

**AN INTEGRATED MODELING APPROACH FOR ESTIMATING THE POTENTIAL
HYDROLOGIC IMPACTS OF URBANIZATION AND CLIMATIC CHANGES IN
HINKSON CREEK WATERSHED**

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HINKSON CREEK WATERSHED

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This is dedicated to my wife Angela, who tolerated my bizarre schedule during the last few years, and our little girl Madeline, who is my inspiration.

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Abstract

Land-use changes and climatic changes are two of the most significant phenomena impacting water regimes globally. Since ongoing land-use changes in the form urbanization and projected climate changes are expected to have significant effects on hydrologic processes in many watersheds during coming decades, it is increasingly important for planners to understand how these stressors affect water regimes in order to develop successful watershed management strategies. Given these concerns, the objective of this research was to develop and utilize integrated modeling approaches in order to characterize potential changes to the water regime in Hinkson Creek Watershed (HCW), Boone County, Missouri. The research consisted of three main objectives: 1) to couple a CA-based urban growth model with a process-based hydrologic model to investigate the potential impacts of urbanization on hydrologic processes in HCW during the next two decades, 2) to develop climate scenarios using downscaled GCM output and couple these with a process-based hydrologic model to estimate the potential impacts of mid- and late-21st century climate changes on streamflow related processes in HCW, and 3) to use downscaled GCM output along with a cellular automata (CA) based urban growth model and a process-based hydrologic model to analyze the combined effects of mid-21st century climatic changes and urbanization on hydrologic processes in HCW. The research provided new insight into how two of the most significant stressors affecting water resources could impact a watershed

in the Midwestern United States. Aside from providing direct estimates of hydrologic changes for HCW that can be referenced by local planners and decision makers, the results from these studies provide a basis for comparison for other watersheds that share similar characteristics. This work also contributes to the field of integrated modeling in natural resources, as there is currently a paucity of research investigating the potential impacts of urbanization and climatic changes on water resources, particularly using high-resolution impervious cover estimates and data from the most recent suite of climate models. In addition, the approaches presented here provide a transferrable modeling framework that can be used by decision makers to analyze watersheds in other regions and help to develop urbanization and climate change mitigation strategies.

Chapter 1: Introduction

1.1 Research background and objectives

1.1.2 Urbanization, impervious surface cover and water resources

The build-up of impervious surfaces resulting from urban and residential development is often a primary disturbance altering the hydrology of watersheds (Paul & Meyer, 2001). In urbanizing watersheds, increased imperviousness can affect the dynamics of surface runoff, evapotranspiration, the infiltration of water into the soil profile, and groundwater recharge, thereby altering the timing and volume of streamflow and affecting the overall hydrologic balance (Arnold & Gibbons, 1996; Paul & Meyer, 2001). Additionally, runoff from impervious surfaces (e.g. rooftops, roads, and parking lots) expedites the flow of water into stream channels, transporting urban pollutants, increasing peak discharge volume, and intensifying flood risk (Arnold & Gibbons, 1996; Kim et al., 2007). Urbanization, which results in increased impervious surface cover (Arnold & Gibbons, 1996), has been widespread and rapid during recent history, with the estimated proportion of the human population living in urban areas increasing from 2.5%–49.5% between the years 1800 and 2010 (UN, 2011b). Therefore, understanding the impacts of urbanization on water resources is a necessary component of sustainable natural resource management, as the two are inextricably linked.

1.1.3 Observed and projected climate changes in the Midwestern United States

Climatic changes during the past century in the Midwestern United States have resulted in increased annual precipitation, surface runoff, and streamflow (Romero-Lankao et al., 2014; Jiménez-Cisneros et al., 2014; Georgakakos et al., 2014). Average annual temperatures have increased across the region, including an increase in the number of consecutive dry, hot days and

heat waves (Pryor et al., 2014; Walsh et al., 2014). Average annual precipitation in the Midwestern region has increased and has been accompanied by a greater frequency and magnitude of intense precipitation events, leading to increased runoff (Pryor et al., 2014; Walsh et al., 2014). In terms of future climate changes in the Midwest, temperatures are projected to increase across the region under all climate scenarios, with minimum temperatures exhibiting greater increases relative to maximums (Romero-Lankao et al., 2014; Walsh et al., 2014; Sun et al., 2015). Projections indicate the possibility of increasingly frequent hot, dry periods lasting from days to weeks (Walsh et al., 2014). Precipitation in the region is projected to increase during the winter, spring, and fall, and decrease during summer (Sun et al., 2015). Additionally, the frequency and magnitude of extreme precipitation events are expected to increase (Sun et al., 2015, Walsh et al., 2014). These projected increased temperatures and changing precipitation regimes are expected to contribute to decreasing soil moisture across much of the Midwest, particularly during summer (Walsh et al., 2014), which will in turn have implications for surface water regimes across the region (Georgakakos et al., 2014). While the directions of projected temperature and precipitation changes are generally consistent across the Midwest, their magnitude varies across the region and is largely dependent on latitude. In the state of Missouri, 21st century climate model projections suggest sizeable precipitation increases during the winter and spring, minor increases during the fall, and decreases during summer (Sun et al., 2015). Mean annual temperatures in Missouri are projected to increase 1.1°C–5°C by the end of this century, with the disparity between emissions scenarios becoming greater as time progresses (Sun et al., 2015; Romero-Lankao et al., 2014). Surface water regimes in watersheds throughout the state of Missouri will be affected by these projected climatic changes.

1.2 Statement of need

Land-use and climatic changes are two of the most significant phenomena impacting water regimes globally (Brown et al., 2014; Chung et al., 2011). Changes to land-cover caused by human activities such as urbanization result in increased impervious surface area, and can affect hydrologic process such as streamflow, surface runoff, evapotranspiration (ET), and groundwater movement (Arnold & Gibbons, 1996; Paul & Meyer, 2001). These hydrologic processes can also be impacted by climatic changes such as increased temperatures and altered precipitation regimes (Arnell & Gosling, 2013; Jiménez-Cisneros et al., 2014). Since ongoing urbanization and projected climate changes are expected to have significant effects on hydrologic processes in many watersheds during coming decades, it is increasingly important for policy makers to understand how these stressors affect water regimes in order to develop watershed management strategies that help address these issues (Bierwagen et al., 2010; Brown et al., 2014). Given these concerns, the research presented herein was designed to provide researchers with transferrable integrative modeling approaches for estimating the potential impacts of urbanization and climate changes on watershed-scale streamflow processes. Additionally, there is currently a scarcity of integrated modeling research investigating the potential future impacts of urbanization and climatic changes on watersheds in the Midwestern United States, and an absence of such research in the state of Missouri, therefore this work is also expected to contribute useful information for decision makers and natural resource managers in the region.

1.3 Research objectives and structure

The overall goal of this research was to develop and utilize integrated modeling approaches to characterize potential changes to water regime processes in Hinkson Creek Watershed (HCW), in Boone County, Missouri. The research consisted of three main objectives:

1) to couple a CA-based urban growth model with a process-based hydrologic model in order to investigate the potential impacts of urbanization on hydrologic processes in HCW, 2) to develop climate scenarios using downscaled global circulation model (GCM) output and couple these with a process-based hydrologic model to estimate the potential impacts of 21st century climate changes on streamflow related processes in HCW, and 3) to use downscaled GCM output along with a CA-based urban growth model and a process-based hydrologic model to analyze the combined effects of both mid-21st century climatic changes and urbanization in hydrologic processes in HCW. Additionally, overall conclusions based on this research and discussions of the findings in the context of previous work conducted in HCW are presented in the final chapter.

Given the aforementioned objectives, the dissertation research presented herein was organized according to the following structure:

- Chapter 2: Forecasting streamflow response to increased imperviousness in an urbanizing Midwestern watershed using a coupled modeling approach. This chapter describes an integrated modeling approach for estimating the potential impacts of projected urbanization (in terms of impervious surface growth) over the next two decades on water regime processes in HCW.
- Chapter 3: Coupling downscaled CMIP5 data with a physically-based hydrologic model to estimate potential climate change impacts on streamflow processes in a mixed-use watershed. This chapter describes an integrated modeling approach for estimating the potential impacts of multiple climate change scenarios on water regime processes in HCW for the mid- and late-21st century.

- Chapter 4: Estimating hydrologic responses to future urbanization and climate changes in a mixed-use Midwestern watershed using an integrated modeling approach. This chapter describes an integrated modeling approach for estimating the potential impacts of climatic changes and urbanization on water regime processes in HCW for the mid-21st century.
- Chapter 5: Conclusions and synthesis.

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Chapter 2: Forecasting streamflow response to increased imperviousness in an urbanizing Midwestern watershed using a coupled modeling approach

2.1 Abstract

Increased impervious surface (IS) cover is often the primary disturbance contributing to altered hydrology in urbanizing watersheds, affecting various components of the hydrologic balance. To improve the understanding of how future urban development will influence watershed streamflow characteristics, and to develop growth strategies that preserve water resources, it is necessary to combine detailed estimates of future IS cover with hydrologic models. A coupled modeling approach is presented to help address this problem. Pixel-based percentage IS cover for the period 2011–2031 was derived using the Imperviousness Change Analysis Tool (I-CAT) for three urban growth scenarios and coupled with the Soil & Water Assessment Tool (SWAT) to simulate the potential hydrologic impacts of future urbanization in Hinkson Creek watershed, located in the Midwestern U.S. state of Missouri. Increases to average annual streamflow (+12.81% to +19.74%), increases to average annual surface runoff (+14.32% to +16.77%), reductions to evapotranspiration (-8.68% to -13.37%), and slight increases to baseflow were observed for the three growth scenarios. The approach used here created a range of possible future conditions for the study watershed and presented a framework that allows planners to couple realistic IS cover estimates with hydrologic models. Additionally, this study emphasized that a controlled, more environmentally conscious growth pattern does not necessarily produce less pronounced hydrologic impacts for the study watershed compared to an uncontrolled growth pattern, underscoring the importance of considering neighboring watersheds when analyzing the hydrologic impacts of urban development for an area.

2.2 Introduction

The build-up of impervious surfaces resulting from urban and residential development is often a primary disturbance altering the hydrology of watersheds (Paul & Meyer, 2001). In urbanizing watersheds, increased imperviousness can affect the dynamics of surface runoff, evapotranspiration, the infiltration of water into the soil profile, and groundwater recharge, thereby altering the timing and volume of streamflow and affecting the overall hydrologic balance (Arnold & Gibbons, 1996; Paul & Meyer, 2001). Additionally, runoff from impervious surfaces (e.g. rooftops, roads, and parking lots) expedites the flow of water into stream channels, transporting urban pollutants, increasing peak discharge volume, and intensifying flood risk (Arnold & Gibbons, 1996; Kim et al., 2007). An improved understanding of how future urban development will influence streamflow characteristics in urbanizing watersheds is crucial for developing urban growth strategies that minimize the hydrological impacts of development and preserve water resources.

2.2.1 Background: integrated modeling

While the independent use of urban growth or hydrological models is relatively common, studies focused on the integration of these two types of models to characterize the effects of urbanization on watershed hydrology are far less common (Choi & Deal, 2008). Wu et al. (2015) coupled future urban growth estimates for the Heihe River basin in Northwest China with a hydrologic model and found that streamflow could increase by over 9% by the year 2050. A study in the Willamette Valley in Oregon used an agent-based landscape change model to evaluate urban development impacts on various streamflow metrics (Wu et al., 2015). Significant flow regime changes were projected for the three basins in the study. Kumar et al. (2013) used a binary cellular automata (CA) based urban growth model, along with the Natural Resources

Conservation Service (NRCS) curve number method, to estimate the future impacts of urbanization on surface runoff for a watershed in India and found that expected urban growth of about 63% could lead to an 11% increase in peak stream discharge. In another study, an integrated CA-Markov model was coupled with the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) to estimate the impacts of urban growth on runoff and flood volumes in the Qinhuai River basin in China (Du et al., 2012). The Qinhuai River basin study was effective in identifying potential changes to peak discharge and flood volume, showing that an impervious ratio increase of 28% could result in a 6% average increase for peak flows, and an 8.5% average increase in simulated flood volume. Lin et al. (2008) used the SLEUTH and CLUE-s land use change models with the Generalized Watershed Loading Function (GWLFL) model to examine the effects of urbanization on watershed hydrology in the Paochiao watershed in Taiwan. Their analysis indicated that future urbanization in the watershed could cause a 22% increase to surface runoff, and that baseflow could decrease by as much as 18%. Choi and Deal (2008) used the output from a CA urban growth model with the Hydrological Simulation Program—Fortran (HSPF) to forecast potential changes to surface runoff and streamflow in the Kishwaukee River basin, an urbanizing watershed near the western edge of Chicago. The study demonstrated that coupling the two models was useful for estimating the potential impacts of urban growth in the watershed, indicating a possible 38.5% increase in surface runoff and a 1.1% decrease in baseflow by the year 2051. Additionally, Arthur-Hartranft et al. (2003) developed a linear regression-based hydrologic module for SLEUTH using observed rainfall-runoff relationships and basin imperviousness to enable researchers to generate runoff estimates based on future land cover changes.

While all of the aforementioned studies were effective in linking urban growth forecasts with hydrologic models to assess the effects of land-use change in watersheds, they largely made use of binary urban growth classifications, rather than more detailed estimates of impervious surface area. Yet incorporating realistic impervious surface area estimates in such coupled modeling analyses is crucial for urban planners and watershed managers. This is due to the fact that a great deal of contemporary urban growth occurs in the form of low-density development, often referred to as urban sprawl, in which developed areas (e.g. pixels) contain only a low percentage of imperviousness (Zhou et al. 2012), and because the percentage of a watershed that is comprised of impervious surface cover is a key indicator for assessing urban stream health (Arnold & Gibbons, 1996; Schueler et al., 2009).

2.2.2 Objective

For this portion of the dissertation research, a semi-distributed hydrologic model, the Soil & Water Assessment Tool (SWAT; Arnold, 1998), was coupled with a CA urban growth model called the Imperviousness Change Analysis Tool (I-CAT; Sunde et al., 2014), which is capable of producing detailed impervious surface cover estimates. The goal of this coupled modeling approach was to simulate the potential impacts of future urbanization on the hydrologic characteristics of a watershed located in the southern portion of the Midwestern United States, and to evaluate the hydrologic effects of possible future urban growth scenarios to determine if an uncontrolled growth pattern resulted in more pronounced hydrological impacts than a controlled growth pattern.

2.3 Methods

2.3.1 Study area

Hinkson Creek Watershed (HCW; Figure 1) is an urbanizing watershed covering an area of approximately 231 km² in central Missouri, U.S.A., within the Lower Missouri-Moreau Basin. Hinkson Creek (HC) flows generally southwest to its confluence with Perche Creek, near the Missouri River. The northern and western portions of Hinkson Creek are situated in the Claypan Till Plains ecological subsection, on Grand Prairie-Prairie Plain land types, which are characterized by thin loess soil with underlying glacial till and claypans (Nigh & Schroeder, 2002). The central and eastern portions of the watershed lie inside the Outer Ozark Border ecological subsection, on Rock Bridge Oak Woodland/Karst Forest Hills land types. These areas consist of well-developed karst features, caves, losing streams, dissected valleys, bluffs, and loess-covered uplands (Nigh & Schroeder, 2002). According to U.S. Geological Survey (USGS) digital elevation models, elevations in HCW range from about 170–290 meters (Gesch et al., 2002). Average annual discharge recorded at HC by a stream gauge site (USGS 06910230) was 1.80 m³/s for the period 2007–2014. The periods of lowest streamflow for HC at the site are August (0.56 m³/s) and November (0.73 m³/s), whereas the highest flow months are March (2.77 m³/s), April (3.45 m³/s), and May (3.01 m³/s). In terms of seasonal discharge, average flow at the HC USGS site is the greatest during spring (3.08 m³/s), followed in descending order by summer (1.59 m³/s), winter (1.36 m³/s), and fall (1.20 m³/s). Weather observations for HCW for the period 1994–2014, recorded at the University of Missouri, Sanborn Field weather station, showed that average annual precipitation was 1013 mm, the mean annual maximum temperature was 18.8°C, and annual average minimum temperature was 7.9°C. The months of highest precipitation for HCW were April, May and June, with 115.7 mm, 129.7 mm and 111.5 mm,

respectively, and the months of lowest precipitation were November, December and January, with 55.5 mm, 44.4 mm and 48.8 mm, respectively. Average seasonal precipitation for HCW was highest during spring (324.3 mm), followed by summer (299.5 mm), fall (220.7 mm), and winter (146.4 mm). The landscape of HCW is comprised of diverse land cover, with urbanized, forested, and agricultural lands being the most prevalent types (NLCD, 2011). Approximately 60% of the city of Columbia, Missouri is located in HCW. A major portion of the catchment is comprised of urban land cover (~30%), with forested (~32%) and agricultural (~36%) areas being the other dominant types (Sunde et al., 2016). Given its current land-use, population growth, and commercial expansion characteristics, HCW typifies an urban watershed (Hubbart & Zell, 2013). Additionally, HCW has been the focus of various efforts to mitigate erosion and nonpoint source pollution, stemming largely from the fact that Hinkson Creek was classified as impaired in 1998 under the guidelines of the Clean Water Act (Hubbart et al., 2010).

Recent population growth in HCW has occurred at a rapid pace. Approximately 59% of the city of Columbia is situated in HCW and, between the years 2000 and 2014, the city population increased by 36.9%, from about 84,000 to over 115,000 (US Census Bureau, 2013). The rapid influx of residents into the area has also been accompanied by large amounts of urban development (i.e. built-up impervious surface areas). From 1980–1990, the amount of impervious surface cover in HCW increased by just 12.7% (+1.74 km²). However, the period of 1990–2000 saw an increase in impervious surface cover of about 24.1% (+3.71 km²), with over twice as much area developed as the previous decade (Zhou et al., 2012). An unprecedented amount of urban development occurred in HCW from 2000–2011, with an estimated 32.5% (+6.21 km²) increase in impervious surface area, much of which was comprised of low-density imperviousness, or sprawl (Zhou et al., 2012; Xian et al., 2011).

2.3.2 Urban growth model (I-CAT)

The Imperviousness Change Analysis Tool (Sunde et al., 2014) is a rule based CA urban growth model that uses GIS multi-criteria evaluation (GIS-MCE; Carver, 1991) to generate spatial grids representing potential future impervious surface growth. The model estimates future impervious surface growth based on historic impervious surface growth patterns, along with a suite of urban growth drivers, which for this study included: slope, elevation, distance to roads, distance to primary urban boundaries, distance to primary urban centroids, distance to water bodies, distance to secondary urban boundaries, and distance to secondary urban centroids. Model users can also incorporate constraints and other urban growth drivers into I-CAT as needed. The I-CAT is calibrated using a trial and error approach, wherein urban growth driver weights are adjusted to generate a suitability grid that is in best agreement with observed impervious surface growth for a given time period. The adequacy of the model calibration (and subsequent validation) is assessed using the relative operating characteristic (ROC) summary statistic, a common tool for assessing the accuracy of land-use change models (Pontius & Schneider, 2001). The model output is comprised of an array of pixels, where each pixel represents a percentage of impervious surface (PIS) cover ranging from 30% to 100%.

The data required to parameterize and execute the I-CAT for this analysis included: road network, elevation, slope, water bodies (derived from LULC as well as USGS streams dataset), and past impervious surface grids for three time points. The three IS grids are used to create change grids for two time intervals which are necessary for model calibration and validation. A road network grid was generated based on Missouri Department of Transportation (MoDOT) road network vectors obtained from the Missouri Spatial Data Information Service. For elevation, a USGS 30 m digital elevation model (Gesch et al., 2002) for the area was used.

Slopes in the study area were derived from the digital elevation model. A grid containing all water bodies in the study area was generated based on USGS National Hydrography Dataset (USGS, 1999) vectors combined with extracted water cover from the USDA 2011 National Land Cover Dataset (NLCD; USDA, 2011). Grid based impervious surface cover datasets for the years 1990 and 2000 from a recent Missouri urban sprawl study (Zhou et al., 2012) were used to calibrate I-CAT. The impervious surface cover data was also updated for the year 2011 based on the most recent NLCD imperviousness classification (Xian et al., 2011). The native resolution of the USGS DEM, NLCD imperviousness, and Missouri imperviousness grids used in I-CAT was 30 m (i.e. 900 m²). In order to maintain consistency throughout the modeling process, all grids derived from these datasets were also sampled using a 30 m resolution, as were all grids derived from the USGS stream network and MoDOT road network vectors.

2.3.3 Watershed hydrologic model (SWAT), description and parameterization

The Soil & Water Assessment Tool (SWAT) is a semi-distributed, continuous watershed hydrologic model that uses physically based input parameters (Arnold et al., 1998; Gassman et al., 2007). The tool was developed to enable land managers and planners to examine the impacts of various management decisions on watershed hydrology, as well as on stream sedimentation and nutrient loading (Gassman et al., 2007). In SWAT, the overall watershed is divided into sub-basins, which are further subdivided into aspatial units referred to as hydrologic response units (HRUs). Each HRU represents portions of a sub-basin that share the same soil, land cover, and slope characteristics. Most physical processes (e.g. surface runoff, infiltration, and ET) in SWAT are modeled at the HRU level (Neitsch et al., 2011). Thus, the overall hydrologic balance, including processes such as precipitation, canopy interception, surface runoff, infiltration, and the movement of water through the soil profile, is simulated at the HRU level (Gassman et al.,

2007; Arnold et al., 2012). The following spatially referenced inputs are required to run the SWAT: a DEM (digital elevation model), soils, land-cover, and daily meteorological data (e.g. precipitation, maximum/minimum temperature, and insolation). The SWAT has been applied widely and effectively for various land cover and climate change assessments (Gassman et al. 2007; Franczyk & Chang, 2009; Kim et al., 2011; Jin & Sridhar, 2012).

The data required to execute and calibrate the SWAT includes: elevation, soil, and land cover grids, as well as climate and streamflow observations. For elevation, the previously mentioned USGS digital elevation model was used. A soil grid was generated based on a map from the US Department of Agriculture (USDA) Soil Survey Geographic Database (SSURGO; USDA, 2015). Land cover data for urban areas in HCW was based on the previously mentioned impervious surface cover datasets, while data for non-urban land cover types was derived from the previously mentioned USDA NLCD. Records from the USGS streamflow gauging station (USGS 06910230) at Hinkson Creek were used for model calibration, and weather observations from Sanborn Field, located in the central portion of HCW on the University of Missouri campus, provided model forcings. The locations and elevations of these stations are listed in Table 1.

2.3.4 Model calibration and validation

The I-CAT was calibrated and validated to simulate future impervious surface growth for the city of Columbia, Missouri and the surrounding vicinity. For calibration, the urban growth parameter weights were adjusted to generate a suitability grid with a high level of agreement with observed impervious surface growth from 1990–2000. The calibration was carried out using a trial and error approach until an acceptable area under curve (AUC) value was obtained using the ROC curve method. Per the calibration, slope and distance to secondary urban boundaries

were the most influential urban growth drivers. The overall influences of the various urban growth drivers, in descending order, were: percent slope, distance to secondary urban boundaries, distance to the primary urban boundary, distance to the road network, distance to the primary urban centroid, distance to water bodies, distance to secondary urban centroids, and elevation. For the validation period, the suitability grid based on the calibrated urban growth parameter weights was accepted and compared with observed impervious surface growth from 2000–2011. The AUC values (Figure 2) for the calibration (AUC = 0.76) and validation (AUC = 0.73) periods indicated that I-CAT generated suitability grids that were acceptable for simulating future impervious surface growth. After calibration and validation, growth demand was derived using a regression approach based on past imperviousness grids. The model was then used to simulate impervious surface growth from 2011–2031, a scenario which will hereafter be referred to as the current trend (CT) growth scenario.

A sensitivity analysis was performed to identify which SWAT parameters most greatly affected the simulated streamflow for HCW. Based on an array of previous studies (Holvoet et al., 2005; White & Chaubey, 2005; Jha et al., 2006; Kannan et al., 2007; Rossi et al., 2008; Cibirin et al., 2010; Joh et al., 2011; Arnold et al., 2012; Ahmadi et al., 2014), a suite of SWAT parameters affecting streamflow output was chosen to test for sensitivity. Overall, 10 parameters were selected for the model calibration: 1) the runoff curve number, 2) the maximum leaf area index, 3) soil bulk density, 4) soil available water capacity, 5) shallow aquifer recharge delay time, 6) the groundwater revap coefficient, 7) the soil evaporation compensation coefficient, 8) soil layer depth, 9) maximum canopy interception, and 10) the plant uptake compensation factor. For this study, the SWAT was calibrated and validated using a split-sample approach, which is widely used in the calibration of watershed models (Moriiasi et al., 2012). Observed monthly

streamflow data for the period of April, 2007–May, 2014 from the USGS gauging station at Hinkson Creek were used. The gauging station is situated in a location that drains approximately 182 km² of the watershed. The observation period was split into two portions; a calibration period from April, 2007–December, 2010 (3 years, 9 months) and a validation period from January, 2011–May, 2014 (3 years, 5 months). The performance of the model was assessed using the Nash-Sutcliffe efficiency (NSE) and the ratio of the root mean square error to the standard deviation of measured data (RSR), two commonly used watershed model performance metrics (Moriassi et al., 2007). For the calibration period the NSE was 0.87 and the RSR was 0.36, and for the validation period the NSE was 0.86 and the RSR was 0.38 (Figure 3). Based on the calibration and validation results, the model performed very well for simulating streamflow (Moriassi et al., 2007) at Hinkson Creek.

2.3.5 Urban growth scenarios and model coupling

Along with the CT scenario, which reflected the growth trend of Columbia for the past 30 years, uncontrolled growth (UG) and controlled growth (CG) scenarios were developed in order to assess the impacts of varying urban growth possibilities in HCW. The UG scenario used 25% more developed grid cells (compared to the CT scenario) with reduced impervious surface density to represent more sprawling, lower density growth. The I-CAT parameter weights were also adjusted to spatially represent a less conservative urban growth pattern. For the UG scenario, this entailed assigning the highest weights to secondary boundary and road (e.g. highways) distances to draw growth away from the central urban area, reducing the weight for slope to allow development on steeper areas, and increasing the weight for distance to water to allow growth closer to waterbodies. Additionally, there were no constraints on how near to public lands or waterbodies growth could occur.

The CG scenario used 25% less developed grid cells (compared to the CT scenario), with higher density imperviousness to represent more concentrated growth. The model parameter weights were also adjusted to represent a more conservative urban growth pattern. For the CG scenario, this entailed assigning higher weights to the primary boundary and centroid parameters to draw growth nearer to the central urban area, assigning higher weight to the slope parameter to prevent growth on steeper slopes, and favoring higher elevation areas away from more forested locations near the Missouri River. Urban development was also restricted from occurring on heavily forested areas and wetlands, within 2 grid cells of any waterbody, or within 4 grid cells of any state park, national forest, or conservation area.

In order to make it possible to investigate the hydrologic effects of the respective scenario types, the total impervious surface area in square meters was held constant between all three scenarios. Similar to scenarios developed in previous urban growth modeling studies (Jantz et al., 2003; Feng et al., 2012; Mitsova et al., 2011; Thapa & Murayama, 2012; Vaz et al., 2012), growth was either further permitted or restricted near waterbodies, forested areas, and areas with higher slope gradients, and model parameters were adjusted to spatially represent more confined or sprawling urban growth patterns.

To compare the effects of the land use changes in HCW, climate was held constant and the SWAT was run using the baseline (2011) land-cover, and land-cover data for the three urban growth scenarios (CT, CG, and UG). In order to characterize the local climate, 20 years (1/1/1995–12/31/2014) of weather observations from the Sanborn Field station were used in the model. The hydrologic response variables that comprise the water yield in the SWAT (Migliaccio & Srivastava, 2007) were examined for the analysis. These variables included stream discharge, surface runoff, evapotranspiration, and baseflow. After a warm-up simulation period

(Jaber & Shukla, 2012) of 7 years, which allowed HCW to reach hydrologic equilibrium, the SWAT was used to simulate discharge for Hinkson Creek at a monthly time-step for 20 years, or a total of 240 months, for each land-cover scenario. In addition to examining the overall annual and monthly hydrologic effects of the land-cover scenarios in HCW, years representing dry, average, and wet conditions were selected using a method similar to that presented in Zhou et al. (2013) in order to examine the effects of the urban growth scenarios in HCW under varying precipitation conditions. Using this approach, 2009 and 2010 were used to represent wet years (90th percentile), 2013 and 2014 were used to represent average years (50th percentile), and 1999 and 2007 were used to represent dry years (10th percentile).

2.4 Results

2.4.1 Urban growth modeling

The estimated amount of impervious surface area within HCW was about 41.49 km² for the 2031 CT scenario, 39.86 km² for the 2031 CG scenario, and about 45.05 km² for the 2031 UG scenario (Figure 4). Compared to the baseline 2011 condition, these estimates represent increases to impervious cover in HCW of 63.88% (+16.17 km²), 57.46% (+14.55 km²), and 77.97% (+19.73 km²), respectively. Under all three of the growth scenarios, impervious surface development was more likely to occur in the sub-basins in the central and southern portions of HCW, where the majority of the Columbia urban area is located. Under the CT scenario, sub-basin 15 had the greatest amount of development (+2.9792 km²) from 2011–2031 and was also the sub-basin with the greatest proportional increase (Figure 5) in impervious surface area (+0.154); sub-basin 7 had the least amount of development (+0.081 ha) as well as the lowest proportional increase in impervious surface area (+0.001). For the CG scenario, sub-basin 17 had the greatest overall amount of development (+3.0048 km²) as well as the greatest proportional

increase in impervious surface area (+0.173); the areas with the least amount of development were sub-basins 3, 4, 6, 7, 8, and 28, where no development occurred, largely because of their greater distance to core urban areas. For the UG scenario, sub-basin 15 had the greatest amount of development (+3.8585 km²) and the largest proportional increase in impervious surface area (+0.199), and the areas with the least amount of development were sub-basins 7 and 8, where no development took place.

2.4.2 Coupled modeling results

There were observed increases for annual streamflow (shown here as a depth/year) under all three growth scenarios, estimated at 61.19 mm (+15.06%) for the CT scenario, 52.05 mm (+12.81%) for the CG scenario, and 80.18 (+19.74%) for the UG scenario (Figure 6). Increases to annual average surface runoff were also observed for the three scenarios: 44.22 mm (+14.47%) for the CT scenario, 43.76 mm (+14.32%) for the CG scenario, and 51.24 mm (+16.77%) for the UG scenario. Considerable reductions to evapotranspiration (ET) were estimated under all of the scenarios: 61.78 mm (-10.19%) for the CT scenario, 52.64 mm (-8.68%) for the CG scenario, and 81.12 mm (-13.37%) for the UG scenario. Additionally, slight increases to groundwater flow (baseflow) were observed for all of the scenarios. The results also indicated that monthly Q95 (analogous to low flow, exceeded by 95% of records) flow could increase by about 31.59% for the CT scenario, 24.15% for the CG scenario, and 37.06% for the UG scenario. Monthly Q5 (high flow periods, exceeded by 5% of records) flow estimates suggest that periods of high flow would be less affected by urban growth compared to low flow periods, with increases of 7.48% for the CT scenario, 6.63% for the CG scenario, and 9.46% for the UG scenario.

As might be expected, surface runoff increases were greatest during the wet and average years (Figure 7). The lower and upper quartiles for changes to surface runoff were: +1.64 mm/+5.67 mm (wet) and +1.51 mm/+5.83 (average) for the CT scenario, +1.56 mm/+5.94 (wet) and +1.39 mm/+5.55 mm (average) for the CG scenario and +1.89 mm/+6.57 mm (wet) and +1.66 mm/+6.91 mm (average) for the UG scenario. Dry years were the least variable in terms of surface runoff increases, where the interquartile range (IQR) for dry years ranged from +1.90 to +2.72 mm, whereas the IQR for wet and average years ranged from +4.03 mm to +4.69 mm and +4.16 mm to +5.25 mm, respectively. The UG scenario resulted in the greatest surface runoff increases overall for all three precipitation conditions, where the lower and upper quartiles were +1.89 mm/+6.57 mm for wet years, +1.66 mm/+6.91 mm for average years, and +2.38 mm/+5.10 mm for dry years. While runoff increases for the CG scenario were greater than those of the CT scenario under wet conditions, increases for the CG scenario were the lowest overall for average and dry conditions (Figure 7). Estimated reductions to ET were relatively similar across all three precipitation conditions (Figure 7). The lower and upper quartiles for changes to ET were: -8.99 mm/-1.70 mm (wet), -7.11 mm/-2.35 mm (average), and -7.30 mm/-1.82 mm (dry) for the CT scenario, -7.57 mm/-1.77 mm (wet), -6.10 mm/-1.96 mm (average), and -6.54 mm/-1.58 mm (dry) for the CG scenario, and -11.74 mm/-2.19 mm (wet), -9.31 mm/-3.10 mm (average), and -9.62 mm/-2.38 mm (dry) for the UG scenario. However, under average conditions, there was markedly lower variation in ET reductions for all three growth scenarios, where the IQR ranged from 4.14 mm to 6.22 mm, compared to 5.81 mm to 9.54 mm for wet conditions, and 4.96 mm to 7.24 mm for dry conditions. The greatest amount of variability for all three scenarios occurred under wet conditions. Decreases to ET were greatest overall under the UG scenario, yet effects of growth on ET were more variable relative to those of the other two

scenarios. The effects of the UG scenario on changes to ET were more variable under wet or dry conditions compared to average conditions. The effects of the various growth scenarios on baseflow were also similar across all three precipitation conditions, yet varied noticeably between scenarios. The lower and upper quartiles for changes to baseflow were: +0.74 mm/+2.52 mm (wet), +0.46 mm/+2.41 mm (average), and +0.14 mm/+2.54 mm (dry) for the CT scenario, +0.18 mm/+1.42 mm (wet), -0.04 mm/+1.51 mm (average), and +0.10 mm/+1.58 mm (dry) for the CG scenario, and +1.38 mm/+4.13 mm (wet), +0.88 mm/+3.94 mm (average), and +0.30 mm/+3.83 mm (dry) for the UG scenario. The most marked changes to baseflow occurred under the UG scenario, which resulted in the greatest amounts of change overall, as well as the most variability. The IQR values for the UG scenario for baseflow ranged from 3.06 mm to 3.54 mm, compared to 1.78 mm to 2.40 mm and 1.25 mm to 1.55 mm for the CT and CG scenarios, respectively.

At the monthly level, increases to surface runoff were greatest during the months of May, June, and July, for all three growth scenarios (Figure 8). The percentage differences, however, were greatest for the months of July (the highest), August, September, October, and November. Percentage increases for surface runoff were greatest for the CG and UG scenarios, depending on the month. Decreases to monthly ET were greatest during the months of April, May, June, and July, and the months with the greatest percentage differences were March, April, and May, and September. The percentage decreases for ET were greatest for the UG scenario, followed by the CT and CG scenarios. Increases to average monthly baseflow were highest for the months of April, May, and June. Monthly percentage increases to baseflow were consistent between February–September; however percentage differences were markedly lower for the months of

October, November, December, and January. The percentage increases for groundwater flow were highest for the UG scenario, followed by the CT and CG scenarios.

2.5 Discussion and conclusions

The estimated differences between hydrologic conditions for each of the urban growth scenarios (CT, CG, and UG) suggested that, relative to baseline conditions, the average annual streamflow, runoff, and baseflow could increase, and that ET could decrease. The results also indicated that the effects between scenarios are not likely to be vastly different from one another in terms of their hydrologic impacts within HCW. It should be noted, however, that the greatest estimated changes for all of the hydrologic variables examined in this study were observed under the UG scenario. In terms of the effects of the different growth scenarios, the estimated changes to surface runoff for the CG scenario (less overall developed area) were nearly identical to those of the CT scenario (more overall developed area) for all precipitation conditions, with monthly average increases to surface runoff sometimes exceeding that of the CT scenario. This suggests that, despite the fact that the CG scenario had 40% less developed area overall (compared to the CT scenario), the concentration of highly impervious surfaces into the watershed and resultant replacement of vegetation led to a nearly equivalent amount of runoff, since a higher proportion of the growth for the scenario occurred within HCW. Estimated decreases to ET under all three of the growth scenarios for the precipitation conditions examined in this study were likely the result of the conversion of undeveloped, vegetated areas to urbanized area. The reduction of canopy cover (trees, shrubs, tall grasses) resulted in less consumptive water use by vegetation (Neitsch et al., 2011), as well as more runoff or infiltration of precipitation that otherwise would have been subject to interception. In terms of the overall average increases to groundwater flow (baseflow), the aforementioned replacement of vegetation likely allowed more water to enter the

soil profile, since not all developed areas were entirely paved (i.e. low density grid cells) and canopy interception was greatly reduced. Surface runoff from developed impervious surfaces in such areas also increased the transfer of water to permeable surfaces such as residential yards, as not all impervious surfaces are directly connected to the urban drainage system. This combination of factors led to the observed increases in overall baseflow. While some studies (Lin et al., 2008; O'Driscoll et al., 2010; Kim et al., 2011; Viger et al., 2011; Zhou et al., 2013) have shown that urbanization can often lead to decreases in baseflow, many used binary urban data, which results in the blockage of all infiltration of water into the soil for developed areas (often at coarser scales than used here), or were carried out in watersheds physically dissimilar to HCW. It has been documented that the effects of urbanization on baseflow are highly variable and that the associated removal of vegetation and reductions to ET often lead to baseflow increases (LeBlanc et al., 1997; Meyer, 2004; O'Driscoll et al., 2010; Price, 2011). In addition, an analysis of hydrologic trends in HCW indicated that baseflow has increased during recent years, a period of considerable urban development (Hubbart & Zell, 2013). This analysis also indicated that a controlled, more environmentally conscious urban growth pattern does not necessarily produce less pronounced hydrologic impacts for a particular watershed than an uncontrolled growth pattern. The similarities of the hydrological effects of the three urban growth scenarios in HCW suggest that strategic spatial allocation of impervious surface growth may not be sufficient in achieving watershed management goals, and strategies incorporating vegetation requirements for developed areas, utilizing various types of pervious developed surfaces, and water routing strategies may be necessary. It should be emphasized that, since the CG scenario was designed to draw growth closer to the urban center, more growth actually occurred within HCW itself, even though 40% less area was developed under the scenario. The

result of this phenomenon was that the most environmentally conscious of the three scenarios had a similar effect compared to the other two. Additionally, while 40% more area was developed under the UG scenario, much of the growth spread out into surrounding watersheds, resulting in diminished hydrological impacts within HCW for that scenario. In terms of past and expected growth, only about half of the observed growth for the Columbia area from 1980–2011 occurred in HCW, and about 1/3 of the expected growth for the CT scenario (2011–2031) is expected to occur in HCW. To highlight this issue, USGS 12-digit basins for the Columbia area are shown relative to past and predicted (for the CT scenario) growth (Figure 9). Of the impervious surface area developed from 1980–2011, about 29% was located in Callahan Creek and Rocky Fork Creek watersheds to the north, about 9% was located in Little Bonne Femme Creek watershed to the south, about 24% was located in Lower HCW, and about 25% was located in Middle HCW. Just 0.5% of the development that took place from 1980–2011 occurred in Upper HCW. Given the current growth trend, roughly 41% is expected to occur in the adjacent watersheds previously mentioned, about 35% is expected to take place in Middle and Lower HCW, and only about 2% is expected to occur in Upper HCW from 2011–2031. Thus, the results also underscore the need for planners to take the surrounding watersheds into consideration when developing future land management strategies.

This coupled modeling study presented a framework for assessing the impacts of future urban growth on watersheds using a CA model capable of simulating pixel level imperviousness, along with a well-established watershed hydrologic model (SWAT). The approach presented here can be applied to other watersheds where there is need to estimate the future impacts of urban growth on selected components of the hydrologic regime. In addition, this study presents an improvement over previous methods through the use of pixel level estimates of the percentage

of impervious surface cover, rather than a binary urban classification scheme, or a scheme using only a few land use/land cover classes, which can obscure the effects of urban growth on various components of the hydrologic regime in a watershed. This approach also provides a framework with which planners and land managers can compare the hydrologic impacts of various urban growth strategies. In the absence of such predictive tools, planners and land managers cannot enact decisions that have taken into consideration the future effects of a growth management approaches, and are thus relegated to reactive watershed management approaches.

By developing three urban growth scenarios to input into the hydrologic model, a range of potential future conditions was created for the study watershed, rather than a single growth outcome. The estimates suggested that, generally, overall annual streamflow volume in HCW could increase by between 12.8%–19.7%, the result of the combined influences of increases to surface runoff, along with decreases to evapotranspiration and baseflow increases that could result from the extensive removal of vegetative cover. The estimated changes to the hydrologic variables brought on by the three urban growth scenarios became less straight forward when the time of year and/or amount of precipitation were taken into consideration. In addition, this analysis also emphasized the fact that a controlled urban growth pattern does not necessarily produce less pronounced hydrologic impacts for a particular watershed than an uncontrolled growth pattern. Since the CG scenario used in this study shares most of the characteristics of similar controlled (i.e. environmentally conscious) growth scenarios used in other studies, it should be noted that, so designed, such a scenario might not achieve the desired goals in a certain watershed. Thus there is need to develop more complex controlled growth scenarios for future coupled modeling analyses, possibly incorporating components such as varied vegetative cover in developed areas, non-traditional pavements that produce lower amounts of runoff, and urban

rainwater harvesting. It should also be noted that, since the characteristics of the vegetative cover can play an important role in the local hydrologic regime, future land use change impact assessments in HCW and similar watersheds could benefit greatly by incorporating information from a detailed survey of the vegetation in the watershed. Future similar studies could also benefit from more detailed information on the redistribution of water used by the urban populace within a watershed, particularly in cities such as Columbia, where municipal water supplies being utilized within the watershed come from an external source. Finally, this study highlighted the fact that large portions of the future growth of Columbia are likely to fall outside of the study watershed, which underscores the importance of considering adjacent watersheds when developing future land management and urban planning strategies.

Table 1: Locations and elevations of streamflow and weather stations in Hinkson Creek Watershed used for this study.

Station name	Latitude	Longitude	Elevation	Drainage area
Hinkson Creek (USGS 06910230)	38.927750°	-92.339944°	177.86 m	180.78 km ²
Sanborn Field Weather Station	38.942301°	-92.320395°	234.01 m	N/A

Figure 1: Hinkson Creek Watershed, land cover, sub-basins, and stream reaches, along with Sanborn Field weather station, and USGS stream monitoring site used for this study.

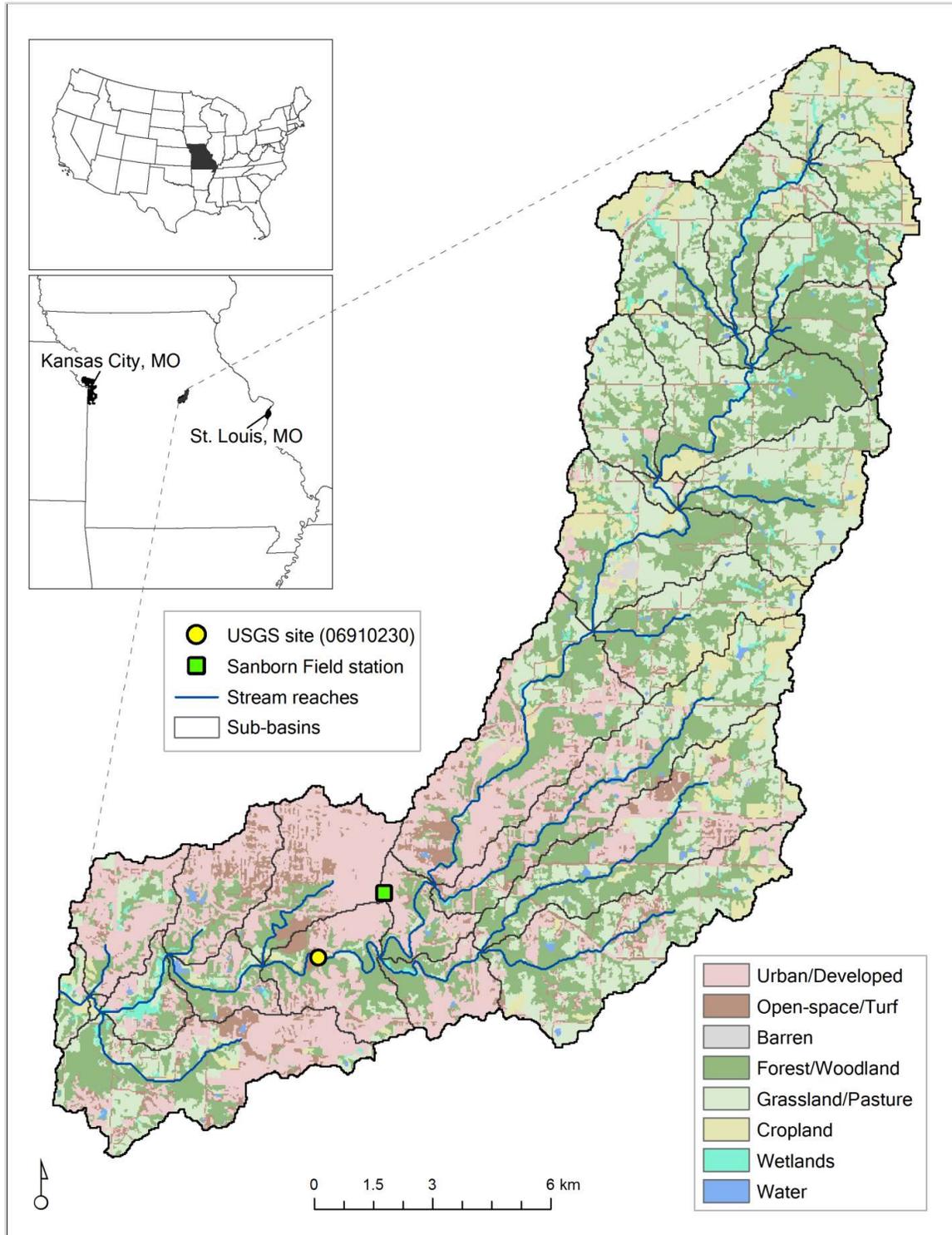


Figure 2: Receiver Operating Characteristic (ROC) curves for the calibration and validation periods used for the Imperviousness Change Analysis Tool (I-CAT).

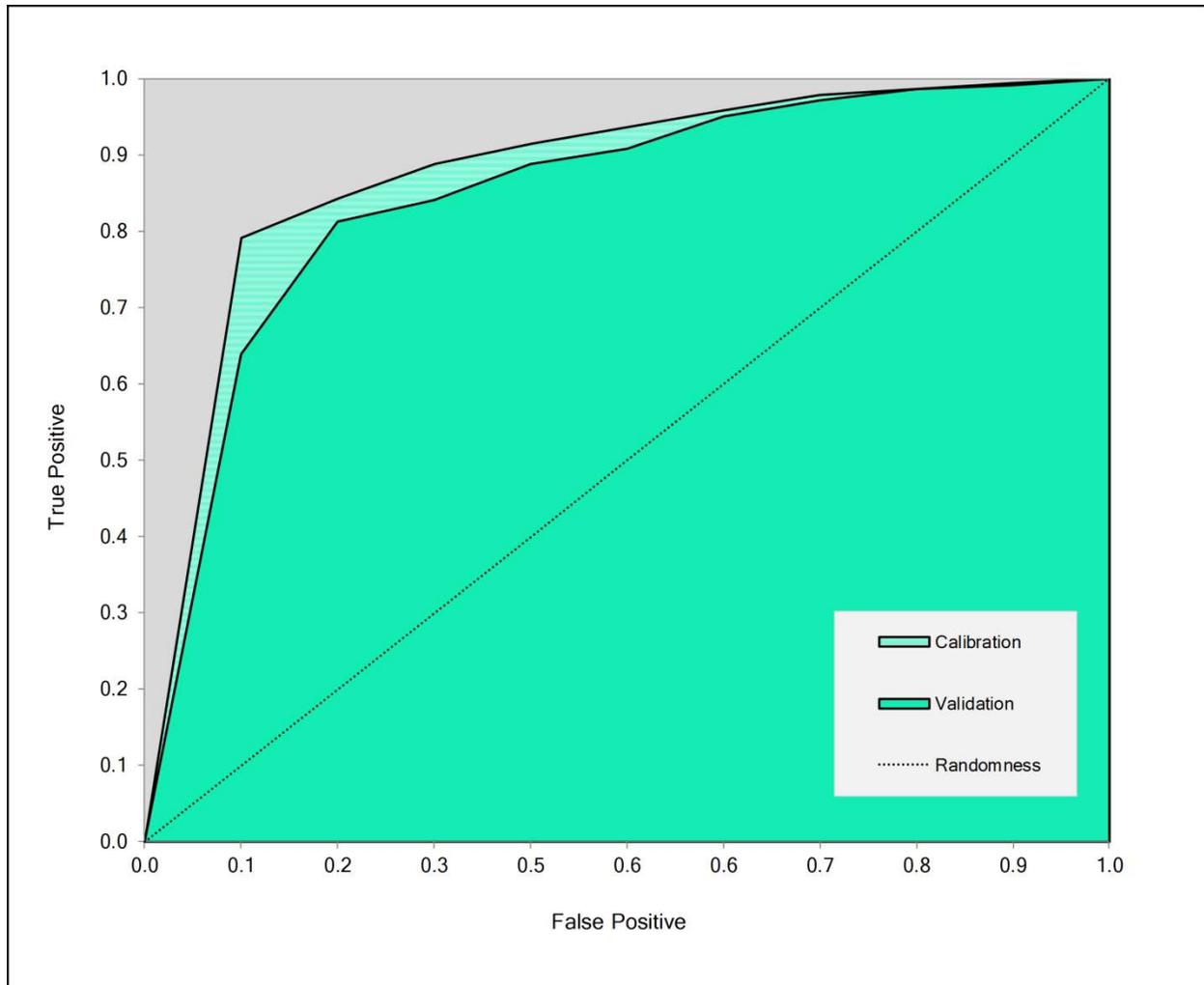


Figure 3: Precipitation and hydrographs for observed and simulated discharge at Hinkson Creek during the calibration (April, 2007–December, 2010) and validation (January, 2011–May, 2014) periods used in this study.

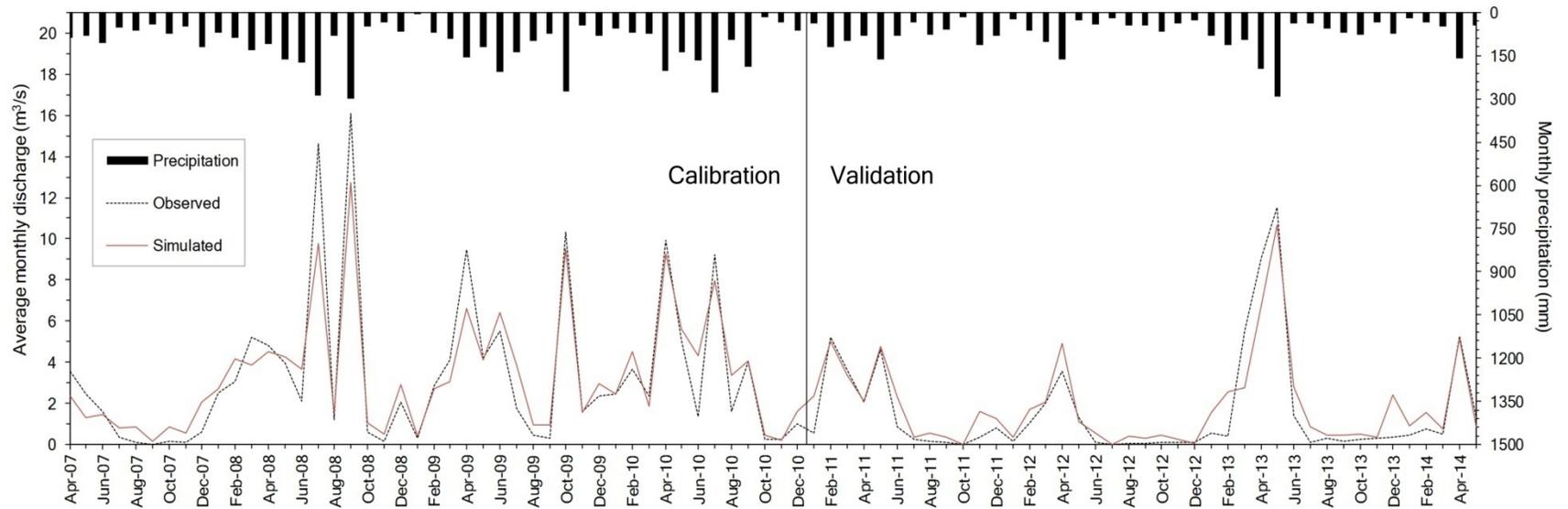


Figure 4: Estimated impervious surface cover for 2031 for Hinkson Creek Watershed for the baseline scenario and three urban growth scenarios (Current Trend, Uncontrolled Growth, and Controlled Growth).

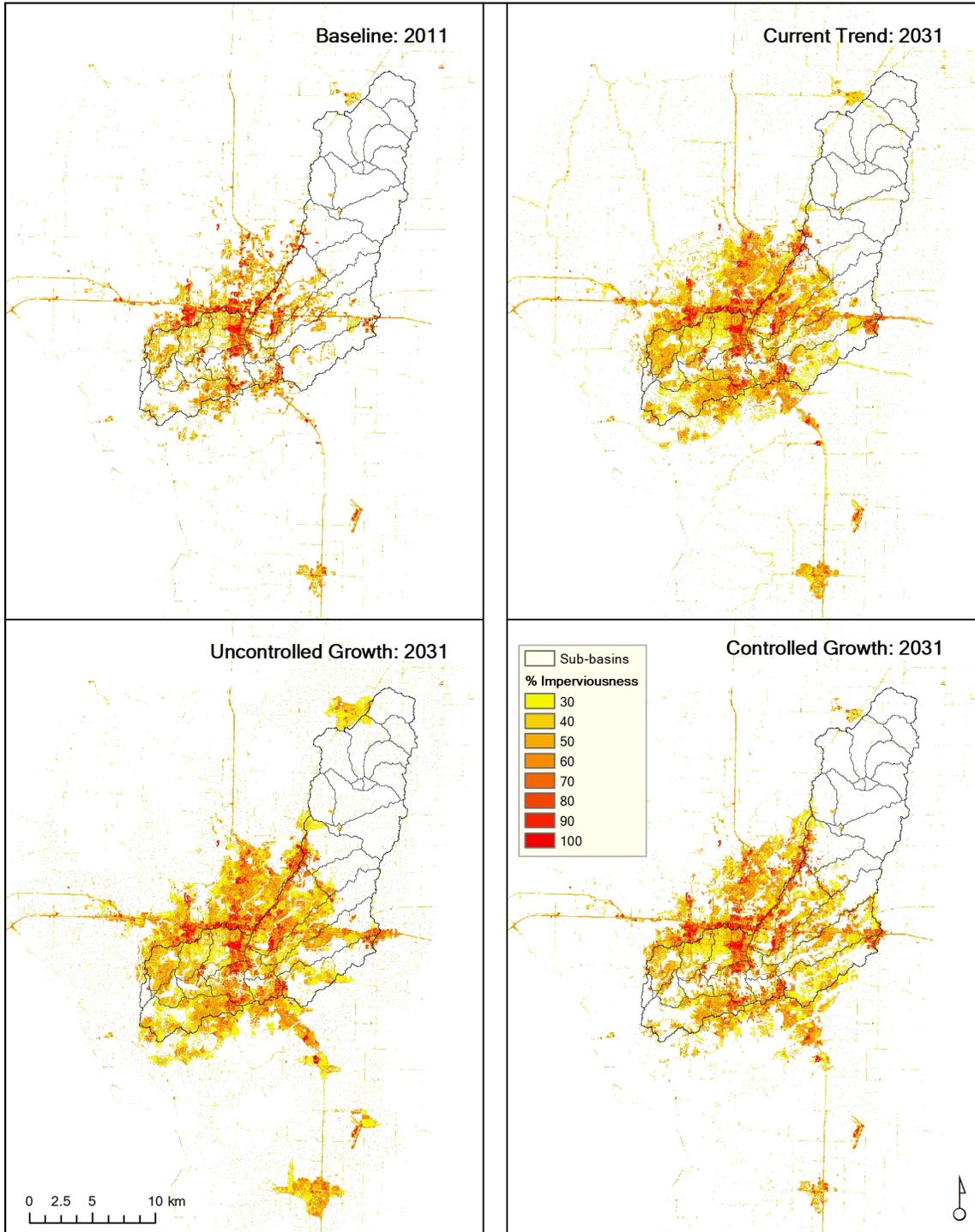


Figure 5: Estimated proportion of developed area for 2031 within sub-basins in Hinkson Creek Watershed for the three urban growth scenarios (Current Trend, Uncontrolled Growth, and Controlled Growth).

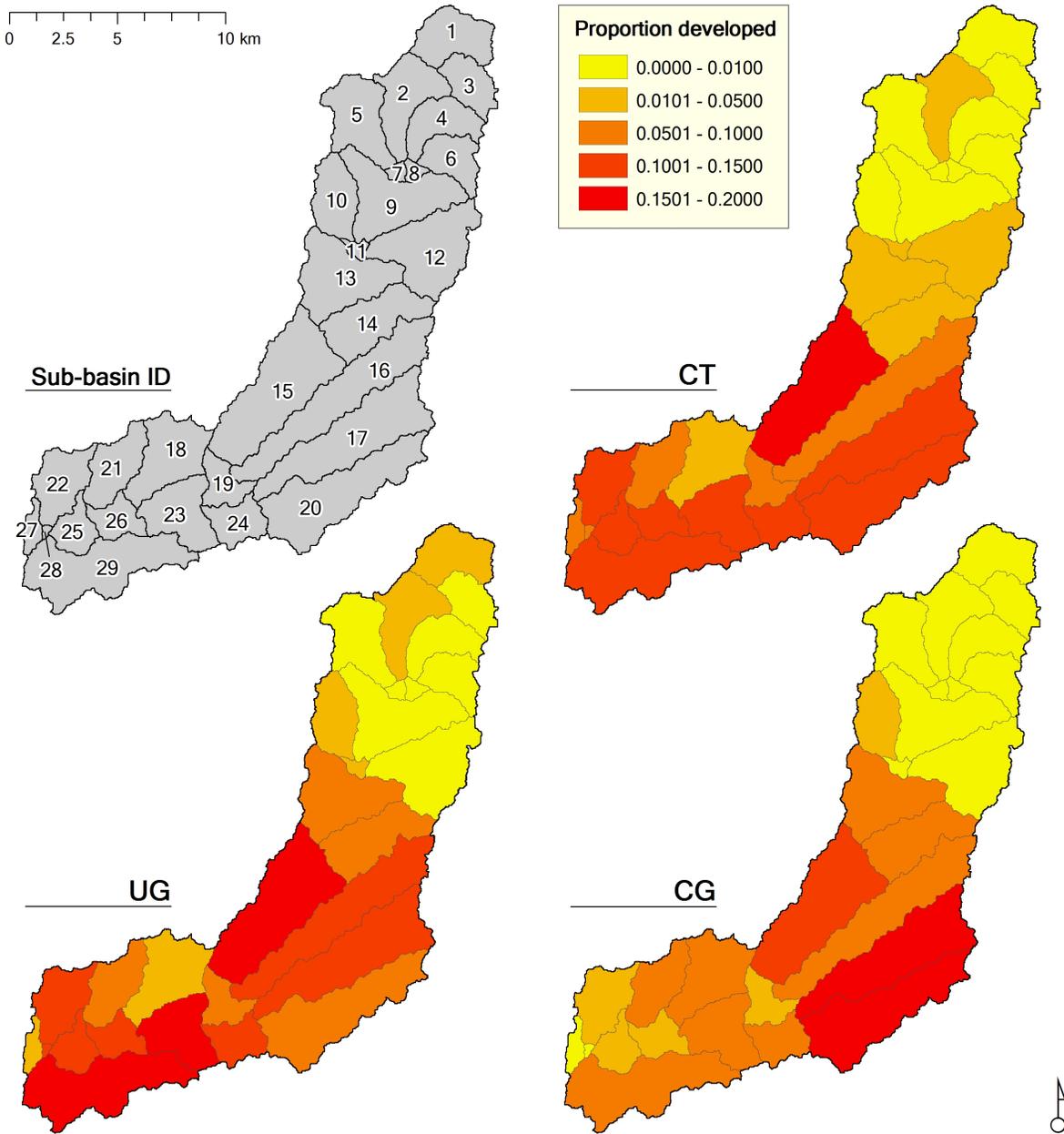


Figure 6: Estimated changes to components of the hydrologic regime for Hinkson Creek Watershed for the period 2011–2031 under the three urban growth scenarios (Current Trend, Uncontrolled Growth, and Controlled Growth).

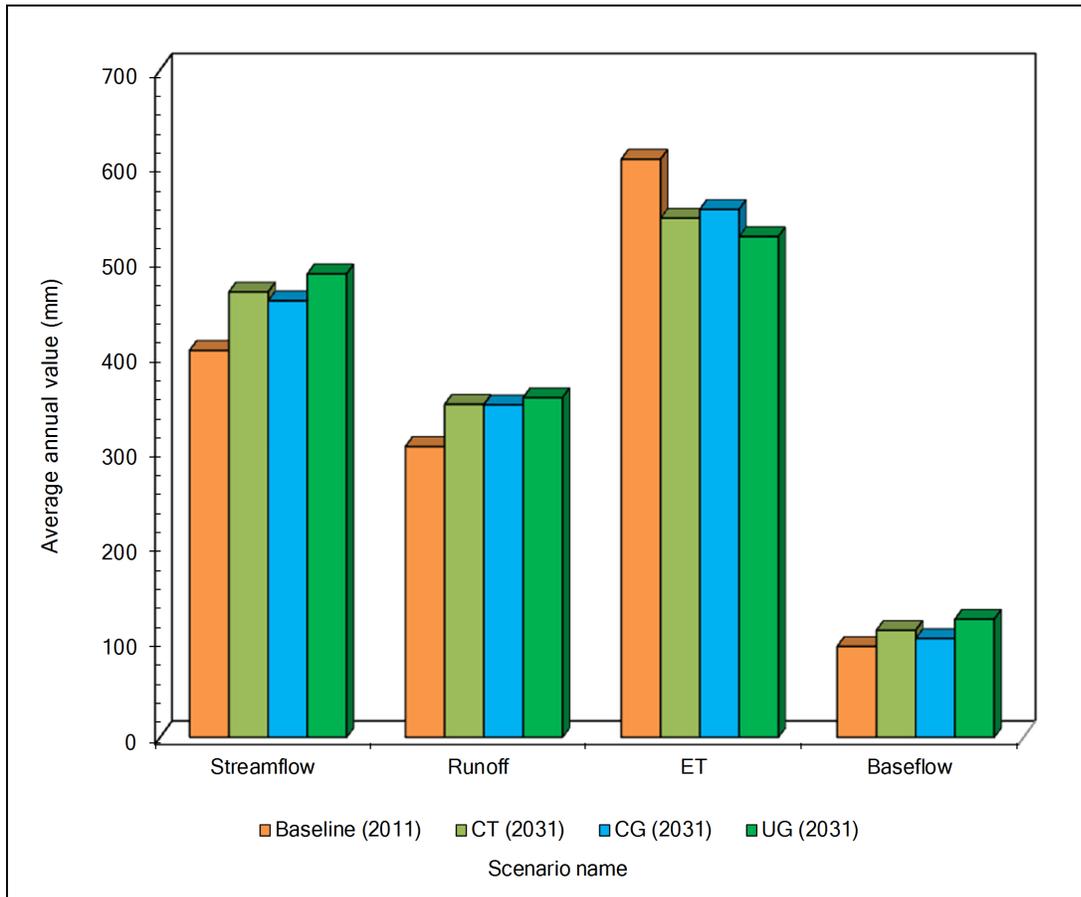


Figure 7: Effects of the different urban growth scenarios on runoff, evapotranspiration, and baseflow under different precipitation conditions (wet, average, and dry).

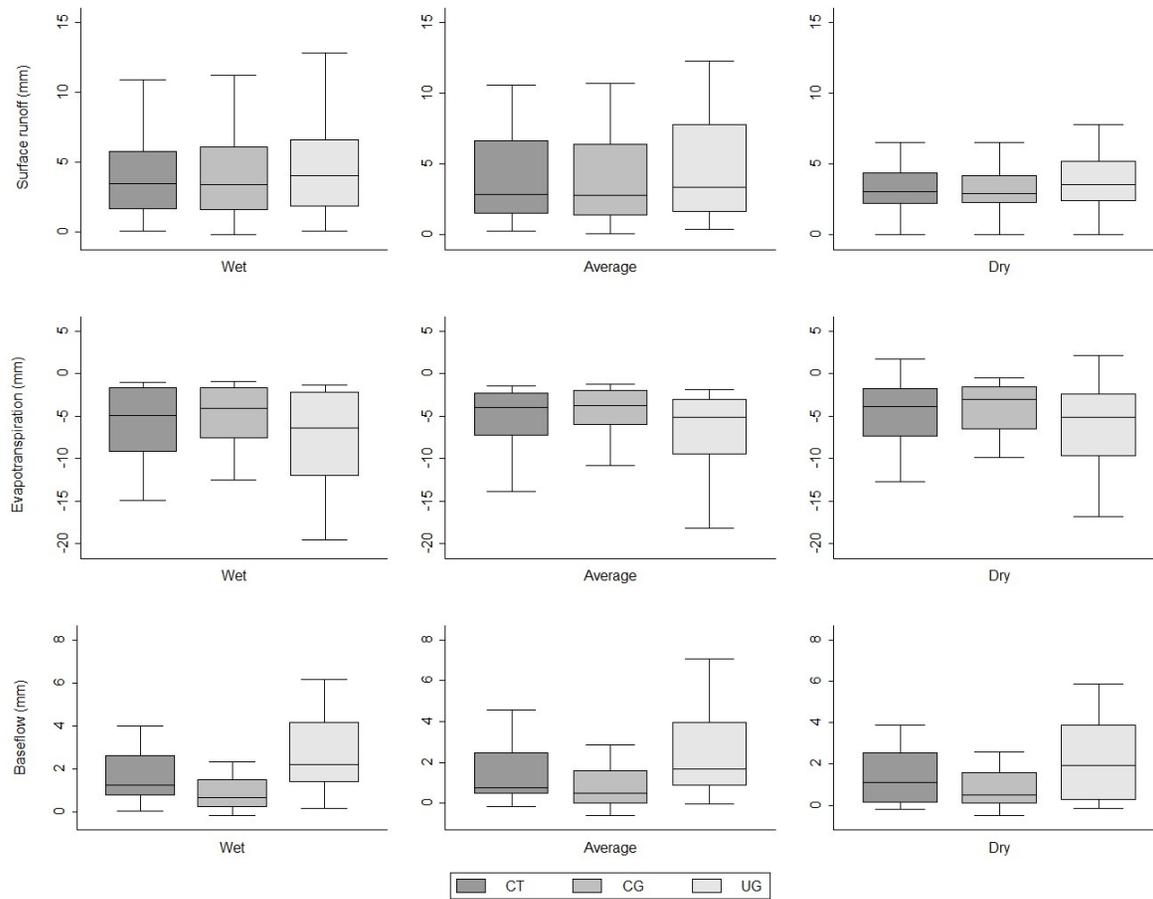


Figure 8: Average monthly differences for surface runoff, evapotranspiration, and baseflow for the baseline condition along with the three urban growth scenarios used for this study.

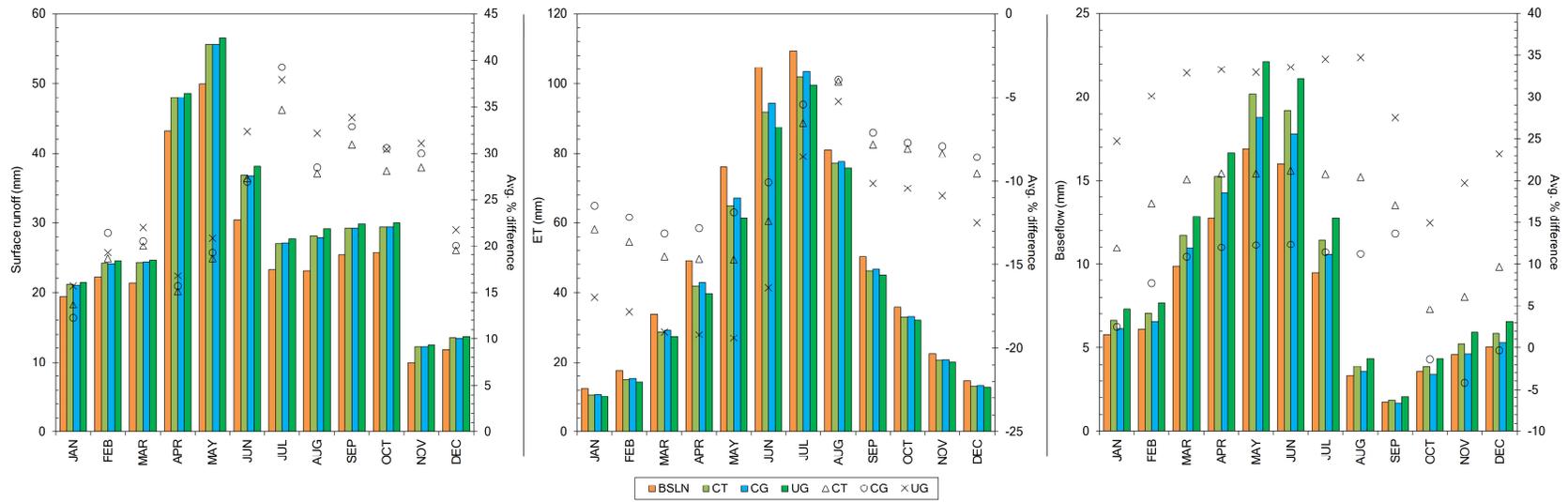
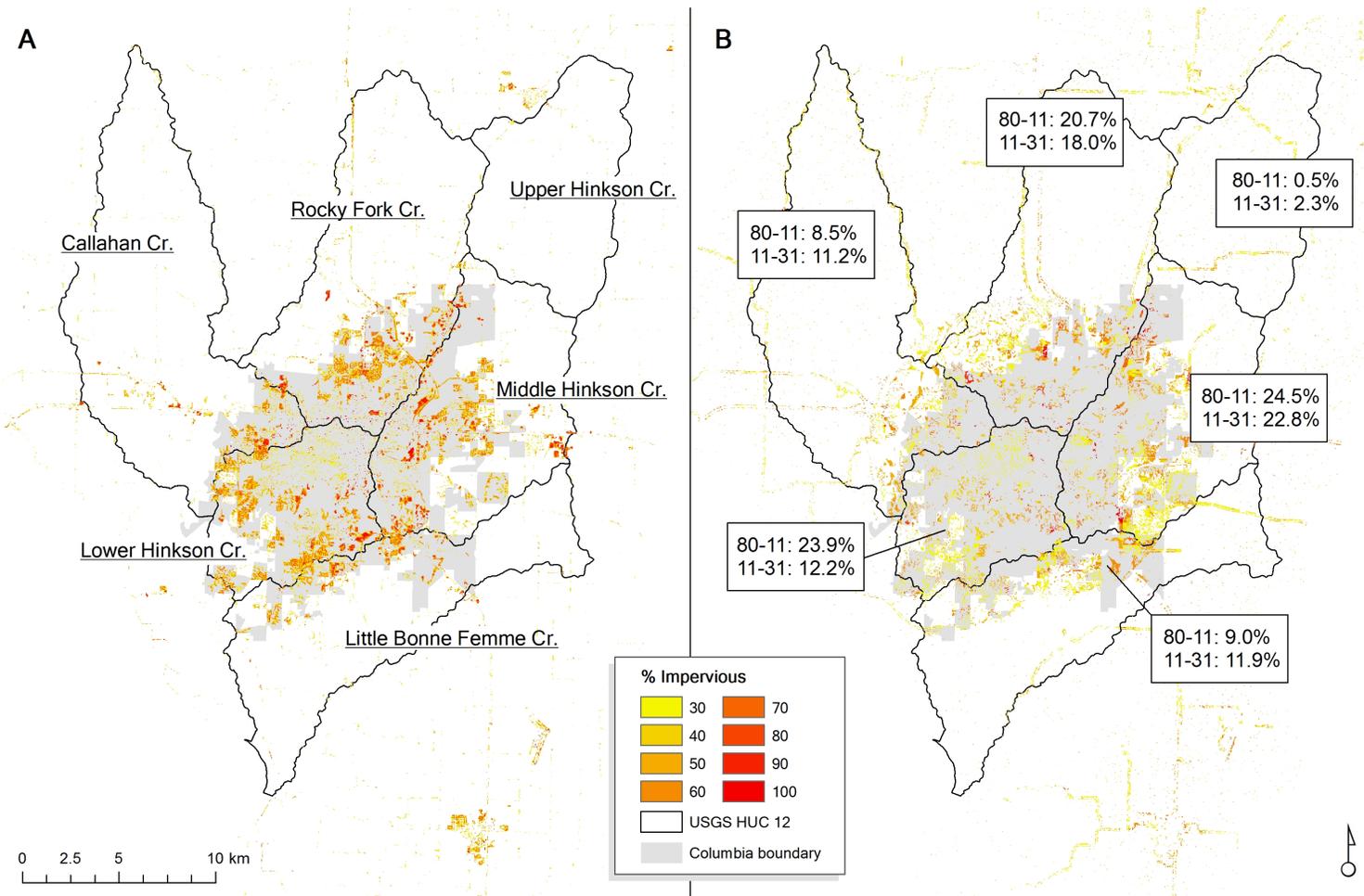


Figure 9: USGS basins for the Columbia, Missouri area, along with impervious surface growth observed from 1980–2011 (A) and projected under the Current Trend scenario for 2011–2031 (B).



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Chapter 3: Coupling downscaled CMIP5 data with a physically-based hydrologic model to estimate potential climate change impacts on streamflow processes in a mixed-use watershed

3.1 Abstract

Climatic changes have altered surface water regimes worldwide, and climate projections suggest that such alterations will continue. To better inform management decisions, climate projections must be coupled with hydrologic models to develop quantitative estimates of watershed scale water regime changes. Such a coupled modeling approach often involves downscaling climate model output, which is generally presented at coarse spatial scales. In this study, Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model projections were analyzed to determine models that represented severe and conservative climate scenarios. Output from GFDL-ESM2G (RCP2.6) and MIROC-ESM (RCP8.5) were selected to represent conservative (Δ_C) and severe (Δ_S) change scenarios, respectively. Climate data were used as forcing for the Soil & Water Assessment Tool (SWAT) to analyze the potential effects of climate change on hydrologic processes in a mixed-use watershed in central Missouri, USA. Results showed mean annual streamflow decreases ranging from -5.9% to -26.8% and evapotranspiration (ET) increases ranging from +7.2% to +19.4%. During the mid-21st century, sizeable decreases to summer streamflow were observed under both scenarios, along with large increases of fall, spring, and summer ET under the Δ_S scenario. During the late 21st century period, large decreases of summer streamflow under both scenarios, and large increases to spring (Δ_S), fall (Δ_S) and summer (Δ_C) ET were observed. This study demonstrated the sensitivity of a Midwestern watershed to future climatic changes utilizing projections from CMIP5 models, and presented an

approach that used multiple climate model outputs to characterize potential watershed scale climate impacts.

3.2 Introduction

Climate projections for the 21st century suggest that rising temperatures and changing precipitation regimes are likely to impact most rivers and streams globally (Arnell & Gosling, 2013; Jiménez-Cisneros et al., 2014). While the severity of future warming is uncertain, even the most conservative climate projections indicate that temperatures will increase in most areas across the world during this century (Collins et al., 2013) and these are expected to result in increased evapotranspiration across most land areas (Jiménez-Cisneros et al., 2014). Potential changes to other components of the hydrologic balance, such as surface runoff, are also driven in large part by projected precipitation changes, which vary across regions, yet there is a high level of agreement in terms of the magnitude and direction of the change for many regions (Arnell & Gosling, 2013). These potential changes will affect streamflow regimes differently across the globe, and are likely to have implications for freshwater ecosystems and water availability for human uses (Jiménez-Cisneros et al., 2014). It is therefore increasingly important to assess and quantify climate change impacts on water regimes by coupling data from climate models with hydrologic models to better inform decision makers in mitigating watershed scale climate change impacts.

Climatic changes during the past century in the Midwestern United States have resulted in increased annual precipitation, surface runoff, and streamflow (Romero-Lankao et al., 2014; Jiménez-Cisneros et al., 2014; Georgakakos et al., 2014). Average annual temperatures have increased across the region, including an increase in the number of consecutive dry, hot days and heat waves (Pryor et al., 2014; Walsh et al., 2014). Average annual precipitation in the

Midwestern region has increased and has been accompanied by a greater frequency and magnitude of intense precipitation events, leading to increased runoff (Pryor et al., 2014; Walsh et al., 2014). In terms of future climate changes in the Midwest, temperatures are projected to increase across the region under all climate scenarios, with minimum temperatures exhibiting greater increases relative to maximums (Romero-Lankao et al., 2014; Walsh et al., 2014; Sun et al., 2015). Projections indicate the possibility of increasingly frequent hot, dry periods lasting from days to weeks (Walsh et al., 2014). Precipitation in the region is projected to increase during the winter, spring, and fall, and decrease during summer (Sun et al., 2015). Additionally, the frequency and magnitude of extreme precipitation events are expected to increase (Sun et al., 2015, Walsh et al., 2014). These projected increased temperatures and changing precipitation regimes are expected to contribute to decreasing soil moisture across much of the Midwest, particularly during summer (Walsh et al., 2014), which will in turn have implications for surface water regimes across the region (Georgakakos et al., 2014). While the directions of projected temperature and precipitation changes are generally consistent across the Midwest, their magnitude varies across the region and is largely dependent on latitude. In the state of Missouri, 21st century climate model projections suggest sizeable precipitation increases during the winter and spring, minor increases during the fall, and decreases during summer (Sun et al., 2015). Mean annual temperatures in Missouri are projected to increase 1.1°C–5°C by the end of this century, with the disparity between emissions scenarios becoming greater as time progresses (Sun et al., 2015; Romero-Lankao et al., 2014). Surface water regimes in watersheds throughout the state will be affected by these projected climatic changes, thus it is important to couple climate projections for the area with hydrologic models to quantify the type and magnitude of change to streamflow related processes.

Climate projections have been coupled to watershed hydrologic models to estimate the potential effects of future climatic changes on surface water regimes in a number of past studies. While the general approach for such impact assessments involves coupling downscaled GCM projections with hydrologic models, various downscaling approaches have been used. Common GCM downscaling approaches for hydrologic modeling include dynamic downscaling using regional climate models (RCMs), and statistical downscaling using empirical statistical methods or stochastic weather generators (Xu, 1999). Using a stochastic weather generator approach for future climate/surface water regime impacts assessment, historic weather observations are analyzed to develop site specific parameters to be input to a selected weather generator to develop daily time series data for variables such as precipitation and temperature (Ficklin et al., 2009; Joh et al., 2011; Sheshukov et al., 2011; Xu, Zhang, Ran, & Tian, 2013). In this approach, the stochastically downscaled climate data are then used to force a hydrologic model in order to estimate potential changes to various components of the hydrologic regime for the study watershed. Other studies incorporated statistically downscaled climate projections derived using past climate observations along with bias-correction techniques and GCM projections to estimate future climate change impacts on surface water regimes (Cherkauer & Sinha, 2010; Chien, Yeh, & Knouft, 2013; Jin & Sridhar, 2012; Mohammed, Bomblies, & Wemple, 2015; Ouyang et al., 2015; Vo et al., 2016). Using this approach, climate projections that have been downscaled from GCM output(s) based on observed climate patterns for a particular study area are coupled with a hydrologic model to determine future estimates for hydrologic variables in the study watershed. Another approach uses a RCM downscaling method, wherein downscaled climate projections are derived by running a regional-scale climate model that incorporates GCM projections boundary conditions and subsequently coupled with a hydrologic model to develop estimated changes to

various hydrologic variables (Ertürk et al., 2014; Narsimlu, Gosain, & Chahar, 2013; Xu, 1999). Additionally, some studies have used an approach combining multiple downscaling methods (Dams et al., 2015).

Ficklin et al. (2009) coupled SWAT with downscaled climate model output to estimate the hydrologic responses of the San Joaquin watershed to climate change and demonstrated that the watershed was highly sensitive to such changes. In another study, the seasonal hydrologic impacts of climate changes for basins surrounding Lake Michigan were estimated using downscaled climate projections from two CMIP3 models using three future emissions scenarios (Cherkauer & Sinha 2010). The study indicated that winter and spring flows would increase under all climate change scenarios for all of the basins. Joh et al. (2011) used a stochastic weather generator along with multi-scenario data from a single GCM to estimate hydrologic changes in a forested watershed in South Korea. Results from the study showed potential monthly increases to evapotranspiration and decreases to stream discharge. Sheshukov et al. (2011) used model output from a GCM ensemble representing one emissions scenario with SWAT to investigate potential hydrologic responses for the Soldier Creek watershed in northeast Kansas. The results showed that surface runoff, baseflow, and streamflow could increase during the spring, but could decrease during summer months due to extended dry periods. In order to capture a wide range of future precipitation trends in the Boise and Spokane River basins, Jin & Sridhar (2012) selected model output from five CMIP3 GCMs to be coupled with SWAT. Modeling results from the study indicated potential decreases in the magnitude of low flows and a shift in the timing of snow-melt, which was an important factor in the study area. Narsimlu, Gosain, & Chahar (2013) used output from a regional climate model with SWAT to investigate the potential effects of climate change in the Upper Sind River Basin, India. The study showed

that monsoon season streamflow could greatly increase due to more extreme precipitation events, and that the area would become more water stressed during periods of low flow. Ensemble GCM climate projections for three emissions scenarios were coupled with SWAT for a study in the Qiantang River basin, China (Xu et al., 2013). Large decreases to annual runoff were observed, along with seasonal increases in the summer and decreases in the fall. In a different study, output from a regional climate model was used in conjunction with SWAT to estimate the potential effects of future climate changes on different water budget components in a Mediterranean watershed in Turkey (Ertürk et al., 2014). Decreases were observed for all water balance components in the watershed under future climate scenarios. In a study that coupled GCM and RCM outputs for three climate change scenarios with multiple watershed hydrologic models, potential increases to spring discharge and large increases to potential summer evapotranspiration were observed (Dams et al., 2015). Mohammed, Bombliès, & Wemple (2015) estimated the potential impacts of climate changes on hydrologic processes in the Lake Champlain basin by using CMIP5 model output for two climate scenarios to force a hydrologic model. The results of the study indicated possible increases to summer baseflow and high flows in the study area. Ouyang et al. (2015) used downscaled CMIP5 model output for three climate scenarios coupled with SWAT to estimate potential hydrologic changes for a basin in eastern China. The results of the analysis showed that, in spite of projected increases to precipitation, streamflow in the basin was likely to decrease, largely due to increased evapotranspiration. Vo et al. (2016) used downscaled model output from three GCMs for one emissions scenario along with the MIKE SHE hydrologic model to estimate the impacts of climate changes on streamflow in a catchment in Vietnam. The analysis suggested that rainy season flows could increase drastically, and that dry season flows would further decrease.

The potential hydrologic process responses to climatic changes estimated in these studies varied directionally given the sometimes vastly different geographic locations, physical characteristics, and precipitation regimes of the study watersheds. Across the studies, however, it was demonstrated that components of the surface water regime such as overall water yield, runoff, baseflow, and evapotranspiration are likely to be affected under future climate scenarios (Cherkauer & Sinha, 2010; Dams et al., 2015; Ertürk et al., 2014; Ficklin et al., 2009; Joh et al., 2011; Mohammed, Bomblies, & Wemple, 2015; Ouyang et al., 2015; Sheshukov et al., 2011; Xu, Zhang, Ran, & Tian, 2013). Further, these projected hydrologic changes were often most pronounced for specific seasons, owing in large part to the climate regime of the respective study watershed (Cherkauer & Sinha, Dams et al., 2015; 2010; Joh et al., 2011; Mohammed, Bomblies, & Wemple, 2015; Ouyang et al., 2015; Sheshukov et al., 2011; Vo et al., 2016; Xu, Zhang, Ran, & Tian, 2013). The preceding studies advanced understanding of potential climate change related hydrologic impacts in a wide range of study areas, and of the relative uncertainty associated with different components of the modeling process, such as the choice of hydrologic model(s), hydrologic parameter uncertainty, and the choice of GCM(s) and emissions scenario(s). In addition, many previous studies did not incorporate an analysis of the relative severity of projected climate change impacts for each GCM prior to the hydrologic impact assessment, and few have utilized outputs from CMIP5 models (Jiménez-Cisneros et al., 2014; Mohammed, Bomblies, & Wemple, 2015; Ouyang et al., 2016), which represent climate processes in greater detail than their predecessors. Over many regions, projections from CMIP5 models have exhibited increased robustness relative to CMIP3 models (Knutti & Sedláček, 2013). There is need to expand the geographic scope of current climate change/hydrologic modeling research for a variety of different watershed types (e.g. urban, rural, and mixed-use), yet there is a lack of

such studies focusing on watersheds in the Midwestern United States, particularly in the southern and central portions of the region. Consequently, continued coupled climate change/hydrologic modeling analyses utilizing climate projections from the latest generation of climate models are needed in order to contribute additional knowledge of potential hydrologic changes in watersheds with a multitude of characteristics.

Given the background and concerns articulated above, the primary objective of this study was to couple downscaled output from two GCMs with a semi-distributed hydrologic model to estimate the potential impacts of climate change on streamflow processes in a representative mixed-use watershed in Missouri, USA. Sub-objectives of this analysis were: a) to determine which GCM projections from the CMIP5 models represented conservative and severe climate change scenarios for the watershed, b) to pair the selected downscaled GCM projections for both the conservative and severe scenarios with a semi-distributed hydrologic model, and c) to bracket the range of future changes of the watershed for selected hydrologic variables.

3.3 Methods

3.3.1 Study area

Hinkson Creek Watershed (HCW; Figure 1) is an urbanizing watershed in central Missouri, U.S.A., covering an approximately 231 km² area. The watershed is located within the Lower Missouri-Moreau Basin and is situated at the intersection of the Claypan Till Plains ecological subsection in the north and the Outer Ozark Border ecological subsection in the south (Nigh & Schroeder, 2002). Additional detailed descriptions of the physical geography, hydrologic characteristics, and climate of HCW are presented in section 2.3.1.

3.3.2 Climate model analysis and scenario development

Future climate projections are primarily derived from modeling results of the Coupled Model Intercomparison Projects (CMIP3 and CMIP5). The CMIP5 modeling results have been incorporated into major climate reports such as the IPCC Fifth Assessment Report (IPCC AR5; Stocker et al., 2013) and the Third National Climate Assessment (NCA3; Melillo, Richmond, & Yohe, 2014), and have been rigorously compared to those of the previous CMIP3 (Flato et al., 2013; Walsh et al., 2014; Sun et al., 2015; Knutti & Sedláček, 2013). Since the General Circulation Models (GCMs) used in the projects typically have horizontal grid-cell resolutions ranging from about 1 to 2 degrees (Flato et al., 2013), results are often downscaled for use with hydrologic models in order to assess the impacts of projected climate changes (Xu, 1999; Jiménez-Cisneros et al., 2014). Incorporating such downscaled climate projections with hydrologic models enables managers to develop scenarios to estimate the potential impacts of climate changes in watersheds across regions such as the Midwestern United States, allowing more localized effects of climate changes to be assessed.

A number of studies indicated that the highest source of uncertainty in climate impact studies arises from differences between projections among GCMs, followed by differences among emissions scenarios (Minville et al., 2008; Chen et al., 2011; Ouyang et al., 2015). In order to bracket a wide range of potential future climate conditions and account for uncertainty in the current work, projections from 35 CMIP5 model and scenario combinations were assessed to determine which represented the most conservative and most severe climate change scenarios, respectively. Using this approach, output from the model showing the least amount of precipitation and temperature change under Representative Concentration Pathway 2.6 (RCP2.6) was used for the conservative change scenario, and output from the model showing the greatest

amount of precipitation and temperature change under Representative Concentration Pathway 8.5 (RCP8.5) was used for the severe change scenario. The Representative Concentration Pathways (RCPs) are emissions scenarios developed as part of the recent Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5). The RCP2.6 scenario represents a stringent greenhouse gas mitigation scenario, whereas the RCP8.5 scenario represents a future where greenhouse gas emissions are largely uncontrolled (Riahi et al., 2011; Vuuren et al., 2011; Cubasch et al., 2013).

Gridded bias-corrected 1/8th degree daily maximum temperature, minimum temperature, and precipitation projections (Brekke et al., 2013) from the CMIP5 multi-model ensemble under scenarios RCP2.6 and RCP8.5 were analyzed. The analysis of the climate model outputs for HCW indicated that MIROC-ESM (Table 2) was consistent in terms of projecting large changes to temperature and precipitation for HCW; thus output from the model was selected to represent the severe change scenario, hereafter referred to as Δ_S . Conversely, GFDL-ESM2G (Table 2) was consistent in projecting only small amounts of change to temperature and precipitation for HCW; output from this model was used to represent the conservative change scenario, hereafter referred to as Δ_C .

Based on the current climate period (1994–2015) in HCW, average observed annual precipitation was 1035 mm, compared to 959 mm–1114 mm for the future climate scenarios (Table 3). Average annual maximum and minimum temperatures in HCW under the baseline climate period were 18.8°C and 7.9°C, with projected increases to max temperature ranging from 0.8°C–7.2°C, and increases ranging from 0.2°C –6.0°C for minimum temperature (Table 3). Seasonal data for the Δ_S scenario suggested that summer precipitation could decrease significantly during summer, and increase during the spring and fall (Table 3; Figure 10). With

the exception of very slight decreases during fall under the Δ_C scenario, temperature increases were observed for every season under both scenarios (Table 3; Figure 10).

3.3.3 Hydrologic model description and parameterization

The Soil & Water Assessment Tool (SWAT), a semi-distributed, physically-based hydrologic model, was chosen for this study due to its demonstrated applicability for long term climate change impact assessments in a wide variety of watershed types (Arnold et al., 1998; Arnold et al., 2012; Gassman, Reyes, Green, & Arnold, 2007). The model was designed to allow researchers to determine the effects of various management decisions, climatic changes, and land-cover changes on water quantity and quality at the watershed scale (Gassman et al., 2007; Arnold et al., 2012). A more detailed description of the theoretical background and model inputs for SWAT is presented in section 2.3.3.

A sensitivity analysis was conducted prior to model calibration to identify the SWAT parameters that most influenced modeled streamflow. After identifying sensitive model parameters, SWAT was calibrated using numerous simulations in which parameter weights were adjusted. Streamflow observations used for model calibration and validation were divided using a split-sample approach (Moriassi et al., 2012) and two widely used hydrologic model performance metrics, the Nash-Sutcliffe efficiency (NSE) and the root-mean-square-error over the standard deviation of the observed data (RSR), were used to assess the performance of SWAT (Moriassi, et al., 2007). Based on the derived NSE and RSR values for this study, SWAT modeled streamflow for HC very effectively. Calibration and validation results for SWAT are presented in Figure 3 and described in further detail in section 2.3.4 along with further details on model sensitivity analysis and calibration.

3.3.4 Climate scenario and hydrologic model coupling

In order to investigate the effects of projected climate changes on components of the water balance in HCW, land cover was held constant and SWAT was run using three unique climate datasets with identical model warm-up data: 1) current climate, 2) the Δ_C scenario, and 3) the Δ_S scenario. For the current climate scenario, data from the Sanborn Field weather station from January 1st, 1996– December 31st, 2015 were used. Climatic variables included: precipitation, maximum temperature, minimum temperature, and incident shortwave solar radiation. Climate data were replicated to enable comparison with the 85-year simulation periods used in the climate projection scenarios. For the Δ_C and Δ_S scenarios, the downscaled climate projections were sampled for HCW for precipitation, maximum temperature, and minimum temperature. The simulation period for the climate projection scenarios was from January 1st, 2016–December 31st, 2100. Since downscaled incident shortwave solar radiation data was unavailable, it was sampled for HCW for the selected GCMs at the native resolutions, which were 2.7906° latitude and 2.8125° longitude for MIROC-ESM (JAMSTEC, AORI, & NIES, 2015) and 2.0225° latitude and x 2° longitude for GFDL-ESM2G (Dunne et al., 2015).

3.4 Results and discussion

3.4.1 Annual and seasonal water regime climate impacts

For comparisons with hydrologic estimates based on the current climate (CC) for HCW, estimates derived from SWAT based on the climate scenarios were grouped by mid-21st century (2040–2069) and late 21st century (2070–2100). For the entire modeling period the estimated mean annual changes to hydrologic components in HCW (Table 4; Figure 11) indicated that overall streamflow was likely to decrease under both the Δ_C (-25.4%) and Δ_S (-14.9%) scenarios. Similarly, decreases to surface runoff were observed for both scenarios ($\Delta_C = -35.0\%$ and $\Delta_S = -$

23.3%). Increases to evapotranspiration (ET) were observed for both the Δ_C (+7.2%) and Δ_S (+19.4%) scenarios during the overall modeling period. Slight increases to baseflow were also observed during the period, with a +1.8% increase under the Δ_C scenario and a +2.7% increased under the Δ_S scenario. For the mid-21st century period the estimated mean annual changes to hydrologic components in HCW (Table 4) suggested sizeable decreases to overall streamflow for both scenarios ($\Delta_C = -26.8\%$ and $\Delta_S = -5.9\%$), as well as decreases to surface runoff for both scenarios ($\Delta_C = -36.3\%$ and $\Delta_S = -12.4\%$). Substantial increases to ET were observed under both scenarios ($\Delta_C = +6.0\%$ and $\Delta_S = +17.7\%$) during the time period. In addition, modest increases to baseflow were observed for the time period under both scenarios ($\Delta_C = +0.2\%$ and $\Delta_S = +12.3\%$). During the late-21st century period, mean annual changes to components of the hydrologic balance in HCW (Table 4) indicated large decreases to overall streamflow for both the Δ_C (-19.0%) and Δ_S (-26.2%) scenarios. Large decreases to surface runoff were also observed under both scenarios during this time period ($\Delta_C = -30.4\%$ and $\Delta_S = -30.2\%$). Increases to ET occurred under both scenarios ($\Delta_C = +10.0\%$ and $\Delta_S = +23.9\%$). baseflow increased to 124 mm (+13.6%) under the Δ_C scenario yet decreased to 92 mm (-15.7%) under the Δ_S scenario.

The hydrologic responses to projected climatic changes in HCW varied seasonally (Table 5; Figure 12). The largest changes to mean seasonal streamflow for the mid-21st century period were observed during the winter and summer under both the Δ_C and Δ_S scenarios. While streamflow decreased during the spring and fall during the mid-century period under the Δ_C scenario, increases were observed for the Δ_S scenario. With the exception of a marginal increase during the fall for the Δ_S scenario, streamflow increased for all seasons under both scenarios during the late 21st century period. Similar to the preceding period, the largest streamflow increases were observed during the winter and summer. Observed changes to mean seasonal

runoff followed a pattern similar to those reported for overall streamflow; however decreases to late century spring runoff were greater than those observed for streamflow (Table 5). Increases to ET for all seasons were observed during both time periods under both scenarios. The largest seasonal increases to ET occurred during winter, spring, and fall under the Δ_S scenario. Simulated changes to seasonal baseflow were modest, with the most notable changes occurring during the mid-century period for spring (increase) under the Δ_S scenario and during the late century period for summer (decrease) under the Δ_S scenario.

To express the variability of the estimated hydrologic changes for all scenarios and time periods (Figure 13), the interquartile range (IQR) was determined. The IQR for winter streamflow ranged from 60.8 mm (Δ_S scenario/late century) to 96.5 mm (Δ_C scenario/late century). During spring, summer, and fall, IQRs for streamflow ranged from: 89.7 mm (Δ_S scenario/late century) to 116.6 mm (Δ_S scenario/mid-century), 69.8 mm (Δ_S scenario/late century) to 106.8 mm (Δ_S scenario/mid-century), and 55.3 mm (Δ_C scenario/late century) to 90.1 mm (Δ_S scenario/mid-century), respectively. For runoff, the IQRs for winter, spring, summer, and fall ranged from: 58.8 mm (Δ_S scenario/late century) to 90.8 mm (Δ_S scenario/mid-century), 72.6 mm (Δ_S scenario/late century) to 102.1 mm (Δ_S scenario/mid-century), 65.6 mm (Δ_C scenario/late century) to 83.3 mm (Δ_S scenario/mid-century), and 47.9 mm (Δ_S scenario/late century) to 88.6 mm (Δ_S scenario/mid-century), respectively. For estimated changes to ET, the IQRs for winter, spring, summer, and fall ranged from: 7.9 mm (Δ_S scenario/mid-century) to 12.2 mm (Δ_C scenario/late century), 23.3 mm (Δ_C scenario/late century) to 57.3 mm (Δ_S scenario/late century), 46.3 mm (Δ_C scenario/late century) to 78.0 mm (Δ_C scenario/mid-century), and 34.2 mm (Δ_C scenario/late century) to 58.3 mm (Δ_C scenario/mid-century), respectively. And for baseflow, the IQRs for winter, spring, summer, and fall ranged from: 14.2 mm (Δ_S scenario/mid-

century) to 18.7 mm (Δ_C scenario/mid-century), 21.3 mm (Δ_S scenario/mid-century) to 31.3 mm (Δ_S scenario/late century), 15.1 mm (Δ_S scenario/late century) to 26.2 mm (Δ_C scenario/late century), and 9.1 mm (Δ_C scenario/mid-century) to 19.5 mm (Δ_C scenario/late century), respectively.

3.4.2 Summary of results

The results showed agreement between the Δ_C and Δ_S scenarios in terms of estimated decreases to mean annual streamflow in HCW (Figure 11), with reductions ranging from -5.9% to -26.8%. Since greenhouse gas emissions are projected to stabilize after mid-century under RCP2.6 (van Vuuren, et al., 2011), which was used for the Δ_C scenario, the estimated changes to annual streamflow for that scenario were greater during the mid-21st century than the late part of the century. Conversely, estimated changes to streamflow under the Δ_S scenario were greater during the latter part of the century. Under both scenarios it is likely that there will be moderate reductions to streamflow in HCW by mid-century and into the late part of the century, even if aggressive emissions reductions are enacted in the near future. These changes to streamflow reflected the estimated annual increases to ET and decreases to surface runoff under both scenarios. Under the Δ_C scenario modest temperature increases lead to increased ET, but this loss of water was not offset by large projected increases to precipitation as in the Δ_S scenario. By the latter part of the century, however, larger increases to precipitation under the Δ_S scenario were no longer enough to compensate for evaporative demand and plant uptake resulting from increasing temperatures, causing large decreases to streamflow and surface runoff, as well as modest baseflow decreases. While mean annual streamflow and surface runoff increased under both scenarios for both time periods, seasonal analysis indicated that both could increase for spring and fall under the Δ_S scenario during the mid-century time period (+14 mm and +26 mm,

respectively). The sign of the change for seasonal streamflow and runoff was the same as shown for the annual with the exception of fall, during the late century time period for both scenarios, where only minimal changes to these processes were estimated. These seasonal increases could be attributed to the relatively large projected mid-century increases to spring and fall precipitation under the Δ_S scenario. Additionally, increased consumption of soil water through evaporative and plant related processes coupled with increases to precipitation likely contributed to some observed increases to baseflow (Price, 2011), as these processes created additional space for water to enter the soil profile during subsequent precipitation events rather than being expedited from the system as runoff. Moreover, seasonal baseflow responses are also affected by the decoupling of the ET/baseflow response during cold seasons, during which overall ET is lower than precipitation (Ficklin et al., 2016). Seasonal results were also consistent with annual estimates in indicating that ET would increase for both scenarios and time periods. Additionally, the modeling results suggested that increasing temperatures under the Δ_S scenario would begin to drive large increases in spring and fall ET, with the most notable increase estimated for springs during the late part of the century. Seasonal increases in temperature and ET were also likely responsible for notable decreases to summer baseflow during late century under the Δ_S scenario, as water that historically replenished the system could be quickly consumed via evaporation and plant uptake heading into the warmest season. By the late 21st century, summer ET under the Δ_S scenario exhibited only slight increases, while the aforementioned increases to fall and spring temperatures begin to more closely resemble those of summer.

3.5 Conclusions

Most previous studies on this subject utilized CMIP3 climate model projections, which have now been replaced by the CMIP5 to be used in current and future impact assessments.

Overall, the CMIP5 models use a smaller native resolution than their predecessors, and also represent climatic processes more accurately (Ficklin et al., 2015; Knutti & Sedláček, 2013). Studies demonstrated that CMIP5 models show an improvement over those of the CMIP3 in terms of simulated daily temperatures (Sun, Miao, & Duan, 2015; Sun et al., 2015), as well as decreased uncertainty in precipitation projections (Woldemeskel et al., 2015), which often vary in magnitude compared to those of the CMIP3 (Ficklin et al., 2015; Sun et al., 2015). This study helped to fill a current need for additional insight into coupling downscaled CMIP5 projections with a hydrologic model, particularly for watersheds in the Midwestern, USA, where few similar studies have focused. Moreover, the approach used in this study incorporated an analysis of CMIP5 model projections prior to hydrologic modeling in order to bracket a large range of uncertainty, a method which is transferrable to other watersheds around the world. Since previous studies using downscaled CMIP5 data have focused on watersheds dissimilar to HCW, in areas such as Northeastern United States (Mohammed, Bomblies, & Wemple, 2015) and eastern China (Ouyang et al., 2015), estimates of surface water regime changes from those studies are not directly comparable to those derived here. However, previous studies in the Midwest region using older CMIP3 model output have produced hydrologic estimates for nearby watersheds. One such study (Cherkauer & Sinha, 2010) derived hydrologic predictions for watersheds in the neighboring states of Illinois and Iowa. Results from that study indicated potential increases to fall, spring, and winter ET, decreases to summer ET, increases to summer runoff, and overall increases to streamflow; some of these trends differ from those simulated in HCW where increases to summer ET, decreases to summer runoff, and decreases to overall streamflow were observed. It is possible that the differences presented in that study could have been a result of the more coarse resolution ($1/8^{\text{th}}$ degree grid-cell) used in the chosen hydrologic

model, which lumped land-use types as well as hydrologic processes. However, another similar study covering three agricultural watersheds in Illinois found that, for the majority of CMIP3 models and scenarios, streamflow was likely to decrease overall, particularly during the summer (Chien et al., 2013). Given the lack of similar research in the geographic area in which HCW resides, the hydrologic estimates presented here serve to add to the overall body of research, and to help provide a basis for future comparison and for decision making. The approach used here could also be transferrable to watersheds in other regions, as it involves analyzing climate model projections prior to model coupling to account for a large portion of modeling uncertainty.

This study presented an approach that utilized downscaled climate data from with a semi-distributed hydrologic model. To address some of the uncertainty associated with climate model projections, a multi-model approach was used wherein output from two CMIP5 GCMs was used to encompass a range of future conditions. An analysis of downscaled climate projections for HCW indicated that output from MIROC-ESM was among the most extreme in terms of temperature increases and deviations from the current precipitation regime; conversely, GFDL-ESM2G was among the models projecting the least amount of temperature and precipitation change for HCW. Results indicated that projected changes to climate in HCW will result in annual decreases to streamflow (-5.9% to -26.8%) and surface runoff (-12.4% to -30.4%) under both scenarios for both the mid and late portions of this century. Similarly, streamflow and runoff are expected to substantially decrease for most seasons, scenarios, and time periods, with the notable exceptions of spring and fall during the mid-21st century under the severe climate change scenario. This analysis also suggested that ET would increase annually and seasonally under all scenarios and time periods. It is therefore likely that there will be decreases to surface water in HCW under even the most conservative climate projections. This raises questions about

management approaches whose approach primarily involves reduction of surface runoff in watersheds such as HCW. For example, a previous management approach in the study watershed sought to reduce runoff in HCW by approximately 50% (MDNR, 2010). However, given that runoff will be markedly reduced under future climate conditions, such approaches might simply exacerbate water scarcity issues. Since HC is typical of many streams in central Missouri, this study also provides an example of how similar watersheds might respond to future climate changes. Moreover, this study helps fill the need for more information on how projected climate changes could impact watershed processes in Midwestern watersheds, for which there have been few studies, particularly using the latest suite of CMIP5 climate models. In addition, this approach involved analyzing CMIP5 model projections prior to hydrologic model coupling to bracket a large portion of the uncertainty involved with this type of analysis and this approach is transferrable to study areas in various regions.

Table 2: Model information for the Coupled Model Intercomparison Project Phase 5 (CMIP5) global circulation models sampled for the Hinkson Creek Watershed climate impact study.

Modeling Center (or Group)	Institute ID	Model Name
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-ESM2G

Table 3: Temperature and precipitation values for Hinkson Creek Watershed for the conservative (Δ_C) and severe (Δ_S) climate scenarios during the mid-century (2040–2069) and late century (2070–2100) time periods.

	Precip. (mm)	Mid-century		Late-century		Change Mid		Change Late	
	Current	Δ_C	Δ_S	Δ_C	Δ_S	Δ_C	Δ_S	Δ_C	Δ_S
Winter	177	135	159	154	171	-42	-19	-23	-6
Spring	326	316	364	313	358	-10	38	-13	32
Summer	308	273	267	304	236	-35	-41	-3	-71
Fall	224	234	324	240	294	10	100	16	71
Year	1035	959	1114	1012	1060	-77	79	-23	25
	Max. (°C)	Mid-century		Late-century		Change Mid		Change Late	
	Current	Δ_C	Δ_S	Δ_C	Δ_S	Δ_C	Δ_S	Δ_C	Δ_S
Winter	5.6	6.5	9.6	6.4	12.0	1.0	4.0	0.8	6.4
Spring	19.0	19.4	22.5	18.9	25.2	0.4	3.5	-0.1	6.2
Summer	30.6	32.4	35.9	31.5	39.7	1.8	5.3	0.9	9.1
Fall	20.0	21.7	24.4	21.5	27.4	1.7	4.3	1.5	7.4
Year	18.8	20.0	23.1	19.6	26.1	1.2	4.3	0.8	7.2
	Min. (°C)	Mid-century		Late-century		Change Mid		Change Late	
	Current	Δ_C	Δ_S	Δ_C	Δ_S	Δ_C	Δ_S	Δ_C	Δ_S
Winter	-4.1	-3.6	-0.7	-3.5	1.6	0.5	3.4	0.6	5.7
Spring	7.6	7.5	10.6	7.2	12.9	-0.2	3.0	-0.5	5.2
Summer	19.5	20.5	23.3	19.9	26.3	0.9	3.8	0.4	6.7
Fall	8.6	9.0	12.1	9.0	14.9	0.4	3.5	0.4	6.3
Year	7.9	8.3	11.3	8.1	13.9	0.4	3.4	0.2	6.0

Table 4: Annual values and changes to water balance variables in Hinkson Creek Watershed for the current, conservative (Δ_C), and severe (Δ_S) future climate scenarios.

Period		<i>All years</i>		<i>Mid-century</i>		<i>Late-century</i>	
		H ₂ O (mm)					
Variable	Current	Δ_C	Δ_S	Δ_C	Δ_S	Δ_C	Δ_S
<i>Streamflow</i>	435	325	370	318	409	352	321
<i>Runoff</i>	321	209	253	204	281	223	224
<i>ET</i>	600	643	717	636	706	660	743
<i>Baseflow</i>	109	111	112	109	122	124	92
		Percent change					
	Variable	Δ_C	Δ_S	Δ_C	Δ_S	Δ_C	Δ_S
	<i>Streamflow</i>	-25.4%	-14.9%	-26.8%	-5.9%	-19.0%	-26.2%
	<i>Runoff</i>	-35.0%	-21.3%	-36.3%	-12.4%	-30.4%	-30.2%
	<i>ET</i>	7.2%	19.4%	6.0%	17.7%	10.0%	23.9%
	<i>Baseflow</i>	1.8%	2.7%	0.2%	12.3%	13.6%	-15.7%

Table 5: Seasonal changes to water balance variables in Hinkson Creek Watershed under the conservative (Δ_C) and severe (Δ_S) future climate scenarios (expressed as change in mm and percentage change).

	<i>Mid-century</i>				<i>Late-century</i>			
	Streamflow Δ_C		Streamflow Δ_S		Streamflow Δ_C		Streamflow Δ_S	
<i>Winter</i>	-37	-38.1%	-22	-23.2%	-23	-24.1%	-30	-30.7%
<i>Spring</i>	-33	-20.9%	14	8.8%	-24	-15.2%	-16	-10.3%
<i>Summer</i>	-39	-34.5%	-43	-38.0%	-33	-29.4%	-69	-61.5%
<i>Fall</i>	-9	-12.4%	25	36.1%	-3	-4.1%	1	0.9%
	Runoff Δ_C		Runoff Δ_S		Runoff Δ_C		Runoff Δ_S	
<i>Winter</i>	-31	-41.3%	-24	-31.9%	-22	-29.0%	-26	-35.5%
<i>Spring</i>	-34	-31.2%	-3	-2.7%	-31	-28.0%	-20	-17.7%
<i>Summer</i>	-43	-54.0%	-41	-51.8%	-40	-50.7%	-55	-70.2%
<i>Fall</i>	-9	-15.7%	28	48.3%	-5	-8.9%	4	7.7%
	ET Δ_C		ET Δ_S		ET Δ_C		ET Δ_S	
<i>Winter</i>	2	5.2%	8	17.7%	3	6.6%	15	33.2%
<i>Spring</i>	15	9.6%	32	20.0%	9	5.4%	73	46.3%
<i>Summer</i>	12	4.3%	28	9.6%	34	11.6%	8	2.7%
<i>Fall</i>	6	5.7%	39	36.3%	15	13.9%	47	43.8%
	Baseflow Δ_C		Baseflow Δ_S		Baseflow Δ_C		Baseflow Δ_S	
<i>Winter</i>	-6	-27.4%	1	6.0%	-1	-7.0%	-4	-16.6%
<i>Spring</i>	2	3.9%	16	36.9%	7	15.8%	3	7.4%
<i>Summer</i>	4	12.5%	-1	-4.5%	7	22.1%	-13	-41.0%
<i>Fall</i>	0	2.7%	-3	-23.6%	2	19.5%	-4	-33.1%

Figure 10: Seasonal comparison of current conditions and future climate projections for Hinkson Creek Watershed based on current data and selected global circulation model outputs.

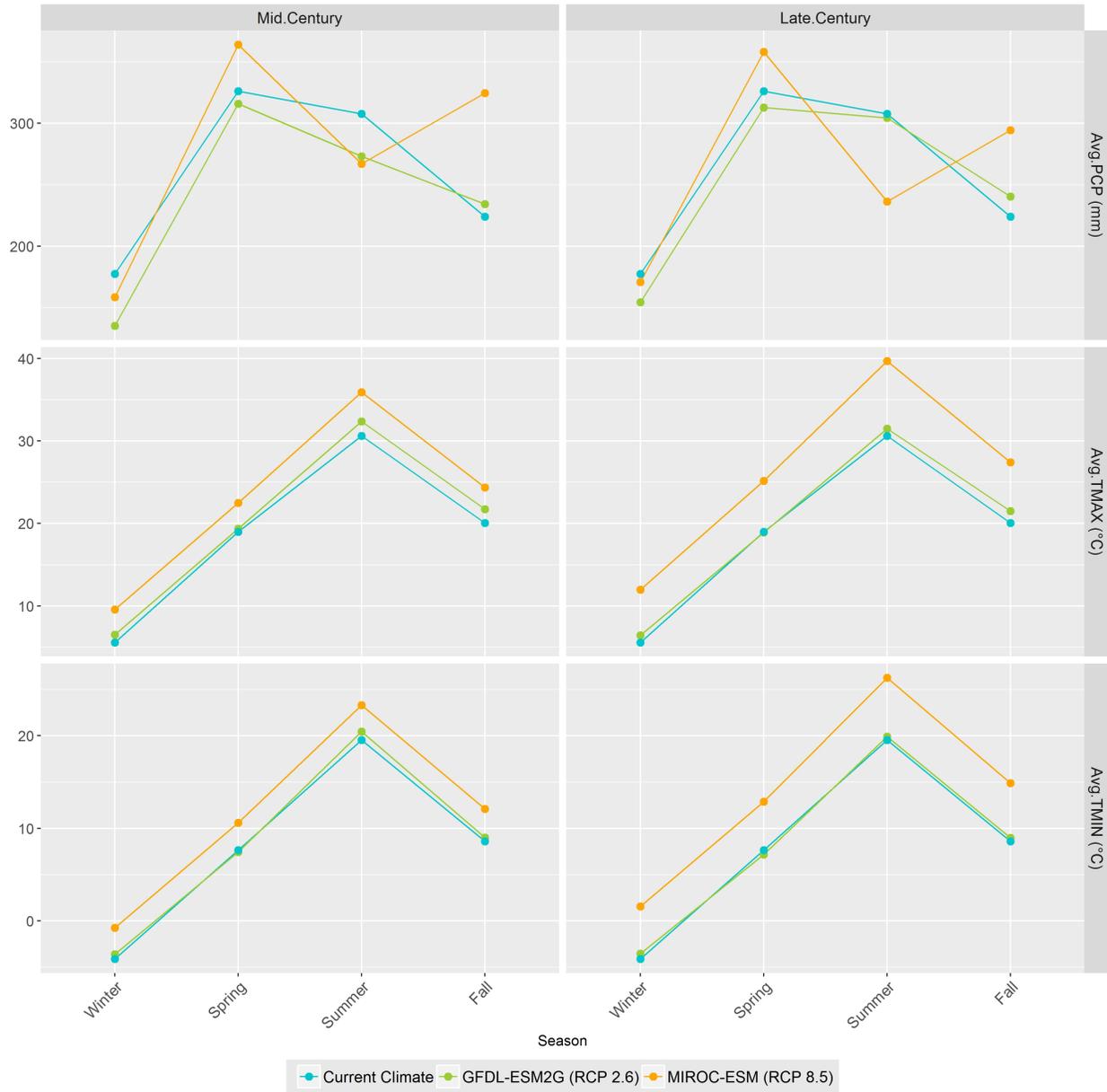


Figure 11: Average annual estimates for simulated hydrologic variables for the current, conservative (Δ_C) and severe (Δ_S) climate scenarios for Hinkson Creek Watershed.

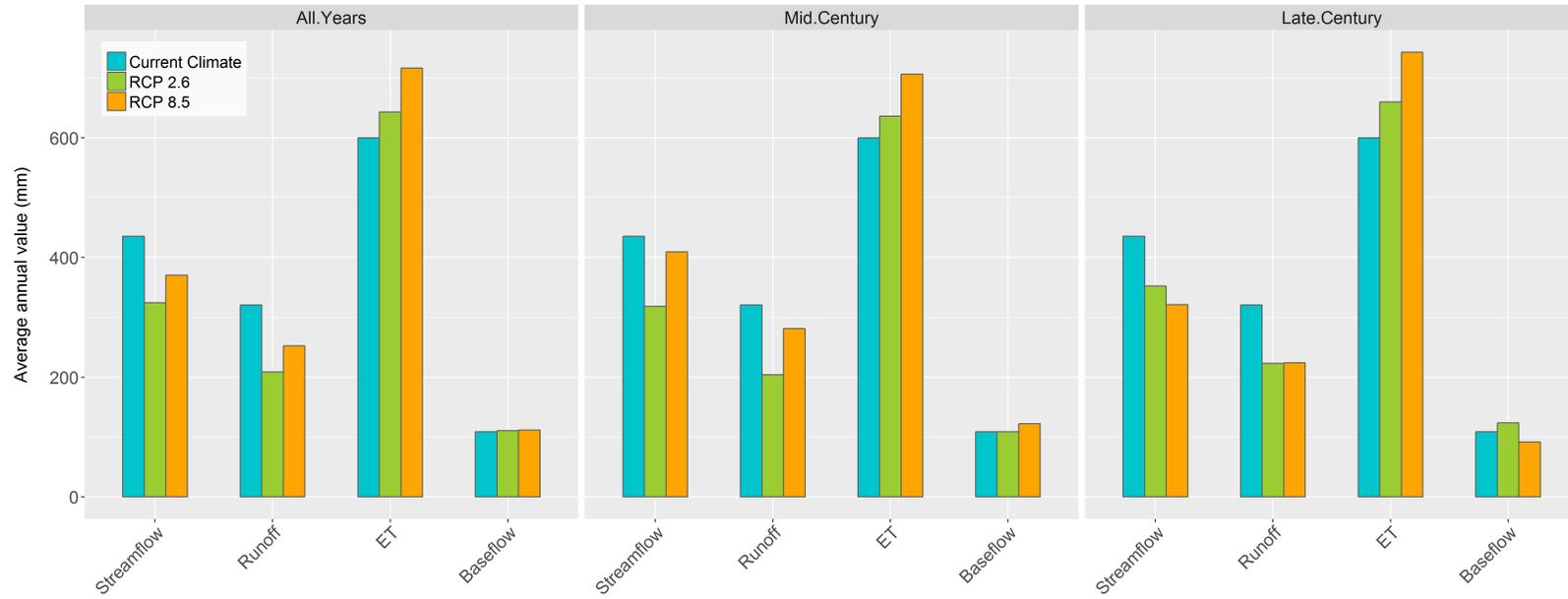


Figure 12: Estimated seasonal mean changes (relative to current climate) for simulated hydrologic variables for the conservative (Δ_C) and severe (Δ_S) climate scenarios in Hinkson Creek Watershed.

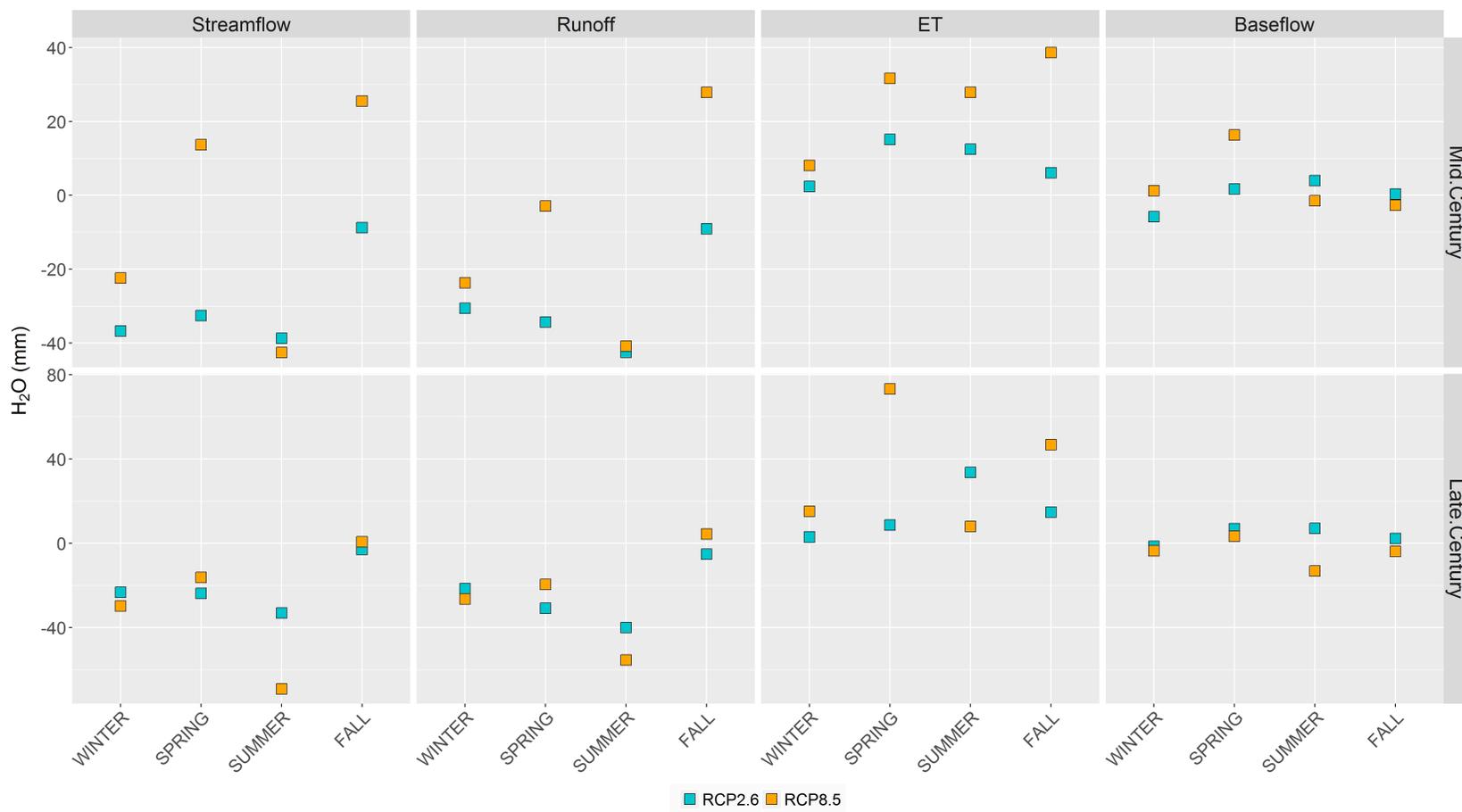
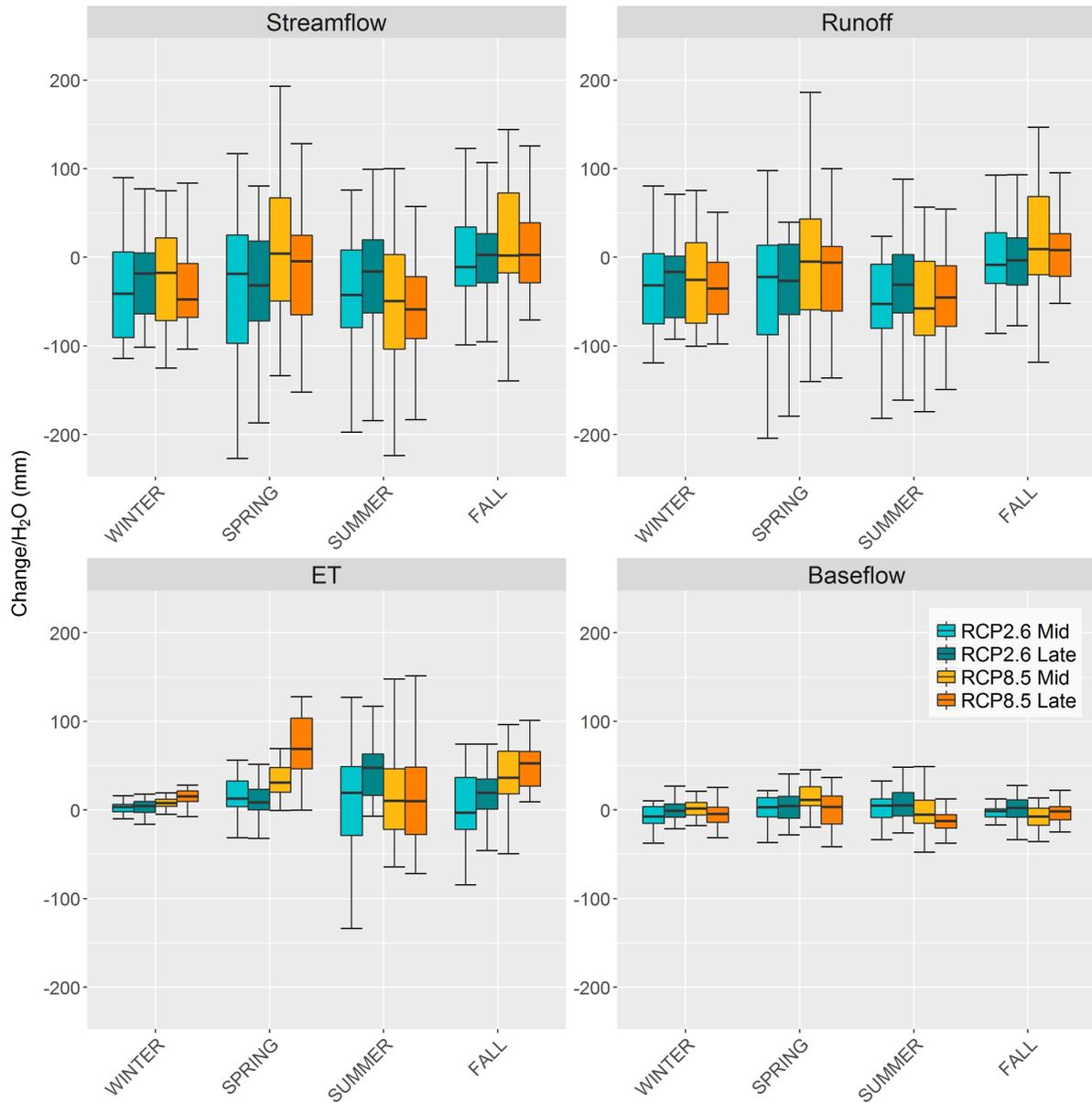


Figure 13: Estimated variability (box-plots) of seasonal changes (relative to current climate) to water regime processes for the conservative (Δ_C) and severe (Δ_S) climate scenarios for Hinkson Creek Watershed for both time periods and scenarios.



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Chapter 4: Estimating hydrologic responses to future urbanization and climate changes in a mixed-use Midwestern watershed using an integrated modeling approach

4.1 Abstract

Future urban development and climatic changes are likely to affect hydrologic regimes in many watersheds during this century. Characterizing and quantifying water regime changes caused by these phenomena is therefore crucial for enabling decision makers to develop climate change and urbanization adaptation strategies. This study presents an approach that uses mid-21st century impervious surface (IS) growth estimates derived from the Imperviousness Change Analysis Tool (I-CAT) with downscaled CMIP5 climate model projections and a hydrologic model (SWAT) to characterize potential water regime changes in a mixed-use watershed in central Missouri, USA. Results for the climate change only (Δ_{CC}) scenario indicated annual streamflow and runoff decreases (-4.5% and -11.2%) and ET increases (+19.5%), while results from the urbanization only (Δ_U) scenario indicated streamflow and runoff increases (+26.4% and +23.6%) and ET decreases (-20.4%). Results for the combined impacts scenario (Δ_{UC}) suggested that urbanization had a larger impact than climate change on annual streamflow and surface runoff, leading to overall increases (18.4% and 8.4%). For the Δ_{UC} scenario, urbanization largely offset the impacts of climate change on annual ET. Seasonal results indicated that the relative influence of each stressor varies by season. Climatic changes most greatly influenced streamflow and runoff during winter and summer, and ET during fall. During some seasons the directional change for hydrologic processes matched for both stressors. This study used a novel modeling technique to investigate the relative influences of mid-21st century urbanization and climatic

changes, and characterized their annual and seasonal impacts in a representative mixed-use watershed, adding to the limited body of research on this topic. This was done using a transferrable approach that can be adapted for watersheds in other regions.

4.2 Introduction

Land-use and climatic changes are two of the most significant phenomena impacting water regimes globally (Brown et al., 2014; Chung et al., 2011). Changes to land-cover caused by human activities such as urbanization result in increased impervious surface area, and can affect hydrologic process such as surface runoff, evapotranspiration (ET), and groundwater movement (Arnold & Gibbons, 1996; Paul & Meyer, 2001). These hydrologic processes can also be impacted by climatic changes such as increased temperatures and altered precipitation regimes (Arnell & Gosling, 2013; Jiménez-Cisneros et al., 2014). Additionally, since most areas have experienced land use changes (e.g. urbanization, deforestation) and climatic changes concurrently, it is often difficult to attribute observed water regime changes to climate change or land cover change alone (Bierwagen et al., 2010; Georgakakos et al., 2014). Given that ongoing urbanization and projected climate changes are expected to have significant effects on hydrologic processes in many watersheds during coming decades, it is increasingly important for policy makers to understand how their combined impacts affect water regimes in order to develop watershed management strategies that help address these issues (Bierwagen et al., 2010; Brown et al., 2014).

Urban development in many regions has been rapid during recent decades and is accompanied by the buildup of impervious surface (IS) cover, which alters the hydrologic characteristics of watershed landscapes (Kumar et al., 2013; Schueler et al., 2009). In some studies, hydrologic models have been coupled with urban growth predictions in order to estimate

the potential impacts of future urbanization on hydrologic processes in watersheds (Choi & Deal, 2008; Kumar et al., 2013; Lin et al. 2008; Sunde et al., 2016; Wu et al., 2015). It has been demonstrated that the future buildup of impervious surface area resulting from urban development can alter the dynamics of streamflow and surface runoff (Kumar et al., 2013; Wu et al., 2015), reduced evapotranspiration (Kim et al., 2011; Sunde et al., 2016), and changes to baseflow (Kim et al., 2011; Sunde et al., 2016). Similarly, hydrologic models have been coupled with climate change projections to characterize the potential future water regime changes in a number of studies (Cherkauer & Sinha, 2010; Chien, Yeh, & Knouft, 2013; Dams et al., 2015; Ficklin et al., 2009; Jin & Sridhar, 2012; Joh et al., 2011; Mohammed, Bomblies, & Wemple, 2015; Ouyang et al., 2015; Sheshukov et al., 2011; Vo et al., 2016; Xu et al., 2013). The hydrologic responses to climatic changes observed in these studies have been variable, owing in large part to differences in the characteristics of the watersheds being analyzed. However it has been consistently demonstrated that hydrologic processes such as surface runoff, streamflow, baseflow, and ET are likely to be impacted by future climatic changes in most areas (Cherkauer & Sinha, 2010; Dams et al., 2015; Ficklin et al., 2009; Joh et al., 2011; Ouyang et al., 2015; Xu et al., 2013). Studies focused on investigating both the individual and combined hydrologic impacts of climatic and land-use changes using integrated hydrologic modeling have shown that the relative influence of these two stressors varies, and that they can affect water regime processes differently depending on watershed characteristics (Cuo et al., 2011; El-Khoury et al., 2015; Fan & Shibata, 2015; Franczyk & Chang, 2009; Mishra et al., 2010; Neupane & Kumar, 2015; Qi et al., 2009; Rahman et al., 2015; Viger et al., 2011). A number of these studies have shown that climatic changes can have more severe impacts than urbanization and/or land-use changes on water regimes (Cuo et al., 2011; Fan & Shibata, 2015; Qi et al., 2009; Rahman et al., 2015;

Wilson & Weng, 2011). In some cases, however, it has been demonstrated that land-use change impacts could have greater impacts than climatic changes on streamflow processes (Mishra et al., 2010). It has also been demonstrated that the relative influence of each stressor can vary across different hydrologic processes (Pervez & Henebry, 2015). In addition, the impacts of climatic and land-cover changes on hydrologic processes can be compounded by one another in some instances (El-Khoury et al., 2015; Franczyk & Chang, 2009; Neupane & Kumar, 2015) and offset by each other in other cases (Viger et al., 2011). Given the uncertainty with regard to how different watersheds will respond to future changes, continued research on the combined effects of urbanization and climatic changes on hydrologic processes is necessary, both to improve the understanding of these phenomena and to develop information with application potential for natural resource managers. Moreover, very few previous studies have incorporated recent CMIP5 climate projections, and most have utilized coarse urban land-cover (e.g. imperviousness) estimates, which can obscure the distribution of groundwater recharge and infiltration in urban areas (Lerner, 2002) and can affect estimated changes to surface runoff and evapotranspiration (Sunde et al., 2016).

Given the preceding background and concerns, the objective of this study was to use an integrated modeling approach to estimate the potential impacts of urbanization and climatic changes in a mixed-use watershed in Missouri, USA. This was achieved by 1) simulating future impervious surface growth for the study watershed using a cellular automata based urban growth model, 2) calibrating and validating a hydrologic model for the study watershed, and 3) using downscaled GCM output and simulated future impervious surface cover as inputs for a hydrologic model to estimate the relative and combined effects of these stressors on streamflow processes for the study watershed.

4.3 Methods

4.3.1 Study area

Hinkson Creek Watershed (HCW; Figure 1) is an urbanizing watershed in central Missouri, U.S.A., covering an approximately 231 km² area. The watershed is located within the Lower Missouri-Moreau Basin and is situated at the intersection of the Claypan Till Plains ecological subsection in the north and the Outer Ozark Border ecological subsection in the south (Nigh & Schroeder, 2002). More detailed descriptions of the climate, physical geography and hydrology of HCW are presented in section 2.3.1. Results from previous portions of this research indicated that future impervious surface development in HCW could potentially lead to increased annual streamflow, runoff, and baseflow, as well as decreased ET. Additionally, previous portions of this research suggested that climatic changes in HCW could lead to decreased streamflow and surface runoff, increased ET, and varying directional changes to baseflow

4.3.2 Urban growth model (I-CAT) description and parameterization

The Imperviousness Change Analysis Tool (I-CAT) was chosen to simulate urban growth for this study because it can be used to generate high resolution impervious surface estimates for a wide variety of study areas (Sunde et al., 2014). The I-CAT is a rule based cellular automata (CA) urban growth model that uses a GIS multi-criteria evaluation (GIS-MCE; Carver, 1991) approach to generate grid-based impervious surface growth estimates. Additional model details and descriptions of the input data are presented in the preceding text in section 2.3.2.

Future impervious surface growth for the Columbia, Missouri urban area was simulated using I-CAT. In order to calibrate the I-CAT, model parameter weights were adjusted using a trial and error approach, until a suitability grid that explained a large amount of impervious surface development observed from 1990–2000 was produced. For model validation, the

resultant suitability grid was assessed based on observed growth from 2000–2011. Calibration and validation metrics for the I-CAT are shown in Figure 2 and the procedure is described in further detail in section 2.3.4.

4.3.3 Hydrologic model (SWAT) description and parameterization

Due to its demonstrated applicability for assessing long term climatic and land-cover change impacts in a wide variety of watershed types (Gassman, Reyes, Green, & Arnold, 2007), the Soil & Water Assessment Tool (SWAT) was selected for this study. The SWAT is a semi-distributed, physically-based, continuous time model that simulates watershed hydrologic processes, designed to allow users to determine the effects of various management decisions on water resources, stream sedimentation, and nutrient loading (Arnold et al., 1998; Gassman et al., 2007; Arnold et al., 2012). More detailed descriptions of the structure of the SWAT model and its input requirements are presented in section 2.3.3.

In order to identify the SWAT parameters that most influenced modeled streamflow for HC, sensitivity analysis was conducted prior to calibrating SWAT. After sensitivity analysis, SWAT was calibrated using numerous iterations in which parameter ranges were adjusted. A split-sample approach (Moriassi et al., 2012) was used to divide streamflow observations for HC into model calibration and validation periods. Two widely used hydrologic model performance metrics, the Nash-Sutcliffe efficiency (NSE) and the root-mean-square-error over the standard deviation of the observed data (RSR), were used to assess the performance of SWAT (Moriassi, et al., 2007). SWAT was very effective for modeling streamflow for HC based on the NSE and RSR values derived for this study. Calibration and validation results for SWAT are presented in Figure 3 and are described in further detail in section 2.3.4 along with additional details regarding model sensitivity analysis and calibration.

4.3.4 Climate, urban growth scenarios, and model coupling

Bias-corrected 1/8th degree daily maximum temperature, minimum temperature, and precipitation outputs (Brekke et al., 2013) from a CMIP5 model were sampled in order to develop a climate change scenario for HCW. The model used for this study was MIROC-ESM (JAMSTEC, AORI, & NIES, 2015) under the RCP8.5 emissions scenario (Riahi et al., 2011; Vuuren et al., 2011; Cubasch et al., 2013). Incident shortwave solar radiation data for HCW was sampled at the native resolution of the MIROC-ESM model (2.7906° latitude x 2.8125° longitude) since downscaled data for that variable was not available. Daily precipitation, maximum temperature, minimum temperature, and incident shortwave solar radiation observations from the Sanborn Field weather station (Figure 1) for the period from January 1st, 1996–December 31st, 2015 were used to characterize the current climate of HCW. Observations for these climate variables were replicated to allow for comparison with the 59-year simulation period (January 1st, 2016–December 31st, 2074) used for the climate projection scenario. Seasonal comparisons for precipitation and temperature for the two climate scenarios are shown in Table 6. In order to characterize potential mid-21st century urban land-cover in HCW, the calibrated I-CAT model was used to estimate future impervious surface growth in the watershed from 2011–2051 under a current growth trend scenario. The resultant 2051 impervious cover grid (Figure 14) was then used to define urban land-cover for the future urbanization scenario for the SWAT simulations.

The climatic and land-cover data described above were used as forcing for the SWAT in order to compare the potential effects of future urbanization and climatic changes in HCW. Using model output for the period January 1st, 2045–December 31st, 2074, four total scenarios were developed for this study: 1) a baseline scenario (current) based on current land-cover and

climate, 2) a climate change only scenario (Δ_{CC}) based on current land-cover and mid-century climate projections, 3) a mid-century urbanization with current climate scenario (Δ_U) based on simulated mid-century imperviousness and current climate, and 4) a mid-century urbanization with climate change scenario (Δ_{UC}) based on mid-century imperviousness and climate change projections.

4.4 Results and Discussion

Model results derived from the SWAT for the four scenarios (current, Δ_{CC} , Δ_U , and Δ_{UC}) scenarios were compared in order to determine the potential effects of future urbanization and climatic changes in HCW. Simulation results at the annual level (Figure 15) indicated that, relative the baseline scenario, streamflow could decrease under the Δ_{CC} (-4.5%) scenario, and increase under the Δ_U (+26.4%) and Δ_{UC} (+18.4%) scenarios (Table 7). The pattern observed for annual changes to streamflow was also reflected in modeled changes to surface runoff, which showed a decreasing trend for the Δ_{CC} scenario (-11.2%), and increases under the Δ_U (+23.6%) and Δ_{UC} (+18.4%) scenarios (Table 7). Results showed large increases to annual ET under Δ_{CC} (+19.5%) scenario, large decreases under the Δ_U (-20.4%) scenario, and modest increases under the Δ_{UC} (+1.9%) scenario. In ascending order, annual baseflow increases were observed for the Δ_{CC} , the Δ_U , and the Δ_{UC} scenarios (Table 7).

The responses of water regime processes in HCW to projected climatic changes and urbanization varied according to season (Figure 16). The largest changes to mean seasonal streamflow occurred during spring ($\Delta_{CC} = +8\%$; $\Delta_U = +24.2\%$ mm; $\Delta_{UC} = +33.8\%$), summer ($\Delta_{CC} = -38.1\%$; $\Delta_U = +35.7\%$ mm; $\Delta_{UC} = -16.6\%$) and fall ($\Delta_{CC} = +46.4\%$; $\Delta_U = +28.5\%$ mm; $\Delta_{UC} = +77.1\%$) for all three scenarios, while the largest changes to seasonal surface runoff occurred during the summer ($\Delta_{CC} = -52\%$; $\Delta_U = +34.7\%$ mm; $\Delta_{UC} = -35.7\%$) and fall ($\Delta_{CC} =$

+58.5%; $\Delta_U = +28.2\%$ mm; $\Delta_{UC} = +92.5\%$) for the three scenarios (Table 8). The largest observed changes to ET occurred during spring for all of the scenarios ($\Delta_{CC} = +20.9\%$; $\Delta_U = -27.9\%$ mm; $\Delta_{UC} = -11.5\%$), during summer for the Δ_{CC} (+12.3%) and Δ_U (-17.8%) scenarios, and during fall ($\Delta_{CC} = +36.6\%$; $\Delta_U = -15.2\%$ mm; $\Delta_{UC} = +25.1\%$) under all three scenarios (Table 8). The largest changes to seasonal baseflow occurred during spring for all three scenarios ($\Delta_{CC} = +37.1\%$; $\Delta_U = +35.4\%$ mm; $\Delta_{UC} = +76.6\%$), and during summer for the Δ_U (+39.1%) and Δ_{UC} (-31.2%) and scenarios (Table 8).

The interquartile ranges (IQR) of the estimates for water regime processes in HCW were determined in order to investigate the variability of the simulated seasonal hydrologic responses under each of scenarios (Figure 17). The IQR for seasonal streamflow for HC ranged from 42.9 mm (Δ_{CC}) to 71.7 mm (Δ_U) during winter, from 70.7 mm (Δ_{CC}) to 111.6 mm (Δ_U) during spring, from 49.2 mm (Δ_{CC}) to 105.5 mm (Δ_U) during summer, and from 57.6 mm (current) to 89.1 mm (Δ_{CC}) during fall. For seasonal runoff, IQR values ranged from 38.7 mm (Δ_{CC}) to 67.2 mm (Δ_U) during winter, from 52.3 mm (Δ_{CC}) to 107.8 mm (Δ_U) during spring, from 41.2 mm (Δ_{CC}) to 95.3 mm (Δ_U) during summer, and from 43.4 mm (current) to 86.4 mm (Δ_{UC}) during fall. The IQRs for seasonal ET ranged from 3.6 mm (Δ_{CC}) to 5.0 mm (Δ_U) during winter, from 10.4 mm (Δ_U) to 24.3 mm (Δ_{CC}) during spring, from 44.6 mm (Δ_U) to 64.5 mm (Δ_{CC}) during summer, and from 23.7 mm (Δ_U) to 38.8 mm (Δ_{UC}) during fall. For seasonal baseflow, IQRs ranged from 12.2 mm (Δ_{CC}) to 16.1 mm (Δ_{UC}) during winter, from 19.2 mm (Δ_{UC}) to 26.4 mm (Δ_U) during spring, from 19.4 mm (Δ_{CC}) to 28.2 mm (Δ_U) during summer, and from 9.0 mm (Δ_{CC}) to 20.9 mm (Δ_U) during fall.

The integrated modeling results indicated that annual streamflow could increase under mid-21st century impervious cover (Δ_U) conditions (Figure 15). This increase, however, could be

partially offset by projected decreases to streamflow under mid-century climate conditions (Δ_{CC}). This is reflected in modeling results derived from the Δ_{UC} scenario, which showed that annual streamflow could increase by roughly 18% when both stressors were considered. The streamflow responses described above are also reflected in estimated changes to surface runoff, where decreases resulting from climatic changes are offset by urbanization, ultimately leading to a projected increase of approximately 8%. Model estimates suggested that annual ET in HCW (Figure 15) could greatly increase under the climate change, however these increases could largely be offset by decreases caused by urbanization, and results from the scenario including both factors (Δ_{UC}) showed an increase of approximately 2% relative to current conditions. The modeling results also indicated that baseflow increases observed for the individual urbanization and climate change scenarios would be compounded when both factors were considered.

The estimated seasonal streamflow changes (Figure 16) indicated that decreases to winter streamflow caused by climatic changes might be partially offset by increases resulting from future urbanization, with a decrease of approximately 10% when both factors (Δ_{UC}) were considered. Spring streamflow increased under all scenarios and the impacts of both stressors amplified the directional change to streamflow for the season, leading to an increase of about 34%. Estimates showed large decreases to summer streamflow for HC resulting from climatic changes, while large increases were observed under the Δ_U scenario; these decreases were not, however, fully offset by urbanization, leading to an estimated reduction of approximately 17% when both factors were considered. Fall streamflow increased under both scenarios, and the directional change was amplified when both factors were considered, with an estimated 77% increase under the Δ_{UC} scenario. With the exception of spring, directional changes to runoff due to the combined impacts of urbanization and climatic changes matched those observed for

streamflow. Small decreases to spring runoff (Table 8) were observed for the Δ_{CC} scenario, but these were offset by urbanization under the scenario including both stressors, which showed a seasonal increase of approximately 17%. While increases to ET were observed for all seasons under the Δ_{CC} scenario, decreases were observed for all seasons under the Δ_U scenario. Estimated increases to seasonal ET during winter and summer due to climatic changes were largely offset when both climate change and urbanization were considered; however, the sign of the change was reversed for spring ET under the Δ_{UC} scenario, leading to a reduction of approximately -12%. The response of fall ET under the Δ_{UC} scenario differed from that of other seasons, as urbanization offset just a small portion of the increases caused by climatic changes, leading to a projected 25% increase when both stressors were considered. Model results indicated that baseflow would be most greatly affected during spring and, when both stressors were considered, the increases were intensified, leading to an estimated 77% increase for the season.

The modeling results suggested that the variability of streamflow and runoff responses in HCW could decrease during the winter, spring, and summer under the scenarios that included climatic changes. Conversely, streamflow and runoff responses were more variable during fall under the same scenarios. Streamflow variability also increased during summer under the urbanization only scenario (Δ_U). In terms of the estimated responses of ET to both stressors, there was minimal variability among all scenarios during winter, which was due to the season being a time of low evaporation and dormancy for vegetation. However, there was greater variability observed for ET responses under scenarios that including the climate change component, particularly during spring and fall. Additionally, the variability of ET responses during spring and summer decreased considerably under the scenarios that including mid-21st century impervious surface cover.

The decreases observed for ET under the mid-21st century urbanization scenario (Δ_U) were likely the consequence of the replacement of forested areas, woodlands, croplands, and pastures with developed urban areas (Sunde, et al., 2016). This resulted in the reduction of canopy cover, and water that otherwise would have been consumed or intercepted by plants (Neitsch et al., 2011) was instead infiltrated or routed as runoff. At both the annual and seasonal time-scale, the model estimates indicated that groundwater flow (baseflow) could increase as a result of both climatic changes and urbanization. Increases during winter and spring occurred under the climate change only (Δ_{CC}) scenario, and during all four seasons under the urbanization only (Δ_U) and combined impacts (Δ_{UC}) scenarios. In terms of urbanization, these baseflow increases likely resulted from the reduction of canopy cover, which made it possible for additional water to infiltrate into the soil profile rather than being intercepted, particularly in areas with low-density development (i.e. pixels with low percentages of imperviousness). A portion of the runoff in these low-density urbanized areas was likely routed to lawns, rather than directly to urban sewerages. Some previous studies (Lin et al., 2008; O'Driscoll et al., 2010; Kim et al., 2011; Viger et al., 2011; Zhou et al., 2013) using an approach similar to that presented here showed that urbanization can sometimes lead to baseflow decreases. However, these studies often used binary (e.g. urban/not urban) urban land cover classifications at coarse scales, which can prevent hydrologic models from allocating realistic amounts of water for infiltration due to the fact that there are numerous pathways for precipitation to recharge groundwater in urban areas (Lerner, 2002). Additionally, these studies were conducted in watersheds that did not share similar physical and climatic characteristics with HCW. In fact, the effects of urban development on baseflow can vary greatly (Lerner, 2002), and studies have demonstrated that the removal of vegetation and ET reductions associated with urbanization can lead to increased baseflow

(LeBlanc et al., 1997; Meyer, 2004; O’Driscoll et al., 2010; Price, 2011). Moreover, a recent study indicated that baseflow increased in HCW during recent years, a time which coincides with intensive urbanization in the watershed (Hubbart & Zell, 2013). It is possible that increased precipitation, paired with increased evaporation and consumption (by plants) of soil water, contributed to the climate induced baseflow increases (Price, 2011) observed in this study, as these could desaturate the soil and allow new precipitation to infiltrate rather than being routed as runoff in some cases. In addition, there is a decoupling of the ET/baseflow response during cold seasons in many areas, which can lead to increased baseflow under climate scenarios with projected precipitation increases (Ficklin et al., 2016).

4.5 Conclusions

This study presented an integrated modeling approach for assessing the individual and combined effects of urbanization and climatic changes on hydrologic processes in a mixed-use watershed. The approach used downscaled GCM output from the latest generation of climate models (CMIP5) and impervious surface growth projections derived from a CA-based urban growth model (I-CAT), along with a process-based hydrologic model (SWAT). Within this modeling framework, multiple urbanization and climate scenarios were developed and used to drive the SWAT to determine the relative impacts of the two stressors. Study results suggested that, at the annual time scale, urbanization had a larger impact than climate change on streamflow and surface runoff, offsetting decreases caused by climatic changes and leading to overall increases. However, this was not the case when seasonal streamflow and runoff were considered. During the winter and summer, climatic changes had a larger impact on these processes than urbanization, and the directional change for streamflow for the two stressors matched during spring and fall. Results also indicated that mid-21st century urbanization in HCW

could cause annual and seasonal (all seasons) ET decreases, while the opposite was true under mid-century climate. When both factors were considered, urbanization almost entirely offset the impacts of climate change on ET at the annual time-scale. At the seasonal time-scale, however, large increases to ET resulting from climatic changes were observed during fall under the multiple effects scenario. Thus, while neither stressor had drastically larger impacts on water regime processes in HCW at the annual time-scale when both factors were considered, there were clear instances when either urbanization or climate change was more influential during various seasons. Moreover, there were also instances when the impacts of the two stressors on hydrologic processes did not diverge directionally during certain seasons. These results underscore the importance of seasonality when considering the combined impacts of future land-cover and climatic changes on hydrologic processes, as the relative importance of either stressor can vary by season. This study also presented a novel approach for assessing the hydrologic impacts of urbanization and climatic change that can be adapted for various regional studies. In addition, the results from this study characterize potential mid-21st century conditions for the study watershed under multiple scenarios and add to the limited body of research in this area, which can also be useful for researchers and managers studying similar watersheds in the region.

Table 6: Seasonal precipitation and temperature for Hinkson Creek Watershed for the current and future climate scenarios used in this study.

	Precip. (mm)		Change	% Change
	Current	Δ_{CC}	Δ_{CC}	Δ_{CC}
Winter	177	162	-15.4	-8.7%
Spring	326	371	44.6	13.7%
Summer	308	268	-39.9	-13.0%
Fall	224	342	118.3	52.8%
Annual	1035	1143	107.6	10.4%
	Max. (°C)		Change	% Change
	Current	Δ_{CC}	Δ_{CC}	Δ_{CC}
Winter	5.6	9.9	4.3	77.7%
Spring	19.0	22.8	3.8	20.2%
Summer	30.6	36.3	5.7	18.5%
Fall	20.0	24.6	4.6	22.9%
Annual	18.8	23.4	4.6	24.5%
	Min. (°C)		Change	% Change
	Current	Δ_{CC}	Δ_{CC}	Δ_{CC}
Winter	-4.1	-0.4	3.7	91.2%
Spring	7.6	10.9	3.3	42.9%
Summer	19.5	23.6	4.1	20.9%
Fall	8.6	12.4	3.8	44.1%
Annual	7.9	11.6	3.7	47.1%

Table 7: Annual values and changes to water balance variables in Hinkson Creek Watershed for the current, mid-century climate change only (Δ_{CC}), mid-century urbanization only (Δ_U), and mid-century climate change/urbanization (Δ_{UC}) scenarios.

Variable	H ₂ O (mm)				Percent Change		
	Current	Δ_{CC}	Δ_U	Δ_{UC}	Δ_{CC}	Δ_U	Δ_{UC}
<i>Streamflow</i>	450	430	569	533	-4.47%	26.43%	18.38%
<i>Runoff</i>	333	295	411	361	-11.25%	23.62%	8.37%
<i>ET</i>	595	711	474	606	19.54%	-20.40%	1.87%
<i>Baseflow</i>	112	128	152	166	14.88%	35.96%	48.26%

Table 8: Seasonal changes (mm) and percentage changes to water balance variables in Hinkson Creek Watershed for the mid-century climate change only (Δ_{CC}), mid-century urbanization only (Δ_U), and mid-century climate change/urbanization (Δ_{UC}) scenarios.

	Streamflow Δ_{CC}		Streamflow Δ_U		Streamflow Δ_{UC}	
<i>Winter</i>	-23	-23.3%	18	17.8%	-9	-9.5%
<i>Spring</i>	13	8.0%	39	24.2%	55	33.8%
<i>Summer</i>	-44	-38.1%	41	35.7%	-19	-16.6%
<i>Fall</i>	34	46.4%	21	28.5%	57	77.1%
	Runoff Δ_{CC}		Runoff Δ_U		Runoff Δ_{UC}	
<i>Winter</i>	-26	-33.9%	10	13.6%	-18	-23.3%
<i>Spring</i>	-4	-3.7%	23	20.0%	19	16.7%
<i>Summer</i>	-42	-52.0%	28	34.7%	-29	-35.7%
<i>Fall</i>	35	58.5%	17	28.2%	56	92.5%
	ET Δ_{CC}		ET Δ_U		ET Δ_{UC}	
<i>Winter</i>	9	19.0%	-10	-22.7%	-3	-7.5%
<i>Spring</i>	33	20.9%	-44	-27.9%	-18	-11.5%
<i>Summer</i>	35	12.3%	-50	-17.8%	6	2.0%
<i>Fall</i>	40	36.6%	-16	-15.2%	27	25.1%
	Baseflow Δ_{CC}		Baseflow Δ_U		Baseflow Δ_{UC}	
<i>Winter</i>	3	12.1%	7	33.7%	8	38.2%
<i>Spring</i>	17	37.1%	16	35.4%	35	76.6%
<i>Summer</i>	-1	-3.9%	13	39.1%	10	31.2%
<i>Fall</i>	-2	-14.4%	4	33.8%	0	3.9%

Figure 14: Grid-based percentage impervious surface cover estimates for Hinkson Creek Watershed for the 2011 baseline period (A) and the 2051 mid-21st century time period (B).

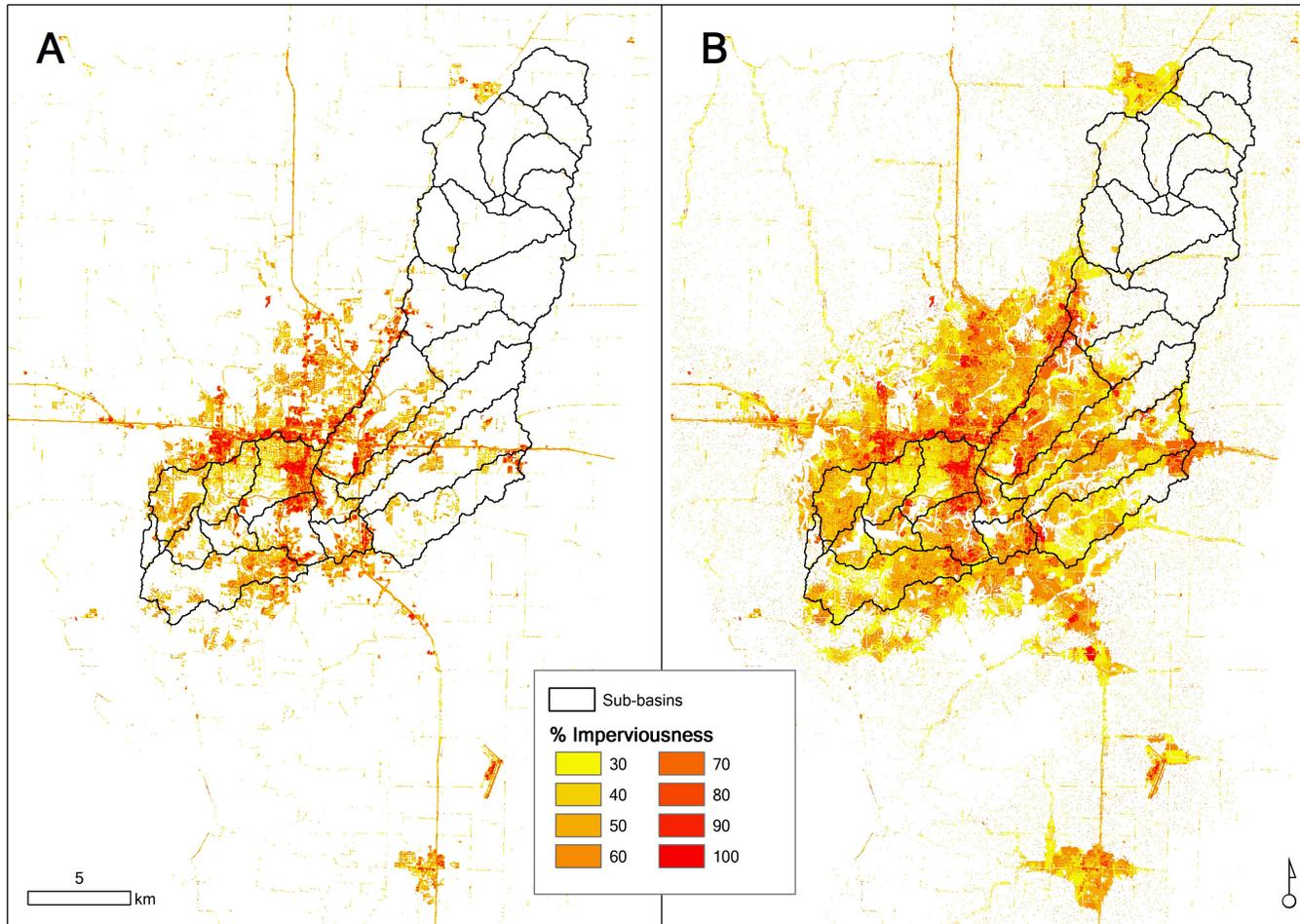


Figure 15: Average annual estimates derived from SWAT for water regime processes in Hinkson Creek Watershed for the current, (climate change only) Δ_{CC} , (urbanization only) Δ_U , and (climate change & urbanization) Δ_{UC} scenarios.

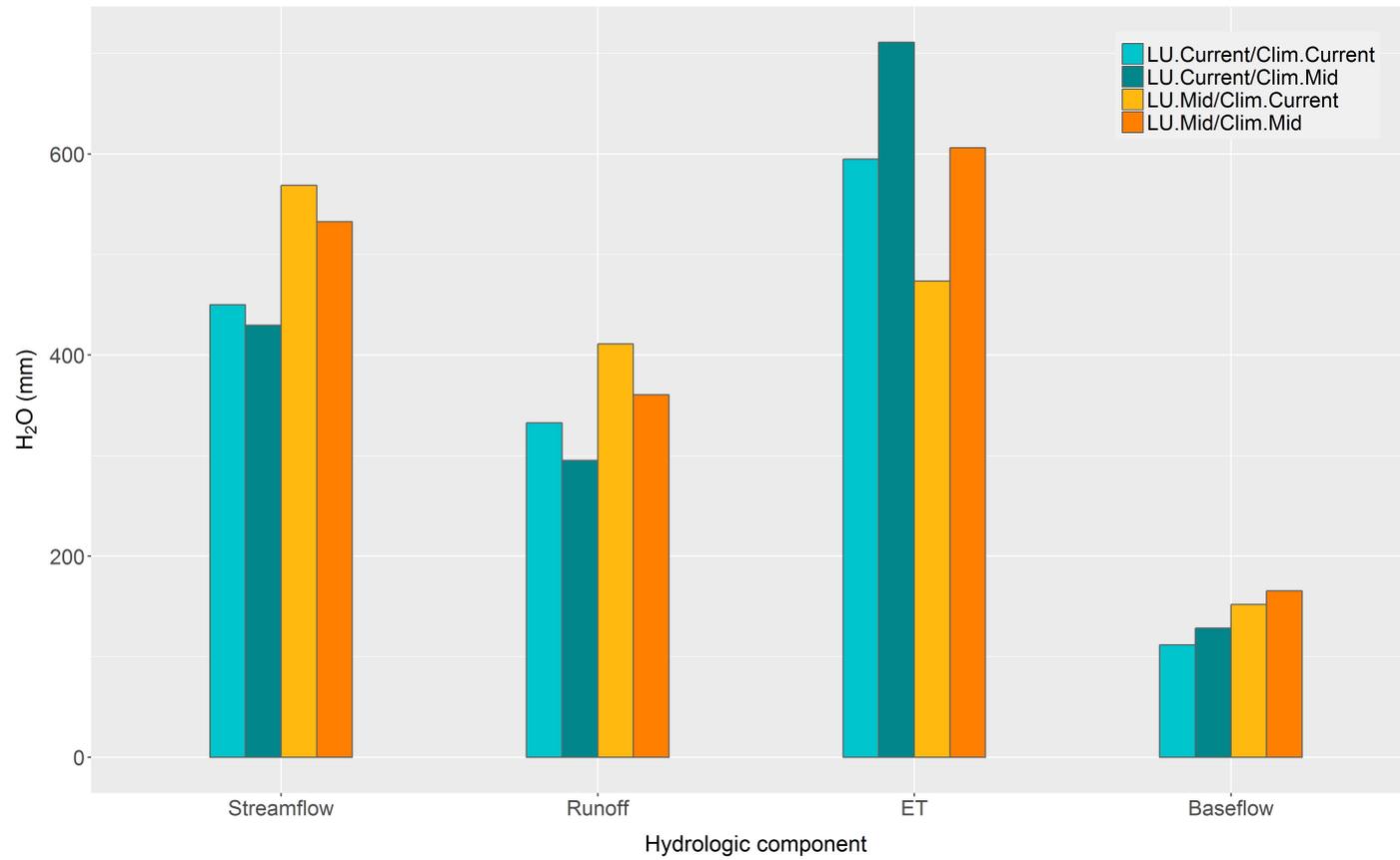


Figure 16: Estimated seasonal mean changes (relative to baseline scenario) for simulated hydrologic variables for the (climate change only) Δ_{CC} , (urbanization only) Δ_U , and (climate change & urbanization) Δ_{UC} scenarios.

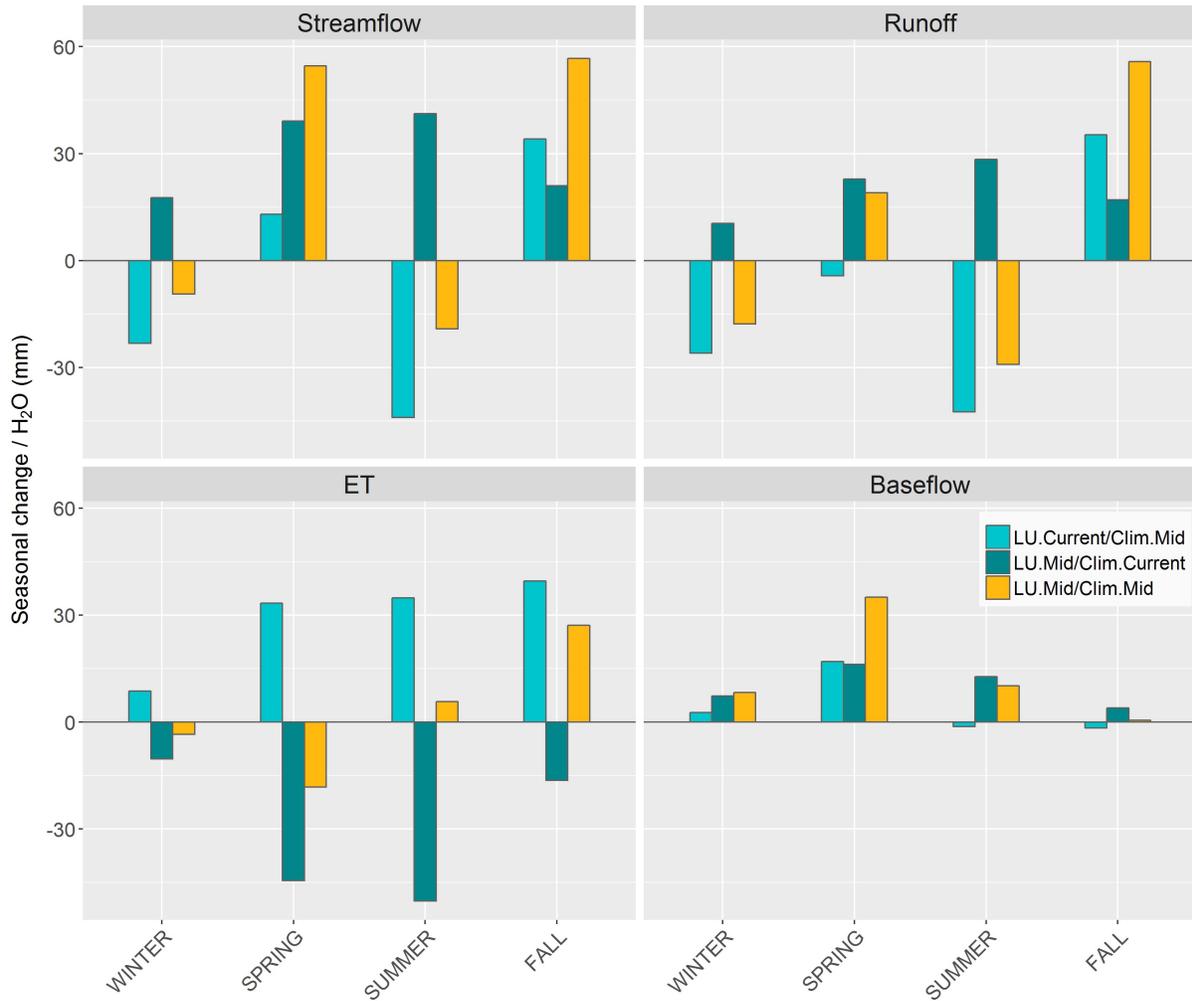
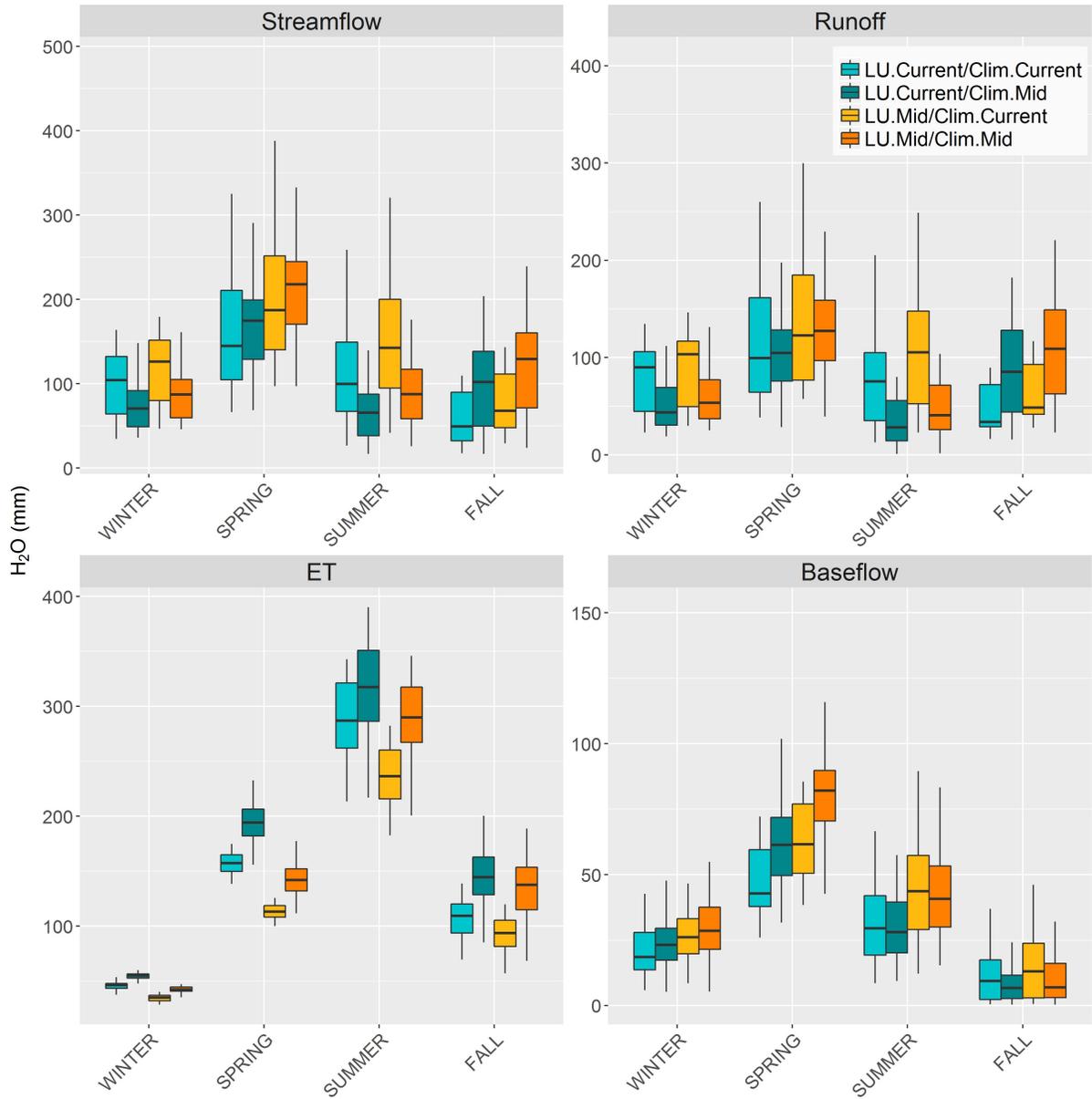


Figure 17: Estimated seasonal variability (box-plots) for water regime processes for the current, (climate change only) Δ_{CC} , (urbanization only) Δ_U , and (climate change & urbanization) Δ_{UC} scenarios.



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Chapter 5: Conclusions and synthesis

5.1 Conclusions

The goal of this research was to develop and utilize an integrated modeling approach to characterize potential changes to the water regime in Hinkson Creek Watershed (HCW), in Boone County, Missouri. The research consisted of three main objectives: 1) to couple a CA-based urban growth model with a process-based hydrologic model in order to investigate the potential impacts of urbanization on hydrologic processes in HCW, 2) to develop climate scenarios using downscaled global circulation model (GCM) output and couple these with a process-based hydrologic model to estimate the potential impacts of 21st century climate changes on streamflow related processes in HCW, and 3) to use downscaled GCM output along with a CA-based urban growth model and a process-based hydrologic model to analyze the combined effects of both mid-21st century climatic changes and urbanization in hydrologic processes in HCW. The research was successful in characterizing potential changes to streamflow related processes arising from both urbanization and climatic changes in HCW using a variety of urban growth and climate change scenarios. Results from this work contribute to a currently limited body of research investigating potential hydrologic changes using integrated modeling techniques, provide detailed estimates of potential changes to hydrologic processes in HCW, provide a basis for comparison for other researchers, and present modeling frameworks that are transferrable and can be utilized for watersheds in various regions.

In the first portion of this research, a framework was presented for assessing the impacts of future urban growth on watersheds using a CA model (I-CAT) capable of simulating pixel level imperviousness, along with a semi-distributed watershed hydrologic model (SWAT). The study represented an improvement over approaches used in other studies as grid-based estimates

of the percentage of imperviousness were used, rather than binary or limited urban classification schemes, which can obscure the effects of urban growth on various components of the water regime. Estimates derived from the study indicated that annual streamflow volume in HCW could increase during the next two decades, a result of the combined influences of increased surface runoff, evapotranspiration decreases, and baseflow increases. The respective impacts of the growth scenarios on hydrologic processes in HCW were more variable when the time of year and amount of precipitation were taken into consideration. The analysis also emphasized the fact that a controlled urban growth pattern does not necessarily produce less pronounced hydrologic impacts than an uncontrolled growth pattern, and such a growth strategy might not yield expected management results. Results from the study also highlighted the fact that large portions of future urban growth in the Columbia, Missouri area are likely to be developed outside of HCW, which emphasized the importance of considering adjacent watersheds when developing future land management and urban planning strategies.

The second portion of the research presented an approach that utilized downscaled climate data for multiple scenarios with a semi-distributed hydrologic model (SWAT). To address uncertainty associated with climate model projections, a multi-model approach was used wherein output from two CMIP5 GCMs was used to encompass a range of future conditions. All available downscaled climate projections for HCW were analyzed to determine the models and scenarios that represented the severe and conservative climate change scenarios for the study watershed. The results indicated that projected changes to climate in HCW could lead to annual streamflow and surface runoff decreases under both scenarios during the mid and late portions of this century. Estimates also indicated that streamflow and runoff in HCW could decrease substantially for most seasons, scenarios, and time periods, with the notable exceptions of spring

and fall during the mid-21st century under the severe change scenario. The results also showed that ET could increase annually and seasonally under all scenarios and time periods. Given these findings, there will likely be decreases to surface water in HCW under even the most conservative climate projections. Considering such potential decreases raises questions about management approaches that primarily involve the reduction of surface runoff, as such approaches might exacerbate water scarcity issues. Since Hinkson Creek is typical of many streams in central Missouri, this study also provided an example of how similar watersheds could respond to climate changes. The study results also helped fill the need for more information on how projected climate changes could impact watershed processes in watersheds in the Midwestern United States, an area for which there is currently limited research, particularly using the latest suite of climate models.

In the third portion of the work, an integrated modeling approach for assessing the individual and combined effects of mid-21st century urbanization and climatic changes on hydrologic processes in HCW was presented. This approach used downscaled GCM output from the latest generation of climate models and impervious surface growth projections derived from a CA-based urban growth model (I-CAT), along with a semi-distributed hydrologic model (SWAT). Multiple urbanization and climate scenarios were developed and used to determine the relative impacts of the two stressors. The results showed that urbanization had a larger impact than climate change on streamflow and surface runoff at the annual time-scale, leading to overall increases for those processes. However, climatic changes in HCW had a greater impact on the same processes during winter and summer, and directional changes for streamflow for the two stressors matched during spring and fall. It was also found that mid-21st century urbanization in HCW could cause annual and seasonal ET decreases, while the opposite was true under mid-

century climate. When both factors were considered, urbanization almost entirely offset the impacts of climate change on ET at the annual time-scale. At the seasonal time-scale, however, large increases to ET resulting from climatic changes were observed during fall under the multiple effects scenario. Thus, while neither stressor had drastically larger impacts on water regime processes in HCW at the annual time-scale when both factors were considered, there were clear instances when one stressor was more influential than the other during various seasons. There were also instances when the sign of the change for the two stressors was the same for some hydrologic processes during certain seasons. The results underscored the importance of seasonality when considering the combined impacts of potential land-cover and climatic changes on hydrologic processes, as the relative importance of each stressor can vary by season. Results from the study also characterized potential mid-21st century water regime conditions for HCW under multiple scenarios and added to the limited body of research using such integrated modeling techniques to estimate potential changes to hydrologic processes.

It should be noted that the modeling approaches presented in this research are best suited to assist in developing watershed management strategies by characterizing trends of hydrologic changes resulting from urbanization and climate change, rather than for purposes such as flood estimation, as the modeling framework likely tends to underestimate peak flows. For example, it has been shown that SWAT sometimes underestimates peak flows (Gassman et al., 2014), and the model was calibrated and validated at the monthly, rather than daily, time-scale for this study. Model output data for SWAT were also summarized at monthly, seasonal, and annual time-scales. Additionally, urbanization is often associated with intensified peak flows (Arnold & Gibbons, 1996) and projected climatic changes for this region include a higher incidence of intense precipitation events (Pryor et al., 2014), so the work presented here likely does not

capture some of the more extreme hydrologic events that could result from these phenomena. The hydrologic routing approach used by SWAT presents another potential source of modeling uncertainty (Neitsch et al., 2009), as the spatial resolution within a watershed is dependent on sub-basin discretization. Since this semi-distributed approach differs from a fully distributed modeling framework, some fine scale effects of land-cover changes (e.g. impervious surface development) could be obscured. It should be mentioned, however, that previous research has shown that model performance for semi-distributed and distributed models can be similar (Abu El-Nasr et al., 2005). Based on these concerns, the opportunity exists for future investigations exploring the effects of urbanization and climatic changes on hydrologic processes in HCW at finer temporal and spatial scales. Such investigations could involve daily or sub-daily (event based) analyses and fine-scale, spatially distributed physical watershed discretizations.

Ultimately, this research presented novel integrated modeling approaches for estimating the potential impacts of urbanization and climatic changes on hydrologic processes. The first portion of the research investigated the impacts of multiple urbanization scenarios on hydrologic processes in HCW over the next two decades, while the second portion investigated the impacts of mid- and late-21st century climatic changes on hydrologic processes in HCW. For the third portion of the work, the impacts of both mid-21st century climatic changes and urbanization on hydrologic processes in HCW were assessed. The research provided new insight into how two of the most significant stressors affecting water resources might impact the water regime in a watershed in the Midwestern United States. Aside from providing direct estimates of hydrologic changes for HCW that can be referenced by local planners and decision makers, the results from these studies provide a basis for comparison for other watersheds that share similar characteristics. This work also contributes to the field of integrated modeling in natural

resources, as there is currently a paucity of research investigating the potential impacts of urbanization and climatic changes on water resources, particularly using high-resolution impervious cover estimates and data from the most recent suite of climate models. In addition, the approaches presented here provide a transferrable modeling framework that can be used by decision makers to analyze watersheds in other regions and help to develop urbanization and climate change mitigation strategies, rather than using reactive watershed management approaches. Additionally, a collaborative adaptive management (CAM) process in HCW is ongoing. This CAM process involves synthesizing input from multiple stakeholders and agencies to establish and achieve water quality benchmarks for HC using a science-based approach. By providing estimates of potential future water regime changes, the information presented in this work can be used by managers to inform such management processes to assist in achieving water quality goals in Hinkson Creek going forward, as urbanization and climatic changes will continue to pose significant future challenges.

5.2 Synthesis

Results from this research contribute to the growing body of work that has been conducted in HCW. Past studies in HCW have investigated surface and groundwater dynamics, the hydrologic characteristics associated with various land-covers, watershed physical and hydroclimatic processes, stream chemistry, and stream habitat conditions (Brown, 2013; Hooper, 2015; Hubbart et al., 2011; Hubbart & Zell, 2013; Hubbart et al., 2014a; Hubbart et al., 2014b; Kellner et al., 2015; Kellner & Hubbart, 2016; Nichols, Hubbart, & Poulton, 2016; Zeiger & Hubbart, 2015; Zeiger & Hubbart, 2016; Zell, Kellner & Hubbart, 2015). Studies in HCW in which the influences of different vegetative land-cover types on soil hydrologic properties (e.g. infiltration bulk density, porosity, volumetric water capacity) were analyzed showed that

groundwater movement can vary significantly between land-cover types (Hubbart et al., 2011; Zell, Kellner, & Hubbart, 2015). In these studies it was demonstrated that bottomland forested areas had higher infiltration rates and greater water storage capacity compared to former agricultural sites, particularly at shallow depths. In addition, it has been found that bottomland hardwood forests in HCW are more seasonally responsive than agricultural sites dominated by grasses, with higher wet season flows and lower dry season flows (Kellner & Hubbart, 2016). Results from hydrologic modeling studies in HCW also revealed that increased runoff, stream sediment concentrations, and stream temperatures were associated with higher proportions of urbanized area in the watershed (Hubbart et al., 2014a; Zeiger & Hubbart, 2015). In addition, a comparative analysis revealed that ET at the Hinkson bottomland hardwood forest was greater than that of the former agricultural site (Brown, 2013). By comparing nested sites in the watershed and a nearby rural site, Hubbart et al. (2014b) also demonstrated that urban heat island effect could influence changes to the urban energy budget, as well as temperatures and precipitation patterns in HCW. An analysis of long term hydrologic responses to urbanization in HCW showed that, while baseflow and runoff tended to decrease after the mid-20th century period in HC, both began to increase during the 21st century (Hubbart & Zell, 2013). It has also been found that high flow events in urbanized areas can serve as a disturbance affecting the composition of aquatic biota in HC, and that urban stream system condition can in turn be characterized by species assemblages in such systems (Nichols, Hubbart, & Poulton, 2016).

Findings from the aforementioned studies provide additional context for the dissertation research presented here. For example, it was found that ET was greater in forested sites compared to former agricultural sites. Similarly, findings presented in chapter 2 indicated that ET could decrease as forested areas in HCW were replaced by urban development. This removal

of forest cover included the addition of residential lawns, which were particularly prevalent with low density development and are similar in character to the former agricultural site, as it is largely dominated by grass cover. While previous work in HCW indicated that bottomland forests were capable of draining and storing a larger amount of water compared to bottomland areas dominated by grasses, results presented in chapters 2 and 4 suggested that the replacement of forested cover by additional residential yards could lead to increased baseflow. It is possible that this discrepancy is the result of the site locations used for the respective studies. In previous work, forested and former agricultural sites were compared only in bottomland areas, whereas the focus of this research was on the watershed as a whole. Nevertheless, these differences highlight potential uncertainty with respect to the dynamics of groundwater movement and storage and present an interesting area for future research in comparing groundwater dynamics for multiple land-cover types across a variety of topographical and geomorphological sites in HCW. Previous studies demonstrating the relationships between urban development density and increased stream sediment concentrations, physiochemical concentrations, and stream temperatures also underscore the importance of characterizing the future effects of urbanization on water regime processes such as surface runoff, which can drive changes to such water quality indicators. In addition to urbanization, future climatic changes are also likely to contribute to changes to water regime processes, and the integrated modeling approaches presented here can be a useful tool for managers seeking to define water quality goals for HC based on expectations of potential future conditions. Previous findings indicating recent increases to baseflow in HC during a time of extensive urbanization reinforce results presented in chapters 2 and 4, in which baseflow increases under multiple urban growth scenarios were observed. However, findings from the same study showed downward trends for baseflow and runoff after the mid-20th

century, which coincided with a period of intensified urbanization, as the period following 1960 corresponded with large population increases subsequent to the construction of Interstate 70 through Columbia (and HCW). Differences between hydrologic responses for the mid-20th and early 21st centuries could be the result of complicated land-cover change dynamics associated with different types of urbanization. For example, mid-20th century urban developments in the area were relatively denser, with smaller residential yards compared to those of the early 21st century, and sufficient time has passed for the reestablishment of vegetation (e.g. mature trees) on areas cleared during mid-20th century development. The aforementioned findings in HCW also presented the reestablishment of previously cleared riparian corridors (i.e. bottomland hardwood forests) as a potential strategy for mitigating water quality and quantity issues associated with urban development. The efficacy of implementing such a strategy could be tested using an inverse problem approach along with the modeling approaches presented here in order to determine the vegetation implementation and land-use management strategies that are most suitable for attaining water quality goals in HCW.

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Vita

Michael Sunde was born in Rolla, Missouri. After leaving the state, his family returned and he spent most of his formative years in Jefferson City, Missouri. He graduated from the University of Missouri in 2009 with a degree in Geography, emphasizing on geoinformation science, and received the University of Missouri Geoinformation Science certificate. After graduation, he began working as a GIS analyst at the Missouri Research and Education Network, where he conducted spatial analysis and cartographic design. With a desire to focus his geospatial skills into the field of natural resources, he returned to the University of Missouri to attend graduate school in 2010. During this time, he was extended the opportunity to pursue a doctorate in Natural Resources. He accepted this privilege and challenge and hopes to continue working in the field of research and education, focusing on addressing environmental issues through spatial modeling and analysis.