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ASSESSMENT OF THE HYDROLOGICAL IMPACTS OF HUMAN ALTERATION OF MARYLAND PIEDMONT STREAMS

By

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Abstract

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Istiak A Bhuyan

The hydrologic regime plays a vital role in aquatic ecosystems. However, these systems are altered by land use change and anthropogenic climate change. Urbanization increases surface runoff and decreases infiltration, while climate change affects precipitation. This study assesses the degree of hydrological impacts to the Maryland Piedmont using stream gauge data from twenty urban to rural sites from 1980 – 2014. Eight sites show significant increasing trends using the Mann-Kendall test, although all but one sites show increases. At the same time, base flow appears to be steady for all sites or decreasing over time. Piedmont streams share many characteristics regardless of size or landcover. August is typically the driest month, while March is the wettest; Winter months tend to have the least variation in discharge, while Summer tends to have the most. All sites responded in the same way to annual climate variations; for example, 2002 was one of the driest years for all sites, followed by one of the wettest years in 2003. Although all sites experienced the same wet years, it appears that rural and urban sites experienced drought in different ways, with urban watersheds having the worst drought in 1998, while 2002 was the driest on record for rural sites. Land cover had other effects as well. In general, urbanized streams have more flashy peaks in their hydrographs, and have a wider range of discharges but a lower median discharge than their rural counterparts. This research will be valuable to assess mitigation strategies in order to protect the ecosystem, infrastructure, and livelihood in the watershed where urban development is inevitable**.**

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Chapter One: Introduction

1.1 Introduction

Increasing human populations affect the natural environment by changing land use and increasing impervious surfaces (Graf, 1999; Poff et al., 2007). These changes drastically alter biological, geomorphic, and hydrologic processes (Kalnay, 2003, Wilk et al., 2001, Ring and Fisher, 1985). DeFries (2004) stresses the importance of assessing the effects of land cover change on streamflow because streamflow has control over other abiotic and biotic elements. Streamflow shapes the physical structure of the bed, banks, and floodplain of the stream, and affects the habitat and functioning of aquatic ecosystems (Leopold et al., 1992). The structure and function of aquatic communities largely depend on the hydrologic processes (Poff and Ward, 1989; Sparks, 1992). Data on the volume and variability of streamflow is needed to assess the condition of the natural hydrologic regime. Human activities commonly affect the flow patterns, velocities, and other hydrologic attributes of streams. These changes are often adverse. For example, drastic alterations in streamflow magnitude and frequency can degrade critical aspects of the streams' physical habitat (Bain et al., 1988). Increased watershed imperviousness is responsible for changes in flood frequency (Brath et al., 2006, Tollan, 2002), severity (Tollan, 2002), base flow (Wang et al., 2006), and mean annual discharge (Costa et al., 2003). Variability in precipitation, temperature, and evapotranspiration rate (Trenberth, 2011; Vörösmarty et al., 2000) can also change peak flows, flow routing times, and runoff volumes (Changnon and Demissie, 1996).

Understanding of the impacts of long-term climatic events and human alteration on the hydrologic regime of the Maryland Piedmont is imperative. It affects the ecological, economic, and water supply of the region. Most studies look at trends in hydrologic data; only a few tried to identify the contribution of either climatic variability or human alterations (Li et al., 2007a; Ma et al., 2008). The objectives of this study are to develop a generalized profile of streamflow characteristics of Maryland's Piedmont region and identify the effects of human alterations. A set of indicators will be established to assess the current condition of selected Piedmont streams. The Mann–Kendall rank correlation coefficient (Mann, 1945; Kendall, 1975) will be used to evaluate the streamflow trends within the region. The combination of the indicators and trend analysis will be used to analyze the adverse effects of human alterations on the streamflow.

1.2 Climatic Variability

Over the past 30 years, Maryland has become wetter and hotter, resulting in more runoff and longer heat waves (MDNR, 2014) More precipitation in the winter and spring, less rain in the summer, and more frequent and intense storm events are projected for Maryland. This will result in more frequent floods and droughts (MDNR, 2014). The increased likelihood of summer drought will affect stream ecosystems, which may lead to increased demand for irrigation and result in drinking water shortages. Distress in precipitation and temperature can drive long-term trends of increasing or decreasing stream discharge. Cyclical changes in climate such as the North Atlantic Oscillation (NAO) or El Nino are often overlaid (Massei, 2008, 2009; Bradbury et al., 2002) with these trends.

These drivers act together to yield day to day weather and ultimately help to determine the temperatures and amount of precipitation that falls on the basin scale.

Climatic factors such as precipitation and temperature, along with anthropogenic activities, such as irrigation, dam construction, and land use change can affect streamflow. The impact of these factors is quite extensive but remain poorly understood (Sun et al., 2008; Praskievicz and Chang, 2009). The International Panel on Climate Change (IPCC) Assessment Reports (Watson et al., 1996; McCarthy et al., 2001; Parry et al., 2007) examined the effects of climate change on stream flows. Other examples including George (2007), Lu and Jiang (2009), Rossi et al. (2009), Timilsena et al. (2009), Liu and Cui (2011), Zhang et al. (2011), and Bell et al. (2012); who also tried to explain how the climatic changes at regional scale impacts the natural streamflow variability.

1.3 Land Use Change

Land use/ Land cover change is one of the most visible ways to observe the human impact on nature and is more visible at the watershed scale than at regional scales. As the human population and economy continue to expand, we are changing more of the Earth's surface. Non-linear relationships, multi-faceted causality, and a lack of understanding of the hydrologic response complicate separating the effects of human alteration from climatic variation (Tollan, 2002). Juckem et al. (2008) studied a small watershed in Wisconsin and found that the timing of hydrologic changes coincided with changes in precipitation. However, the magnitude of base flow and stormwater runoff were amplified by changes in agricultural land management. Naik and Jay (2011) tried separating the human and climatic influences on the Columbia River hydrologic cycle. They examined records since 1858 to analyze human influences concentrating different usage including irrigation withdrawals, flow regulation, reservoir management, mining, and deforestation. Zhang et al. (2011) used a combined statistical and water-balance approach to separate the impact of climate variability on annual streamflow of a river basin from those by human activities.

1.4 Hydrologic Effects of Land Use

Changes in land use significantly impact the volume and speed of surface runoff. Vegetative cover captures most of the precipitation through interception and infiltration, even more in evapotranspiration by the trees (Hough, 1986). Open lands, such as a pasture or cultivated land, allows less infiltration than a forest area and is often more prone to runoff and overland flow, which can quickly transport exposed soil from cultivated fields. Impermeable surfaces (i.e. roofs, parking lots, and roads) allow no infiltration, forcing all water that falls on them to run off. Changes in land cover within a watershed can have dramatic effects on stream discharge and response to storms, either increasing total yield and increasing the incidence of flash floods, or decreasing and smoothing the hydrograph (Zheng, 2008). Humans also have intervened in the natural process by regulation of flows, building dams (Graf, 1999; Poff et al., 2007; Biemans et al., 2011), excessive withdrawals (Gerten et al., 2008), and land use change (Piao et al., 2007). These changes lead to a drastic variation in the magnitude and timing of stream flow and are instigating the decline in the health of aquatic ecosystems (Carlisle et al., 2011; Poff and Zimmerman, 2010). In some areas, water supplies have become severely stressed (Vörösmarty et al., 2000;

Alcamo et al., 2003). While most studies primarily focused on trend detection (Yu et al., 2002; Burns et al., 2007; Novotny & Stefan, 2007) or emphasized extreme water conditions such as flooding and drought (Lehner et al., 2006). However, relatively few papers have considered changes the entire flow regime, including the characteristics of flow variation, magnitude, timing, frequency, duration, and rate of change. Numerous studies have examined the impact of land use, withdrawals, dams, and/or climate change on streamflow or water resources over vast, diverse (regional, continental, or global) domains. They were primarily focused on irrigation withdrawals (Döll et al., 2009; Biemans et al., 2011), climate change (Arnell, 1999; Thompson et al., 2005), anomalies (McCabe and Wolock, 2010, Piao et al., 2007) on streamflow and surface runoff. These studies have mostly focused on the specific element of global change (i.e. withdrawals, land use, or climate) rather than the relative and combined effects. Moreover, the impacts of urbanization have been largely left unstudied at this global scale.

1.5 Research Objectives and Questions

To assess the specific hydrologic attributes of a stream affected by human activities, in-depth knowledge of hydrologic responses is required. Stream gauge data collected by the U.S. Geological Survey (USGS) is one of the primary sources to evaluate natural flow characteristics and quantify the alterations made by human influences. Daily stream data can also play a significant role to identify streams at risk for biological impairment from the loss of aquatic habitat. Analysis of streamflow has led to the identification of important temporal and spatial variations, but the availability of high-quality data (Dai and Trenberth, 2002) remains a principal limitation in streamflow studies. Human interventions and local non-climatic factors can also obscure the responses of catchments to 20th-century climate change (Bates et al., 2008). In addition to anthropogenic alterations, future changes in climate will likely further impact natural streamflow (Karl et al., 2009; Bates et al., 2008).

Most studies used streamflow as a driving force (Poff, 1997) of stream health and ecology (Richter, 1997), focusing on spatial and temporal variation in the natural flow regime (Stanford, 1996). Development projects such as dams, hydraulic power plants, and bridges alter the natural flow (Ward, 1997; Dynesius and Nilsson, 1994) of the stream and have environmental (Rosenberg, 1995) and ecological impacts (Johnson, 1998). On a watershed level, such impacts on hydrologic processes are reflected in fluctuations of the natural flow, which in turn have ominous effects on the ecosystem and environment. A better understanding of the effects of land use change on watershed processes has become a crucial issue for the sustainable development, planning, and water resources management (Potter, 1991; DeFries, 2004). Although studies have identified the impacts of structures such as dams and mills in Maryland (Allen, 2012), there is little information available about the changes in streamflow patterns associated with changes in land use in Piedmont Maryland. This study aims to examine the hydrologic responses to land use changes by comparing streams at a different level of imperviousness (rural and urban streams). The main research questions of this study are:

I. What are the general characteristics of streamflow in the Piedmont region of Maryland?

II. How has human alteration of the landscape affected streamflow over time?

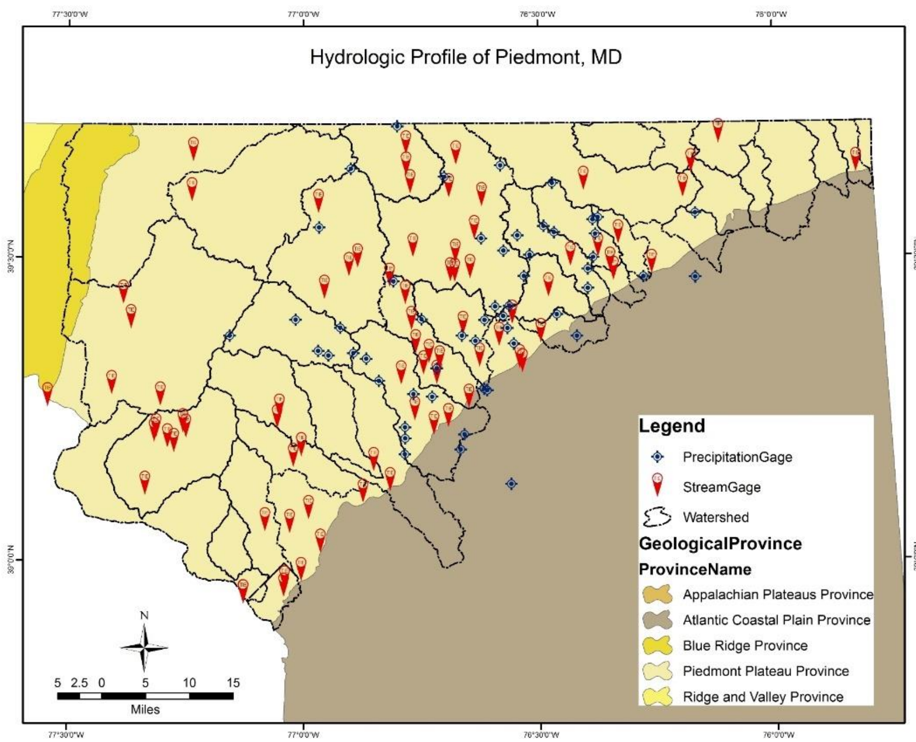
This study seeks a better understanding of hydrologic processes, including flow patterns and annual trend. It will strive to measure how the natural flow regime is changing due to land use changes. Results of this study may equip us to prepare for sustainable development, policy changes, and climate change adaptation in the future.

1.6 Study Area

Maryland, which covers 10,460 square miles, lies between 37°53' and 39°43' north latitude and between 75°04' and 79°29' west longitude. It is known as "America in Miniature[1]," because it spans several physiographic provinces. Maryland's elevation increases gradually from the Atlantic Ocean across the Coastal Plain to the Fall Line, where it rises rapidly through the Piedmont region (Figure 1) to the ridges of the Appalachian Plateau, climaxing in the Highlands of the Allegheny Plateau. Streams have rapid flow with a relatively steep gradient in the Piedmont and Appalachian Provinces. Numerous rapids and gorges offered opportunities for hydropower development, particularly adjacent to the fall line. This source was utilized locally by the early grain and grist mills. However, the present potential for hydroelectric power has declined (Vokes and Edwards, 1974).

[1] According to DiLisio (2004), the author of this moniker is unknown.

Figure 1: Map of the Maryland Piedmont



Mill dams in the area can increase the rate of erosion (Walter and Merritts, 2008). Sediments from early agricultural activity accumulated in the reservoirs of 18th & 19th century mill dams. Later, when these dams were abandoned, they frequently breached, leading to the entrainment of the stored 'legacy' sediments (Merritts et al., 2011). The mobilization of legacy sediments is mostly associated with larger flows, which tend to be seasonal and increasingly associated with urbanization (Allen, 2012).

1.7 Structure of the Thesis

This thesis contains six chapters. Chapter 1 begins with the Introduction and Research Question. Chapter 2 reviews the previous scientific literature on the impact of climate change and land cover change on water resources, with an emphasis on current observations and future projections. This chapter will also review statistical methods for identifying trends in hydrologic time series. Chapter 3 examines stream discharge data for twenty sites using various statistical analyses such as flow duration analysis to compare urban and rural watersheds. By substituting space for time, I am able to assume the effects of urbanization over time by looking at watersheds that have different levels of urbanization right now. Chapter 4 uses time series analysis to look for trends in stream hydrology due to increasing urbanization over time. Finally, Chapter 5 will discuss the main research findings and outcomes, while Chapter 6 will finish the thesis with the conclusions, limitations, and suggestions for future research in the Maryland Piedmont.

1.8 Summary

Streamflow is considered a critical factor in stream health and aquatic ecology, but it is not measured for the majority of rivers. The Appalachian Piedmont is an important geological province in the eastern USA that is rapidly urbanizing and home to several major cities and millions of people. Understanding the hydrologic cycle in the Piedmont and how human alteration influences it is essential to the future sustainable development of the area. This study will bridge the information gap between scientists and resource managers to determine where and when altered flows are a potential cause of poor stream health. This study will try to establish new statistical models for evaluating and predicting flow alteration using the river gauging network data and land use/land cover across broad geographic areas.

Chapter Two: Literature Review

2.1 Introduction

This chapter summarizes the literature on streamflow, climatic variability and water resources, hydrologic observations, trend analysis, and the impact of human alteration. The objective is to provide a comprehensive summary of recent approaches, identifying research gaps within the study area. The chapter begins by focusing on the importance of streamflow to humans and aquatic ecosystems. Then it provides the summary of how climatic variability stresses water resources and how to establish a general hydrologic profile of the region. Trend detection techniques applied in hydrologic analysis follows and finishes with a summary of the literature studied and how this thesis adds to the literature.

2.2 Streamflow

Stream flow is a primary source of fresh water and is indispensable to the health of the aquatic ecosystems and the natural flow regime. Humans have intervened the natural process by regulating flows, building dams (Graf, 1999; Poff et al., 2007; Biemans et al., 2011), excessive withdrawals (Gerten et al., 2008), and land use/cover changes (Piao et al., 2007). These changes lead to a drastic variation in the magnitude and timing of streamflow, which instigates the decline in aquatic ecosystem health (Carlisle et al., 2011; Poff and Zimmerman, 2010). The resulting water supplies have become severely stressed (Vörösmarty et al., 2000; Alcamo et al., 2003) in some areas. Most studies focused on trend detection (Yu et al., 2002; Burns et al., 2007; Novotny & Stefan, 2007), emphasizing the extreme water conditions such as flood and drought (Lehner et al., 2006). However, very few studies consider changes to the entire flow regime.

Land cover change alters the vegetative coverage, surface roughness, evapotranspiration, and subsequently, the runoff response of the watershed (Costa et al., 2003). Additionally, it leads to increases in water demand (municipal, industrial, and recreational purposes), changes the drainage network and the physical environment, and upsurges waste disposal is ensuing stress to streams and aquifers (Lindh, 1972). Precipitation events also trigger the intensification of runoff as imperviousness increases due to urbanization (Tang et al., 2005; Harbor, 1994; Costa et al., 2003; Galster et al., 2006; Kim et al., 2001; Siriwardena et al., 2006). Paved surface lessens infiltration and the time to peak (Simmons and Reynolds, 1982, Descroix et al., 2011; Ng and Marsalek, 1989; Nagasaka and Nakamura, 1999). Increase in urbanization can impact base flow due to drops in groundwater recharge rates (Harbor, 1994; Brun and Band, 2000; Rose and Peters, 2001; Ott and Uhlenbrook, 2004) leading to lower stream flows during the dry season (Cuo et al., 2009).

Physical characteristics of the watershed (topography, soil, and vegetation), climate and human activities heavily influence the hydrologic processes. Climate Change and other water-related issues have rendered the necessity of studying changes in these processes. Human activities are responsible for intensifying climate change and land cover changes (Scanlon et al., 2007) resulting the stress in a global hydrologic cycle in recent years

(Brutsaert and Parlange, 1998). On the other hand, land cover changes, such as deforestation or afforestation, have led to increased or decreased stream flows in different areas (Fohrer et al., 2001; Brown et al., 2005). Land use/land cover (LULC) change affects both human and physical environments and plays a fundamental role in various environmental and socioeconomic applications from local, regional, to global scales (Vitousek 1994; Foody 2002). LULC change has considerable impacts on streamflow and non-point source pollution (Bhaduri et al. 2000). With limited water resources and continuing development, sustainable management strategies of streams are important to prevent a water crisis. Many studies have tried to understand the influence of human activities and climate change (Chiew and McMahon, 2002) on natural hydrological processes. Some of them apply different models to analyze the responses of indicators to various watershed scenarios. Although the hydrological model is a powerful tool for such research, the results of studies have numerous uncertainties caused by shortcomings in the structure, limited time series data, parameter calibration, and scale problem coupled with a hydrology model (Zhang et al., 2011).

2.3 Water Resources and Climate Change

The Sun drives the climatic system and the hydrologic cycle. Both are intrinsically linked so that a change in one can induce a change in the other due to their in-depth inter-connection (Kundzewicz, 2004). However, greenhouse gas emissions and land use changes have altered the energy balance (Forster et al., 2007, IPCC, 2008). Anthropogenic greenhouse gasses emission is a very probable cause of the rise in global surface temperature over the course of the 21st century (IPCC, 2007a), and it is estimated that global mean surface temperatures have increased by 0.74°C ± 0.18° C (linear trend) over the last ~100 years (1906-2005) (Trenberth et al., 2007). It is expected that a warmer climate will lead to increases in evaporation and a higher specific humidity resulting in an intensification of the hydrologic cycle (Huntington, 2006).

A changing climate also has the potential to affect the intensity, timing, and frequency of precipitation events and their translation into the surface runoff (Bates et al., 2008). Based on location, these projected changes can have both positive and adverse effects. Changes in precipitation can be more variable than temperature, as precipitation is very site-specific and profoundly influenced by not only topography but also by local and regional atmospheric patterns (IPCC, 2007a). Thus, precipitation changes will not be translated linearly into hydrologic changes (infiltration or surface runoff), as these again depend on the catchment characteristics.

On a global scale, Maryland is considered to have a relatively low stress level with respect to the projected ratio of water withdrawals to water availability under the higher emissions (A2) scenario for 2050. As the Advisory Committee on the Management and Protection of the State's Water Resources noted in 2004, Maryland has enough water to meet present and future needs. However, the current projections indicate that flooding will increase: 100-year floods will increase by 10-20 %, and 10-year storms will increase by 16-30% in recent years. There is a greater probability that more intense rain and windstorms will hit Maryland as ocean waters warm up, accompanied by higher storm surges. Increased frequency and variability of extreme rainfall may lead to flooding, surface runoff, and high energy flows, impacting water quality, stormwater infrastructure, and water and wastewater treatment infrastructure. Therefore, due to this nonlinearity, possible changes can have both positive and adverse effects on the hydrologic system (and no effects at all) depending on the sign, magnitude of the modification and the geographical location. For example, a higher temperature can result in increased evapotranspiration with increased atmospheric water-holding capacity. It can cause water loss from the soil surface (Dai et al., 2004) or create stress on growing demand for potable water for domestic or agricultural use. Whereas an increase in the magnitude of a rainfall event has the potential to cause damaging floods or increased erosion and might adversely affect water supply systems and water abstraction due to decreased water quality, high turbidity, and disrupted systems.

Localized information on possible future impacts is needed, to anticipate changes and to devise appropriate adaptation measures, to reduce exposure or develop coping strategies. At the local scale, the greatest uncertainties and challenges exist for identifying climate change indications (Stott et al., 2010) and modeling future impacts (Milly et al., 2005; Nohara et al., 2006). Hydro-climatic information and historical records from monitoring networks have always played an important part in decision-making in water management, especially in planning and operating water resource systems. However, with anthropogenic-induced climate change and the possibility of experiencing new or changing hydro-climatic conditions, alternatives in addition to the traditional approaches to water resources planning and management are needed to adapt successfully to these anticipated changes. Long-term hydrologic observations will always play a major role in providing data for detecting and quantifying changes along with possible trends, hydrologic modeling, evaluating projected future conditions and appraising possible adaptation strategies for sustainable planning and decision-making.

2.4 The Role of Hydrological Observations

Any climatic changes are more likely to result in impacting the physical environment especially the hydrologic cycle. It may trigger stress in water availability for municipal and industrial use, changes in water demand for irrigation, quality water deterioration, higher surface runoff of stormwater and wastewater, or sea level rise. Long-term historical records are more beneficial to hydrologist rather than short time records because they are not influenced by any noise or natural variability (Cohn and Lins, 2005). Evaluating the historical data as time series analysis is beneficial because of: (1) understanding of natural variability; (2) developing accurate representations of streamflow, and (3) establishing a baseline for model development. It will also help to determine the changes in hydrologic cycle, the forecast of future stress, and sustainable design too for water quality, aquatic ecosystem protection, and flood hazard mitigation. In the context of changing climatic conditions, such measurements can provide critical information for understanding variability within observations, the detection, and attribution of emerging climate change signals (Burn et al., 2012).

Observational hydrologic data has always played a major role in appraising decisions in water resource sector to assess different planning options. For example, past hydrologic records have been used to provide information about future water availability and to design water infrastructure considering other factors including current and expected water demand increases due to population growth. Traditionally according to the principle of stationarity, water resource systems have been developed based on historical hydro-climatological information. Assuming that streamflow will remain unaffected in future, with some inter-annual or inter-decadal variability. In hydrology, stationarity refers to the perception that stream flow varies within static lower and upper bounds, defining the maximum variability extent (Milly et al., 2008). However, if climate, the main driver of the hydrological cycle is changing, this assumption of stationarity may no longer be valid. Moreover, additional information on whether and how the hydrological system is changing is needed. In hydrologic data, changes in time series can affect all parts of the flow regime. For example, the high, mean, and low flows, and the timing and frequency of streamflows of a certain magnitude. Such changes may be evident themselves as a gradual change over time, which can occur as a linear change, as several smaller step changes or in a curved manner (Hirsch et al., 1991; Kundzewicz & Robson, 2004). Step changes/regime shift as rapid change of the magnitude of trend at one change point or multiple points in the time series or oscillations with or without period clusters can also happen, as they are presented in the time series as shown in Figure 2.

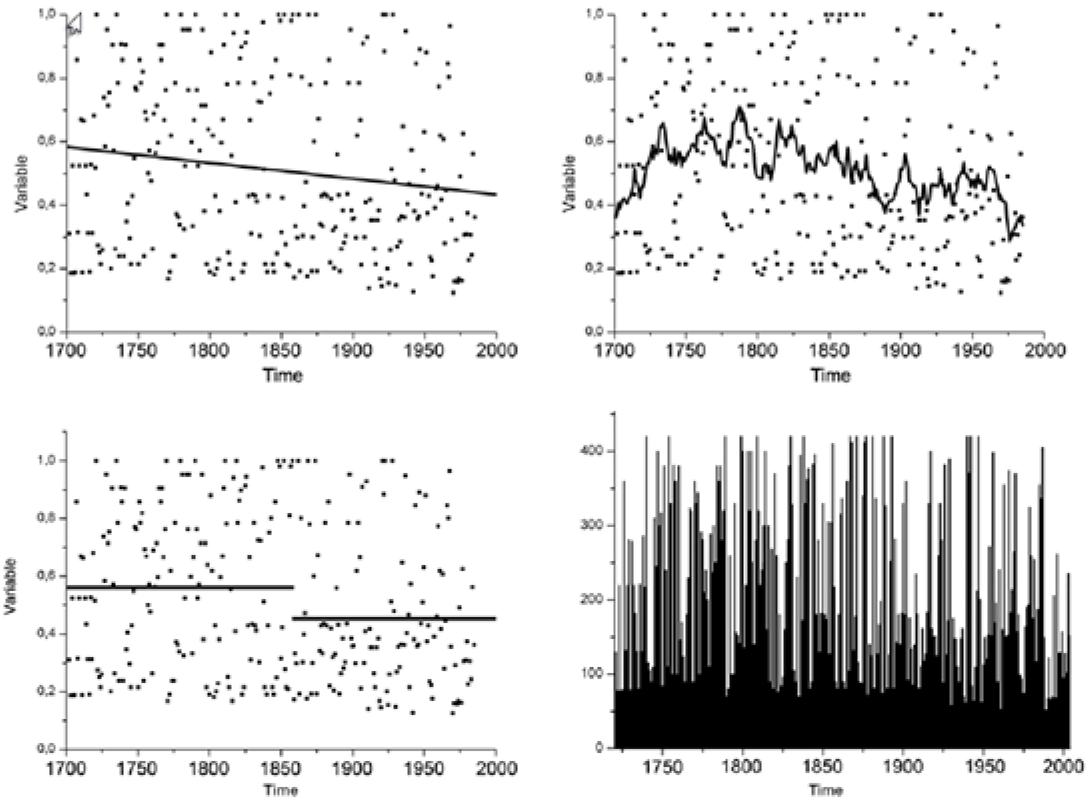


Figure 2: Time series with possible characteristics of a) trend, b) oscillation, c) regime shift or d) noise (Omstedt, 2005)

Evaluating records of an existing monitoring network for hydrologic research is indispensable. Many studies have established and used data for the determination of the effects of climate variability and changes in hydro-climatic variables (Birsan et al.; 2005, Hannaford & Marsh, 2006, 2008; Hodgkins & Dudley, 2006; Khaliq et al.; 2008, 2009; and Hannaford & Harvey, 2010). Burn et al., (2012) showed that only ~30% of the studies used data from pristine catchments or near-natural catchments with limited disturbances such as land use change or water abstractions. The benefit of using data from an active network is that it can be analyzed for long-term trend as the time-series has reached an appropriate length for any analysis to be statistically significant. An inadequacy of such an approach is that these networks were often established for observational purposes other than hydro-climatic extreme events (Burn et al., 2012). Depending on the purpose, some parts of the flow regime will have better accuracy than others. Therefore, only a few hydrologic monitoring stations perform well across the entire range of flows (Hannaford & Marsh, 2008). Consequently, the quality of data might not be ideal for the purpose of monitoring an anthropogenically induced climate change signal. As a result, a rigorous quality control process, including meta-data information for the time series used should be recommended (Kundzewicz & Robson, 2004). Moreover, only appropriate data should include for further analysis. Such a thorough selection process of measuring stations and their associated time series can limit the number of usable sites and might affect the coverage if the regional analysis performed, and spatial representativeness of study sites over large areas is needed. A reference hydrologic dataset can provide quality-controlled data sets for the detection of climate-driven changes in streamflow. Therefore, some countries have specifically assigned stations to such networks, to allow the assessment and identification of such changes. The networks consist of either existing and/or new hydrologic monitoring sites or have capitalized on existing sites for monitoring and detection of climate-driven trends in hydro-climatic records. Examples of these reference networks include the Hydro-Climatic Data Network (HCDN) in the USA (Slack & Landwehr, 1992), Canada's reference the Hydrometric Basin Network (RHBN) (Harvey et al., 1999), and the UK Benchmark Network (Marsh, 2010).

However, to analyze for a better understanding of general characteristics and trend in hydrologic data, other climatic indicators should also be analyzed. Alexander et al. (2006) investigated global changes in temperature and precipitation extremes and reported statistically significant changes in minimum temperatures and precipitation, although with less spatial coherence for the latter. Precipitation changes differ in magnitude a from region to region, reducing the global average change (Zhang et al., 2007). Therefore, the regional analysis is more applicable. Osborn & Hulme (2002) analyzed precipitation patterns in the United Kingdom from 1961 to 2001 and found daily precipitation tends to become more intense in winter and less intense in summer. These findings are also supported by an updated analysis of the data up to 2006 (Maraun et al., 2008). Based on the historical records from the HCDN of the USA, large-scale increasing trends in low flows were reported for the Midwest region (Douglas et al., 2000), while McCabe & Wolock (2002) were able to detect increasing streamflow for annual minimum flows and annual median flows in the eastern USA. In the Canadian Prairies, an influence of the temperature change on low streamflow in catchments with natural flow regimes was found, resulting in a declining streamflows from 1912-1993 to 1969-1993 (Yulianti & Burn, 1998). A later study on the timing of low flows in the RHBN up to the year 2003 showed that the majority of streams experienced trends indicating a shift towards earlier occurrences of winter low flow, whereas no predominant signal of earlier or later summer low flows could be detected (Ehsanzadeh & Adamowski, 2010). A pan-European study by Stahl et al. (2010) on low flows confirmed more recent national and regional trend studies, with increasing trends in winter and decreasing low flows for the regional low flow periods for most of the catchments investigated, especially in southern parts of Europe.

2.5 Trend Analysis

The hydro-climatic system is very complex in nature and requires an enhanced understanding of complicated time and space variations. To evaluate the trend in a hydrologic data series, it is important to consider the characteristics of data such as length and distribution, the structure of the data, the possible existence of monotonic or step trend, and seasonal fluctuations (Cluis et al., 1989). Some of the widely used trend detection techniques in hydrologic research are the Monte Carlo Simulation (Yue et al., 2002), bootstrap method (Douglas et al., 2000; Di Stefano et al., 2000; Chingombe et al., 2005), and regression analysis (Svensson et al., 2005; Shao et al., 2010; Timofeev and Sterin, 2010). Most of the climatic phenomenon exhibits non-stationary characteristics with non-normal distribution (Hirsch and Slack, 1984; Lattenmaier, 1988) and seasonality (Kundzewicz and Robson, 2004). They display some autocorrelation, and they are not independent. Therefore, a strong statistical test is essential in hydrologic research which will provide reliable result even if the data exhibits non-normal distribution or skewed without much manipulation. Based on the historical records, a non-parametric statistical analysis is performed in this study. The Mann-Kendall (MK) test which is a non-parametric test does not have any assumption on how the data is distributed (Yue et al., 2002).

The Mann-Kendall (Mann, 1945; Kendall, 1975) test is a rank-based non-parametric test. It assesses the randomness (Zhang et al., 2001; Déry and Wood, 2005; Kallache et al., 2005; Zume and Tarhule, 2006, Burn et al., 2010) of data against the existence of monotonic trend or not (Yue et al., 2003). The MK test is extensively applied in trend detection for hydro-climatic parameters because of its resilience to the skewed distribution, missing or null values, and outliers (Lins and Slack, 1999; Partal and Küçük, 2006). As the MK trend analysis is a rank-based test, it emphasizes more on the order of the rank rather than actual values. Thus, if there is missing values or outliers, the result would be affected much. It also produces significant results if there is a break in data series (Lemaitre, 2002; Chaouche et al., 2010). The MK test is deemed to be more applicable if the changes are gradual in nature (Chaouche et al., 2010). However, using the MK test is not always ideal. For normally distributed data, the Monte Carlo simulation (Önöz and Bayazit, 2003) and bootstrap based slope test (Yue and Pilon, 2004) yields better results regardless of their linearity. When analyzing trends in hydroclimatic time series, not only is it imperative to check for the trends but also how these changes oscillate within different time scales (e.g. intra-annual, inter-annual, decadal events). A traditional tool that has frequently been used to detect oscillatory signals is the Fourier Transform (FT), which uses sine and cosine basis functions. The FT provides time-averaged results and extracts details from the signal frequency but loses its temporal information (Drago and Boxall, 2002). As a result, the location of the frequency within the signal cannot be identified (Oh et al., 2003). Fourier analysis is more suited if the stream has low fluctuations and is often stationary (Labat 2005).

With the advantages of robustness and widely accepted in the scientific community for hydrologic research, applying MK test is not always ideal. If the dataset presents serial correlation that may lead to misleading results. Serial correlation may very often present in hydrologic data, and it may exhibit a significant trend when are is absent of a significant trend (Hamed and Rao, 1998; Partal and Küçük, 2006). Another common issue with the

MK test is identifying the slope after trend detection. Even though the slope may be negligible in magnitude, but it exemplifies the dissimilarity of statistical and practical significance. A trend can be statistically significant but may not have any practical meaning and vice versa (Yue et al., 2002). Ancillary information and judgment must be taken into consideration to interpret the results that are both statistically and practically significant.

2.6 Summary of the Literature Review

The literature review in this chapter originates with an overview of stream flow and how it is essential to both human society and aquatic ecosystems. The two principle forces causing the changes in the pristine condition are either human activity or climate change (Figure 3). Then it explores the possibilities, current research, and the challenges associated with the analysis of long-term hydrologic data to identify direct human alteration of stream flow or climate-driven trends. There appears to be no research asserting that either human alterations or climate change is more responsible for the current state of river systems, as they are reciprocal. So, it can be said that human-induced land use change impact the climate, and the climate acts as an active agent for streamflow changes.

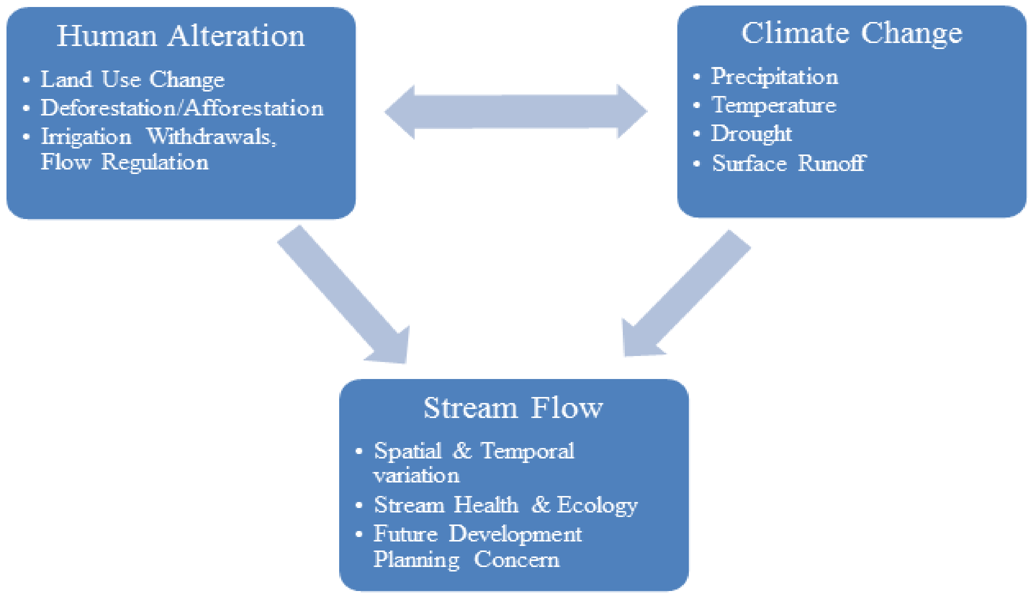


Figure 3: Conceptual Relationship between Human Alteration and Changing Climate Impacting Streamflow

Since rapid climate change and anthropogenic activities heavily influence the management of water projects, it is essential to better understand the effects of these two major factors on hydrologic processes. Based on the literature studied, empirical indicators will be developed to quantify the degree of change in streamflow variation within Piedmont Maryland. For change detection, trend analyses of historical observations are widely applied. And the Mann-Kendall test will be applied for trend detection in this study. This study explores how low flows and other empirical indicators impacted the water resources and may have changed due to climatic influences in Piedmont Maryland.

Chapter Three: Hydrologic Response of Maryland Piedmont Streams to Urbanization and Land Cover Change

3.1 Introduction

The objective of this study is to establish a hydrologic profile of the Piedmont in Maryland to determine the variability of the natural flow regime. This study plans to proceed in two steps to disentangle the impacts of urbanization from climate change on stream hydrology. The first goal is to establish the hydrologic profile by characterizing the natural flow regime of Piedmont area. The second goal is to identify a set of indicators that can assess the potential impact of human alteration on streamflow. This study will provide a comprehensive understanding of hydrologic processes, including flow patterns and annual trend. It will also attempt to measure how the natural flow regime is changing with human alteration and land use changes within the region. It will be useful to assess the baseline condition for future development projects and policy making.

3.2 Methods

3.2.1 Selection of Gauging Stations

This study uses the daily mean discharge for USGS stream gauge stations in the National Water Information System (USGS, 2001). The stations are located within the Maryland Piedmont and were selected using the following criteria, which was adapted from Murphy et al. (2013).

- Good and consistent hydrologic data quality (predominantly at extreme flow ranges)
- Near-natural flow regime - zero or stable water abstractions and discharges (impact less than 10% of flow at or more than Q95)
- Long record length (minimum 15 years)
- Stations must be representative of the hydrologic conditions within the Maryland Piedmont with good geographical coverage

The gauges are located upstream of dams so that they are not influenced by them. This study uses data from the years 1981–2014, where a water year extends from October 1 to September 30 (Gordon et al., 1992). The data series ideally need to be free from any other artificial influences for better results. Based on the selection criteria described above, twenty stream gauges were selected. They vary in level of urbanization and range in size from 0.07 to 143 km^2 (Table 1). These stations can be used to monitor and detect climate-driven trends in all ranges of the streamflow regime.

Table 1: List of stream gauges

Gauge ID	Stream Name	Drainage area (km^2)	Years of record	No. of years	Imperviousness (%)
1583580	Baisman's Run at Broadmoar MD	3.91	1999-2014	16	0.5277
1586210	Beaver Run Near Finksburg	36.39	1982-2014	33	1.8927
1581960	Beetree Run at Bentley Springs	25.1	1999-2014	16	
1589330	Dead Run at Franklintown	14.3	1980-1987, 1998-2014	25	35.425
1589100	East Branch Herbert Run at Arbutus	6.35	1980-1989, 1998-2014	27	34.183
1581870	George's Run Near Beckleysville	41	2000-2014	15	0.8106
1581830	Grave Run Near Beckleysville	19.94	2000-2014	15	0.1284
1581810	Gunpowder Falls at Hoffmanville	70.58	2000-2014	15	
1589197	Gwynns Falls Near Delight	10.46	1998-2014	17	16.340
1589238	Gwynns Falls Tributary at Mcdonogh	0.07	1999-2014	16	0.01
1585104	Honeygo Run Near White Marsh	6.14	1999-2014	15	10.638
1589440	Jones Falls at Sorrento	67.1	1996-2014	19	5.4096
1584050	Long Green Creek at Glen Arm	24.33	1980-2014	35	1.1577
1585230	Moores Run at Radecke Ave At Baltimore	9.1	1996-2014	19	28.274
1585095	N. Fork Whitemarsh Run Near Wt Marsh	3.37	1992-2009	18	24.564
1586000	North Branch Patapsco River at Cedarhurst	143.86	1980-2014	35	2.5850
1583100	Piney Run at Dover	31.98	1982-1988, 1996-2014	26	0.9786
1589340	Rognel Hgts Storm Sewer Outfall at Baltimore	0.06	1998-2010	13	35.3723
1585200	W. Branch Herring Run at Idlewylde	5.65	1980-1987, 1996-2014	27	23.469
1585090	Whitemarsh Run Near Fullerton	6.98	1995-2014	20	26.7446

3.2.2 Construction of Streamflow Indicators

Streamflow records were analyzed over the period of 1980-2014 for the twenty stations that met the criteria. It is desirable to work with a complete dataset in order to assess changes in the flow patterns. However, some stations contain data gaps with missing flow measurements. Anthropogenic changes to the hydrologic regime are not expected to be evenly distributed spatially or temporally.

Thirteen indicators of the flow regime were carefully selected from the literature and grouped into two categories: Graphical and Statistical (Table 2). These indicators will be used to compare the selected streams at different time periods. The four graphical indicators will establish the general hydrologic character of the flow regime, and include: Hydrograph, Mean Monthly Discharge, Flow Duration Curve, and a Base Flow Index graph. The nine statistical indicators include measures of the percent impervious land cover, as well as the minimum and maximum discharge values over one to 90-day periods.

Table 2. Indicators used in this study.

Graphical Indicators

- Hydrograph
- Mean Monthly Discharge
- Flow Duration Curve
- Base Flow Index

Statistical Indicators

- Mean Annual Discharge
- High-Flow Index
- Low-Flow Index
- Base Flow Index
- 1-day min/max ratio
- 7-day min/max ratio
- 30-day min/max ratio
- 90-day min/max ratio
- Percentage of Imperviousness

3.2.3 Graphical Indicators

3.2.3.1 Hydrograph

A hydrograph displays the discharge of a stream over time. It is one of the simplest ways to graphically represent the complex dynamics of the watershed by a single curve. The interaction between watershed characteristics and storm events shapes the discharge hydrograph. The volume of the runoff over a time interval is equal to the area under the hydrograph. The structure of the hydrograph is highly influenced by the storm events and physiography of the watershed. In general, the rising limb is often shaped by climatic factors, whereas watershed characteristics influence the recession limb. Watersheds with high vegetation and forest coverage have higher infiltration and storage capacities. Moreover, they offer larger resistance to surface flow, hence a larger base time and smaller peak discharges.

3.2.3.2 Mean Monthly Discharge

The Mean Monthly Discharge is a plot of the average discharge for each month over the time period of the analysis. It allows the visualization of the wettest and driest months of the year, making it possible to compare sites for changes in the timing and relative size of low flow and high flow conditions.

3.2.3.3 Flow Duration Curve

The Flow Duration Curve (Figure 4) is the cumulative frequency plot that demonstrations the percentage of time during which the discharge was likely to be equal or exceeded some specified value of interest. It is another way of representing stream flow data combining in one curve the flow characteristics of a stream throughout the ranges of discharge. Flow duration curves are generally divided in five zones, representing high flow (0-10%), moist conditions (10-40%), mid-range flow (40-60%), dry conditions (60-90%), and low flow (90-100%). These ranges can be used as a general indicator of the hydrologic condition of the stream.

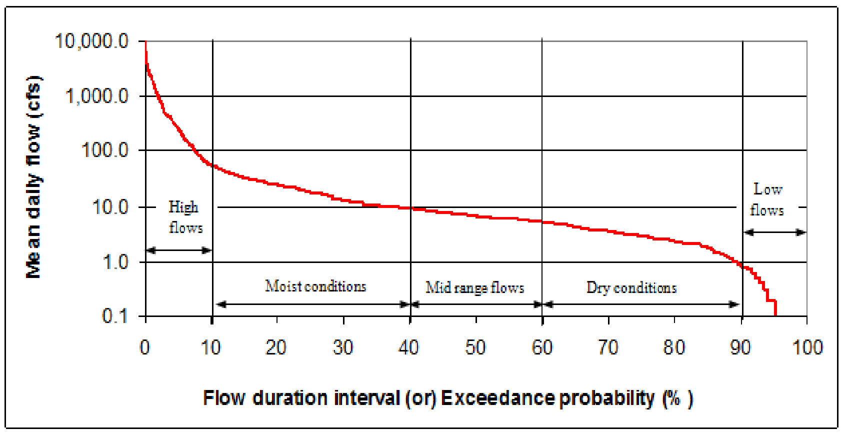


Figure 4: Representative Flow Duration Curve

3.2.3.4 Base Flow Index

Base flow is the relatively stable flow of any natural storage (i.e. aquifer, lakes) which is replenished by infiltrated precipitation or surface runoff. Often it is considered as the typical day-to-day flow in the watershed, and at times, it could be a lower value than mean annual flow, which is influenced by storm events (CWCB, 2008). Base flow is estimated through hydrograph analysis. Several analytical methods have been developed to separate base flow from the quick flow. The separation is often calculated by using standard analytical methodologies or tracer techniques or a mass balance approach (Pinder and Jones, 1968; McCuen, 1989). Neff et al. (2005), Scanlon et al. (2006) and Nolan et al. (2007) reviewed the relative advantages of several base flow separation methods including recursive digital filter methods. However, in hydrologic analysis, the Baseflow Index (BFI) is more widely used among researchers (Richter et al., 1997). The USGS has a BFI raster dataset (Wahl and Wahl, 1988, 1995; Wolock, 2003) but in this study, the Indicator of Hydrologic Alteration (IHA) software by the Nature Conservancy was used to calculate it. Baseflow Index is the ratio between the moving average of the seven-day minimum flow and the mean flow for the year.

3.2.4 Statistical Indicators

Stream flow and watersheds are dynamic systems that are naturally variable. This variability is essential to sustain ecosystem functions (Poff et al., 1997). The statistical indicators selected for this study will help us characterize the natural variability and the human alteration of it within the Piedmont Maryland. The statistical indicators developed in this study are listed in Table 3. The imperviousness of the watershed is collected from USGS Water Data and the other indicators are developed from the daily mean discharge data.

Table 3: Statistical Indicators

Indicators	Definition	Stream flow Impacts
Mean Annual Flow	The arithmetic mean of all of the individual daily mean flows for a given water year	Water Availability, Reliability of Streamflow
Percentage of Imperviousness	The percentage of the watershed that is covered by impervious surfaces	Higher surface runoff, Low percolation to ground water
Base Flow Index	Minimum 7-day mean divided by mean annual flow for each year	Degree of stressful low-flow conditions, standardized by a stream's mean annual flow.
High-Flow Index	(75^{th} – 25^{th})/50^{th} percentile	Variation of median flows
Low-Flow Index	(90^{th} – 10^{th})/50^{th} percentile	Variation of most flows
01-day Max/Min	Ratio of Annual Max and Min 01-day mean discharge	Structure of river channel morphology and physical habitat condition
03-day Max/Min	Ratio of Annual Max and Min 03-day mean discharge	
07-day Max/Min	Ratio of Annual Max and Min 07-day mean discharge	
90-day Max/Min	Ratio of Annual Max and Min 90-day mean discharge	

3.3 Results and Discussion

The graphical and statistical indicators were developed to help us to understand the natural regime of the Piedmont region. Together they characterize the changes to stream flow caused by land cover changes, precipitation, and human alteration of the gauged site. The gauges were selected carefully to not be impacted by any impoundments. Thus, the variations in these stations are due to the movement of water throughout the study area. The historical observation record analyzed covers water years through 1980 to 2014. Out of twenty gauged stations, only six stations are selected to discuss further here. These stations are:

- ❖ Urban Streams (imperviousness > 20%)
    1. Dead Run at Franklintown (1589330)
    2. East Branch Herbert Run at Arbutus (1589100)
    3. Whitemarsh Run Near Fullerton (1585090)

- ❖ Rural Stream (imperviousness < 20%)
    1. Beaver Run Near Finksburg (1586210)
    2. Long Green Creek at Glen Arm (1584050)
    3. North Branch Patapsco River at Cedarhurst (1586000)

3.3.1 Graphical Indicators

The generalized flow pattern of the Piedmont is illustrated below using stream hydrographs, graphs of the mean monthly stream flow, flow duration curves, and the base flow index. The hydrologic characteristics of Piedmont streams found in this study are consistent with findings of other representative rural or urban streams. The hydrographs (Figure 5) are relatively steady with sudden spikes after storm events. The steeper rising limbs are more prominent in urbanized streams than the rural ones. The mean daily flows in the winter season (November to February) are very low and do not differ much over the season because the steady baseflow dominates the low flows in the cold seasons. Due to snowmelt and breakup of river ice, March is the wettest month. Stream flow starts to lessen during summer and August seems to be the driest month. The daily flows over the warm season are quite different among the years, primarily because of the large inter-annual variations in spring snowmelt process and fall rainfall fluctuations.

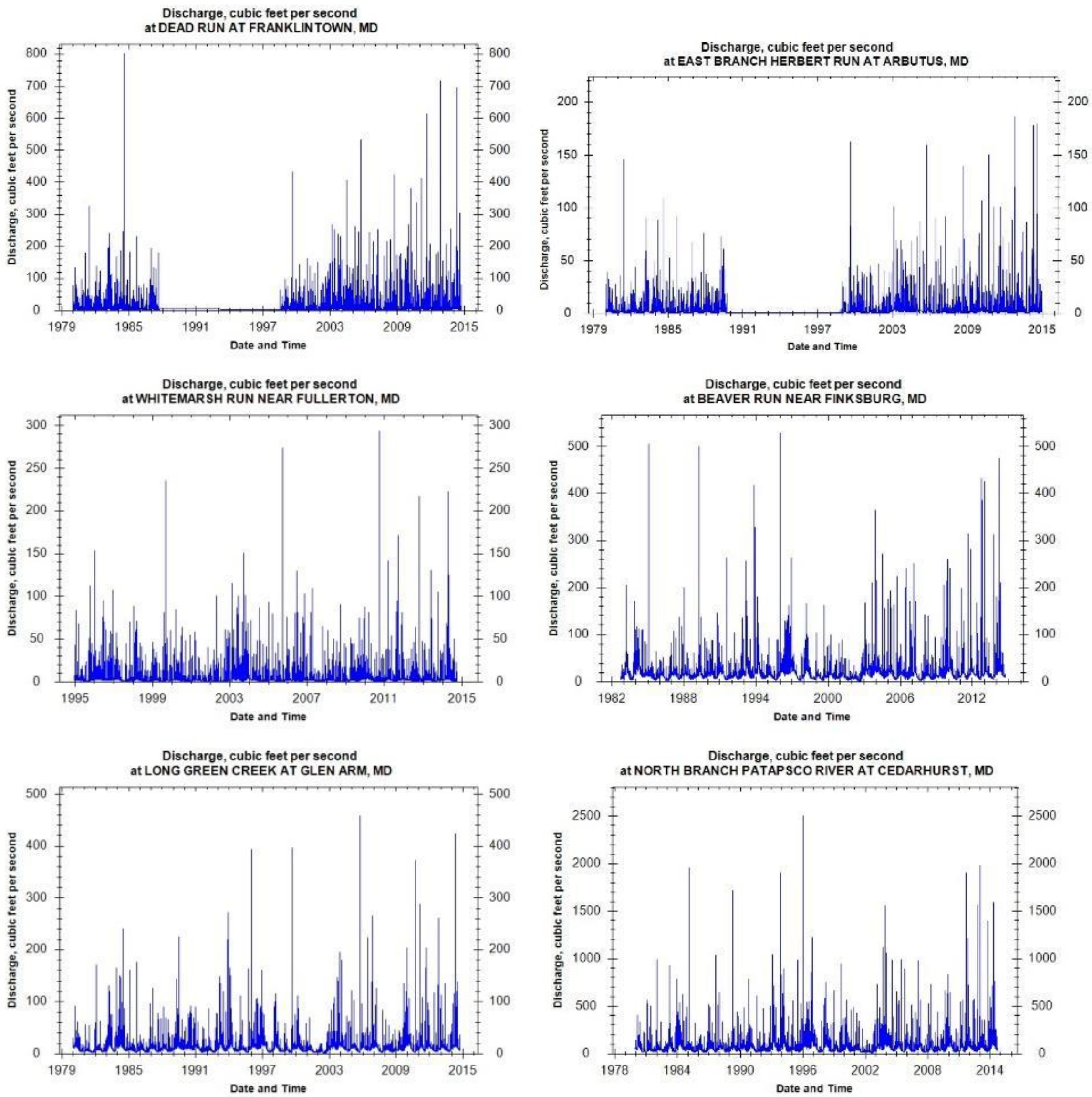


Figure 5: Hydrograph of Selected Watersheds

The mean monthly graph (log-based) in Figure 6 also displays similar results. March seems to be the wettest month, and there is a decline in streamflow until August. To fully understand the seasonal variation in long-term streamflow data: precipitation, direct runoff, evapotranspiration data are needed. Future research can be done examining how the climatic factors are influencing the seasonal variation in streamflow.

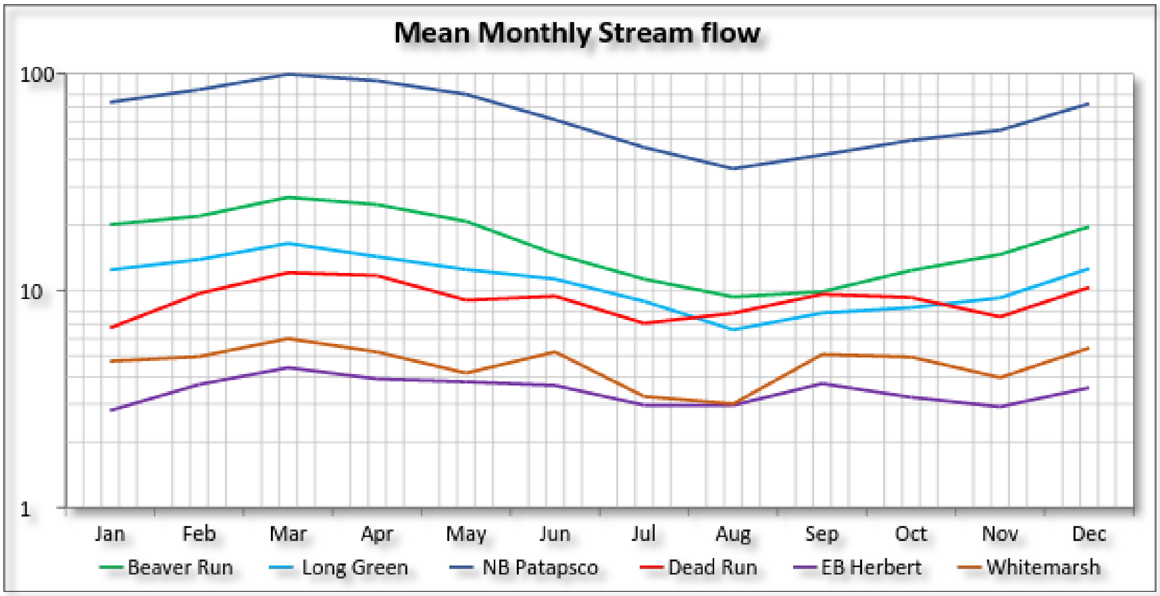


Figure 6: Mean Monthly Streamflow (log-based)

The streamflow pattern and seasonal variation are necessary for ecological balance, policy making, and development decision making. Most of the aquatic life cycle is synced with the seasonal variations; it is essential for their natural aquatic habitat. And a better understanding of streamflow pattern can help flow augmentation, river channeling where needed. It can be very beneficial for farming activities.

The Flow Duration Curves (Figure 7) for selected watersheds show comparable results to the hydrographs. The rural streams have higher median discharges than the urban streams, while the urban streams have a greater range of discharges. The rural streams have a narrower range of discharges for their median flow range (40-60%), making the hydrograph more horizontal in this middle range for the rural streams. The reason behind this phenomenon may be a higher percentage of imperviousness of urban streams leads to more surface runoff and less resident time for stream flow. The urban streams have relatively steeper curve during high flows for shorter periods, meaning they are more prone to flash floods. The regulation of streamflow by dams or reservoir storage exhibits much flatter and gradual curve like the rural streams. And the rural streams also show the relatively flatter curve comparing to urban streams, due to the moderate base flow sustained throughout the year in rural streams. The imperviousness in urban streams prevents water from percolating to groundwater resulting in base flow.

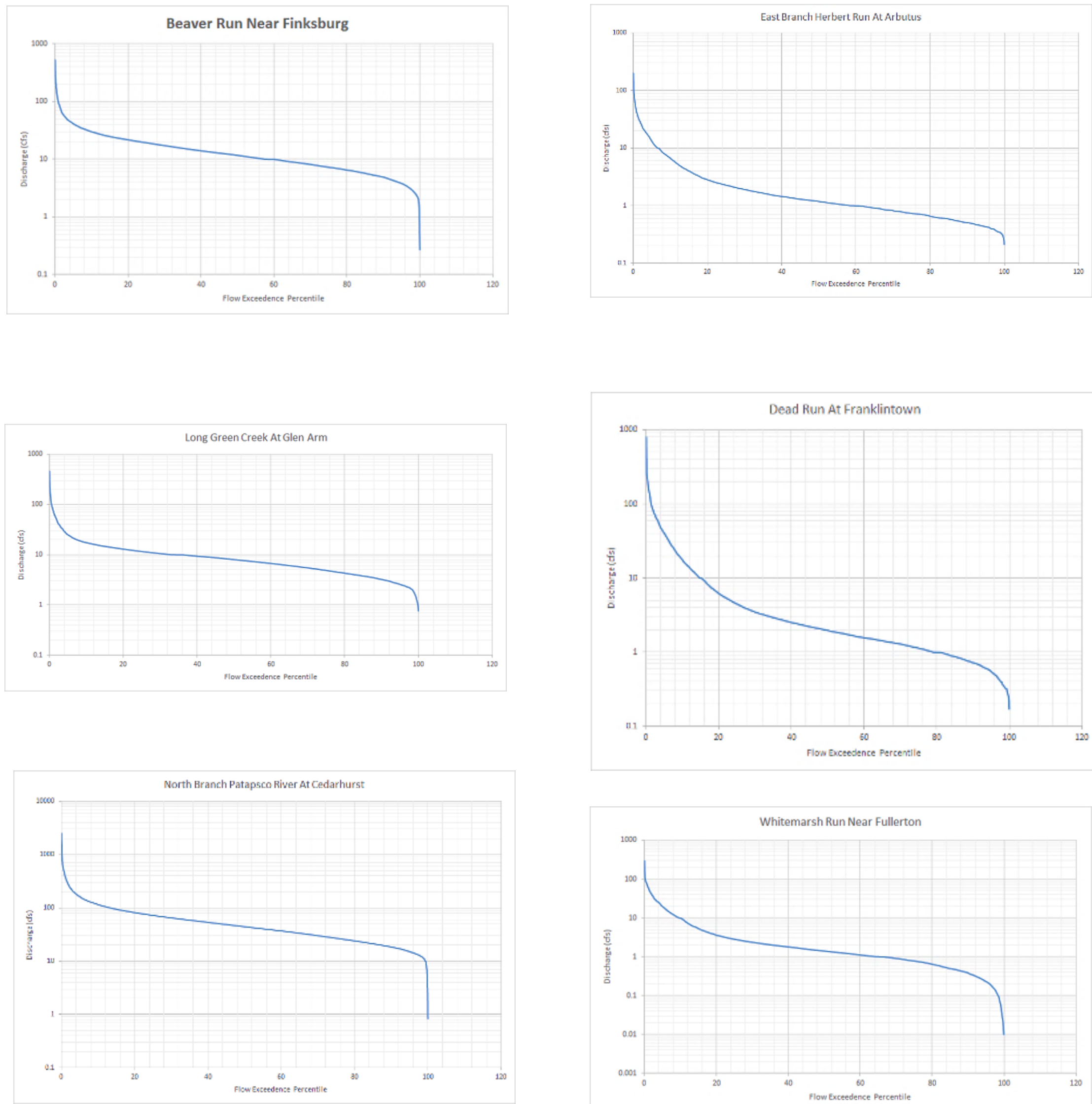


Figure 7: Flow Duration Curves of Selected Watersheds

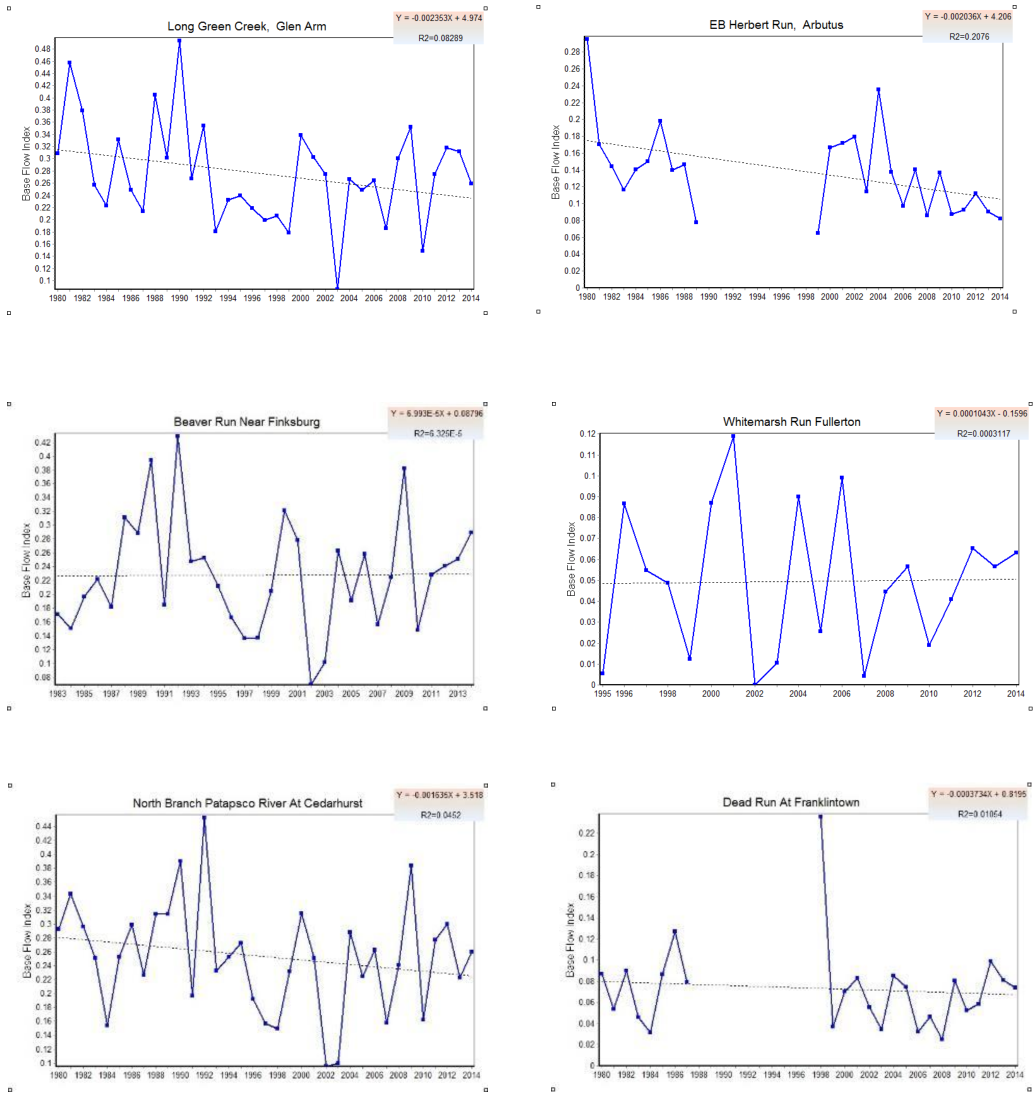


Figure 8: Base Flow Index of Selected Watersheds

Base flow Index (Figure 8) declines for most of the gauged stations over the analysis period. The urbanized streams show less variability and have lower index values than rural streams. Higher imperviousness prevents water from percolating to groundwater and causes more surface runoff, and may be the reason behind this phenomenon.

3.3.2 Statistical Indicators

Daily streamflow data from the selected stations are applied to summarize the natural flow regime in Table 4.

Table 4: Summary of Data Stations

Station ID	Imperviousness	Mean Annual Flow	Base Flow Index	Percentile (90-10)/50	Percentile (75-25)/50	1-Day Max/Min	3-day Max/Min	7-Day Max/Min	30-day Max/Min	90 Day Max/Min
1583580	0.528	1.72	0.277	2.031	1.023	54.545	24.951	13.086	6.955	3.105
1586210	1.893	17.20	0.223	2.083	1.058	66.774	34.781	20.464	8.485	3.741
1581960		14.04	0.374	6.413	1.413	37.447	18.231	9.329	4.472	2.384
1589330	35.425	8.89	0.074	9.000	1.650	572.727	197.76	109.272	18.425	3.681
1589100	34.184	3.45	0.139	5.158	1.300	254.286	95.094	47.746	11.331	3.041
1581870	0.811	21.51	0.280	1.650	0.813	63.333	30.265	15.187	6.411	2.783
1581830	0.128	10.35	0.297	1.671	0.299	38.000	21.938	11.325	5.787	3.022
1581810		36.69	0.286	1.778	0.963	50.619	24.242	13.091	6.187	2.983
1589197	16.340	0.03	0.138	2.241	0.828	200.000	87.265	40.799	14.659	3.967
1589238	0.010	5.45	0.224	1.783	0.957	119.130	43.931	20.211	8.465	3.045
1585104	10.638	4.02	0.076	4.564	1.386	816.667	358.20	89.846	20.555	4.460
1589440	5.410	32.60	0.238	2.050	0.950	85.811	35.516	18.921	7.185	3.017
1584050	1.158	11.21	0.266	1.838	0.888	53.600	26.490	14.736	6.703	3.449
1585230	28.274	0.29	0.031	8.000	1.592	700.000	293.30	167.400	28.815	3.910
1585095	24.565	65.87	0.252	8.345	1.745	71.923	30.358	17.240	7.130	3.395
1586000	2.585	2.27	0.024	2.156	1.011	2240.00	650.93	240.620	23.226	5.010
1583100	0.979	15.28	0.334	1.608	0.767	42.826	20.417	11.486	5.264	2.444
1589340	35.372	0.02	0.000	15.571	4.286				66.578	3.544
1585200	23.470	2.84	0.086	4.982	1.391	340.625	126.13	51.925	12.144	3.214
1585090	26.745	4.66	0.052	6.413	2.479	1094.74	341.15	109.658	20.192	3.894

3.3.3 Correlation Analysis of Parameters

A Spearman Rank Correlation analysis was performed using the ‘spearman’ function in Python’s SciPy stats module. Table 5 contains the correlations for variables that have a significant association at the 95% confidence level. Percentage of Imperviousness shows a positive correlation with both the Low Flow Index and the High Flow Index. But the correlation between mean annual flow and percentage of imperviousness is not statistically significant. Only the Base Flow Index shows moderate positive correlation with the mean annual flow. Moreover, both High and Low Flow Index displays a high degree of association.

Table 5: Spearman Rho Ranked Correlation Analysis.

Only significant values ($p < 0.05$) are displayed.

	imperv	MnAnnQ	BaseFI	LowFI	HiFI	1Day	3Day	7Day	30Day	90Day
imperv	1.0									
MnAnnQ	---	1.0								
BaseFI	---	0.660	1.0							
LowFI	0.616	---	-0.651	1.0						
HiFI	0.570	---	-0.584	0.911	1.0					
1Day	---	---	---	---	---	1.0				
3Day	---	---	-0.530	---	---	---	1.0			
7Day	---	---	---	---	---	---	---	1.0		
30Day	---	-0.688	-0.990	0.644	0.572	---	0.563	---	1.0	
90Day	---	-0.572	-0.827	0.477	---	---	0.454	---	0.842	1.0

3.3.4 Examining Statistical Indicators in the Context of Changes Over Time

A plot of the mean annual discharge (Figure 9) for the six example stations shows that all six sites experienced the same set of drought years and wet years. Summarizing from Table 4, the average of the twenty study sites is a mean annual flow of 12.92 CFS, ranging as high as 65.87 CFS for N. Fork Whitemarsh Run near White Marsh, and as low as 0.02 CFS for the Rognel Heights Storm Sewer Outfall at Baltimore.

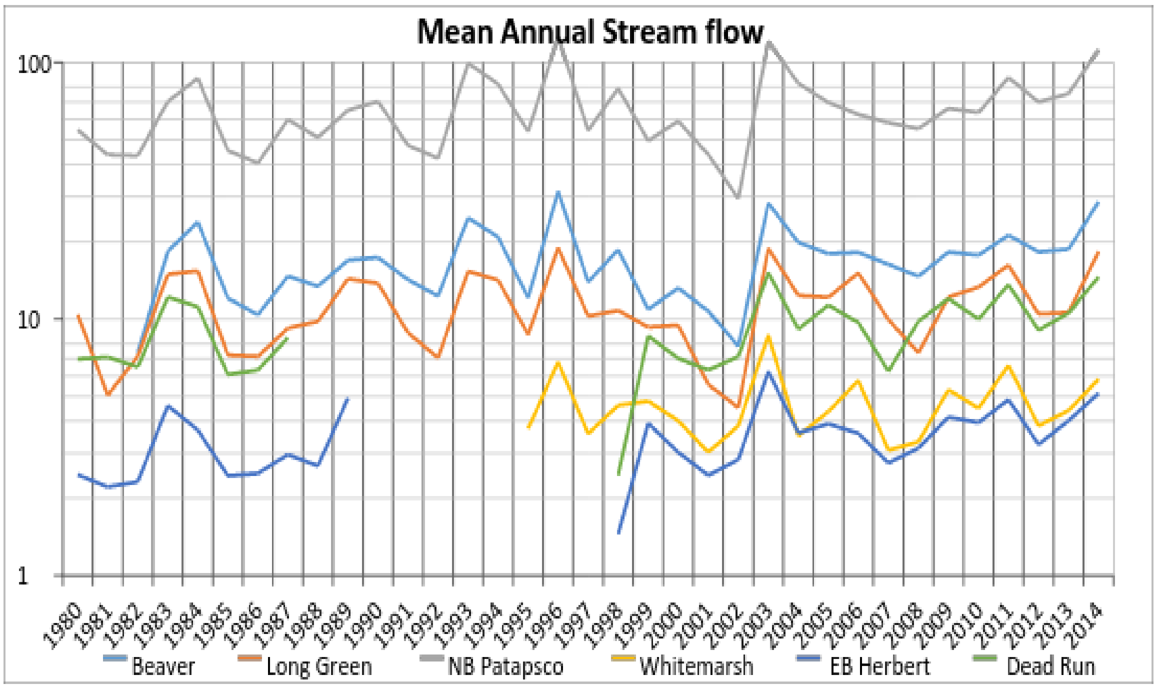


Figure 9: Mean Annual Streamflow (log-based)

It appears that urban and rural streams experienced the most extreme drought in different years (Table 6). The driest years were 2002 for rural sites, and 1998 for the urban sites. This unusual phenomenon needs further investigation. Furthermore, it was curious that the driest year or second-to-driest year of 2002 was followed by the wettest or second-to-wettest year of 2003. This would seem to indicate that the system is sensitive to climatic variability when it is present.

Table 6: Comparison between Highest and Lowest flow year

	Rural Stations	Urban Stations
Lowest Streamflow year	2002	1998

The mean annual flow variability ranges from 0.02 CFS to 65.87 CFS. The high flow percentile varies from 1.6 CFS to 9.0 CFS where average flow percentile ranges 0.77 CFS to 1.65 CFS. The standard deviation for them is 3.65 and 0.84 respectively. The smaller standard deviation for average flow indicates that they are relatively close to mean. Which supports the steady base flow throughout the region, but it increases a little between March and June and decreases during August through October. The variability for high and low flow occurrences of 01 -, 03 -, 07 -, 30 – and 90 – day are also summarized in Table 4. The yearly base flow index was illustrated in Figure 8 for each station. The BFI graphs indicated the small range of variability for the low-flow events is consistent with groundwater discharge comprising a significant portion of observed base flows in Piedmont regions.

Based on the data, it can be said that the flow variables increased as the percentage of the urban area increased. The stations with lower imperviousness have comparatively higher mean annual flow and base flow. Moreover, more urbanized catchments exhibit relatively higher average flow and high flow percentile. It also can be said for the shorter time period the catchments with lower imperviousness shows higher flow variability. However, the phenomenon changes over time and becomes reverse. So, urbanized areas slowly and gradually increasing streamflow and natural variability. In most cases, human alteration by land use change is responsible for these changes.

3.4 **Summary**

It appears from this analysis that as imperviousness increases, there is the probability of more extreme flow patterns (flash floods, surface runoff) with a moderate decline in base flow as seen in the Base Flow Index. But the mean annual flow might not be affected by these increases in flash flooding.

Streamflow detected at the watershed level reflects the integration of natural variations, climatic events, and human-induced changes. Lately, the development of indicators to assess hydrologic variability from long-term data become very imperative for aquatic health (Arthington et al., 2006). To comprehend the complexity of natural stream variability requires many parameters. There is also a need to reduce the indices commonly used in Indicator of Hydrologic Alteration (IHA). It is a very powerful and useful tool in hydrologic research. But it requires to download the software, install it into a system. And then insert the data; create a project to run the analysis. It can compare two-timeframe of a single station but could not compare two stations. The main objective of this study is to eliminate all those processes. IHA uses 33 parameters to evaluate the stream condition. Here, only thirteen indicators were able to represent the aquatic health. It seeks to evaluate methodically long-term (1980 - 2014) daily flow data of the Maryland Piedmont to quantify the flow variability in response to human alteration. The graphical indicators depict the generalized view of the region. However, the statistical indicators yield some interesting results. The gradual increase in streamflow highlights the effects of an increase in impervious surface within the region. Even though, the other impacts of urbanization i.e. increase in water demand were not taken into consideration. A year to year land use change study can provide better understanding in this regard.

Human alteration and climatic fluctuations affect the natural variability in streamflow. However, the main challenge is to determine and separate the effects of these two on flow changes (Yang et al., 2004; Lu et al., 2013; Lu and Jiang, 2014). The study was able to establish the significant effects of urbanization on the hydrologic response of the watershed. Its findings also ask more question which needs further investigation. Future research should: (1) investigate storm-based streamflow analysis; (2) consider the year to year land use change data; (3) comparing highest and lowest flow years of urban and rural streams.

Chapter Four: Trend Analysis of Piedmont Maryland Streams

4.1 Introduction

Urban development and climate change are two possible explanations for long-term changes in stream discharge. Land cover changes associated with urbanization can play a decisive role in the alteration of streamflow and surface runoff (Kuchment, 2004). Zhang et al. (2007) concluded that precipitation variations in the Northern Hemisphere have anthropogenic origins, causing precipitation increases in the mid-latitudes, and decreases in the subtropics. Natural variability cannot explain the trend of the global surface temperature of last 30 years (Hegerl et al., 1996). Instead, many studies tried to link streamflow to anthropogenic change with climate variables, including temperature (Santer et al., 2011; Allen and Stott, 2003; Hegerl et al., 1996), precipitation (Zhang et al., 2007, Min et al., 2011), and snow melt (Barnett et al., 2008; Pierce et al., 2008).

The previous chapter (chapter three) found a static, direct relationship between the degree of urban land cover and several measures of stream hydrology. Because the land cover is not static but increasing monotonically (increasing without periods of decrease), it would stand to reason that stream hydrology should also be changing over time in response to these changes in land cover. In this chapter, I investigate changes in stream hydrology over time to answer the question, "How are streams in the Maryland Piedmont changing over time in response to changes in land cover and climate change?" To answer this question, the following three techniques are applied:

1) Standardized Departure Analysis: examine the deviation of stream discharge from the annual mean,
2) Mann-Kendall Test: to determine the presence of a statistically significant trends in stream discharge, and
3) Sen's Estimate of Slope: to estimate the rate of change, if any, in stream discharge.

4.2 Methods

Twenty stream gauges were selected from the Piedmont of Central Maryland (Table 1, Figure 1). These gauges measure discharge from a variety of watersheds; some watersheds have undergone rapid increases in impervious surfaces over the past 60 years, while other have remained largely rural or suburban, with a much lower coverage by impervious surfaces. A dataset of the last 30 years, from 1980 to 2014, is used for the analysis. Although forty years' worth of data is considered satisfactory to conduct a trend analysis study (Partal, 2010), some other authors have also used forty years or less for their trend analysis studies (e.g. Domroes et al., 2005; Chaouche et al., 2010; Makokha et al., 2010; Karaburun et al., 2011).

4.3 Standardized Departures Analysis

The Standardized Departure Analysis (Figure 10) was conducted on three urban and three rural watersheds. This analysis subtracts each station's long term (1945 to 2019) mean discharge from each year's mean annual discharge for that station, and then standardizes the value by the standard deviation. Figure 10 displays the standardized annual mean discharge of rural streams in green and urban streams in red. In general, all six sites display the same pattern of dry and wet years, with 2002 being an especially dry year, and 2019 being an unusually wet year. All six sites appear to have similar levels of variability over time. Trends in discharge will be evaluated later using the Mann-Kendall test, but a visual assessment of figure 10 appears to show annual discharges increasing since 2000 for all six sites. Based on the demographic data, the Piedmont region had the highest annual growth during 2000-2010. Lins et al. (1999) and Douglas et al. (2000) have also found increases in annual stream flows in the eastern U.S.

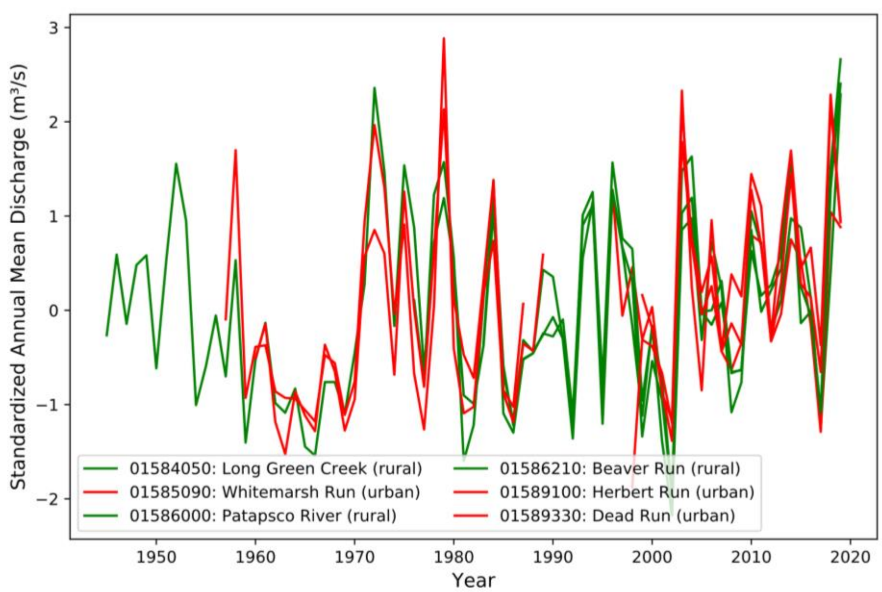


Figure 10: Standardized Departures Analysis of Urban and Rural Streams

For both urban and rural streams, the changes after 2000 appear to be a gradual increase rather than an abrupt step change to a different regime. Gradual trends versus sudden step changes in streamflow have different consequences. Trends indicate a continual change with no indication of an eventual maximum, while step changes indicate a shift in a new regime that will likely remain the same. The nature of the change (trend or step), also has policy and sustainability implications. For the Piedmont region, the progressive increase in the stream flow with the steady base flow for urban stream indicates that the area may be becoming more susceptible to flash floods, higher surface runoff, and increased water pollution. These are locally caused problems that can also be solved locally with policies directed towards limiting impervious surfaces.

4.4 **The Mann-Kendall Nonparametric Test for Trend**

Non-parametric tests are widely applied for the analysis of hydrologic data, which is subject to a lack of normality and right skew. For detecting trends, a commonly used statistical test for hydrological data is the Mann-Kendall nonparametric test (Mann, 1945; Kendall, 1975), which is used to assess the presence of a monotonic trend, or a trend that is increasing or decreasing over time, but not changing direction. The MK test uses ranks to determine the presence of trends and may be used in cases with missing and non-normally distributed data. A minimum 25 years of data are required to attain a significant result in a time series analysis (Burn et al., 2002). In this study, the Makesens (2002) macro for Microsoft Excel is used to perform the Mann-Kendall test on the data for selected stations. The MK test statistic S and the variance were calculated for each dataset to obtain the standard normal value, Z-score. In the data analysis of this study, the significant level used was α = 5% (or 95% confidence intervals) for a two-sided probability. The absolute value of this Z-score was then compared to the critical two-tailed Z-value (area under the normal curve) of α/2. The Z values in a two-tailed test for α = 5% are ± 1.96. If the calculated MK Z-score is outside the range of -1.96 and +1.96, the trends are statistically significant.

The null hypothesis (H_o) is there is no trend, and annual mean stream discharge is increasing and decreasing randomly. The alternative hypothesis (H_1) is that a positive or negative monotonic trend exists. Moreover, that as we examine values at the end of the time series, they are probably to be higher or lower than the values at the start of the time series (Hirsch and Slack, 1984; Mohsin and Gough 2010; Karaburun et al., 2011). The Z value is calculated by examining the standard normal cumulative distribution; a positive Z score indicates an increasing trend, while a negative Z score indicates a downward trend in annual mean stream discharge. Moreover, the annual time series is considered in the study to investigate events that are fluctuating in long terms, such as multi-year and decadal events.

4.5 Sen's Method for Estimating the Slope of a Trend

The Sen (1968) nonparametric method for estimating the slope of a trend was also performed using the Makesens (2002) macro. The Sen's method can be applied where the trend can be assumed to be linear, although it allows missing data. This algorithm produces estimates of a linear equation to fit the distribution of annual mean discharges over time.

4.6 Results and Discussion

The Mann-Kendall test is applied to analyze how the trends in each time series used in this study have varied over the study period. The modified MK test is applied for each gauge stations from the start to the end of the study period. The standard normal Z-score can be used in the MK test only when the number of observations in a dataset is more than 10. The results of the MK test and the Sen's Estimate of Slope are shown in Table 7. Five stream sites have significant (95% confidence level) upward trends, while no sites have a significant downward trend. Of the five stream sites with significant upward trends, four are considered urban due to a high level of impervious surfaces. All stream sites except three have positive slopes. The Q column is the Sen's estimator for the true slope of a linear trend, expressed as the amount of change per year. The B value is the estimate of the constant, or the Y-intercept, or can be interpreted as the estimated annual mean discharge for the first year of the series, 1980. The Makesens Marco also produces graphs with a trend line. Six selected graphs are displayed below in Figure 11, while the rest of the stream gauge figures can be found in Appendix I.

Table 7: Results of the Mann-Kendall Test and Sen's Estimate of the Slope

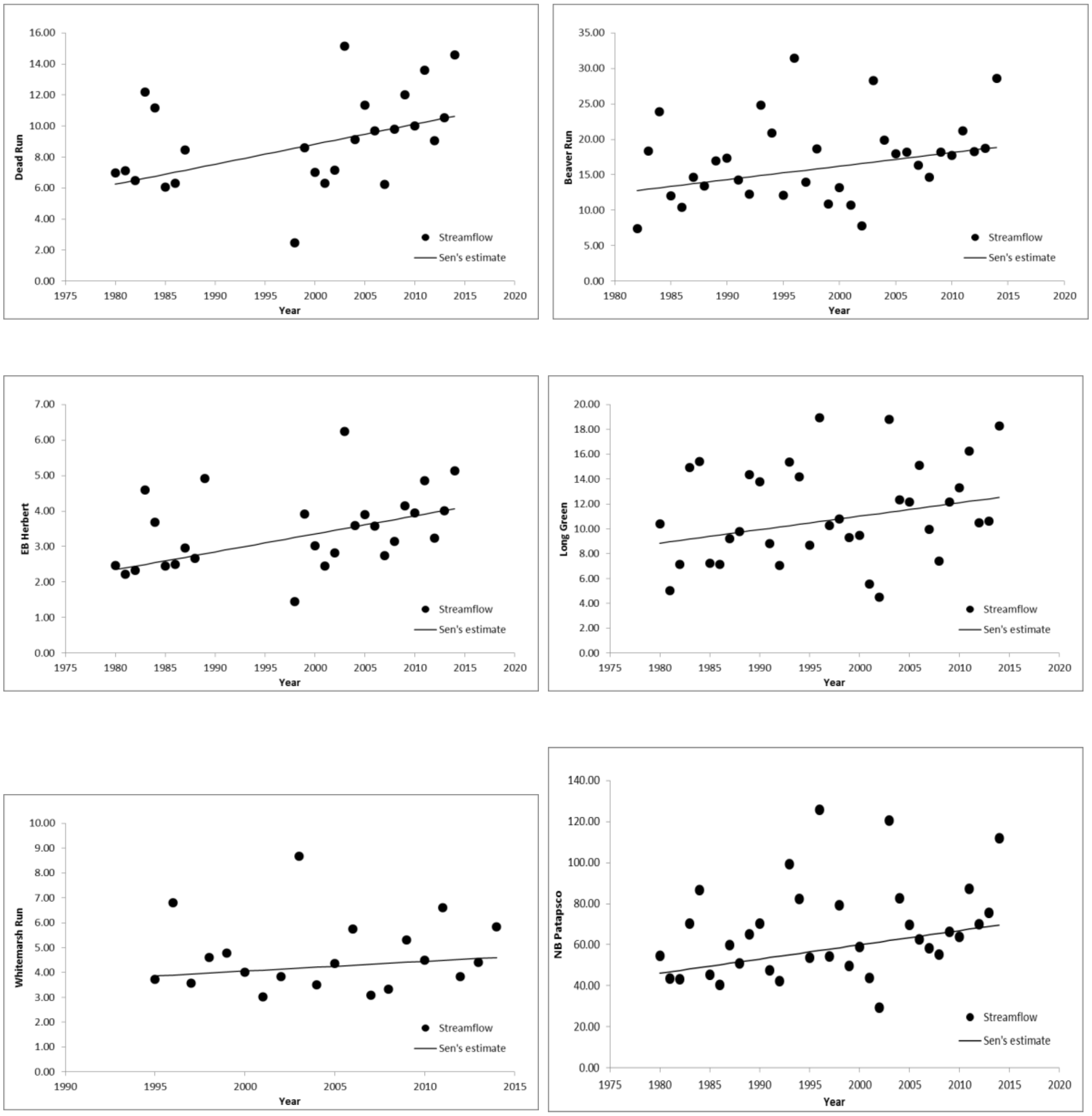
TREND STATISTICS

Piedmont, Maryland

				Mann-Kendall trend			Sen's slope estimate									
Time series	First year	Last Year	n	Test S	Test Z	Signific.	Q	Qmin99	Qmax99	Qmin95	Qmax95	B	Bmin99	Bmax99	Bmin95	Bmax95
Baisman	*1999*	*2014*	*16*		1.58		0.046	-0.055	0.151	-0.025	0.121	0.46	3.28	-2.39	2.46	-1.60
Beaver Run	*1982*	*2014*	*33*		1.91	+	0.190	-0.095	0.424	-0.004	0.362	12.41	18.63	7.84	17.41	8.91
Beetree Run	*1999*	*2014*	*16*		1.85	+	0.427	-0.530	1.108	-0.078	0.834	0.87	28.99	-16.93	15.38	-9.12
Dead Run	*1980*	*2014*	*25*		2.55	*	0.129	-0.003	0.294	0.035	0.227	6.24	9.16	3.50	8.21	4.93
EB Herbert	*1980*	*2014*	*27*		2.92	**	0.051	0.009	0.091	0.016	0.076	2.34	2.97	1.95	2.85	2.04
George's Run	*2000*	*2014*	*15*		1.68	+	0.600	-0.765	1.432	-0.147	1.141	1.96	41.88	-20.09	24.35	-12.52
Grave Run	*2000*	*2014*	*15*		1.58		0.270	-0.449	0.719	-0.105	0.571	1.61	22.65	-10.71	12.47	-6.82
Gunpowder Falls	*2000*	*2014*	*15*		1.39		1.101	-1.366	3.049	-0.509	2.623	4.58	75.25	-49.91	51.36	-38.04
Gwynns Delight	*1998*	*2014*	*17*		2.18	*	0.199	-0.074	0.366	0.021	0.319	0.02	7.26	-4.36	4.88	-2.99
Gwynns Mcdonogh	*1999*	*2014*	*16*		0.50		0.000	-0.001	0.003	-0.001	0.002	0.02	0.07	-0.04147	0.0607	-0.0276
Honeygo Run	*1999*	*2014*	*16*		0.77		0.062	-0.205	0.317	-0.120	0.248	2.3305	9.41409	-4.68648	6.9267	-2.6668
Jones Falls	*1996*	*2014*	*19*		0.84		0.239	-1.525	1.749	-0.753	1.277	26.953	69.7997	-12.1116	50.425	-0.3063
Long Green	*1980*	*2014*	*35*		1.53		0.108	-0.093	0.281	-0.030	0.234	8.8519	12.4754	5.74508	11.338	6.28109
Moores Run	*1996*	*2014*	*19*		2.87	**	0.011	0.002	0.023	0.003	0.019	-0.0132	0.24002	-0.31307	0.1951	-0.1717
N. Fork	*1992*	*2014*	*18*		-0.76		-0.019	-0.111	0.089	-0.079	0.056	2.4646	4.36233	0.4086	3.6884	0.96281
NB Patapsco	*1980*	*2014*	*35*		2.13	*	0.694	-0.169	1.471	0.048	1.220	46.066	66.6462	37.9798	61.393	39.3205
Piney Run	*1982*	*2014*	*26*		1.37		0.159	-0.147	0.476	-0.070	0.376	12.351	19.4529	6.39808	17.358	7.80556
Rognel Hgts	*1998*	*2014*	*13*		-0.31		0.000	-0.003	0.002	-0.002	0.001	0.0277	0.09508	-0.02309	0.0721	-0.0084
Whitemarsh Run	*1995*	*2014*	*20*		0.62		0.039	-0.135	0.173	-0.082	0.147	3.2741	7.54125	0.16185	6.3841	0.91625
W Branch	*1996*	*2014*	*19*		0.84		0.024	-0.088	0.143	-0.053	0.116	2.4681	5.16967	-0.4728	4.5067	0.26527

** if trend at $\alpha = 0.01$ level of significance ; * if trend at $\alpha = 0.05$ level of significance; + if trend at $\alpha = 0.1$ level of significance

Figure 11 can be used as a visual aid for interpreting the results from Table 7. Urban stations are displayed on the left and rural stations are on the right. Urban stations show relatively higher slopes (Q) and Z-scores, meaning they have a higher upward trend. This indicates that urban watersheds appear to have increasing stream discharge. Rural streams also mostly have increasing discharges, but at a nearly flat slope, that is not significant. Interestingly, most rural stations show higher B values, representing a higher average discharge. This is consistent with the results from Chapter Three, which indicate that rural streams are more dominated by the base flow.



(Urban Streams) (Rural Streams)

Figure 11: MK Trend Analysis of Stream Flow

Interpreting the results of Table 7 does not lead to the definitive conclusion that all stations in Piedmont Maryland have increasing discharge. Certainly, most urban streams have a significant increase, while almost all streams have increases that are not significant. This would lend support to the hypothesis that increasing discharges in the streams of the

Maryland Piedmont are likely due to changing landcover, although the effect of climate should not be ruled out. Further research is needed fully to understand the hydrologic process in the region with comparing precipitation data and geomorphic data.

The stream flow at the watershed and any changes observed in it are the results of the integrated response of the anthropogenic activities and the climatic factors. The Piedmont Maryland region has undergone significant land use changes in recent times. The observed trends of increasing discharge for urban streams are consistent with findings of (Burn et al., 2002), Yue et al. (2003), Stewart et al. (2004), and Zhang et al. (2000). The bulk of the change in stream flow is most likely due to human interventions rather than the climatic factors. The increase in paved surface, with its impact on surface runoff and groundwater penetration, may cause the increase in discharge in urban areas. During the summer seasons when evapotranspiration rates are high, little change is observed in the stream flow. As the climatic factors dominate the watershed's hydrology, the observed trends are considered the accumulative impact of human alteration and the climate change. The changes resulting from anthropogenic forcing are overwhelming and cumulative, since anthropogenic climate change and land cover change appear to have a similar influence on streamflow. Further studies should focus on finding the dominating force in streamflow change in the region. These processes may not be independent of one another.

Some studies have recommended studying trends for different hydroclimatic variables to understand the relationship between hydrology and climate. Considering this, the objective of this research was to analyze the trends that may exist in the time series of streamflow. Streamflow tends to reflect how a catchment area has been responding to the variability in climate (Gaucherel, 2002). The evaluation of hydroclimatic trends on a smaller spatial scale provides information on watershed dynamics (Gautam et al., 2010). The findings and results obtained from this study will be useful for many aspects of infrastructure design, modeling, and management of water resources (such as in planning and monitoring of integrated and adaptive water management programs). Trend detection and analysis in hydroclimatic variables can also bring out issues which need to be considered as part of adaptation and mitigation efforts associated with climate change. This implies that public policies created to address the impacts of climate change for a specific region should be done based on the knowledge of that region, rather than on the global climate change information (Clark et al., 2000). The results of trend analysis in these hydroclimatic variables can also be incorporated into prediction models of future scenarios applied to many different fields, such as in agriculture (e.g. growing seasons, irrigation schemes, crop productions) and food security, water supplies, extreme weather forecast, etc.

4.7 Conclusion

The trend analysis of the Maryland Piedmont hydrologic data reveals the existence of an slightly increasing trend in annual mean discharge. The MK tests were applied to the mean annual flow, and the results showed that there is a slight positive trend in five of the twenty sites. This result agrees with other observed trends from the regional to the continental scale. This study did not consider the monthly, seasonally based, and periodic components. The gradual increase in discharge may be influenced by similar climatic factors and anthropogenic factors. However, the more urban stations displayed stronger increases. The lack of a significant trend at all sites may be due to the coarse temporal scale of the analysis that may not show fine-scale trends, or due to masking of a real change due to general variability or variations that are seasonal. The observed hydrologic changes can be closely tied to human interventions. The region has undergone rapid urbanization which can be related to high surface runoff resulting higher stream discharges. Some climatic factors may also affect the streamflow over the study area. No single factor acts as the driver for the observed trends in the study area, but anthropogenic activities seem the most dominant one.

Future studies could incorporate some quantitative linkages between the most dominant climatic factors that affect trends and land use change. This may potentially explain the gradual increase in surface runoff in streamflow and steady base flow in rural streams. It would also be beneficial to overlay the precipitation data from nearby with the streamflow records to compare the surface runoff in the study area. Finally, the results obtained from this present study presented some baseline information about the important indicators that affect the streamflow in Piedmont Maryland. This information can be integrated into the methods/models aiming to investigate how natural fluctuations (e.g. changes in climate, fluctuations of climate indices) can affect streamflow. Furthermore, the analysis obtained from this study can serve as grounds for basing the water resources design and planning within the watershed covered by the study area, as it involves making reasonable predictions or assumptions about future hydro-climatic conditions.

Chapter 5: Discussion

5.1 Discussion

Although the Earth is constantly changing, these changes have accelerated recently. Most of the scientific community is certain that humans are responsible for these rapid changes. Hydrologic parameters, especially streamflow, are one of the key indicators of human alteration to the natural regime. Sometimes these impacts are too gradual to be immediately apparent. Streamflow can be an example of this because it slowly alters aquatic habitats, affects groundwater availability, and increases the flashiness of streams.

The results of this study align with other studies conducted in the USA, but there are not many studies done in the Maryland Piedmont region. There was the initial step to visually reviewing the data as most major changes in pattern or slope are usually evident. From the visual inspection, it seems that the annual flow series of the Piedmont region exhibits slight upward trend since 2000, while baseflow has remained steady over the period. The indicators developed in this study were beneficial to get the present scenario of the hydrologic condition in Piedmont region. The average of the mean annual flow is 12.92 CFS with as high as 65.87 CFS for N. Fork Whitemarsh Run near White Marsh station and as low as 0.02 CFS for Rognel Heights Storm Sewer Outfall at Baltimore station. The smaller standard deviation (0.84) of the high flow percentile indicates the base flow is steady throughout the season. In the case of urbanized streams, the BFI displays less variability than the rural streams. All twenty stations show a gradual increase in the streamflow that is especially prominent in catchments with higher imperviousness. The urbanized streams also display sudden peaks in their hydrographs where those are steeper than rural streams. The peak flow of any stream is more likely to 30-100% greater in urbanized streams comparing to less urbanized streams (Leopold et al., 1995). The Piedmont region has experienced numerous human-induced modifications in the name of development. The year 2000 appears to be a change point in this study. According to the U.S. Census in 2010, the total population was 3,330,197 with over 140 urban clusters within the Piedmont region, while the population is projected to be 3,925,750 by the year 2040 with 0.54% annualized growth rate.

Table 8: Comparison between population projections

Population (growth rate)	Piedmont Region	State of Maryland
2010	3,330,197	5,773,552
2025	3,688,000 (0.68%)	6,429,750 (0.72%)
2040	3,925,750 (0.54%)	6,889,700 (0.59%)

Table 8 indicated the steady but gradual increase in population in the Piedmont region which is closely parallel to the state of Maryland estimates. If we consider the overall land use of the Piedmont region, this growth seems more alarming. The influx of local migration tends to explore newer places to live and develop those pristine areas. Sometimes governments also give incentive to these proceedings, and in most cases, the environment is given the least consideration. The Piedmont region experienced the highest growth at 0.75% during 2000-2010 at the time where the economic recession was prominent. Annually, an average of 27,630 acres of agriculture and forest land was lost, mostly to development, between 1973 and 2010, and a total of over one million acres have developed since 1973 (MDP, 2010). Such land use change alters the hydrologic regime and subsequent shifts in the morphologic characteristics of streams usually attributed to the increase in impervious surface cover resulting from urbanization.

The correlation analysis indicated there is a strong positive association between mean annual streamflow and the base flow, but not with the percentage of imperviousness. The departure analysis indicated the variability in the streamflow with a gradual increase over the year. After the year 2000, the variability becomes more radical and, hydrographs become steeper in urbanized areas. Lins et al. (1999) and Douglas et al. (2000) also found similar results with an increase in annual stream flows in the eastern part of the USA.

The Mann–Kendall (MK) test performed in Chapter four provided some interesting insight regarding the streamflow in the Piedmont region. The results indicate that all but one site is increasing, but only five are significant increases. These findings also resonate with the results of indicators developed in the chapter there. The hydrologic characteristics of the Maryland Piedmont region is changing over time. The change is gradual, and the more urbanized streams are getting relatively higher streamflow than the rural streams. Furthermore, it is apparent that the trends in streamflow started approximately during the early 2000s, which could be related to the rapid development and human intervention to that area. Considering the trends in streamflow, the months of the year in which this variable is most dynamic is in April and August. The precipitation and snow melts may cause the variation greatly over April. August is the most sensitive to any changes temperature and is the driest month of the year. A detailed study on the precipitation may illustrate a statistically significant result with the surface runoff and snow to water conversion. A comprehensive spatiotemporal study is recommended to investigate this important factor. Development of a robust analytic tool from long-term dataset to assess the possible changes in natural regime is recommended. Further investigation should perform using the precipitation stations nearby for run off analysis. Moreover, if the flow and precipitation stations are situated relatively close to each other, it may be said that the similarity is caused by similar climatic factors influencing the study area.

Based on the analysis and the results, it is of great importance to consider the ecological, aquatic, economic, and social impacts of a gradual increase in streamflow. With little more precipitation, it could cause havoc to the region. Maryland is vulnerable to coastal flooding due to sea level rise. Moreover, as the streams of Maryland are now close in the range of overflowing, it is becoming more vulnerable day by day. The vulnerability may further accumulate with extensive rainfall, rapid unplanned urbanization, flash flood. These extreme climatic events can also impact the human life greatly. With the floods and rapid surface runoff, the water quality can deteriorate rapidly. Institutional changes in policy level, streamflow regulation, and management should be reevaluated and updated with present climatic change scenario taken into consideration. Future streamflow scenarios depended on some other factors were not considered in this study. Changes in weather pattern and precipitation heavily influence the magnitude and frequency of streamflow. Water demand of the region likely to increase with growing population and a spike in temperature. A decrease in summer flow may result in droughts and could also adversely affect the municipal drinking water supply. Now is the most crucial time than ever to take our environment more seriously and work together to make it more sustainable for the future.

CHAPTER 6: CONCLUSION

6.1 Conclusion

The hydrologic characteristics of the Maryland Piedmont region are gradually changing. Increasing streamflow with higher surface runoff and relatively constant baseflow is prevailing condition throughout the region. Human alteration in the form of land use change, imperviousness, and rapid urbanization has identified as one of the key factors responsible for the streamflow variability. This study provides an overall scenario of the hydrologic condition of Piedmont Maryland based on statistical and graphical indicator established after rigorous literature review. It also sets out a link to associate the streamflow changes with human alteration. The steep peaks in hydrograph, the sharper decline in flow duration curve, and relatively steady baseflow indicates the change in land use pattern in the stream catchment. Seasonal variability with the extreme condition is also shifting through time. Although many other factors may be responsible for these changes, urbanization is one of the key elements contributing to it.

The magnitude of streamflow variability is not only associated with human alteration. Climatic factors such as Temperature, Precipitation, and Evaporation also play a great deal in these changes. Water demand, irrigation can indirectly contribute to the transformation. However, all these factors can be linked to anthropogenic activities. Ultimately, human-induced changes are directly or indirectly responsible for changes in hydrologic parameters, especially streamflow. A complete understanding of the sensitivity and nature of these changes are critical to future policy making in Piedmont region. We must anticipate not only the current stress but also future extreme scenarios to sustain future water availability. Few stresses in streamflow are already indicating the adverse effect of climatic changes and it is expected to worsen over time. Now it is high time to address this situation by starting a rigorous hydro-climatic study in the region. Utilizing indicators with other climatic factors and comparing them with yearly urbanization is recommended.

References

Alcamo, J., Doll, P., Henrichs, T., Kaspar, F, Lehner, B., Rosch, T., and Siebert, S. 2003. Global estimates of water withdrawals and availability under current and future “business-as-usual” conditions, Hydrolog. Sci. J., 48, 339–348, doi:10.1623/hysj.48.3.339.45278

Archer, D.R., 2007. The use of flow variability analysis to assess the impact of land use change on the paired Plynlimon catchments, mid-Wales. J. Hydrol. 347 (3– 4), 487–496

Arnell, N. W. 1999. Climate change and global water resources, Global Environ. Change, 9, S31–S49, doi:10.1016/S0959-3780(99)00017-5

Arthington, A.H., Bunn, S.E., Poff, N.L., Naiman, R.J., 2006. The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications 16 (4), 1311–1318

Ashagrie, A.G., de Laat, P.J.M., de Wit, M.J.M., Tu, M., Uhlenbrook, S., 2006. Detecting the influence of land use changes on discharges and floods in the Meuse River Basin – the predictive power of a ninety-year rainfall-runoff relation? Hydrol. Earth Syst. Sci. 10, 691–701

Bain, M.B., Finn, J.T., and Brooke, H.E., 1988, Streamflow regulation and fish community structure: Ecology, v. 69, p. 382–392

Bates, B. C., Kundzewicz, Z. W., Wu, S., and Palutikof, J. P. (Eds.) 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva

Bathurst, J.C., Iroume, A., Cisneros, F., Fallas, J., Iturraspe, R., Novillo, M.G., Urciuolo, A., de Bievre, B., Borges, V.G., Coello, C., et al., 2011. Forest impact on floods due to extreme rainfall and snowmelt in four Latin American environments 1: field data analysis. J. Hydrol. 400 (3–4), 281–291

Biemans, H., Haddeland, I., Kabat, P., Ludwig, F., Hutjes, R. W. A., Heinke, J., von Bloh, W., and Gerten, D. 2011. Impact of reservoirs on river discharge and irrigation water supply during the 20th century, Water Resour. Res., 47, W03509, doi:10.1029/2009WR008929

Birsan, M.-V., Molnar, P., Burlando, P. & Pfaundler, M. 2005. Streamflow trends in Switzerland. Journal of Hydrology, 314, 312–329

Brath, A., Montanari, A. & Moretti, G. 2006. Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty). Journal of Hydrology, 324, 141-153

Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA, 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology 310, 28–61 doi:10.1016/j.jhydrol.2004.12.010

Brun, S.E., Band, L.E., 2000. Simulating runoff behavior in an urbanizing watershed. Comput. Environ. Urban Syst. 24, 5–22

Burn, D. H., & Elnur, M. A. 2002. Detection of hydrologic trends and variability.Journal of Hydrology , 255, 107-122

Burn, D. H., Hannaford, J., Hodgkins, G. A., Whitfield, P. H., Thorne, R. & Marsh, T. 2012. Reference hydrologic networks II. Using reference hydrologic networks to assess climate-driven changes in streamflow. Hydrological Sciences Journal, 57(8), 1580–1593

Burns, D. A., J. Klaus & M. R. McHale, 2007. Recent climate trends and implications for water resources in the Catskill Mountain region, New York, USA. Journal of Hydrology 336(1–2): 155–170.

Carlisle, D. M., Wolock, D. M., and Meador, M. R. 2011 Alteration of streamflow magnitudes, and potential ecological consequences: A multiregional assessment, Front. Ecol. Environ., 9, 264–270, doi:10.1890/100053

Changnon, S. A. & Demissie, M. 1996. Detection of changes in streamflow and floods resulting from climate fluctuations and land use-drainage changes. Climatic Change, 32, 411-421

Chaouche, K., Neppel, L., Dieulin, C., Pujol, N., Ladouche, B., Martin, E., Salas, D., Caballero, Y., 2010. Analyses of precipitation, temperature and evapotranspiration in a French Mediterranean region in the context of climate change. Comptes Rendus Geoscience, 342(3): 234-243

Chingombe, W., Gutierrez, J.E., Pedzisai, E., Siziba, E., 2005. A study of hydrological trends and variability of Upper Mazowe Catchment-Zimbabwe. Journal of

Sustainable Development in Africa, 7(1): ISSN:1520-550 Fayetteville State University, Fayetteville, North Carolina

Costa, M. H., Botta, A. & Cardille, J. A. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. Journal of Hydrology, 283, 206-217

Cuo, L., Lettenmaier, D.P., Alberti, M., Richey, J.E., 2009. Effects of century of land cover and climate change on the hydrology of the Puget Sound basin. Hydrol. Process. 23, 907–933

Doll, P., Fiedler, K., and Zhang, J. 2009. Global-scale analysis of river flow alterations due to water withdrawals and reservoirs, Hydrol. Earth Syst. Sci., 13, 2413–2432

Dai, A., Trenberth, K. E. & Qian, T. (2004). A global data set of Palmer drought severity index for 1870– 2002: Relationship with soil moisture and effects of surface warming. American Meteorological Society, 5, 1117–1130

DeFries R, Eshleman K N. Land-use change and hydrologic processes: a major focus for the future. Hydrological Processes, 2004, 18: 2183—2186

Descroix, L., Esteves, M., Yero, K.S., Rajot, J.L., Abdou, M.M., Boubkraoui, S., Lapetite, J.M., Dessay, N., Zin, I., Amogu, O., Bachir, A., Moussa, I.B., Le Breton, E., Mamadou, I., 2011. Runoff evolution according to land use change in a small Sahelian catchment. Hydrol. Earth Syst. Sci. Discuss. 8, 1569–1607

DiLisio, James. 2014. Maryland Geography: An Introduction. JHU Press.

Di Stefano, C., Ferro, V., Porto, P., 2000. Applying the bootstrap technique for studying soil redistribution by caesium-137 measurements at basin scale. Hydrological Sciences Journal, 45(2): 171-183

Döll, P., Fiedler, K., and Zhang, J. 2009. Global-scale analysis of river flow alterations due to water withdrawals and reservoirs, Hydrol. Earth Syst. Sci., 13, 2413–2432

Domroes, M., El-Tantawi, A., 2005. Recent temporal and spatial temperature changes in Egypt. International Journal of Climatology, 25(1): 51-63

Douglas, E.M., Vogel, R.M., Kroll, C.N., 2000. Trends in floods and low flows in the United States: Impact of spatial correlation. Journal of Hydrology, 240(1–2): 90-105

Drago, A.F., Boxall, S.R., 2002. Use of the wavelet transform on hydro-meteorological data. Physics and Chemistry of the Earth, 27(32–34): 1387-1399

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., et al. 2007. Changes in Atmospheric Constituents and in Radiative Forcing. Climate Change 2007: The Physical Science. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Galster, J.C., Pazzaglia, F.J., Hargreaves, B.R., Morris, D.P., Peters, S.C., Weisman, R.N., 2006. Effects of urbanization on watershed hydrology: the scaling of discharge with drainage area. Geology 34, 713–716

Gaucherel, C., 2002. Use of wavelet transform for temporal characterization of remote watersheds. Journal of Hydrology, 269(3): 101-121

Gautam, M.R., Acharya, K., Tuladhar, M.K., 2010. Upward trend of streamflow and precipitation in a small, non-snow-fed, mountainous watershed in Nepal. Journal of Hydrology, 387(3–4): 304-311

George, S., 2007. Streamflow in the Winnipeg River basin, Canada: trends, extremes and climate linkages. J. Hydrol. 332, 396–411

Gerten, D., Rost, S., von Blo, W., and Lucht, W. 2008. Causes of change in 20th century global river discharge, Geophys. Res. Lett., 35, L20405, doi:10.1029/2008GL035258

Graf, W. L. 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts,Water Resour. Res., 35, 1305–1311

Hamed, K.H., Rao, A.R., 1998. A modified Mann-Kendall trend test for autocorrelated data. Journal of Hydrology, 204(1–4): 182-196

Hannaford, J. & Harvey, C. L. 2010. UK seasonal river flow variability in near-natural catchments, regional outflows and long hydrometric records. Role of Hydrology in Managing Consequences of a Changing Global Environment. British Hydrological Society Third International Symposium, 96–102

Hannaford, J. & Marsh, T. 2006. An assessment of trends in UK runoff and low flows using a network of undisturbed catchments. International Journal of Climatology, 26, 1237–1253.

Hannaford, J. & Marsh, T. J. 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. International Journal of Climatology, 28(10), 1325–1338

Harbor, J.M., 1994. A practical method for estimating the impact of land-use change on surface runoff, groundwater recharge and wetland hydrology. J. Am. Plan. Assn. 60–1, 95–108

Hirsch, R. M., Alexander, R. B. & Smith, R. A. 1991. Selection of methods for the detection and estimation of trends in water quality. Water Resources Research, 27(5), 803–813

Hirsch, R.M., Slack, J.R., 1984. A nonparametric trend test for seasonal data with serial dependence. Water Resources Research, 20(6): 727-732

Hodgkins, G. A. & Dudley, R. W. 2006. Changes in the timing of winter-spring streamflows in eastern North America, 1913-2002. Geophysical Research Letters, 33(6), L06402.

IPCC. 2007. Climate Change 2007: Synthesis Report - An Assessment of the IPCC. Intergovernmental Panel on Climate Change, Cambridge University Press Cambridge, UK

Jackson, R. B., Carpenter, S. R., Dahm, C. N., McKnight, D. M., Naiman, R. J., Postel, S. L., and Running, S. W. 2001. Water in a changing world, Ecol. Appl., 11, 1027–1045

Kalnay E, Cai M. Impact of urbanization and land-use change on climate. Nature, 2003, 423: 528－531

Karaburun, A., Demirci, A., Kara, F., 2011. Analysis of spatially distributed annual seasonal and monthly temperatures in Istanbul from 1975 to 2006. World Applied Sciences Journal 12(10): 1662-1675

Karl, T. R., Melillo, J. M., and Peterson, T. C. (Eds.) 2009. Global Climate Change Impacts in the United States. Cambridge University Press, New York

Kendall, M.G., 1975. Rank Correlation Measures. Charles Griffin, London

Khaliq, M. N., Ouarda, T. & Gachon, P. 2009. Identification of temporal trends in annual and seasonal low flows occurring in Canadian rivers: The effect of short-and long-term persistence. Journal of Hydrology, 369(1-2), 183–197. Elsevier.

Khaliq, M., Ouarda, T., Gachon, P. & Sushama, L. 2008. Temporal evolution of low-flow regimes in Canadian rivers. Water Resources Research, 44(8), W08436

Kim, Y., Lee, K., Sung, I.H., 2001. Urbanization and the groundwater budget, metropolitan Seoul area, Korea. Hydrogeol. J. 9, 401–412

Kundzewicz, Z. W. 2004. Searching for change in hydrological data. Hydrological Sciences Journal, 49(1), 3–6

Kundzewicz, Z.W., Robson, A.J., 2004. Change detection in hydrological records—A review of the methodology. Hydrological Sciences Journal, 49(1): 7-19

Labat, D., 2005. Recent advances in wavelet analyses: Part 1. A review of concepts. Journal of Hydrology, 314(1–4): 275-288

Lehner, B., P. Droll, J. Alcamo, T. Henrichs & F. Kaspar, 2006. Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis. Climatic Change 75(3): 273–299

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1992, Fluvial processes in geomorphology: New York, Dover Publications, Inc., 522 p.

Lettenmaier, D.P., 1988. Multivariate nonparametric tests for trend in water quality. JAWRA Journal of the American Water Resources Association, 24(3): 505-512

Li, K.Y., Coe, M.T., Ramankutty, N., De Jong, R., 2007a. Modeling the hydrological impact of land-use change in West Africa. J. Hydrol. 337, 258–268

Lindh, G., 1972. Urbanization: a hydrological headache. Ambio 1 (6), 185–201

Lins, H.F., and J.R. Slack, Streamflow trends in the United States, Geophys. Res. Lett., 26, 227- 230, 1999

Liu, Q., Cui, B., 2011. Impacts of climate change/variability on the streamflow in the Yellow River Basin, China. Ecol. Model. 222, 268–274

Lu, X.X., Jiang, T., 2009. Larger Asian rivers: climate change, river flow and sediment flux. Quatern. Int. 208, 1–3

Ma, Z.M., Kang, S.Z., Zhang, L., Tong, L., Su, X.L., 2008. Analysis of impacts of climate variability and human activity on stream flow for a river basin in arid region of northwest China. J. Hydrol. 352, 239–249

Makokha, G.L., Shisanya, C.A., 2010. Trends in mean annual minimum and maximum near surface temperature in Nairobi City, Kenya. Advances in Meteorology, 2010

Mann, H.B., 1945. Non-parametric tests against trend. Econometrica 13, 245-259

Maryland Department of Natural Recourses, 2002, www.mdp.state.md.us/msdc/popproj (date accessed 5 August, 2013)

Maryland Department of Planning - http://www.mdp.state.md.us/OurWork/smartGrowth.shtml

Maryland Department of Planning, 2002, www.mdp.state.md.us/msdc/popproj (date accessed 5 August, 2013)

McCabe, G. J. and Wolock, D. M. 2010. Century-scale variability in global annual runoff examined using a water balance model, J. Climatol., 31, 1739–1748, doi:10.1002/joc.2198, 2010

McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S., 2001. Climate Change 2001: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

McVicar, T.R., 2012. Detecting changes in streamflow after partial woodland clearing in two large catchments in the seasonal tropics. J. Hydrol. 416–417, 60–71

Milly, P. C. D., Dunne, K. & Vecchia, A. V. 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature, 438(7066), 347–350

Mohsin, T., Gough, W., 2010. Trend analysis of long-term temperature time series in the Greater Toronto Area (GTA). Theoretical and Applied Climatology, 101(3): 311-327.

Nagasaka, A., Nakamura, F., 1999. The influence of land-use changes on hydrology and riparian environment in northern Japanese landscape. Landscape Ecol. 14, 543–556

Ng, H.Y.F., Marsalek, J., 1989. Simulation of the effects of urbanization on basin streamflow. Water Resour. Bull. 25 (1), 117–124

Nohara, D., Kitoh, A., Hosaka, M. & Oki, T. 2006. Impact of climate change on river discharge projected by multimodel ensemble. Journal of Hydrometeorology, 7(5), 1076–1089

Novotny, E. V. & H. G. Stefan, 2007. Stream flow in Minnesota: indicator of climate change. Journal of Hydrology 334(3–4): 319–333.

Oh, H.-S., Ammann, C.M., Naveau, P., Nychka, D., Otto-Bliesner, B.L., 2003. Multi-resolution time series analysis applied to solar irradiance and climate reconstructions. Journal of Atmospheric and Solar-Terrestrial Physics, 65(2): 191-201

Ott, B., Uhlenbrook, S., 2004. Quantifying the impact of land-use changes at the event and seasonal time scale using a process-oriented catchment model. Hydrol. Earth Syst. Sci. 8 (1), 62–78

Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

Partal, T., 2010. Wavelet transform-based analysis of periodicities and trends of Sakarya basin (Turkey) streamflow data. River Research and Applications, 26(6): 695-711

Partal, T., Küçük, M., 2006. Long-term trend analysis using discrete wavelet components of annual precipitations measurements in Marmara region (Turkey). Physics and Chemistry of the Earth, 31(18): 1189-1200

Peña-Arancibia, J.L., van Dijk, A.I.J.M., Guerschman, J.P., Mulligan, M., Bruijnzeel, L.A.,

Piao, S., Friedlingstein, P., Ciasis, P., de Noblet-Ducoudre, N., Labata, D., and Zaehle, S. 2007. Changes in climate and land use have a larger direct impact than rising CO2 on global river runoff trends, P. Natl. Acad. Sci., 104, 15242–15247

Piao, S., Friedlingstein, P., Ciasis, P., de Noblet-Ducoudre, N., Labata, D., and Zaehle, S. 2007. Changes in climate and land use have a larger direct impact than rising CO2 on global river runoff trends, P. Natl. Acad. Sci., 104, 15242–15247

Poff, N. L. and Zimmerman, J. K. H. 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows, Freshwater Biol., 55, 194–205

Poff, N. L., Olden, J. D., Merritt, D. M., and Pepin, D. M. 2007. Homogenization of regional river dynamics by dams and global biodiversity implications, P. Natl. Acad. Sci. USA, 104, 5732–5737

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47, 769–784

Poff, N.L., and Ward, J.V., 1989, Implications of streamflow variability and predictability for lotic community structure—A regional analysis of streamflow patterns: Canadian Journal of Fisheries and Aquatic Sciences, v. 46, p. 1,805–1,818.

Potter K W. 1991. Hydrological impacts of changing land management practices in a moderate-sized agricultural catchment. Water Re-sour Res, 27: 845—85

Praskievicz, S. and Chang, H. 2009. A review of hydrological modelling of basin-scale climate change and urban development impacts, Prog. Phys. Geogr., 33, 650–671, doi:10.1177/0309133309348098

Richter, B.D., Baumgartner, J.V., Wigington, R., Braun, D.P., 1997. How much water does a river need? Freshw. Biol. 37 (1), 1–249

Ring, P.J., Fisher, I.H., 1985. The effects of changes in land use on runoff from large catchments in the upper Macintyre Valley, NSW. Hydrology and Water Resources Symposium, Sydney, 14 -16 May, 1985. The Institution of Engineers, Australia, National Conference Publication 85/2:153-158

Rose, S., Peters, N.E., 2001. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. Hydrol. Process. 15, 1441–1457

Rossi, a., Massei, N., Laignel, B., Sebag, D., Copard, Y., 2009. The response of the Mississippi River to climate fluctuations and reservoir construction as indicated by wavelet analysis of streamflow and suspended-sediment load, 1950–1975.

Schulze, R.E., 2000. Modelling hydrological responses to land use and climate change: a southern African perspective. Ambio 29 (1), 12–22

Shao, Q., Li, Z., Xu, Z., 2010. Trend detection in hydrological time series by segment regression with application to Shiyang River Basin. Stochastic Environmental Research and Risk Assessment, 24(2): 221-233

Simmons, D.L., Reynolds, R.J., 1982. Effects of urbanization on base flow of selected south-shore streams, Long Island, New York. Water Resour. Bull. 18 (5), 797–805

Siriwardena, L., Finlayson, B.L., McMahon, T.A., 2006. The impact of land use change on catchment hydrology in large catchments: the Comet River, Central Queensland, Australia. J. Hydrol. 326, 199–214

Slack, J. R. & Landwehr, J. M. 1992. Hydro-Climatic Data Network(HCDN): A U.S. Geological Survey Streamflow Data Set for the United States for the Study of Climate Variations, 1874-1988

Sparks, R.E., 1992, Risks of altering the hydrologic regime of large rivers, in Cairns, J.B., and others, eds., Predicting ecosystem risk—Volume XX. Advances in modern environmental toxicology: Princeton, N.J., Princeton Scientific Publishing, p. 119–152

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. 2004. Changes toward earlier streamflow timing across western North America. Journal of Climate , 18, 1136-1155

Sun, G., McNulty, S. G., Moore Myers, J. A., and Cohen, E. C. 2008. Impacts of multiple stresses on water demand and supply across the southeastern United States, J. Am. Water Resour. Assoc., 44, 1441–1457, doi:10.1111/j.1752-1688.2008.00250.x

Svensson, C., Kundzewicz, W.Z., Maurer, T., 2005. Trend detection in river flow series: 2. Flood and low-flow index series. Hydrological Sciences Journal, 50(5): 824

Tang, Z., Engel, B.A., Pijanowski, B.C., Lim, K.J., 2005. Forecasting land use change and its environmental impact at a watershed scale. J. Environ. Manage. 76, 35–45

Thomson, A. M., Brown, R. A., Rosenberg, N. J., Srinivasan, R., and Cesar Izaurralde, R. 2005. Climate change impacts for the conterminous USA: An integrated assessment, Part 4:Water resources, Climatic Change, 69, 67–88, doi:10.1007/s10584-005-3610-y

Timilsena, J., Piechota, T., Tootle, G., Singh, A., 2009. Associations of interdecadal/ interannual climate variability and long-term Colorado river basin streamflow. J. Hydrol. 365, 289–301

Timofeev, A., Sterin, A., 2010. Using the quantile regression method to analyze changes in climate characteristics. Russian Meteorology and Hydrology, 35(5): 310-319

Tollan, A. 2002. Land-use change and floods: What do we need most, research or management? 8 ed.: IWA Publishing

Tomer, M.D., Schilliing, K.E., 2009. A simple approach to distinguish land-use and climate-change effects on watershed hydrology. J. Hydrol. 376, 24–33

Trenberth, K. E. 2011. Changes in precipitation with climate change, Clim. Res., 47, 123–138, doi:10.3354/cr00953

Trenberth, K. E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., et al. 2007. Observations: Surface and Atmospheric Climate Change. Climate Change 2007: The Physical Science. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM. 1997. Human domination of earth’s ecosystems. Science 277: 494–499

Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B. 2000. Global water resources Vulnerability from climate change and population growth, Science, 289, 284–288, doi:10.1126/science.289.5477.284

Wahl, K.L., Wahl, T.L., 1988. Effects of regional ground water declines on streamflows in the Oklahoma Panhandle. In: Proceedings of Symposium on Water-Use Data for Water Resources Management: Tucson, Arizona. American Water Resources Association, pp. 239-249.

Wahl, K.L., Wahl, T.L., 1995. Determining the flow of comal springs at New Braunfels, Texas, in Proceedings of Texas Water’95,August 16–17, 1995, San Antonio, Texas: American Society of Civil Engineers, pp. 77–86.

Wang, G., Liu, J., Kubota, J., Chen, L., 2007. Effects of land-use changes on hydrological processes in the middle basin of the Heihe River, northwest China. Hydrol. Process. 21 (10), 1370–1382

Wang, G., Zhang, Y., Liu, G. & Chen, L. 2006. Impact of land-use change on hydrological processes in the Maying River basin, China. Science in China, Series D: Earth Sciences, 49, 1098-1110

Watson, R.T., Zinyowera, M.C., Moss, R.H., 1996. Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

Wilk, J., Andersson, L., Plermkamon, V., 2001. Hydrological impacts of forest conversion to agriculture in a large river basin in northeast Thailand. Hydrol. Process. 15, 2729–2748

Wolock, D.M., 2003. Base-flow index grid for the conterminous United States: US Geological Survey Open-File Report 03-263.

Yu, P. S., T. C. Yang & C. K. Wu, 2002. Impact of climate change on water resources in southern Taiwan. Journal of Hydrology 260(1–4): 161–175

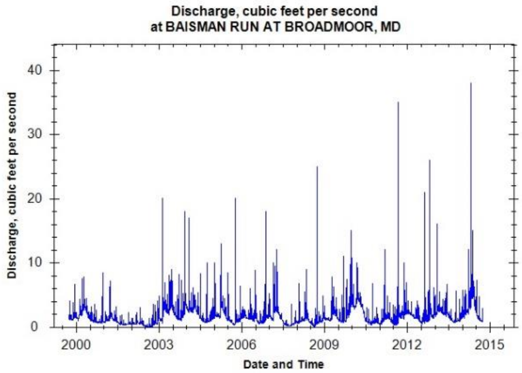
Yue, S., Pilon, P., & Phinney, B. 2003. Canadian streamflow trend detection: impacts of serial and cross correlation. Hydrological Sciences , 48 (1), 51-63

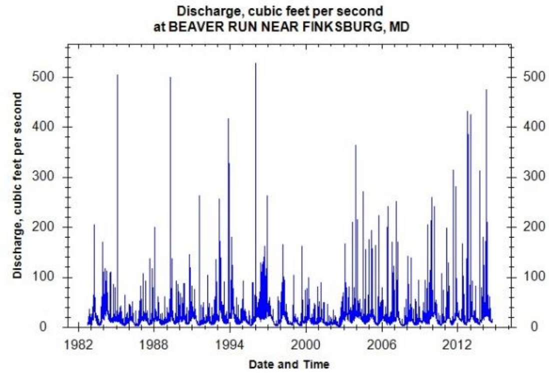
Yue, S., Pilon, P., Phinney, B., Cavadias, G., 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrological Processes, 16(9): 1807-1829

Zhang, X., Harvey, K., Hogg, W., & and Yuzyk, R. 2000. Trends in Canadian streamflow. 15th Conference on Hydrology. 80th American Meterological Society Annual Meeting. Long Beach, California

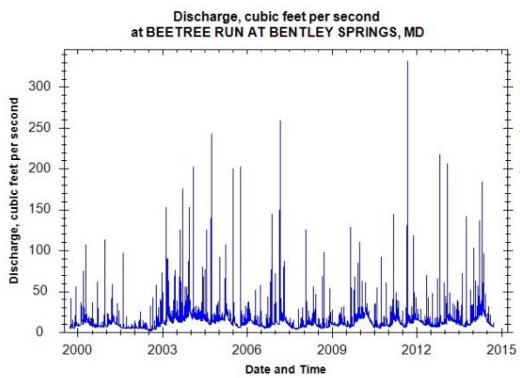
Zhang, Y., Guan, D., Jin, C., Wanga, A., Wua, J., Yuan, F., 2011. Analysis of impacts of climate variability and human activity on streamflow for a river basin in northeast China. J. Hydrol. 410, 239–247.

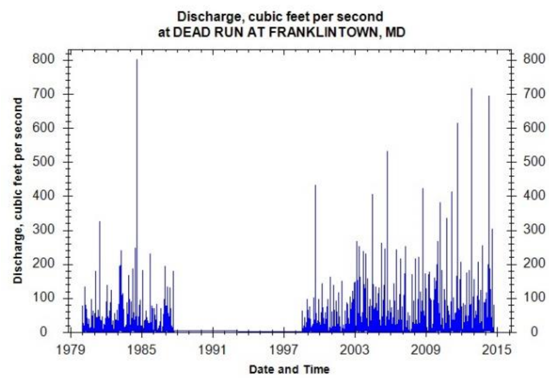
Appendix I

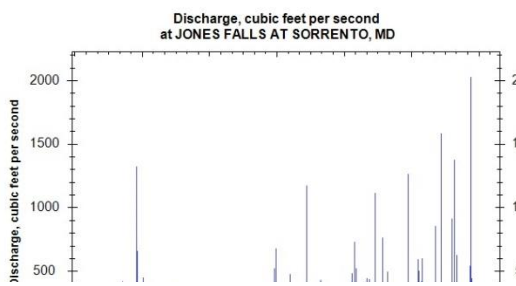


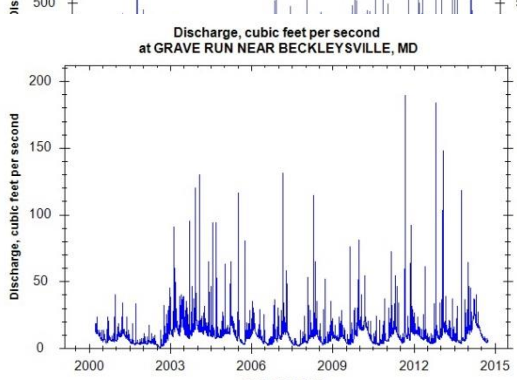


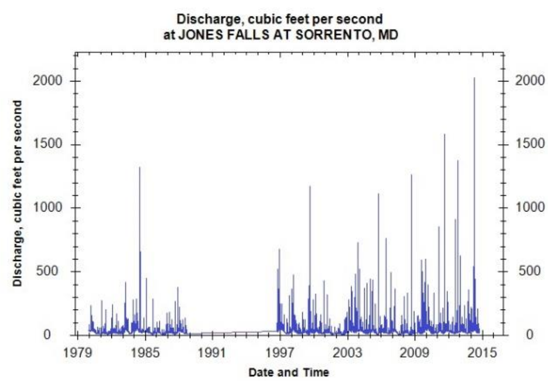
Hydrograph



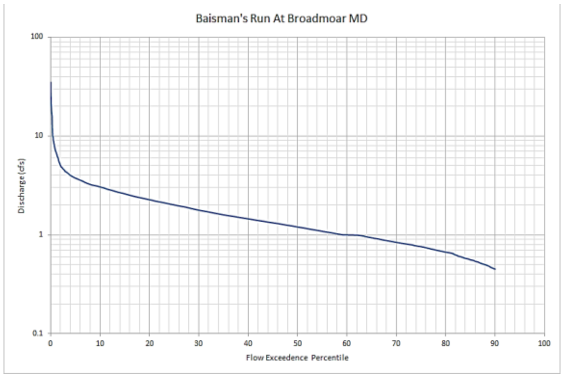


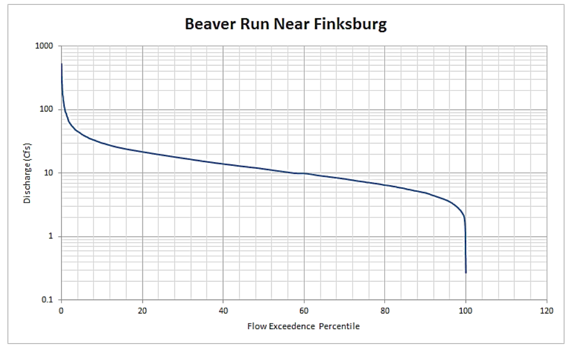


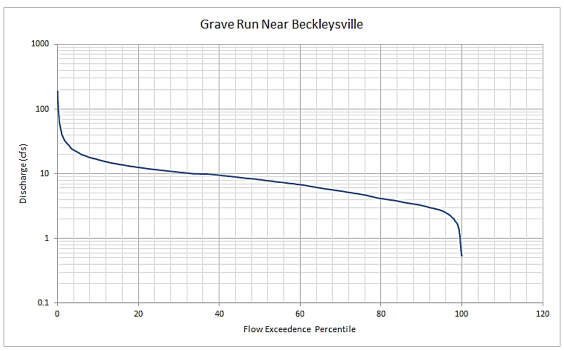


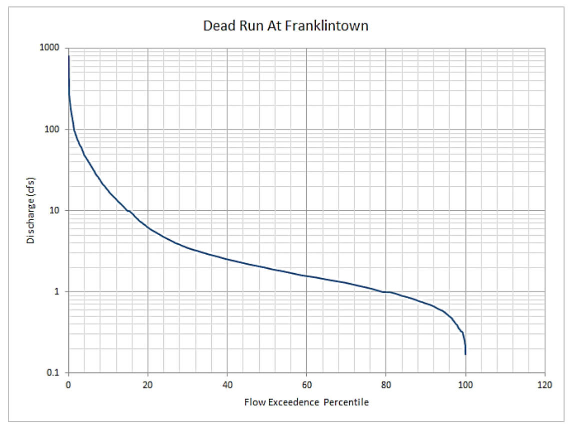


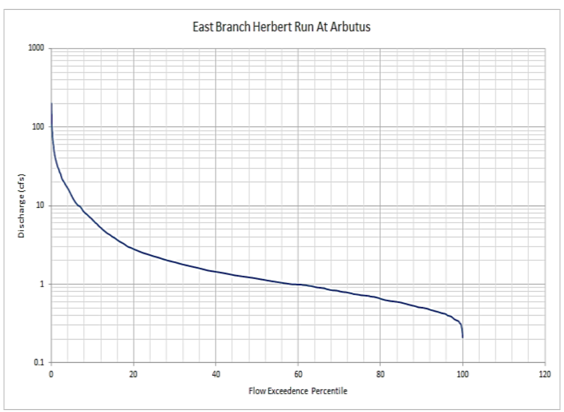
Flow Duration Curves

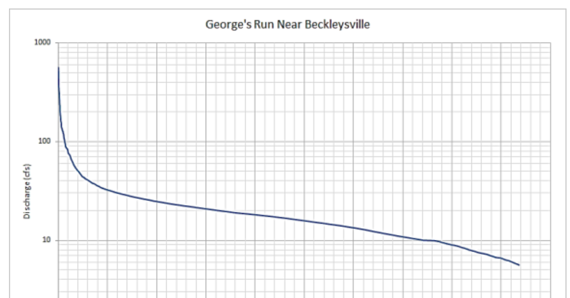


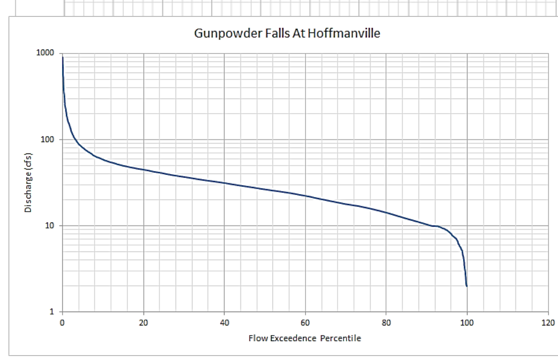


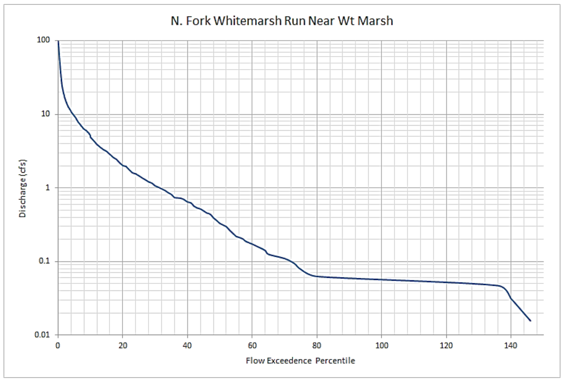


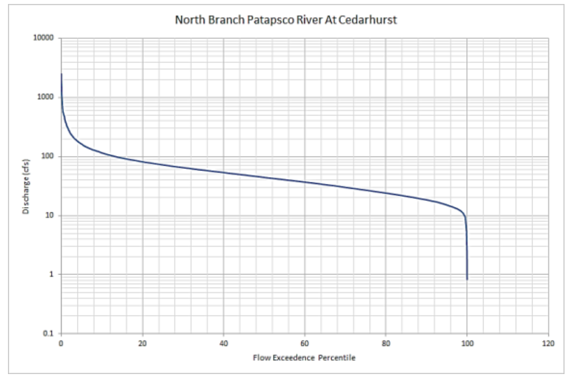


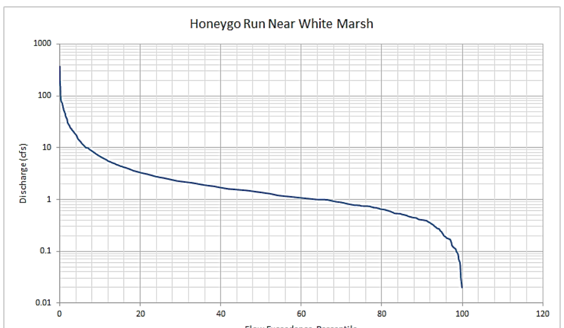


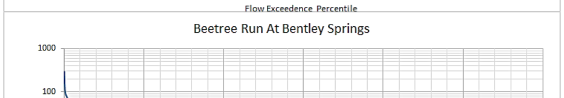


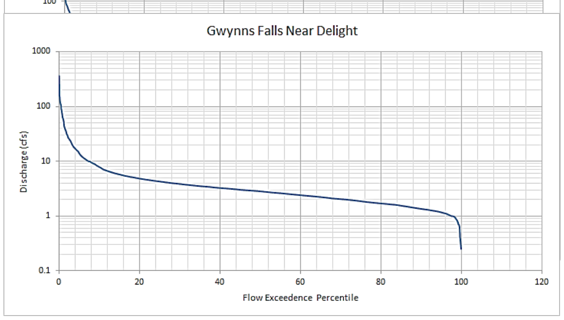


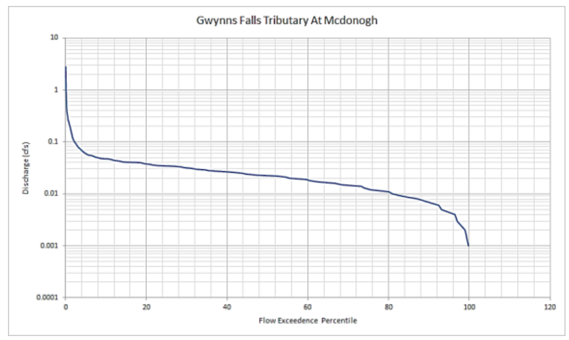

N. Fork Whitemarsh Run Near Wt Marsh
Discharge (cfs)
100
10
1
0.1
0.01
0
20
40
60
80
100
120
140
Flow Exceedence Percentile

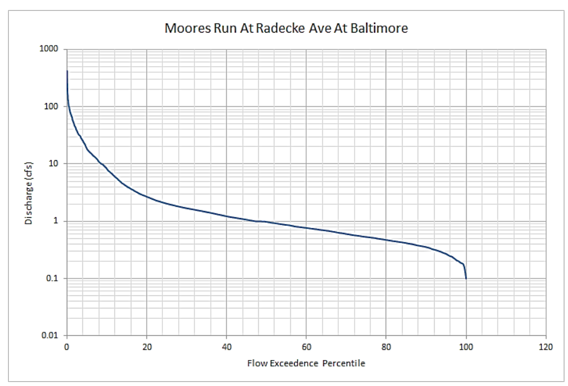

North Branch Patapsco River At Cedarhurst
Discharge (cfs)
10000
1000
100
10
1
0.1
0
20
40
60
80
100
120
Flow Exceedence Percentile

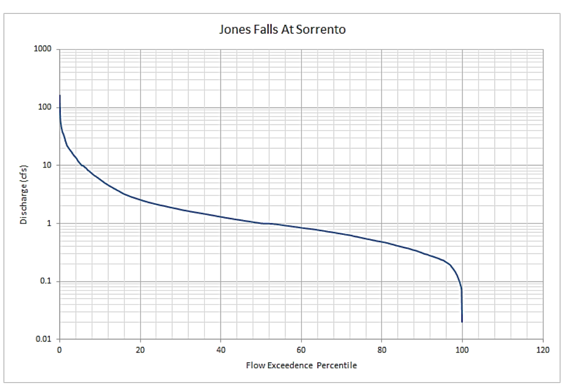

Honeygo Run Near White Marsh
Discharge (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
120
Flow Exceedence Percentile

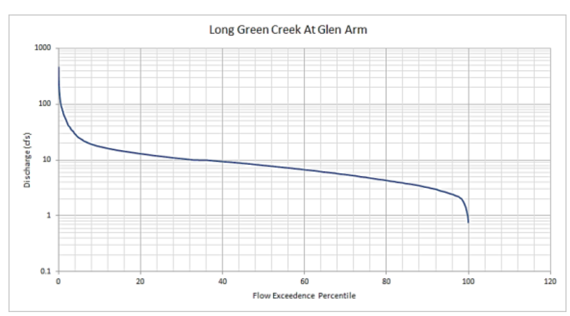

Beetree Run At Bentley Springs
1000
100

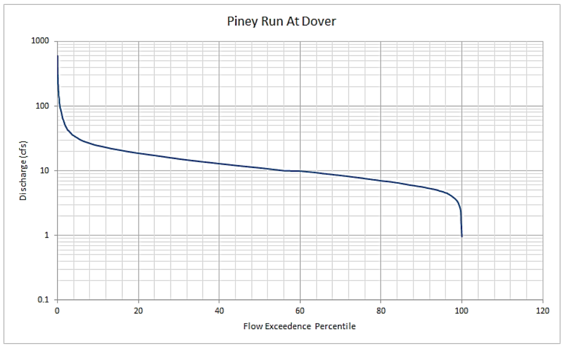

Gwynns Falls Near Delight
Discharge (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
120
Flow Exceedence Percentile

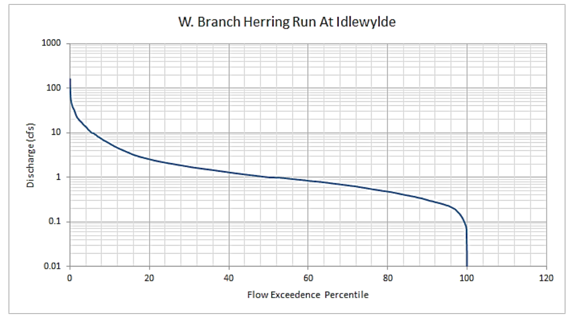

Gwynns Falls Tributary At Mcdonogh
Discharge (cfs)
10
1
0.1
0.01
0.001
0.0001
0
20
40
60
80
100
120
Flow Exceedence Percentile

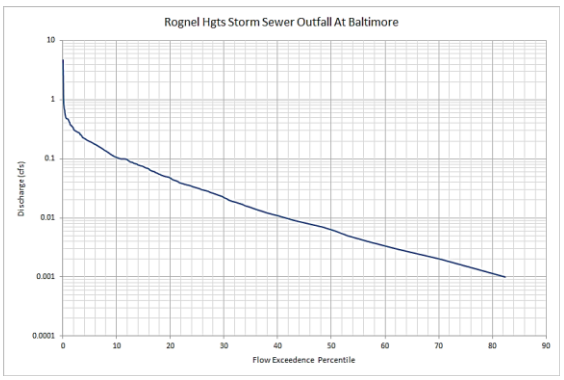

Moores Run At Radecke Ave At Baltimore
Discharge (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
120
Flow Exceedence Percentile

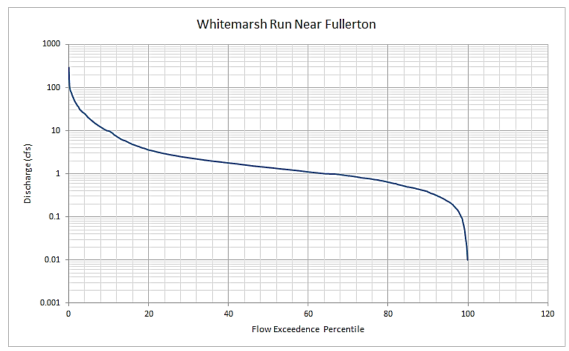

Jones Falls At Sorrento
Discharge (cfs)
1000
100
10
1
0.1
0.01
0
20
40
60
80
100
120
Flow Exceedence Percentile


Long Green Creek At Glen Arm
Discharge (cfs)
1000
100
10
1
0.1
0
20
40
60
80
100
120
Flow Exceedence Percentile

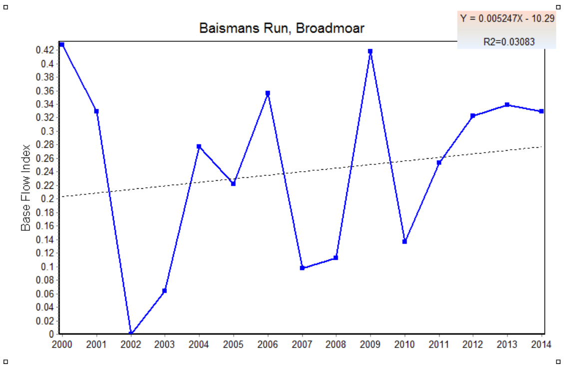

Piney Run At Dover
Discharge (cfs)
Flow Exceedence Percentile

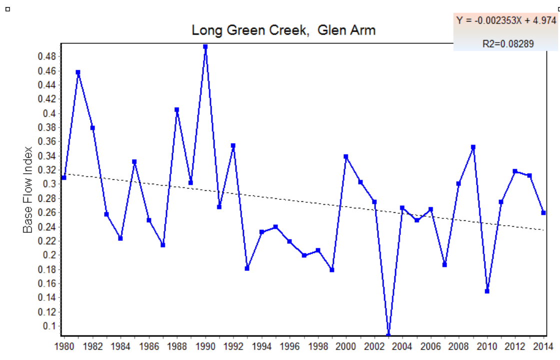

W. Branch Herring Run At Idlewylde
Discharge (cfs)
Flow Exceedence Percentile

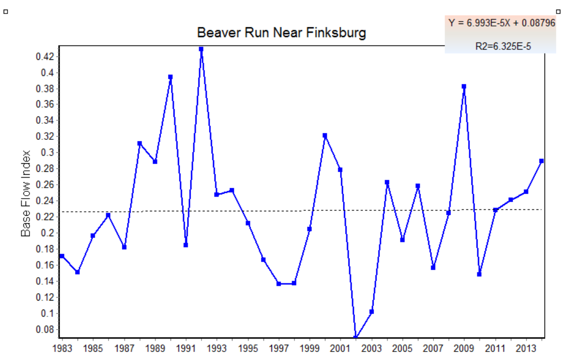

Rognel Hgts Storm Sewer Outfall At Baltimore
Discharge (cfs)
Flow Exceedence Percentile

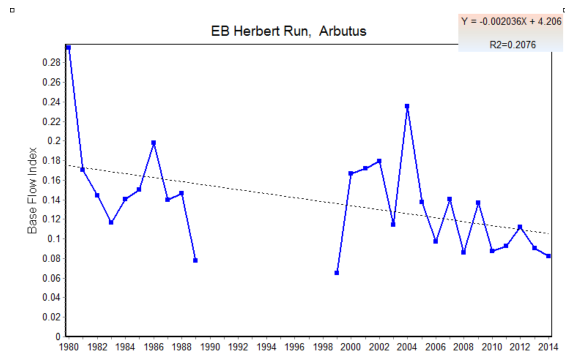

Whitemarsh Run Near Fullerton
Discharge (cfs)
Flow Exceedence Percentile

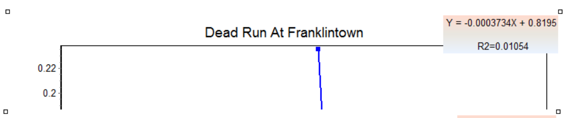
Base Flow Index (BFI)

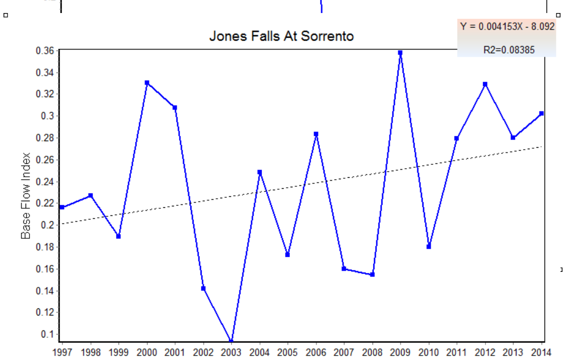


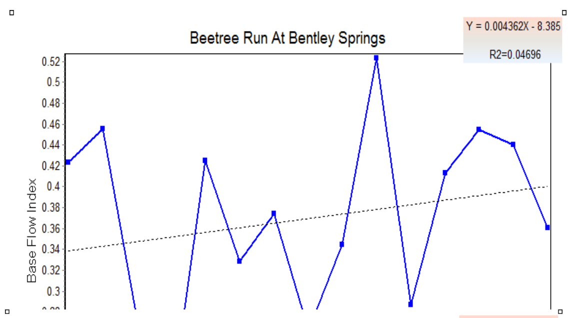


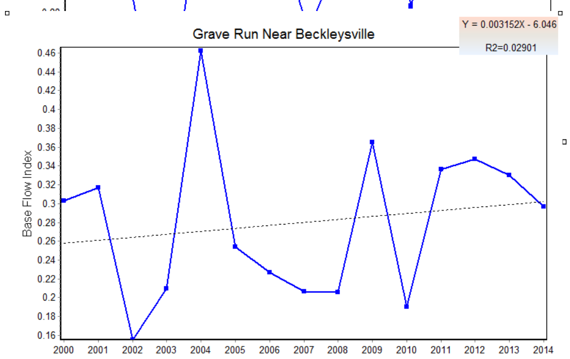


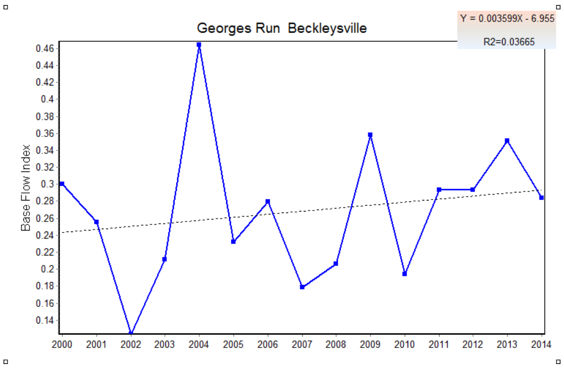


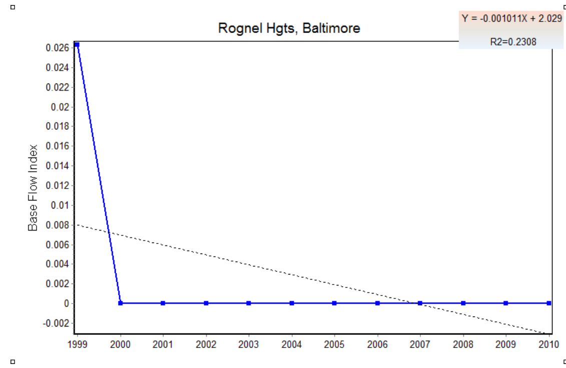


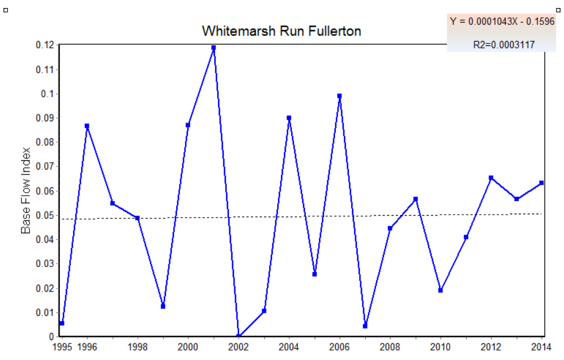


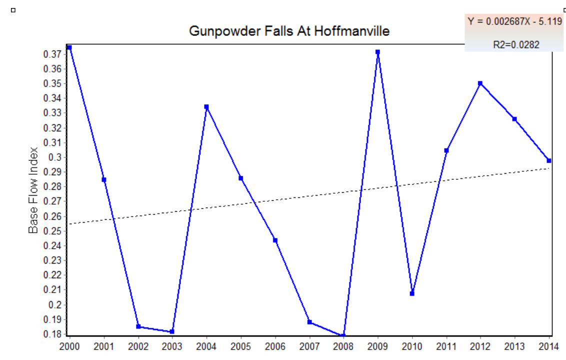


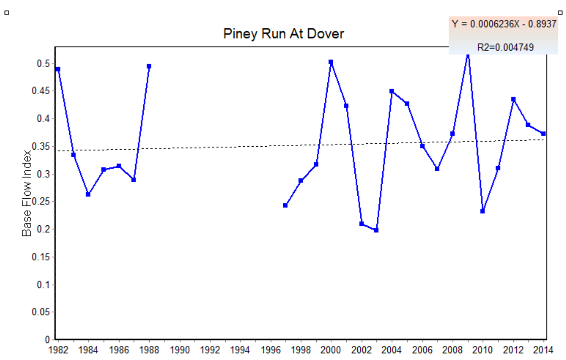


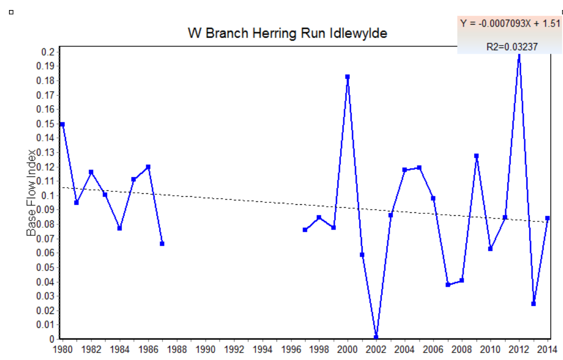

Georges Run Beckleysville
Y = 0.003599X - 6.955
R2=0.03665
Base Flow Index

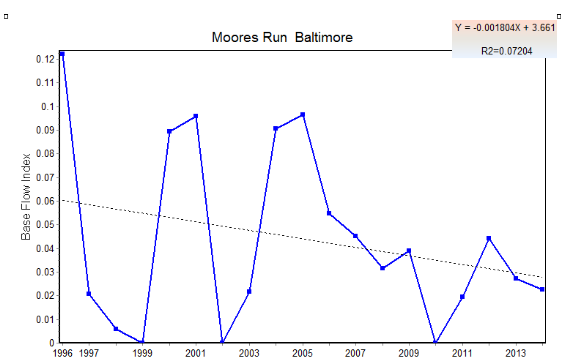

Rognel Hgts, Baltimore
Y = -0.001011X + 2.029
R2=0.2308
Base Flow Index

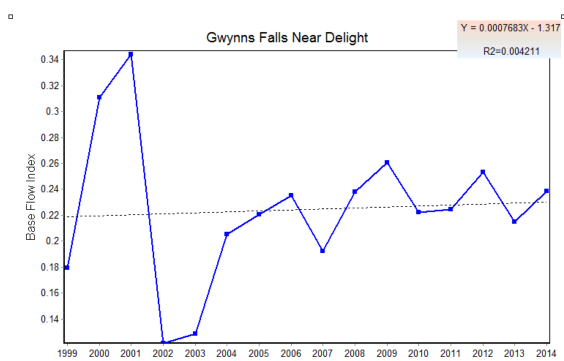

Whitemarsh Run Fullerton
Y = 0.0001043X - 0.1596
R2=0.0003117
Base Flow Index

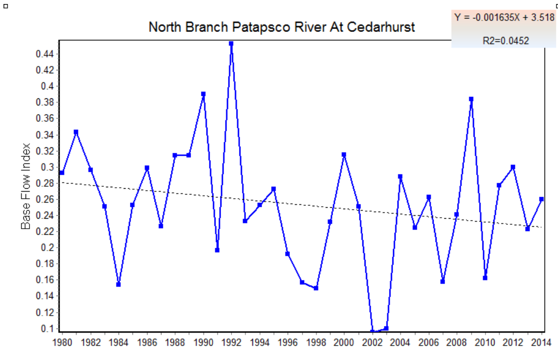

Gunpowder Falls At Hoffmanville
Y = 0.002687X - 5.119
R2=0.0282
Base Flow Index

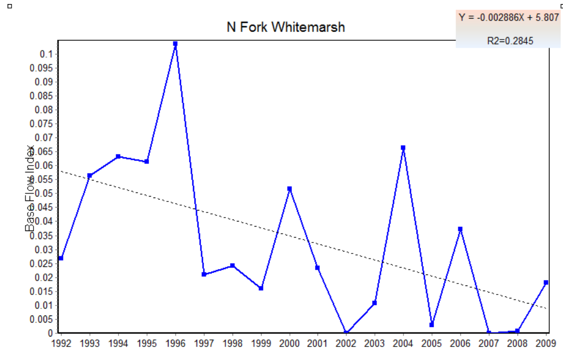

Piney Run At Dover
Y = 0.0006236X - 0.8937
R2=0.004749
Base Flow Index

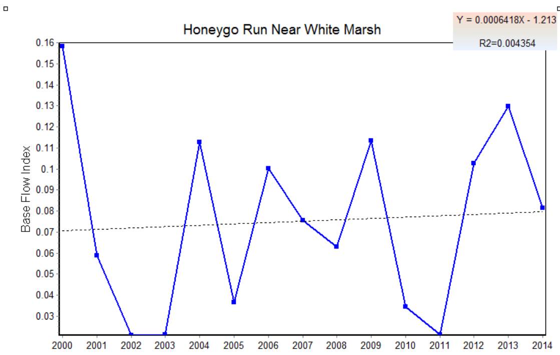

W Branch Herring Run Idlewylde
Y = -0.0007093X + 1.51
R2=0.03237
Base Flow Index

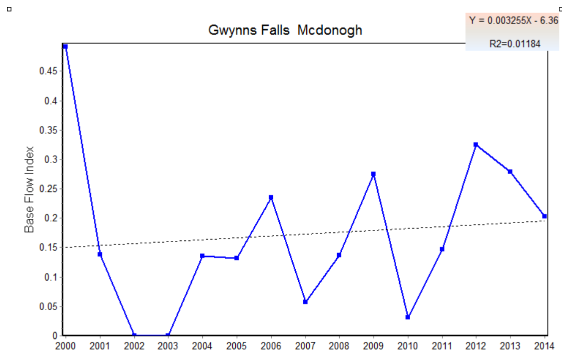

Moores Run Baltimore
Y = -0.001804X + 3.661
R2=0.07204
Base Flow Index


Gwynns Falls Near Delight
Y = 0.0007683X - 1.317
R2=0.004211
Base Flow Index


North Branch Patapsco River At Cedarhurst
Y = -0.001635X + 3.518
R2=0.0452
Base Flow Index


N Fork Whitemarsh
Y = -0.002886X + 5.807
R2=0.2845
Base Flow Index


Honeygo Run Near White Marsh
Y = 0.0006418X - 1.213
R2=0.004354
Base Flow Index


Gwynns Falls Mcdonogh
Y = 0.003255X - 6.36
R2=0.01184
Base Flow Index

Curriculum Vitae

Education

Doctor of Engineering in Transportation Engineering August, 2017 - Present
Morgan State University, Baltimore, MD

Master of Science in Geography and Environmental Planning May, 2015
Towson University, Towson, MD

Post Graduate Diploma in Water Resources Development April, 2012
Institute of Water and Flood Management (IWFM), BUET, Bangladesh

Bachelor of Science in Geography and Environment October, 2009
University of Dhaka, Dhaka-1000, Bangladesh.

Awards

National Traffic Safety Scholar (2019, 2020), awarded by Lifesavers National Conference on Highway Safety Priorities

Experience

Academic Experience

Graduate Research Fellow August, 2017 – Present
Urban Mobility and Equity Center, NTC
Morgan State University, Baltimore, MD

Lecturer (Adjunct Faculty)
Morgan State University, Baltimore, MD
Department of Transportation and Urban Infrastructure Studies (TUIS)

Graduate Teaching and Research Assistant August, 2012 – May, 2014
Graduate Teaching and Research Assistant
Towson University, Towson, MD

Research Assistant (Data & GIS) May, 2010 - June, 2010
Disaster Research Training and Management Centre (DRTMC), Dhaka Bangladesh

Teaching Assistant, University of Dhaka, Bangladesh
June, 2009 – April, 2010

Industry Experience

GIS Analyst February, 2017 – August, 2017
Baltimore Gas and Electric (BG&E), Baltimore, MD

GeoSpatial Data Technician September, 2015 – May -2016
Xcel Energy Inc. Amarillo, TX

GIS Intern January,2015 – April,2015
Department of Public Works, Baltimore County, Maryland

Senior Data and GIS Analyst July,2011 - May,2012
Department of Urban and Regional Planning (DURP), BUET, Dhaka Bangladesh

GIS Analyst August,2010 – March,2011
Center for Urban Studies (CUS), Dhaka Bangladesh

Publications

Academic Journal

Bhuyan, Istiak A.; Chavis, Celeste; Barnes, Phillip; Nickkar, Amirreza; 2019. GIS-Based Equity Gap Analysis Case Study of Baltimore Bike Share Program, Urban Science

Nickkar, Amirreza; Bhuyan, Istiak A.; Chavis, Celeste; Barnes, Phillip; Banerjee, Snehanshu 2018. A Spatial-Temporal Gender and Land Use Analysis of Bikeshare Ridership: The Case Study of Baltimore City, City, Culture and Society 18 (2019): 100291.

Banerjee, Snehanshu; Bhuyan, Istiak A.; 2019. Correlation of Crime Rate with Transit Connectivity and Transit Demand at Census Block Group Level, Transit 2013 (2013)

Thebpanya, Paporn, Bhuyan, Istiak A., 2015. Urban Sprawl and The Loss of Peri-Urban Land: Case Study of Nakhon Ratchasima Province, Thailand, Papers of the Applied Geography Volume 1 Issue 1

Technical Reports

Chavis, Celeste; Barnes, Phillip; Grasso, Susan; Bhuyan, Istiak A; Nickkar, Amirreza; 2018. Bicycle Justice or Just Bicycles? Analyzing Equity in Baltimore's Bike Share Program; UMEC, NTC, Morgan State University

Conference Paper/Posters

Ahangari, Samira; Chavis, Celeste; Olowokande, Gbenga; Bhuyan, Istiak A.; Jones, Anita; 2019. Understanding Access to Grocery Stores in Food Deserts in Baltimore City, Transportation & Development Institute (T&DI) of ASCE

Bhuyan, Istiak A; Chavis, Celeste; Barnes, Phillip; Nickkar, Amirreza; 2018. Equity Gap Analysis of Baltimore Bike Share System, Transportation Research Board, 98h Annual Meeting

Bhuyan, Istiak A., Kang S. Lu, Nashid K Khadem. 2013. Vulnerability Assessment of Tropical Cyclones in Coastal Bangladesh. Abstracts of the AAG 2013 Meeting in Annapolis, Maryland

Bhuyan, Istiak A., Nashid K Khadem. 2010. Urban Land use Change with Changing Climatic Conditions: A Remote Sensing Approach. Climate Change: Spatial Concerns and Mitigation Strategies

Bhuyan, Istiak A., Md. Adnan Khan, Md. Mafizur Rahman. 2010. Assessment of Risk under the Changing Climatic Condition for the Coastal Areas of Bangladesh. Linking Disasters and Development: The Next 10 years, Newcastle, UK

Conference Presentations

Ahangari, Samira; Bhuyan, Istiak A; Lee, Young-Jae; 2019. GIS Approach to Identify the Potential Service Areas and Feasibility for Demand Response Feeder Transit Service: US metropolitan Suburban Areas, International Conference on Demand Responsive and Innovative Transportation Services

Bhuyan, Istiak A; Chavis, Celeste; 2019. Shared Bus-Bike Lane Safety Analysis: Assessing Multimodal Access and Conflicts Using Computer Vision Tools, Transportation & Development Institute (T&DI) of ASCE

Professional Memberships

Student Member, The American Society of Civil Engineers (ASCE)

Student Member, ITE Student Chapter, Morgan State University (serving as Vice Precedent, 2019-2020)

Student Member, Maryland State Geographic Information Committee (MSGIC)

Life Member, Omicron Delta Kappa (ODK)