The role of riparian buffers in the provision of hydrologic ecosystem services across an urban landscape considering climate change

by

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Abstract

An estimated 66% of the total global population will live in urban areas by 2050 (Salerno, Gaetano, & Gianni, 2018). Urbanization causes various environmental impacts ranging from habitat loss to altered hydrologic processes, which stem from increased runoff volume and rate, reduced infiltration, and decreased time of concentration (US EPA, 2018; Wakode et al, 2017). Thus, man-made and natural waterways will have to convey a larger volume of surface runoff than ever before. The evaluation of potential changes in hydrologic functionality represented by changes in runoff, infiltration, and flooding risk must become a key component of land management and watershed planning as "urbanization without sound management would increase flood risks" (Ahiablame & Shakya, 2016). The overall goal of this research was to develop a deeper understanding of the role of riparian buffers in provision of flood regulating hydrologic ecosystem services (HESs) in an urbanizing watershed. Indicators of flood regulation quantified in this research include changes in total inflow volume and peak inflow. Historic (event-based and continuous) and climate change precipitation data (CMIP5), in conjunction with four riparian buffer land use scenarios, were used to evaluate the impact of climate change and riparian buffer management on HES provision in the Blue River Watershed in the Kansas City area using PCSWMM modeling software. Results indicated riparian buffer restoration around all streams including ephemeral streams offers the greatest flood regulating HESs, providing significant total inflow reduction across the watershed and more frequent reduction of peak inflow. Flood regulating HESs were still provided when the riparian buffer was restored around main channels only but to a much lesser extent. Similar trends were observed under event-based and continuous model simulations. While the datasets utilized in this study are site specific, the findings are widely

applicable. With the threat of urbanization and climate change on the rise, policy makers should use these findings to support creation of policy to restore and protect riparian areas.

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List of Commonly Used Abbreviations

BRW	Blue River Watershed
EM	Ensemble mean
GI	Green infrastructure
HES	Hydrologic ecosystem service
HUC	Hydrologic unit code
IPCC	Intergovernmental Panel on Climate Change
LID	Low impact development
KC	Kansas City
MARC	Mid-America Regional Council
MRLC	Multi-Resolution Land Characteristics
MEA	Millennium Ecosystem Assessment
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
PCSWMM	Personal Computer Storm Water Management Model
RCP	Representative concentration pathway
SCM	Stormwater control measure
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey

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Dedication

I dedicate this thesis to my dog Maggie who recently passed. I'm sorry you didn't like grad office life, but it was certainly worth a shot. Thank you for your love of adventure and helping me stay balanced when working from home.

I dedicate this thesis to my family and best friend, John. Thank you all for your love, support, and encouragement. I love you all.

Chapter 1 - Introduction

1.1 Problem Statement

An estimated 66% of the total global population will live in urban areas by 2050 (Salerno, Gaetano, & Gianni, 2018). Urbanization causes various environmental impacts ranging from habitat loss to altered hydrologic processes, which stem from increased runoff volume and rate, reduced infiltration, and decreased time of concentration (EPA, 2018; Wakode et al., 2017). Thus, man-made and natural waterways have to convey a larger volume of surface runoff than ever before. The evaluation of potential changes in hydrologic functionality represented by changes in runoff, infiltration, and flooding risk must become a key component of land management and watershed planning as "urbanization without sound management would increase flood risks" (Ahiablame & Shakya, 2016). For this reason, sustainable development practices which reduce environmental impact such as green infrastructure or low impact development and protective policies which place limits on the extent and location of development are needed in urban areas (Ahmadisharaf et al., 2020; Qi et al., 2012; Vogel et al., 2015). Sustainable development, according to Salerno et al. (2018), requires planning ahead in order to reduce future setbacks and the environmental impact of development while maintaining quality of ecosystem services which improve the quality of life in cities.

Policy must be coherent and reflect up-to-date scientific findings in order to reduce environmental impact while preserving the quality of life in urban areas (Serag El Din et al., 2012). While urban areas require connectivity and amenities provided by impervious infrastructure, system resiliency depends on sustainable development with attention given to hydrologic functionality that is achieved by maintaining water storage among other factors (The World Bank, 2020; Vogel et al., 2015). The ecological needs of the watershed must be maintained to achieve this goal. This requires agreement between the “state-of-the-science", or current knowledge, and “state-of-the-art", as dictated by policy. The disconnect between science and policy has been a consistent shortfall that must be overcome to improve management decisions (NRC, 2002). This disconnect is often due in part to political and economic factors as well as the inability to effectively communicate the extent of environmental losses that stem from management decisions. Since it is difficult to quantify the vast array of benefits from more sustainable development practices and those involved in policymaking are not often experts on protecting ecosystems, policy does not protect the environment as much as it should (MEA, 2005). Policy-makers need informative but digestible statistics on urban-environmental interactions that are not often available (Boyle Torrey, 2004; Pejchar et al., 2006).

The Millennium Ecosystem Assessment (MEA) discusses ecosystem services which are “benefits people obtain from ecosystems” with the purpose of sharing current scientific knowledge in a relevant and useful way (MEA, 2005). Ecosystem services include regulating, provisioning, supporting, and cultural services (MEA, 2005). Hydrologic ecosystem services (HESs) are a subset of ecosystem services and describe those services that are linked to hydrologic processes such as flood regulation, water supply, and water quality (Brauman, 2015).

When land is developed, ecosystem services are typically lost. The value of these ecosystem service losses is not well represented in decision-making (Boyle Torrey, 2004; MEA, 2005; Pejchar et al., 2006). Ecosystem services which enter the market, such as provisioning services, largely influence resource management decisions; however, non-market ecosystem services such as the HESs listed above and many other regulating, supporting, and cultural services, tend to be overlooked despite their value often being greater than market services (MEA, 2005). A better balance between land development for urbanization and conservation of these services must be established (Pejchar et al., 2006). The importance of this has already been realized by some due to observation of continued flooding or loss of species; worldwide, over 280 programs are in place or being established to help enhance HESs (Brauman, 2015). Yet, a better understanding of HES value and the implications of the trade-offs that are being made during land development must be established (McDonough et al., 2017b). Quantifying these services can aid in sustainable development and protection of the environment (Brauman et al., 2007). In doing so, the disconnect between science and policy may be overcome.

There is a great need for long-term planning due to the rapid decline of ecosystem services and climate change (MEA, 2005). Moving forward, a systems and future-focused approach should be taken when discussing watershed management and land development (Randhir & Raposa, 2014). Modeling is a useful tool in projecting future impacts of development and could be used to help understand environmental trade-offs which stem from land-use decision making (Boulos, 2017; McDonough et al., 2017a; McDonough et al., 2017b). There have been numerous studies that have attempted to better understand the connection between ecosystem services and watershed management. Randhir and Raposa (2014) have explored the application of collaborative modeling to develop a better understanding of how different conservation practices perform in urban ecosystem preservation and improvement. Likewise, McDonough et al. (2017b) explored the relationship between stormwater control measures (SCMs) and ecosystem services using PCSWMM. Studies such as these will help improve understanding of the impact land management decisions have on the environment which can then inform policy and land management. Further exploration of hydrologic impact by use of different land management strategies and climate change across urbanizing watersheds is crucial for sustainable development.

1.2 Objectives

The overall goal of this research is to develop a deeper understanding of the impact of land development and climate change on hydrologic ecosystem services (HESs) provided by riparian buffers in an urbanizing watershed. A hydrologic model was used to examine the potential of a riparian buffer to reduce flooding risk in an urban area through evaluation of peak inflow and total inflow volume. This research addressed the following questions:

1. Can riparian buffers aid in flood regulation via decreasing peak inflow and total inflow volume across an urbanizing watershed?
2. What impact will climate change have on riparian buffer provision of these flood regulating ecosystem services in an urban landscape?

1.3 Research Significance

The Blue River Watershed, located in the Kansas City area, has experienced severe hydrologic damage due to the spread of urbanization. The removal of natural land cover has led to both water quantity and water quality issues throughout the watershed including severe flooding and impaired waters (KC, 2020; Patti Banks Associates, 2007). Local engineers, leaders, and activists are working to better understand these issues and identify the actions needed to mitigate further damage (The Nature Conservancy, 2019; Heartland Conservation Alliance, 2013a; Mid-America Regional Council, 2015).

Managing water quantity has been a consistent struggle in the Blue River Watershed. Extensive flooding in the lower watershed has resulted in roughly $250 million being spent on flood prevention since 2003 (Patti Banks Associates, 2007). Despite this investment, the threat of flooding remains and continues to rise as urban areas extend into the headwaters. Potential land development scenarios were explored in this study to identify how to reduce the risk of flooding and the role of riparian buffers in this effort.

Issues with water quantity management have led to water quality issues throughout the watershed. A portion of the watershed— the city of Kansas City, Missouri (KCMO)— is under a consent decree due to the quality and treatment of its natural water resources which violates the Clean Water Act (US EPA, 2016). Several management decisions have led to the Consent Decree. One of the main management issues is the presence of a combined sanitary sewer (CSS) system (KC, n.d.). In a CSS system, rainwater and sewage flow through the same pipes. This setup requires all water to undergo treatment before being released back into the environment. The greater volume of water requiring treatment puts additional stress on the wastewater treatment system; thus, the CSS system in parts of the city has overflowed during periods of heavy rainfall. KCMO must spend a total of $2.5 billion over the course of 25 years to improve its sanitary sewer system and the risk of these overflows (US EPA, 2016). Removing the CSS system is a complex process as new infrastructure must be provided by the city to create two separate systems— one for stormwater and one for wastewater.

In response to the consent decree, a variety of other projects to manage water quality and quantity are underway in Kansas City. The US EPA is requiring the City to invest at least $1,600,000 in supplemental environmental projects (SEP) to improve the environmental condition of the area (US EPA, 2016). These include the Keep Out the Rain KC campaign which aims to remove sources of stormwater entering the sanitary sewer system and implementation of green infrastructure (KC, n.d.). Due to the deepening understanding of watershed management and involvement of environmentally-focused organizations such as The Nature Conservancy, it is likely that green infrastructure will be incorporated throughout the Blue River Watershed as it continues to develop (The Nature Conservancy, 2019; KC, n.d.). Stakeholders have expressed great interest in the value of riparian buffer preservation and ecosystem services. Thus, this research aims to evaluate the capability of riparian buffers to improve hydrologic function across the Blue River Watershed and identify to what extent riparian buffers must be implemented to provide ecosystem services at a desirable level.

Local governments and organizations involved in managing the Blue River Watershed such as the Mid-America Regional Council (MARC) are working to improve their understanding of the future of the watershed and environmental implications of potential management decisions. Thus, a holistic, systems approach to watershed management is being explored. Proactive management decisions depend on decision-makers' understanding of the possible hydrologic impacts of development (MEA, 2005). Watershed modeling offers the unique opportunity to examine the impact of different land management decisions on the hydrologic processes of the area and ecosystem service provision (Boulos, 2017; Yen et al., 2016). Knowledge gathered through this research must be integrated with climate change projections to make informed management decisions for the Blue River Watershed.

The findings of this research are relevant to urbanizing watersheds across the globe. The impact of management decisions especially in terms of location and extent of riparian buffer preservation on ecosystem services within an urbanizing watershed must be understood to make sustainable decisions. Support for policy aimed to preserve these ecosystem services and integration of climate change projections is needed. Management of this sort is crucial to preserve quality of life and ecosystem services as urbanization continues to spread (MEA, 2005).

Chapter 2 - Literature Review

2.1 Giving Value to the Environment: Ecosystem Services

The importance of the environment and its benefits is represented by ecosystem services. An ecosystem service is defined "benefits that people obtain from ecosystems" (MEA, 2005). Ecosystem services provide benefits to nearby communities they provide to through reducing ecological footprint and improvements in health, quality of life, and ecological resilience for the community (Gómez-Baggethun & Barton, 2013). The United States EPA created the National Ecosystem Services Classification System (NESCS): Framework Design and Policy Application in 2015. This document aims to provide a framework for "systematically identifying and tracing these linkages [between natural and human systems]," ultimately providing a way to determine the impacts of changes in the ecosystem especially due to policy and management on the welfare of humans (US EPA, 2015, xiii).

There are four main categories of ecosystem services: provisioning, supporting, regulating, and cultural (**Error! Reference source not found.**) (MEA, 2005). Provisioning services are t ypically tangible goods, such as food or fibers, and are easily quantified and including in the global GDP and easy to think about. Ecosystem services belonging to other categories are not as easily quantified, making them more vulnerable to undervaluation; when undervaluation occurs, management decisions that negatively impact the provision of these services is likely (McDonough et al., 2017a). Ecosystem services at risk include supporting services, which provide habitat and gene pool protection, thus supporting the ecosystem, regulating services, which are provided by regulating ecosystem processes such as erosion control and climate regulation, and cultural services, which provide opportunities for recreation, education, and spiritual enjoyment (MEA, 2005).

Table 2.1. The four main categories of ecosystem services are provisioning, supporting, cultural, and regulating services. From the examples listed, it is clear cultural and supporting services are much harder to quantify than provisioning and regulating services (MEA, 2005; McDonough et al., 2017a).

Provisioning	**Supporting**	**Cultural**	**Regulating**
• Food production • Water • Wood • Fiber • Fuel	• Nutrient cycling • Soil formation • Primary productivity • Habitat provision	• Spiritual • Aesthetic • Educational • Recreational	• Climate regulation • Flood regulation • Water purification

Humans have altered ecosystems more extensively over the past 50 years than ever before (MEA, 2005). This is largely due to the need to harvest more and more resources to meet growing global demands. While these alterations increase economic and human well-being gains, the environment has been damaged, resulting in a loss of ecosystem services. The Millennium Ecosystem Assessment (2005) describes the globe's current use of most ecosystem services as unsustainable, including 70% of regulating and cultural services. Drivers of ecosystem change, such as urbanization, economic factors, and resource demand, will continue to increase throughout the next century, with climate change becoming a larger concern. If ecosystem services continue to degrade, the likelihood of achieving any of the United Nations Sustainable Development Goals– which are seventeen goals related to improving sustainability and quality of life across the globe– is diminished (United Nations, 2020). Moving forward, changes in both policy and practice are needed to prevent the further degradation of these services (MEA, 2005).

2.1.1 Hydrologic Ecosystem Services

Hydrologic ecosystem services (HESs) are services related to the hydrologic cycle and underlying hydrologic processes (MEA, 2005). Realized benefits may include diverted water supply, in situ water supply, water damage mitigation, spiritual and aesthetic services, and supporting services (Table 2.2; Brauman et al., 2007). In order to provide these services, the ecosystem must have quality hydrologic function. Attributes of the contributing area and other ecosystem factors affect the value of HESs provided; the main driver of HESs is often vegetation (Brauman et al., 2007).

Table 2.2 Hydrologic processes completed by the ecosystem, ecohydrologic processes, have a direct impact on the ecosystem, providing various benefits. These benefits are hydrologic ecosystem services (modified from Brauman et al., 2007).

<table>
<tr><th>Ecohydrologic Process or Ecosystem Factor (Cause)</th><th>Hydrologic Attribute (Effect)</th><th>Hydrologic Ecosystem Service (Benefit)</th></tr>
<tr><td>Local Climate

Vegetation Water Use</td><td>Quantity
(storage, flow)</td><td rowspan="4">Diverted Water Supply
(water for commercial, municipal, agricultural, or industrial use)

In Situ Water Supply
(hydropower, freshwater products, recreation, transportation)

Water Damage Mitigation
(flood regulation, sedimentation)

Spiritual and Aesthetic
(educational, religious, or tourism values)

Supporting
(water and nutrients for habitat, preserves other ecosystem services)</td></tr>
<tr><td>Filtration

Chemical and Biological Processes

Contaminants from Land Use (Agriculture, Urbanization)</td><td>Quality
(nutrients, pathogens, salinity, sediment)</td></tr>
<tr><td>Soil Creation

Surface Modification

Flow Path Alteration

River Bank Changes</td><td>Location
(up/downstream, ground/surface, in/out of channel)</td></tr>
<tr><td>Control of Flow Speed

Water Storage

Seasonality of Water Use</td><td>Timing
(peak inflows, base flows, velocity)</td></tr>
</table>

The provision of HESs is spatially and temporally dependent (Brauman et al., 2007; Terrado et al., 2014). The size of precipitation event as well as the location, extent, and type of ecosystem present in a watershed impact HES provision. For example, deforestation in several small Oregon watersheds was linked to increases in peak flow for up to a two-year storm, while larger watersheds experienced no changes in peak flow (Brauman et al., 2007). Likewise, studies on wetland provision of HESs have indicated great variability in their ability to provide HESs depending on topography and wetland and watershed characteristics (Kadykalo & Findlay, 2016). In a review of such studies, Kadykalo and Findlay (2016) found most studies reported wetlands provide HES benefits in terms of flow regulation including reductions in base flow and flooding magnitude and duration. The general variability in magnitude of these benefits make evaluation on a watershed scale essential for developing a more accurate understanding of HESs provision (Acreman & Holden, 2013; Terrado et al., 2014).

In urban areas located along waterbodies, the HES of flood regulation is especially important. Both natural and human factors drive flood regulation (Li et al., 2019). With this, variability and extent of flooding depends heavily on land cover characteristics and precipitation. Vegetation plays a large role in regulating and lowering flood peaks and low flows (Brauman et al., 2007). Further research on the relationship between vegetation, more specifically conservation, and flooding in urban watersheds is underway (The Nature Conservancy, 2019).

2.1.2 Ecosystem Service Quantification

Ecosystem services are lost when land is disturbed from its original state (MEA, 2005). Policy and decision-making often fails to consider the value of these losses (Boyle Torrey, 2004; MEA, 2005; Pejchar et al., 2006). A number of factors need to be taken into consideration to improve understanding of how ecosystem services relate to beneficiaries, urbanization, and policy (Brauman et al., 2007). In an effort to improve the consideration of ecosystem services, quantification of these services is a key focus of current research. Quantification of ecosystem services provides valuable information needed to accurately assess synergies and tradeoffs to make sustainable development decisions reflecting the needs of the community and environment (Brauman et al., 2007). Recent efforts focus on developing indexes or standardized procedures for ecosystem service quantification (Logsdon, 2011; Logsdon & Chaubey, 2013). Evaluation of both the ecosystem service's market and intrinsic value is needed to accurately represent its worth (MEA, 2005). Prior to valuation, ecosystem services must be quantified. Quantification of ecosystem services under different scenarios can be completed using watershed models (Ahiablame & Shakya, 2016; McDonough et al., 2017b; Yen et al., 2016).

2.2 Urbanization and Hydrology

Urbanization is the conversion of natural land cover to less pervious or sometimes impervious land to support human habitation or industrial and commercial activity (US EPA, 2020). The disruption of natural land cover causes shifts in the hydrologic balance; reduced infiltration and decreased time of travel are consistent effects of urbanization (Wakode et al., 2017; McDonough, 2018). These shifts are caused by decreased surface roughness, which leads to increases in both peak and total discharge (Figure 2.1; Ahiablame et al., 2012). Overall, urbanization places greater stress on waterways to convey this rate and volume of discharge.

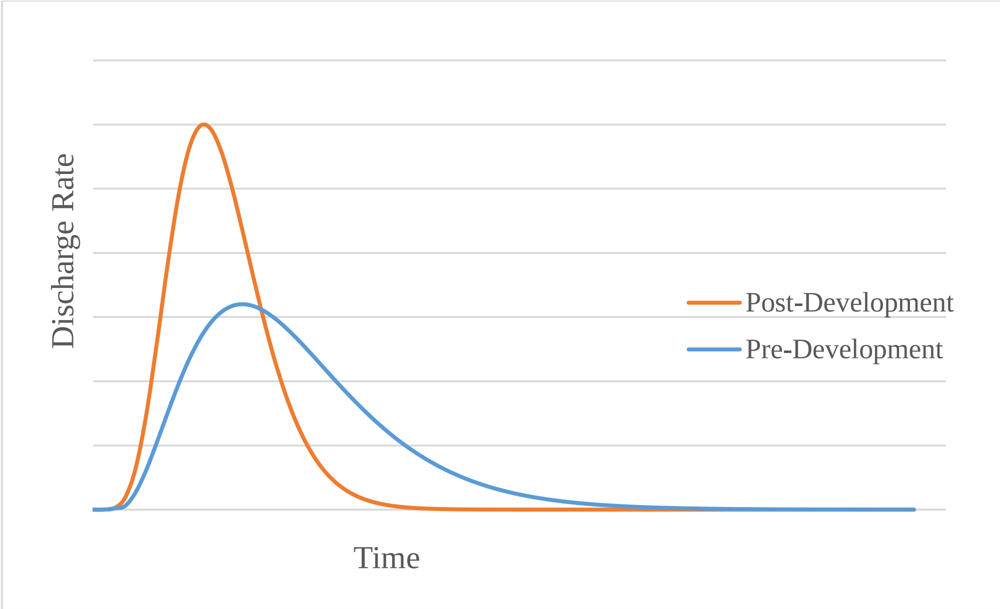

Figure 2.1. Urbanization, represented by the "post-development" curve, causes shifts in the hydrograph from pre-development conditions, "pre-development" curve. A reduction in time to peak discharge as well as an increase in peak discharge and total volume, the area under the curve, characterize this shift (modified from US EPA, 2020).

The characteristics of a stream's contributing land and climate dictate flow regime (Charlton, 2008). In urban systems, upstream factors such as land management decisions, legal requirements, and hydrologic service programs heavily affect the benefits realized downstream (Brauman, 2015). Careful management and evaluation of upstream actors aids in hydrologic ecosystem service provision.

The shifts in the hydrologic balance and hydrograph increase the risk of flooding and flood peak in urban areas (Charleton, 2008). Streams do not build their channels to convey flood flow; flooding is a natural geomorphological process (Charleton, 2008). During these events, a great deal of geomorphological work is done on the channel and water flows onto the floodplain. The floodplain is the relatively flat area next to a river inundated when flood flow occurs. Charleton (2008) notes the amount of geomorphologic work done by a flood is determined by its flow and frequency of occurrence. Regional flood frequency curves have been created to display the relationship between a flood return period and its discharge compared to the mean annual flood.

2.2.1 Exploration of Sustainable Development Strategies

With improved knowledge of more sustainable development strategies, city planners can help aid in biodiversity and conservation efforts by thoroughly considering how different development schemes will affect the ecosystem (MEA, 2005; Soga et al., 2014). Soga et al. (2014) focused on the distribution of biodiversity with two main categories—land sharing and land sparing. Land sharing is defined by "development [which] is more evenly, but less intensively, distributed, such that a larger land area is needed to accommodate a given number of houses, and greenspaces tend to be more fragmented but on average closer to residential areas" (Soga et al., 2014, pg 1379). Land sparing is when a more even distribution of biodiversity exists with it being scattered "across the whole of a landscape but in a large number of smaller, fragmented, greenspaces" (Soga et al., 2014, pg 1379). It was determined that the best-fit development scheme depends on the level of urbanization and species present. Thus, regional if not watershed-scale evaluation is needed.

Another more sustainable strategy is conservation development. Pejchar et al. (2006) describe conservation development as "a potential but rarely realized development strategy that integrates conservation of biodiversity and ecosystem services with development" (pg 30). Under conservation development, a forested riparian buffer or wetlands separate streams from developed and agricultural land. Limitations and benefits of this strategy were evaluated from a biophysical, economic, and institutional standpoint. A clear benefit of conservation development is ecosystem service provision. Conservation development provides significantly more ecosystem services than conventional development, which could include carbon and water storage, biodiversity, beauty, fire protection, and water purification (Pejchar et al., 2006). Currently, various obstacles prevent implementation of conservation development. Improved education of parties involved and quantification of benefits provided through conservation development would help shift policy in this direction (Pejchar et al., 2006). Analysis of this sort that considers factors beyond development extent is needed to provide watershed protection (Ahmadisharaf et al., 2020). This information will aid in maximizing ecosystem services and improve understanding of how development and climate change will affect the extent to which services are experienced.

2.2.2 Impact Mitigation with Low Impact Development

Mitigation of the hydrologic impacts of urbanization is important for improving system resiliency (Vogel et al., 2015). Many studies have focused on low impact development (LID) as a potential mitigation technique for the hydrologic impacts of urbanization. LID are "techniques [which] rely on distributed runoff management measures that seek to control stormwater by reducing imperviousness and retaining, infiltrating and reusing stormwater on the development site where it is generated" (Qin et al., 2012). LID techniques are synonyms for green infrastructure (GI) and stormwater control measures (SCM); all of these technologies work to restore pre-development condition hydrographs by providing supplemental water storage in urban areas, increasing system resiliency and maximizing watershed ecosystem services (Randhir & Raposa, 2014; Vogel et al., 2015). Overall, these techniques differ from traditional stormwater management, which directs water into pipes and away as quickly as possible, in how water is treated as a resource instead of a waste (Vogel et al., 2015).

Ahiablame and Shakya (2016) explored the effectiveness of varying LID practices such as rain barrels, bioretention cells, rain gardens, and porous pavement impact the hydrology of an urbanized watershed in Illinois using PCSWMM watershed modeling software. In this study, previous land cover data was used— looking at NLCD data from 1992, 2001, 2006, and predicted 2030 land use. Twenty-four scenarios of varying LID implementation were evaluated. This study indicates that some forms of LID cannot greatly reduce urban runoff or prevent flooding risk due to the great amount of land development they must compensate for (Ahiablame & Shakya, 2016). The best performing combined LID scenario resulted in a maximum annual runoff volume reduction of 47% (Ahiablame & Shakya, 2016). Regardless of the level of implementation, LID alone was not able to stop all flooding, with varying performance depending on storm intensity and duration, and can be costly to implement and maintain. Literature review conducted by Qin et al. (2012) found similar results. Simply incorporating LIDs throughout the watershed cannot resolve all the damage that has been done; "a rain barrel won't solve the flooding issue by holding back all the stormwater, however it is a good start and it gets homeowners thinking about water conservation" (Ahiablame & Shakya, 2016, pg 9). A similar study conducted by McDonough et al. (2017b) in a Midwest watershed had similar findings: green roofs and rain barrels were not helpful in hydrologic ecosystem service provision, flood regulation included. For this reason, a systems approach must be utilized during development planning to reduce overall environmental impacts especially on hydrologic processes.

2.3 Protecting Natural Waterways

A fault in traditional watershed management currently in practice is the failure to protect natural waterways (AUMA, 2020). In response, bank restoration and flood protection measures are the most frequent river engineering projects (Biron et al., 2014). Unfortunately, the resulting designs often reduce floodplain accessibility to the river and harm the ecosystem, deferring the natural abilities of the river's flood system (Biron et al., 2014). The value of the floodplain must be respected during development and planning. Floodplains play a key role in improving water quality, providing ecosystem services, and providing some safety in floods by acting "as safety valves…, where water can be poured without causing serious harm to the human economy" (Kiedrzyńska et al., 2014, pg 960). Floodplains also provide opportunity for water exchange, reducing the volume of water entering the river by increasing the volume absorbed into the ground (Charleton, 2008).

2.3.1 Riparian Buffer Functionality

Generally speaking, the riparian buffer is the wooded area adjacent to a stream (Charleton, 2008). The riparian buffer provides a connection between contributing land and its corresponding water body through hydrologic interaction of surface and subsurface processes (NRC, 2002).

Riparian buffers provide a number of ecosystem services, including water quality and quantity benefits, habitat, and erosion control, which makes them a valuable component of any stream system (Charleton, 2008; Friends of the Kaw, 2013; NRC, 2002). When water in the channel is high, it is able to extend into the riparian buffer area. The main water quantity benefits of interest include regulating stream flow, stream and bank stabilization, and storing floodwater (Butler, 2005). Flooding can provide newly exposed land in the riparian area for fresh vegetation to develop, improving bank stability for the following flood (NRC, 2002). The presence of healthy vegetation within this area reduces the speed of water entering the channel by increasing the surface roughness, which reduces the subsequent risk of erosion. As water flows into the channel, the riparian vegetation slows it, providing an opportunity for infiltration and nutrient removal (Butler, 2005). Ultimately, these functions reduce flood damage downstream of the riparian buffer (NRC, 2002).

Significant alterations of over 70% of riparian buffers in the western United States due to dam construction, stream diversion, or consistent flooding has occurred (Butler, 2005). Others studies indicate riparian buffer has reached 95% in some areas (NRC, 2002). Disturbance of the riparian buffer results in the loss of many of its ecological functions, directly affecting stream health and stability (NRC, 2002). Riparian buffers are most beneficial when applied throughout an entire watershed with no disturbance. Failing to preserve this land in the headwaters results in substantially less benefits as water travels downstream (Hawes & Smith, 2005). Policy that prevents the disturbance of riparian buffers ensures the system is continuous and connected, optimizes benefits (Hawes & Smith, 2005; Li et al., 2019).

2.3.2 Current Policy

Inconsistent treatment of riparian buffers is due to the diversity of regulations between various jurisdictions driven by "the lack of a consistent definition for 'riparian'" (NRC, 2002, pg 29). As previously stated, riparian buffers are most effective when they are part of a continuous network (Hawes & Smith, 2005). Policy changes that normalize the protection of riparian buffers is needed to achieve maximum benefits.

Implementation of riparian buffer projects will require cooperation between local governments and landowners (Butler, 2005). Holistic strategies, which aim to return hydrologic regimes of the watershed to their natural state, would provide the best opportunity for riparian buffer function (NRC, 2002). Evaluation of the hydrologic ecosystem services provided by riparian buffers supports the creation of such policies.

2.4 Climate Change and Hydrologic Ecosystem Services

Easterling et al. (2017) reported an increase in annual precipitation throughout most of the Midwest, Northeast, and Northern and Southern Plains of United States in the Climate Science Special Report when examining the average annual precipitation from 1901-1960 to 1986-2015. This trend will continue throughout the 21st century with increases in both precipitation intensity and frequency (Easterling et al., 2017). The 2017 Climate Science Special Report detailed a 13% increase in 5-yr maximum daily precipitation from 1901-2016, 12% increase in 99th percentile precipitation from 1958-2016, and increases in the number of 5-yr, 2 day events from 1901-2016 and 1958-2016 of 40% and 11% respectively (Wuebbles et al., 2017). Likewise, utilizing climate change projections, Willems et al. (2012) found rainfall intensity increases of 10-60% for small urban catchments from recent years to 2100.

From a hydrologic standpoint, climate change will exacerbate floods in areas experiencing increased precipitation (IPCC, 2014). Increases in flooding may cause water quality decline, destruction of property, loss of business and livelihood, and public health issues (IPCC, 2014). The combined pressures of climate change and urbanization cause flood vulnerability of cities to continue to rise (Willems et al., 2012). The magnitude of these effects depends on socioeconomic factors and location (IPCC, 2014). Evaluation of the combined effects of land development and projected storm events provides a better representation of future system needs. Current design standards and policies typically view the design flood as stationary, failing to adjust the flood for climate change (Gilroy & McCuen, 2012). This decision could be detrimental and result in systems being improperly designed, in short designed to fail. The failure of a water management system designed in this way would require more monetary repairs than a future-focused designed system (IPCC, 2014). Therefore, the acknowledgement and incorporation of climate change projections is crucial in proper evaluation of land development options.

2.4.1 Climate Change Models

Due to changing climate, the use of historically derived Intensity-Duration-Frequency (IDF) curves is becoming less suitable (Willems et al., 2012). For this reason, climate change projections and the resulting precipitation are being explored. In creating climate change models, various greenhouse gas concentrations are used to predict the atmosphere's response. Global Climate Models (GCMs) are coarse on both temporal and spatial scales (Willems et al., 2012). GCMs are based on projected pathways of greenhouse gas emissions (RCPs). The higher the RCP, the higher the projected global temperature and annual carbon emission (Williams et al., 2017). These models are downscaled to Regional Climate Models (RCMs) to provide finer resolution data for watershed assessment. With any model, the numerical values delivered are merely predictions and should be evaluated in reference to one another to determine the change in magnitude experienced (Willems et al., 2012).

2.5 Watershed Modeling

Evaluation of different land development scenarios is possible with the use of watershed modeling. Watershed models are a tool in determining which land use scenarios balance development of urban areas with conservation and protection of the ecosystem and biodiversity (Logsdon & Chaubey, 2013). Various research projects across the globe have investigated or continue to investigate this relationship.

Watershed modeling has increased in popularity in recent years (Yen et al., 2016). Models of varying complexity and specialties (i.e. water quality, water quantity, and asset management) are utilized worldwide to evaluate a number of environmental factors and changes (Boulos, 2017; Yen et al., 2016). However, not all models are suitable for all watersheds and projects. The characteristics of the watershed and goals of the project guide model selection (Ahiablame et al., 2012). For example, USDA-ARS created the SWAT, a process-based, semi-distributed watershed model (Yen et al., 2016). This model is best suited for agricultural areas. The US EPA created SWMM and later PSCWMM, the model used in this study, for modeling of urban areas (US EPA, 2016). When a model is well selected and created, its outputs can ease complex decisions at the watershed scale (Yen et al., 2016).

2.5.1 Climate Change and Land Development

The International Panel on Climate Change (IPCC) stresses the importance of integration of climate change predictions in improving resiliency of development (IPCC, 2014). Climate change and land development projections modeled in conjunction with one another provide the best representation of potential future conditions. Wu et al. (2013) explored the impact of climate and land cover change on the hydrologic processes of urban stream headwaters using SWMM software. The land cover change scenarios considered were characterized by the percent and location of impervious area. The greatest interest was in the impact of these changes on stream flow regime. Land change scenarios had a greater impact on stream flow than climate change alone, with the combined changes having the greatest impact. It was found that "important hydrological changes occur at thresholds below 10% [impervious surface]." This study found significant changes already at 8% (Kolka et al., 2013). Another study by Terrano et al. (2014) found changing climate extremes had a large impact on HES provision in a heavily modified watershed. It was suggested that land neighboring streams be protected to increase HES provision and increase resilience to climate change (Terrano et al., 2014). Due to the spatial and temporal variability and general uncertainty of climate change, Easterling et al. (2017) recommend various future scenarios be considered in site-specific evaluation. With this, further exploration of ecosystem service quantification should be performed (Logsdon & Chaubey, 2013; Maragno et al., 2018).

Chapter 3 - Methods

3.1 Study Area

The Blue River Watershed (HUC #1030010101) is located south of the Kansas City metropolitan area and is part of the Lower Missouri-Crooked watershed (HUC #10300101). As such, it serves as a tributary to the Missouri River. The Blue River Watershed has areas in both Kansas and Missouri (Figure 3.1). The headwaters of the watershed are in Kansas, moving northeast towards the outlet. The Blue River is a fifth order stream with its major tributaries being Brush, Indian, Tomahawk, Wolf, and Coffee Creeks (Missouri, n.d.).

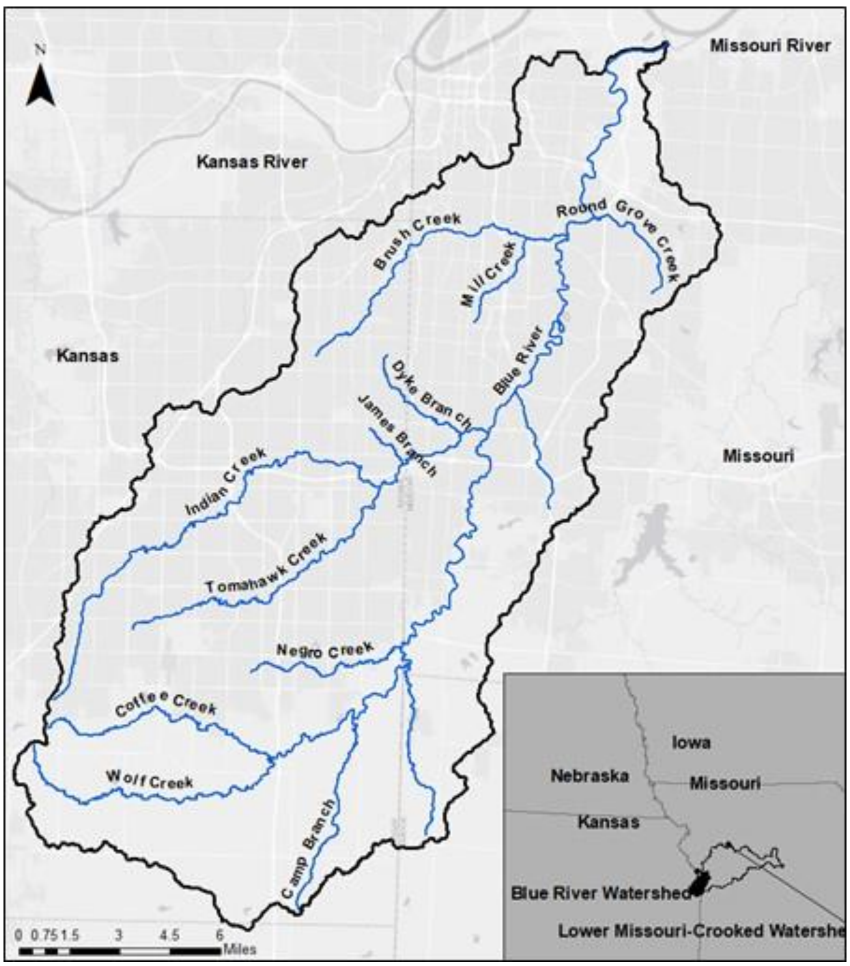

Figure 3.1 The Blue River Watershed is a tributary to the Missouri River with parts in both Kansas and Missouri. The main stream channel is shown in blue (Thomas, 2020).

The entire watershed is nearly roughly 75,000 hectares (185,000 acres) with multiple cities in its boundary including Olathe, Overland Park, Leawood, Prairie Village, and Kansas City (MARC, 2019). The watershed spans five counties with notable area in Johnson, Jackson, and Cass counties (Figure 3.2 The Blue River Watershed has area in five counties, overlapping twenty cities).

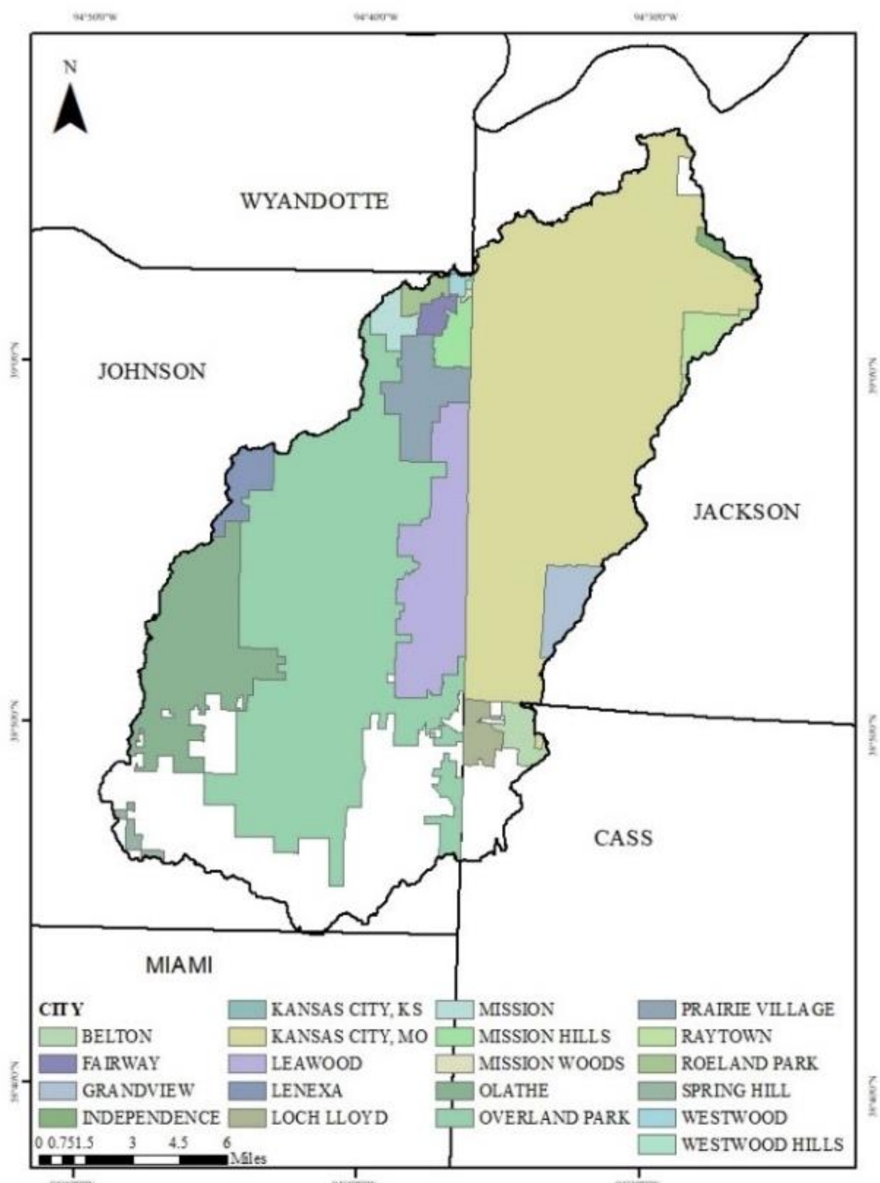

Figure 3.2 The Blue River Watershed has area in five counties, overlapping twenty cities (MARC, 2010).

3.1.1 Physiographic History of the Blue River Watershed

The Blue River Watershed is mainly located in the physiographic region of the Osage Cuestas (Wingfield, 2007). The word "cuesta" means hill or cliff in Spanish. Thus, series of ridges are found in this area along with other landforms such as rolling hills and flat plains. Limestone and shale compose most of the rock near the surface in the region (Kansas, 2010). The rocks in the Blue River Watershed are part of the Carboniferous system, most specifically the Pennsylvanian subsystem which occurred 318 million years ago (Kansas, 1998). As such, streams in the region typically have sand, silt, and rock fragments in them (Kansas, 2010).

The level-three ecoregion classification of the Blue River Watershed is primarily Central Irregular Plains (Figure 3.3; US EPA, n.d.). The upper Blue River Watershed is located in the unglaciated part of the ecoregion. The Central Irregular Plains is known for its generally flat landscape and claypan soils (Karstensen, 2009). The Blue River Watershed was primarily covered by tallgrass and oak-hickory forests prior to development (US EPA, n.d.). However, the extensive urbanization and agriculture seen in the Blue River Watershed has caused the majority of natural land cover to be removed (Figure 3.3Figure 3.3 The majority of the Blue River Watershed is located in the Central Irregular Plains level three ecoregion. Near the outlet, the watershed extends into the Western Corn Belt Plains ecoregion (US EPA, n.d.). Today, this region is primarily used for agriculture. However, Kansas City is a hotspot of development (MRLC, 2011). ; MRLC, 2011).

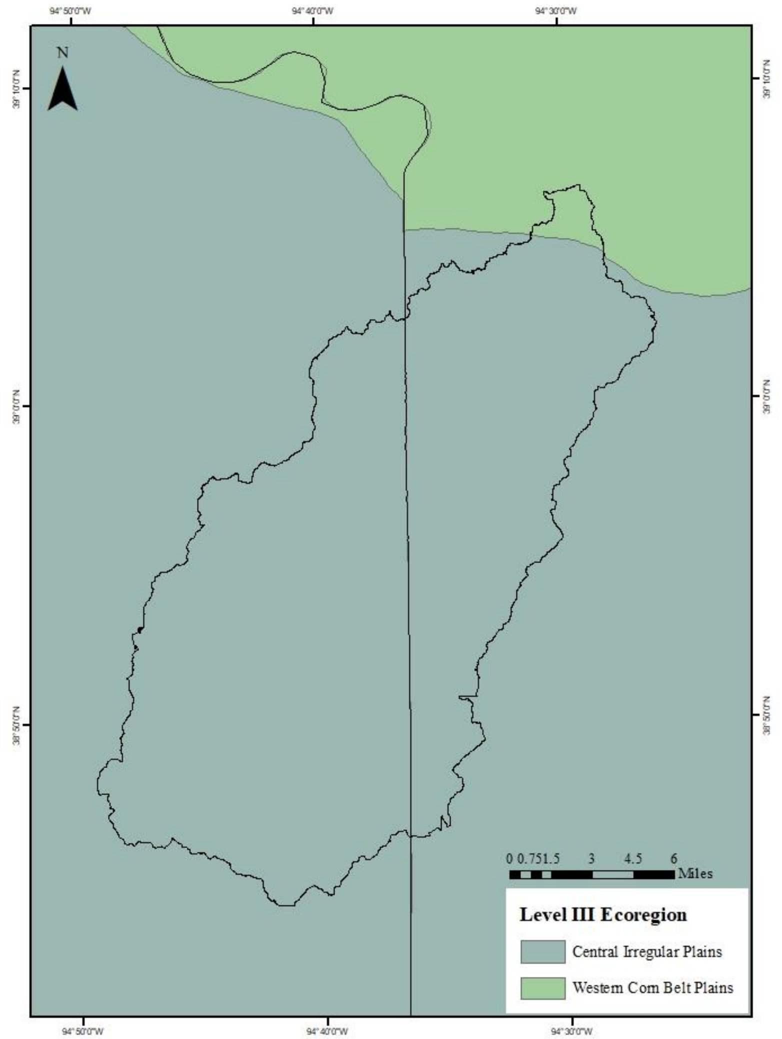

Figure 3.3 The majority of the Blue River Watershed is located in the Central Irregular Plains level three ecoregion. Near the outlet, the watershed extends into the Western Corn Belt Plains ecoregion (US EPA, n.d.). Today, this region is primarily used for agriculture. However, Kansas City is a hotspot of development (MRLC, 2011).

3.1.2 Current State of the Blue River Watershed

A land use/land cover gradient exists within the watershed, with urbanization dominating the northern area and rural land uses (e.g. grazing land, cropland) in the headwaters in the southern portion of the watershed (Figure 3.4 Land use/land cover in the Blue River Watershed from the 2011 National Land Cover Dataset). The amount of urban area in the watershed is predicted to increase, with some areas of the headwaters estimated to urbanize at a rate of 8.89% per year (Ji et al., 2016). Notable areas of deciduous forest are still present along the main channel and in parts of the headwaters of the Blue River. However, wide-spread disturbance of the riparian buffer, resulting from urbanization, has clearly occurred in the Tomahawk and Indian Creek tributaries.

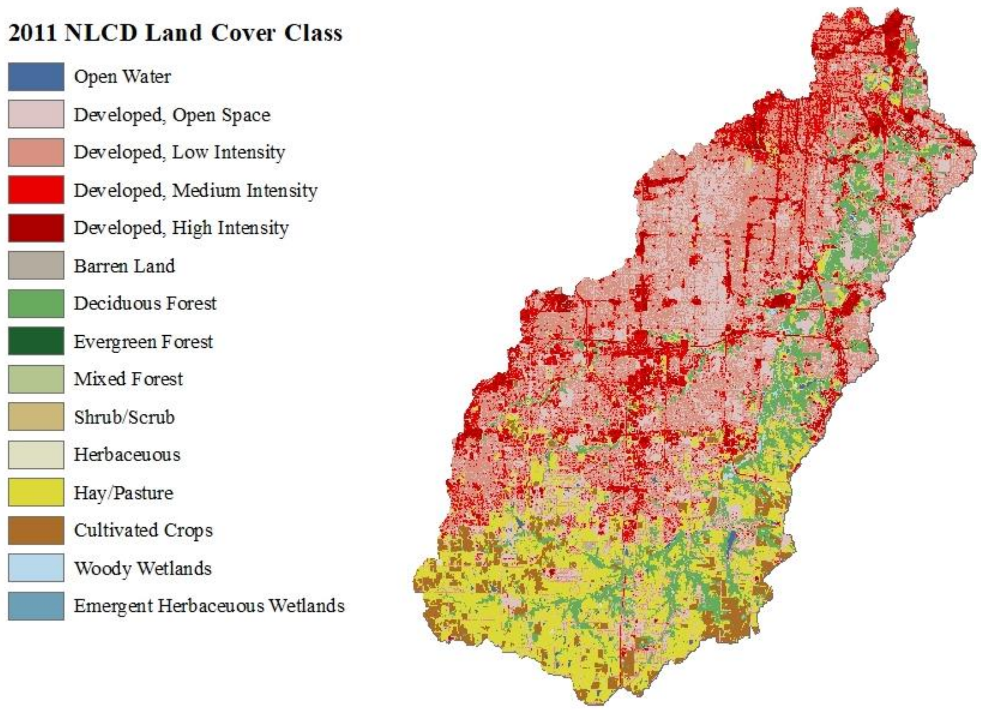

Figure 3.4 Land use/land cover in the Blue River Watershed from the 2011 National Land Cover Dataset (Homer et al., 2011).

3.1.2.1 Inconsistency in Policy

As previously mentioned, a number of cities, including Leawood, Olathe, Grandview, and Raytown, occupy the land contributing to the Blue River Watershed (MARC, 2019). Within each of these communities, different governing bodies are at play, creating difficulty for watershed unity. This political division of the watershed has presented some difficulties in management and funding allocation. Currently, riparian buffers in parts of the Blue River are more protected than others due to different policies and zoning requirements in place (Table 3.1; Lenexa, 2020;

Overland Park, 2020; Kansas City, 2020). For this reason, great variability in stream health and conditions are observed (Pitchford et al., n.d.).

Table 3.1 Greater variation in stream setback ordinances exists throughout the watershed. The width, allowed use, and definition of the riparian buffer area is inconsistent (Overland Park, 2020; Lenexa, 2020; Kansas City, 2020).

Location	Basis	Width Suggested
Overland Park	Minimum distance from high water mark based on contributing area	Area < 25 acres: ~15 ft 25-40 acres: 30 ft 40-160 acres: 60 ft 160-5000 acres: 100 ft Area > 5000 acres: 120 ft
Lenexa	Zonal widths, with suggested minimum width dictated by stream order and condition Zones: Streamside: 25 ft Middle: based on stream condition and order Outer: 25 ft	1st Order: 100-150 ft 2nd Order: 150-250 ft 3rd Order: 200-300 ft
Kansas City, MO	Zonal widths, with middle zone depending on slopes, floodplain Zones: Streamside: 25 ft Middle: based on floodplain, slope Outer: 75 ft baseline, can extend to 250 ft	Varies greatly depending on location and amount of disturbance in zones

3.1.2.2 Conservation Efforts

A variety of conservation efforts have been made in the Blue River Watershed and will continue to expand in the coming years. Many local jurisdictions have worked to create and expand recreational services along the Blue River and its tributaries. For example, the Johnson County Parks and Recreation organization has led a streamway parks system effort which focuses on this mission. This system supports park and trail development around streams, riparian vegetation preservation, flood control, and avoidance of property damage due to proximity of buildings around a stream. One project included in this system is a streamway trail, completed in fall 2017 along Coffee Creek. This included 3.4 miles of paved trails along with four bridges (Johnson, 2017). It is expected that more trails will be developed along the Blue River in the future. Similar conservation projects and movements are seen across the watershed. Increased interaction between community members and waterways will likely improve knowledge of the stream's conditions.

3.1.3 Future of the Blue River Watershed

Understanding the history, current state, and potential future of the Watershed is crucial in developing a more positive outlook. The urbanization seen in the lower Blue River Watershed is expected to extend into the upper Watershed in coming years. With this, the stability of the upper Blue River will be threatened. Understanding this, however, provides land planners and local officials with the opportunity to adjust their development plans to be more sustainable.

In planning for this migration, the Mid-America Regional Council developed several land use scenarios for the year 2040 (MARC, 2015). This includes a built-out scenario and a recommended land use scenario. Currently, according to a data layer developed by MARC, there are 26,000 acres of impervious surface in the watershed. The built-out and recommended land use scenarios contain around 35,000 and 26,000 acres respectively (MARC, 2015). In addition to these land development scenarios, MARC created the MetroGreen Action Plan. This plan focuses on protecting, restoring, and enhancing environmental features in the Kansas City area. The importance of floodplains and their function as well as stream corridor preservation is a key driver of this plan (MARC, 2015).

Several jurisdictions have also been considering future scenarios. Due to expansion in the early 2000s, the Coffee Creek area developed a framework for their future development (HNTB, 2005). With this, the "Master Plan for Coffee Creek" was created and published in July 2005. The plan was developed in response to the need for a common vision for the area as it continues to develop. This plan acknowledges and considers different factors that influenced the plan's creation, provides recommendations, and strategy for implementation of the master plan. Factors discussed include school districts, transportation, market considerations, and the environment (HNTB, 2005). Under this plan, the stream corridor in Coffee Creek will be protected from development.

Consistent and informed actions must be taken as the Blue River Watershed continues to develop (Pitchford et al., n.d.). Consistency in policy is of the most concern as the watershed continues to urbanize. Watershed modeling provides a unique opportunity to consider different scenarios to improve understanding of how and where to preserve ecosystem services during this development (McDonough, 2018).

3.1.4 Ecosystem Service Loss in the Blue River Watershed

Due to the increase in urbanization, agriculture, and general disturbance of nature in the Blue River Watershed, many ecosystem services are being reduced (McDonough, 2018). This reduction is expected to intensify with the continued reduction in natural vegetation due to land development. Some of the main ecosystem services being impacted by these changes include habitat, flood regulation, and various cultural services provided by natural areas. Due to the financial strain of flooding in the watershed, the loss of hydrologic ecosystem services is the most recognized.

As a river city, severe flooding has troubled the Kansas City area since its settlement with the most recent notable events in 2010 and 2017 (McDonough, 2018). Since 2003, roughly $250 million has been invested in the lower Blue River to prevent flooding (Patti Banks Associates, 2007). This investment was the reaction of monetary damage and loss of life due to flooding in the

Blue River Watershed. Flood prevention projects have resulted in greatly altered, engineered channels near the outlet of the watershed, a loss of around 2.6 miles of the Blue River (Pitchford et al., n.d.).

Persistent flooding in the lower Blue River Watershed exemplifies the importance of preserving the health and hydrologic performance of the upper watershed. If the entire watershed becomes severely urbanized with little attention given to the hydrologic implications of the development, flooding and stream channel conditions would drastically worsen, and other ecosystem services would be lost. Unless changes in engineering mindset and water management are made, the upper Blue River Watershed may have a similar fate as urbanization spreads. Thus, the importance and magnitude of the flood regulating services provided by natural vegetation within the riparian buffer must be explored. Integrating this knowledge in land management practice would prevent additional damages and complications in the watershed.

3.2 PCSWMM Model

3.2.1 Model Basics

Computational Hydraulics International (CHI) created the Personal Computer Storm Water Management Model (PCSWMM) in 1984 as an extension of the US EPA SWMM5 model (James et al., 2010; McDonough, 2018). PCSWMM is a semi-lumped, deterministic hydrologic model with capabilities of simulating water quality and water quantity for event-based and continuous precipitation (Rossman & Huber, 2016). PCSWMM is best suited for urban areas (Ahiablame & Shakya, 2016). As such, modeling of low impact development is possible (e.g., McDonough et al., 2017b; Rossman & Huber, 2016).

The two main equations satisfied by PCSWMM at each time step are Manning’s and continuity. Manning’s equation (Equation 3-1) computes the rate of runoff (Q, cfs) based on surface roughness coefficient (*n*), subcatchment slope (*S*, ft/ft), hydraulic radius of the given area (R_x, ft), and subcatchment area experiencing flow (A_x, ft^2) (Rossman & Huber, 2016). The area of the subcatchment represents an idealized, rectangular subcatchment of width (*W*) and height, depth of water minus depression storage depth (d-d_s). Assuming the hydraulic radius equals the difference between water depth and depression storage, Manning's equation can be simplified as presented in Equation 3-1.

$$Q = \frac{1.49}{n} W S^{\frac{1}{2}} (d - d_s)^{5/3} \qquad \text{(Equation 3-1)}$$

In this study, infiltration was accounted for in PCSWMM using the Green-Ampt equation (Equation 3-2). The cumulative infiltration depth (*F*, units of length), at time t is calculated from the effective hydraulic conductivity (K_e, units of length/time), time (t), average matric suction at the wetting front (S_{avg}, units of length), and fillable porosity (*M*, units of L^3/L^3) (Huffman et al., 2013).

$$F = K_e t + S_{avg} M \ln(1 + \frac{F}{S_{avg} M}) \qquad \text{(Equation 3-2)}$$

The force main equation assigned in the model for this study was the Hazen-Williams equation (Equation 3-3). With this equation, friction or head loss through a pipe (H_f, m) is estimated from pipe length (*L*, m), discharge (*q*, L/s), pipe roughness coefficient (*C*), and actual inside pipe diameter (*D*, mm) (Huffman et al., 2013).

$$H_f = \frac{1.21 * 10^{10} L (\frac{q}{C})^{1.852}}{D^{4.87}} \qquad \text{(Equation 3-3)}$$

Dynamic wave routing was utilized as the routing method for this study. Under this routing scheme, the complete one-dimensional Saint-Venant flow equations are solved. This calculates the flow within each conduit based on continuity (Equation 3-4) and momentum (Equation 3-5; James et al., 2010). Variables considered in calculation include cross sectional area (*A*), flow rate (*Q*), distance (x), time (t), hydraulic head (H), friction slope (S_f), local energy loss per unity length (h_L), and acceleration due to gravity (g) (James et al., 2010). Dynamic wave routing accounts for backwater flow, entrance/exit losses, flow reversal, pressurized flow, and channel storage, making it the optimal and most "theoretically accurate" routing method (James et al., 2010).

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad \text{(Equation 3-4)}$$

$$\frac{\partial \mathrm{Q}}{\partial \mathrm{t}} + \frac{\partial (\frac{Q^2}{A})}{\partial \mathrm{x}} + \mathrm{gA}\frac{\partial \mathrm{H}}{\partial \mathrm{x}} + \mathrm{gA}S_f + \mathrm{gA}h_L = 0 \qquad \text{(Equation 3-5)}$$

Evaporation data is entered into PCSWMM as a single constant value, monthly average values, or daily values. Temperature data entered into PCSWMM can also be used to calculate evaporation during the simulation period (Rossman & Huber, 2016).

3.2.1.1 Water Routing

In PCSWMM, water is routed throughout the watershed through various features of the model: subcatchments, conduits, and junctions. Routing of the model is assigned based on the DEM. When assigning routing, each subcatchment is only allowed one outlet: another subcatchment, conduit, or junction. Conduits represent the stream channel or a pipe. As water flows through the conduits, it passes through junctions. These junctions serve as connections between the conduits. Within each subcatchment, a percentage of water can be routed to flow onto pervious or impervious surfaces before being routed to the outlet (Rossman & Huber, 2016).

At each time step, the model computes a water balance. First, water infiltrates into the pervious surface of the watershed. The water that does not infiltrate within the subcatchment flows to the outlet. In the absence of a natural channel or pipe network, the runoff from a subcatchment flows into the next downstream subcatchment. The water is distributed evenly across the receiving subcatchment. In the presence of a natural channel or pipe network, the subcatchment would instead be routed into a conduit or junction. The water will flow through the conduit unless the volume of water exceeds the capacity at a junction. When a junction receives flow above its capacity, water is allowed to pond at the junction. This symbolizes flooding, ensuring the water is not lost to the system and can return to the conduit when storage is available (Rossman & Huber, 2016).

3.2.2 Model Development

PCSWMM was used to model the hydrologic impact of different land development scenarios on the Blue River watershed. Kelsey McDonough built a model of the Blue River Watershed during the pursuit of her doctorate degree at Kansas State University (McDonough, 2018). McDonough updated this model in March 2020 to improve model performance. In updating the model, McDonough used a filled digital elevation model with 3-m spatial resolution from the 2011 National Elevation Dataset (Homer et al., 2011) to represent watershed topography and the National Hydrography Dataset stream network to delineate the watershed and create subcatchments (McDonough, 2018). In the updated model, 76 subcatchments were created using the automatic delineation tool in PCSWMM, in addition to a conduit and junction system to represent the flow of water through the watershed (Table 3.2). Subcatchments were sized as to not exceed 1,000 hectares. The conduit system represents the main channel and tributaries of the Blue River, with junctions connecting each conduit. In the event of storage being exceeded, ponding was allowed at each junction (McDonough, 2018).

Table 3.2 PCSWMM model features utilized in flow routing of the calibrated watershed model.

Model Feature	Description
Subcatchments	The watershed was delineated into 76 subcatchments based on the DEM and stream network. Each subcatchment is lumped in nature. The area-weighting tool was utilized to determine subcatchment model parameters (% impervious, Manning's roughness, infiltration characteristics, etc.).
Conduit System	The DEM was used to determine where water would concentrate in the watershed. The conduit system represents the main stream network in the watershed. The entire model contains 69 conduits.
Junctions	The junctions serve to connect the conduits throughout the system. Sixty-nine junctions exist in the calibrated model. Hydrologic conditions were evaluated at six of the junctions corresponding to USGS stream gage locations.

The 2011 National Land Cover Database, the most recent data set available at time of original model creation, was used to define land cover across the watershed (McDonough, 2018). Land cover provided by this dataset acts as the baseline of comparison in this research. Subcatchment and infiltration-related attributes were determined based on the NLCD dataset and soil survey spatial and tabular data (SSURGO 2.2) using the Area Weighting Tool in PCSWMM (Table 3.3; Table 3.4). The Green-Ampt and Hazen-Williams equations were used to calculate infiltration throughout the watershed and head loss through pipes under pressure respectively (McDonough, 2018). Average monthly evaporation rates based on historic data was used in the model (Table 3.5; NOAA 1982a; NOAA, 1982b).

Table 3.3 Subcatchment attributes were assigned based on land use/land cover data provided by the NLCD 2011 dataset (modified from James et al., 2010).

Land Use/ Land Cover	Grid-code	%IMPERV[1]	DSPERV[2] (mm)	DSIMPERV[3] (mm)	NPERV[4]	NIMPERV[5]
Open Water	11	0	0	0	0	0
Perennial Ice/Snow	12	0	0	0	0	0
Developed, Open Space	21	10	2.54	1.27	0.034	0.012
Developed, Low Intensity	22	30	2.54	1.27	0.034	0.012
Developed, Medium Intensity	23	60	2.54	1.27	0.034	0.012
Developed, High Intensity	24	90	2.54	1.27	0.034	0.012
Barren Land	31	0	2.54	0	0.05	0
Deciduous Forest	41	0	7.62	0	0.40	0
Evergreen Forest	42	0	7.62	0	0.40	0
Mixed Forest	43	0	7.62	0	0.40	0
Dwarf Scrub	51	0	5.08	0	0.24	0
Shrub/Scrub	52	0	5.08	0	0.24	0
Grassland/ Herbaceous	71	0	5.08	0	0.24	0
Sedge/ Herbaceous	72	0	5.08	0	0.24	0
Lichens	73	0	5.08	0	0.15	0
Moss	74	0	5.08	0	0.15	0
Pasture/Hay	81	0	5.08	0	0.13	0
Cultivated Crops	82	0	5.08	0	0.17	0
Woody Wetlands	90	0	7.62	0	0.40	0
Emergent Herbaceous Wetlands	95	0	7.62	0	0.15	0

[1] Percent impervious area
[2] Depth of depression storage of pervious area
[3] Depth of depression storage of impervious area
[4] Manning's N for pervious area
[5] Manning's N for impervious area

Table 3.4 Hydraulic properties by soil type used in model development (modified from James et al., 2010).

Soil Type	Suction Head (mm)	Conductivity (mm/hr)	Initial Deficit (frac.)
Sand	49.5	120.4	0.417
Loamy Sand	61.2	30	0.401
Sandy Loam	110	0.43	0.412
Loam	88.9	10.9	0.434
Silt Loam	166.9	6.6	0.486
Sandy Clay Loam	218.4	1.5	0.33
Clay Loam	208.8	1.0	0.309
Silty Clay Loam	273.1	1.0	0.432
Sandy Clay	493	0.5	0.321
Silty Clay	292.1	0.5	0.423
Clay	316.2	0.25	0.385

Table 3.5 Average monthly evaporation rate in the Blue River Watershed (NOAA, 1982a; NOAA, 1982b).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Average pan evaporation (cm)	3.5	4.7	8.8	13.8	48.6	20.2	22.5	20.6	14.5	11.4	6.1	4.0
Average free water surface evaporation (cm)	2.6	3.4	6.5	10.2	13.8	15.0	16.6	15.2	10.7	8.4	4.5	2.9

Several additional subcatchment attributes were also assigned during model development. Subarea routing was set to "PERVIOUS" with the percent routed set at 5% for all subcatchments in the model meaning the runoff from 5% of the impervious area in each subcatchment is routed to pervious land instead of directly to the outlet at each time-step. Zero Imperv (%) represents the percent of impervious land that has no depression storage available, and this value was set at 25%. Flow length within each subcatchment was assumed to be 30 m for all subcatchments.

The Transect Creator tool in PCSWMM was used to create cross-sections of each stream segment using the DEM layer (McDonough, 2018). Potential transects generated by the tool were evaluated on a conduit-by-conduit basis. The best-fit cross-section was selected for each conduit and assigned. After selecting the most representative transects, each channel was assigned a Manning's N of 0.03 corresponding to "earth bottom, rubble sides" and the overbanks a value of 0.1, "very weedy reaches of natural streams" (Huffman et al., 2013).

Overall, model creation required four main datasets: 2011 NLCD, gSSURGO 2.2, the 3-m DEM, and the National Hydrography Dataset (Table 3.6). From these datasets, subcatchments, conduits, and junctions were assigned attributes utilized by PCSWMM in hydrologic simulation (Table 3.6). Several of the attributes were adjusted through the calibration process as described below, in Section 3.2.3 Model Calibration and Validation.

Table 3.6 Summary of datasets used in PCSWMM model creation of the Blue River Watershed (McDonough, 2018).

Watershed Characteristic	Data Source	Model Parameters Determined
Land Cover	2011 NLCD	Percent Impervious, N Imperv, N Perv
Soils	gSSURGO 2.2	Suction Head, Conductivity, Initial Deficit
Flow Routing, Topography	DEM (3-m resolution) National Hydrography Dataset	Inlet and Outlet of Subcatchments Subcatchment Area, Width Junction and Conduit Elevations

3.2.3 Model Calibration and Validation

In the updated model, McDonough calibrated and validated the model at the USGS stream gage closest to the outlet of the watershed, station 06893578, analysis location 6, located at

39°03'30", 94°30'42" (Figure 3.5 Physical appearance of the calibrated Blue River Watershed model. The model was calibrated to total inflow at USGS stream gage 06893578 located near the outlet of the watershed, shown in yellow (USGS, 2020).; USGS, 2020). Streamflow data from USGS gage 06893578 and15-minute rainfall data collected through the Johnson County StormWatch program at their station located at the intersection of Roe Avenue and Tomahawk Creek (Johnson County, 2020) were used in model calibration (using 2017 data) and validation (using 2016 data). The hydrograph produced by the model was compared to the observed hydrograph from the USGS gauge using the Nash-Sutcliffe Efficiency (NSE), a commonly used statistical measure (James et al., 2010; McDonough, Moore, & Hutchinson, 2017; McDonough, 2018). If the observed and modeled hydrograph match perfectly, an NSE of "1" is achieved (Nash & Sutcliffe, 1970). The Sensitivity-Based Radio Tuning Calibration (SRTC) tool in PCSWMM was utilized to calibrate user-selected parameters within an assigned percent uncertainty by optimizing the NSE (McDonough, 2018). Only three parameters were allowed to change in calibration: subcatchment length which represents the flow of overland sheet flow (50% uncertainty), channel roughness (10% uncertainty), and zero percent impervious (50% uncertainty). The percent uncertainty utilized in calibration was within the range recommended by other research (James et al., 2010; McDonough, 2018). The model achieved an "excellent" rating at the calibrated stream gage location for total streamflow, with NSE values of 0.666 and 0.534 for 2017 and 2016, respectively. This means "the model is suitable for planning, preliminary design, and final design purposes" (Shamsi & Konan, 2017).

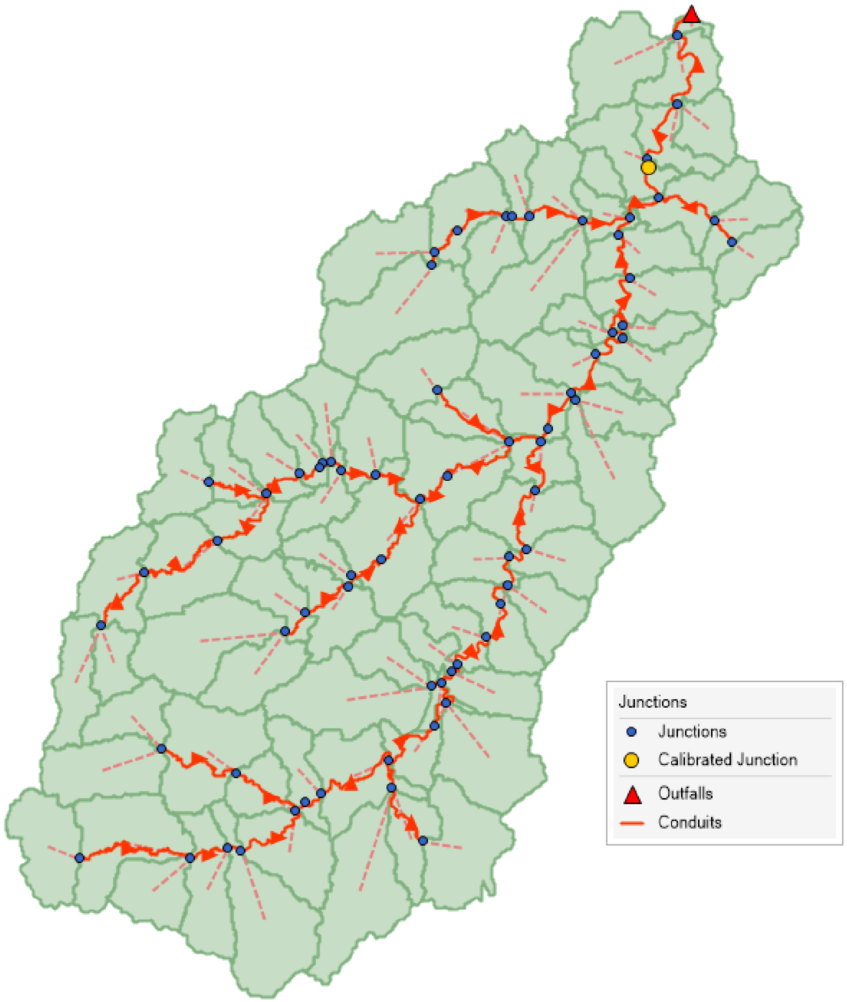

Figure 3.5 Physical appearance of the calibrated Blue River Watershed model. The model was calibrated to total inflow at USGS stream gage 06893578 located near the outlet of the watershed, shown in yellow (USGS, 2020).

3.2.4 Pipe Network

At time of model creation, the stormwater pipe network was not available throughout the entire watershed. The data that was available was incomplete and contained errors such as duplicate pipes. For this reason, the pipe network was not included in the model. Thus, all water was routed as surface flow when not infiltrated before making its way to the conduit system.

Regardless, due to how PCSWMM operates, each subcatchment can only have one outlet (Rossman & Huber, 2016). The subcatchments would have to be further divided to allow this specific of routing. Yang et al. (2018) investigated the impact of the level of pipe network inclusion on model performance in a much smaller watershed. For an area with one drainage system, it was found that pipe network simplification did not significantly impact the reported inflow. In this investigation, each land parcel was typically its own subcatchment. Thus, adding every curb inlet and pipe to a nested model the size of the Blue River Watershed is meaningless unless thousands of subcatchments are created. It should be noted that the lack of pipe network inclusion likely does not uniformly impact model performance. Areas with a mix of impervious and natural land cover are likely more impacted than areas with very dense development or very low-density development. In areas with these extremes, water flows quickly over the impervious area as it would in a pipe or flows less quickly over the pervious area where there are fewer pipes. Regardless, model performance during calibration indicates the model is a quality representation of the hydrologic processes that dominate rainfall/runoff processes at the spatial scale of the Blue River Watershed.

3.3 Land Development Scenarios

Four riparian buffer land use scenarios were created to observe the hydrologic impact of changes in land cover of the riparian buffer throughout the watershed (Table 3.7). Scenarios were created with the interests of local jurisdictions and policy makers in mind. The primary buffer width utilized in scenario creation, 150 feet, was determined based on evaluation of stream setback ordinances of various jurisdictions in the watershed discussed in Section 3.1.2.1 Inconsistency in Policy.

Table 3.7. Summary of land development modeling scenarios with quantifying descriptors.

Scenario Number	Description
Baseline 1A	**Baseline Scenarios (Current Conditions)** 1A- 2011 NLCD; original calibrated model with 16,095 hectares of impervious cover
1B	1B- 2011 NLCD with 150 ft buffer (1,400 hectares) around the conduit system, representing the riparian buffer around main channels; baseline scenario for Scenarios 2 and 3; 16,095 hectares of impervious cover
1C	1C- 2011 NLCD with 150 ft buffer (7,647 hectares) around National Hydrography layer which includes ephemeral streams; baseline scenario for Scenario 4; 16,095 hectares of impervious cover
2	**Conversion of Riparian Buffer to Managed Green Space** Scenario 1B with conversion of all natural vegetation within the 150 ft buffer around the conduit network to a managed green space 90 hectares of natural vegetation were removed; all developed land within the buffer was left as is; 16,175 hectares of impervious cover
3	**Restoration of Riparian Buffer of Main Channels** Scenario 1B with restoration of riparian buffer within the 150 ft buffer around the conduit network 180 hectares of impervious area converted to deciduous forest; all natural land within the buffer was left as is; 15,913 hectares of impervious cover
4	**Restoration of Riparian Buffer of All Streams** Scenario 1C with restoration of riparian buffer within the 150 ft buffer around all streams 1,031 hectares of impervious area converted to deciduous forest; all natural land within the buffer was left as is; 15,064 hectares of impervious cover

3.3.1 Routing with Buffers

In the Hydrology Manual for SWMM, Rossman and Huber (2016) describe how riparian buffers can be modeled by routing flow from one subcatchment into another. This methodology was utilized in each of the scenarios involving a buffer such that the new, large subcatchment was routed to the buffer subcatchment and then to the original outlet of the subcatchment (Figure 3.6). This was done in each subcatchment containing a segment of the conduit system, the main channel, for Scenarios 1B, 2, and 3 and in each subcatchment containing a segment of the National Hydrography layer, any stream including ephemeral streams, for Scenarios 1C and 4.

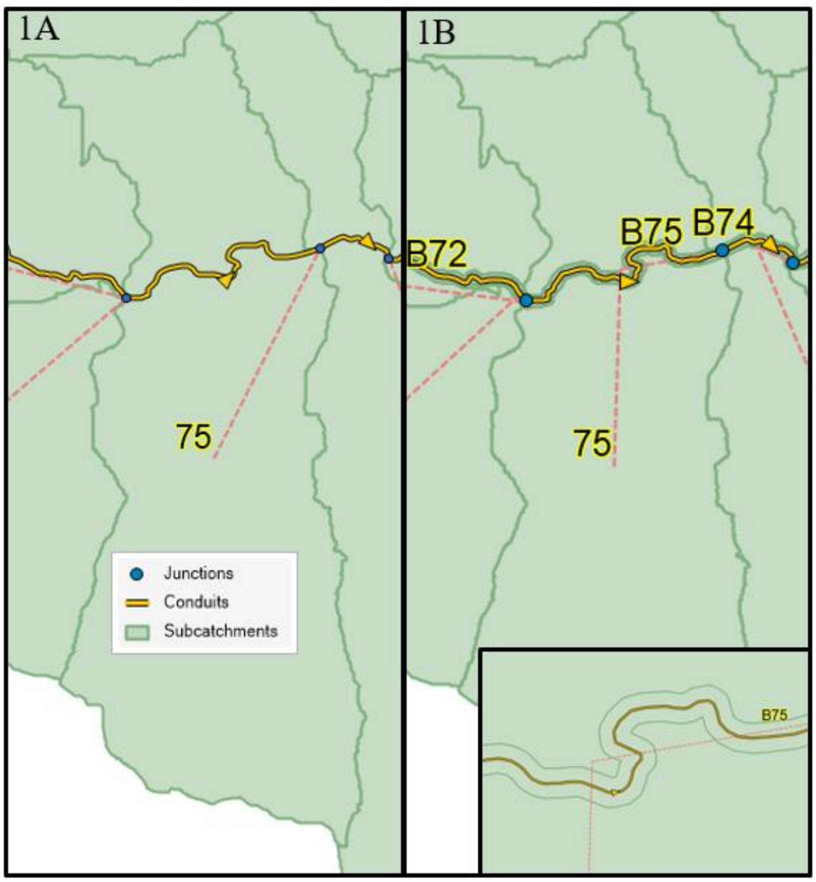

Figure 3.6 Prior to adding the buffer, the large subcatchment was routed to the junction which is connected to the conduit system (1A). With the buffer, runoff from the large subcatchment was routed to the buffer subcatchment within it, then to the junction. The dashed red line represents the routing pathway. Routing to the buffer before the junction simulates the hydrologic processes occurring in the buffer area.

3.3.2 Scenarios 1A-1C: Baseline Comparison

The baseline scenarios were created to mirror the routing in the scenarios (**Error! Reference source not found.**). Land use as reported in the 2011 NLCD was used (Figure 3.4 Land use/land cover in the Blue River Watershed from the 2011 National Land Cover Dataset). No changes were made to the calibrated hydrologic and physical parameters. The results of these scenarios were referenced when considering the impact of the different land cover changes integrated in the model scenarios.

Scenario 1A

Scenario 1A represents the original, calibrated model created by Dr. McDonough (McDonough, 2018). The NLCD 2011 dataset was utilized to estimate percent impervious cover. No changes were made to the calibrated attributes or model layout.

Scenario 1B

Scenario 1B is the baseline, calibrated model (Scenario 1A) with the addition of a 150-foot buffer around the conduit system. This area represents the riparian buffer around main stream channels with land use as is. Scenario 1B served as the baseline comparison for Scenarios 2 and 3 which also involve a 150-foot buffer around the conduit system.

In creating Scenario 1B, the buffer tool in ArcMap was used to create a dissolved 150-foot buffer around the conduit system of the original, calibrated model (Scenario 1A) (Figure 3.7). The Union tool was then used to add the newly created buffers to the subcatchment layer from Scenario 1A. In doing this, every subcatchment with a riparian buffer was split into two subcatchments – the subcatchment and the riparian buffer subcatchment. As such, Scenario 1B contains 149 subcatchments. The routing methodology previous discussed in the Routing with Buffers section of this chapter was utilized: overland flow of the original subcatchments were routed to their corresponding buffer and then to the original subcatchment outlet, typically a junction. From the junction, water was routed to the next downstream conduit. Each buffer was assigned the same calibrated attributes as its corresponding subcatchment. Land use and soil characteristics that were not altered during calibration were updated using a look-up table to reflect the conditions in the large and buffer subcatchments.

Figure 3.7. Scenario 1B required creation of a 150-foot buffer around the conduit system, shown in blue. For routing purposes, these buffers were made into their own subcatchments to allow for simulation of varying conditions in the buffer area.

Scenario 1C

Scenario 1C is the baseline, calibrated model (Scenario 1A) with the addition of a 150-foot buffer around the National Hydrography Dataset. This area represents the riparian buffer around all streams, including ephemeral streams, with land use as is. Scenario 1C served as the baseline comparison for Scenario 4, which also involves a 150-foot buffer around the National Hydrography Dataset.

Creating Scenario 1C required similar procedures as described for Scenario 1B. The only difference being the 150-foot buffers were created around the National Hydrography Dataset instead of the conduit system (Figure 3.8). Identical steps were taken to add the buffers to the original subcatchment layer of Scenario 1A, update flow routing, and assign buffer attributes. Due to the increased complexity of the National Hydrography Dataset, 151 subcatchments are included in Scenario 1C. Land use and soil characteristics that were not altered during calibration were updated using a look-up table to reflect the conditions in the large and buffer subcatchments.

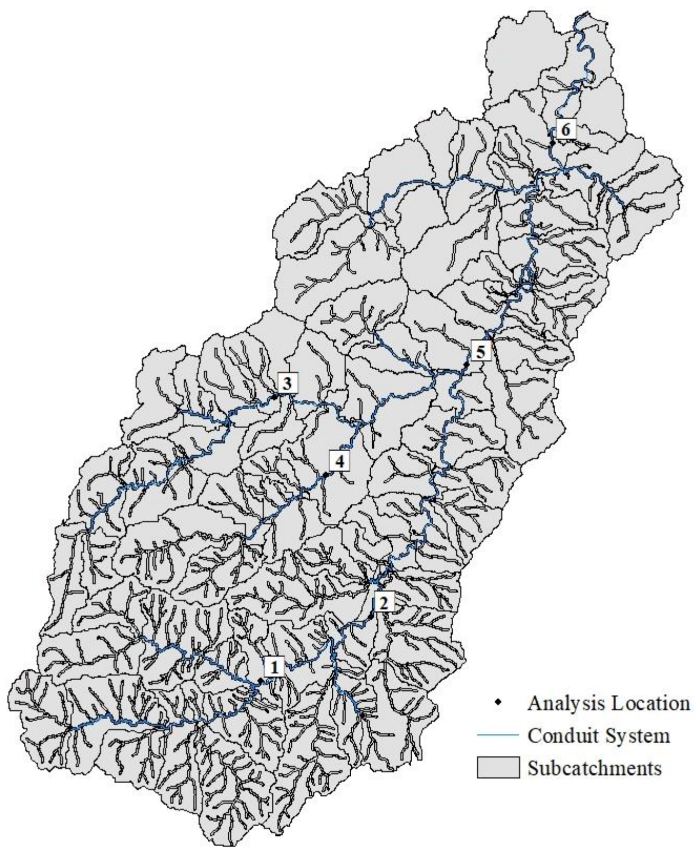

Figure 3.8. Scenario 1C required creation of a 150-foot buffer around the National Hydrography Dataset, which extends well beyond the conduit system shown in blue. For routing purposes, these buffers were made into their own subcatchments to allow for simulation of varying conditions in the buffer area.

3.3.3 Scenario 2: Conversion of Riparian Buffer to Managed Green Space

Scenario 2 was created using the subcatchment layer of Scenario 1B and converting all area within the 150-foot buffer of the conduit system to a managed green space. All natural and agricultural land (NLCD gridcodes 41, 42, 43, 51, 52, 71, 72, 73, 74, 81, 82, 90, and 95) within the buffer was converted to turf grass; all developed land cover was left as is. Land cover attributes, percent impervious, depression storage, and Manning's roughness coefficient were assigned to the managed green space based on the associated values for developed, open space (Table 3.3). No changes were made to the land cover in subcatchments outside of the buffer subcatchments. Due to the land cover gradient in the Blue River Watershed, more alterations to land cover were made in the headwaters than the highly developed tributaries (Figure 3.9).

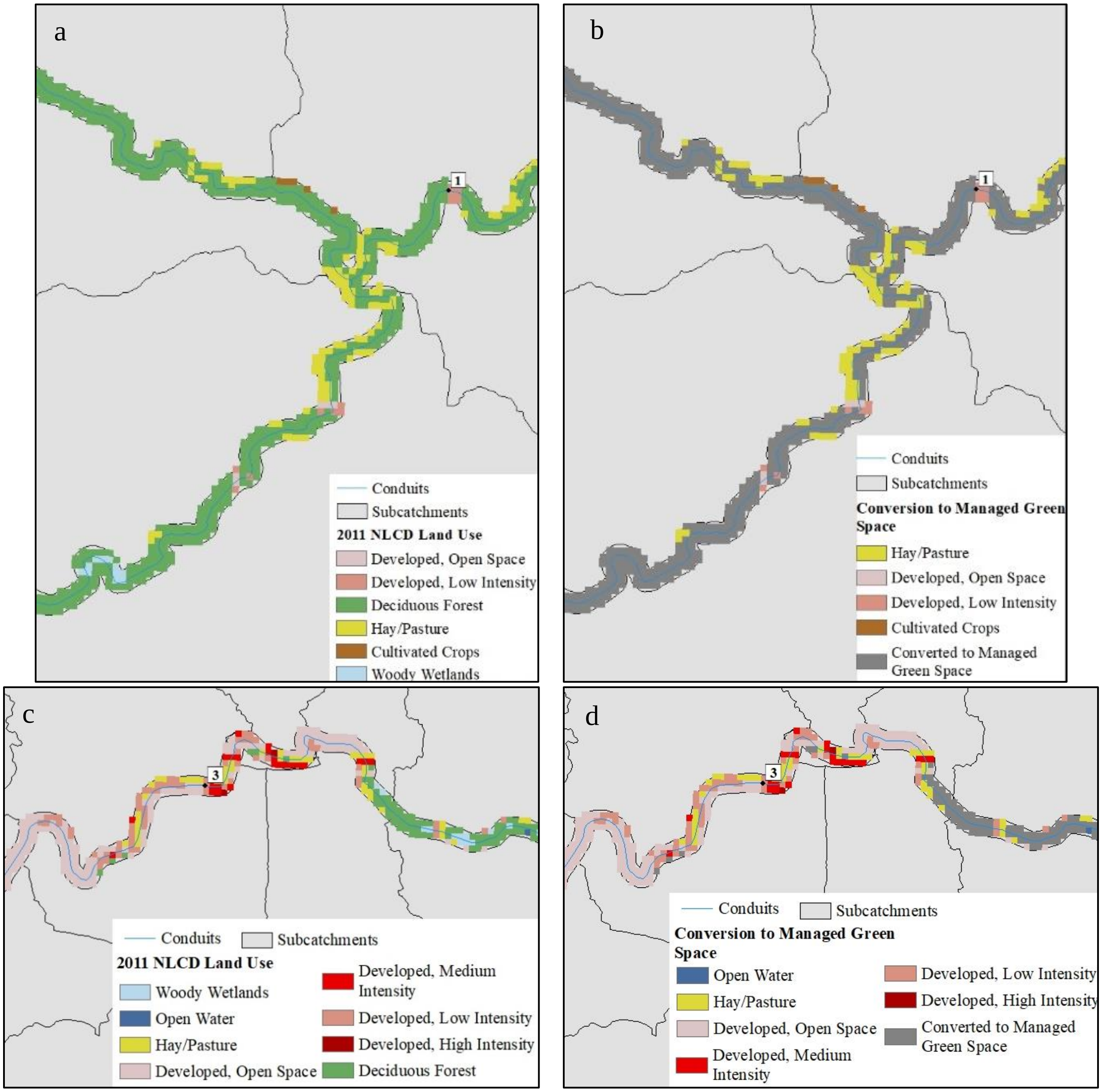

Figure 3.9 Conversion of the riparian buffer to managed green space required removal of all natural vegetation and agricultural land. This conversion involved the largest percent of buffer in the headwaters where the Blue River Watershed is largely undeveloped (a-b). The highly developed tributaries required less land conversion for this management scenario (c-d).

Previous research has found forested riparian buffers provide ecosystem services of greater extent and value than grass buffers (Pennsylvania Land Trust Association, 2014). As such, Scenario 2, conversion of the riparian buffer to a managed green space, will provide quantification of the difference in benefits observed between these vegetation types. Conversion to a managed green space represents what would happen if land adjacent to the Blue River and its tributaries was converted to golf courses or urban parks and the original vegetated cover was lost.

3.3.4 Scenario 3: Restoration of Riparian Buffer of Main Channels

Scenario 3 was created using the subcatchment layer from Scenario 1B and converting all developed area (NLCD gridcode 21, 22, and 23) within the 150-foot buffer of the conduit system to deciduous forest. All other natural land cover such as shrubs or grassland was left as is. Approximately 181 hectares of developed land was converted to deciduous forest in this process. Land cover attributes, percent impervious, depression storage, and Manning's roughness coefficient were assigned based on the values presented for deciduous forest (Table 3.3). No changes were made to the land cover present outside of the buffer. This management scenario required very little land to be restored in the headwaters where the riparian buffer is mostly intact. Alternatively, riparian buffers in the more developed parts of the Watershed required large amounts of impervious cover to be removed (Figure 3.10).

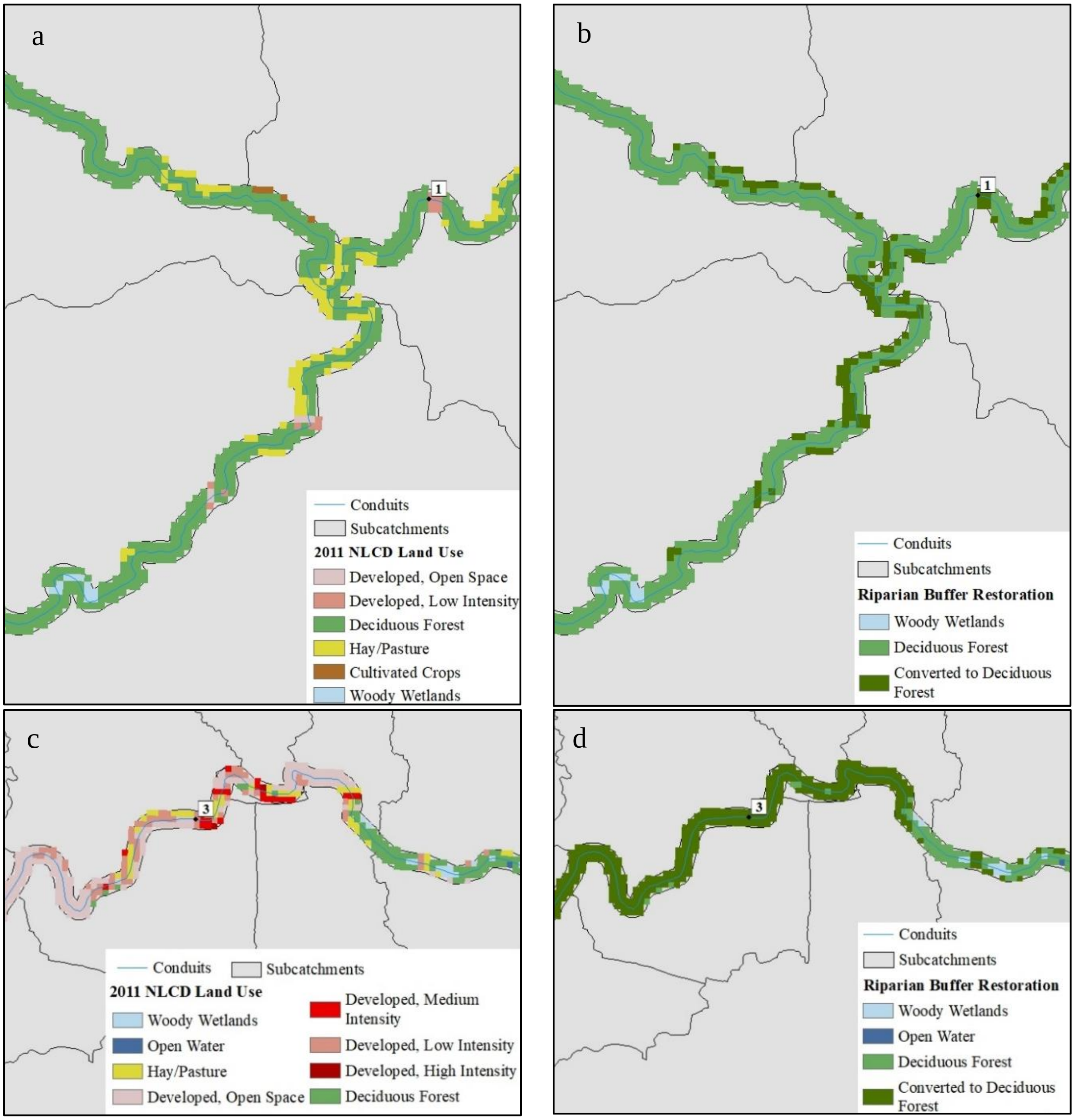

Figure 3.10. Restoration of the riparian buffer of main channels required minimal land conversion in the largely undeveloped headwaters (a-b). In more disturbed parts of the watershed, such as Station 3 (c-d), restoration of the buffer required large amounts of impervious cover to be removed.

Scenario 3 represents the restoration of the riparian buffer around the main stream channel. Evaluation of the hydrologic ecosystem services provided under Scenario 3 compared to Scenario 2, conversion of the riparian buffer to a managed green space, will provide greater insight into the importance of vegetation type and the use of this land.

3.3.5 Scenario 4: Restoration of Riparian Buffer of All Streams (Including Ephemeral Streams)

Scenario 4 was created using the subcatchment layer created by Scenario 1C and converting all developed area (NLCD gridcode 21, 22, and 23) within the 150-foot buffer of the National Hydrology Dataset to deciduous forest. Approximately 1,031 hectares of developed land was converted to deciduous forest in this process. Land cover attributes, percent impervious, depression storage, and Manning's roughness coefficient, were assigned based on the values presented for developed, open space (Table 3.3). No changes were made to the land cover present outside of the buffer. Again, restoration of the riparian buffer was not as difficult or involved in the headwaters where urbanization has not yet spread; urbanization throughout the Blue River Watershed required much more land conversion to restore the buffer at Stations 3-6 (Figure 3.10).

Scenario 3 represents the restoration of the riparian buffer of all streams including ephemeral streams. Ultimately, riparian buffer restoration at this scale provides protection of all major natural flow paths throughout the watershed. Comparison of Scenario 4 with Scenarios 2 and 3 will provide insight into the importance of restored buffers being present along streams of lower order throughout a watershed.

3.4 Precipitation Events Considered

3.4.1 Event-Based Precipitation

Upon scenario development, five event-based storms were used to simulate the watershed's response to precipitation events of varying depths (Table 3.8). Rainfall data from NOAA's Atlas 14 Point Precipitation Frequency Estimates was used to represent the precipitation depth for each precipitation event at the Shawnee 2 S station. The Shawnee 2 S and Olathe 3 E stations, both located within the Blue River Watershed, were within 0.04 inches of each other for every average recurrence interval (NOAA, 2017). Thus, values reported for the Shawnee 2 S station are representative of the entire watershed. NOAA's Atlas 14 provides depth and intensity ranges for storms with varying durations and recurrence intervals based on historic rainfall. The 24-hour storm with 1, 2, 3, 10, and 25-year return intervals was simulated using the SCS, Type II rainfall distribution with a 15-minute hydrograph interval. Simulations were ran for five days with the 24-hour precipitation event beginning at the start of simulation to ensure water was able to flow entirely through the system.

Table 3.8. NOAA Atlas 14 event-based precipitation depths for the Shawnee 2 S station (NOAA, 2017).

Storm Recurrence Interval & Duration	Precipitation Depth with 90% confidence interval	
	in	mm
1-year, 24-hour	3.08 (2.53-3.79)	78 (64-96)
2-year, 24-hour	3.65 (2.99-4.49)	93 (76-114)
5-year, 24-hour	4.63 (3.78-5.69)	118 (96-145)
10-year, 24-hour	5.48 (4.45-6.76)	139 (113-172)
25-year, 24-hour	6.71 (5.32-8.49)	170 (135-216)

Due to climate change, an increase in the frequency of these storms will be observed (Easterling et al., 2017). Currently, the precipitation depth provided of subsequent storms is typically somewhere in the upper range of the previous storm's 90% confidence interval, i.e. the 2-year, 24-hour storm depth is estimated to be 3.65" which is within the 90% confidence interval of the 1-year, 24-hour event of 2.53"-3.79" (Figure 3.11). If storms become more intense and frequent due to climate change, it is likely these storms will shift toward the more extreme range of their confidence intervals. This would result in a 1-year, 24-hour storm similar in depth to that of the current 2-yr, 24-hour storm and so on. Thus, it is increasingly important to consider the hydrologic response of the watershed to larger, more intense precipitation events.

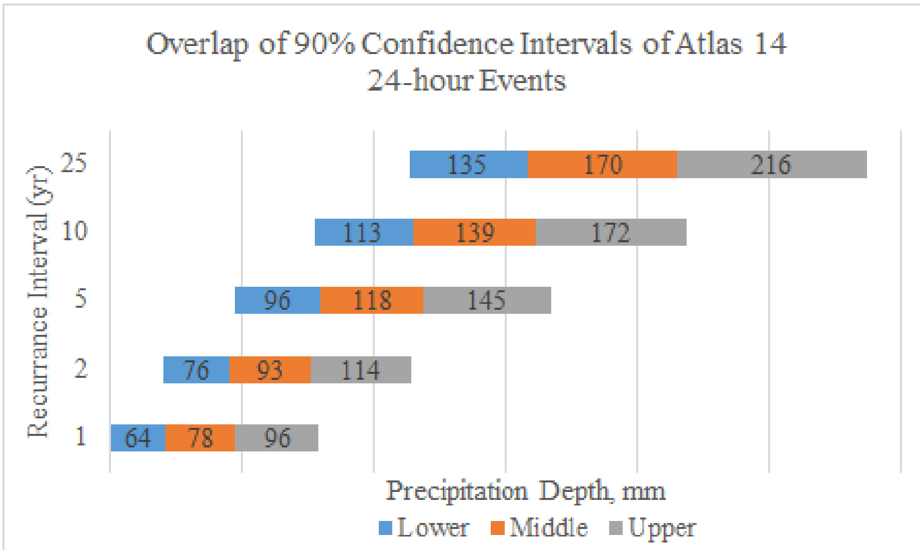

Figure 3.11. Overlap of 90% confidence intervals of Atlas 14 24-hour precipitation events at the Shawnee 2 S station (NOAA, 2017).

3.4.2 Continuous Precipitation

Historic and future climate change projected rainfall data for the Blue River Watershed were utilized to run continuous model simulations. Due to the temporal resolution of the climate change projections, all data was collected on a daily time-scale. When simulated in PCSWMM, the precipitation duration was assumed to be six hours with a constant intensity. All continuous simulations were ran for the months of May-July, part of the wet season in the Blue River Watershed (Weather Atlas, 2020).

3.4.2.1 Historic Precipitation Data

Historic daily precipitation data for the Blue River Watershed were obtained from the Johnson County Executive Airport NOAA rain gage. Various rain gages throughout the watershed were considered; the Johnson County Executive Airport rain gage was selected for use based on data availability. Missing data points were assumed to be zero, and suspect data was assumed to be correct. This data was used for the months of May-July 2014 and 2017. NOAA (2020) reports the Blue River Watershed area experienced roughly 830 mm (32 inches) of precipitation, well below the average annual rainfall of approximately 41 inches or 104 centimeters, in 2014 (Kansas State University, n.d.). Record flooding occurred in 2017 in the watershed, with annual total precipitation of nearly 1150 mm (45 inches) (Erdman, 2017; NOAA, 2020). During the months of May-July, 279 mm of rain fell in 2014 and 508 mm fell in 2017 (Table 3.10 Summary of precipitation reported at the Johnson County Executive Airport from May-July for the years of 2014 and 2017 and the ensemble mean of the 2050 and 2099 climate change projections (NOAA, 2020).Figure 3.12).

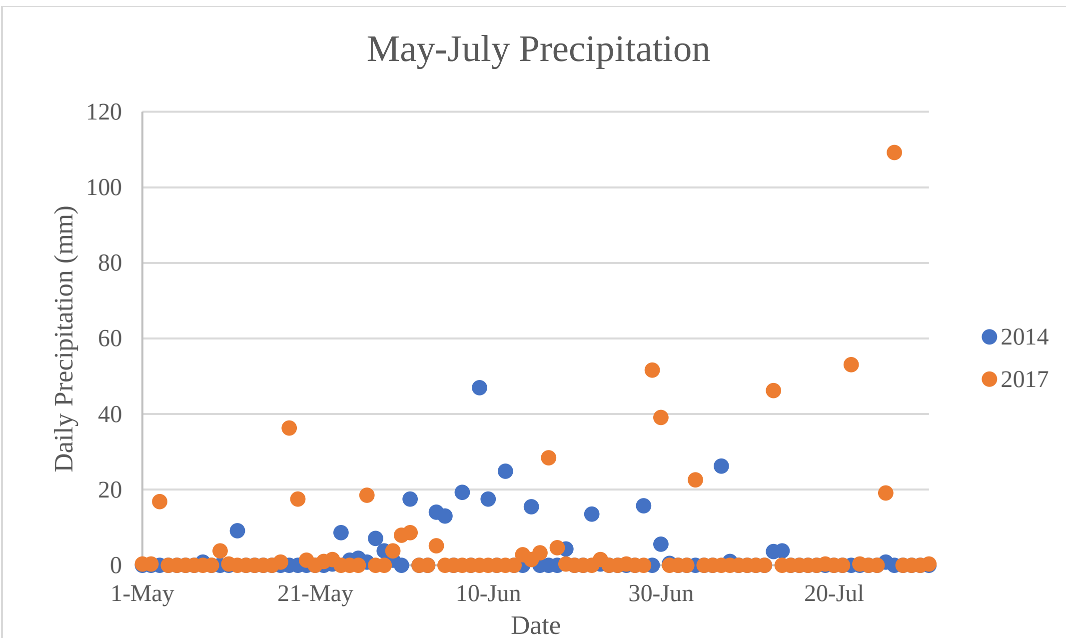

Figure 3.12 Daily precipitation at the Johnson County Executive Airport from May-July for the years of 2014 and 2017 (NOAA, 2020).

3.4.2.2 Climate Change Precipitation Data

Researchers at Kansas State University performed a validation of thirty-six global climate models (GCMs) within the Coupled Model Intercomparison Project Phase 5 (CMIP5) using historical, observed precipitation data from 1950-2005 in the Blue River Watershed (Laura Krueger, Kansas State University, personal communication, 23 October 2019). From this, eighteen of the GCM models were downloaded from two downscaled climate projection sources: GDO LOCA and Multivariate Adaptive Constructed Analogs (MACA V2) (Lawrence Livermore National Laboratory, 2016; University of Idaho, n.d.). These datasets were validated using precipitation data from six National Oceanic and Atmospheric Administration (NOAA) stations within or near the watershed (Figure 3.13). The six stations were selected based on their length of coverage. Analysis of several statistical parameters including Mann-Kendall trend test, Spearman's correlation coefficient, percent bias, and root mean square error guided the identification of seven models which reported precipitation comparable to observed data (Table 3.9). The seven models selected had a positive trend in the Mann-Kendall trend test, indicating variables were increasing together, and a Spearman's correlation coefficient (an assessment of the degree of similarity) greater than 0.4 (Laura Krueger, Kansas State University, personal communication, 23 October 2019). The projected daily precipitation by each of these models was used for the same period as the historical, observed data from NOAA, May-July, for the years of 2050 and 2099. The year 2050 was selected as it represents the end of the near-future projections; the year 2099 was selected to represent the far-future projection. Subcatchments were assigned the nearest rain gage for these model runs.

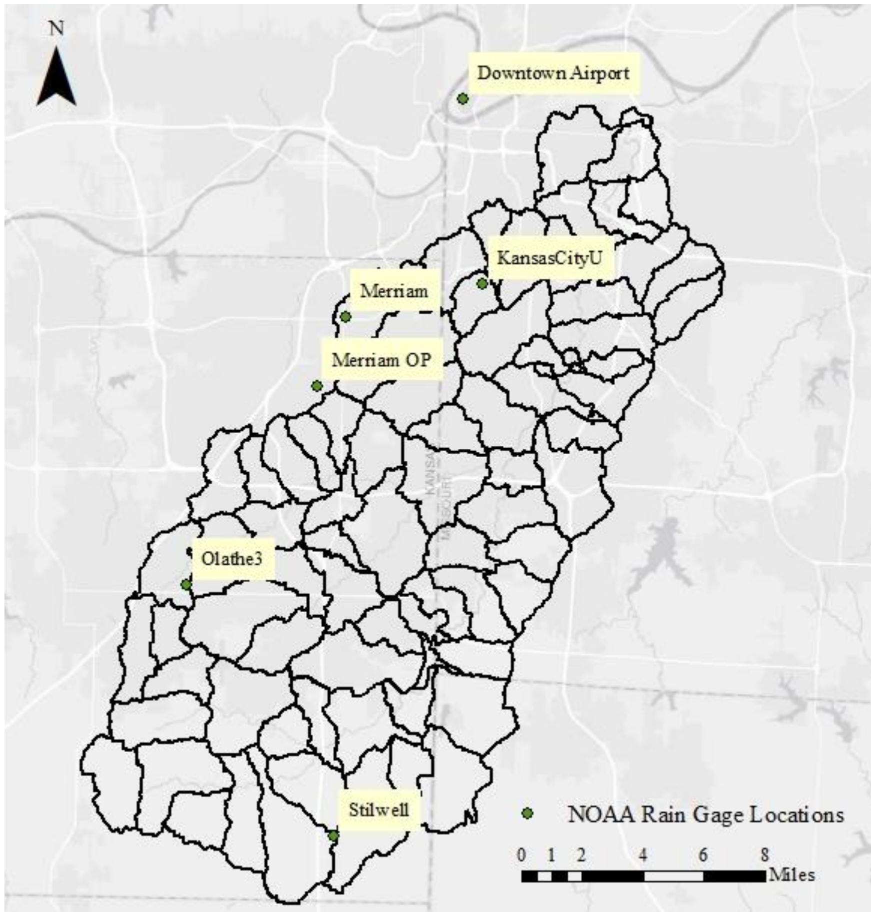

Figure 3.13 NOAA rain gage locations utilized in the continuous climate change data runs (NOAA, 2020).

Table 3.9. Summary of downscaled climate models determined to be comparable to historical, observed data in the Blue River Watershed. Each of these GCMs are of RCP 4.5, representing a middle ground projection of greenhouse gas emissions (Laura Krueger, Kansas State University, personal communication, 23 October 2019).

Downscaled Climate Projection Source	GCM Model Name	RCP	ID
GDO LOCA	CCSM4.6	4.5	A
	NorESM1-M.1		B
	MRI-CGCM3.1		C
MACA V2	NorESM1-M		D
	MIROC-ESM		E
	MIROC-ESM-CHEM		F
	MRI-CGCM3		G

3.4.2.3 Comparison of Historic Precipitation to Climate Change Projections

Due to the uncertainly of how climate change will impact precipitation, it should be noted that the years selected could be wet, dry, or average years. Furthermore, one projection cannot be deemed more correct than the other as they are all merely predictions of future precipitation. For this reason, analysis was based on the average results of all projections, and the result of each projection is not compared to that of others. Further details on each climate change projection can be viewed in Appendix A- Climate Change Projection Summary.

A general comparison of the historic precipitation data to precipitation under the climate change projections is important in assessing scenario performance under each riparian buffer management scenario. The ensemble mean or average of all projections considered for 2050 and 2099 have 29 days in the months of May-July with over 3 mm of rainfall, wet days. Historic NOAA precipitation data for the years of 2014 and 2017 indicates ten fewer days of precipitation exceeding 3 mm occurred in those years compared to the climate change projections. The number of days with precipitation exceeding 25 mm, event days, under the average projections for 2050 and 2099 were below what was experienced in 2017 when the Blue River Watershed saw record flooding (Table 3.10). Looking at only at these two years, this suggests an increase in lower depth events may occur in the future.

Table 3.10 Summary of precipitation reported at the Johnson County Executive Airport from May-July for the years of 2014 and 2017 and the ensemble mean of the 2050 and 2099 climate change projections (NOAA, 2020).

Year	Total Precipitation (mm):	Total Days with Precipitation >3mm:	Total Days with Precipitation >25mm:
2014	279	19	2
2017	508	19	7
Ensemble Mean 2050	375	29	3
Ensemble Mean 2099	437	29	4

3.5 Hydrologic Ecosystem Services Quantification

Ecosystem services, "benefits people obtain from ecosystems," are challenging but important to quantify (MEA, 2005; Brauman et al., 2007). With this, quantitative indices have been created to represent the provision of various ecosystem services (McDonough et al., in review). In this study, the provision of several indicators of flood regulating ecosystem services across the Blue River Watershed were quantified: total inflow volume and peak inflow. Decreases in either of these quantities indicates flood regulating ecosystem services are being provided to a greater extent.

3.5.1 Analysis Locations

Model outputs were evaluated at six USGS stream gage locations throughout the Blue River Watershed (Table 3.11**Table 3.9. Summary of downscaled climate models determined to be comparable to historical, observed data in the Blue River Watershed. Each of these GCMs are of RCP 4.5, representing a middle ground projection of greenhouse gas emissions (Laura Krueger, Kansas State University, personal communication, 23 October 2019).**; Figure 3.14). Stations 1-4 are located near the headwaters of their corresponding tributaries; Stations 5-6 are located towards the outlet of the watershed.

Table 3.11 Summary of USGS stream gage locations evaluated (Modified from McDonough, 2018; USGS, 2020).

Site ID	Station Name	Station Number	Coordinates	Total Contributing Area (Hectares)
1	Blue R NR Stanley, KS	06893080	38°48'45", 94°40'32"	11,615
2	Kenneth Rd., Overland Park, KS	06893100	38°50'32", 94°36'44"	17,307
3	Indian C at Overland Park, KS	06893300	38°56'26", 94°40'16"	6,753
4	Tomahawk C NR Overland Park, KS	06893350	38°54'22", 94°38'24"	4,642

5	Blue River at Kansas City, MO	06893500	38°57'25.2", 94°33'32.0"	47,304
6	Blue River at Stadium Drive in Kansas City, MO	06893578	39°03'30", 94°30'42"	65,403

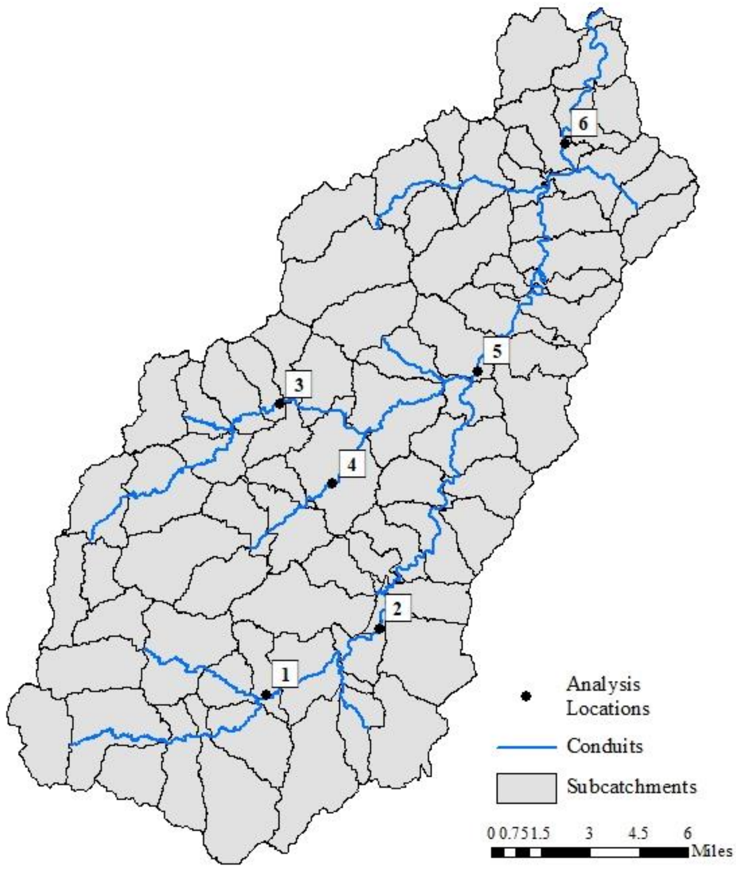

Figure 3.14 Locations of data analysis throughout the Blue River Watershed. Each of the analysis locations is a USGS stream gage.

3.5.2 Statistical Analysis

R Studio was used to conduct Tukey's Honest Significant Difference test with a p-value of 0.05 to determine if the difference in peak inflow and total inflow volume between treatment runs was significant. Two factors were considered in the linear model: scenario and rainfall. Due to the nature of the code utilized, the combined impact of scenario and rainfall could not be deduced. Instead, conclusions regarding how different rainfall events compare to one another across all scenarios and how different scenarios compare to one another across all rainfall events were made.

Statistical analysis was completed at the six rain gage locations mentioned above. The locations were not statistically analyzed against one another due to the confounding nature of watershed modeling. Tukey's test was completed for both the event-based and continuous precipitation data. Overall, the purpose of this statistical analysis is to determine if a significant difference in peak inflow and total inflow volume are experienced under the different scenarios at the six analysis locations throughout the Blue River Watershed.

Chapter 4 - Results and Discussion

4.1 Simulation Results

Across all model simulations, several common trends were observed. Scenario 2, conversion of natural vegetation within the riparian buffer of the main channel to a managed green space, caused increases in total inflow volume and peak inflow, indicating a decrease in flood regulating HES provision. Scenario 3, restoration of the riparian buffer of the main channel by conversion of developed and agricultural land to deciduous forest, typically caused decreases in total inflow volume and peak inflow. Likewise, Scenario 4, restoration of the riparian buffer of all stream channels including ephemeral streams by conversion of developed and agricultural land to deciduous forest, caused decreases in total inflow volume and peak inflow. Flooding regulating HES provision was increased under these scenarios due to the restoration of natural land cover which increased surface roughness and depression storage and slowed the flow of water, providing the opportunity for more infiltration.

Total inflow volume and peak inflow were used as indicators of flood regulating ecosystem services and were evaluated at six USGS stream gage locations throughout the watershed (Figure 4.1). Stations 1 and 2 are in relatively undeveloped areas compared to the rest of the Blue River Watershed. The remaining stations are located in highly urbanized areas. Impervious cover decreased throughout the watershed under Scenarios 3 and 4 which involve riparian buffer restoration; increases in impervious cover were observed under Scenario 2, conversion of the riparian buffer to a managed green space (Table 4.1).

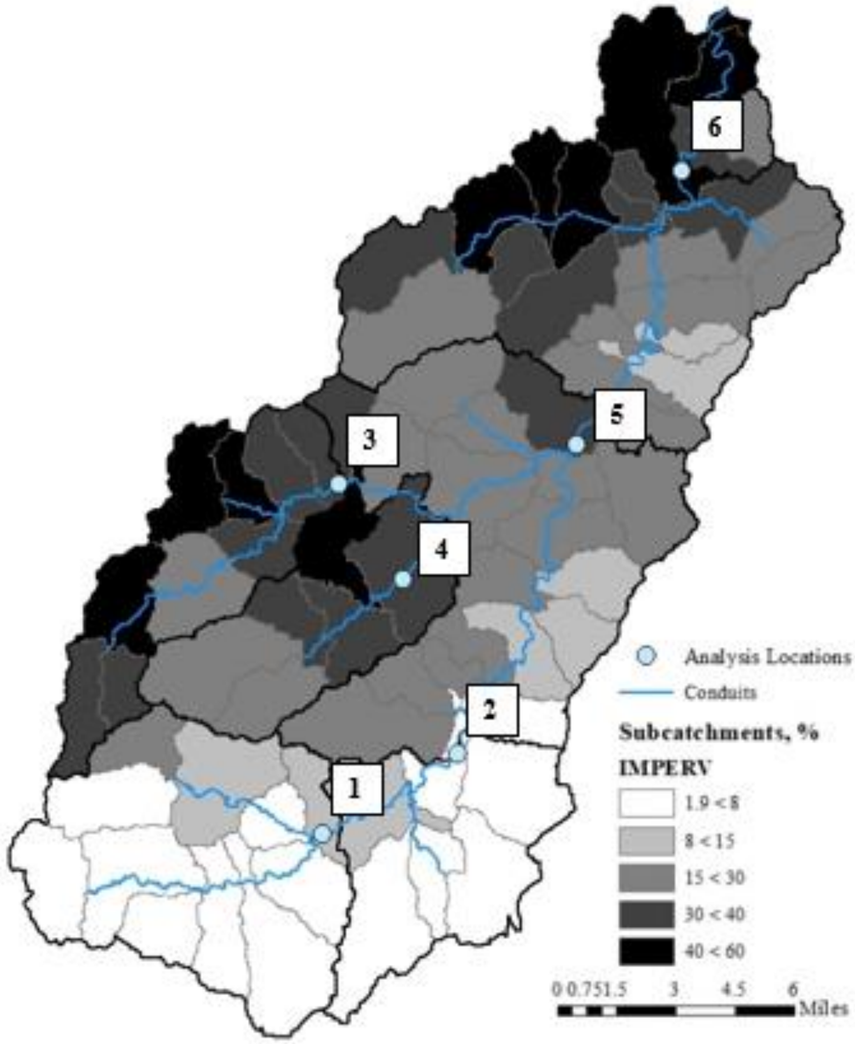

Figure 4.1 Locations of analysis of flood regulating HES indicators in the Blue River Watershed. The percent impervious area of each subcatchment under the baseline scenario, land use as-is, is shown.

Table 4.1 Summary of impervious land use contributing to each station (hectares, followed by percent of contributing area) under the average baseline, 1B, and each riparian buffer management scenario.

Scenario	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Baseline	697 6.0%	1,058 6.1%	2,445 36.2%	1,,390 29.9%	9,004 19.0%	14,737 22.2%
2	715 6.2%	1,086 6.3%	2,453 36.2%	1392 30%	9,069 19.2%	14,817 22.4%
3	693 6.0%	1,053 6.1%	2,422 35.9%	1,384 29.8%	8,927 18.9%	14,596 22.0%
4	625 5.4%	945 5.5%	2,278 33.7%	1,279 27.6%	8,349 17.6%	13,387 20.2%

All model results were evaluated in terms of percent increase or decrease from the average baseline scenario, Scenario 1B, unless another scenario of comparison is specified. First, the results of the event-based model simulations were evaluated in terms of percent change in total inflow volume and peak inflow. The same was then done for the results of the continuous model simulations. Then, statistical analysis was performed, comparing each of the scenarios to the baseline and then to each other. The statistical analysis was first evaluated for event-based simulation results, followed by continuous simulation results. The impact of precipitation event on total inflow and peak inflow was also evaluated. Finally, statically significant findings were summarized and discussed.

4.1.1 Event-Based Results

4.1.1.1 Total Inflow Volume

The impact of riparian buffer management on flood regulating HES was quantitatively assessed by calculating the percent difference in total inflow between each riparian buffer management scenario and the baseline under each storm event considered. Evaluation of this indicator showed a common trend among each scenario. Scenarios 3 and 4, which involve restoration of the riparian buffer of main and all streams respectively, caused decreases in total inflow across the watershed (Figure 4.2). A decrease in total inflow was seen due to the increase in surface roughness and depression storage of the buffer area. The increase in surface roughness slowed water, providing more opportunity for infiltration. Decreases in total inflow indicate the provision of flood regulating HES was improved under these scenarios. On the contrary, Scenario 2, which involves further disturbance of the riparian buffer by conversion of natural vegetation to a managed green space, resulted in increases in total inflow across the watershed (Figure 4.2). An increase in total inflow was observed due to the decrease in surface roughness and the opportunity to infiltrate. The increase in total inflow indicates a loss of flood regulating HES. All scenarios had the greatest impact on total inflow volume under the 24-hour storm with a 1-year return interval; percent change decreases with increasing storm return interval. This suggests riparian buffers play a larger role in smaller rainfall events due to the limited water storage available. At some point during model simulation, the ground became saturated and no addition water could be infiltrated.

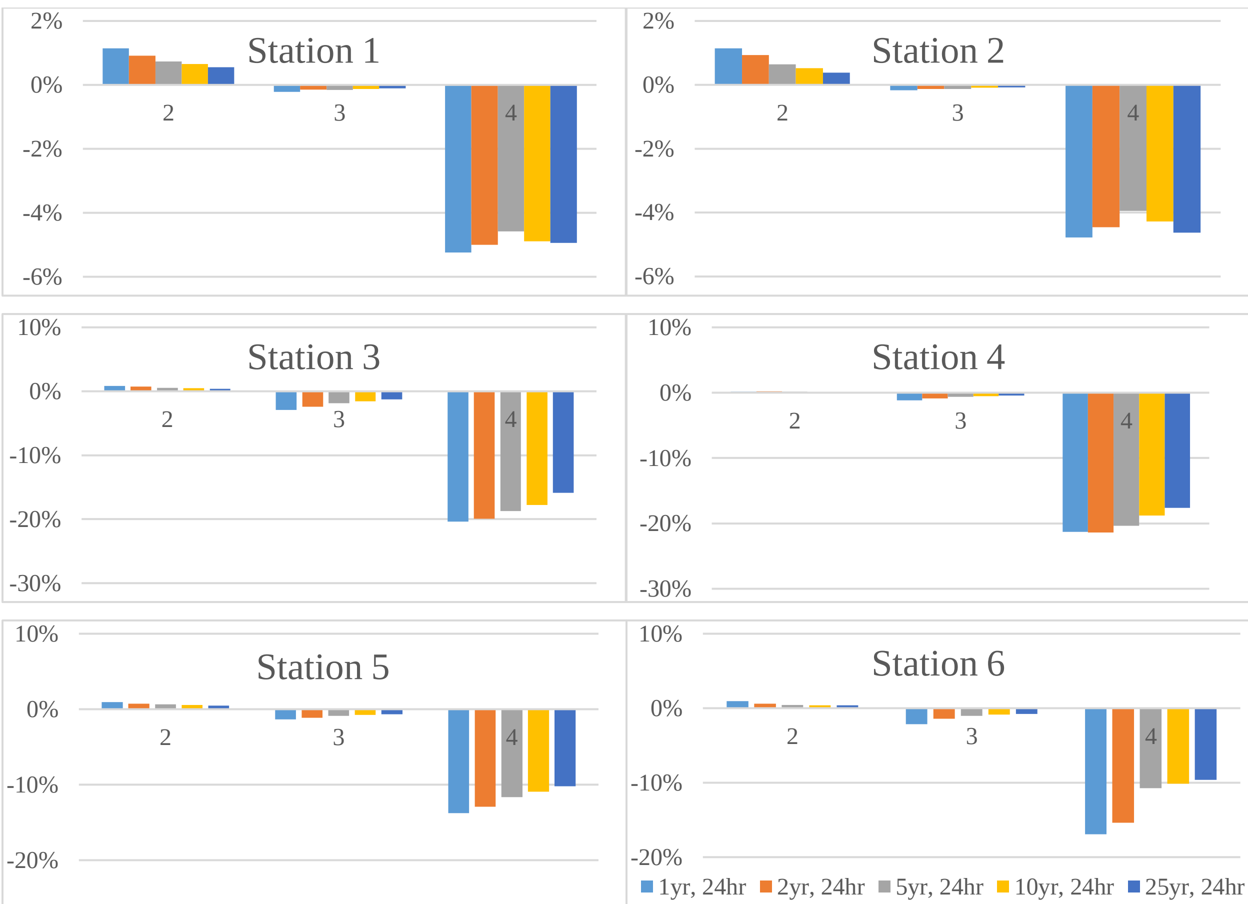

Figure 4.2 Percent change in total inflow volume between the average baseline to Scenarios 2, 3, and 4 under event-based simulations. Slight increases in total inflow were observed under Scenario 2, conversion of natural vegetation in the riparian buffer of main channels to a managed green space. Scenarios 3, restoration of the riparian buffer of the main channel, and 4, restoration of the riparian buffer of all streams including ephemeral streams, resulted in decreases in total inflow. The reduction in total inflow under Scenario 4 was roughly ten times greater than that of Scenario 3.

The magnitude of change observed was drastically smaller under scenarios involving the riparian buffer of the main channel only, Scenarios 2 and 3, than the scenario involving the riparian buffer of all streams including ephemeral streams, Scenario 4 (Figure 4.2). This is due to the amount of land impacted by the management scenario: 1400 hectares of buffer are included in Scenarios 2 and 3 compared to 7650 hectares of buffer included in Scenario 4. The increase in area being restored under Scenario 4 increased the amount of water storage available. With this, the percent reduction in total inflow volume increased by roughly tenfold in parts of the watershed when the riparian buffer of all channels including ephemeral streams was restored.

Spatial variability in the magnitude of change was also observed (Figure 4.2). Given the conditions of the watershed at Stations 1 and 2, relatively undeveloped compared to the rest of the watershed, the lower magnitude of percent change under each scenario is not surprising. Under Scenarios 3 and 4, the amount of impervious area removed from the riparian buffer at these stations is much less than what is removed at all other stations. There is also very little accumulation of flow in the headwaters, so the increase in total inflow observed under Scenario 2 is relatively low at these locations. The largest percent difference in total inflow volume was seen at Stations 3 and 4 when comparing Scenario 4 to the baseline (Figure 4.2). Stations 3 and 4 are located in heavily urbanized areas of two separate tributaries to the Blue River. Thus, conversion of developed land within the buffer to deciduous forest has a major impact even though minor accumulation of flow has occurred.

4.1.1.2 Peak Inflow

The impact of riparian buffer management on flood regulating HES was also quantitatively assessed by calculating the percent difference in peak inflow between each riparian buffer management scenario and the average baseline under each storm event considered. Evaluation of the percent change in peak inflow indicated great spatial variability in the impact of Scenario 4, riparian buffer restoration around all streams including ephemeral. This management scenario caused large decreases in peak inflow at Stations 3 and 6, but caused notable increases at Stations 4 and 5. The decreases in peak inflow are due to the increased surface roughness which slowed the flow of water. The cause of the increase in peak inflow at Station 4 was unclear and requires additional investigation. The confounding nature of hydrology was likely to blame for the increase in peak inflow seen at Station 5 as Stations 1-4 flow to this junction and notable increases were observed at Station 4. Regardless, a decrease in peak inflow was still observed at Station 6 due to the more consistent decrease in inflow rate observed at all other contributing stations. Due to the smaller amount of land effected by the management scenario, Scenarios 2 and 3, which involved only main channels, never affected peak inflow by more than 5% in either direction (Figure 4.3).

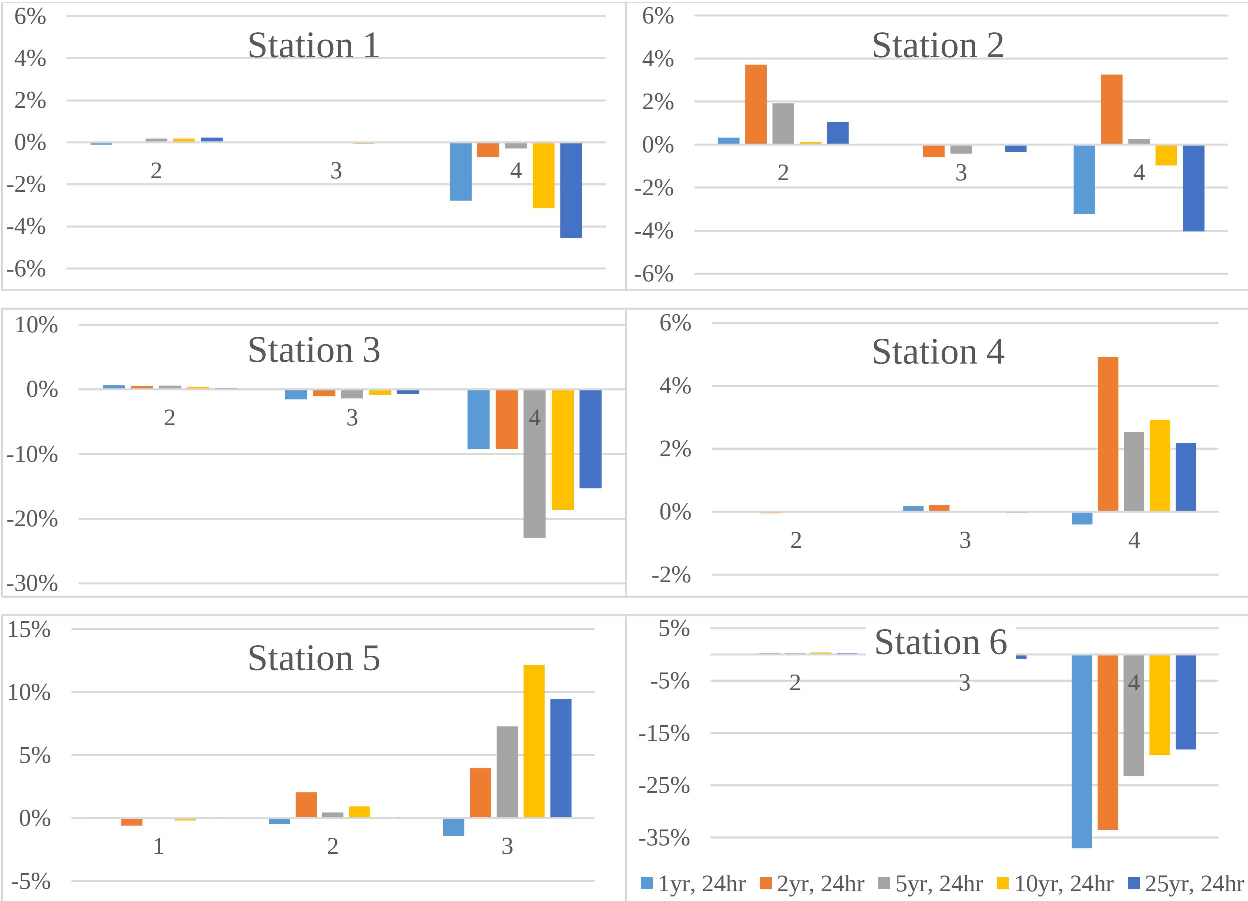

Figure 4.3 Percent change in peak inflow between the average baseline, Scenario 1B, to Scenarios 2, 3, and 4 under event-based simulations. Scenario 2, conversion of natural vegetation in the riparian buffer of main channels to a managed green space, typically resulted in slight increases in peak inflow. Scenarios 3, restoration of the riparian buffer of the main channel, and 4, restoration of the riparian buffer of all streams including ephemeral streams, typically resulted in decreases in peak inflow. However, an increase in peak inflow of various storms was observed at Stations 4 and 5 under the riparian buffer restoration scenarios, Scenarios 3 and 4. (Note: most of the graphs have a different y-axis range due to the great variability in direction and magnitude of impact.)

Spatial variability in the percent change in peak inflow was observed. Most notably, at Station 6, the only management scenario to have a notable impact on peak inflow was restoration of the riparian buffer of all streams including ephemeral streams, Scenario 4 (Figure 4.3). Relatively small changes in peak inflow were observed in the headwaters, Stations 1 and 2, as well as Stations 3 and 4 where very little accumulation of flow has occurred.

The largest reduction in peak inflow was seen at Station 6 when the riparian buffer of all streams was restored under the 1-year, 24-hour storm (Figure 4.3). As the recurrence interval increased, the percent change in peak inflow decreased. This is due to the infiltration capacity of the system and the distribution of rainfall during simulation. At some point, the ground becomes saturated or is not able to infiltrate as quickly as precipitation is falling, both in and outside of the riparian buffer. For this reason, a reduction in the percent change in peak inflow was observed as the recurrence interval of the storm increases. This pattern of decreasing impact was seen at Stations 3 as well.

4.1.2 Continuous Results

4.1.2.1 Total Inflow

Changes in total inflow volume were evaluated under each riparian buffer management scenario for continuous simulation as well. Quantification of flood regulating HESs was achieved by calculating the percent difference in total inflow between each riparian buffer management scenario and the average baseline, 1B, under each continuous precipitation simulation considered.

Evaluation of the percent change in total inflow under continuous simulation indicated similar results as event-based result evaluation. Scenario 2, conversion of natural vegetation to a managed green space in the riparian buffer area of main channels, caused a consistent increase in total inflow volume under all continuous simulations and at every station (Figure 4.4). Total inflow increased due to the decreased opportunity for infiltration to occur due to decreased surface roughness and storage. Scenarios 3 and 4, which restored the riparian buffer, caused consistent decreases in total inflow volume, indicating provision of flood regulating HESs. The magnitude of total inflow reduction under Scenario 4, riparian buffer restoration of all channels including ephemeral streams, was much greater than that of Scenario 3, riparian buffer restoration of main channels (Figure 4.4). The increase in HES provision under Scenario 4 was caused by the increase in area of the riparian buffer restored which increased the amount of water storage available.

Figure 4.4 Percent change in total inflow between the average baseline, Scenario 1B, to Scenarios 2, 3, and 4 under continuous simulations. Scenario 2, conversion of natural vegetation in the riparian buffer of main channels to a managed green space, caused increases in total inflow across the watershed. Scenarios 3, restoration of the riparian buffer of the main channel, and 4, restoration of the riparian buffer of all streams including ephemeral streams, resulted in decreases in total inflow. However, the reduction in total inflow under Scenario 4, restoration of all buffers, was on average 18 times greater than that of Scenario 3. Values reported as 2050 Average and 2099 Average represent the ensemble mean of projections considered.

Spatially, each scenario has the largest impact in the headwaters. As water travels towards the outlet, the percent change in total inflow volume lessens. The percent change at Stations 5 and 6 are nearly identical to one another under each riparian buffer management scenario. However, when considering scenarios which restore the riparian buffer, flood regulating benefits experienced in the lower watershed would not be experienced to the same extent if restoration throughout the whole watershed did not occur.

Comparison of the percent change under 2017 simulation to that of 2014 and the ensemble mean result of the climate change projections indicated a decrease in flood regulating HESs under all riparian buffer management scenarios (Figure 4.4). This decrease is HES provision under 2017 simulation was due to the amount of large events and total rainfall experienced in 2017 compared to the other simulation periods considered. The percent change in total inflow experienced during simulation of the ensemble mean climate change projections for both 2050 and 2099 was much more comparable to 2014. This was reflected by their comparable impact on total inflow reduction.

4.1.2.2 Peak Inflow

Changes in peak inflow were evaluated under each riparian buffer management scenario for continuous simulation as well. Quantification of flood regulating HES was achieved by calculating the percent difference in peak inflow between each riparian buffer management scenario and the average baseline, 1B. Evaluation of the percent change in peak inflow under continuous simulation provided more uniform results than event-based analysis (Figure 4.5). In general, Scenario 2, conversion of the riparian buffer to a managed green space, caused a slight increase in peak inflow due to the decrease in surface roughness associated with natural vegetation conversion to a managed green space. This allowed the water to travel more easily across the landscape and reduced infiltration. Scenarios 3 and 4 caused decreases in peak inflow with restoration of riparian vegetation (Figure 4.5). A reduction in peak inflow was observed due to the increase in surface roughness and opportunity for infiltration. All scenarios exhibited lesser impact on peak inflow under 2017 precipitation events than the other simulation periods (Figure 4.5).

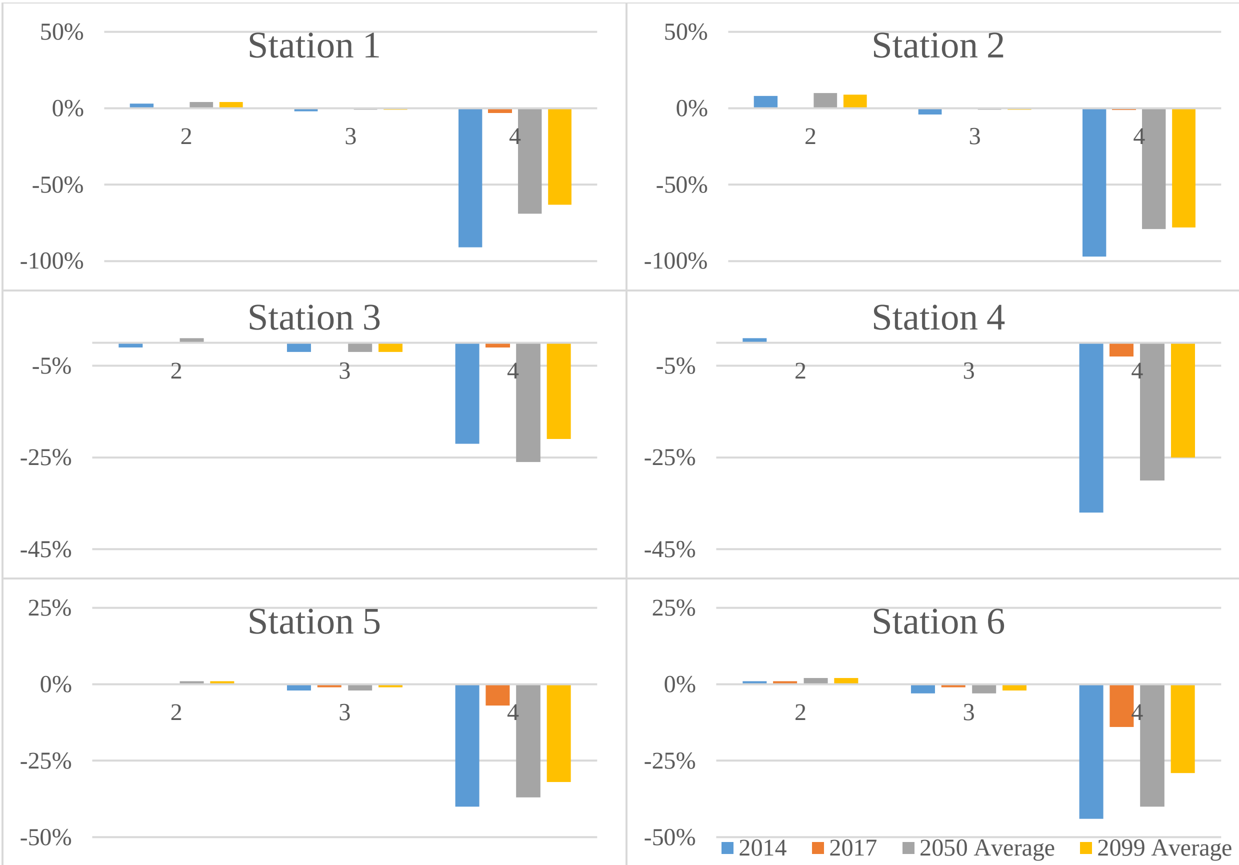

Figure 4.5 Percent change in peak inflow between the average baseline, Scenario 1B, to Scenarios 2, 3, and 4 under continuous simulations. The percent change in peak inflow is shown on the vertical axis. The results of each scenario are coupled on the horizontal axis, showing the percent change of each continuous simulation considered. Scenario 2, 3, and 4 represent conversion of the riparian buffer to a managed green space, restoration of the riparian buffer around main channels, and restoration of the riparian buffer around all streams including ephemeral streams respectively. Values reported as 2050 Average and 2099 Average represent the ensemble mean of projections considered.

A much larger decrease in peak inflow was seen under Scenario 4, restoration around all streams, than Scenario 3, restoration around main streams, across the watershed. There is spatial variability in the magnitude of peak inflow reduction under Scenario 4, as expected given the land use gradient and propagation of flow across the watershed (Figure 4.6).

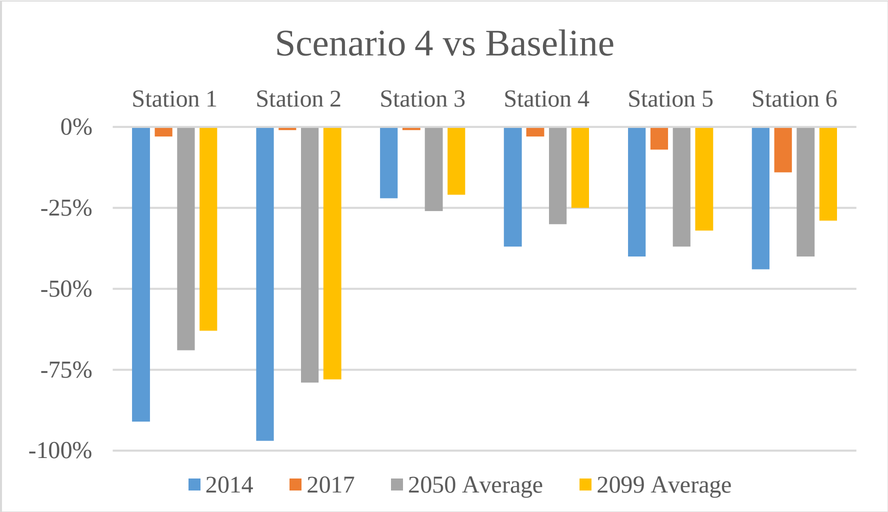

Figure 4.6 Summary of percent change in peak inflow from the average baseline, Scenario 1B, to Scenario 4, restoration of the riparian buffer of all channels including ephemeral streams, across the watershed. Values reported as 2050 Average and 2099 Average represent the ensemble mean of projections considered.

4.2 Statistical Analysis of Simulation Results

Total inflow volume and peak inflow reported for Scenarios 2, 3, and 4 was compared to the values reported for 1B and then to each other using Tukey's Honest Significant Difference test. A p-value of less than 0.05 indicated a statistically significant difference, thus rejecting the null hypothesis of H_o) $\mu 1B=\mu 2=...=\mu 4$ for the alternative hypothesis of H_1) $\mu 1B\neq\mu 2\neq...\neq\mu 4$. The same method was utilized to compare the impact of precipitation on total inflow volume and peak inflow. Due to the confounding nature of hydrology, analysis was completed on a station-by-station basis. Statistical analysis of event-based simulation results and continuous simulation results was completed.

4.2.1 Event-Based Simulation Analysis

4.2.1.1 Total Inflow Volume

Statistical analysis of the total inflow volume resulting from each riparian buffer management scenario under the five event-based storms was completed. A significant increase in total inflow of roughly 0.5% on average was experienced under Scenario 2, conversion of the riparian buffer of main channels to a managed green space, compared to the baseline. The lowest percent change in total inflow between Scenario 2 and the baseline was experienced at Station 4. This station is in a highly developed part of the watershed, thus only two hectares of impervious area were added during conversion of natural vegetation to a managed green space. The largest impact of this land cover conversion was seen in the headwaters at Station 1, however a comparable percent change in total inflow was seen at Stations 2, 5, and 6. Scenario 3, restoration of the riparian buffer of main channels, resulted in significant decreases in total inflow at all stations except Station 1 when compared to the baseline. The largest percent change in total inflow under Scenario 3 was observed at Stations 3 and 6. Scenario 4 also resulted in significant decreases in total inflow across the watershed when compared to the baseline, 1B, and Scenarios 2 and 3 (**Error! Reference source not found.**). The magnitude of the percent change between Scenario 4 a nd each of the other scenarios was much greater than that of the other scenarios compared, 5-20% as opposed to 0-5%. This is due to the amount of land converted to deciduous forest under this scenario compared to other scenarios. A significant difference in total inflow was seen under each precipitation event considered with the exception of the 1yr vs 2yr at Stations 3 and 4 when comparing Scenario 4 to the baseline.

Table 4.2 The difference in total inflow, m^3, between each scenario and the baseline, 1B, and each other was calculated during statistical analysis. The value reported is the combined difference of each comparison under all events considered. Cells that are highlighted indicate a significant change in total inflow at that station was observed under the scenario comparison. Scenario 2, conversion of the buffer to a managed green space, caused significant increases in total inflow compared to 1B and Scenario 4, riparian buffer restoration of all streams. Scenario 3, riparian buffer restoration of main channels, caused significant decreases in total inflow but was not as beneficial as Scenario 4.

Comparison	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
1B vs 2	3.66E+04	4.86E+04	2.24E+04	3.60E+03	1.46E+05	1.50E+05
1B vs 3	-7.00E+03	-8.40E+03	-7.62E+04	-2.00E+04	-2.08E+05	-3.32E+05
1B vs 4	-2.51E+05	-3.50E+05	-7.58E+05	-5.98E+05	-2.74E+06	-3.55E+06
2 vs 3	-4.36E+04	-3.83E+05	-9.86E+04	-2.36E+04	-3.54E+05	-4.82E+05
2 vs 4	-2.87E+05	-1.96E+06	-7.80E+05	-6.01E+05	-2.89E+06	-3.70E+06
3 vs 4	-2.44E+05	-1.57E+06	-6.82E+05	-5.78E+05	-2.54E+06	-3.22E+06

These results indicate riparian buffer restoration reduces total inflow volume throughout an urbanizing watershed. Disturbance of this area, Scenario 2, resulted in significant increases in total inflow at each analysis location, placing extra stress on the waterway. When the riparian buffer was restored around all streams, additional and more consistent benefits are observed. Restoration of riparian buffers around main channels was not always enough to provide significant total inflow reduction benefits.

Statistics indicated that significantly different results were observed under each precipitation event considered when comparing the scenarios to one another and the baseline (Table 4.3). The only exception to this was observed at Stations 3 and 4 when comparing the total inflow of Scenario 4, restoration of the riparian buffer around all streams including ephemeral, to the baseline under the 1yr and 2yr return interval storms. There is insufficient evidence to conclude if these storms had a significantly different impact on the difference in total inflow between these two scenarios at the given location. This suggests restoration of the riparian buffer around all streams provided benefits of similar magnitude under these storm events meaning its capacity exceeds the 1yr storm. All other storms evaluated under each of the scenario comparisons and locations were statistically different from one another.

Table 4.3 The difference in total inflow, m^3, between each precipitation event under the different scenario comparisons was calculated during statistical analysis. The value reported is the combined difference of each comparison under all scenarios considered (the two or three being compared). Cells that are highlighted indicate a significant change in total inflow at that station was observed under the precipitation event comparison.

Station		1yr-10yr	25yr-10yr	2yr-10yr	5yr-10yr	25yr-1yr	2yr-1yr	5yr-1yr	2yr-25yr	5yr-25yr	5yr-2yr
1B vs 2	1	-4.2E+06	1.9E+06	-3.1E+06	-1.3E+06	6.1E+06	1.1E+06	2.9E+06	-5.0E+06	-3.1E+06	1.8E+06
	2	-6.4E+06	3.0E+06	-4.7E+06	-2.0E+06	9.4E+06	1.7E+06	4.4E+06	-7.7E+06	-5.0E+06	2.7E+06
	3	-2.8E+06	1.6E+06	-2.2E+06	-9.4E+05	4.4E+06	6.4E+05	1.9E+06	-3.8E+06	-2.6E+06	1.2E+06
	4	-2.0E+06	9.8E+05	-1.5E+06	-6.7E+05	3.0E+06	4.6E+05	1.3E+06	-2.5E+06	-1.7E+06	8.7E+05
	5	-1.7E+07	8.0E+06	-1.3E+07	-5.5E+06	2.5E+07	4.2E+06	1.1E+07	-2.1E+07	-1.4E+07	7.2E+06
	6	-1.8E+07	7.1E+06	-1.2E+07	-4.9E+06	2.5E+07	5.8E+06	1.3E+07	-1.9E+07	-1.2E+07	6.9E+06
1B vs 3	1	-4.2E+06	1.9E+06	-3.1E+06	-1.3E+06	6.1E+06	1.1E+06	2.9E+06	-4.9E+06	-3.1E+06	1.8E+06
	2	-6.4E+06	3.0E+06	-4.7E+06	-2.0E+06	9.4E+06	1.7E+06	4.4E+06	-7.7E+06	-5.0E+06	2.7E+06
	3	-2.8E+06	1.6E+06	-2.1E+06	-9.4E+05	4.4E+06	6.4E+05	1.8E+06	-3.8E+06	-2.6E+06	1.2E+06
	4	-2.0E+06	9.8E+05	-1.5E+06	-6.7E+05	3.0E+06	4.6E+05	1.3E+06	-2.5E+06	-1.7E+06	8.7E+05
	5	-1.7E+07	8.0E+06	-1.3E+07	-5.5E+06	2.5E+07	4.2E+06	1.1E+07	-2.1E+07	-1.4E+07	7.2E+06
	6	-1.8E+07	7.1E+06	-1.2E+07	-4.9E+06	2.5E+07	5.8E+06	1.3E+07	-1.9E+07	-1.2E+07	6.9E+06
1B vs 4	1	-4.1E+06	1.8E+06	-3.0E+06	-1.2E+06	5.9E+06	1.1E+06	2.9E+06	-4.8E+06	-3.0E+06	1.8E+06
	2	-6.2E+06	2.9E+06	-4.6E+06	-2.0E+06	9.1E+06	1.6E+06	4.3E+06	-7.5E+06	-4.9E+06	2.6E+06
	3	-2.6E+06	1.6E+06	-2.0E+06	-8.8E+05	4.1E+06	5.8E+05	1.7E+06	-3.5E+06	-2.4E+06	1.1E+06
	4	-1.8E+06	9.1E+05	-1.4E+06	-6.3E+05	2.7E+06	4.1E+05	1.2E+06	-2.3E+06	-1.5E+06	7.9E+05
	5	-1.6E+07	7.7E+06	-1.2E+07	-5.3E+06	2.4E+07	4.0E+06	1.1E+07	-2.0E+07	-1.3E+07	6.9E+06
	6	-1.7E+07	6.9E+06	-1.2E+07	-4.7E+06	2.4E+07	5.5E+06	1.3E+07	-1.9E+07	-1.2E+07	7.1E+06
2 vs 3 vs 4	1	-4.1E+06	1.8E+06	-3.0E+06	-1.2E+06	6.0E+06	1.1E+06	2.9E+06	-4.9E+06	-3.1E+06	1.8E+06
	2	-6.3E+06	2.9E+06	-4.6E+06	-2.0E+06	9.2E+06	1.6E+06	4.3E+06	-7.6E+06	-4.9E+06	2.7E+06
	3	-2.6E+06	1.6E+06	-2.0E+06	-9.0E+05	4.2E+06	6.0E+05	1.7E+06	-3.6E+06	-2.5E+06	1.1E+06
	4	-1.9E+06	9.4E+05	-1.5E+06	-6.5E+05	2.8E+06	4.2E+05	1.2E+06	-2.4E+06	-1.6E+06	8.2E+05
	5	-1.6E+07	7.8E+06	-1.2E+07	-5.4E+06	2.4E+07	4.0E+06	1.1E+07	-2.0E+07	-1.3E+07	7.0E+06
	6	-1.7E+07	6.9E+06	-1.2E+07	-4.8E+06	2.4E+07	5.6E+06	1.3E+07	-1.9E+07	-1.2E+07	7.0E+06

4.2.1.2 Peak Inflow Analysis

Quantification of changes in peak inflow under the four riparian buffer management scenarios demonstrates the spatial dependency of this flood regulating indicator (Table 4.4).

Further disturbance of the riparian buffer, Scenario 2, caused increases in peak inflow at Stations 1, 2, 4, and 6 and a significant decrease at Station 5. Likewise, Scenarios 3 and 4 which involve riparian buffer restoration caused significant decreases in peak inflow at Stations 1, 2, 3, and 6 but increases in peak inflow at Stations 4 and 5 (Table 4.4). Since water from Station 4 flows to Station 5, the increase in peak inflow at Station 5 was likely due to the increase in peak observed downstream.

Table 4.4 The difference in peak inflow, m^3/s, between each scenario and the baseline, 1B, and each other was calculated during statistical analysis. Cells that are highlighted indicate a significant change in peak inflow at that station was observed under the scenario comparison. The value reported is the combined difference of each comparison under all events considered. Scenario 2, conversion of the buffer to a managed green space, caused a consistent increase in peak inflow compared to 1B and Scenario 4, riparian buffer restoration of all streams. Scenario 3, riparian buffer restoration of main channels, caused decreases in peak inflow but was not as beneficial as Scenario 4 at most stations.

Comparison	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
1B vs 2	0.4	3.3	0.7	0.0	-1.0	1.8
1B vs 3	-0.1	-0.7	-1.8	0.1	3.4	-5.8
1B vs 4	-7.3	-4.0	-29.5	5.8	43.6	-142.3
2 vs 3	-0.4	-4.0	-2.6	0.1	4.3	-7.6
2 vs 4	-7.6	-7.3	-30.3	5.8	44.6	-144.2
3 vs 4	-7.2	-3.3	-27.7	5.7	40.2	-136.5

Statistics indicated that significantly different results were observed under each precipitation event considered when comparing the scenarios to one another and the baseline with some exceptions when Scenario 4, restoration of the riparian buffer of all streams, was involved in the analysis (Table 4.5). When the riparian buffer was restored to this extent, Scenario 4, and compared to the baseline only the larger storms resulted in peak inflows statistically different from one another at Station 3. At Station 3, the statistics failed to reject the null hypothesis when comparing the differences in peak inflow of the 1yr vs 2yr, 1yr vs 5yr, and 2yr vs 5 yr, and 5yr vs 10yr storms (Table 4.5). The same was observed at Station 5 for the 1yr vs 2yr and 5yr vs 10yr storms. Under the linear model comparing Scenarios 2, 3, and 4, the difference in peak inflow between all storms was statistically significant except the 1yr vs 2yr at Station 3 (Table 4.5). These results suggest riparian buffer restoration of all streams, Scenario 4, had similar impacts on the peak inflow observed under storms of lower return interval. This is due to the decrease in speed of water flowing across the landscape with the greater surface roughness and extent of the riparian buffer.

Table 4.5 The difference in peak inflow, m^3/s, between each 24-hour precipitation event under the different scenario comparisons was calculated during statistical analysis. The value reported is the combined difference of each comparison under all scenarios considered (the two or three being compared). Cells that are highlighted indicate a significant change in peak inflow at that station was observed under the precipitation event comparison.

Station		1yr-10yr	25yr-10yr	2yr-10yr	5yr-10yr	25yr-1yr	2yr-1yr	5yr-1yr	2yr-25yr	5yr-25yr	5yr-2yr
1B vs 2	1	-135	78	-88	-46	213	47	90	-166	-123	43
	2	-225	110	-190	-85	335	35	140	-300	-195	104
	3	-118	156	-94	-51	275	24	68	-250	-207	43
	4	-90	17	-63	-15	107	27	75	-80	-32	48
	5	-389	132	-283	-93	521	106	295	-415	-226	189
	6	-351	184	-264	-119	535	87	232	-448	-303	145
1B vs 3	1	-135	77	-88	-46	212	47	89	-165	-123	42
	2	-225	107	-193	-88	332	32	137	-300	-195	105
	3	-118	156	-94	-51	274	24	67	-249	-207	43
	4	-90	17	-63	-15	107	27	75	-80	-32	48
	5	-393	129	-281	-96	522	112	297	-410	-225	185
	6	-348	184	-262	-118	531	86	230	-445	-302	143
1B vs 4	1	-133	73	-84	-41	206	49	92	-157	-114	43
	2	-225	101	-188	-85	326	37	140	-289	-186	103
	3	-103	148	-80	-49	251	23	54	-228	-197	31
	4	-94	16	-62	-15	110	32	79	-78	-32	46
	5	-433	129	-316	-114	563	117	319	-445	-243	202
	6	-348	171	-269	-119	519	79	229	-440	-290	150
2 vs 3 vs 4	1	-134	75	-85	-43	208	48	91	-160	-117	43
	2	-225	104	-188	-85	329	37	140	-292	-189	103
	3	-108	150	-85	-50	258	24	58	-235	-200	35
	4	-92	17	-62	-15	109	31	77	-78	-32	47
	5	-421	128	-304	-108	549	117	313	-433	-237	196
	6	-348	175	-267	-119	523	81	229	-442	-294	148

4.2.1.3 Event-Based Analysis Summary

Overall, Scenario 2, conversion of the riparian buffer to a managed green space, did not provide flood regulating HES. Instead, disturbance of the riparian buffer caused significant increases in total inflow and peak inflow throughout the watershed when compared to the baseline. The statistics failed to reject the null hypothesis when comparing Scenario 2 to Scenario 3, restoration of the riparian buffer of main channels, at Stations 1, 3, 4, and 5 for both flood regulating indicators considered. Regardless, comparison of Scenario 2 to the baseline indicated consistent increases in total inflow volume and peak inflow, decreasing flood regulating HES. Scenarios 3 and 4, which restored the riparian buffer to different extents, proved to be more beneficial than Scenario 2 and the baseline. Restoration of the riparian buffer around all streams including ephemeral, Scenario 4, provided the greatest and most consistent decreases in total inflow volume. In some areas, Scenario 4 caused an increase in peak inflow. Other studies have observed this phenomenon as well (Kadykalo & Findlay, 2016).

4.2.2 Continuous Simulation Statistical Analysis

The four riparian buffer management scenarios were run under fifteen continuous simulations as well. Two historic datasets, May-July 2014 and 2017, were ran in addition to May-July of the years 2050 and 2099 under seven different climate change projections. Results from these simulations were evaluated using the same methodology as the event-based simulation results. Due to the uncertainty of climate change projections, the average result of all climate change projections should be considered as opposed to the result of each projection individually.

A comparison of the daily precipitation values was completed in Chapter 3 of this report (pg 55). In summary, the average climate change projection, ensemble mean, for May-July of 2050 and 2099 predicts precipitation somewhere between what was experienced in 2014 and 2017. The average projection included 29 days with precipitation exceeding 3 mm, 10 days more than May-July of 2014 and 2017. Thus, the results of the climate change projections provide insight into the performance of riparian buffers under continuous simulation with more frequent, small rainfall events.

4.2.2.1 Total Inflow Volume

Statistical analysis indicated a significant difference in total inflow was observed between each scenario and the baseline, 1B, and each of the other scenarios at all analysis locations (Table 4.6). The only exception to this was observed at Station 4 when comparing Scenarios 2, conversion of the riparian buffer of main channels to a managed green space, to Scenario 3, restoration of the riparian buffer around main channels. When results were statistically significant, conversion of the riparian buffer to a managed green space caused an increase in total inflow volume under all continuous simulations. This is due to the decreased opportunity for infiltration to occur caused by the decreased surface roughness and storage. Restoration of the riparian buffer of main channels, Scenario 3, caused significant decreases in total inflow volume due to the increase in surface roughness and storage (Table 4.6). The same trend was observed under Scenario 4, restoration of the riparian buffer of all channels including ephemeral (Table 4.6). Again, the decrease in total inflow volume occurred due to the increase in surface roughness and storage.

Table 4.6 The difference in total inflow, m^3, between each scenario and the baseline, 1B, and each other was determined during statistical analysis. Cells that are highlighted indicate a significant change in total inflow at that station was observed under the scenario comparison. The value reported is the combined difference of each comparison under all events considered. Scenario 2, conversion of the buffer to a managed green space, caused significant increases in total inflow compared to 1B and Scenario 4, riparian buffer restoration of all streams. Scenario 3, riparian buffer restoration of main channels, caused significant decreases in total inflow compared to the baseline and Scenario 2, with one exception, but was not as beneficial as Scenario 4.

Comparison	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
1B vs 2	2.52E+05	3.42E+05	2.25E+05	4.96E+04	1.15E+06	1.59E+06
1B vs 3	-2.85E+04	-4.15E+04	-6.30E+05	-2.20E+05	-1.76E+06	-3.36E+06
1B vs 4	-1.28E+06	-1.61E+06	-4.22E+06	-3.93E+06	-1.50E+07	-2.37E+07
2 vs 3	-2.80E+05	-3.83E+05	-8.55E+05	-2.69E+05	-2.91E+06	-4.95E+06
2 vs 4	-1.53E+06	-1.96E+06	-4.44E+06	-3.98E+06	-1.61E+07	-2.53E+07
3 vs 4	-1.25E+06	-1.57E+06	-3.59E+06	-3.71E+06	-1.32E+07	-2.04E+07

Under all scenario comparisons considered, the total inflow reported at all stations was significantly different from May-July 2014 to May-July 2017. This is reflective of the large differences in total inflow observed historically. Total inflow under each of the climate change projections was somewhere between what was observed under 2014 and 2017 simulations. Flood regulating HES were provided to a larger extent under the average climate change projections than what was observed under 2017 simulation. The percent decrease in total inflow volume under the average climate change projection exceeded 50% under Scenario 4 at all analysis locations. This is due to the distribution of the precipitation under the projections, less total precipitation fell in smaller increments than under 2017 simulation. Flood regulation HESs were provided by each of the riparian buffer restoration scenarios under all continuous simulations indicating riparian buffers have the ability to provide these services under a variety of precipitation scenarios.

Overall, quantification of changes in total inflow under continuous model simulation demonstrated the importance of widespread riparian buffer restoration in flood regulating HESs.

Under Scenario 4, full riparian buffer restoration around all streams, the largest and most consistent decrease in total inflow was observed.

4.2.2.2 Peak Inflow

Statistical analysis indicated riparian buffer restoration increases the provision of flood regulating HES in terms of reduction in peak inflow. Alternatively, Scenario 2, conversion of the riparian buffer to a managed green space, caused significant increases in peak inflow due to the reduction in surface roughness, allowing water to flow across the landscape more easily (Table 4.7). Compared to the baseline scenario, restoration of the riparian buffer, Scenarios 3 and 4, restoration of the riparian buffer of main channels and all channels including ephemeral streams respectively, caused significant decreases in peak inflow at all locations except Station 4 under Scenario 3. Restoration of the riparian buffer around main channels was not statistically different than conversion of this area to a managed green space except at Station 6. This is due to the small amount of land conversion involved in these scenarios. However, the statistical analysis of each of these scenarios to the baseline indicates riparian buffers cannot be disturbed if an increase in flood regulating HES is desired. Peak inflow reduction depends on the ability of the landscape to slow the flow of water and the storage capacity of the land as well.

Table 4.7 The difference in peak inflow, m^3/s, between each scenario and the baseline, 1B, and each other was calculated during statistical analysis. Cells that are highlighted indicate a significant change in peak inflow at that station was observed under the scenario comparison. The value reported is the combined difference of each comparison under all events considered. Scenario 2, conversion of the buffer to a managed green space, caused significant increases in peak inflow compared to 1B and Scenario 4, riparian buffer restoration of all streams. Scenario 3, riparian buffer restoration of main channels, caused total inflow to decrease except at Station 4. Scenario 3 was not as beneficial as Scenario 4.

Comparison	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
1B vs 2	0.6	1.1	0.2	0.0	1.6	2.1
1B vs 3	-0.2	-0.2	-0.8	0.1	-2.2	-3.2
1B vs 4	-9.2	-9.9	-9.9	-9.6	-43.9	-41.6
2 vs 3	-0.8	-1.3	-1.0	0.1	-3.8	-5.3
2 vs 4	-9.8	-11.0	-10.0	-9.7	-45.5	-43.7
3 vs 4	-9.0	-9.7	-9.0	-9.7	-41.7	-38.4

When evaluating the difference between each scenario and the baseline, the peak inflow reported for the simulation of May-July 2017 was significantly higher than the total inflow from all climate change projections and 2014 across the watershed. Again, it should be noted again that the years selected under the climate projections could have been dry, wet, or average years. Thus, it can only be concluded that the riparian buffer scenarios have the potential to provide greater flood regulating HES in the future if precipitation trends shift to include more frequent small precipitation events.

4.2.2.3 Continuous Analysis Summary

As was the case in event-based simulations, scenarios which restore the riparian buffer provided flood regulating HESs to a greater extent than what is experienced under current conditions or disturbance of the buffer. Scenario 2, conversion of the buffer to a managed green space, again caused significant increases in total and peak inflow throughout most of the watershed. Scenario 4 provided more consistent reductions in peak inflow throughout the watershed under continuous simulation than event-based.

4.3 Summary of Results and Discussion

The impact of four riparian buffer management scenarios and various precipitation events on the provision of flood regulating HESs was quantified using outputs from the PCSWMM model. Indicators of flood regulating HESs considered include decreases in peak inflow and total inflow volume.

The change in total inflow volume was quantified at each station under the different riparian buffer management scenarios. Comparison of the baseline scenario to the management scenarios indicated riparian buffer restoration, Scenarios 3 and 4, provides significant decreases in total inflow volume under both event-based and continuous simulation (Figure 4.7). The magnitude of impact observed at Stations 1 and 2 is much less than what is observed in other parts of the watershed. These stations are in fairly undeveloped areas where the riparian buffer of the main channel is largely intact. Thus, only four hectares of impervious surface were removed from the buffers flowing to Station 1 and one additional hectare between Station 1 and 2. Further disturbance of the riparian buffer, Scenario 2, resulted in significant increases in total inflow volume under all precipitation events and locations considered (Figure 4.7). When comparing event-based and continuous simulation results, it should be noted that the distribution of the precipitation in the continuous simulations allowed antecedent moisture conditions to be established and provided the riparian buffer with time to infiltrate and for evapotranspiration to occur. This resulted in larger percent reductions in total inflow under continuous simulation.

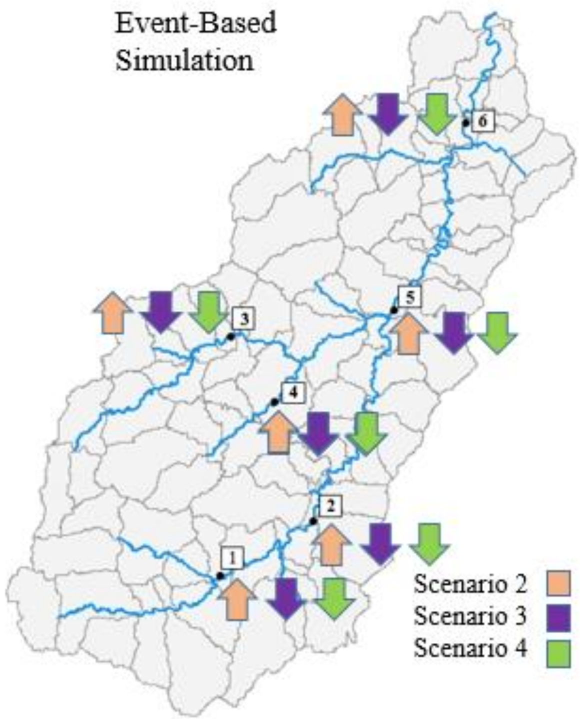

Figure 4.7 Summary of significant differences in total inflow volume from baseline to riparian buffer management scenario under event-based (left) and continuous (right) simulations. An upward pointing arrow indicates a significant increase, a downward pointing arrow indicates a significant decrease, and the lack of an arrow at a station for a scenario indicates no significant change in total inflow was observed.

The same methodology was utilized to quantify changes in peak inflow. Comparison of the baseline scenario to the management scenarios indicated riparian buffers typically provide reductions in peak inflow, Scenarios 3 and 4 (Figure 4.8). Significant reductions in peak inflow of the largest magnitude were often realized under Scenario 4, riparian buffer restoration of all streams including ephemeral streams. All management scenarios caused significant changes in peak inflow under event-based and continuous simulation. The inclusion of smaller, less intense precipitation events in continuous simulation allowed a larger percent reduction in peak inflow to be observed. Due to the increase in surface roughness, the restored riparian buffer vegetation slowed the flow of water to the stream. The significant increase in peak inflow under Scenario 2 under continuous simulation and lack thereof in event-based simulation is attributed to the establishment of antecedent moisture conditions in the former. Conversion of natural vegetation to a managed green space in this scenario caused the surface roughness to decrease, accelerating the flow of water across the landscape.

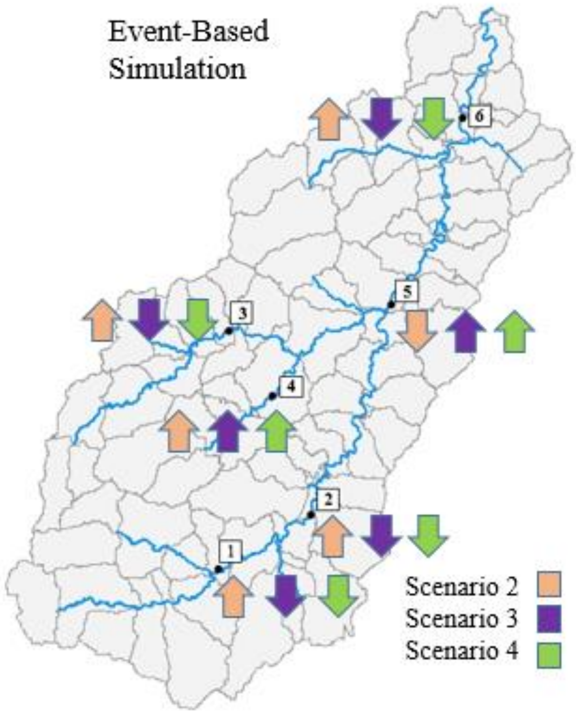

Figure 4.8 Summary of statistically significant changes in peak inflow from baseline to riparian buffer management scenario under event-based (left) and continuous (right) simulations. An upward pointing arrow indicates a significant increase, a downward pointing arrow indicates a significant decrease, and the lack of an arrow at a station for a scenario indicates no significant change in total inflow was observed.

Overall, disturbance of the riparian buffer was confirmed to be detrimental to flood regulating HES provision. Scenario 2 involved conversion of all natural vegetation within the riparian buffer of main channels to be converted to a managed green space. This change in land cover corresponds with a decrease in surface roughness. Statistical analysis demonstrated the negative impact of decreased surface roughness on flood regulating HES. Scenarios that include restoration of the riparian buffer provided flood regulating HES to a greater degree throughout the Blue River Watershed. Scenario 3 involved restoration of the riparian buffer around main stream channels (Figure 4.9). With this, 180 hectares of impervious surface were replaced with deciduous forest. Scenario 4 involved restoration of the riparian buffer around all stream channels including ephemeral (Figure 4.9). This involved conversion of 1031 hectares of impervious surface to deciduous forest. Under each of these management scenarios, an increase in surface roughness was associated with the land cover change. The increased roughness slowed the flow of water, increasing infiltration. Statistical analysis demonstrated the positive impact of this phenomenon on flood regulating HES. Analysis of the magnitude of change in total inflow and peak inflow indicated HES provision increases as more land is in restored to riparian vegetation.

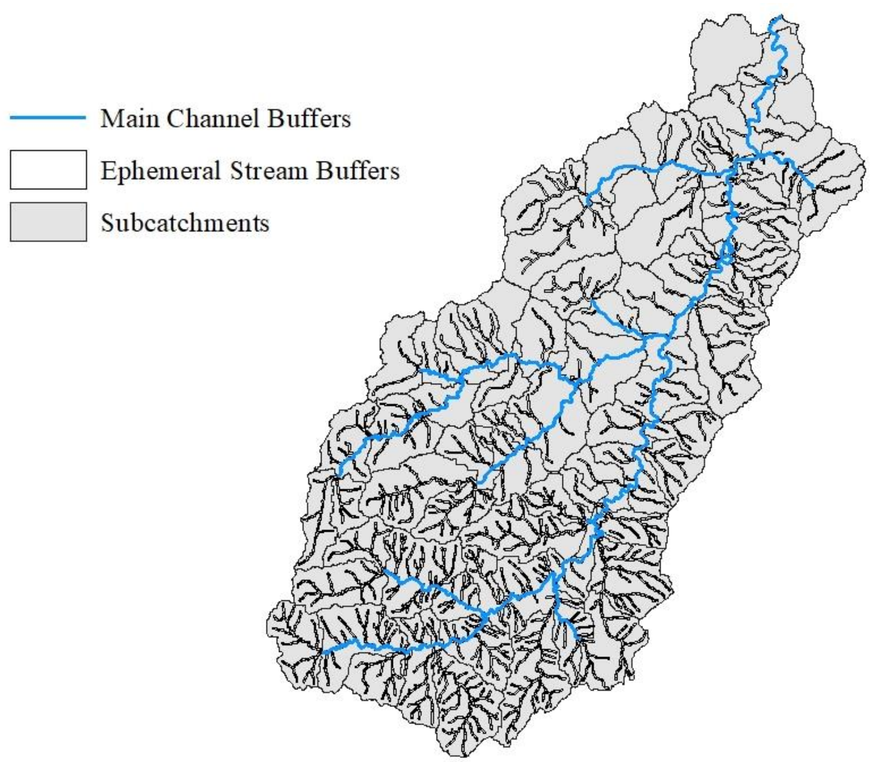

Figure 4.9 Scenario 3 involves restoration of the riparian buffer around main streams. These buffers are represented by buffers shown in blue. In Scenario 4, the riparian buffer is restored around all channels including ephemeral streams. This buffer network includes all blue and black buffers shown on the map, an increase in restored area of roughly 850 hectares compared to main channel riparian buffer restoration only.

Chapter 5 - Conclusions

Projected increases in urbanization and the impacts this will have has heightened research in more sustainable development (MEA, 2005; Soga et al., 2014). Ecosystem resiliency, its ability to maintain structure and bounce back from stresses, decreases with urbanization (McDonough, 2015). This is due to the decline in ecosystem health and ecosystem service provision that stems from removal or disturbance of the natural ecosystem (MEA, 2005). A key example is the hindrance of the system's hydrologic functionality, placing the man-made and natural environment in danger of further damage due to flooding (Charleton, 2008). Climate change has made urban areas become hot spots for many risks, flooding included (IPCC, 2014). Likewise, Williams et al (2012) project an increase in city vulnerability to flooding due to climate change. System resiliency can be restored through the preservation of ecosystem services and careful planning (McDonough, 2015).

The combined impacts of climate change and urbanization on ecosystem health, especially in regard to hydrologic function, must be evaluated in order for informed land management decisions to be made (IPCC, 2014; Terrado et al., 2014). Easterling et al. (2017) suggest site-specific evaluation of these impacts. When combined with the quantification of ecosystem services, modeling of climate change and urbanization impacts can help identify where conservation and restoration efforts should be made (Maragno et al., 2018). From this information, management decisions and policy that provide greater provision of ecosystem services throughout a watershed can be made (Brauman, 2015; Maragno et al., 2018).

This research investigated the role of riparian buffers in provision of flood regulating ecosystem services under event and continuous simulation considering climate change. Two indicators of flood regulation were quantified– changes in peak inflow and total inflow volume–

under four different riparian buffer management scenarios. PSWMM simulations were ran for 24-hour precipitation events of varying return intervals to better understand the capacity of riparian buffers to provide HESs. Continuous model simulation was completed for May-July using historic precipitation from 2014 and 2017 and climate change projections for 2050 and 2099. Overall, the findings of this research can help guide management decisions and policy in urbanizing watersheds to improve system resiliency by preservation of ecosystem services.

The impact of four riparian buffer management scenarios on flood regulation HESs in an urbanizing watershed were evaluated in this research. Scenarios include leaving land use in the riparian buffer as is, conversion to a managed green space, restoration of riparian vegetation around main channels, and restoration of riparian vegetation around all channels including ephemeral. The as-is scenario acted as the baseline of comparison in determining if the other management scenarios would be beneficial in providing additional flood regulating HESs.

The findings indicated riparian buffers have a large impact on the provision of flood regulating HESs, a trend observed in other research as well (Acreman & Holden, 2013; Maragno et al., 2018). When natural land cover within the riparian buffer was converted to a managed green space, increases in peak inflow and total inflow volume were observed. Total inflow volume increased significantly across the watershed in both event-based and continuous simulation. Peak inflow only increased significantly at two stations in the watershed under event-based simulation and at four stations in continuous simulation. Stations in areas that are already flashy, Stations 3 and 4, did not see significant changes in peak inflow under this management scenario. Under climate change projections, disturbance of the riparian buffer resulted in reductions in flood regulating HESs as well. Overall, riparian buffers are capable of providing flood regulating HESs in a variety of precipitation scenarios. This information along with the uncertainty of how climate change will actually impact precipitation exemplifies the need to prevent further alterations to land in the riparian area. Disturbing the riparian buffer will increase the risk of flooding, exacerbating the issue. Local land managers should use this information when making zoning decisions, especially for new park areas. Although these spaces are green, parks primarily of turf grass negatively affect the hydrologic stability of the watershed and should be kept at a distance from stream channels. However, as noted by previous studies, placement of park land around stream channels prevents other infrastructure from being built in the area. Brody and Highland (2013) found the monetary property damage of floods can be reduced by nearly $950,000 under this management scheme when the amount of open space is maximized.

Holistic watershed management in the form of riparian buffer restoration proved to be very beneficial across the Blue River Watershed, increasing the provision of flood regulating HESs. Restoration of riparian buffers aided in flood regulation by decreasing peak inflow and total inflow volume across the land use gradient. The greatest flood regulating HES benefits were observed under Scenario 4 which involved restoration of the riparian buffer around all streams including ephemeral streams. Protecting natural waterways to this extent caused significant reductions in peak inflow and total inflow volume at all analysis locations under continuous simulation. Total inflow volume was significantly reduced across the watershed under event-based simulation as well.

The climate change projections considered included an increase in the frequency of smaller precipitation events. Under these conditions, riparian buffers play a significant role in peak inflow and total inflow volume reduction. Scenario 4 provided reductions in total inflow of over 50% at all stations under the average 2050 projection and average 2099 projection when compared to the baseline. Scenario 3 provided significant benefits throughout most of the watershed as well but never exceeded 11%. Given the uncertainty of how climate change will actually impact future precipitation, restoration of the riparian buffer of all streams including ephemeral streams is the most proactive management decision. This would provide significant flood regulation benefits as well as a number of other ecosystem services.

5.1 Policy: A Way of Respecting the Stream

As the Blue River Watershed continues to develop, a holistic approach to watershed management should be pursued. A fault in common watershed management currently in practice is failure to protect natural waterways. River function and mobility overtime must be considered during development to prevent future damage (Biron et al., 2014). Many of the development scenarios considered in this report use the conduit network or main stream channel as a reference point. It is important to understand that the natural shape of this network will likely change over time. This is mainly due to bank erosion due to water moving at a higher speed than the bank can handle and natural migration of the channel (Charleton, 2008).

Relevant policies that provide more protection for the streams, riparian buffers, and floodplains in the watershed are needed. These policies should focus on allowing sufficient access to the stream's floodplain and reducing disturbance in vulnerable areas. Currently, many jurisdictions in the watershed have some sort of stream set-back policy, but uniformity in policy would help ensure consistent protection and prevent confounding of increased stress.

Preservation of the riparian buffer offers benefits throughout the watershed, as demonstrated by the results of this research. Since development reduces the ability for water to infiltrate, protecting natural hydrologic function throughout the watershed near the channel is important. Protection of headwaters streams is especially important because of their vulnerability due to their small size and typical "integration into the landscape" (Pennsylvania, 2014). Without restoration of riparian area in the upper watershed, benefits achieved in the lower, more developed parts of the watershed would be reduced (Coleman, 2007; Pennsylvania, 2014). In general, consistent protection of this area is needed to maximize the benefits provided throughout the watershed. Flood reduction benefits increase as more land is preserved around streams. Based on watershed modeling results, the greatest flood and inflow reduction benefits are achieved when ephemeral streams are included in the restored riparian buffer network.

5.2 Knowledge Sharing

In order to make true change, community members and professionals alike must develop a better understanding of watersheds and deepen their commitment to watershed health (NRC, 2002). Likewise, interdisciplinary collaboration is needed to improve the understanding and protection of ecosystem services (McDonough et al., 2017a). This will require professionals to share their knowledge in a timely and digestible manner (MEA, 2005; Boyle Torrey, 2004; Pejchar et al., 2006).

A similar strategy must be taken to better inform the public. In a water quality survey conducted in 2012, the Mid-America Regional Council (MARC) found:

"only nine percent of area residents know that they live in a watershed"

(Heartland, 2013b).

This knowledge gap demonstrates the need for concise and easily understandable information to be made more readily available. Local agencies should enhance community engagement to gain support of improved watershed management concepts and help improve overall understanding. Similarly, basic hydrology and watershed concepts should be integrated in community and youth educational programs. The Blue River Watershed Association (BRWA) acknowledges the power of educating today's youth and their pivotal role in achieving real behavioral change (Smith, 2015). As such, the BRWA has developed a program for urban youth to assist in water quality monitoring of the river. The program allows youth to develop a better understanding of water resources and the things that impact them, while providing an opportunity to explore STEM and meet leaders in the community.

In order to reduce flood risk across the Blue River Watershed, areas which provide key hydrologic ecosystem services must be identified and protected. This research demonstrates the need for full riparian buffer restoration in the watershed to reduce the hydrologic stress on waterways. Restoring the riparian buffer throughout the watershed will require a shift in how water is viewed and managed. Currently, stormwater is seen as a waste that is routed to drains and channels, often concrete, as quickly as possible. When water and the environment as a whole is seen as a resource needing protection and careful management, the ecosystem services provided by it can be more fully realized. With consistent protection of riparian buffers, system resiliency can be improved.

5.3 Future Research

Future research to improve the understanding of the relationship between riparian buffers and ecosystem services is needed, including:

1. The impact of riparian buffer restoration or disturbance on the provision of other ecosystem services, including other indicators of flood regulation not explored in this research.
2. The impact of riparian buffer restoration on flood extent using 2D watershed modeling.
3. Modeling of potential restoration policies, i.e. variable width depending on stream order or contributing area, would be helpful in evaluating which policy is best for a given watershed.

4. Integration of stream channel erosion estimates to determine the riparian buffer's role in protecting stream health.
5. Integration of projected land use or green infrastructure outside of the riparian buffer in conjunction with various riparian buffer management scenarios.
6. Would integration of a secondary buffer around the riparian area provide significantly more ecosystem services? What other limits need to be placed on urban development to preserve ecosystem services?

Further analysis of climate change projections would be helpful in better understanding the future role of riparian buffers. Daily precipitation totals were used in this study, requiring a variety of assumptions about storm duration. Improved temporal resolution of climate change projections and historic rainfall data should be pursued.

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Appendix A- Climate Change Projection Summary

Table A.0.1 Summary of 2050 and 2099 climate change projections.

2050 Projections								
		Station ID						
		0	**1**	**2**	**3**	**4**	**5**	**Average**
A	Total Precipitation (mm), May-July:	368	369	367	344	353	333	356
	May-July,>3mm:	24	29	30	28	28	28	28
	May-July,>25mm:	5	3	4	1	2	2	3
B	Total Precipitation (mm), May-July:	402	400	405	425	457	439	421
	May-July,>3mm:	24	28	27	30	30	31	28
	May-July,>25mm:	5	3	2	1	4	5	3
C	Total Precipitation (mm), May-July:	358	365	373	376	388	332	365
	May-July,>3mm:	25	32	32	33	34	35	32
	May-July,>25mm:	3	2	2	2	2	1	2
D	Total Precipitation (mm), May-July:	392	425	427	438	462	469	436
	May-July,>3mm:	30	31	32	32	32	32	32
	May-July,>25mm:	4	4	4	5	6	3	4
E	Total Precipitation (mm), May-July:	391	421	433	464	485	503	450
	May-July,>3mm:	24	25	25	26	27	27	26
	May-July,>25mm:	3	4	4	4	4	7	4
F	Total Precipitation (mm), May-July:	217	222	218	214	207	220	216
	May-July,>3mm:	25	26	23	24	20	27	24
	May-July,>25mm:	0	0	0	0	1	0	0
G	Total Precipitation (mm), May-July:	363	385	374	379	388	394	380
	May-July,>3mm:	32	36	33	31	32	34	33
	May-July,>25mm:	2	2	2	2	2	2	2
Average	Total Precipitation (mm), May-July:	356	370	371	377	391	384	**375**
	May-July,>3mm:	26	30	29	29	29	31	**29**
	May-July,>25mm:	3	3	3	2	3	3	**3**
2099 Projections								
		Station ID						
		0	**1**	**2**	**3**	**4**	**5**	**Average**
A	Total Precipitation (mm), May-July:	552	523	521	511	517	478	517
	May-July,>3mm:	27	0	32	38	33	35	28
	May-July,>25mm:	7	0	9	5	6	6	6
B	Total Precipitation (mm), May-July:	434	423	424	415	399	377	412

	May-July,>3mm:	26	29	32	34	25	31	30
	May-July,>25mm:	6	5	6	3	5	4	5
C	Total Precipitation (mm), May-July:	534	545	564	583	597	549	562
	May-July,>3mm:	31	39	42	43	41	41	40
	May-July,>25mm:	5	4	4	4	4	4	4
D	Total Precipitation (mm), May-July:	403	426	422	441	471	485	441
	May-July,>3mm:	22	26	25	25	28	30	26
	May-July,>25mm:	5	6	5	5	6	6	6
E	Total Precipitation (mm), May-July:	262	285	292	299	311	343	299
	May-July,>3mm:	22	24	23	22	23	27	24
	May-July,>25mm:	2	2	2	3	3	4	3
F	Total Precipitation (mm), May-July:	307	318	317	318	317	319	316
	May-July,>3mm:	23	22	21	20	18	20	21
	May-July,>25mm:	4	4	4	4	4	4	4
G	Total Precipitation (mm), May-July:	482	508	509	524	522	511	509
	May-July,>3mm:	38	41	39	39	37	38	39
	May-July,>25mm:	2	4	3	3	2	2	3
Average	Total Precipitation (mm), May-July:	425	433	436	441	448	437	**437**
	May-July,>3mm:	27	26	31	32	29	32	**29**
	May-July,>25mm:	4	4	5	4	4	4	**4**

Appendix B- PCSWMM Simulation Results

Table B.0.1 Total inflow, cubic meters, at each station during event-based simulation. All values are a direct output of PCSWMM.

Station 1					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	2.41E+06	3.55E+06	5.39E+06	6.65E+06	8.53E+06
1B	2.27E+06	3.38E+06	5.20E+06	6.46E+06	8.33E+06
2	2.30E+06	3.41E+06	5.24E+06	6.50E+06	8.37E+06
3	2.27E+06	3.37E+06	5.19E+06	6.45E+06	8.32E+06
1C	2.24E+06	3.30E+06	5.05E+06	6.25E+06	8.02E+06
4	2.15E+06	3.21E+06	4.96E+06	6.14E+06	7.92E+06
Station 2					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	3.83E+06	5.53E+06	8.20E+06	1.03E+07	1.32E+07
1B	3.60E+06	5.27E+06	7.96E+06	9.98E+06	1.30E+07
2	3.64E+06	5.32E+06	8.01E+06	1.00E+07	1.30E+07
3	3.60E+06	5.26E+06	7.95E+06	9.97E+06	1.30E+07
1C	3.55E+06	5.15E+06	7.77E+06	9.71E+06	1.25E+07
4	3.43E+06	5.03E+06	7.64E+06	9.55E+06	1.24E+07
Station 3					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	2.63E+06	3.29E+06	4.53E+06	5.49E+06	7.12E+06
1B	2.29E+06	2.92E+06	4.13E+06	5.08E+06	6.71E+06
2	2.30E+06	2.95E+06	4.16E+06	5.10E+06	6.73E+06
3	2.22E+06	2.85E+06	4.06E+06	5.00E+06	6.62E+06
1C	2.09E+06	2.65E+06	3.72E+06	4.58E+06	6.11E+06
4	1.82E+06	2.34E+06	3.36E+06	4.17E+06	5.64E+06
Station 4					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	1.84E+06	2.30E+06	3.17E+06	3.84E+06	4.81E+06
1B	1.73E+06	2.19E+06	3.06E+06	3.73E+06	4.71E+06
2	1.73E+06	2.19E+06	3.06E+06	3.73E+06	4.71E+06
3	1.71E+06	2.17E+06	3.04E+06	3.71E+06	4.69E+06
1C	1.48E+06	1.88E+06	2.62E+06	3.24E+06	4.13E+06
4	1.36E+06	1.72E+06	2.43E+06	3.03E+06	3.88E+06
Station 5					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	1.39E+07	1.82E+07	2.55E+07	3.11E+07	3.92E+07
1B	1.26E+07	1.68E+07	2.39E+07	2.95E+07	3.75E+07
2	1.27E+07	1.69E+07	2.41E+07	2.96E+07	3.77E+07

3	1.24E+07	1.66E+07	2.37E+07	2.92E+07	3.72E+07
1C	1.17E+07	1.56E+07	2.22E+07	2.74E+07	3.49E+07
4	1.09E+07	1.46E+07	2.11E+07	2.62E+07	3.37E+07
Station 6					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	1.99E+07	2.52E+07	3.18E+07	3.65E+07	4.35E+07
1B	1.82E+07	2.39E+07	3.08E+07	3.57E+07	4.28E+07
2	1.83E+07	2.41E+07	3.09E+07	3.58E+07	4.30E+07
3	1.78E+07	2.36E+07	3.05E+07	3.54E+07	4.25E+07
1C	1.64E+07	2.18E+07	2.87E+07	3.33E+07	3.99E+07
4	1.51E+07	2.02E+07	2.75E+07	3.21E+07	3.87E+07

Table B.0.2 Percent change in total inflow between each scenario and the baseline, 1B, and each other. Percent change was calculated by subtracting the value received from the first listed scenario from the second, dividing by the first and multiplying by 100, ie for 1B vs 2: (Total Inflow 2-Total Inflow 1B)/(Total Inflow 1B)*100.

	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 2	**1yr**	1.1%	1.1%	0.8%	0.2%	1.0%	0.9%
	2yr	0.9%	0.9%	0.7%	0.2%	0.7%	0.6%
	5yr	0.7%	0.6%	0.6%	0.1%	0.6%	0.4%
	10yr	0.7%	0.5%	0.5%	0.1%	0.5%	0.4%
	25yr	0.6%	0.4%	0.4%	0.1%	0.5%	0.4%
	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 3	**1yr**	-0.2%	-0.2%	-2.9%	-1.2%	-1.4%	-2.1%
	2yr	-0.1%	-0.1%	-2.4%	-0.9%	-1.1%	-1.4%
	5yr	-0.2%	-0.1%	-1.9%	-0.7%	-0.9%	-1.0%
	10yr	-0.1%	-0.1%	-1.6%	-0.5%	-0.7%	-0.8%
	25yr	-0.1%	-0.1%	-1.3%	-0.4%	-0.7%	-0.7%
	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 4	**1yr**	-5.2%	-4.8%	-20.4%	-21.3%	-13.8%	-16.9%
	2yr	-5.0%	-4.5%	-19.9%	-21.4%	-12.9%	-15.4%
	5yr	-4.6%	-3.9%	-18.7%	-20.4%	-11.6%	-10.7%
	10yr	-4.9%	-4.3%	-17.8%	-18.8%	-10.9%	-10.1%
	25yr	-4.9%	-4.6%	-15.8%	-17.6%	-10.2%	-9.6%
	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
2 vs 3	**1yr**	-1.3%	-1.1%	-3.5%	-1.2%	-2.4%	-2.7%
	2yr	-1.2%	-1.1%	-3.4%	-0.9%	-1.8%	-2.1%
	5yr	-1.0%	-0.7%	-2.4%	-0.7%	-1.7%	-1.3%
	10yr	-0.8%	-0.3%	-2.0%	-0.5%	-1.4%	-1.1%
	25yr	-0.6%	0%	-1.6%	-0.4%	-1.3%	-1.2%
	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**

2 vs 4	**1yr**	-6.5%	-5.8%	-20.9%	-21.4%	-14.2%	-17.5%
	2yr	-5.9%	-5.5%	-20.7%	-21.5%	-13.6%	-16.2%
	5yr	-5.3%	-4.6%	-19.2%	-20.6%	-12.4%	-11.0%
	10yr	-5.5%	-4.5%	-18.2%	-18.8%	-11.5%	-10.3%
	25yr	-5.4%	-4.6%	-16.2%	-17.6%	-10.6%	-10.0%
	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
3 vs 4	**1yr**	-5.3%	-4.7%	-18.0%	-20.5%	-12.1%	-15.2%
	2yr	-4.7%	-4.4%	-17.9%	-20.7%	-12.0%	-14.4%
	5yr	-4.4%	-3.9%	-17.2%	-20.1%	-11.0%	-9.8%
	10yr	-4.8%	-4.2%	-16.6%	-18.3%	-10.3%	-9.3%
	25yr	-4.8%	-4.6%	-14.8%	-17.3%	-9.4%	-8.9%

Table B.0.3 Peak inflow, m^3/s, at each station during event-based simulations. All values are a direct output of PCSWMM.

Station 1					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	190.4	240.1	282.2	327	404.7
1B	191.4	238.4	280.7	326.4	403.8
2	191.2	238.4	281.2	327	404.7
3	191.4	238.4	280.6	326.2	403.7
1C	189.7	240.3	281.9	319.6	390.7
4	186.1	236.8	279.9	316.2	385.4
Station 2					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	127.4	178.1	276.5	352.1	458
1B	123.9	156.3	261.1	348.6	456.6
2	124.3	162.1	266.1	349	461.4
3	123.9	155.4	260	348.5	455
1C	122.5	153	252.1	345.5	443.9
4	119.9	161.4	261.8	345.2	438.2
Station 3					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	91.47	114.3	164	213.7	372.4
1B	87.19	111.5	154.7	205.5	361.6
2	87.73	112.1	155.6	206.3	362.5
3	85.86	110.3	152.5	203.7	359
1C	85.45	108.1	135.1	186	335.5
4	79.15	101.2	119.1	167.2	306.2
Station 4					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	172.4	199.1	247.3	261.6	278.7

1B	172	199	247.2	261.7	278.8
2	172	198.9	247.2	261.7	278.8
3	172.3	199.4	247.2	261.7	278.7
1C	170.9	203.5	249.1	263.8	280.6
4	171.3	208.8	253.4	269.3	284.9
Station 5					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	296	406.8	604.3	710.7	800
1B	303.4	410.5	598.6	692.5	824.7
2	303.2	408.1	598.5	691.2	823.9
3	302	418.9	601.2	699	825.4
1C	300.2	413.2	602.8	715.1	814.9
4	299.1	426.8	642.2	776.8	902.8
Station 6					
Scenario	**1yr, 24hr**	**2yr, 24hr**	**5yr, 24hr**	**10yr, 24hr**	**25yr, 24hr**
1A	274.7	357.9	532.5	656.4	831.5
1B	353.9	440.9	585.3	704.2	887.7
2	354.4	442	587.3	706.7	890.8
3	351	436.6	578.8	696.6	880.1
1C	240.4	314.9	474	594	755
4	222.7	293.2	449.1	568.7	726.7

Table B.0.4 Percent change in peak inflow between each scenario and the baseline, 1B, and each other. Percent change was calculated by subtracting the value received from the first listed scenario from the second, dividing by the first and multiplying by 100, ie for 1B vs 2: (Peak Inflow 2-Peak Inflow 1B)/(Peak Inflow 1B)*100.

	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 2	**1yr**	-0.1%	0.3%	0.6%	0.0%	-0.1%	0.1%
	2yr	0.0%	3.7%	0.5%	-0.1%	-0.6%	0.2%
	5yr	0.2%	1.9%	0.6%	0.0%	0.0%	0.3%
	10yr	0.2%	0.1%	0.4%	0.0%	-0.2%	0.4%
	25yr	0.2%	1.1%	0.2%	0.0%	-0.1%	0.3%
	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 3	**1yr**	0.0%	0.0%	-1.5%	0.2%	-0.5%	-0.8%
	2yr	0.0%	-0.6%	-1.1%	0.2%	2.0%	-1.0%
	5yr	0.0%	-0.4%	-1.4%	0.0%	0.4%	-1.1%
	10yr	-0.1%	0.0%	-0.9%	0.0%	0.9%	-1.1%
	25yr	0.0%	-0.4%	-0.7%	0.0%	0.1%	-0.9%
	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 4	**1yr**	-2.8%	-3.2%	-9.2%	-0.4%	-1.4%	-37.1%
	2yr	-0.7%	3.3%	-9.2%	4.9%	4.0%	-33.5%

	5yr	-0.3%	0.3%	-23.0%	2.5%	7.3%	-23.3%
	10yr	-3.1%	-1.0%	-18.6%	2.9%	12.2%	-19.2%
	25yr	-4.6%	-4.0%	-15.3%	2.2%	9.5%	-18.1%
	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
2 vs 3	**1yr**	0.1%	-0.3%	-2.1%	0.2%	-0.4%	-1.0%
	2yr	0.0%	-4.1%	-1.6%	0.3%	2.6%	-1.2%
	5yr	-0.2%	-2.3%	-2.0%	0.0%	0.5%	-1.4%
	10yr	-0.2%	-0.1%	-1.3%	0.0%	1.1%	-1.4%
	25yr	-0.2%	-1.4%	-1.0%	0.0%	0.2%	-1.2%
	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
2 vs 4	**1yr**	-2.7%	-3.5%	-9.8%	-0.4%	-1.4%	-37.2%
	2yr	-0.7%	-0.4%	-9.7%	5.0%	4.6%	-33.7%
	5yr	-0.5%	-1.6%	-23.5%	2.5%	7.3%	-23.5%
	10yr	-3.3%	-1.1%	-19.0%	2.9%	12.4%	-19.5%
	25yr	-4.8%	-5.0%	-15.5%	2.2%	9.6%	-18.4%
	Storm	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
3 vs 4	**1yr**	-2.8%	-3.2%	-7.8%	-0.6%	-1.0%	-36.6%
	2yr	-0.7%	3.9%	-8.3%	4.7%	1.9%	-32.8%
	5yr	-0.2%	0.7%	-21.9%	2.5%	6.8%	-22.4%
	10yr	-3.1%	-0.9%	-17.9%	2.9%	11.1%	-18.4%
	25yr	-4.5%	-3.7%	-14.7%	2.2%	9.4%	-17.4%

Table B.0.5 Summary of total inflow, cubic meters, at each analysis location for May-July 2014 and 2017 continuous model simulations. Values reported are based on the ensemble mean.

	Station 1		**Station 2**		**Station 3**	
Scenario	**2014**	**2017**	**2014**	**2017**	**2014**	**2017**
1A	1.99E+06	5.86E+06	2.69E+06	8.90E+06	6.39E+06	1.31E+07
1B	9.04E+05	4.57E+06	1.10E+06	6.97E+06	4.33E+06	1.10E+07
2	1.08E+06	4.87E+06	1.34E+06	7.39E+06	4.50E+06	1.12E+07
3	8.71E+05	4.57E+06	1.05E+06	6.93E+06	3.84E+06	1.05E+07
1C	2.47E+05	3.34E+06	2.13E+05	5.15E+06	2.56E+06	8.44E+06
4	2.71E+04	2.89E+06	1.33E+04	4.61E+06	1.07E+06	6.33E+06
	Station 4		**Station 5**		**Station 6**	
Scenario	**2014**	**2017**	**2014**	**2017**	**2014**	**2017**
1A	4.06E+06	8.21E+06	2.23E+07	5.28E+07	3.52E+07	7.90E+07
1B	3.43E+06	7.59E+06	1.41E+07	4.40E+07	2.35E+07	6.67E+07
2	3.46E+06	7.66E+06	1.49E+07	4.51E+07	2.47E+07	6.83E+07
3	3.26E+06	7.44E+06	1.28E+07	4.26E+07	2.10E+07	6.40E+07
1C	1.45E+06	4.91E+06	6.81E+06	3.25E+07	1.21E+07	4.91E+07

4	3.86E+05	3.38E+06	2.78E+06	2.56E+07	5.69E+06	3.87E+07

Table B.0.6 Summary of total inflow, cubic meters, under climate change projections (A-G) for May-July 2050. View Table 3.9 for full names of the climate change projections.

	Station 1							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	2.29E+06	3.19E+06	2.45E+06	3.36E+06	3.66E+06	1.26E+06	2.60E+06	2.69E+06
1B	9.96E+05	1.56E+06	1.09E+06	1.63E+06	2.29E+06	4.07E+05	1.18E+06	1.31E+06
2	1.20E+06	1.85E+06	1.30E+06	1.93E+06	2.57E+06	5.34E+05	1.40E+06	1.54E+06
3	9.69E+05	1.52E+06	1.07E+06	1.59E+06	2.26E+06	3.97E+05	1.16E+06	1.28E+06
1C	3.15E+05	4.64E+05	3.22E+05	4.44E+05	1.17E+06	1.25E+05	4.11E+05	4.64E+05
4	7.07E+04	1.19E+05	5.10E+04	3.74E+04	7.13E+05	0.00E+00	1.16E+05	1.58E+05
	Station 2							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	2.94E+06	4.29E+06	2.95E+06	4.59E+06	5.37E+06	1.52E+06	3.37E+06	3.58E+06
1B	1.12E+06	1.91E+06	1.17E+06	1.99E+06	3.39E+06	4.25E+05	1.43E+06	1.63E+06
2	1.39E+06	2.31E+06	1.43E+06	2.42E+06	3.79E+06	5.74E+05	1.73E+06	1.95E+06
3	1.09E+06	1.85E+06	1.16E+06	1.94E+06	3.34E+06	4.13E+05	1.40E+06	1.60E+06
1C	2.59E+05	3.91E+05	2.84E+05	3.68E+05	1.75E+06	9.82E+04	4.30E+05	5.11E+05
4	4.64E+04	8.16E+04	4.44E+04	8.52E+03	1.20E+06	0.00E+00	1.24E+05	2.16E+05
	Station 3							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	7.35E+06	1.03E+07	8.25E+06	1.06E+07	1.12E+07	3.75E+06	8.09E+06	8.51E+06
1B	4.67E+06	7.25E+06	5.19E+06	7.51E+06	8.70E+06	1.88E+06	5.08E+06	5.75E+06
2	4.86E+06	7.51E+06	5.45E+06	7.79E+06	8.91E+06	2.01E+06	5.30E+06	5.98E+06
3	4.06E+06	6.59E+06	4.53E+06	6.80E+06	8.10E+06	1.48E+06	4.43E+06	5.14E+06
1C	3.02E+06	4.62E+06	3.34E+06	4.86E+06	6.57E+06	1.08E+06	3.51E+06	3.86E+06
4	1.34E+06	2.14E+06	1.44E+06	2.29E+06	4.43E+06	1.84E+05	1.72E+06	1.93E+06
	Station 4							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	4.78E+06	6.62E+06	5.41E+06	6.80E+06	7.04E+06	2.57E+06	5.32E+06	5.50E+06
1B	3.84E+06	5.66E+06	4.31E+06	5.83E+06	6.24E+06	1.83E+06	4.26E+06	4.57E+06
2	3.89E+06	5.71E+06	4.36E+06	5.90E+06	6.28E+06	1.88E+06	4.30E+06	4.62E+06
3	3.63E+06	5.43E+06	4.07E+06	5.59E+06	6.05E+06	1.67E+06	4.00E+06	4.35E+06
1C	1.91E+06	2.66E+06	2.04E+06	2.74E+06	3.83E+06	7.36E+05	2.19E+06	2.30E+06
4	7.41E+05	1.04E+06	6.58E+05	1.01E+06	2.34E+06	5.06E+04	8.97E+05	9.63E+05
	Station 5							

Scenario	A	B	C	D	E	F	G	Ensemble Mean
1A	2.52E+07	3.57E+07	2.76E+07	3.71E+07	4.09E+07	1.23E+07	2.76E+07	2.95E+07
1B	1.47E+07	2.33E+07	1.63E+07	2.43E+07	3.09E+07	5.49E+06	1.63E+07	1.88E+07
2	1.56E+07	2.46E+07	1.73E+07	2.58E+07	3.21E+07	6.06E+06	1.74E+07	1.98E+07
3	1.30E+07	2.13E+07	1.45E+07	2.23E+07	2.92E+07	4.50E+06	1.45E+07	1.71E+07
1C	7.76E+06	1.15E+07	8.65E+06	1.25E+07	2.12E+07	2.43E+06	9.71E+06	1.05E+07
4	3.39E+06	4.94E+06	3.78E+06	5.61E+06	1.47E+07	3.75E+05	5.10E+06	5.42E+06
	Station 6							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	4.16E+07	5.47E+07	4.34E+07	5.72E+07	6.10E+07	2.00E+07	4.37E+07	4.59E+07
1B	2.64E+07	3.74E+07	2.77E+07	3.92E+07	4.71E+07	1.02E+07	2.76E+07	3.08E+07
2	2.78E+07	3.92E+07	2.92E+07	4.11E+07	4.87E+07	1.10E+07	2.90E+07	3.23E+07
3	2.32E+07	3.38E+07	2.44E+07	3.53E+07	4.39E+07	8.03E+06	2.40E+07	2.75E+07
1C	1.45E+07	1.97E+07	1.54E+07	2.12E+07	3.23E+07	4.53E+06	1.63E+07	1.77E+07
4	6.95E+06	9.21E+06	7.48E+06	1.00E+07	2.23E+07	9.22E+05	8.87E+06	9.39E+06

Table B.0.7 Summary of total inflow, cm, under climate change projections for May-July 2099. View Table 3.9 for full names of the climate change projections.

	Station 1							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	3.60E+06	2.76E+06	4.08E+06	3.38E+06	2.15E+06	2.21E+06	3.57E+06	3.11E+06
1B	1.83E+06	1.33E+06	1.88E+06	1.89E+06	1.06E+06	1.18E+06	1.67E+06	1.55E+06
2	2.15E+06	1.58E+06	2.25E+06	2.17E+06	1.24E+06	1.36E+06	1.98E+06	1.82E+06
3	1.78E+06	1.30E+06	1.83E+06	1.85E+06	1.03E+06	1.15E+06	1.63E+06	1.51E+06
1C	4.65E+05	3.82E+05	5.67E+05	6.06E+05	3.14E+05	4.05E+05	6.13E+05	4.79E+05
4	3.08E+04	5.36E+04	1.60E+05	2.64E+05	5.25E+04	1.30E+05	2.15E+05	1.29E+05
	Station 2							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	4.78E+06	3.64E+06	5.33E+06	4.70E+06	2.90E+06	3.04E+06	4.72E+06	4.16E+06
1B	2.24E+06	1.56E+06	2.14E+06	2.52E+06	1.41E+06	1.53E+06	2.00E+06	1.91E+06
2	2.69E+06	1.90E+06	2.65E+06	2.91E+06	1.66E+06	1.78E+06	2.41E+06	2.29E+06
3	2.19E+06	1.51E+06	2.07E+06	2.47E+06	1.38E+06	1.49E+06	1.95E+06	1.87E+06
1C	4.17E+05	3.17E+05	4.58E+05	6.77E+05	3.46E+05	4.37E+05	5.99E+05	4.64E+05
4	9.98E+03	2.47E+04	1.28E+05	3.62E+05	5.45E+04	1.43E+05	2.25E+05	1.35E+05
	Station 3							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	1.20E+07	9.21E+06	1.35E+07	1.06E+07	6.52E+06	7.17E+06	1.14E+07	1.01E+07

1B	8.68E+06	6.45E+06	9.11E+06	8.07E+06	4.40E+06	5.25E+06	7.64E+06	7.09E+06
2	8.94E+06	6.65E+06	9.45E+06	8.32E+06	4.57E+06	5.43E+06	7.95E+06	7.33E+06
3	7.88E+06	5.81E+06	8.07E+06	7.47E+06	3.96E+06	4.80E+06	6.77E+06	6.39E+06
1C	5.56E+06	4.19E+06	5.55E+06	5.90E+06	3.02E+06	3.68E+06	4.96E+06	4.69E+06
4	2.65E+06	2.08E+06	2.26E+06	3.71E+06	1.57E+06	2.11E+06	2.39E+06	2.40E+06
	Station 4							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	7.64E+06	5.78E+06	8.60E+06	6.80E+06	4.27E+06	4.52E+06	7.30E+06	6.42E+06
1B	6.59E+06	4.91E+06	7.28E+06	5.95E+06	3.50E+06	3.92E+06	6.06E+06	5.46E+06
2	6.64E+06	4.93E+06	7.37E+06	5.99E+06	3.55E+06	3.93E+06	6.14E+06	5.51E+06
3	6.33E+06	4.70E+06	6.95E+06	5.73E+06	3.33E+06	3.75E+06	5.77E+06	5.22E+06
1C	2.95E+06	2.37E+06	3.16E+06	3.41E+06	1.80E+06	2.06E+06	2.90E+06	2.66E+06
4	1.02E+06	9.28E+05	9.88E+05	1.97E+06	7.60E+05	9.92E+05	1.17E+06	1.12E+06
	Station 5							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	4.21E+07	3.25E+07	4.69E+07	3.74E+07	2.24E+07	2.55E+07	4.01E+07	3.52E+07
1B	2.86E+07	2.11E+07	2.92E+07	2.70E+07	1.43E+07	1.78E+07	2.49E+07	2.33E+07
2	3.01E+07	2.23E+07	3.10E+07	2.83E+07	1.51E+07	1.87E+07	2.64E+07	2.46E+07
3	2.64E+07	1.93E+07	2.63E+07	2.54E+07	1.31E+07	1.65E+07	2.25E+07	2.14E+07
1C	1.50E+07	1.14E+07	1.43E+07	1.71E+07	8.19E+06	1.06E+07	1.37E+07	1.29E+07
4	7.20E+06	5.38E+06	5.68E+06	1.10E+07	4.19E+06	6.17E+06	6.71E+06	6.62E+06
	Station 6							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	6.76E+07	5.27E+07	7.29E+07	5.76E+07	3.42E+07	4.07E+07	6.33E+07	5.56E+07
1B	4.87E+07	3.64E+07	4.86E+07	4.31E+07	2.28E+07	2.95E+07	4.15E+07	3.86E+07
2	5.08E+07	3.81E+07	5.10E+07	4.48E+07	2.39E+07	3.07E+07	4.36E+07	4.04E+07
3	4.47E+07	3.29E+07	4.33E+07	3.99E+07	2.04E+07	2.69E+07	3.67E+07	3.50E+07
1C	2.82E+07	2.10E+07	2.58E+07	2.79E+07	1.32E+07	1.81E+07	2.33E+07	2.25E+07
4	1.59E+07	1.12E+07	1.18E+07	1.82E+07	7.12E+06	1.07E+07	1.16E+07	1.24E+07

Table 0.8 Percent change in total inflow between each scenario and the baseline, 1B, and each other was calculated under each of the continuous precipitation simulations. Percent change was calculated by subtracting the value received from the first listed scenario from the second, dividing by the first and multiplying by 100, ie for 1B vs 2: (Total Inflow 2-Total Inflow 1B)/(Total Inflow 1B)*100.

		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 2	2014	20%	22%	4%	1%	6%	5%
	2017	7%	6%	1%	1%	3%	2%
	2050 Average	18%	19%	4%	1%	6%	5%

	2099 Average	18%	20%	3%	1%	5%	5%
		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 3	2014	-4%	-4%	-11%	-5%	-10%	-11%
	2017	0%	-1%	-4%	-2%	-3%	-4%
	2050 Average	-2%	-2%	-11%	-5%	-9%	-11%
	2099 Average	-2%	-2%	-10%	-4%	-8%	-9%
		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 4	2014	-97%	-99%	-75%	-89%	-80%	-76%
	2017	-37%	-34%	-42%	-55%	-42%	-42%
	2050 Average	-88%	-87%	-66%	-79%	-71%	-69%
	2099 Average	-92%	-93%	-66%	-80%	-72%	-68%
		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
2 vs 3	2014	-19.4%	-21.6%	-14.7%	-5.8%	-14.1%	-15%
	2017	-6.2%	-6.2%	-6.3%	-2.9%	-5.5%	-6.3%
	2050 Average	-16.9%	-17.9%	-14.0%	-5.8%	-13.6%	-14.9%
	2099 Average	-17%	-18.3%	-12.8%	-5.3%	-13%	-13.4%
		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
2 vs 4	2014	-97.5%	-99%	-76.2%	-88.8%	-81.3%	-77%
	2017	-40.7%	-37.6%	-43.5%	-55.9%	-43.2%	-43.3%
	2050 Average	-89.7%	-88.9%	-67.7%	-79.2%	-72.6%	-70.9%
	2099 Average	-92.9%	-94.1%	-67.3%	-79.7%	-73.1%	-69.3%
		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
3 vs 4	2014	-96.9%	-98.7%	-72.1%	-88.2%	-78.3%	-72.9%
	2017	-36.8%	-33.5%	-39.7%	-54.6%	-39.9%	-39.5%
	2050 Average	-87.7%	-86.5%	-62.5%	-77.9%	-68.3%	-65.9%
	2099 Average	-91.5%	-92.8%	-62.4%	-78.5%	-69.1%	-64.6%

Table B.0.9 Summary of peak inflow, m^3/s, at each analysis location for May-July 2014 and 2017 continuous model simulations.

	Station 1		**Station 2**		**Station 3**	
Scenario	**2014**	**2017**	**2014**	**2017**	**2014**	**2017**
1A	16	175	17	144	48	95
1B	14	175	12	144	45	95
2	14	175	13	144	45	95
3	13	175	12	144	45	95
1C	4	174	2	144	39	95
4	1	170	0	143	35	95
	Station 4		**Station 5**		**Station 6**	
Scenario	**2014**	**2017**	**2014**	**2017**	**2014**	**2017**
1A	36	114	141	400	126	404

1B	35	114	131	396	111	414
2	35	114	131	397	113	416
3	35	113	128	394	108	409
1C	26	113	100	390	85	379
4	22	110	78	369	62	356

Table B.0.10 Summary of peak inflow, m^3/s, under climate change projections for May-July 2050. View Table 3.9 for full names of the climate change projections.

	Station 1							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	18	16	17	15	49	9	19	20
1B	16	14	15	13	50	6	16	18
2	17	14	15	13	51	6	17	19
3	16	13	14	13	49	6	16	18
1C	6	6	5	3	50	1	9	12
4	4	6	3	1	47	0	5	9
	Station 2							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	17	14	18	16	59	7	20	22
1B	13	10	14	11	59	3	16	18
2	14	11	15	12	60	4	17	19
3	13	10	14	11	58	3	16	18
1C	3	3	3	1	58	0	5	10
4	2	3	1	0	51	0	2	8
	Station 3							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	61	53	49	47	83	29	54	54
1B	58	50	46	44	83	24	51	51
2	59	50	47	44	83	25	51	51
3	57	49	45	43	82	23	50	50
1C	52	46	42	38	82	14	47	46
4	45	41	38	31	78	8	42	40
	Station 4							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	47	41	37	34	75	22	40	42
1B	46	40	37	34	75	21	39	42
2	46	40	37	34	75	21	39	42
3	46	40	37	34	75	21	39	42
1C	41	34	30	24	75	9	34	35
4	37	32	28	20	71	5	30	32

	Station 5							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	160	145	142	141	283	73	157	157
1B	148	136	132	130	281	56	148	147
2	149	137	134	131	283	58	150	149
3	146	134	130	127	280	53	146	145
1C	124	117	108	99	280	25	133	127
4	93	92	86	75	262	9	113	104
	Station 6							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	135	129	127	133	224	60	138	135
1B	121	117	114	116	221	43	127	123
2	123	119	116	119	222	45	129	124
3	118	114	111	110	220	40	124	120
1C	98	98	91	86	217	17	113	103
4	70	76	68	65	200	8	92	83

Table B.0.11 Peak inflow, m^3/s, under the climate change scenarios for 2099. View Table 3.9 for full names of the climate change projections.

	Station 1							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	13	14	17	21	20	20	26	19
1B	10	11	15	18	17	18	24	16
2	11	11	16	19	18	18	24	17
3	10	11	15	18	17	18	24	16
1C	2	4	9	10	6	12	19	9
4	0	2	9	10	2	8	16	7
	Station 2							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	13	11	17	23	23	22	29	19
1B	9	7	12	18	18	18	24	15
2	10	8	14	20	19	19	25	16
3	8	7	12	18	17	18	23	15
1C	1	2	4	8	4	7	12	5
4	0	1	5	7	1	4	9	4
	Station 3							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	40	47	56	63	58	59	73	57
1B	37	44	53	61	55	57	72	54
2	37	44	53	61	55	57	72	54

3	36	44	51	60	54	56	72	53
1C	31	39	48	56	46	52	71	49
4	24	34	44	50	39	46	68	44
	Station 4							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	30	37	43	45	42	44	58	42
1B	29	36	43	44	41	43	58	42
2	29	36	43	44	41	43	58	42
3	29	36	43	44	41	43	57	42
1C	20	29	37	39	32	38	55	36
4	17	25	35	35	27	34	52	32
	Station 5							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	120	131	149	184	170	168	214	162
1B	107	119	139	176	160	159	206	152
2	109	120	141	178	162	161	208	154
3	104	116	138	174	158	157	205	150
1C	78	91	122	163	129	141	194	131
4	55	67	97	143	100	118	165	106
	Station 6							
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Ensemble Mean**
1A	142	138	135	165	149	146	180	151
1B	132	128	123	151	137	136	170	139
2	134	131	125	155	138	138	172	142
3	128	124	119	147	134	134	168	136
1C	106	102	99	138	111	120	157	119
4	89	87	77	121	87	99	138	100

Table B.0.12 Percent change in peak inflow between each scenario and the baseline, 1B, and each other was calculated under each of the continuous precipitation simulations: 2014 and 2017, as well as the ensemble mean (E.S.) for the 2050 and 2099 climate change projections. Percent change was calculated by subtracting the value received from the first listed scenario from the second, dividing by the first and multiplying by 100, ie for 1B vs 2: (Peak Inflow 2-Peak Inflow 1B)/(Peak Inflow 1B)*100.

		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 2	2014	3%	8%	-1%	1%	0%	1%
	2017	0%	0%	0%	0%	0%	1%
	2050 E.M.	4%	10%	1%	0%	1%	2%
	2099 E.M.	4%	9%	0%	0%	1%	2%
		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 3	2014	-2%	-4%	-2%	0%	-2%	-3%

	2017	0%	0%	0%	0%	-1%	-1%
	2050 E.M.	-1%	-1%	-2%	0%	-2%	-3%
	2099 E.M.	-1%	-1%	-2%	0%	-1%	-2%
		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
1B vs 4	2014	-91%	-97%	-22%	-37%	-40%	-44%
	2017	-3%	-1%	-1%	-3%	-7%	-14%
	2050 E.M.	-69%	-79%	-26%	-30%	-37%	-40%
	2099 E.M.	-63%	-78%	-21%	-25%	-32%	-29%
		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
2 vs 3	2014	-7.1%	-7.7%	0%	0%	-2.3%	-4.4%
	2017	0%	0%	0%	-0.9%	-0.8%	-1.7%
	2050 E.M.	-5.3%	-5.3%	-2%	0%	-2.7%	-3.2%
	2099 E.M.	-5.9%	-6.3%	-1.9%	0%	-2.6%	-4.2%
		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
2 vs 4	2014	-92.9%	-100.0%	-22.2%	-37.1%	-40.5%	-45.1%
	2017	-2.9%	-0.7%	0%	-3.5%	-7.1%	-14.4%
	2050 E.M.	-52.6%	-57.9%	-21.6%	-23.8%	-30.2%	-33.1%
	2099 E.M.	-58.8%	-75.0%	-18.5%	-23.8%	-31.2%	-29.6%
		Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
3 vs 4	2014	-92.3%	-100%	-22.2%	-37.1%	-39.1%	-42.6%
	2017	-2.9%	-0.7%	0%	-2.7%	-6.3%	-13%
	2050 E.M.	-50%	-55.6%	-20%	-23.8%	-28.3%	-30.8%
	2099 E.M.	-56.3%	-73.3%	-17.0%	-23.8%	-29.3%	-26.5%

Appendix C- RStudio Code

```
install.packages("multcompView")

library(multcompView)#Set working directorysetwd("_")

getwd(_)

#Load file into RStudio
file <-"1_PeakInflow.csv" #Change name of file you are loading
data<-read.table(file, header=TRUE, sep = ",", dec = ".") #Load your file into R Studio
data1 <- data.frame(data) #Convert your file to a dataframe
View(data1) #View your file - it should look like it does in the CSV!

#Run ANOVA & a Tukey test on your dataset
#Here, we will start with 'Scenario' as the x-value and 'Peak Inflow' as the y-value
 model1 <- lm(data1$PeakInflow ~ data1$Scenario + data1$Rainfall) #Create a linear regression model for your dataset
summary(model1) #See the results of your linear regression model. Remember p<0.05 is significant!
anova(model1) #Run an ANOVA on your linear regression model.

aov1 <- aov(data1$PeakInflow ~ data1$Scenario + data1$Rainfall) #Fit the analysis of variance model
Tukey1 <- TukeyHSD(aov1, conf.level = 0.95) #Run the Tukey method; adjust confidence level as necessary

Tukey1[["data1$Scenario"]] #View your results. The far left column shows the two scenarios that have been compared. The adjusted p-value indicates whether the difference is significant.
Tukey1[["data1$Rainfall"]] #View your results. The far left column shows the two scenarios that have been compared. The adjusted p-value indicates whether the difference is significant.
```

plot(aov1) #You can plot the results of your AOV. Use the arrows in the plot window to cycle through the graphs - there are 4 in total.
plot(Tukey1, las=1) #You can plot the results of your Tukey test. Use the arrows to cycle through the plots - there are two in total.

```
#Create a boxplot of your results >> Let's start w/ Scenario as the factor
generate_label_df <- function(Tukey1, variable){
	Tukey.levels <- Tukey1[[variable]][,4]
	Tukey.labels <- data.frame(multcompLetters(Tukey.levels)['Letters'])
	Tukey.labels$treatment=rownames(Tukey.labels)
	Tukey.labels=Tukey.labels[order(Tukey.labels$treatment) , ]
	return(Tukey.labels)
}

LABELS <- generate_label_df(Tukey1 , "data1$Scenario")

my_colors <- c(
rgb(143,199,74,maxColorValue = 255),
	rgb(242,104,34,maxColorValue = 255),
rgb(111,145,202,maxColorValue = 255)
)

a1 <- boxplot(data1$PeakInflow ~ data1$Scenario , ylim=c(min(data1$PeakInflow) , 1.1*max(data1$PeakInflow)) , col=my_colors[as.numeric(LABELS[,1])] , ylab="Peak Inflow" , main="")
over <- 0.1*max( a1$stats[nrow(a1$stats),] )
text( c(1:nlevels(data1$Scenario)) , a1$stats[nrow(a1$stats),]+over , LABELS[,1]  , col=my_colors[as.numeric(LABELS[,1])] )

#Create a boxplot of your results >> Now use Rainfall as the factor
```

```
generate_label_df <- function(Tukey1, variable){
	Tukey.levels <- Tukey1[[variable]][,4]
Tukey.labels <- data.frame(multcompLetters(Tukey.levels)['Letters'])
	Tukey.labels$treatment=rownames(Tukey.labels)
	Tukey.labels=Tukey.labels[order(Tukey.labels$treatment) , ]
return(Tukey.labels)
}

LABELS <- generate_label_df(Tukey1 , "data1$Rainfall")

my_colors <- c(
	rgb(143,199,74,maxColorValue = 255),
	rgb(242,104,34,maxColorValue = 255),
	rgb(111,145,202,maxColorValue = 255)
)

a2 <- boxplot(data1$PeakInflow ~ data1$Rainfall, ylim=c(min(data1$PeakInflow) ,
1.1*max(data1$PeakInflow)) , col=my_colors[as.numeric(LABELS[,1])] , ylab="Peak Inflow" ,
main="")
over <- 0.1*max( a2$stats[nrow(a2$stats),] )
text( c(1:nlevels(data1$Rainfall)) , a2$stats[nrow(a2$stats),]+over , LABELS[,1]  ,
col=my_colors[as.numeric(LABELS[,1])] )
```