater Harvesting	Rainwater Harvesting	Rainwater Harvesting
Rank 2	Vegetated Roof	Vegetated Roof	Vegetated Roof	Vegetated Roof	Vegetated Roof
Rank 3	Bio-retention Basin	Sand Filter	Sand Filter	Bio-retention Basin	Sand Filter
Rank 4	Sand Filter	Bio-retention Basin	Bio-retention Basin	Sand Filter	Bio-retention Basin
Rank 5	Retention Basin	Retention Basin	Retention Basin	Retention Basin	Retention Basin

The results of the BMP analysis further support the implications of the statistical analysis of stakeholder preference as they show little variability in the output. All four sub watersheds and the larger scale watershed have the same first and second ranked stormwater control measures. All watersheds received the same top five recommended stormwater control measures, with the only variability being in the third and fourth ranked outputs, which were either sand filter or bio-retention for each basin. The results support the conclusion that for this region, using the broad scale watershed would be more appropriate than using the finer scale sub-watersheds for stormwater management implementation as the results are so similar. Because there was a lack of variation in preference amongst the sub-watersheds, it would most likely cost the planner or developer precious time and resources to work at such a fine scale. Thus it would be more efficient and effective to work at the larger watershed scale.

In response to one of the applied objectives of this study, the following outputs of the BMPDSS will be recommended to Montgomery County for implementation in the Tom's Creek Watershed in future development: rainwater harvesting, vegetated roofs, bio-retention basins, sand filters, and retention basins.

3.5.4 Are watershed scale and stakeholder preference important factors in WSM?

The literature supports the notion that scale is an important factor in WSM. (McCarty et al. 1956; Schumm, 1991, NRC, 2008). The results of this research would suggest that there are clearly scales that are too fine for WSM implementation.. However the appropriate scale of action will vary from place to place. Opinions and geographic factors did not differ enough across the sub-watersheds to suggest the use of the finer scale. If WSM planning and implementation were to be carried out at the fine scale, it could cost stakeholders and agencies important resources. Further research could narrow down the most appropriate scale for WSM implementation, but this study suggests that WSM should be implemented at the scale of the overall Tom's Creek basin or possibly even at a broader scale.

Stakeholder preferences provided some insight as to what residents may look for in stormwater management, however they did not prove to have an effect on implementation scale, in this specific case study. Their preferences were extremely useful in the selection of possible stormwater BMPs to implement in the case study watershed. The findings of this study show that, overall, the Tom's Creek watershed stakeholders find aesthetics, safety, and environmental protection more important in stormwater management and low implementation and maintenance costs less important.

3.6 Limitations of Study

This study had several limitations associated with it, including, the survey medium, transferability of the results, the types of stakeholders surveyed, and a low response number. The first limitation in this study is related to using the online survey as a data collection tool. The intention of using this medium as tool was to facilitate the user's ability to take the survey efficiently, however, it is unlikely that everyone who received a survey advertisement owned a computer or had sufficient computer skills to participate. This specific limitation could have played a part in the low response rate. This limitation could have also produced bias within the results, as people who own computers and are proficient in using them tend to be wealthier and more educated, thus the survey response would be unequally represented demographically.

Another possible limitation of this study surrounds its application. WSM is recommended for areas under pressure for development. It is somewhat less useful as a retrofit to areas that are already developed or urbanized, limiting the application of this study's results to watersheds that are developing. Furthermore, the geography and demographics of this watershed could also have had an effect on the results. Thus, this case study may best be transferred in application to watersheds that are similar in geography and demographics.

A third limitation involves the type of stakeholders surveyed in this study. Although this study surveyed land owners and renters in the case study watershed and sub-watersheds, there are other stakeholders that use and value any watershed. It may be important in future study to include those stakeholders in the study and analysis. Some of these stakeholders include, but are not limited to, people who use public lands and commercial spaces in the watershed but do not live there, government entities, non-profit or private entities who value the land's resources or space, and people whose water quality could be affected downstream.

A final limitation results from the low response rate. A high response rate would strengthen the findings of this study. The low response rate could suggest that stakeholders do not hold enough interest in stormwater management for them to choose to participate in this case study. Thus their lack of opinion or lack of voice could imply that stakeholder opinion does not or should not affect scale. However, if similar research was carried out with different advertising or in a different region, the response could be quite different.

3.7 Conclusion

The findings suggest that the fine scale sub-watersheds used in this study are not the most appropriate scale for WSM implementation in this region. However, the results do not suggest that working at the scale of the Tom's Creek watershed (or a watershed of the smallest HUC size) is best, only better than the fine-scale sub-watersheds. This study simply narrows the field by eliminating using sub-watersheds smaller than the smallest HUC size. The notion that scale is an important factor in WSM is supported by the result that implementation at the finer scale would be inefficient and unnecessary; This research adds to the growing body of literature surrounding watershed-based stormwater management and more specifically, it is a starting point for scale studies in WSM.

Although stakeholder preferences did not prove to have an effect on implementation scale in this particular study, they did provide some insight as to what stakeholders in this watershed are seeking in stormwater management. The basic results of the stakeholder survey and BMPDSS analysis can be used by the governing body of the Tom's Creek watershed for future application of WSM. The findings of this study support the conclusion that stakeholders of Tom's Creek watershed find costs to be less important than aesthetics, safety, and environmental protection.

WSM could be strengthened by further comparison studies at larger scales and in watersheds of different topography and demographics. Further study could also be done on how working at different scales effects implementation costs. Another study that is applicable to this area of WSM research includes looking at how or if stakeholders' preferences change when they have better understanding of how their preferences translate in on the ground implementation.

3.8 Acknowledgements

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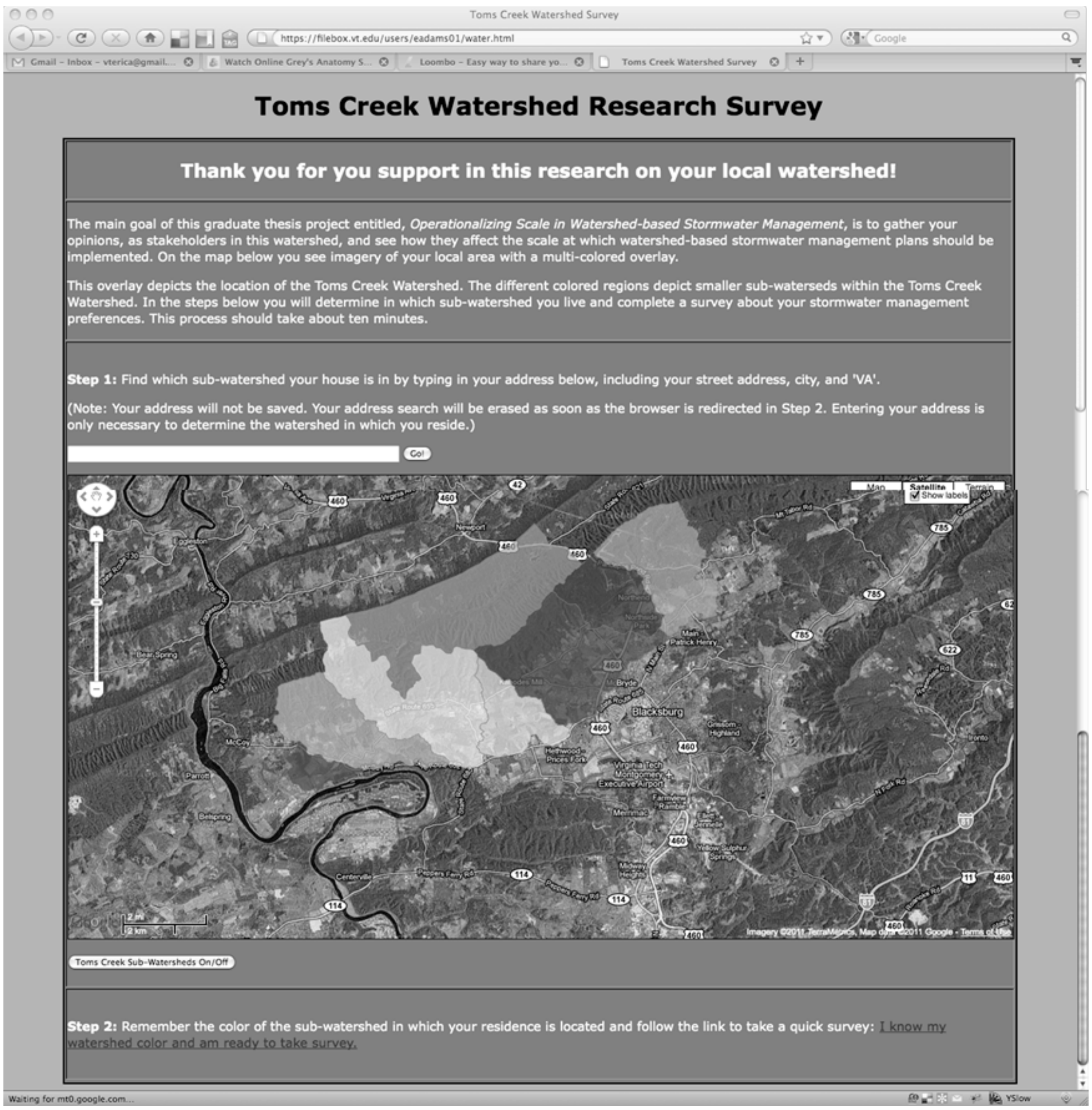
Appendix A: Survey Documents

The survey used for this research was offered online. There were a total of two webpages visited by each user: a home introductory page and the survey itself. Both pages were hosted by Virginia Tech. Virginia Tech's filebox interface was used to house the introductory page, and survey.vt.edu, the school's open survey tool, was used to house the survey itself. The user directed their browser to the home page where they read a small introduction to the project, shown below.



Following this they were asked to complete Step 1, where they geocoded their address to locate the sub-watershed where they reside. Once they located themselves they were asked to complete Step 2 by following a link to the survey. Both of these steps are shown in the Figure above. The home page can still be viewed at: https://filebox.vt.edu/users/eadams01/water.html.
The map of the sub-watersheds was created by Erica Adams using ArcGIS in 2009

The Survey Page
The Survey read as follows:

Tom's Creek Watershed Stormwater Management Survey

Dear Stakeholder,

Thank you for your time and participation in this survey.

I am a master's student in the Department of Geography at Virginia Tech working under the advisement of Dr. Korine Kolivras. For my graduate thesis, I am studying how stakeholders and residents opinions affect scale in watershed-based stormwater management in the Tom's Creek Basin. The purpose of this survey is to gather stakeholders' and residents' preferences and opinions on the implementation of stormwater controls in their watershed. This data will be used to analyze the affects of stakeholder opinions on scale in watershed-based stormwater management.

Stormwater controls are simply the devices or methods that are installed on land that has been developed in order to intercept and redirect increased stormwater runoff in a defined area. You may often see these in the form of ditches/swales, storm drains, retention/detention ponds, bio-retention, etc. Stormwater controls are necessary in developed areas to prevent flooding and can be useful in slowing and filtering runoff before it reaches local water bodies.

Participation in this survey is voluntary. You can stop at any time, if need be. There are minimal risks to participation and all information gathered will be kept confidential and anonymous. No identifying or self-incriminating information will be gathered. All responses will be transmitted securely. Questions about the study can be directed to me, Erica Adams, at eadams01@vt.edu.

Thank you again for your participation in this survey. It should take between 5 and 10 minutes.

Sincerely,
Erica Adams

Section One: Please select the choice that applies to you. You may select only one choice for each question.

1. In what color sub-watershed are you located when you search your address on the map on the previous page? If you do not live in the watershed, please select 'other' and provide an explanation of how you are a stakeholder in this watershed, i.e. local developer, local government official, local organization with interest in watershed, etc). If you live on a border of two watersheds, select the one that your parcel lies most within?

- Red
- Orange
- Yellow
- Green
- Aqua/Light Blue
- Dark Blue
- Purple
- Pink
- other:

2. How important are aesthetic benefits of stormwater controls to you? In other words how important is it to you for stormwater controls to be visually pleasing and to "blend in" with the surrounding landscape?

- Not Important
- Somewhat Important
- Moderately Important
- Very Important
- Extremely Important

3. How important is safety/liability/nuisance of stormwater controls to you? (For example, standing pools of water without fencing, or mosquitoes)

- Not Important
- Somewhat Important
- Moderately Important
- Very Important
- Extremely Important

4. How important are low initial installation costs of stormwater controls to you, if the trade off is quality of control (how well it works?) and environmental protection?

- Not Important
- Somewhat Important
- Moderately Important
- Very Important
- Extremely Important

5. How important are low ongoing maintenance costs of stormwater controls to you, if the trade off is quality of control (how well it works) or environmental protection?

- Not Important
- Somewhat Important
- Moderately Important
- Very Important
- Extremely Important

6. How important to you are pollutant removal and environmental protection capabilities in stormwater controls?

- Not Important
- Somewhat Important
- Moderately Important
- Very Important
- Extremely Important

Section Two: Please rank the importance of the following stormwater management criteria in order of their importance to you. Use numbers 1 through 5, 1 being least important and 5 being most important. **Please use each number only once,** and use all numbers 1 through 5.

7. Aesthetics (visual appearance of stormwater controls)

☐

8. Safety/Nuisance (e.g. standing pools of water; mosquitos)

☐

9. Low Implementation Costs

☐

10. Low Maintenance Costs

☐

11. Pollutant Removal/Environmental Protection Capabilities

☐

Section Three: Please select the choice that applies to you. You may select only one choice for each question.

12. Please select your gender:

○ Female

○ Male

13. Please select which applies to you:

○ I own land/a home/a building in this watershed.

○ I rent land/a home/a building in this watershed.

14. Select the age bracket that applies to you:

○ 18-19

○ 20-29

○ 30-39

○ 40-49

○ 50-59

○ 60-69

○ 70-79

○ 80-84

○ 85+

15. Select the income bracket that applies to you:

- Less than $10,000
- $10,000 - $14,999
- $15,000 - $24,999
- $25,000 - $34,999
- $35,000 - $49,999
- $50,000 - $74,999
- $74.000 - $99,999
- $100,000 - $149,999
- $150,000 - $199,999
- $200,000+
- Prefer not to say

Finally, is there anything you would like to add?

Thank you for your support in this research on your local watershed!

The survey can no longer be accessed since it has been closed. However it was located at: https://survey.vt.edu/survey/entry.jsp?id=1270612925397

Appendix B – Additional Explanation of the Analytic Hierarchy Process

This appendx contains information about the multiple criteria decision making model used in the BMPDSS in this study.

Introduction to Multiple Criteria Decision Making

Multi-Criteria Decision Making (MCDM) methods aim to facilitate and structure decision making when there are multiple, and often conflicting evaluations to be made on several alternatives. Most MCDM methods are made to solve objective problems where precise factual, mathematical, or statistical criteria are being considered, while some models are subjective, reflecting the user's moral or ethical opinions and judgements of non-mathematical criteria. Only a few models are capable of taking both objective and subjective criteria into consideration. (Massam, 1988) This research requires the use of a MCDM method that will allow the decision maker to choose the most appropriate stormwater management practice, based on many subjective and objective criteria, where there are several alternative practices that could be applicable.

There are many types of MCDM techniques available today. In choosing which method to use it is important to recognize the type of problem you are assessing. First, is the problem continuous or discrete? Meaning, could the outcome be one of an infinite number of alternatives or one of several defined alternatives. (Belton, p. 7) Multiple Objective Decision Making methods (MODM) are typically used for continuous problems, and Multiple Attribute Decision Making (MADM) is mostly applied to discrete problems. (Levy, 2005) MODM and MADM are two major types of MCDM. Additive MADM models are most commonly used for discrete problems, and there are several methods under this heading. (Massam, 1988) These models seek to reduce each alternative to a single score based on the cumulative addition of the criteria ranking for each alternative. That single score represents attractiveness of the alternative as compared to other alternatives. (Massam, pp. 49-50) Multi-dimensional scaling and outranking are two MADM methods that are appropriate when there are few criteria to be evaluated. (Belton, 1986) However, this research will be evaluating alternatives based on more than a few criteria. Literature suggests that there are two prominent discrete MCDM methods that consider evaluations with many criteria: Multiple Attribute Utility Theory (MAUT) and the Analytic Hierarchy Process (AHP). (Belton, 1986) MAUT is most appropriate in super-objective problem scenarios, as its main purpose is to maximize overall utility. (Zeleny, 1982) AHP offers the ability to evaluate subjective data and include stakeholders, which is necessary for this research. Lopez et al. explains AHP's overall abilities well: "AHP enables the incorporation of qualitative, subjective and intangible information, in complex decision-making problems and situations with multiple criteria, stakeholders and decision-makers, high uncertainty (lack of information) and high risk (what is at stake). These properties are useful in environmental assessment and choice," (Lopez et al., 2006)

Background of the Analytic Hierarchy Process:

The analytical hierarchy process is one of the most commonly used MCDM methods available today. (Belton, 1986) The method was developed by Thomas L. Saaty in the 1970s and since then, has been used, studied and refined for many problem studies in many fields all over the world. (http://www.business.pitt.edu/faculty/saaty.html) Daniel Schmoldt wrote, "The analytic hierarchy process provides the objective mathematics to process the inescapably subjective and personal preferences of an individual or a group in making a decision." (Schmoldt, pg.15) AHP is a comprehensive and mathematically structured method applied to solving problems that have multiple alternatives and the evaluation is based on multiple subjective and objective criteria. This decision making method uses a hierarchal structure to decompose a problem into levels of evaluation that can be weighted according to their impact on the level above. These levels are in the form of a goal, alternatives for that goal, and the criteria by which to evaluate the alternatives, (Saaty, 1988) AHP uses pairwise comparisons and vector algebra to weight the criteria and rank alternatives. The highest ranking provides the optimal choice for the user (Steiguer et al., 2003) This process allows the client to choose which criteria is more or less important based on individual needs and wants, so it takes into account both facts and opinions of the user. AHP can be used by an individual or groups to yield decisions reflective of each user's priorities. (Saaty, 1989)

Steps in the Analytical Hierarchy Process

There are three steps in implementing the Analytical Hierarchy Process:

1. Establish a hierarchy with an overall goal,
2. Do pairwise comparisons, and
3. Rank or weight possible alternatives.

In step 1, in order to establish a hierarchy with an overall goal, a user must construct a set of alternatives for reaching that goal and a set of criteria for evaluating the alternatives.

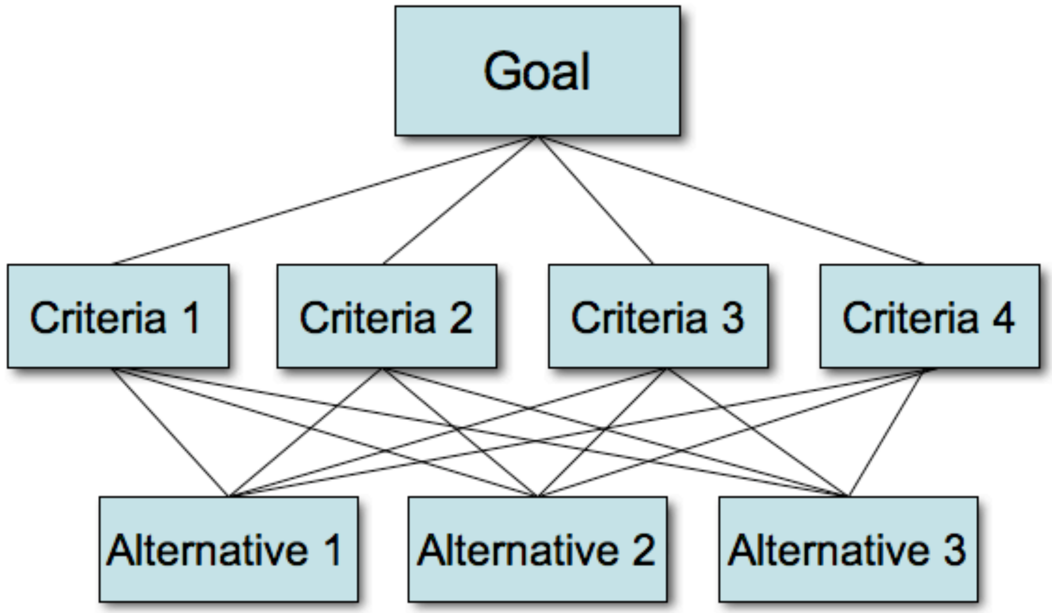


Figure 4. Analytical Hierarchy Process Diagram

For example, a client with the goal of purchasing a new house may find three houses (alternatives) that they are interested in purchasing, houses A, B, and C. With AHP, they would then choose some criteria on which to base their evaluation of each house. For this example, the client will evaluate their alternatives based on the following criteria: price, safety of the neighborhood, proximity to schools, and minimum of three bedrooms. (Most problems that are analyzed using the analytical hierarchy process are much more complex. This example is simple in order to illustrate the steps of the process more clearly). The example hierarchy for home-buying is illustrated in Figure 2.

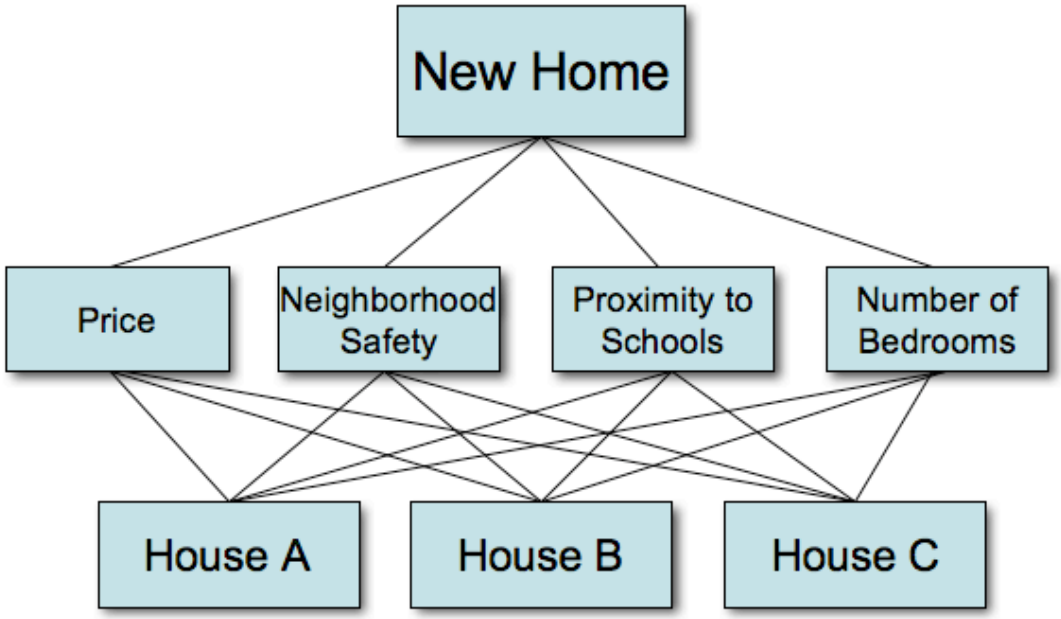


Figure 5. Home-buying Example Analytical Hierarchy Process Diagram

It is important to note, that in hierarchy development, the clients can choose any criteria they wish. The criteria can be based on scientific facts and mathematics, or simply opinions and estimations.

In step 2, pairwise comparison matrices are constructed in order to award a level of priority to each criterion. In this step, each individual criterion is compared, one by one, with every other criterion, using a scale of relative importance: 1-9 (Table 1).

Table 11. AHP Rankings scale of Importance (Berittella, 2007)

Numerical values	Verbal scale	Explanation
1	Equal importance of both elements	Two elements contribute equally
3	Moderate importance of one element over another	Experience and judgment favour one element over another
5	Strong importance of one element over another	An element is strongly favoured
7	Very strong importance of one element over another	An element is very strongly dominant
9	Extreme importance of one element over another	An element is favoured by at least an order of magnitude
2,4,6,8	Intermediate values	Used to compromise between two judgments

The client may say, for example, house price is much less important than the number of bedrooms, which is the most important criteria, and price is moderately less important than the safety of the neighborhood, which is still very important. Thus in this comparison, the client decided to award number of bedrooms an intensity of 9 over price, and neighborhood safety an intensity of 3 over price. In this decision, price has 1/9 the weight of number of bedrooms and 1/3 the weight of neighborhood safety. Table 2 shows the matrix that displays the level of priority awarded to each criterion in the example pairwise comparisons.

Table 12. Example Criteria Pairwise Comparisons

Criteria being weighted	Price	Safe Neighborhood	Proximity to a school	Min. 3 bedrooms
Price (least important)	1	1/3	5	1/9
Safe Neighborhood (moderately less important)	3	1	7	1/3
Proximity to a school (moderately important)	1/5	1/7	1	1/7
Min. 3 bedrooms (most important)	9	3	7	1

In this step, it is important to note that the priority rankings can be based on carefully measured standards, or the client's feelings and estimations. For example, number of bedrooms is an easily measured criteria with the unit being bedrooms. However, the different neighborhoods would most likely not have a unit of safety assigned to them, so the client would have to devise some manner of evaluating the neighborhoods. This could be based on an easily measured unit, such as the number of occurrences of criminal actions in the past ten years, or it could be based whether the client felt safe when entering the home and neighborhood. After all selected criteria have been weighted, pairwise comparisons of the alternatives are completed based on each criterion. For example, Table 3 compares the three houses based on proximity to schools. The rationale is that a distance between three and four miles is satisfactory, a distance between two and three miles is moderately favored, distance between one and two miles is strongly favored, and distance less than one mile is most favored. The client has decided that anything over four miles from a school is unsatisfactory.

Table 13. Example Alternative Pairwise Comparisons (based on criteria)

House X v. House Y	Distance to School (miles)		Preferred	Intensity
	X	Y		
House A v. House B	3.1	1.9	Y (House B)	7
House A v. House C	3.1	2.5	Y (House C)	5
House B v. House C	1.9	2.5	X (House B)	7

A preference intensity of 7 was awarded to House B in the first comparison because its distance of 1.9 miles from a school was strongly favored over House A's distance of 3.1 miles from a school. An intensity of 5 was awarded to House C in the second comparison because its distance of 2.5miles from a school was moderately favored over House A's. Finally, an intensity of 7 was awarded to House B over House C. This process of comparing the alternatives in pairs would be carried out for each criterion.

In the final step, ranking of the possible alternatives based on priorities is achieved. The process involves solving matrices based on application of vector algebra. A brief description of the mathematical concept is described below.

A rank of importance was awarded to each criterion in step 2. In step 3, this rank is multiplied into a vector weight, which is basically a percentage of importance as compared to other criteria's vector weights. Vector weight for each criterion is in the form of a decimal, and the sum of all criteria weights is equal one. The criterion with the highest decimal is of highest weight, preference, or importance. Vectors are also derived for each alternative based on each criterion and multiplied with the weight of that criterion. This number is usually a very small decimal. Finally, all of the values calculated using the criteria are added together for each alternative, and a decimal ranking is provided for each alternative. The sum of the decimal rankings of the alternatives is one. The highest decimal ranking represents the alternative that best achieves the goal in the decision being made.

Applications of the Analytical Hierarchy Process

AHP is used all over the world in a variety of different fields including, government, business, education, healthcare, and urban and environmental planning. It is also used in various decision-making situations, such as, choice, ranking, resource allocation, quality management, benchmarking (wikipedia.org). Although it does not have a long history of use in environmental fields, because of AHP's ability to evaluate qualitative and quantitative criteria, it is quickly gaining popularity in environmental decision-making situations. Some specific environmental applications of AHP include:

- Conflict Resolution- Examples: Integrated Watershed Management and global climate change mitigation strategies in transportation
- Regional and Urban Planning- Example: Site Selection-landfills
- Environmental Management- Example: Forestry Policy decision

Criticism of the Analytical Hierarchy Process

Although the Analytical Hierarchy Process has been widely accepted around the world and has become commonly used and taught in many sectors, it has its critics. In

2001, an in-depth article on AHP was published that discussed many critical issues related to AHP including, rank reversal, transitivity, and inconsistency in prioritizing criteria and alternatives (Forman, 2001).

According to the article rank reversal can occur when the addition or removal of an irrelevant alternative (often thought of as copies of other alternatives) changes the rank of the existing alternatives. This does not occur often and newer models of AHP have been designed to accommodate this. (Forman, 2001) Transitivity is best described through an example, using criteria A, B, and C. If a client says A is twice as preferable as B and B is four times as preferable as C, then A should be eight times as preferable as C. However, AHP allows each pairwise comparison to be assessed individually by the client, so there could be inconsistencies, or intransitive relationships formed. A user should be careful in assigning rank, however intransitive relationships do not often affect the final result. (Forman, 2001) Finally, the article mentions that there can be inconsistencies in prioritizing criteria and alternatives when translating a subjective opinion into an objective scale. This is certainly true, however, this has rarely caused any problems in the decision-maker's ability to reach a successful result. AHP was innately made to take both objective and subjective criteria into account. (Forman, 2001)

Justification for use of the Analytic Hierarchy Process

The Analytic Hierarchy Process was chosen for this project because of its ability to integrate both subjective and objective information in complex multiple-criteria problems, while minimizing conflict between numerous stakeholders, so the best decision can be made. Furthermore, previous applications of this theory have demonstrated its ability to facilitate decision-making in environmental fields. AHP will aid this research as the base of Virginia Tech BMP Decision Support Software (VT BMP DSS), a software that assists in decision-making for stormwater best management practices. The software will allow the decision maker to decipher the most appropriate stormwater management options based on their site conditions and personal priorities. This software will be discussed further in the Methods section of this proposal. AHP allows complex decision-making to be carried out in a simple and organized way, and is the most appropriate MCDM for the conditions of this project.

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Appendix C – IRB Approval Letter

MEMORANDUM
DATE: August 10, 2010
TO: Korine Kolivras, Erica Adams
FROM: Virginia Tech Institutional Review Board (FWA00000572, expires June 13, 2011)
PROTOCOL TITLE: Operationalizing Scale in Watershed-Based Stormwater Management
IRB NUMBER: 10-553

Effective August 10, 2010, the Virginia Tech IRB Administrator, Carmen T. Green, approved the new protocol for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at http://www.irb.vt.edu/pages/responsibilities.htm (please review before the commencement of your research).

PROTOCOL INFORMATION:
Approved as: **Exempt, under 45 CFR 46.101(b) category(ies) 2**
Protocol Approval Date: **8/10/2010**
Protocol Expiration Date: **NA**
Continuing Review Due Date*: **NA**
*Date a Continuing Review application is due to the IRB office if human subject activities covered
under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.