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A Conceptual Modeling Framework for Hydrological Ecosystem Services and Its Application to the Impacts of Climate Change and Urban Expansion

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A CONCEPTUAL MODELING FRAMEWORK FOR HYDROLOGICAL ECOSYSTEM SERVICES AND ITS APPLICATION TO THE IMPACTS OF CLIMATE CHANGE AND URBAN EXPANSION

by

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ABSTRACT

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Under the Supervision of Professor Woonsup Choi

Ecosystem services (ESs) are used as intermediates for researchers, stakeholders, and the public to understand and deal with the current environmental situation and problems, and ESs-related studies have drawn increasing attention. The quantitative assessments of ESs to calculate how much the ecosystem can benefit human beings and society, are still under development. Hydrological ESs, a subset of ESs that is related to water bodies and the surrounding environment, carry several challenges and opportunities for both hydrological and ESs modeling. Specifically, new quantitative tools with the capability to simulate explicit spatial and temporal scales are desired, and such tools should be comprehensive and include climate, geology, land cover, soil, and topography. Also, studies of the impacts of land use/landcover (LULC) and climate changes on hydrological ESs are limited by the current methods and techniques.

This dissertation study was designed to achieve the following objectives: (1) build a coupled modeling framework so that hydrological information can be converted to hydrological ESs by developing a conceptual connection between three functions: data development, modeling, and results analysis; (2) demonstrate the importance of hydrological ESs at fine temporal scales by simulating hydrological ESs with the framework in the case study; (3) examine impacts of LULC and climate changes on hydrological ESs (water provision, flood regulation, and sediment regulation) with the framework and a series of climate and urban expansion scenarios in the Milwaukee River basin, USA.

The framework was designed (objective 1) with integration of data processing, hydrological and ESs modeling, and output analysis which are supported by national data products. With such procedural streamlining, simulation of hydrological ESs are more straightforward and less time-consuming than the separated processes. This framework resolves the design limitations of both current ES models that cannot simulate at fine temporal scales and hydrological models that cannot convert hydrological information to ESs.

Results from the fine temporal analyses (objective 2) of water provision ES, flood regulation ES, and sediment regulation ES indicate that that annual results alone in ESs simulation and analysis for management plans are not adequate for time-sensitive planning and including results at fine temporal scales is necessary for some ESs that are event-based or have large seasonal variations. Based on such results, more timely relevant policy suggestions can be provided to decision-makers.

Results of objective 3 showed that, compared to LULC, the climate-change scenarios have much larger impacts on hydrological ESs, and results under climate change show quite large variations among different climate models, years, and months. Additionally, the interactions among different ESs have also been identified. This approach with the framework and impact scenarios can better support management plans with different scenarios for decision-makers.

In summary, the framework designed in this study is an innovative tool that resolves the issue of fine temporal scales that cannot be addressed with current tools and methods, and contributes to the impact studies under LULC and climate changes with new insights from multiple variations and interaction analyses.

Dedicated to

my parents,

my wife,

and my son

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CHAPTER 1. INTRODUCTION

1.1 Problem Statement

ESs, which are defined as “benefits that people obtain from ecosystems” (Millennium Ecosystem Assessment (MA) 2005, p. 40), are used to help deal with environmental problems such as biodiversity decline and global warming (de Groot et al. 2010). It includes provisioning, regulating, supporting, and cultural services (MA 2005). Although studies have been conducted to quantify the value of ESs over the decades, assessment tools such as ESs models are still under development (Bagstad et al. 2013a). Without quantitative evaluations of the value of ESs, the importance of these services does not draw the attention of decision-makers (Nelson et al. 2009). Hydrological ESs, a subset of terrestrial ESs related to water, are also affected by complex interactions of many environmental factors and require a robust understanding and the skills for prediction and assessment (Guswa et al. 2014).

Three specific problems regarding how to improve ESs modeling will be discussed, as follows:

(1) Studies related to temporal scales of ESs are limited. Temporal scale is very coarse in previous studies, usually on an annual basis (Kandziora et al. 2013) and is not afforded the attention it merits. ESs are not homogenous spatially and temporally, which causes the scale issue in ecological research (Zhang et al. 2013). Most ecological functions are non-linear across space and time; however, such temporal non-linearity has been ignored by previous simulation studies (Koch et al. 2009).

Specifically, for hydrological ESs, temporal-scale issues are critical. The hydrological ESs is controlled by the water availability temporally (Chang and Bonnette 2016). Limited studies have been conducted with a focus on hydrological ESs (e.g. Bai et al. 2013; Gao et al. 2017; Leh et al. 2013; Samal et al. 2017; Yang et al. 2015), with only a few of them on a seasonal basis (e.g. Notter et al. 2012; Schmalz et al. 2016). For instance, some hydrological processes (e.g. floods), are highly associated with fine temporal scales (daily and hourly) and a complete understanding of such processes for ESs modeling is particularly important (Kaptue et al. 2015). Because floods have short time frames, annual results may not be adequate for management activities (Haile et al. 2011). Previous ESs studies focused on sediment regulation also with annual outputs (Gao et al. 2017; Leh et al. 2013; Logsdon & Chaubey 2013). In general, they tested different LULC scenarios on the study areas to calculate different sediment yields for comparison and tradeoffs, neither of which captures the seasonal changes in sediment associated with extreme hydrological events nor provides guidance as in this study and Schmalz et al. (2016). As mentioned earlier, ESs models were limited to the annual scale with their design, and most studies focused on the tradeoffs of different LULC scenarios or mapping of the spatial distribution of ESs (Bai et al. 2013; Gao et al. 2017; Guswa et al. 2014; Leh et al. 2013). Other hydrological models capable of simulating hydrological variables at fine temporal resolutions were also utilized in previous studies (Logsdon & Chaubey 2013; Notter et al 2012; Schmalz et al. 2016), but only Schmalz et al. (2016) conducted their study at the seasonal scale. Thus, further studies at fine temporal scales in hydrological ESs are still needed.

(2) Climate-change impact does not merit enough attention compared to LULC-change impact. LULC and climate-change are the two main factors impact spatial and temporal heterogeneity of ESs (Hoyer & Chang, 2014; de Groot et al. 2010; Schröter et al. 2005). Urban expansion with increased population is one of the dominant LULC change that would influence the supply and demand of numerous types of ESs (Eigenbrod et al. 2010). Several studies have

explicitly considered the impacts of LULC change on ESs (e.g. Estoque & Murayama 2012; Logsdon & Chaubey 2013; Polasky et al. 2010). However, how climate change will impact ESs has not been well studied compared to LULC-change impacts (Shaw et al. 2011). Based on the current climate projections, if mean annual water volume remains at the same level under climate change, the increased seasonal variations of water volume and frequency of extreme hydrological events (e.g. floods, droughts) will have substantial effects on hydrological ESs (Chang & Bonnette 2016). When considering hydrological ESs, climate-change impact must be included because it is the major factor affecting the quantity and timing of water movement (Hoyer & Chang 2014).

Several issues are revealed in impact studies. First, different ESs are not independently existed, but they have either positive or negative relationships under LULC and climate-change impacts (Rodríguez et al. 2006; Tilman et al. 2002). One ES could serve as impact factor for another ES, and all the ESs are interrelated (Fan et al. 2016). Changes in one ES leading to opposite effects of other services should be mitigated, while the ones that affect each other positively should be enhanced in management plans (Chan et al. 2006). Second, the combined effects of both LULC and climate change are hard to analyze because of the difficulties of downscaling from global to regional, or from annual to daily, the uncertainties, and the interactions of the two factors (Wu 2014). Techniques for identification and calculation of the relative importance of each driver and combined effects of changes are still under development (Bai et al. 2019). Earlier studies quantitatively assessed ESs under LULC or climate change separately even though those changes occurred simultaneously (Fan et al. 2016). Finally, studies of impacts of climate change on hydrological ESs have been conducted with general circulation models (GCMs), but uncertainties from GCMs are often the largest sources of uncertainties in such studies (Chen et al. 2011; Woldemeskel et al. 2012; Zhang et al. 2014). Few studies have focused on analysis and discussion of the interactions among different ESs, the relative importance of each factor, the uncertainties of GCMs, or the fine temporal scales. Thus, further studies that can assess impacts of LULC and climate change on hydrological ESs with a focus on interaction among ESs, combined effects of both factors, climate model uncertainties, and fine temporal scales are greatly needed.

(3) Coupled modeling frameworks can take advantage of both ESs and hydrological models, but such studies are limited. Converting hydrological information from modeling is appealing because it provides common values that are easy to understand, but it requires translation processes that hydrological models do not contain (Guswa et al. 2014). ESs models are still under development, and currently still operate at an annual scale (Guswa et al. 2014). The interdependencies between different types of natural resources have been given attention, but integrated management methods for end users are still needed (van der Kwast et al. 2013).

Regarding hydrological ESs, the two most prominent tools—hydrological models with valuation tools and ESs models—have been applied, studied, and compared in numerous studies (Bagstad et al. 2013a; Chang & Bonnete 2016; Fan et al. 2016; Gao et al. 2017; Leh et al. 2013; Vigerstol & Aukema 2011). Some comprehensive, physically-based hydrological models (e.g. Soil & Water Assessment Tool (SWAT)) were used to estimate several ESs (Francesconi et al. 2016). ESs models, on the other hand, are orientation-designed and developed for ESs simulation with multiple other types of ESs other than hydrological models and thus have had the most applications in previous research (Vigerstol & Aukema 2011). Vigerstol and Aukema (2011) reviewed different types of hydrological ESs modeling tools and concluded that traditional hydrological tools provide more detailed scientific results, while ESs models are easier to understand by non-experts in presenting a general picture of ESs.

Some investigations of coupling hydrological and ESs models (e.g. Cline et al. 2004; Wlotzka et al. 2013) focus not on hydrological ESs but on other ESs, while other studies (e.g. Lemberg et al. 2002; Notter et al. 2012; Qiu & Prato 1998) simply use hydrological results as ESs for analysis. Except for tests with limited number of models for coupling (e.g. van der Kwast et al. 2013; Yalew et al. 2014), no good example of integrated coupling exists to date. Without a standardized framework for coupling these models, the modeling processes would be massive and redundant when unifying scales and formatting data during the conversion from hydrological models to ESs models. In addition, the data preparation, results analysis, and display would add unnecessary time. Methods and frameworks thus are needed for coupling models of hydrological ESs.

1.2 Research Objectives

The overall goal of this study is to design a conceptual modeling framework for quantifying multiple hydrological ESs at fine temporal scales. The specific research objectives of this study (Figure 1.1) are to:

(1) Build a coupled modeling framework so that hydrological information can be converted to hydrological ESs by developing a conceptual connection between three functions: data development, modeling, and results analysis (Chapter 2) (Objective 1);

(2) Demonstrate the importance of hydrological ESs at fine temporal scales by simulating hydrological ESs with the framework in the case study (Chapter 2) (Objective 2). The study will answer the following research questions:

- What are the hydrological ESs in term of annual average and annual changing trends?
- What are the hydrological ESs in term of monthly average and monthly changing trends?

- What is the difference between the results at monthly and annual scales?

(3) Examine impacts of LULC and climate changes on hydrological ESs with the framework and a series of climate and urban expansion scenarios in the Milwaukee River basin, USA (Chapter 3) (Objective 3). The study will answer the following research questions:

- How do LULC change impacts hydrological ESs compared to climate change?
- What are the variations and uncertainties among the hydrological ESs results with different climate models?
- What are the tradeoffs or synergies among different hydrological ESs?

The Milwaukee River basin was selected as study area based on the conditions that: (1) The southeast part of the basin, where the city of Milwaukee is located, is the most densely populated and urbanized area in the state, whereas the LULC in the northern portion consists primarily of agricultural land, both of which are the main LULC change classes that impact hydrological processes and further impact hydrological ESs. (2) Regional high-quality climate data and LULC data are available from previous related studies which could save time for the processes. (3) The gauging data of streamflow and sediment for the four gauges in the basin are continuous and complete which could support the hydrological calibration and validation to reduce modeling uncertainties.

To achieve Objective 1, I designed a conceptual-modeling framework in Chapter 2, including a data-development function, a modeling function with both a hydrological model and an ESs model, and a results-analysis function. The data-development function includes functionalities that support organizing, developing, and assigning spatial and temporal data into the hydrological and ESs models for setup. This function is based on a geographic information system (GIS) and model-attributes editor of the Hydrologic Simulation Program-Fortran (HSPF) (Duda et al. 2012). The hydrological and ESs modeling function executes hydrological and ESs simulations. Hydrological simulation based on HSPF is conducted on winHSPF.exe which is a user-interface of HSPF. The hydrological ESs simulations are based on three adopted equations from Logsdon and Chaubey (2013). The results-analysis function performs spatiotemporal analyses and visualization of the simulated outputs with a GIS platform and MATLAB modules.

For Objective 2, the framework was applied to the basin with substantial urban LULC. In this paper, I evaluated three hydrological ESs at finer temporal scales compared to previous studies. National datasets were prepared in the data-development function for both hydrological and ESs models. Then the HSPF model was set up, calibrated, and validated. Next, hydrological simulations together with ESs datasets were input to the ESs model with three adopted calculation methods for simulation. Finally, results from both hydrological and ESs modeling were input to the results-analysis function to get annual, annual average, monthly, and monthly average results and figures for comparison.

To achieve Objective 3 of the study, the impacts of LULC and climate changes on hydrological ESs, the framework was applied to the study area with four scenarios named baseline, LULC, climate, and combined, so that each impact could be calculated separately and compared. The baseline scenario was built with historical climate and LULC data. The future LULC scenario was developed with a cellular-automata (CA) model with current and historical LULC maps and an urban-expansion mechanism. The future climate scenario was designed with projections of statistical downscaled climate models. The combined scenario used both future LULC and climate data. The calibrated and validated HSPF was executed with the new dataset, and then hydrological simulations were used in ESs modeling. Finally, the results were analyzed and displayed by the results-analysis function.

1.3 Dissertation Organization

This dissertation includes four chapters. Chapter 1 includes the problem statement and research objectives. Chapter 2 has the design of the conceptual-modeling framework for hydrological ESs and a case study to test the importance of fine temporal scales. Chapter 3 evaluates the impacts of LULC and climate changes on hydrological ESs in the study area. Chapter 4 summarizes the major research findings and provides recommendations for future research. At the time of this submission, the work in Chapter 2 and 3 have already been published in peer-reviewed journals. The framework design, once converted from conceptual to an actual user-interface tool, will also be published.

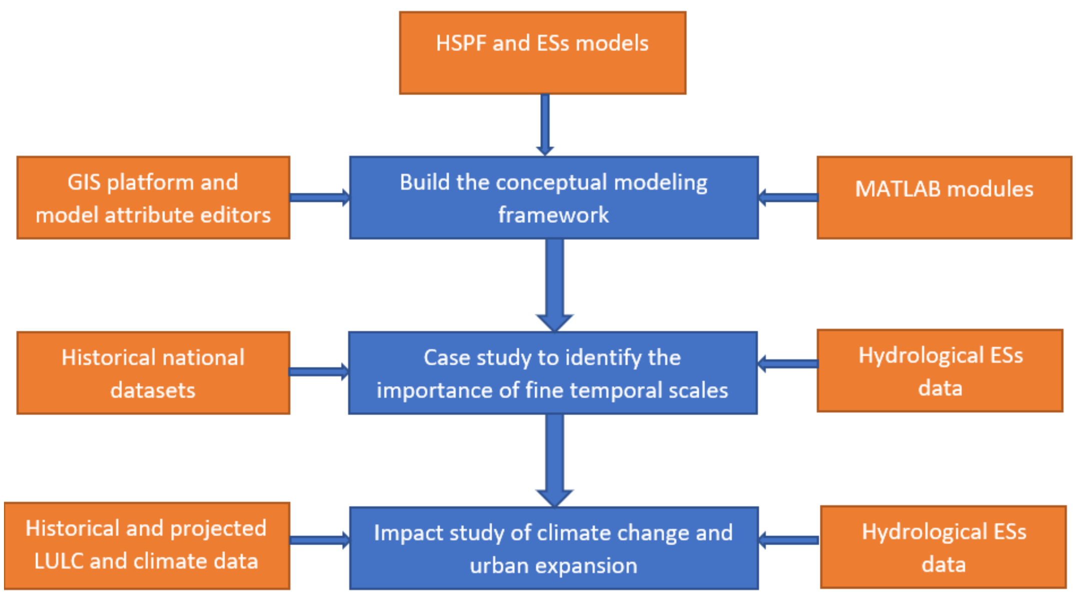


Figure 1.1. Flowchart of the research

CHAPTER 2. A CONCEPTUAL MODELING FRAMEWORK FOR HYDROLOGICAL ECOSYSTEM SERVICES

Abstract

ESs help people understand and deal with current environmental situations and problems, and ESs-related research has been increasing recently. However, the quantitative evaluations of ESs that can be easily understood by decision-makers are still in development. Specifically, new methods are needed for hydrological ESs with the requirements of spatially and temporally explicit variables related to different environmental factors. This paper presents a conceptual modeling framework that aims to convert hydrological information to hydrological ESs at fine temporal scales by developing a conceptual connection of three functions: data development, hydrological and ESs modeling, and results analysis. Then, the framework was applied to a study basin to demonstrate the importance of hydrological ESs at fine temporal scales. Results of water provision ES, flood control ES, and sediment regulation ES were produced at fine temporal scales in the framework, which indicates that timely and relevant policy suggestions can be provided to decision makers. The framework and the methodology can be applied to different watersheds and offer a template for future coupling of different environmental models.

Keywords: conceptual framework; hydrological modeling; ecosystem services modeling; hydrological ecosystem services

2.1 Introduction

Human beings benefit enormously from the functions of ecosystems at various scales; such functions include the food and water provision, air and climate regulation, and recreational amenities (de Groot et al. 2010). The benefits that human beings obtain from ecosystems are referred to as ESs (MA 2005). Although studies have been conducted to identify and value ES over the decades, the development of assessment tools such as ESs simulation models is still new (Bagstad et al. 2013a). Without quantitative evaluations of the actual benefits that can be obtained from ecosystems, the importance of these services does not draw adequate attention from decision-makers (Nelson et al. 2009).

Hydrological ESs, a subset of terrestrial ESs related to water, are affected by the interactions of various environmental indicators and require a robust understanding and the skills for prediction and assessment (Guswa et al. 2014). Hydrological models can simulate spatially and temporally explicit hydrological processes, and enhance the understanding of hydrological processes (Bhatt et al. 2014). However, most hydrological models are not designed to include functions that convert hydrological results to the ESs as easily understood by decision-makers (Guswa et al. 2014). On the other hand, ESs models are still under development, and hydrological ESs simulation is limited (Guswa et al. 2014).

ESs models and related quantitative research that have been built and conducted are limited in several ways. For example, the two ESs models that have been mostly applied, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Tallis & Polasky 2009) and Artificial Intelligence for Ecosystem Services (ARIES) (Villa et al. 2011), are comprehensive ESs models that cover many kinds and aspects of ESs. However, neither of these two models uses temporally explicit methods to model hydrological ESs, nor can they generate temporally explicit results. More importantly, temporal-scales issues with ESs modeling have not been studied in detail. The complex hierarchical organization of natural processes and heterogeneity across time and space make the scale of ecological research very important (Zhang et al. 2013). Furthermore, the beneficiaries of natural ESs and their observation systems are in different spatial and temporal scales (Scholes et al. 2013). Most ecological functions are nonlinear spatially and temporally; however, such temporal nonlinearity has been ignored by previous studies without considering corresponding temporal scales to simulate the nonlinearity of ESs (Koch et al. 2009).

Combining ESs and hydrological models can improve them both, which would effectively accelerate the ESs modeling processes that need fine scales. Studies have been conducted to couple different types of hydrological and ESs models for hydrological ESs (e.g. Cline et al. 2004; Wlotzka et al. 2013). To achieve the goal of converting hydrological information to ESs with fine scales, I designed a conceptual modeling framework in this paper, including a data development function, a modeling function with a hydrological model and an ESs model, and a results analysis function. With this framework, I established procedures for hydrological ESs data preparation, simulation, and analysis supported by national geospatial data products. This framework could help decision-makers easily understand hydrological ESs. The framework was applied to a basin with substantial urban land covers. In this paper, I evaluated three hydrological ESs variables at fine temporal scales (monthly and average monthly).

The first hydrological ES is water provision ES. Limited studies have been conducted with a focus on hydrological ESs (e.g. Bai et al. 2013; Gao et al. 2017; Leh et al. 2013; Samal et al 2017; Yang et al. 2015), with only a few of them on a seasonal or monthly basis (e.g. Notter et al. 2012; Schmalz et al. 2016). Compared to Notter et al. (2012), who used monthly hydrological results to calculate the ESs indices, this study not only uses daily hydrological data but also produces monthly and seasonal ESs indices which can provide more detailed information for decision-makers. Like Schmalz et al. (2016), the seasonal ESs has been calculated to capture the high and low water provisions in different seasons. Furthermore, this study also compares annual and monthly changes to highlight the necessity of fine-temporal-scales results.

The second hydrological ES is flood regulation ES. Because floods have short time frames, annual results may not be adequate for management activities. With the ability of this framework to simulate monthly and seasonal ESs output, these extreme events could be captured, and related remedies could be designed. Unlike previous ESs studies (e.g. Logsdon & Chaubey 2013; Samal et al. 2017), the flooding regulation ESs simulated in this study can not only predict the annual flooding risk but also pinpoint the months and seasons when regulation for ES should be applied.

The third hydrological ES is sediment regulation ES. When it comes to sediment regulation, even if sediment yields were low in a year, they could be quite high in some months; thus, attention should be given to such months. Previous ESs studies focused on sediment regulation with annual outputs (Gao et al. 2017; Leh et al. 2013; Logsdon & Chaubey 2013). In general, they tested different LULC scenarios on the study areas to calculate different sediment yields for comparison and tradeoffs, neither of which captures the seasonal changes in sediment associated with extreme hydrological events nor provides guidance as in this study and Schmalz et al. (2016).

In short, this study focuses on finding the changes in hydrological ESs at fine temporal scales compared to previous hydrological ESs studies. As mentioned earlier, ESs models (e.g. InVEST) were limited to the annual scale with their design, and most of the studies focus on the tradeoffs of different LULC scenarios or mapping the spatial distribution of ESs (e.g. Bai et al. 2013; Gao et al. 2017; Guswa et al. 2014; Leh et al. 2013). Other hydrological models (e.g. SWAT) capable of simulating hydrological variables at fine temporal scales were also utilized in previous studies (e.g. Logsdon & Chaubey 2013; Notter et al. 2012; Schmalz et al. 2016), but only Schmalz et al. (2016) conducted their study at the seasonal scale and the smallest hydrological unit in SWAT. Thus, further studies at fine temporal scales in hydrological ESs are still needed.

The novelty of this work lies in developing the conceptual framework and demonstrating the importance of evaluating hydrological ESs at fine temporal scales compared to previous studies (Schmalz et al. 2016). The results of the framework showed that hydrological ESs were temporally sensitive, and with this conceptual modeling framework, these changes at fine temporal scales could be captured and relevant management plans and policies could be made accordingly.

The upcoming sections of this article provide details of this framework. Detailed literature of current problems of research is discussed in Section 2.2. In Section 2.3, I introduce hydrological and ESs models used for the framework and explain each function in the framework. I also describe data sources and the study site in Section 2.3. Results and discussion for each ES are provided in Section 2.4, followed by conclusions in Section 2.5.

2.2 Literature review

2.2.1 Hydrological ESs

ESs are the benefits people receive from the conditions and processes of ecosystems, including provisioning, regulating, supporting, and cultural services (MA 2005). Hydrological ESs are the benefits obtained from ecosystems reliant on supply of water (Brauman 2015). These benefits provided by ecosystems include (de Groot et al. 2010):

(1) Provisioning services include water supply for drinking, agricultural use, hydropower, transportation, and industrial use.

(2) Regulation services

- Climate regulation. Ecosystems can influence climate through LULC change and sequestering or emitting greenhouse gases through biologically-mediated processes.

- Water regulation. The changes in ecosystems, for instance converting some high-water storage LULC (wetland, forests, etc.) to some low ones (farmland, urban, etc.), could significantly affect the hydrological ESs.

- Erosion regulation. The changes in runoff and LULC can affect soil retention and the prevention of landslides.

- Water purification and waste treatment. Biotic and abiotic processes can purify polluted water and can remove and decompose organic wastes.

(3) Cultural services include recreation, ecotourism, and biodiversity.

(4) Supporting services include soil formation and oxygen production.

In order for decision-makers to easily assess the value of the ESs, they need the ESs to be expressed commonly and connect to general values (Carpenter et al. 2015; Nelson et al. 2009; Qiu & Turner 2015). Additionally, improved quantification methods are needed to model the mutual interactions among different ESs and to help make management decisions for conservation of ESs (de Groot et al. 2010). Guswa et al. (2014) provided content of hydrological ESs including scenarios analysis, payment for water services, spatial planning, and listed the general challenges such as appropriate scales, monetization of hydrological processes, and robustness when facing complexity. Monetizing hydrological information from modeling is appealing because it converts ESs to common currency for easy understanding, but it requires translation processes that are still under development (Guswa et al. 2014).

There are certain challenges in valuing ESs. Different types of ESs have different valuation methods, and those methods are based on different assumptions, and some of the methods are controversial (Kareiva 2011). Moreover, different ESs from various first-generation studies are usually not applicable to other locations (Guerry et al. 2015). Some of ESs cannot be estimated using any of the available methods due to data availability or the difficulty of extracting the desired information from the ecosystems, which could lead to underestimates or double-counting of the ESs (MA 2005). Indicators are needed for the ecosystem functions that contribute to ESs, and that are applicable to any other watersheds, and such indicators can be compared among different study areas or with different scenarios (Logsdon & Chaubey 2013). Connecting hydrological responses to ecosystem functions, Logsdon and Chaubey (2013) proposed and demonstrated five quantitative methods for provisional and regulatory ESs that could be applied generally through different watersheds, which were adopted in this study.

2.2.2 Temporal Scales

ESs are obtained non-homogeneously across time and space, which causes a scale issue in ecological research (Zhang et al. 2013). The scales and spatiotemporal extent of models should correspond with the biophysical and socio-economic processes they are associated (Agarwal et al. 2002). Ecosystems can offer different services at various spatial and temporal scales. For the spatial scales, an ecosystem can offer local services (e.g. streamflow regulation service by vegetation at the habitat and community level (Guo et al. 2000)), regional services (e.g. spatial valuation for agricultural products, forest products, and tourism services for a county (Cheng et al. 2006)), or global services (e.g. services in regard to CO_2, N and P cycling and sequestration, and climate regulation (Hufschmidt 1983)). In temporal dimensions, an ecosystem can offer long-term (crops and fodder provisioning services at annual scale (Kandziora et al. 2013)) or short-term services (e.g. wave attenuation provided by marshes, mangroves, seagrasses, and coral reefs at seasonal scales (Koch et al. 2009)). Both spatial and temporal scales in modeling need to match the scales of the actual services.

Compared to studies on spatial scales of ESs (e.g. Grêt-Regamey et al. 2015; Hein et al., 2006; Kandziora et al. 2013; Konarska et al. 2002; Wegehenkel et al. 2006), studies related to temporal scales of ESs are limited. Temporal scales are coarse, usually at an annual basis (Kandziora et al., 2013), and issues related them have not received the attention they merit. Most ecological functions are highly dynamic and non-linear across time (e.g. Farnsworth 1998; Gaston et al. 2000; Petersen et al. 2003). However, such temporal non-linearity has been ignored by some previous studies that lead to over/under estimation of the ESs (Balmford et al. 2002; Barbier 2007; Brander et al. 2006). Furthermore, for socio-ecological systems, providers and beneficiaries may not be at the same temporal scales, and connection should be built across scales (Heffernan et al. 2014; Hein et al. 2006; Seppelt et al. 2013;). Thus, non-linearity and cross-scales issued of temporal scales should be addressed in the future studies.

Specifically, for hydrological ESs, temporal-scale issues are critical. Temporal water availability determines the hydrological ESs (Chang & Bonnette 2016). The value of hydrological ESs could be very low during dry seasons even in the humid areas (Jaeger et al. 2013). Indicators of hydrological ESs should be quantifiable, scalable, and explicit in time and space (Bagstad et al. 2013a; Carpenter et al. 2015). In term of hydrological processes, the amounts of rainfall usually are expressed at coarse temporal scales (annual), though intensity of rainfall expressed at daily or hourly scales can impact the surface runoff and then cause flooding or droughts (Haile et al. 2011). A full understanding of rainfall-runoff events with corresponding temporal scales is particularly important for hydrological and ESs models for simulating ESs under environmental changes (Kaptue et al. 2015).

Previous studies were conducted with various spatially explicit models for environmental indicators and ESs, such as ARIES (Villa et al. 2009), Multiscale Integrated Models of Ecosystem

Services (Boumans et al. 2015), and InVEST (Bagstad et al. 2013b; Tallis et al. 2013; Tallis & Polasky 2009). However, fine temporal climate variability, which are projected to increase, were not captured by the previous studies (Hayhoe et al. 2007; Horton et al. 2014; Wood et al. 2002) It is important for capturing the temporal-scale issues related to water provisioning, flood and erosion regulation, and other ESs (Vigerstol & Aukema 2011). For example, InVEST does not operate at seasonal or monthly scales for nutrient loading so that management with such temporal scales could not be made (Bai et al. 2019). A fine temporal modeling method is required for time-fluctuating runoff and related hydrological ESs (Hoyer & Chang, 2014). With considering the time-fluctuating climate and LULC and the impacts of these changes, models that incorporate fine temporal scales for hydrological ESs modeling are crucial (Bagstad et al. 2013b). Lüke and Hack (2018) compared the results of the SWAT, the Resource Investment Optimization System model and InVEST in Nicaragua and found that SWAT has the most detailed temporal and spatial scales in ESs while the other two models are lower in scales. Schmalz et al. (2016) conducted the study with SWAT and transferred the results into ESs valuation at monthly scale (aggregated from daily results) to reveal some seasonal changes in water, vegetation, and erosion regulations which could provide important information for stakeholders. Nevertheless, all these studies have missed the fine-temporal-scales issue in hydrological ESs.

A standardized framework and method is needed for calculating ESs at fine temporal scales (Post et al. 2007). Without such framework, there will be a temporal mismatch between the data and the ESs, which would lead different analysis results as uncertainties (de Groot et al. 2002). Thus, building a standardized framework with the ability to capture the most appropriate temporal scales of ESs is crucial, especially for hydrological ESs.

2.2.3 Coupling models

The interdependencies between different types of natural resources have been given attention, but integrated management methods (e.g. coupling spatial planning tools) are needed for end users (van der Kwast et al. 2013). Integration of models of climate, ecology, hydrology, and socio-economic systems for ESs modeling are needed (Barth et al. 2004; Ludwig et al. 2003; Wechsung et al. 2008). These models are designed for different objectives and for different ecological processes (Arciniegas & Janssen 2012). These planning tools, however, only offer results for part of an ecosystem or one ES, and ignore the interactions between different ESs, which can cause assessment bias (van der Kwast et al. 2013). Thus, while developing models for future scenarios, feedback regarding different ESs needs to be taken into account. This requires dynamic coupling of several different models to address the interactions between different ESs.

Regarding hydrological ESs, the two most prominent tools—hydrological models with valuation tools and ESs models—have been applied, studied, and compared in numerous studies (e.g. Bagstad et al. 2013a; Chang & Bonnete 2016; Fan et al. 2016, 2018; Gao et al. 2017; Leh et al. 2013; Vigerstol & Aukema, 2011). Some comprehensive, physically-based hydrological models (e.g. SWAT) include multiple landscape components and could comprehensively estimate several ESs (Francesconi et al. 2016). ESs models, on the other hand, are orientation-designed and developed for ESs simulation with multiple other types of ESs other than hydrological models and thus have the most applications in previous research (Vigerstol & Aukema 2011). Vigerstol and Aukema (2011) reviewed different types of hydrological ESs modeling tools and concluded that traditional hydrological tools provide more detailed scientific results, while ESs models are easier to be understood by non-experts in presenting a general picture of ESs. Vigerstol and Aukema

(2011) also concluded that hydrological models are more suitable for fine spatial- and temporal-scales simulation, while ESs models are good for scenario studies.

Several models have recently been used for ESs valuation. The Variable Infiltration Capacity model is a large-scale, semi-distributed hydrological model (Liang et al. 1994) and has simulated provisioning hydrological ESs (Vigerstol & Aukema 2011) and flood regulation (Lee et al. 2015). The SWAT (Arnold et al. 2012) is a process-based, spatially distributed hydrological model that is used to evaluate water yield (Karabulut et al. 2015) and water quality (Logsdon & Chaubey 2012). A linked terrestrial–aquatic model was created and applied to compute dynamic ESs in the agricultural Yahara watershed, including a process-based agroecosystem model (Carpenter et al. 2015), a terrestrial hydrology model (Coe 2000), a three-dimensional groundwater flow model (Harbaugh 2005), and a hydrological routing model. Human and biogeophysical models were coupled to quantify ESs at global (Boumans et al. 2002) and watershed (Costanza et al. 2002) scales. The Patuxent Landscape Model (Costanza et al. 2002) is a spatially explicit, process-based model for the impacts of both the magnitude and spatial patterns of human settlements and agricultural practices on hydrological ESs, plant productivity, and nutrient cycling in the landscape. Finally, an agent-based modeling framework was used to calculate valuation of ESs information for LULC decisions (Groeneveld et al. 2017; Heckbert et al. 2014). In sum, very few studies have tried to combine both the hydrological and ESs models for the hydrological ESs modeling.

The current-dominant coupling method is the one-way coupling of different models with transferring the results of one model to the next one (Bowyer et al. 2012). Some investigations of coupling hydrological and ESs models (e.g. Cline et al. 2004; Wlotzka et al. 2013) focus on other ESs rather than hydrological ESs, while other studies (Lemberg et al. 2002; Notter et al. 2012; Qiu

& Prato 1998) simply used hydrological results as ESs for analysis. Samal et al. (2017) coupled a terrestrial and an aquatic ecosystem process models and modeled hydrological ESs spatially and temporally. Hohenthal et al. (2015) presented a framework including Drivers, Pressures, State, Impacts, and Responses for a local assessment of changes in the water-related ESs in the Taita Hills, Kenya. With the exception of tests with limited number of models for coupling (e.g. van der Kwast et al. 2013; Yalew et al. 2014), no good example of integrated dynamic coupling exists to date.

Without a standardized framework for coupling these models, the modeling processes would be massive and redundant when unifying scales and formatting data during the conversion from hydrological models to ESs models. In addition, the data preparation, results analysis, and display would add unnecessary time.

2.3 Materials and Methods

2.3.1 Hydrological Model

The HSPF (Duda et al. 2012) was employed in this study to simulate streamflow and sediment yields. HSPF is a comprehensive, physically based, semi-distributed hydrological model (Bicknell 1997). It has been applied to study hydrological variables such as streamflow, sediment yield, and nonpoint source pollution in many projects conducted around the world (e.g. Alarcon et al. 2009; Choi et al. 2017; Hayashi et al. 2008; Hsu et al. 2010; Tzoraki & Nikolaidis 2007).

In HSPF, the study area is first divided into subbasins according to topography as each subbasin is the smallest catchment that contains a stream channel with no branch (Bicknell 1997). Each subbasin is configured to have three basic components, namely pervious land segments (PERLND), impervious land segments (IMPLND), and stream channel/reservoir (RCHRES)

(Bicknell 1997). Land surface processes are simulated for PERLND and IMPLND first. Simulation results from PERLND and IMPLND are then passed to RCHRES for channel/reservoir or hydraulic processes simulation. With LULC, imperviousness, climate, reaches, and subbasin data, the hydrological modeling function will be set up. The PERLND, IMPLND, and RCHRES are assigned based on subbasin delineation, LULC classes, weather stations, and the ratio of perviousness and imperviousness for each LULC type. The geometric and hydraulic properties of an RCHRES are represented in HSPF by an FTABLE, which describes the relationships between stage, surface area, volume, and discharge for the reach segment (Bicknell 1997).

The hydrological processes of the model are based on the water-balance equation (Equation 2.1).

$$SMC_t = SMC_{t-1} + \sum_{t=1}^{T} (P_t - R_t - ET_t - G_t) \tag{2.1}$$

where *SMC* is the soil moisture content, *t* is time in days, *T* is the total days, *P* is the daily amounts of precipitation, *R* is the runoff, *ET* is the actual evapotranspiration, and *G* is the deep groundwater (percolation). All the units are in mm.

The data products I used for HSPF are listed in Table 2.1.

Table 2.1. Summary of data sets used for hydrological modeling

Data sets	**Spatial Resolution**	**Source**
Digital elevation data	30 m	US Geological Survey (USGS) (U.S. Geological Survey 2016a)
Land cover map	30 m	National Land Cover Database (NLCD) (Vogelmann et al. 2001)
Climate data	8 km	University of Wisconsin-Madison (Wisconsin Initiative on Climate Change Impacts 2011)
Streamflow and sediments yield data	N/A	USGS (U.S. Geological Survey 2016b)

The model parameters were calibrated against the measured streamflow data for the period 1986–1995 and were subsequently validated for the period 1996–2005 in the previous study (Logsdon & Chaubey 2013). The calibration period was selected considering the timing of the National Land Cover Database (NLCD) data and the availability of streamflow data. The comparison with the measured streamflow was conducted in terms of relative error (RE) and the Nash–Sutcliffe Efficiency (NSE). Sediment data have very limited availability; thus, available daily numbers were averaged to monthly ones and compared with simulated results.

2.3.2 ESs Model and Methods

To evaluate ESs, quantitative methods created by Logsdon and Chaubey (2013) were used with modifications to configure the fine temporal scales requirement. In this paper, the time step was a day, and the results were analyzed both monthly and seasonally to illustrate the change of water demand throughout the year.

2.3.2.1 Water Provision ES

The water provision ES was calculated as the index of water provisioning (WPI) (Equation 2.2).

$$WPI_t = \frac{MF_t/MF_{EF}}{MF_t/MF_{EF} + qne_t/n_t} \tag{2.2}$$

where *WPI* is water provision index at time *t*, *MF* is the mean flow (m^3/s), MF_{EF} is the long-term environmental flow requirement (m^3/s), *qne* is the number of times the flow is less than environmental flow requirements in the time step, and *n* is the total number of units in the time step.

The WPI equation adopted in this study does not include water quality index (due to the data scarcity) unlike the original equation developed by Logsdon and Chaubey (2013). The WPI ranges from 0 to 1, where 0 indicates that the provision of water quantity is not met at all, and 1 indicates that the provision of water quantity is met for the entire period. Based on Tennant (1976), 30% of the average flow for each month was used as MF_{EF} to sustain good aquatic ecosystem functioning. The *qne* value was calculated on a daily basis.

I then grouped individual monthly WPI numbers into three categories with respect to the mean and standard deviation to examine the distribution of monthly WPI numbers. Category A is for those above the mean by one standard deviation or more, category B is for those within one standard deviation from the mean, and category C is for those below the mean by one standard deviation or more.

2.3.2.2 Flood Regulation ES

The flood regulation ES was calculated as the flood regulation index (FRI). FRI incorporates three flood characteristics—quantity, duration, and extent of the flooding (de Guenni et al. 2005)—and is calculated according to Equation 2.3.

$$FRI = \frac{1}{\exp[w_1 \cdot \left(\frac{DF}{DF_{LT}}\right) + w_2 \cdot \left(\frac{QF}{QF_{LT}}\right) + w_3 \cdot \left(\frac{FE}{FE_{LT}}\right)]} \tag{2.3}$$

where *DF* is the duration of flood events (days), *QF* is the average magnitude of flooding events (m^3/s), *FE* is the number of flood events per month or year, *w1*, *w2*, and *w3* are user-designed weights for each component of flooding (the sum of the weights is 1), and the *LT* subscript represents long-term (historical) data.

The FRI ranges from 0 to 1, with 0 representing the maximum regulation needed and 1 representing no regulation needed. As discussed in the Section 2.1, flood-regulation ES is time-sensitive. With this adopted method, the FRI will be calculated for each month with daily data to highlight seasonal changes in flood events and their effects. Long-term, observed, streamflow data from the study area were used to determine the flood flow (calculated as the 10th percentile of the flow), which then was used to calculate the long-term values for the average duration of flood events, average magnitude of flood events, and average number of flood events per year.

The individual monthly FRI numbers were then divided into two categories: A (FRI = 1 as no flood) and B (FRI < 1 as flood events) for further analysis.

2.3.2.3 Sediment Regulation ES

The sediment regulation ES was calculated as the sediment regulation index (SRI), which is defined in Equation 2.4:

$$SRI = \exp(1 - (S/S_{max})) \tag{2.4}$$

where S is the monthly/annual erosion rate (ton/ha) and S_{max} is the monthly/annual maximum allowable (or natural) rate of sediment (ton/ha).

The range of SRI is 0 to constant e. When the monthly sediment equals to or is less than the allowable sediment, the SRI is equal to or larger than 1, meaning no regulation is needed. If the sediment is greater than the maximum allowable sediment, the ERI is less than 1, indicating that sediment regulation is needed. The maximum allowable sediment load used was the area-weighted US Department of Agriculture 'T' factor for tolerable soil loss (Soil Survey Staff 2018). It was determined to be 1.34 ton/ha/year and then converted to monthly data, weighted by flow data.

The counts of SRI by month were then grouped into three categories: A is for those above the mean by one standard deviation or more, B is for those within one standard deviation from the mean, and C is for those below the mean by one standard deviation or more.

2.3.3 The Conceptual Framework and Workflow

The complete conceptual workflow of the framework is portrayed in Figure 2.1 (Pan & Choi 2019). The framework consists of three main functions, namely data development, modeling, and results analysis, each of which is further described below.

In the data development function, digital elevation model (DEM) data were used to create a watershed boundary and stream network. Then, the watershed boundary, weather station map, imperviousness map, LULC map, and stream network were used to assign properties for each subbasin and stream segment. At the end, all the data were inputted to the data model loader for initializing the hydrological model.

The modeling function has two components: hydrological and ESs models. In this study, hydrological model (HSPF) outputs were fed into the three hydrological ESs models described previously. In the hydrological model, with the data from the data development function, all the parameters were initialized with default values and some numerical data were manually input. Then, the model was calibrated against the observed data by optimizing sensitive parameters, and the simulations were conducted with the best combination of parameters. In the ESs model, the three ESs were simulated with the hydrological outputs and other manually inputted data.

In the results analysis function, the hydrological ESs results were produced as grids and then aggregated to subbasin and basin scales for different research purposes. With regard to temporal scales, the results were calculated in daily steps and then aggregated to monthly and annual scales for different purposes. This paper presents an example of results at different temporal scales.

Furthermore, an impact analysis can be conducted by adopting various scenarios such as climate change and LULC change.

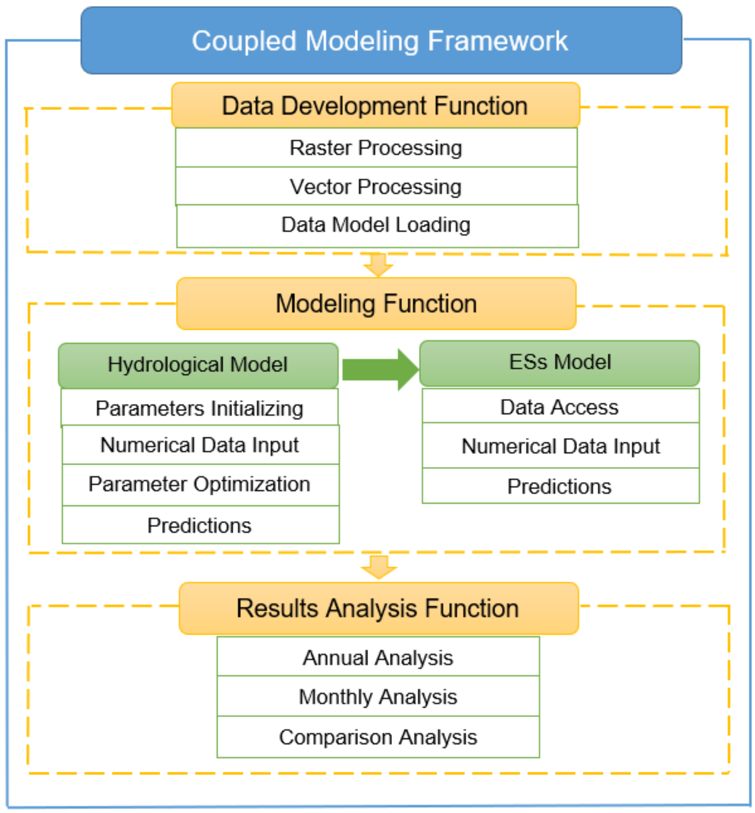


Figure 2.1 Workflow of the modeling framework (Pan & Choi 2019)

2.3.4 Study Area

I tested the framework in the Milwaukee River basin (Figure 2.2), which includes 13 cities, 32 towns, and 24 villages. The total population of the basin is about 1.3 million, and the basin area is about 2267 km^2. The southeast part, where the city of Milwaukee is located, is the most densely populated and urbanized area in the state, whereas the land cover in the northern portion consists primarily of agricultural land. Across the basin, predominant land cover classes include forest

(11%), wetland (12%), planted/cultivated (43%), and urban (32%). The basin has topography comprised of rolling moraine over bedrock, and it slopes downward from northwest to southeast, exiting to Lake Michigan (Wisconsin Department of Natural Resources 2001).

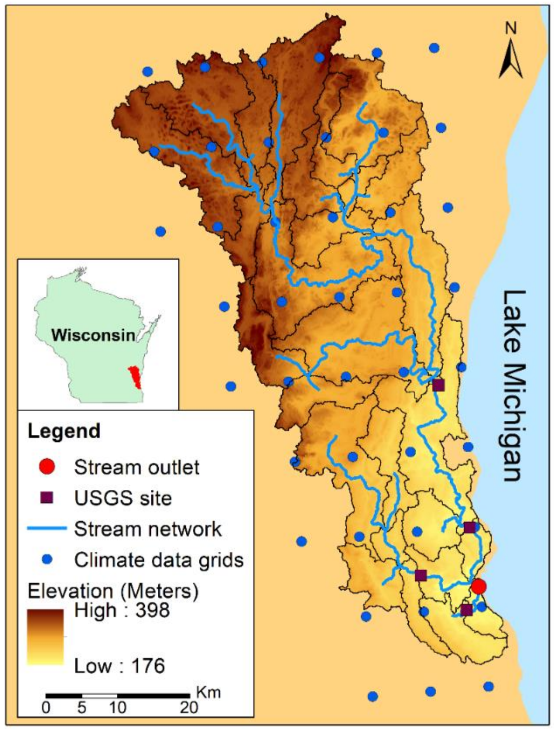


Figure 2.2. Study area: Milwaukee River basin boundary, subbasins delineated for hydrological modeling, streamflow measurement sites, elevation, climate data grids, and stream network

2.4 Results and Discussion

2.4.1 Hydrological Modeling

For the calibration period, the RE was 2.13% and the NSE was 0.71 at the USGS streamflow measurement site (site number 04087000, the second one from north in Figure 2.2). They were 4.87% and 0.54 for the validation period, respectively. The time series of observed and simulated flow are shown in Figure 2.3. Overall, the results of streamflow calibration and validation show good performance of the HSPF model.

The simulated and measured total suspended solids were then compared on monthly and annual bases (see Figure 2.4) without calibration since daily measurements were not available. The RE numbers at annual and monthly scales are 3.26% and 9.57%, respectively. The comparison indicates overestimation at both monthly and annual scales, whereas the monthly simulations show larger overestimation.

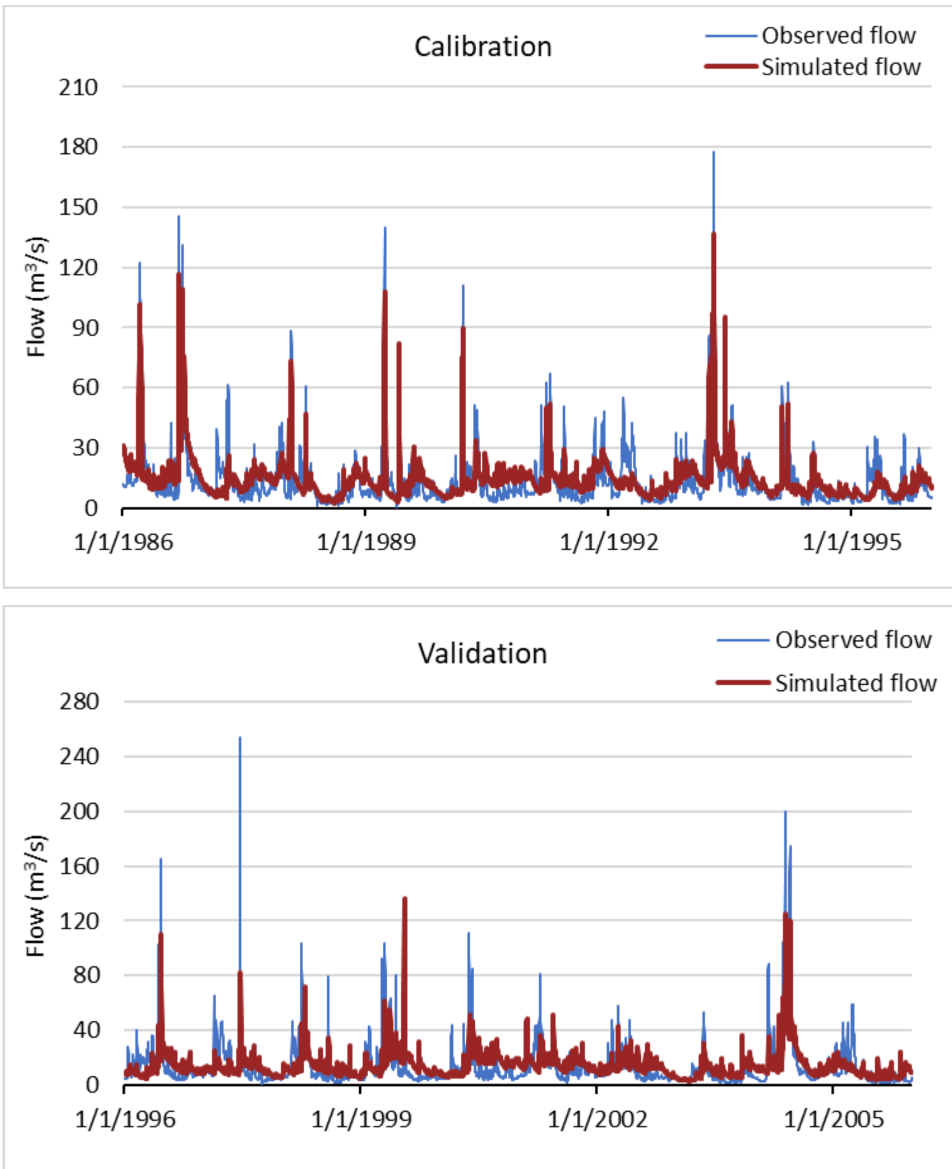


Figure 2.3. Hydrological time series for calibration and validation periods at the USGS streamflow measurement site Milwaukee River at Milwaukee, WI (04087000)

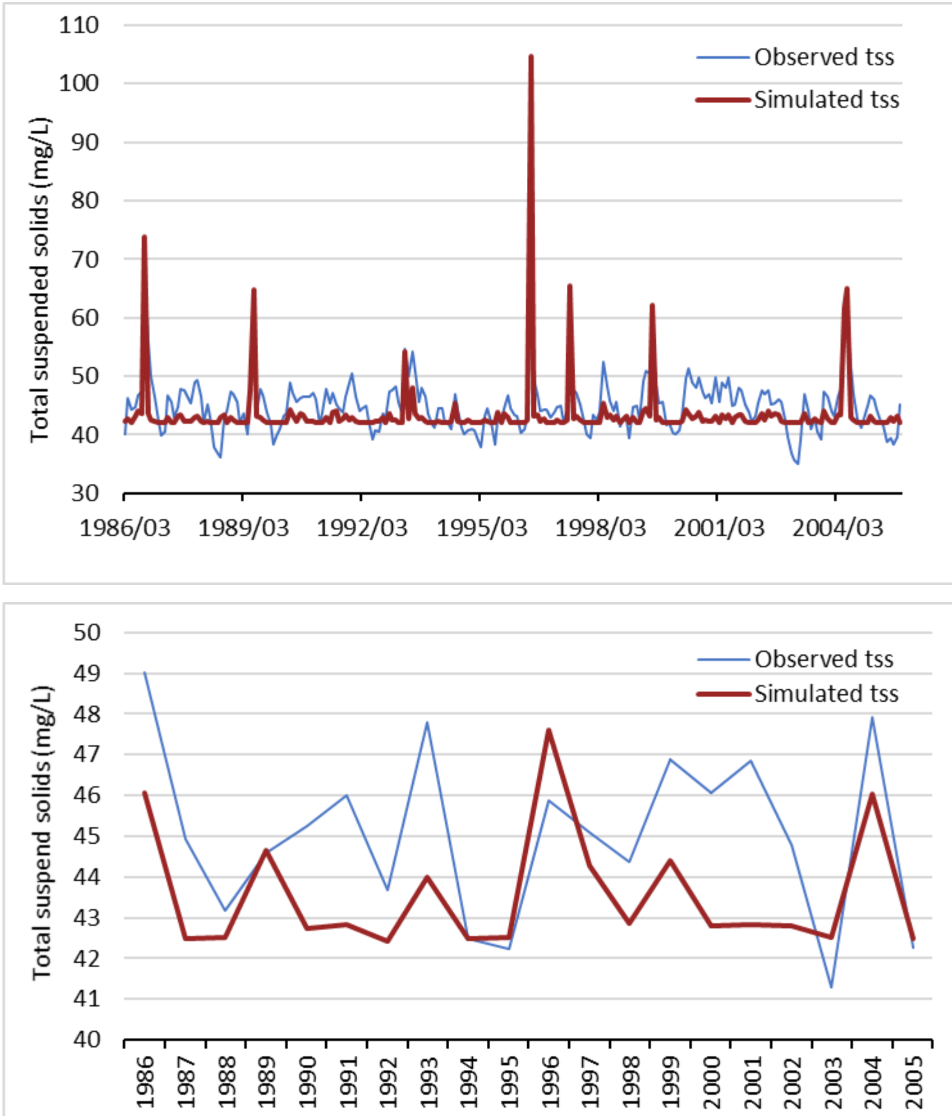


Figure 2.4. Total suspended solids as monthly (top) and annual (bottom) time series between simulation and observation

2.4.2 ESs Modeling

2.4.2.1 Water Provision Index (WPI)

The WPI (Equation 2.2) was calculated both as annual and monthly time series for the entire basin (Figure 2.5). The annual WPI ranges between 0.35 and 0.85 and reveals a slightly decreasing trend during the study period. The diminished water provision could be caused by some natural processes such as reduced precipitation, increased evaporation, and/or water table depression, as well as some human effects such as overconsumption of water for domestic or industrial use. The monthly WPI fluctuates wildly, between less than 0.2 and 1.0, and monthly WPI numbers below 0.2 occur more frequently in the second half.

I would like to further highlight some notable differences between annual and monthly results in Figure 2.5. For example, in the years 1986 and 2004, the annual WPI was very high, but the monthly WPI was very low in the late summer of those years. The monthly WPI in those years was as low as those when the annual WPI was quite low, such as in the periods 1987–1988 and 2002–2003. In the years 1988, 1998, and 2003, the annual WPI was low but the monthly WPI in the late spring or early summer of those years was very high even compared to some years (such as 1986 and 2004) with a high annual WPI. These findings indicate that annual WPI alone cannot provide enough or adequate information about when the shortages occur.

The monthly WPI time series was converted to the mean monthly WPI (Figure 2.6) to examine the seasonal variability in the study basin. Figure 2.6 reveals high water provisions in spring and very low water provisions in summer. Given the results at different temporal scales of the water provisions, the management plan for this basin could focus on low-flow seasons to keep the level of water provision stable.

The category counts described in Section 2.3.2.1 for each month are provided in Table 2.2. For category A, spring (March to May) has the most counts, and for category C, spring has the least counts, which indicates high water provision in spring. Category A has the least counts and Category C has the most counts in summer and early autumn (July to Oct), which indicates low provision in this season. This further demonstrates that monthly results can provide information for water provision management considering seasonal variations.

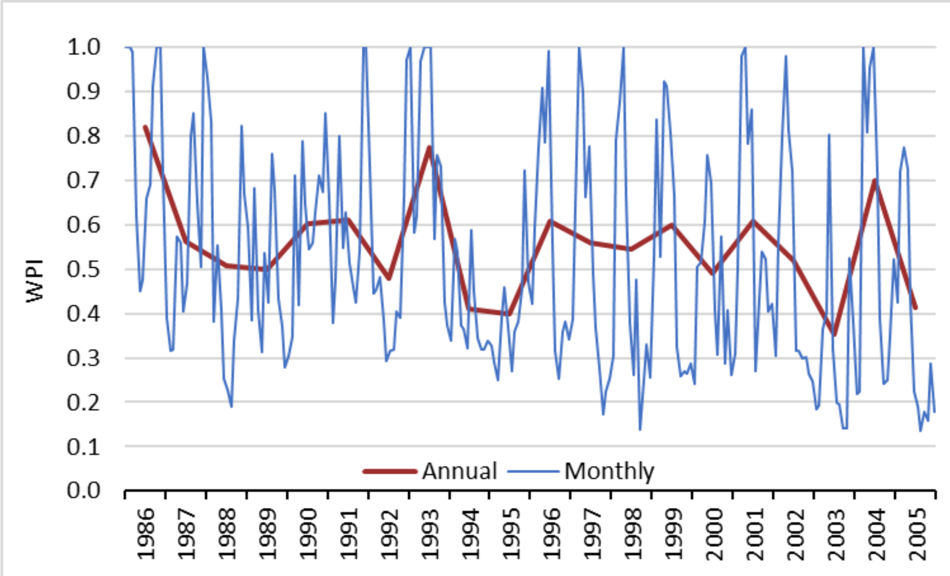


Figure 2.5. Annual and monthly water provision index time series. WPI: water provision index

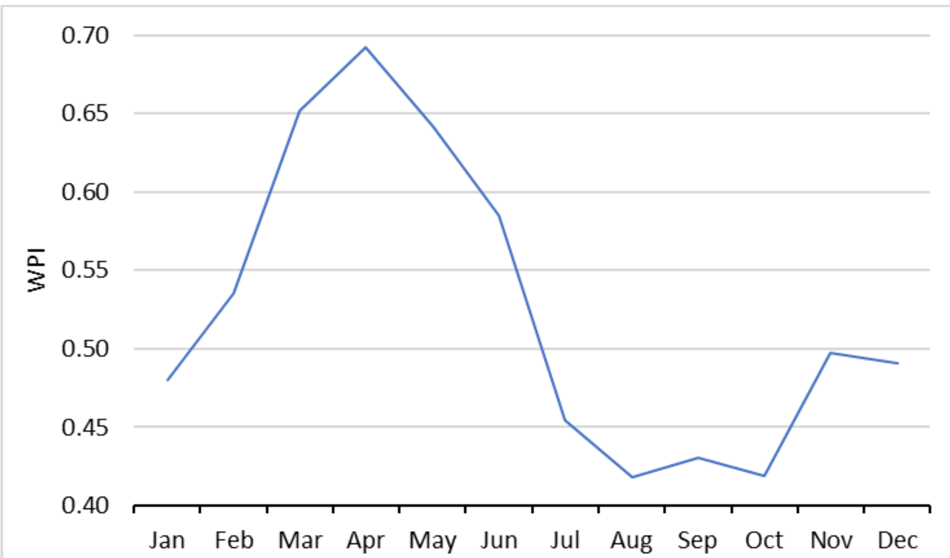


Figure 2.6. Mean monthly water provision index

Table 2.2. Counts of monthly water provision index numbers above the mean by one standard deviation or more (A), within one standard deviation from the mean (B), and below the mean by one standard deviation or more (C)

Month \ **Category**	**A**	**B**	**C**
Jan	3	14	3
Feb	4	14	2
Mar	8	11	1
Apr	9	11	0
May	8	12	0
Jun	6	12	2
Jul	1	13	6
Aug	1	16	3
Sep	2	11	7
Oct	1	13	6
Nov	3	14	3
Dec	4	10	6

2.4.2.2 Flood Regulation Index (FRI)

The FRI (Equation 2.3) was calculated as both annual and monthly time series (Figure 2.7), and mean monthly as well (Figure 2.8). As mentioned before, 0 represents the maximum regulation needed and 1 represents no needed regulation.

The annual FRI (Figure 2.7) mostly hovers around 0.3-0.5, which indicates that management is needed to some extent to regulate the flood effects most of the time. However, the monthly FRI numbers are 1 most of the time and very low occasionally, which means no flood regulation is needed for most of the time. The monthly FRI shows that flood regulations were not required except for certain months. Equation 2.3 indicates that the magnitude and duration of flood events highly impact FRI. These findings reveal that further flood regulation will only be needed for certain months or seasons. Annual results were not adequate for the flood regulation management plans.

Figure 2.8 reveals that spring is the time when the study basin is most vulnerable to flooding, while winter is relatively safe from flooding. The category counts described in Section 2.3.2.2 are provided in Table 2.3 for each month. Together with Figure 2.8, these results indicate that the study area is subject to more flood events from March to July compared to other seasons. Thus, decision-makers should establish some seasonal and temporary management (e.g. moveable dams) to prevent or reduce flood duration and magnitude, and such controls should be implemented for the spring and early summer in the future.

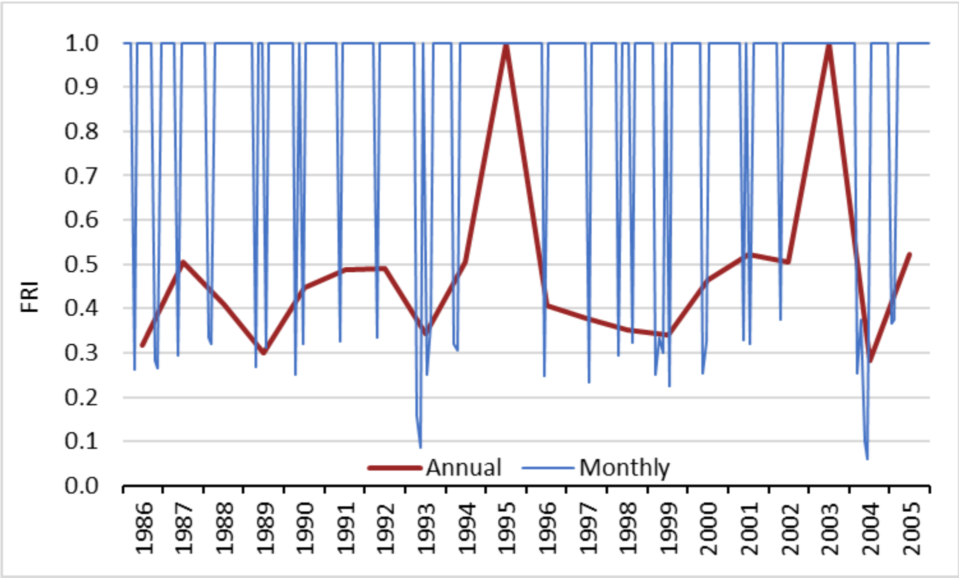


Figure 2.7. Annual and monthly flood regulation index time series. FRI: flood regulation index

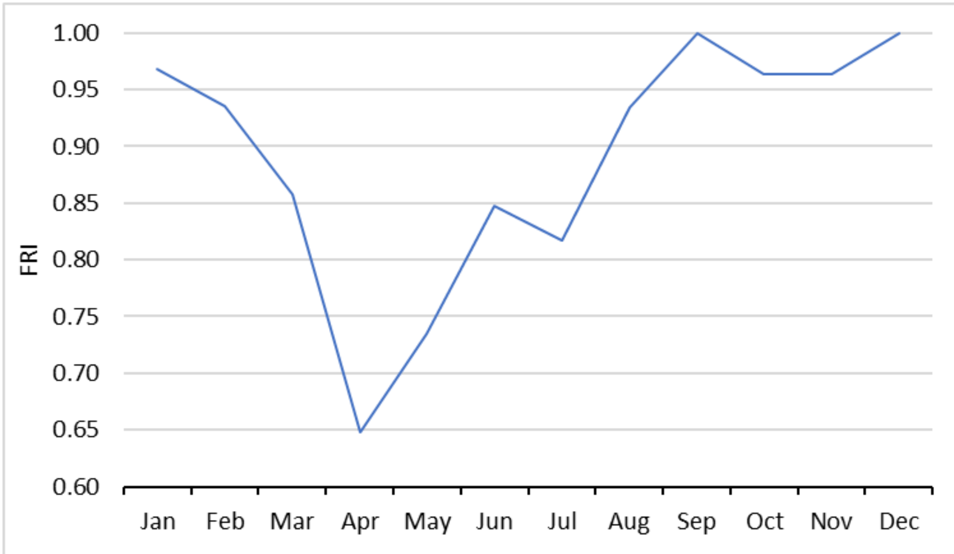


Figure 2.8. Mean monthly flood regulation index

Table 2.3. Counts of flood regulation index numbers equal to 1 (A) and less than 1 (B)

Month \ Category	A	B
Jan	19	1
Feb	18	2
Mar	16	4
Apr	10	10
May	13	7
Jun	16	4
Jul	15	5
Aug	18	2
Sep	20	0
Oct	19	1
Nov	19	1
Dec	20	0

2.4.2.3 Sediment Regulation Index (SRI)

The monthly and annual time series of SRI are presented in Figure 2.9, and the mean monthly SRI is presented in Figure 2.10. As shown in Figure 2.9, the annual SRI generally fluctuates around 0.8 with a fairly wide range (above 1.1 and below 0.4). The monthly SRI shows similar fluctuations with a larger variability. Although some years (e.g. 1986, 1989, 1996, and

1997) have very low monthly values, their annual SRI is rather high, and for the year 2004, the monthly values are very high, whereas the annual SRI value is low. Based on these findings, it should be noted by decision-makers that, with monthly results of SRI, some months of high demand of regulation would be found in low demand years. It suggests that they should plan and apply sediment regulations with more detailed time steps than annual.

The mean monthly SRI in Figure 2.10 reveals that the SRI is lowest in June. However, spring is the season with the most precipitation. This indicates that the highest sediment regulation demand did not come with the largest precipitation, and it also was associated with temporal soil erodibility variation (Bajracharya et al. 1992). The counts of monthly SRI in Table 2.4 as described in Section 2.3.2.3 show that the further the month is away from June, the fewer the counts of A are, which means less regulation is needed. Along with Figure 2.10, these monthly results indicate more regulation is needed in summer than the rest of the year.

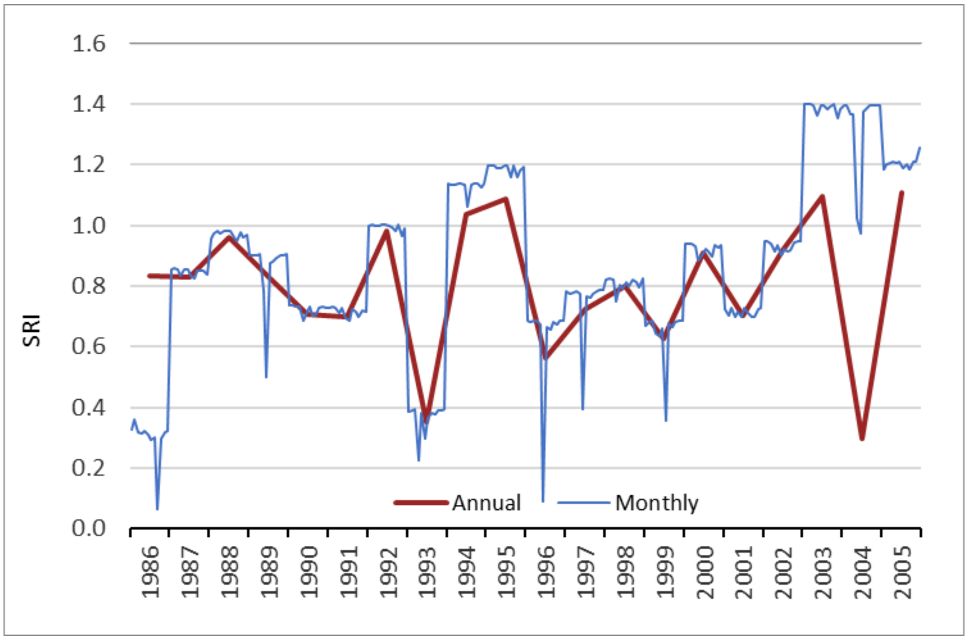


Figure 2.9. Annual and monthly sediment regulation index time series. SRI: sediment regulation index

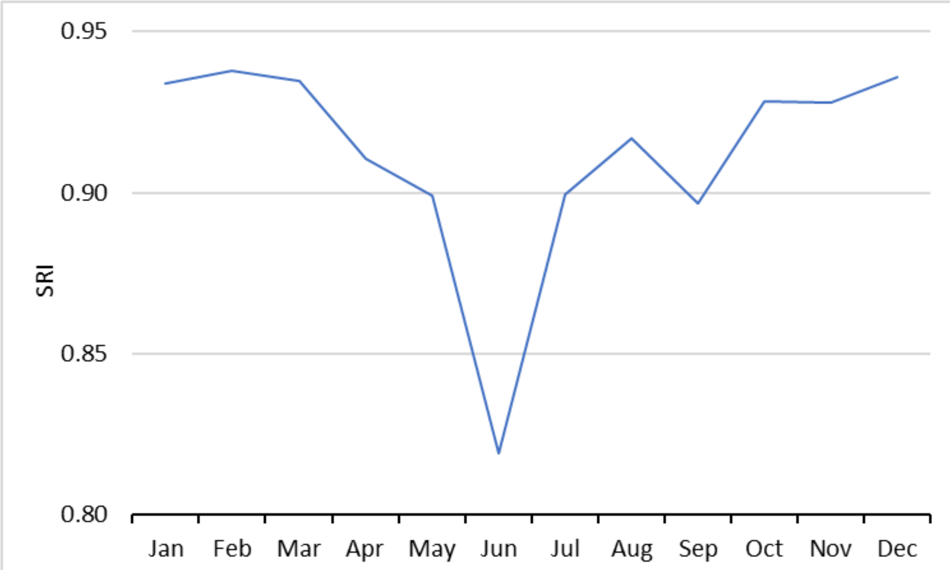


Figure 2.10. Mean monthly sediment regulation index

Table 2.4. Counts of sediment regulation index numbers above the mean by one standard deviation or more (A), within one standard deviation from the mean (B), and below the mean by one standard deviation or more (C)

Category / **Month**	**A**	**B**	**C**
Jan	2	14	4
Feb	2	14	4
Mar	2	14	4
Apr	2	14	4
May	2	15	3
Jun	5	12	3
Jul	3	13	4
Aug	2	15	3
Sep	2	14	4
Oct	2	14	4
Nov	2	14	4
Dec	2	14	4

2.5 Conclusions

In this paper, a conceptual modeling framework that can simulate ESs with fine scales was built to conduct ESs studies with fine temporal scales. The framework includes both a hydrological model and an ESs model. This framework can preprocess and access the input data efficiently and can simulate hydrological ESs at the same temporal scales as the hydrological model used in this study. With this framework, hydrological results were converted to indices results for evaluating water provision, flood control, and sediment regulation in different ways, such as a general increasing or decreasing trend, detailed analysis of the changes, and seasonal changes to be used by decision-makers. The results of the three hydrological ESs at both annual and monthly scales reveal that annual results alone in ESs simulation and analysis for management plans are not adequate for time-sensitive plans, and including fine temporal scales is necessary for some ESs that are event-based or have large seasonal variations.

The design of the framework established a strategy for the integration of data development, hydrological and ESs modeling, and output analysis supported by national data products for multiple research purposes. The framework established in this study not only confirms the necessity of the function to study the hydrological ESs with fine temporal scales, but also creates a workflow for combining different types of ESs and hydrological models for various hydrological ESs-related research. With the connection of functions and tools in a procedural streamlining, the processes of ESs modeling are very straightforward and could be applied for ESs modeling in any basin in the U.S. for studies like the study area in this paper. For other study areas where hydrological research has already been conducted, only ESs data preparation and ESs modeling execution would be needed for ESs modeling. Additionally, thanks to the flexibility of the framework, other hydrological models with different mechanisms, other types of ESs models, and different climate or LULC scenarios could be used in this framework.

CHAPTER 3. IMPACTS OF CLIMATE CHANGE AND URBAN EXPANSION ON HYDROLOGICAL ECOSYSTEM SERVICES IN THE MILWAUKEE RIVER BASIN

Abstract

LULC and climate change could affect water quantity and quality and thus hydrological ESs. Hydrological ESs information can be easily understood by decision-makers for conservation planning in response to these impacts. However, studies of these impacts on hydrological ESs are limited by the current methods and techniques. I attempted to find out how the LULC and climate changes impact hydrological ESs at different temporal scales so that decision-makers can easily understand hydrological ESs variations for guiding management plans. In this study, I analyzed the impacts of LULC and climate changes on hydrological ESs in the Milwaukee River basin, USA with a conceptual modeling framework that can simulate multiple hydrological ESs. The model framework was applied with a series of climate and urban expansion scenarios. Two hydrologic responses (streamflow and sediment) and three hydrologic ESs (WPI, FRI, and SRI)) were calculated Major findings include: (1) the climate-change scenario created a much larger impact on the results than that of LULC; (2) results under climate change show quite large inter-months, inter-annual, and inter-model variations; and (3) simultaneous decreasing trends between WPI and FRI were found at monthly scales under the climate-change scenario indicating more extreme events (flooding and droughts). This approach with the framework and impact scenarios can support management planning for decision-makers with detailed results and temporal precision.

Keywords: LULC change; climate change; hydrological ecosystem services; conceptual framework

3.1 Introduction

ESs are defined as benefits that human beings obtain from earth's ecosystem functions (MA 2005). With their significance in terms of provision, regulation, supporting, and cultural services, conservation and improvement of ecosystems have been the crucial challenge to the sustainability of ecosystems, and research programs have been applied at different levels (Guerry et al. 2015; Daily et al. 2009). The evaluation methods of ESs are still under development, although studies of ESs have been conducted over the decades (Bagstad et al. 2013a). Further development of ESs models that are able to simulate ESs with the integration of different disciplines in planning and conservation is crucial (Bagstad et al. 2013b). Because hydrological ESs are affected by complex interactions of many environmental factors, robust understanding and skills for prediction and assessment are required (Guswa et al. 2014).

LULC and climate changes are the two main factors affecting the spatial and temporal heterogeneity of ESs (Hoyer & Chang, 2014; de Groot et al. 2010; Schröter et al. 2005). LULC change has major impacts on ecosystems and the services they provide to people (Daily et al. 2009), resulting in varying amounts and spatial distributions of ESs (Lautenbach et al. 2012). Urban expansion with an increased population is one of the dominant LULC change that would influence the provision and regulation of numerous types of ESs (Eigenbrod et al. 2010). Another major factor that affects the ESs is climate change (Parmesan & Yohe 2003). Climate change was expected to increasingly impact the provision and value of ESs around the world (Staudinger et al. 2012). Impacts on natural ecosystems, such as water scarcity, flood, and species habitat disappearance, would come about in unpredictable ways and levels (Boyd 2010).

Although climate change have received significant recognition (MA 2005), impacts of climate change on ESs have not been well studied (Shaw et al. 2011). When considering hydrological ESs, climate change that shifts the temporal and spatial distribution of water and alters water quality need to be carefully considered (Hoyer & Chang 2014). Numerous impact studies of LULC change on ESs have been conducted (e.g. Liu et al. 2013; Nelson et al. 2009; Polasky et al. 2011; Portela & Rademacher 2001), while studies of climate-change impacts on ESs are limited (Chang & Bonnette 2016). Furthermore, few studies have investigated hydrological ESs under impacts of both LULC and climate changes, and they have mostly focused on coastal protection services for flooding and erosion at a monthly scale (Arkema et al. 2013), and water supply, nutrient retention, and sediment retention at an annual scale (Hoyer & Chang 2014; Roy et al. 2012). But the evaluation of hydrological ESs, such as runoff, flooding, and erosion control under climate change at fine temporal scales has been rarely conducted. As mentioned in Pan & Choi 2019, hydrologic ES were temporally sensitive, and these fine temporal changes should be captured to reflect the complex hierarchical organization of ecosystem processes and heterogeneity across time. Thus, an approach or tool that can assess the impacts of LULC and climate changes on hydrological ESs at fine temporal scales is greatly needed for informing stakeholders and decision-makers.

Currently, hydrological models and ESs models are the most popular tools for hydrological ESs, but both are deficient when modeling LULC and climate-change impacts on hydrological ESs at fine temporal scales. Most hydrological models do not include functions that convert hydrological results to ESs for decision-makers (Guswa et al. 2014). On the other hand, modeling by ES models is limited and underdevelopment, since the temporal scale in ESs modeling is still an issue that has not been fully considered (Guswa et al. 2014). A comprehensive, temporally explicit framework that couples hydrological and ESs modeling would effectively accelerate the ESs modeling processes. Studies have been conducted with few different types of hydrological and ESs models for hydrological ESs (Cline et al. 2004; Fan et al. 2016; Samal et al. 2017; Wlotzka et al. 2013). Cline et al. (2004) combined a hydrological model with an ESs model to evaluate the spatial and temporal patterns of fish density. Wlotzka et al. (2013) coupled hydrological and ESs models and assessed the C and N cycling for crop growth. Fan et al. (2016) used the SWAT and a conservation model to spatially analyze the relationships among different hydrological ESs under climate change. Nevertheless, these coupled modeling studies either did not focus on hydrological ESs, or have fine-temporal-scales.

To overcome the weaknesses of previous impact studies of hydrological ESs as described above, the conceptual modeling framework from a previous study was applied (Pan & Choi 2019) in the Milwaukee River Basin to simulate three hydrological ESs indices under LULC and climate changes in this study. The framework includes a data-development function, a modeling function with hydrological and ESs models, and a results-analysis function. This framework can capture the fine temporal changes in some hydrologic ES (e.g., water provision, floods) and thus benefit relevant management plans and policies accordingly.

Based on above-mentioned challenges, three research questions are addressed:

(1) How does LULC change impact hydrological ESs compared to climate change?

(2) What are the variations and uncertainties among the hydrological ESs results with different climate models?

(3) What are the tradeoffs or synergies among different hydrological ESs?

Detailed literature, methods, and results are covered in the following sections. In Section 3.2, the literature of LULC and climate-change impacts on hydrological ESs are reviewed. Study area and scenarios design together with the framework are introduced in Section 3.3. Results are presented in Section 3.4, and the discussion of each hydrological response and ESs index under different scenarios is provided in Section 3.5. Finally, conclusions are given in Section 3.6.

3.2 Literature review

3.2.1 The impacts of LULC change on hydrological ESs

LULC change has been identified as one of the major drivers causing the decreases of ESs (Cardinale et al. 2012; Foley et al. 2005). Urbanization, deforestation, and agriculture are the major drivers of aquatic ecosystem degradation; they affect water quantity and quality with diffusion pollution and by changing infiltration, evapotranspiration rates, and groundwater (Sample et al. 2016). LULC change can impact drinking water or recreation by alteration of baseflow during rainless periods. LULC change can also impact hydrological regulation by affecting the control of floods and the retention of nutrients and sediment (Brauman et al. 2007). The dominant challenge in designing policies by decision-makers to protect multiple ESs is that tradeoffs across multiple ESs need to be considered (Liu et al. 2013). Scenario analysis is the most common method to analyze the impacts of different potential LULC change on ESs and to generalize tradeoffs among different scenarios for providing optimal management plans to policymakers and stakeholders (Geneletti 2013).

Several impact studies of LULC change on ESs have been conducted with simple ESs or considering tradeoffs across different ESs. Polasky et al. (2010) evaluated the impacts of a set of different LULC change scenarios on water quality in Minnesota, USA and found that agricultural expansion led to large declines in water quality and carbon storage. Estoque and Murayama (2012) analyzed the potential impacts of future LULC change on ESs, finding that the total value of ESs would decrease by 2020 if current urbanization patterns continue. Portela and Rademacher (2001) presented a dynamic systems model that showed how different LULC change patterns degraded the value of ESs provided by the Brazilian Amazonia and found out that, over a 100-year simulation, the value of ESs declined for both agriculture and pasture. Logsdon and Chaubey (2013) created three LULC-change scenarios for watershed ESs and discovered improved erosion regulation under both the forested and urban scenarios. However, studies that investigate how the LULC-change scenarios could mitigate the impact of climate change on hydrological ESs are limited.

3.2.2 The impacts of climate change on hydrological ESs

Climate change is expected to intensify the hydrological cycle which would further impact the distribution and functioning of hydrological ESs (Sample et al. 2016). The increased greenhouse-gas concentration from human activities has already led to significant changes in earth's climate, and future climate change is projected to be even more striking, with global average temperatures expected to rise between 1.1 and 6.4 °C by 2100 depending on future emissions from human activities (IPCC 2007). Such climate change will alter the water distribution spatially and temporally and the form of precipitation (e.g. snow vs. rain) globally (Chang & Bonnette 2016). Based on the current climate projections, if mean annual water volume remains at the same level under climate change, the increased seasonal variations of water volume and frequency of extreme hydrological events (e.g. floods, droughts) will have substantial effects on hydrological ESs (Chang & Bonnette 2016). For example, provisioning services (Bellard et al. 2012) will be directly affected. Regulating services will be indirectly and directly affected by climate change because of the changes on LULC and number of events, respectively (Hao et al. 2017; Luo et al. 2014).

Limited studies have been conducted for climate-change impacts on ESs but all on coarse temporal scales. Hoyer and Chang (2014) assessed freshwater yield, nutrient retention, and sediment preservation under multiple LULC and climate-change scenarios on an annual scale, finding water yields are highly sensitive to climate change. Samal et al. (2017) quantified hydrological ESs with different climate models and LULC-change scenarios at regional scales by linking terrestrial and aquatic ecosystem process models and found that climate change affected flooding, drinking water, fish habitat, and nitrogen export. Though the linked model operated at a daily level, the results still focused on spatial distribution and annual scale. Bangash et al. (2013) evaluated impacts of climate change with several scenarios on water provision and erosion control services in a densely populated basin and found both decreased at annual scales. Nevertheless, no study focuses on fine temporal scales such as monthly and daily scales to identify the detailed changes in hydrological ESs related to such scales.

Tradeoffs or synergies exist among different hydrological ESs, which are determined by whether the existence of one ESs mitigates others, or several ESs could coexist in the same system. (Rodríguez et al. 2006). Tradeoffs between different ESs are that one service improves with the impairment of others (Fan et al. 2018). For instance, the climate change of hydrological ecosystems might increase the water provision and decrease the regulation ESs (Fan et al. 2016). Synergies occur if multiple ESs improve or impair at the same time under the environmental impacts (Bennett et al. 2009; Raudsepp-Hearne et al. 2010). For example, water provision ES and flood regulation ES could both be impaired if extreme events increased under climate change. Demonstring the tradeoffs or synergies among ESs under climate change can offer information for finding the management practices that could attenuate the tradeoffs or enhance synergies in order to achieve minimal regulation and management applications and avoid unnecessary losses (Carreno et al. 2012).

3.2.3 The combined impacts of both LULC and climate changes on hydrological ESs

Climate-change impacts are currently the major focus on environmental politics (IPCC 2007) and climate change is expected to become an important driver of ESs changes. LULC is also projected to the main driver of ESs changes in the future (Sala et al. 2000). They could impact distribution and functioning of ESs simultaneously (Schröter et al. 2005), which are interactive and complex spatially and temporally (Chen et al. 2013).

Estimating the impacts of LULC and climate changes on ESs is complex since different ESs may have different response to the same set of factors (Fan et al. 2016). Also, as discussed in Section 3.2.2, different ESs are associated with each other and they have either positive or negative mutual relationships under LULC and climate-change impacts (Rodríguez et al. 2006; Tilman et al. 2002). One ES could serve as impact factor for other ESs and all the ESs are interrelated (Fan et al. 2016). Changes in one ES leading to opposite effects of other services should be mitigated while the ones that affect each other positively should be enhanced by management plans (Chan et al. 2006). Limited studies have analyzed and compared the impacts of both drivers on bundles of ESs at the watershed scale to discover interactions among ESs.

Climate change will aggravate the negative impacts of LULC change on hydrological ESs (MA 2005). For instance, there were both changes in annual snow cover and the vegetation that together influence surface albedo and further impacts the ecosystem (Bouraoui et al. 2002). the combined effects of both LULC and climate change are hard to analyze because of the difficulties of downscaling from global to regional, or from annual to daily, the uncertainties, and the interactions of the two factors (Wu 2014). Most research on the impacts of LULC and climate changes on ESs has focused primarily on one of them solely (e.g. LULC: Li et al., 2017; Zank et al. 2016; climate: Rocca et al. 2014; Stubbington et al. 2017, 2018). However, the comparisons of relative importance and combined effects of LULC and climate changes on ESs is much attractive to decision-makers (Fu et al. 2017). This is especially essential for hydrological ESs, which are sensitive to both LULC and climate changes as discussed in Sections 3.2.1 and 3.2.2. Techniques for identification and calculation of the relative importance of each driver and combined effects of ESs changes are still under development (Bai et al. 2019). Earlier studies quantitatively assessed ESs under LULC or climate change separately even though those changes occurred simultaneously (Fan et al. 2016).

In recent years, studies have mostly conducted for historical changes and their impacts, but not current and future conditions (Lin et al. 2015; Zuo et al. 2016). Hence, such results of these studies could not reflect and project future impacts and thus have limited influence (Chen et al. 2018). Some studies on the future impacts of climate change on hydrological ESs have been conducted with climate-change scenarios derived from GCMs (e.g. Panagopoulos et al. 2014; Pervez & Henebry 2015; Shrestha et al. 2017; Wilson & Weng 2011). However, uncertainties from GCMs are often the largest sources of uncertainties in such studies (Chen et al. 2011; Woldemeskel et al. 2012; Zhang et al. 2014). Few studies have focused on analysis and discussion of the uncertainties of impact on hydrological ESs of different GCMs.

Some studies have explicitly considered the impacts of future LULC and climate changes on specific ESs, for example, by modelling hydropower potential (Christensen & Lettenmaier 2007; Lehner et al. 2005) or water quality (Mehdi et al. 2015; Wilby et al. 2006) under different future scenarios. Liu et al. (2013) examined changes in ESs that result from alternative scenarios based on key factors—LULC change, land management practices, and climate change—and found out that there is no simple linear interpretation of the impacts of LULC and climate changes together. Carvalho-Santos et al. (2016) applied four hypothetical LULC scenarios under current and future climate conditions to assess combined impacts of both LULC and climate changes and their results showed that future climate might reduce low flows, which could be aggravated with eucalyptus/pine LULC-change scenario while future climate may increase soil erosion and nitrate concentration, which could be aggravated by agriculture LULC-change scenario. Hoyer and Chang (2014) estimated and mapped the provision-of-freshwater ES for the Tualatin and Yamhill basins of northwestern Oregon under a series of urbanization and climate-change scenarios centered on the year 2050, and their results suggested that water-yield ES estimates were highly sensitive to climate, especially in the lowlands, while nutrient-export and retention ESs estimates were overwhelmingly driven by LULC. Nevertheless, none of these studies considered interaction among different ESs, the relative importance of each factor, the uncertainties of GCMs, or the fine temporal scales.

Based on the literature reviewed above, the study of LULC and climate impacts on hydrological ESs should focus on: (1) tradeoffs and synergies among different hydrological ESs under different impact scenarios; (2) combined and relative importance of impacts under LULC and climate changes; (3) model-uncertainties issues caused by uncertainties in the GCMs projections and additional uncertainties inherent in the ESs models themselves. All such uncertainties need to be quantified to capture the full range of potential climate-change impacts on different ESs. Detailed findings according to these issues will be addressed in the results and discussion sections.

3.3 Materials and Methods

3.3.1 Study site

The Milwaukee River basin (Figure 1) was selected as the study area. The Milwaukee metropolitan area in the southeast region of the basin contains 90 percent of the population and is highly urbanized. The LULC of the northern part is primarily agricultural. The topography of the basin consists of rolling moraine over bedrock (Wisconsin Department of Natural Resources 2001). The basin slopes downward from northwest (inland) to southeast (lakeshore). Three major rivers exist in the basin, namely Milwaukee, Menomonee, and Kinnickinnic. They merge in downtown Milwaukee and empty into Lake Michigan.

The climate type of the study area is humid continental climate (Köppen climate classification Dfb), which includes four distinct seasons with wide variations in temperature and precipitation. The mean temperature ranges from January -7.3 °C to July 21.8 °C during 1971–2000 (Choi et al. 2017). Average annual precipitation is about 862 mm, with wet summers and dry winters (Wisconsin State Climatology Office 2007). Mean annual streamflow measured at the main gauge (USGS 04087000) was approximately 219 mm during 1915–2008, with high in spring and low in late summer/early autumn (Choi et al. 2017). Current monthly average temperature and precipitation are shown in Appendix A (Choi et al. 2017), and current average streamflow for the four sites are presented in Appendix B (Choi et al. 2017).

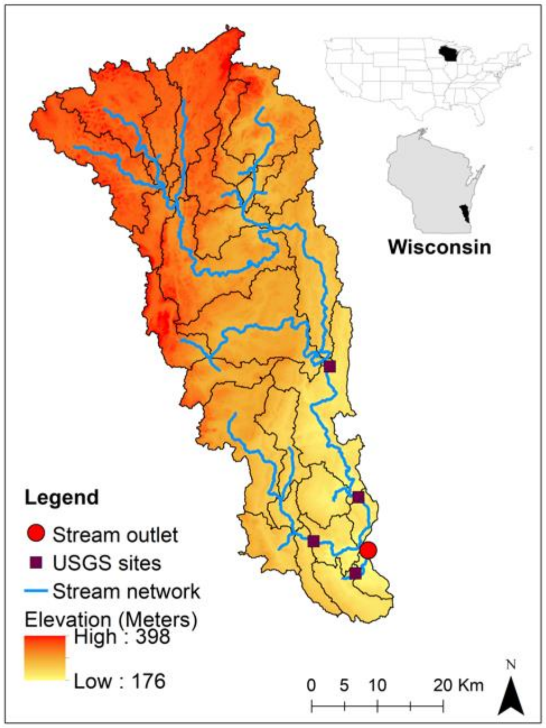


Figure 3.1. The Milwaukee River basin boundary and elevation, along with subbasins delineated for hydrological modeling, U.S. Geological Survey (USGS) streamflow-measurement sites, and stream network. More details of the USGS sites can be found in Appendix C (Choi et al. 2017)

3.3.2 Impact scenarios

3.3.2.1 Scenarios design

The same four scenarios (baseline, LULC change, climate change, and combined change scenarios) as in Choi et al. 2017 were used. (Table 3.1) (). For the baseline scenario, both LULC and climate forcing data come from historical period (National Land Cover Database (NLCD) 2001 and downscaled 1961-2000 climate data). For the LULC scenario, the LULC information was updated according to 2050 LULC map (cellular automata (CA) 2050 (referred to as CA 2050 hereafter)), and the climate data is the same as that of the baseline scenario. For the climate scenario, future climate data (downscaled 2046-2065) was used as input, and the LULC data is the same as that of the baseline scenario. For the combined scenario, both the LULC map and climate data were updated to future periods.

With the four scenarios, 1) the baseline scenario was used to evaluate historical ESs; 2) the LULC-change impact was evaluated by comparing the baseline scenario with the LULC scenario to show how LULC-change impairs the future ESs; 3) the climate-change impact was evaluated by comparing the baseline and climate-change scenarios to reveal the projected effects on the studied hydrological ESs; 4) the combined scenario showed joint effects.

Table 3.1. Hydrological and ESs modeling setup consisting of different climate and LULC scenarios (Choi et al. 2017)

Modeling scenarios	**Acronym**	**Climate data**	**LULC data**
Baseline	Baseline	Downscaled 1961-2000	NLCD 2001
LULC change only	LULC	Downscaled 1961-2000	CA 2050
Climate change only	Climate	Downscaled 2046-2065	NLCD 2001
LULC and climate combined changes	Combined	Downscaled 2046-2065	CA 2050

3.3.2.2 LULC scenario

The NLCD 2001 with a resolution of 30 m × 30 m derived from satellite imageries from the Multi-Resolution Land Characteristics Consortium (Homer et al. 2012) was used as the baseline LULC map. It was clipped for the study area, and the LULC classes have been aggregated for simplicity as shown in Figure 3.2a (Detailed aggregation can be found in Appendix D (Choi et al. 2017)). The future LULC map (CA 2050) was developed with two CA models for modeling residential and commercial expansion respectively (Li et al. 2018). Detailed urban-expansion results from the CA models are shown in Appendix E (Choi et al. 2017). The probability of a cell being converted to urban class (U_i) with the CA models is described as follows:

$$Ui = f\ (Pi, Ni, Ci, Ri) \tag{3.1}$$

where P_i is the global probability of conversion to urban LULC based on spatial-environmental and socio-economic influence, N_i is the neighborhood effect, C_i is the constraint factor for some areas that should be excluded (e.g., water, mountain), and R_i represents the random factor. Residential and commercial LULC information in 1990, 2000 and 2010 was employed for the CA model building, calibration and validation respectively, and a kappa index value (95.13%) was acquired in the assessment of the modeling performance.

LULC information and maps are presented in Table 3.2 and Figure 3.2. As shown in Table 3.2, the developed class was projected to increase by 8.25% by 2050 whereas planted/cultivated, class the other major LULC class was projected to decrease by 4.06%. The forest, shrubland, and other vegetation classes also were projected to decrease in different percentages. The two major LULC classes-developed and planted/cultivated-with the most absolute changes in CA 2050 are depicted in Figure 3.2b. It can be clearly observed that expansion is projected around the current urban area, especially in the northern part of the study area where planted/cultivated class occupies the most.

Table 3.2. LULC statistics and projected changes by 2050

LULC type	**Current (km^2)**	**Current (%)**	**2050 (km^2)**	**2050 (%)**	**Change (%)**
Water	21.21	0.96	20.94	0.94	-1.27
Developed	714.28	32.18	773.18	34.83	8.25
Barren	1.83	0.08	1.85	0.08	1.09
Forest	240.47	10.83	224.48	10.11	-6.65
Shrubland	15.00	0.68	14.02	0.63	-6.53
Herbaceous	15.87	0.71	15.00	0.68	-5.48
Planted/Cultivated	949.56	42.77	911.03	41.04	-4.06
Wetlands	261.71	11.79	259.45	11.69	-0.86

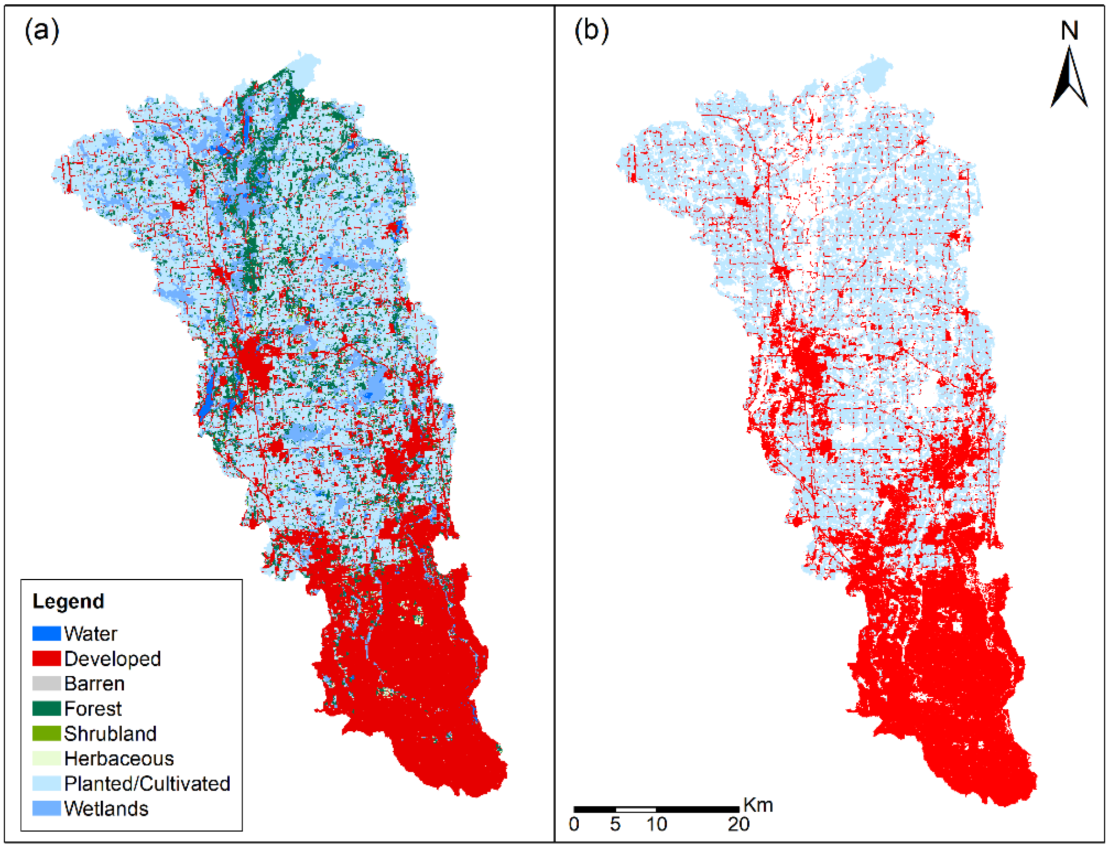


Figure 3.2. LULC of 2001 (a) and developed and planted/cultivated LULC of 2050 (b) for the Milwaukee River basin

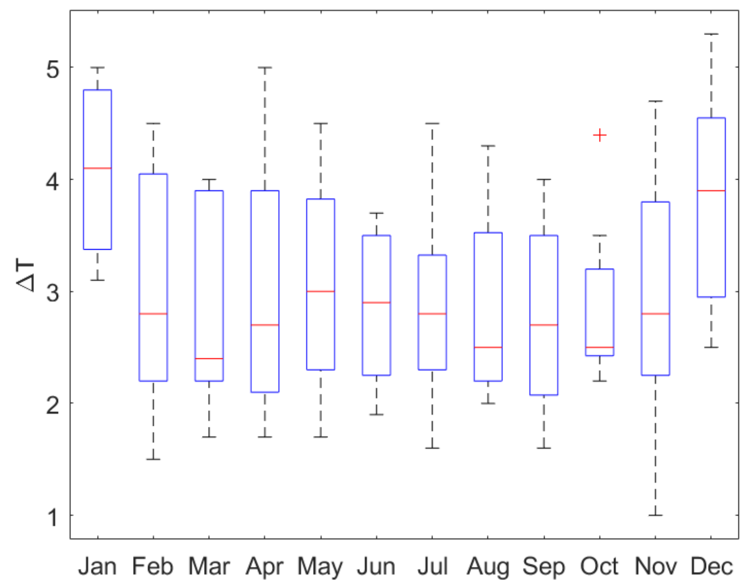
3.3.2.3 Climate scenario

The climate data used in this study were derived from the dataset created by the Wisconsin Initiative on Climate Change Impacts (Wisconsin Initiative on Climate Change Impacts 2011). The dataset is a result of statistical downscaling of nine GCMs (details are listed in Appendix F (Choi et al. 2017)). This dataset has an approximately 10-km grid resolution and includes two periods: Historical (1961–2000) and future (2046–2065). The A1B greenhouse gas emissions scenario was selected as its CO_2 concentration increase lies in the middle of the six Special Report on Emissions Scenarios (A1B, A1FI, A1T, A2, B1, and B2) (Meehl et al. 2007).

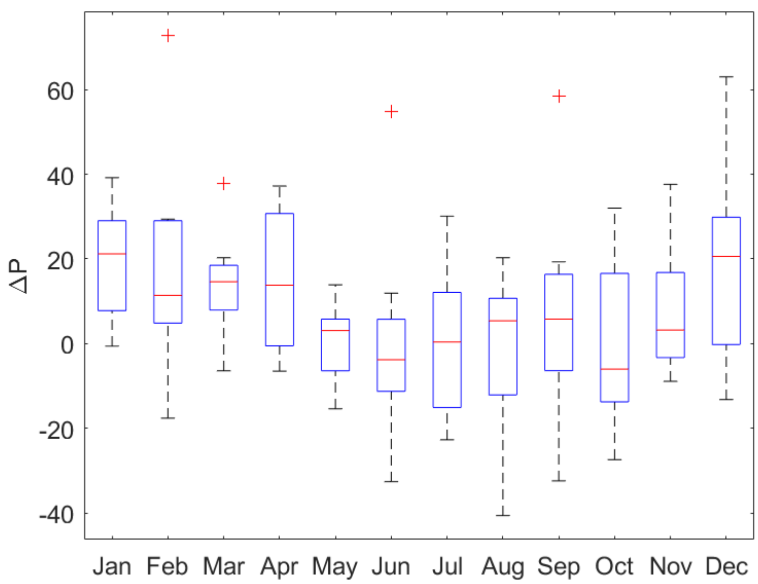
Detailed climate data are presented in Table 3.3 and Figure 3.3. The GCMs outputs are very similar to the measured historical data (Table 3.3) with a slightly lower temperature (7.8 °C to 7.95 °C) and close standard deviation (0.7-1.2 °C to 0.8 °C). The precipitation data of the GCMs and measured historical are also very close (792-827mm to 816mm), and the standard deviation (inter-annual variations) are a bit higher (109-220mm to 114mm). All the GCMs were projected to increase in temperature of 2.3-4.1°C for the future period, and most of the GCMs were projected to increase in precipitation of 46-139mm except two (csiro_mk3_5 as -22mm and gfdl_cm2_0 as -100mm). Figure 3.3 depicts average monthly changes in precipitation and temperature between historical and future periods. The temperature was projected to increase by different amounts from month to month, and January and December have the largest increase with a median value close to 4°C. The future climate scenario was projected to increase in precipitation for spring and winter while decreasing in summer and fall.

Table 3.3. Average annual temperature (T in °C) and precipitation (P in mm) for 1961-2000 and 2046-2065 from the historical data and downscaled GCMs. (Standard deviations across the years are in parentheses. Changes (T in °C and P in %) between historical and future periods are listed at the end of each row. The largest and smallest precipitation values from each period are shown in bold) (Choi et al. 2017)

	1961-2000		**2046–2065**		**Change**	
Dataset	**T**	**P**	**T**	**P**	**T**	**P**
Historical	7.95(0.8)	816(114)	N/A	N/A	N/A	N/A
cccma_cgcm3_1	7.8(0.9)	814(146)	11.4(0.9)	868(151)	3.6	6.63
cnrm_cm3	7.8(1.2)	**792(137)**	11(0.7)	931(147)	3.2	17.55
csiro_mk3_0	7.8(0.7)	809(154)	10.1(0.6)	855(184)	2.3	5.69
csiro_mk3_5	7.8(1.1)	826(222)	11(1.3)	804(225)	3.2	-2.66
gfdl_cm2_0	7.8(0.7)	**792(119)**	11(0.8)	**692(133)**	3.2	-12.63
giss_model_e_r	7.8(0.8)	821(109)	10.2(0.5)	**944(121)**	2.4	14.98
miub_echo_g	7.8(1.1)	798(127)	11.9(1.2)	864(136)	4.1	8.27
mpi_echam5	7.8(0.9)	**827(159)**	10.6(0.9)	876(162)	2.8	5.93
mri_cgcm2_3_2a	7.8(0.7)	**827(129)**	10.7(0.6)	893(115)	2.9	7.98



(a)



(b)

Figure 3.3. Distribution of avearage monthly changes in (a) temperature (T in °C) and (b) precipitation (P in %) between 1961–2000 and 2046–2065 by the nine projected GCMs. (The horizontal lines within the boxes indicate lower quartile, median, and upper quartile values Whiskers represent the most extreme values within 1.5 times the interquartile range. Additionally, signs denote outliers. Same for other box-whisker plots) (Choi et al. 2017)

3.3.3 Conceptual model framework

3.3.3.1 The framework

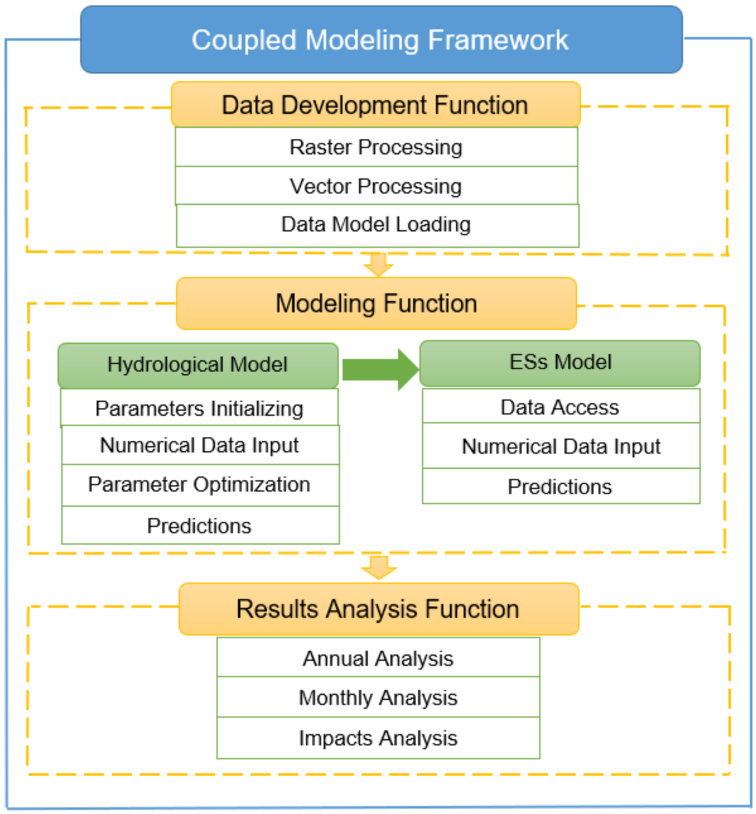


Figure 3.4. Workflow of the modeling framework (Pan & Choi 2019)

The workflow of the conceptual framework created by Pan and Choi (2019) is portrayed in Figure 3.4. The framework consists of three functions: Data development, modeling, and results analysis. The data-development function generates input data for hydrological and ESs modeling with spatial and temporal processing of preliminary raster and vector data. The modeling function, which includes both hydrological and ESs modeling, first conducts hydrological modeling with calibration, validation, and projection and then transports the hydrological results to ESs modeling to simulate hydrological ESs with ESs parameters. The results-analysis function processes the hydrological and ESs results at different spatial and temporal scales under different scenarios.

3.3.3.2 Hydrological model

The HSPF (Duda et al. 2012) was applied in this study to simulate streamflow. It is a comprehensive, physically based, semi-distributed hydrological model that has been applied to study hydrological variables under different impact scenarios in several previous studies (e.g., Alarcon et al. 2009; Hayashi et al. 2008; Hsu et al. 2010).

The whole Milwaukee River basin was first divided into subbasins based on stream network and then each subbasin was separated into three basic components, namely pervious land segments (PERLND), impervious land segments (IMPLND) and stream channel/reservoir (RCHRES) based on subbasin delineation, LULC classes, weather stations, and the ratio of perviousness and imperviousness for each LULC class (Bicknell 1997).

The hydrological processes of the model are based on the water-balance equation (Equation 3.2).

$$SMC_t = SMC_{t-1} + \sum_{t=1}^{T}(P_t - R_t - ET_t - G_t) \tag{3.2}$$

where *SMC* is the soil moisture content, *t* is time in days, *T* is the total days, *P* is the daily amounts of precipitation, *R* is the runoff, *ET* is the actual evapotranspiration, and *G* is the deep groundwater (percolation). All the units are in mm.

Data products used in HSPF for this study are listed in Table 3.4.

Table 3.4. Summary of data sets used for hydrological modeling

Data sets	**Spatial Resolution**	**Source**
Digital elevation data	30 m	USGS (U.S. Geological Survey 2016a)
Land cover map	30 m	NLCD (Vogelmann et al. 2001)
Climate data	10 km	Wisconsin Initiative on Climate Change (Wisconsin Initiative on Climate Change Impacts 2011)
Streamflow and sediments yield data	N/A	USGS (U.S. Geological Survey 2016b)

The model parameters were calibrated and validated against the measured streamflow data in the previous study (Choi et al. 2017). The comparison with measured streamflow was conducted in terms of RE and the NSE. Sediment measurements have very limited availability, thus available daily measurements were averaged to monthly ones for comparison with simulations.

3.3.3.3 ESs model and equations

Three modified quantitative methods (Logsdon & Chaubey 2013) were employed with the capability of modeling at fine temporal scales. The input data for both hydrological and ESs modeling are at daily scale, and the results are presented as daily and monthly, respectively.

(1) Water provision ES

The water provision ES was calculated as the WPI (Equation 3.3).

$$WPI_t = \frac{MF_t/MF_{EF}}{MF_t/MF_{EF} + qne_t/n_t} \tag{3.3}$$

where *WPI* is water provision index, *MF* is the mean flow (m^3/s), MF_{EF} is the long-term environmental flow requirement (m^3/s), *qne* is the number of times the flow is less than environmental flow requirements in the time step, and *n* is the total number of units in the time step.

The WPI ranges from 0 to 1 where 0 indicates that provision of water quantity is not met at all, and 1 indicates that provision of water quantity is met for the entire time frame. Base on Tennant (1976), 30% of average flow for each month was used as MF_{EF} to sustain good aquatic ecosystem functioning. The *qne* value was calculated on a daily basis.

(2) Flood regulation ES

The flood regulation ES was calculated as the FRI which incorporates three flood characteristics: Quantity, duration, and frequency of the flooding (de Guenni et al. 2005) as in Equation 3.4.

$$FRI = \frac{1}{\exp[w_1 \cdot \left(\frac{DF}{DF_{LT}}\right) + w_2 \cdot \left(\frac{QF}{QF_{LT}}\right) + w_3 \cdot \left(\frac{FE}{FE_{LT}}\right)]} \tag{3.4}$$

where *DF* is the average duration of flood events (days), *QF* is the average magnitude of flooding events (m^3/s), *FE* is the number of flood events (frequency), *w1*, *w2*, and *w3* are user designed weights for each component of flooding (the sum of the weights is 1), and the *LT* subscript represents long-term (historical) data.

The FRI ranges from 0 to 1 with 0 representing maximum regulation needed and 1 representing no regulation needed. With this adopted method, the FRI will be calculated for each month with daily data to highlight seasonal changes in flood events and their effects. Long-term observed streamflow data from the study area were used to determine the flood flow (calculated as the 90th percentile of the flow), which then was used to calculate the long-term values for the average duration of flood events, the average magnitude of flood events, and the average number of flood events per year.

(3) Sediment regulation ES

The sediment regulation ES was calculated as the SRI, which is defined in Equation 3.5:

$$SRI = \exp(1 - (S/S_{max})) \tag{3.5}$$

where S is the monthly or annual erosion rate (ton/ha) and S_{max} is the monthly or annual maximum allowable (or natural) rate of sediment (ton/ha).

The range of the SRI is 0 to constant e. When the S equals to or is less than S_{max}, the SRI equals to or is larger than 1, meaning no regulation is needed. If S is greater than S_{max}, the SRI is less than 1, indicating that sediment regulation is needed. The SRI is close to 0 when S is much larger than S_{max}. The S_{max} used was the area-weighted US Department of Agriculture's 'T' factor for tolerable soil loss (Soil Survey Staff 2018). It then was converted to monthly data, weighted by flow data.

3.4 Results

3.4.1 Hydrological modeling under impacts

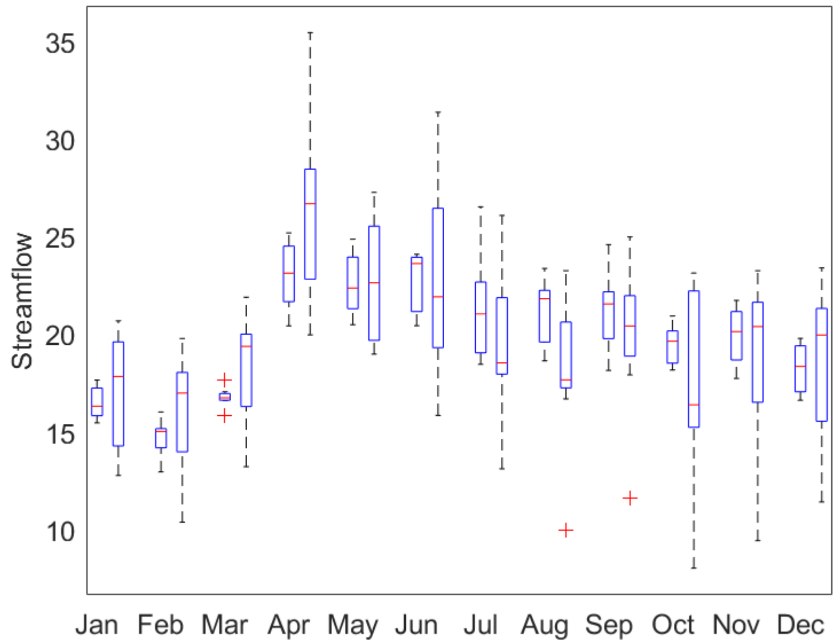
Streamflow and sediment were simulated with the calibrated HSPF model under the four scenarios for the ESs modeling. Detailed calibration and validation processes and simulations can be found in Choi et al. (2017). An RE of 2.13% and an NSE of 0.71 were acquired by comparing simulated streamflow to observed data at the USGS site (04087000) for calibration. For the validation period, they are 4.87% and 0.54, respectively. The calibration and validation results of streamflow overall show good performance of the HSPF model. The simulated and observed sediment were compared at monthly and annual scales without calibration, since daily measurements were not available. The RE are 3.26% and 9.57%, respectively, which indicates overestimation at both scales.

The streamflow simulations simulated by HSPF under different scenarios are presented in Table 3.5 with annual averages. The baseline streamflow simulations range from 18.41 m3/s with model gfdl_cm2_0 to 21.45 m3/s with model csiro_mk3_5. Streamflow simulation under the LULC scenario all decreased by no more than 1.2%, which is fairly small compared to changes in the simulations under the climate scenario. The streamflow simulations under the climate scenario have a large inter-model variation in changes ranging from a 30.02% decrease with model gfdl_cm2_0 to an 18.36% increase with model giss_model_e_r. Half of the streamflow simulations under the climate scenario decreased. For streamflow simulations under the combined scenario, the increasing and decreasing trends for simulations with each GCMs are the same as the simulations under the climate scenario with small additional decreases in values. Such decreases generally reflect decreases under the LULC scenario.

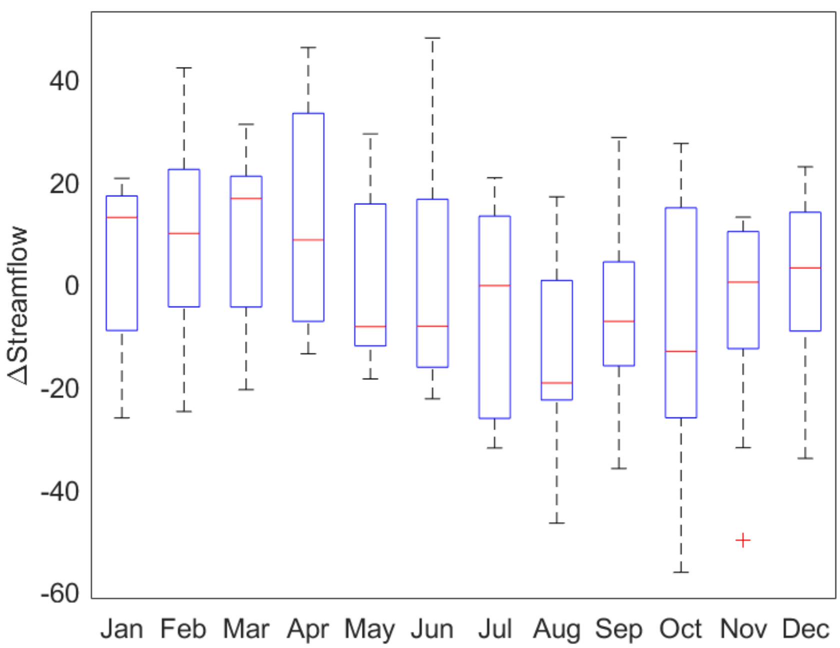
The impacts on streamflow under the climate scenario were further analyzed with monthly averages as showed in Figure 3.5. According to Figure 3.5a, inter-model variations were projected to increase in all cold seasons and be especially higher in the rainy months (April to June and October) but change very slightly in warm months of July to September. Base on the changes in Figure 3.5b, streamflow was projected to increase in months of January to April with April having the largest inter-model variation while streamflow decreases in the months of May to October with October having the largest inter-model variation. In summary of Figure 3.5a and 3.5b, it can be noticed that streamflow in April was projected to increase not only in magnitude and inter-model variation but also compared to May and June so that more contrast appeared between spring and summer. The increases and decreases in average monthly streamflow simulations generally correspond to the precipitation data (Figure 3.3b).

Table 3.5. Simulated annual average streamflow(m^3/s) with the nine GCMs models (Changes (%) from the baseline scenario are listed behind each future scenario. The largest and smallest values from each scenario are shown in bold.)

Model	Baseline	LULC	change	Climate	change	Combined	change
cccma_cgcm3_1	19.89	19.67	-1.11	19.99	0.47	19.77	-0.64
cnrm_cm3	18.77	18.77	0.00	21.91	16.70	21.77	15.96
csiro_mk3_0	19.79	19.67	-0.61	20.63	4.22	20.45	3.31
csiro_mk3_5	**21.45**	**21.36**	-0.43	17.12	-20.18	17.02	-20.65
gfdl_cm2_0	**18.41**	**18.23**	-0.95	**12.88**	-30.02	**12.91**	-29.88
giss_model_e_r	19.71	19.47	-1.19	**23.32**	18.36	**23.12**	17.32
miub_echo_g	19.17	19.07	-0.50	18.93	-1.24	18.73	-2.25
mpi_echam5	20.61	20.45	-0.80	20.40	-1.02	20.08	-2.60
mri_cgcm2_3_2a	20.46	20.40	-0.29	21.23	3.78	20.99	2.59



(a)



(b)

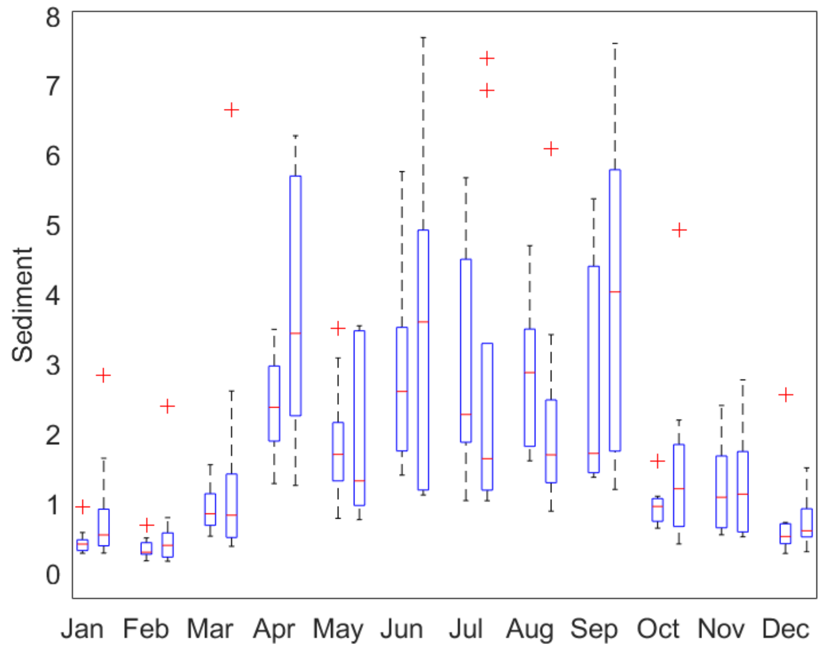
Figure 3.5. Monthly average of simulated streamflow (m^3/s) under the baseline and climate scenarios (a) and the changes (%) between them (b) with the nine GCMs models (a. boxplots for each month are in order as the baseline and climate scenarios. Same for Figure 3.6)

The sediment simulations under different scenarios are shown in Table 3.6. The annual averages of simulated sediment basically follow the pattern of streamflow because water volume is the most important factor that is related to sediment yield. The simulated sediment under the LULC scenario are projected to decrease with most models except gfdl_cm2_0 (9.6% increase) and mri_cgcm2_3_2a (0.41% increase). The impacts of LULC change on sediment simulations are still quite small compared to the impacts of climate change with a large variation in changes range from 12.47% decrease to 98.84% increase. Simulated sediment with six models increased and three of them decreased. Simulate sediment under the combined scenario were slightly different from the simulations under the climate scenario reflecting the combined effects with both the climate and LULC scenarios.

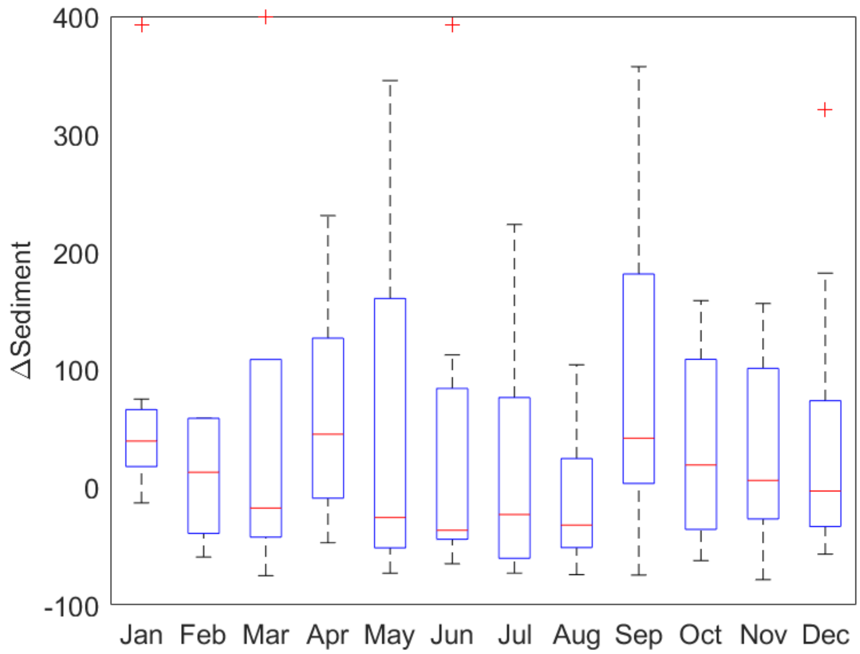
Monthly averages of simulated sediment are depicted in Figure 3.6. As shown in Figure 3.6a, the increasing and decrease trends through the year are generally corresponding with streamflow simulations. However, the inter-model variations of warm and rainy months (April to September) were much larger than the cold and dry months (October to March), especially in the simulations under the climate scenarios. According to Figure 3.6b, the changes between simulated sediment under the baseline and climate scenarios also follow the streamflow-simulations changing trend and reveal that rainy and warm months have higher inter-model variations than cold and dry months. Such large inter-model variation and increases in rainy and warm months indicate that sediment simulations are sensitive to high volume streamflow once the streamflow is over certain thresholds, the sediment yield would not change with the same scales as streamflow.

Table 3.6. Simulated annual average sediment (thousand tons/year) with the nine GCMs models (Changes (%) from the baseline scenario are listed behind each future scenario. The largest and smallest values from each scenario are shown in bold.)

Model	**Baseline**	**LULC**	**change**	**Climate**	**change**	**Combined**	**change**
cccma_cgcm3_1	20.40	19.04	-6.65	24.54	20.29	23.56	15.47
cnrm_cm3	15.29	**14.83**	-3.02	21.56	41.02	21.54	40.91
csiro_mk3_0	24.68	24.26	-1.71	22.21	-10.03	20.64	-16.37
csiro_mk3_5	**28.37**	**28.00**	-1.30	24.84	-12.47	24.43	-13.89
gfdl_cm2_0	**13.95**	15.29	9.60	**14.44**	3.54	**14.84**	6.38
giss_model_e_r	18.05	17.04	-5.59	30.94	71.42	28.65	58.70
miub_echo_g	15.75	15.31	-2.82	31.34	98.94	29.99	90.38
mpi_echam5	22.30	21.68	-2.80	20.18	-9.52	19.07	-14.47
mri_cgcm2_3_2a	22.40	22.49	0.41	**34.00**	51.84	**33.62**	50.12



(a)



(b)

Figure 3.6. Monthly average of simulated sediment (thousand tons/month) under the baseline and climate scenarios (a) and the changes (%) between them (b) with the nine GCMs models

Table 3.7. Simulated annual average streamflow (m^3/s) for each LULC class under the baseline and LULC scenarios (The simulations were averaged for all GCMs)

LULC type	Baseline	LULC	Change
Water	0.21	0.20	-0.01
Developed	10.28	10.93	**0.65**
Barren	0.02	0.02	0.00
Forest	2.35	2.16	**-0.20**
Shrubland	0.15	0.14	-0.01
Herbaceous	0.16	0.15	-0.01
Planted/cultivated	9.27	8.74	**-0.53**
Wetlands	2.55	2.49	-0.06
Total	24.99	24.83	-0.16

The streamflow simulations under the LULC scenario were further analyzed to explore possible reasons for the limited impacts on streamflow simulations. The annual average of streamflow simulations from each LULC class under the baseline and LULC scenarios were calculated and compared as shown in Table 3.7. Streamflow from developed and planted/cultivated together contribute 78% of total streamflow in both scenarios. With the LULC-change impacts, streamflow from Developed increased 0.65 m^3/s and that from Planted/cultivated decreased 0.53 m^3/s. With the decreases from all the rest of LULC classes, the total streamflow decreased slightly by 0.16 m^3/s.

3.4.2 ESs modeling under impacts

The modeling results of the three types of ESs under the four scenarios were summarized and analyzed by annual averages (Table 3.8 to Table 3.10). The monthly ESs results were converted to the monthly average (Figure 3.7 to Figure 3.9) to examine the seasonal variations under the four scenarios. The inter-annual results for each ES are depicted in Figure 3.10.

The annual averages of WPI under the four scenarios are presented in Table 3.8. The results under the baseline scenario range from 0.85 to 0.91 indicating good water provision through the historical period. The WPI under the LULC scenario is slightly larger than those under the baseline scenario with a range from 0.86 to 0.92, indicating positive impacts on water provision. The results under the climate scenario show large inter-model variation with a range from 0.68 to 0.91, which indicates that, with some climate-change-model projections, water provision would be severely impaired (e.g. gfdl_cm2_0) while, with some others, water provision would be slightly improved (e.g. cnrm_cm3). The combined scenario results in similar inter-model variation in WPI as in the climate scenario.

As for the FRI in Table 3.9, annual averages under the baseline scenario ranging from 0.39 to 0.5 state the necessity of flood regulation for the historical period. Results under the LULC scenario with a range from 0.41 to 0.5 show slightly increases (less regulation needed). The FRI with the nine GCMs model shows a large inter-model variation with a range from 0.40 to 0.56 and equal probabilities for increases and decreases in need of flood regulation among the nine models. The combined scenario results in almost identical FRI as in the climate scenario.

All the SRI results in Table 3.10 are larger than 1 which means for annual averages of SRI, no sediment regulation was needed for either historical or future periods. However, the changes between the results under the baseline and future scenarios which indicates the impacts of different scenarios show different inter-model variations. The climate scenario resulted in the largest variation in impacts from a decrease of 0.45 to an increase of 0.16; the combined scenario resulted in slightly smaller variation than the climate scenario, and the LULC scenario resulted in the smallest impacts from a decrease of 0.03 to an increase of 0.04.

Table 3.8. Summary of the WPI results with the nine GCMs models (Absolute changes from the baseline scenario are listed behind each future scenario. The largest and smallest values from each scenario are shown in bold. Same for Table 3.9 and 3.10.)

Model	**Baseline**	**LULC**	**Change**	**Climate**	**Change**	**Combined**	**Change**
cccma_cgcm3_1	0.89	0.91	0.02	0.87	-0.02	0.86	-0.03
cnrm_cm3	0.86	0.88	0.02	**0.91**	0.05	**0.91**	0.05
csiro_mk3_0	0.86	0.88	0.02	0.86	0.00	0.85	-0.01
csiro_mk3_5	**0.85**	**0.86**	0.02	0.77	-0.08	0.76	-0.09
gfdl_cm2_0	0.87	0.88	0.02	**0.69**	-0.18	**0.68**	-0.19
giss_model_e_r	0.90	0.91	0.01	0.93	0.03	0.93	0.02
miub_echo_g	0.89	0.90	0.01	0.84	-0.05	0.84	-0.06
mpi_echam5	0.89	0.90	0.01	0.88	-0.01	0.87	-0.02
mri_cgcm2_3_2a	**0.91**	**0.92**	0.01	**0.91**	0.01	**0.91**	0.00

Table 3.9. Summary of the FRI results with the nine GCMs models

Model	**Baseline**	**LULC**	**Change**	**Climate**	**Change**	**Combined**	**Change**
cccma_cgcm3_1	**0.39**	**0.41**	0.02	**0.40**	0.01	**0.40**	0.01
cnrm_cm3	0.49	0.49	0.00	0.43	-0.06	0.43	-0.07
csiro_mk3_0	0.47	0.47	0.00	0.44	-0.02	0.45	-0.02
csiro_mk3_5	0.46	0.46	0.00	0.49	0.04	0.49	0.03
gfdl_cm2_0	**0.50**	**0.50**	0.00	**0.56**	0.06	**0.56**	0.06
giss_model_e_r	0.47	0.47	0.00	**0.40**	-0.07	**0.40**	-0.06
miub_echo_g	0.48	0.48	0.00	0.44	-0.04	0.44	-0.04
mpi_echam5	0.48	0.48	0.00	0.44	-0.04	0.43	-0.04
mri_cgcm2_3_2a	0.46	0.46	0.00	0.43	-0.03	0.43	-0.03

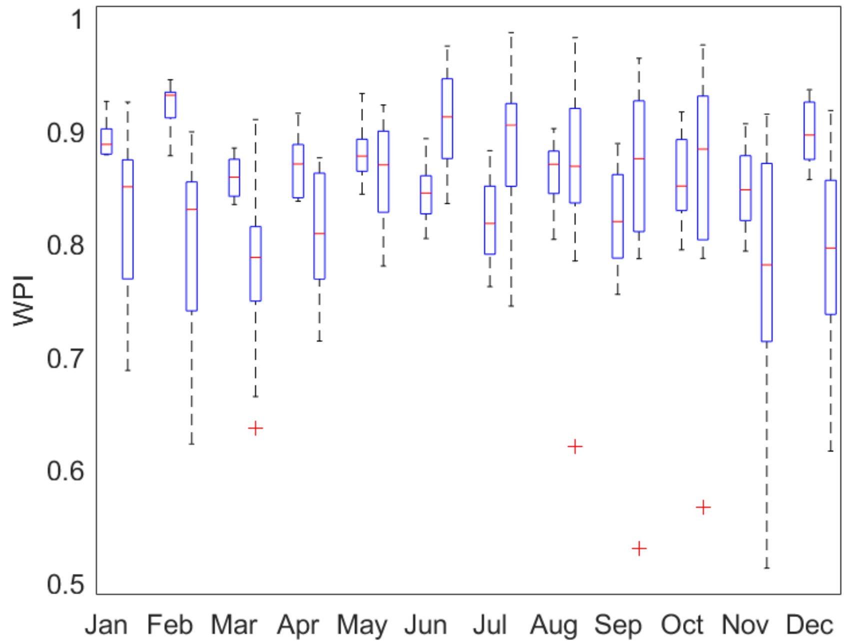
Table 3.10. Summary of the SRI results with the nine GCMs models

Model	**Baseline**	**LULC**	**Change**	**Climate**	**Change**	**Combined**	**Change**
cccma_cgcm3_1	1.57	1.61	0.04	1.56	-0.01	1.58	0.01
cnrm_cm3	1.76	1.77	0.01	1.53	-0.23	1.52	-0.24
csiro_mk3_0	**1.52**	**1.54**	0.02	1.50	-0.02	1.55	0.03
csiro_mk3_5	1.53	**1.54**	0.00	1.62	0.08	1.63	0.10
gfdl_cm2_0	**1.79**	1.76	-0.03	**1.95**	0.16	**1.93**	0.14
giss_model_e_r	1.64	1.67	0.03	**1.27**	-0.37	**1.30**	-0.34
miub_echo_g	1.76	**1.78**	0.02	1.31	-0.45	1.33	-0.44
mpi_echam5	1.60	1.64	0.03	1.54	-0.06	1.56	-0.04
mri_cgcm2_3_2a	1.65	1.63	-0.02	1.26	-0.39	1.30	-0.35

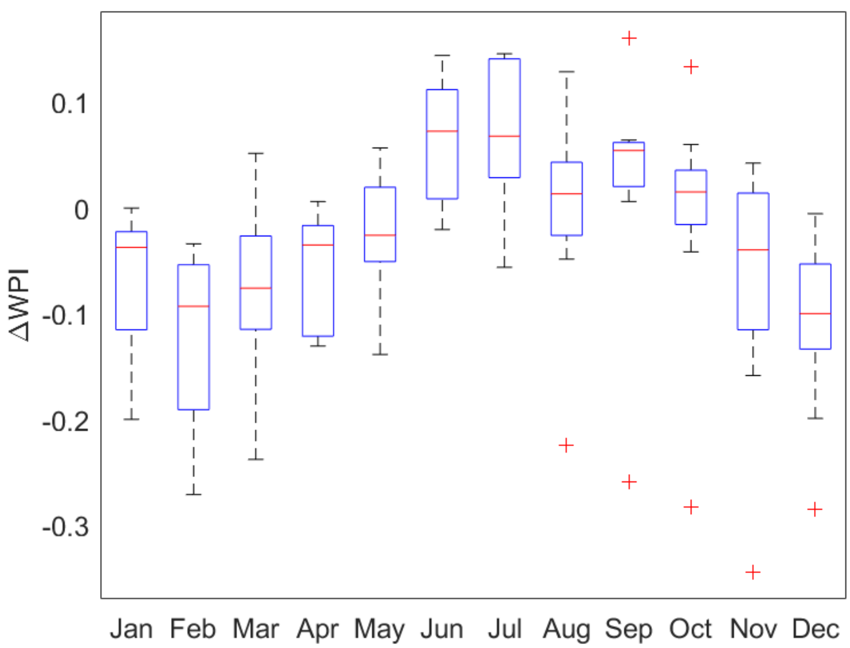
Monthly average WPI are depicted in Figure 3.7. Based on Figure 3.7a, the WPI under the baseline scenario has large values in cold months and seasons (November to April) and small values in warm ones (June to October) while WPI under the climate scenario has the opposite monthly distributions. Also, the climate scenario resulted in large inter-model variations all through the year compared to the baseline scenario. According to Figure 3.7b, WPI increases in warm months and decreases in cold ones under the climate scenario. Furthermore, large inter-model variations exist in both decreased (February and November) and increased (June and July) results. Such months are the transition months between different seasons.

According to Figure 3.8a of monthly average FRI, the results under both the baseline and climate scenarios are high in cold months (October to March) and low in warm ones (April to September), while results under the climate scenario have much larger inter-model variations for most months except May and July. Figure 3.8b shows that FRI generally decreases under the climate scenario except for June and October. These two months also present the largest inter-model variations and are the beginning and the end of the warm period.

The monthly average results of SRI as shown in Figure 3.9a present similar trends as that of the FRI results but with large seasonal variations. Furthermore, results under the climate scenario have larger inter-model variations than those under the baseline scenario in cold months (October to February) while having similar variations in warm months (April to September). Figure 3.9b shows that SRI under the climate scenario decreases for most months except February to June. The largest inter-model variations exist in January with a decrease and February with an increase.

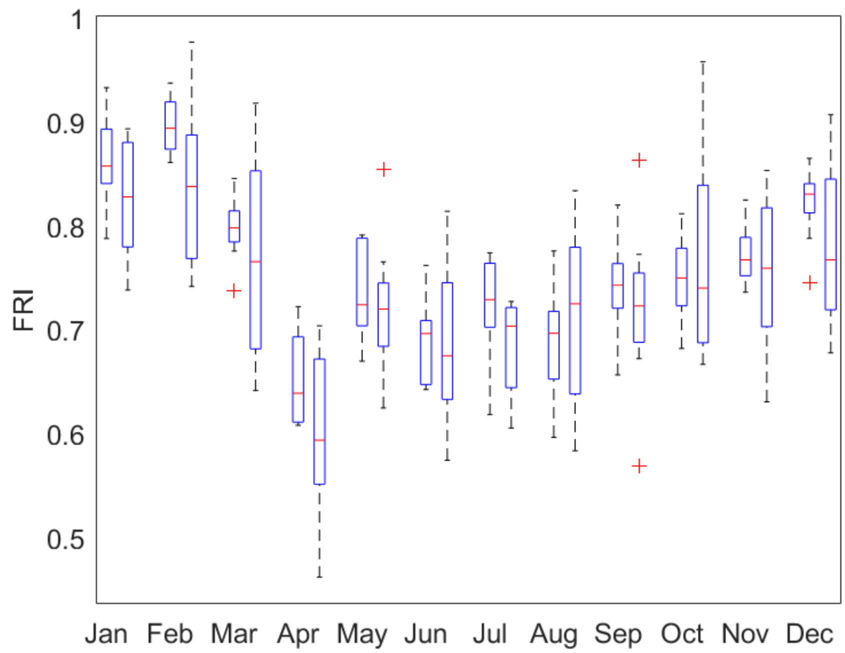


(a)

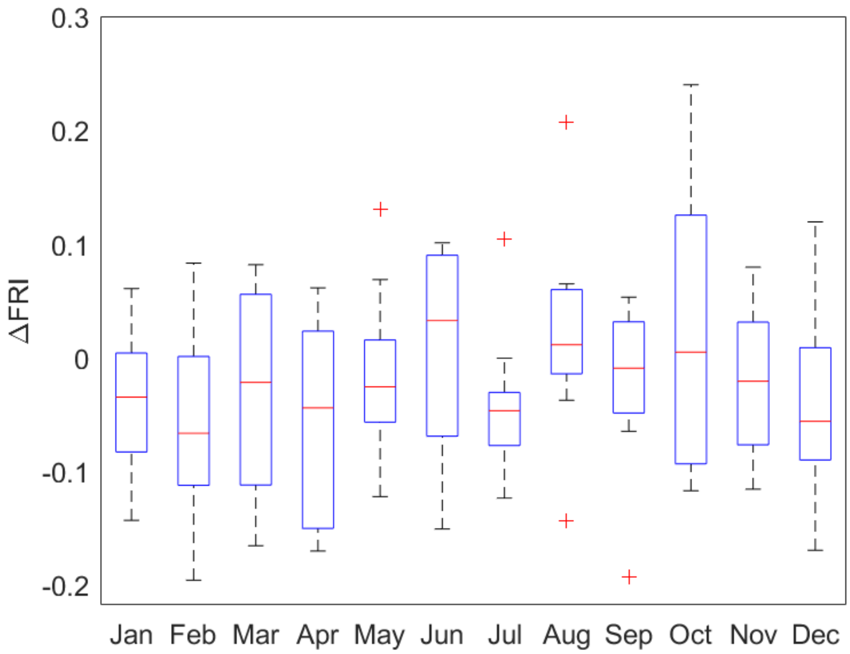


(b)

Figure 3.7. Monthly average of WPI under the baseline and climate scenarios (a) and the changes between them (b) with the nine GCMs models (a. boxplots for each month are in order as the baseline and climate scenarios. Same for Figure 3.8 and 3.9)

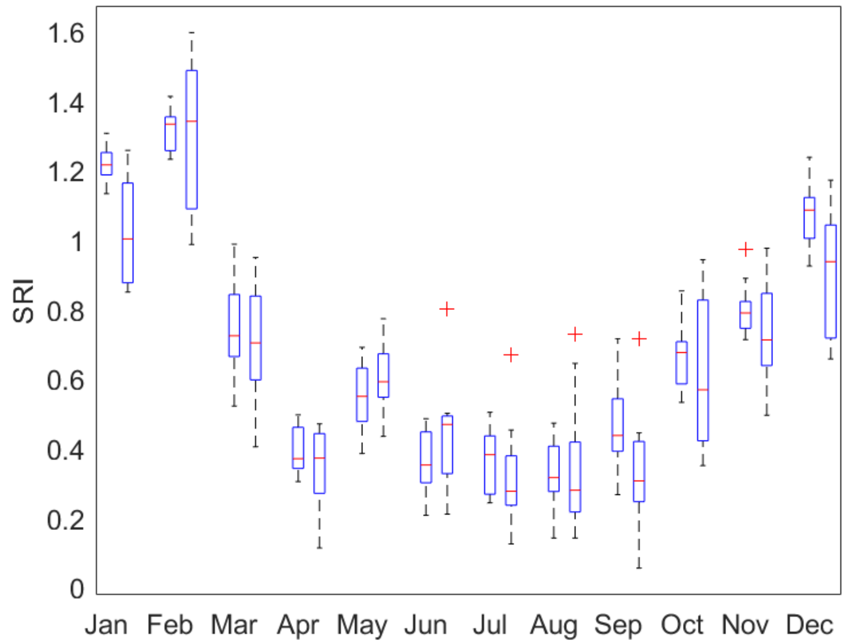


(a)

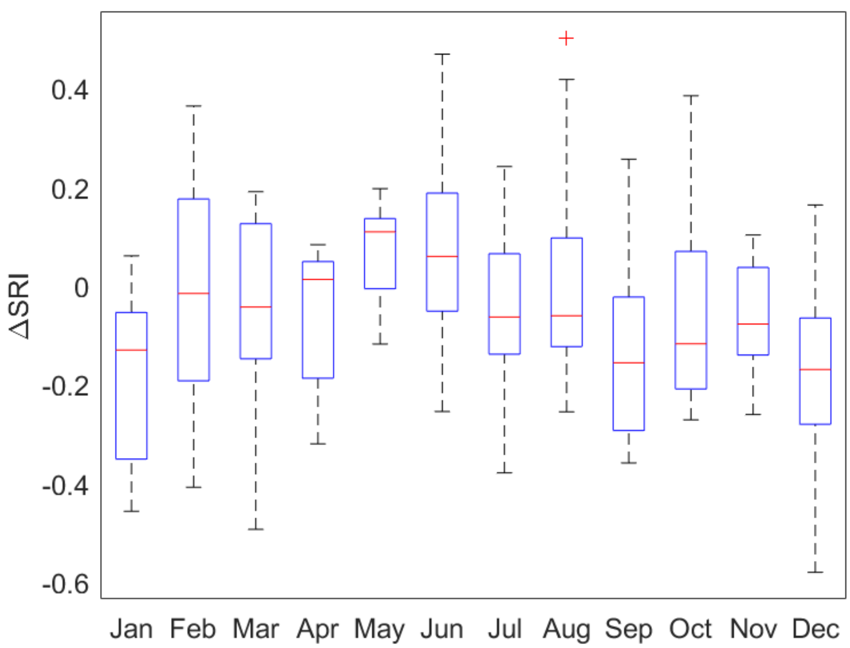


(b)

Figure 3.8. Monthly average of FRI under the baseline and climate scenarios (a) and the changes between them (b) with the nine GCMs models



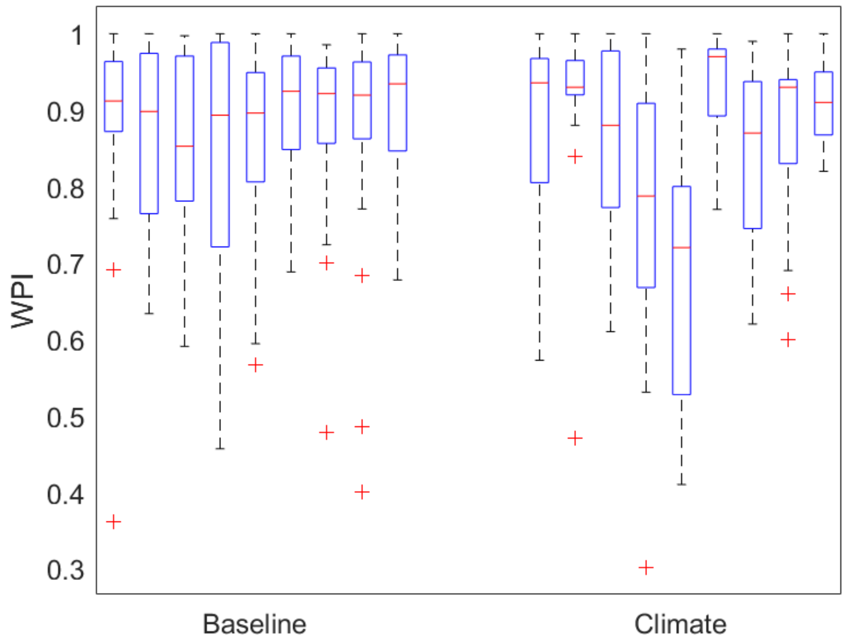
(a)



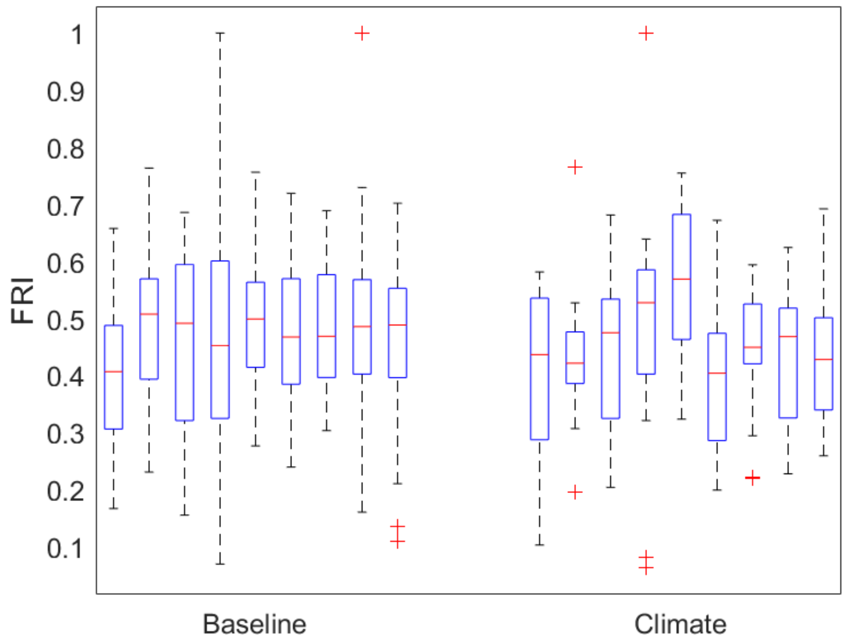
(b)

Figure 3.9. Monthly average of SRI under the baseline and climate scenarios (a) and the changes between them (b) with the nine GCMs models

Figure 3.10a of inter-annual variations of WPI shows that results under the baseline scenario have different inter-annual variations but similar medians among different GCMs while results under the climate scenario generate a large range of inter-annual variations and large variation among medians with all the GCMs. The model with the largest inter-annual variation of WPI under both scenarios is gfdl_cm2_0 and the model with the smallest one is cnrm_cm3. The climate scenario also resulted in larger ranges of inter-annual variations and medians in FRI respectively than the Baseline scenario with very close medians and varied inter-annual variations (Figure 3.10b). The largest and smallest variations of FRI under the climate scenario are cccma_cgcm3_1 and cnrm_cm3, respectively. Figure 3.10c depicts a large range of inter-annual variations of SRI under both baseline and climate scenarios, but the medians under the climate scenario vary more than those under the baseline scenario. The largest and smallest variations of SRI under the climate scenario are cnrm_cm3and gfdl_cm2_0, respectively.


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
WPI
Baseline
Climate

(a)


1
0.9
0.8
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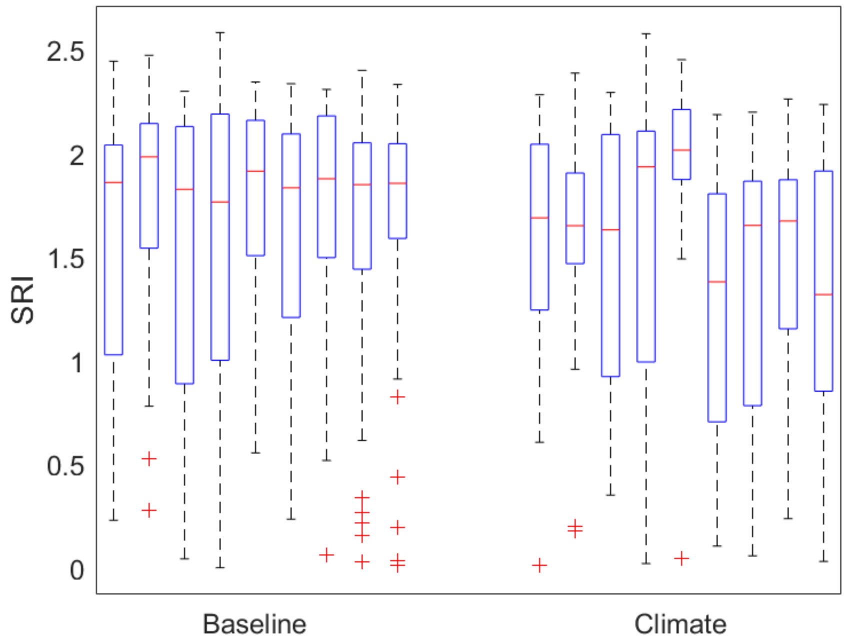
0.5
0.4
0.3
0.2
0.1
FRI
Baseline
Climate

(b)



(c)

Figure 3.10. Inter-annual variations of the three ESs under the baseline and climate scenarios with the nine GCMs models (each boxplot represents results with one climate model in order as in Table 3.3. a: WPI; b: FRI; c: SRI)

3.5 Discussion

Based on the hydrological simulations presented in Section 3.4 and Choi et al. (2017), the LULC-change impacts on hydrological simulation are negligible due to the moderate LULC change and the offsetting effects under different LULC classes. Since only one future LULC-change scenario was considered in this study and the future LULC map (CA 2050) developed for this study is close to realistic urban development without any assumption of management plans, the LULC-change impacts on hydrological simulations and ESs are very limited. Moreover, the impacts caused by urban expansion (increased by 60 km^2) may also be offset by the reduction of planted/cultivated lands as shown in Table 3.2 (decreases by 40 km^2). Such hydrological simulations lead to negligible hydrological ESs results. Gao et al. (2017) reported that hydrological

ESs decreased under an agricultural expansion scenario and increased underwater and soil conservation scenarios. Hoyer and Chang (2014) found that water yield is not sensitive to urban-expansion scenarios while nutrient loading and sediment export are very sensitive to urban-expansion scenarios. Bai et al. (2013) also stated that agricultural expansion resulted in the lowest water yield and the highest one was generated by forestry expansion. According to Logsdon and Chaubey (2013), an extreme urban scenario had very limited impacts on hydrological ESs compared to an extreme agricultural scenario. The impacts of urban expansion thus have limited impacts on hydrological simulations and ESs of the study area.

Climate change, different from LULC change, has very large impacts on hydrological simulations (Choi et al. 2017) and ESs. Annual hydrological simulations generally reflect climate change, especially in precipitation as shown in Table 3.3 and Table 3.5; simulations with models of decreased projections in precipitation also decreased substantially. Monthly simulations also correspond with precipitation data but with different inter-model variations between streamflow (small) and sediment (large). Annual changes in ESs also reflect precipitation as shown in Table 3.3 and Table 3.8 to 3.10 that WPI with models of decreased projection in precipitation also decreased, and FRI and SRI, which are regulation services, are increased with the precipitation increases. Monthly ESs results also show quite large changes and inter-model variations under climate change but with different trends that will be discussed in the next paragraphs. Fan et al. (2016) conducted a similar study and found that current climate scenarios resulted in much more water yield than LULC scenarios. Hoyer and Chang (2014) stated that water yield is very sensitive to different climate-change scenarios compared to LULC scenarios. Samal et al. (2017) demonstrated that climate has a greater influence on future aquatic ESs than changes in LULC.

ESs results from this study also indicate that the climate-change impacts on hydrological ESs are quite a bit larger than those under LULC change.

Changes in monthly average WPI under the climate scenario showed different monthly trends from that of the streamflow simulation and precipitation data. In monthly averages of precipitation and streamflow (Figure 3.3b and 3.5), the changes started to increase from September, peak in April, and then bottom in August while the WPI (Figure 3.7) changes started to increase from March, peak in July, and then bottom in February, which is almost opposite to that of streamflow and precipitation. To investigate this difference, the changes in monthly average of percent of days that flow is less than environmental flow requirements (qne/n of Equation 3.3) for nine models were calculated and plotted (Figure 3.11). Comparing Figure 3.11 with Figure 3.7b, the larger the changes in monthly average of qne/n, the larger the changes in monthly average of WPI. In addition, the inter-model variations of WPI of all months have a similar changing trend as that of qne/n. Such findings indicate that for those months with increased water volume, qne/n also increased, which resulted in decreases in WPI and vice versa. Thus, the number of days in each month that environmental flow requirement was not met contributed more than the water volume and highlights the necessity of using a hydrological ESs method to analyze climate impacts on water provision instead of water volume alone. The inter-annual variations of qne (Figure 3.12) also show similar changing patterns between the baseline and climate scenarios as that of WPI (Figure 3.10a); changes in medians and variations with different GCMs models are similar for both WPI and qne. This finding further substantiates that qne highly affects WPI and indicates that climate change results in changes in qne different from water volume.

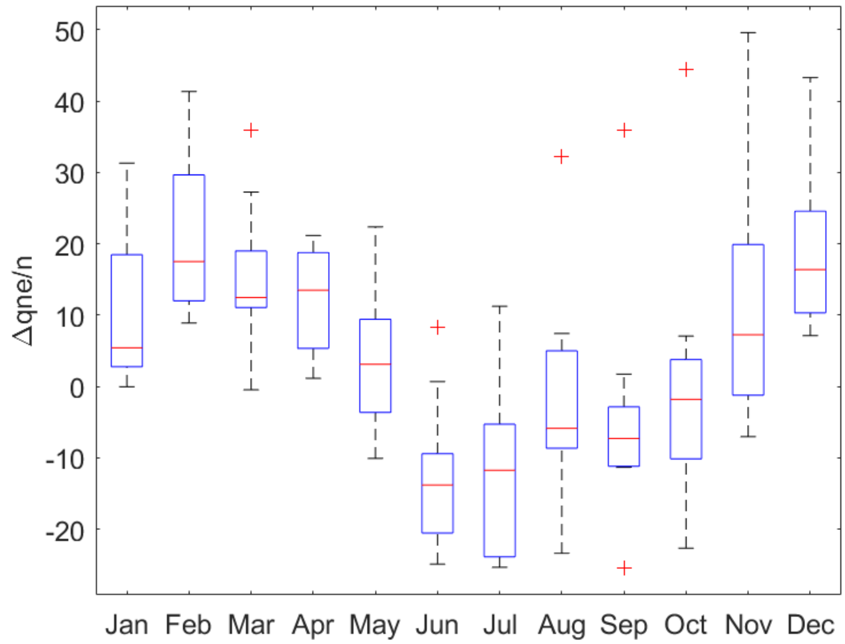


Figure 3.11. Changes in monthly average of the percentage of days that flow is less than environmental flow requirements (qne/n) for WPI calculation between the baseline and climate scenarios with the nine GCMs models

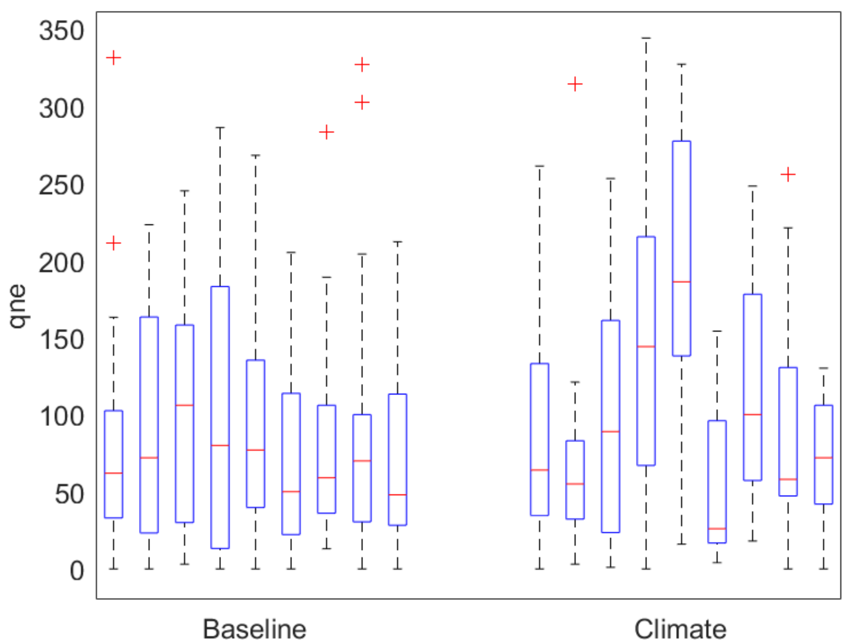
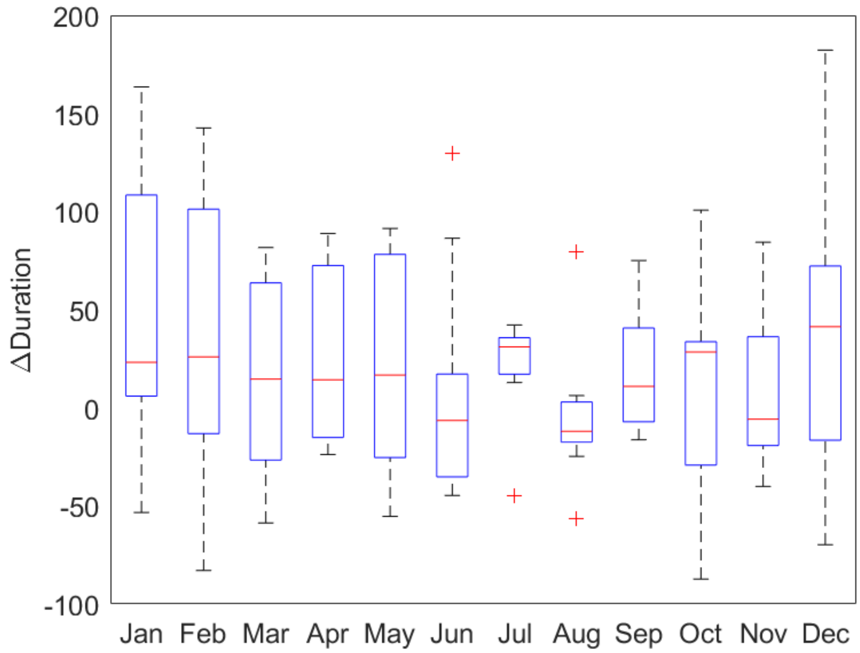


Figure 3.12. Inter-annual variations of the number of days that flow is less than environmental flow requirements (qne) under the baseline and climate scenarios with the nine GCMs models (each boxplot represents results with one climate model in order as Table 3.3.)

Changes in monthly average of FRI present a different monthly changing trend from both that of WPI and water volume. From the monthly water volume and qne results discussed in the last paragraph, climate change resulted in the same monthly changing directions for both water volume and qne/n. Based on such similar changes, FRI was supposed to increase in months with both increased water volume and qne/n and vice versa because higher monthly water volume but more days that environmental flow requirements were not met indicate more extreme flow events and larger event volumes. However, the results in Figure 3.8b do not fit with Figure 3.3 or Figure 3.11. Hence, the three inputs of FRI calculation (Equation 3.4) were analyzed, and the results are presented in Figure 3.13. The changes in monthly average of flood magnitude and frequency (Figure 3.13b and c) have similar changing trends as those of both qne/n (Figure 3.11) and precipitation (Figure 3.3b) while flood duration (Figure 3.13a) has very similar monthly changing trends as FRI. Such trends indicate that flood duration has the most influence on FRI compared to flood magnitude and frequency. These results are different from the weights they were given ($w_{duration}$: 0.4; $w_{magnitude}$: 0.4; $w_{frequency}$: 0.2). Figure 3.13 and Table 3.11 together also demonstrate that climate change resulted in changes in magnitude, duration, and frequency of flood at both annual and monthly scales. Six of nine annual results with GCMs models for FRI, flood duration, magnitude, and frequency show impaired impacts under climate change, and monthly results also showed impaired impacts for most months and models.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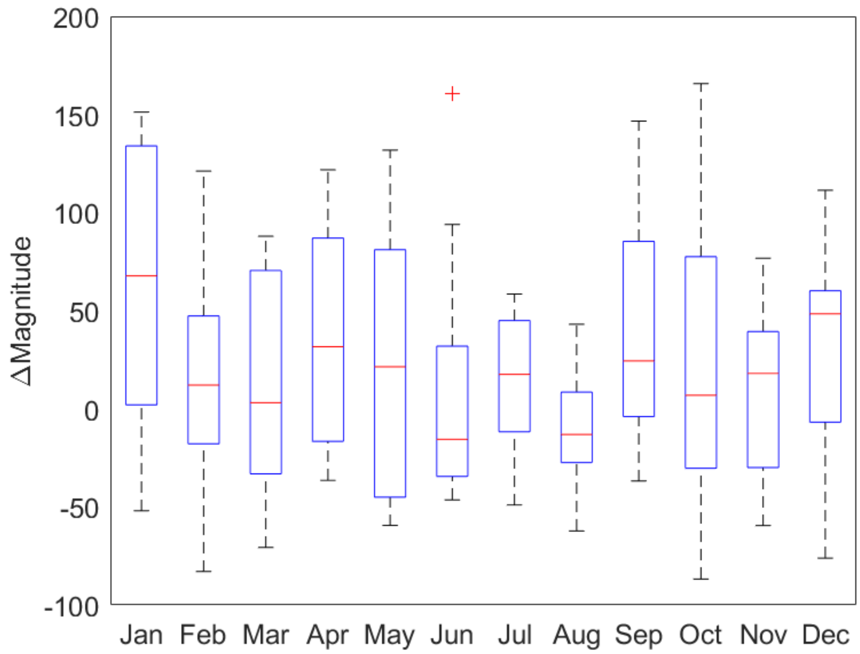
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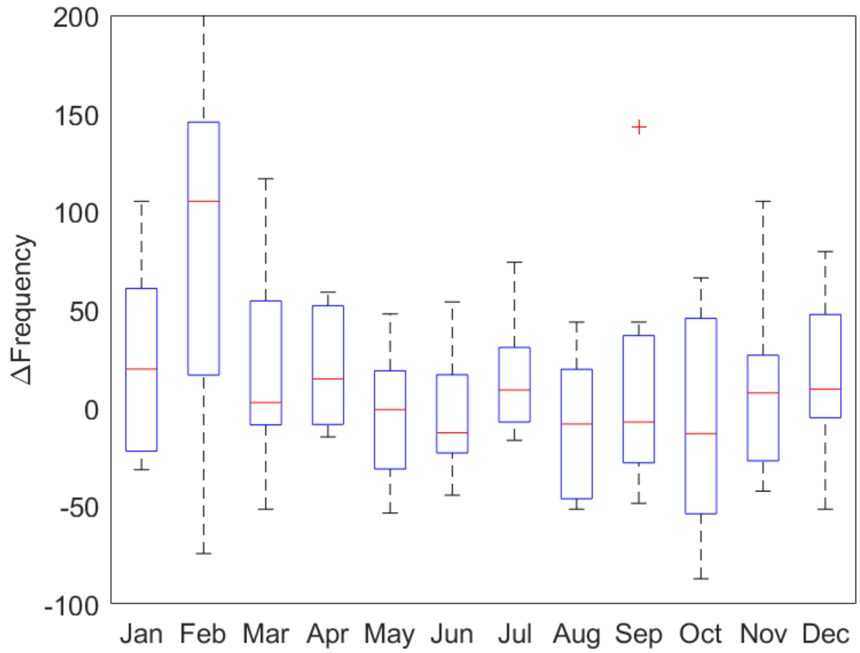

(c)

Figure 3.13. Percentage changes in monthly average of the three inputs for FRI calculation between the baseline and climate scenarios with the nine GCMs models (a. flood duration; b. flood magnitude; c. flood frequency)

Table 3.11. Summary of percentage changes in the three inputs for FRI calculation between the baseline and climate scenarios with the nine GCMs models

Climate models	**Δ Flood duration**	**Δ Flood magnitude**	**Δ Flood frequency**
cccma_cgcm3_1	-2.04	-8.72	16.39
cnrm_cm3	11.89	10.61	32.34
csiro_mk3_0	10.46	0.23	5.15
csiro_mk3_5	-8.95	11.03	-19.07
gfdl_cm2_0	-12.78	-7.33	-30.89
giss_model_e_r	13.17	20.64	32.93
miub_echo_g	6.75	28.09	1.97
mpi_echam5	13.99	11.53	-0.24
mri_cgcm2_3_2a	0.19	-0.04	15.66

Comparing changes in monthly average of precipitation (Figure 3.3b) and SRI (Figure 3.9b), it can be observed that SRI changes generally follow the monthly changing trend of precipitation changes (more precipitation results in more sediment and then low SRI and vice versa). However, when comparing changes in monthly average of sediment (Figure 3.6b) and SRI (Figure 3.9), they are different in both monthly changing trend and inter-model variations. Since the relation between sediment rates and maximum allowable rates of sediment is the only variable used in SRI calculation, and water volume and sediment are the only indirect factors that could affect the SRI results, the changes in monthly average of percentage of days that sediment rate is more than maximum allowable rates of sediment (S_{max} of Equation 3.5) were calculated and displayed in Figure 3.14. The results in Figure 3.14 shows a similar monthly changing trend as that of SRI indicating that the more days in the month that sediment rates were higher than the maximum allowable rates of sediment, the more regulation is required (low SRI values) and vice versa. The changes in annual average of the percentage of $S > S_{max}$ (Table 3.12), however, show different patterns from that of SRI (Table 3.10); three of nine models have same changing direction (should be different directions since SRI is regulation needed). Such findings indicate that when considering sediment regulation services, both sediment rates and how the rates compare to the maximum allowable rates should be included, which requires hydrological simulation and ESs modeling.

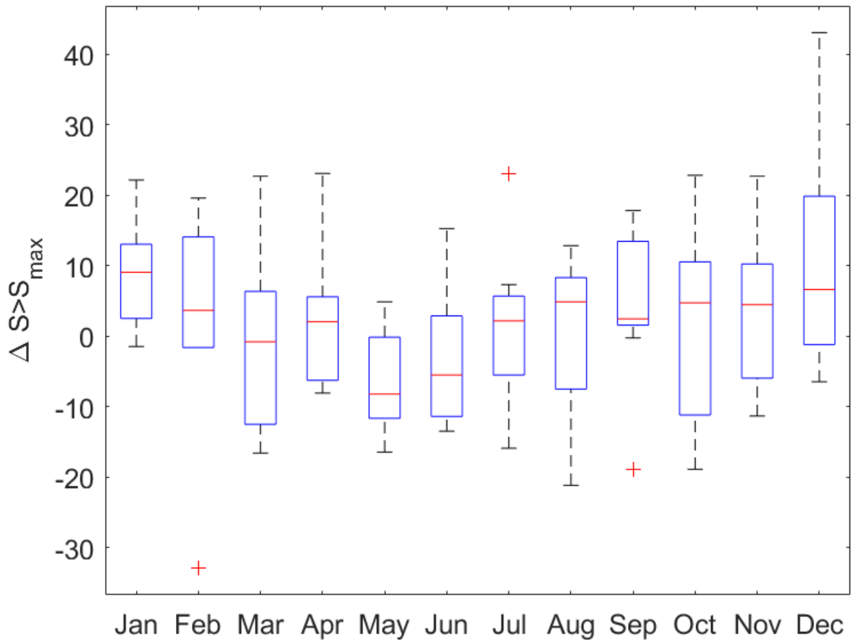

Figure 3.14. Changes in monthly average of percentage of the days sediment rate is more than maximum allowable rate of sediment ($S > S_{max}$) between the baseline and climate scenarios with the nine GCMs models

Table 3.12. Summary of percentage of the days that sediment rate is more than the maximum allowable rate of sediment ($S > S_{max}$) under the baseline and climate scenarios with the nine GCMs models (annual average).

Climate models	**Baseline**	**Climate**	**Change**
cccma_cgcm3_1	23.08	21.05	-2.02
cnrm_cm3	15.38	15.79	0.40
csiro_mk3_0	25.64	26.32	0.67
csiro_mk3_5	25.64	26.32	0.67
gfdl_cm2_0	10.26	5.26	-4.99
giss_model_e_r	15.38	36.84	21.46
miub_echo_g	7.69	31.58	23.89
mpi_echam5	20.51	10.53	-9.99
mri_cgcm2_3_2a	17.95	31.58	13.63

3.6 Conclusions

In this chapter, with the conceptual-modeling framework for hydrological ESs and the design of the scenario study, new insights were found regarding hydrological ESs under LULC-and-climate-change impacts in the urbanizing study area. My study includes LULC and climate-change scenarios and compares their impacts at both annual and monthly scales; and the latter are limited in the hydrological ESs literature. The findings of this study could offer decision-makers and stakeholders more insights for land management plans.

The key findings of this study are that climate change has larger impacts on hydrological ESs than LULC change, and such impacts include increased inter-model, inter-annual, and inter-monthly variations. LULC change impacts are limited due to modest urban expansion projections and offsetting from the reduction of planted/cultivated LULC class. Annual and monthly results under climate change show substantial increased inter-model variations. The results also reveal that climate change created increased inter-annual variations for all the GCMs models. Additionally, inter-monthly variations were also increased by climate change based on the monthly average results. Although changes in annual ESs results and inter-model variations corresponded to water volume, the monthly ESs results do not correspond to water volume: (1) water provision was more sensitive to the low flow that did not meet the environmental requirement than to the water volume; (2) flood regulation is more sensitive to the changed flood duration caused by climate change than the changed magnitude and frequency; (3) sediment regulation results are affected by changed water volume as well as the changed ratio between sediment rates and maximum allowable rates. Such findings could provide decision-makers with detailed and novel insights for management and conservation plans.

This study establishes a standard workflow for hydrological ESs modeling under LULC and climate-change impacts supported by national data products. Due to the timeframe limit and data availability, this study only utilized one LULC-change scenario and one emission scenario of the climate models. Future studies could focus on adopting multiple LULC and climate-change scenarios for the analysis of tradeoffs and uncertainties. In addition, with more scenarios involved, the sensitivity of temporal scales could also be further demonstrated.

CHAPTER 4. CONCLUSION

4.1 Overview

This dissertation presents a conceptual modeling framework that aims to convert hydrological information to hydrological ESs at fine temporal scales. The overall goal of this study is to demonstrate the importance of hydrological ESs at fine temporal scales and the impacts of LULC and climate changes on hydrological ESs. Three main objectives of this dissertation are to:

(1) Build a coupled modeling framework so that hydrological information can be converted to hydrological ESs by developing a conceptual connection of three functions: data development, modeling, and results analysis (Chapter 2).

(2) Demonstrate the importance of hydrological ESs at fine temporal scales by simulating hydrological ESs with the framework in the case study (Chapter 2).

(3) Examine impacts of LULC and climate changes on hydrological ESs with the framework and a series of climate and urban expansion scenarios in the Milwaukee River basin, USA (Chapter 3).

For Objective 1, the framework with integration of data processing, hydrological and ESs modeling, and output analysis supported by national data products was built with several tools. The framework was accomplished by three functions: The data-development function supports data organization, development, and assortment for the hydrological model and ESs model setup. The modeling function executes hydrological and ESs simulations. The results-analysis function performs spatiotemporal analyses and visualization with modeling results.

For Objective 2, results of the water-provision ES at both monthly and annual scales capture the high and low water provisions in different seasons and compare annual and monthly changes to highlight some annual high values with monthly low values or vice-versa. Results of the flooding-regulation ES simulated in this study not only predicted the flooding risk per year but also pinpointed the months and seasons when regulation should be applied. Finally, sediment-regulation ES at both annual and monthly scales illustrate the different patterns between annual and monthly results and suggested seasons that needed more regulations.

For Objective 3, results show that, compared to the LULC scenario, the climate-change scenario has much larger impact on hydrological ESs, and results under climate change show substantial increased variations of different climate models, years, and months. In addition, the interactions among different ESs have also been identified. LULC-change impacts are limited due to modest urban expansion projections and offsetting from the reduction of planted/cultivated LULC class. Annual and monthly results under climate change show substantial increased inter-model variations. The results also reveal that climate change created increased inter-annual variations for all the GCMs models. Additionally, inter-monthly variations were also increased by climate change based on the monthly average results. Although changes in annual ESs results and inter-model variations are corresponded to water volume, the monthly ESs results are not corresponded to water volume which are shown as: water provision was more sensitive to the changed percentage of the low flow that did not meet the environmental requirement than to the increased water volume which resulted in decreased water provision; flood regulation is more sensitive to the changed flood duration caused by climate change than the changed magnitude and frequency; sediment regulation results are affected by changed water volume as well as the changed ratio between sediment rates and maximum allowable rates. Such findings could provide decision-makers with detailed and novel insights for management and conservation plans.

4.2 Key Findings and Implications

In this paper, a conceptual modeling framework (Objective 1) that can simulate hydrological ESs at fine temporal scales was built to conduct ESs studies that are time-sensitive. This framework resolves the design limitations of both current ESs that cannot simulate at fine temporal scales and hydrological models that cannot convert hydrological information to ESs. First, with this framework, hydrological results can be converted to indices for evaluating water provision, flood regulation, and sediment regulation in different ways, such as a general increasing or decreasing trend, detailed analysis of the changes, and seasonal changes for decision-makers. Second, this framework can preprocess and access the input data at daily or hourly scales and can simulate hydrological ESs at the same temporal scales as the hydrological model (daily, monthly, and annual), which certainly fills the gap of the incapability of current ESs models at annual scale. The design of the framework establishes a strategy for the integration of data development, hydrological and ESs modeling, and output analysis supported by national data products for multiple research purposes. With such procedural streamlining, simulation of hydrological ESs is more straightforward and less time-consuming than the separated processes. Additionally, the framework could be smoothly applied to ESs modeling in any watershed in the U.S. with regional dataset and information. Furthermore, for other study areas where hydrological research has already been conducted, only ESs data preparation and ESs model execution would be needed. Finally, thanks to the flexibility of the framework, other hydrological models with different mechanisms or design, other ESs models, and different LULC or climate-change scenarios could be used in this framework for further comparison and uncertainties analysis.

Results from fine temporal analyses (Objective 2) of water-provision ES, flood-regulation ES, and sediment-regulation ES indicate that annual results alone in ESs simulation and analysis for management plans is not adequate for time-sensitive plans and including results at fine temporal scales are necessary for some ESs that are event-based or have large seasonal variations. Based on such results, more timely relevant policy suggestions and novel insights for management and conservation plans can be provided to decision-makers.

The design of this impacts study (Objective 3) with the framework establishes a standard workflow for hydrological ESs modeling under LULC and climate-change impacts supported by national data products. This approach with the framework and impact scenarios can better support management plans for decision-makers. In this dissertation, with the newly designed conceptual modeling framework and scenario study, new insights were found regarding hydrological ESs under LULC and climate-change impacts in the urbanizing study area. My research including LULC and climate-change scenarios and comparing their impacts at both annual and monthly scales is novel in the hydrological ESs literature. The key findings of this study are that climate change has larger impacts on hydrological ESs than LULC change, and such impacts include increased inter-model, inter-annual, and inter-monthly variations.

4.3 Limitation and Recommendation for Future Research

The major limitation of this study lies in the uncertainties brought by each step of the framework in Figure 4.1. Some simple actions have been applied to reduce the uncertainties of each steps (Figure 4.1). Statistical downscaling created uncertainties in the future climate data, and I used historical climate data to verify them. LULC data generated by CA modeling introduced uncertainties of different growing patterns, and historical LULC data were used for calibration and validation. USGS-gauged hydrological data were compared with hydrological simulations for reduction of uncertainties created by hydrological modeling. However, some uncertainties are inevitable in any modeling study even with the actions taken, and such uncertainties cascaded through the whole framework procedure and accumulated in ESs modeling where I displayed the variations among different climate models. Use of a Monte Carlo model or other iterative procedure to generate a probability distribution of multiple model results would be the most effective method to address this issue. However, such methods were beyond the scope of this dissertation.

Furthermore, with the limit time for this research, only one LULC-change scenario and one emission scenario for the climate models were applied. Future studies could focus on adopting multiple LULC and climate-change scenarios for the analyses of tradeoffs and uncertainties. In addition, with more scenarios involved, the sensitivity of temporal scales could also be further demonstrated. Finally, the modeling framework is still at the conceptual stage which includes all the necessary functions but not a user-friendly interface that could further assistant stakeholders and the public for understanding the processes and results. Such an interface could be built on a GIS platform, as a separate interface, or as a web-based interface depending on the workload and requirement from the stakeholders.

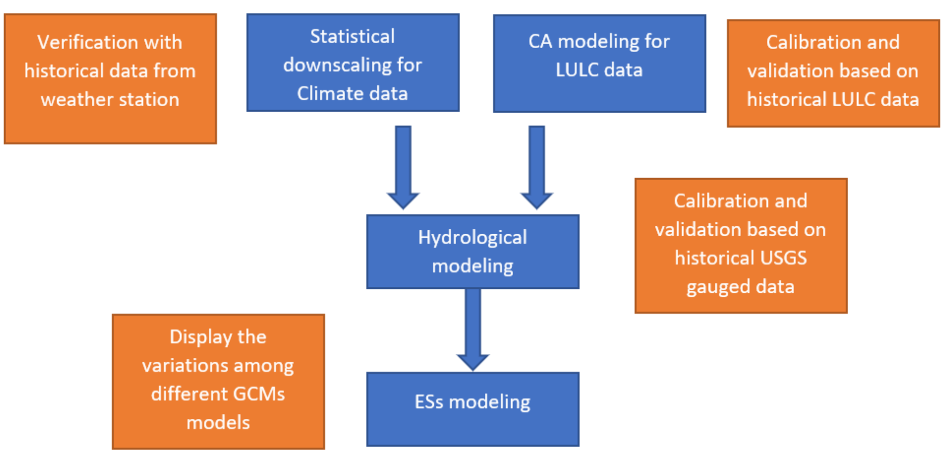

Figure 4.1. Sources of uncertainties in the framework procedure and actions taken for reduction

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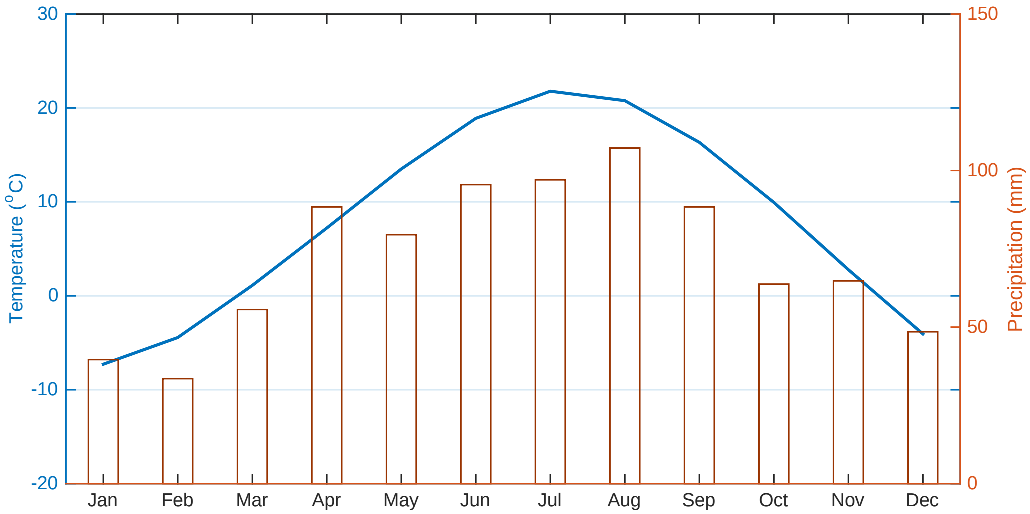
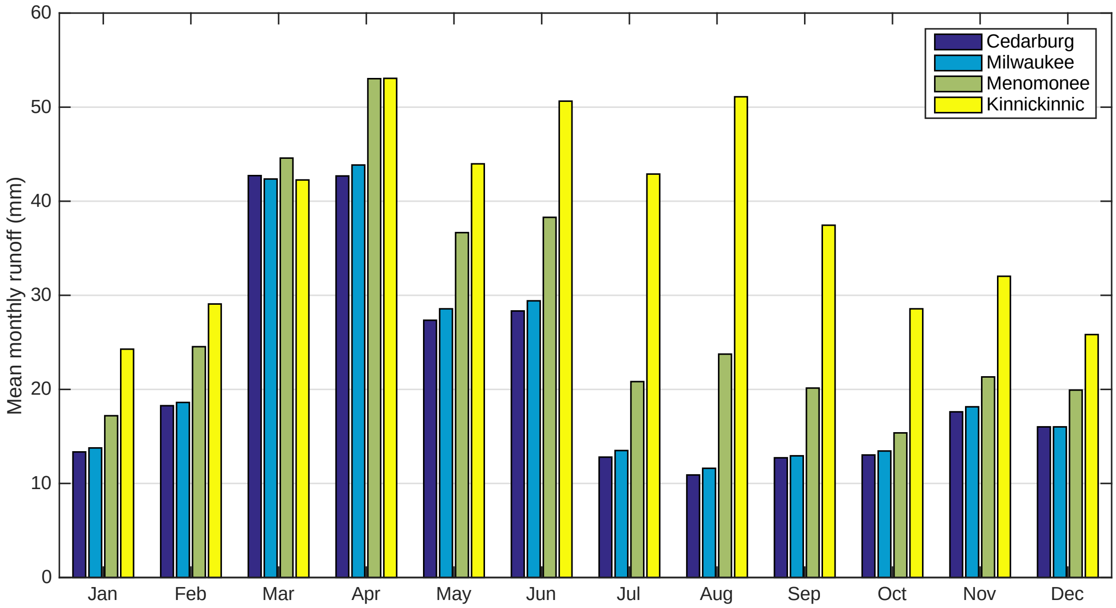
Appendices

Appendix A: Mean monthly temperature (line) and precipitation (bar) during 1971-2000 for Southeastern Wisconsin Climate Division



(plotted from the data available on http://www.aos.wisc.edu/%7Esco/clim-history/division/4709-climo.html after unit conversion)

Appendix B: Mean monthly runoff during 1983-2008 from the four USGS sites



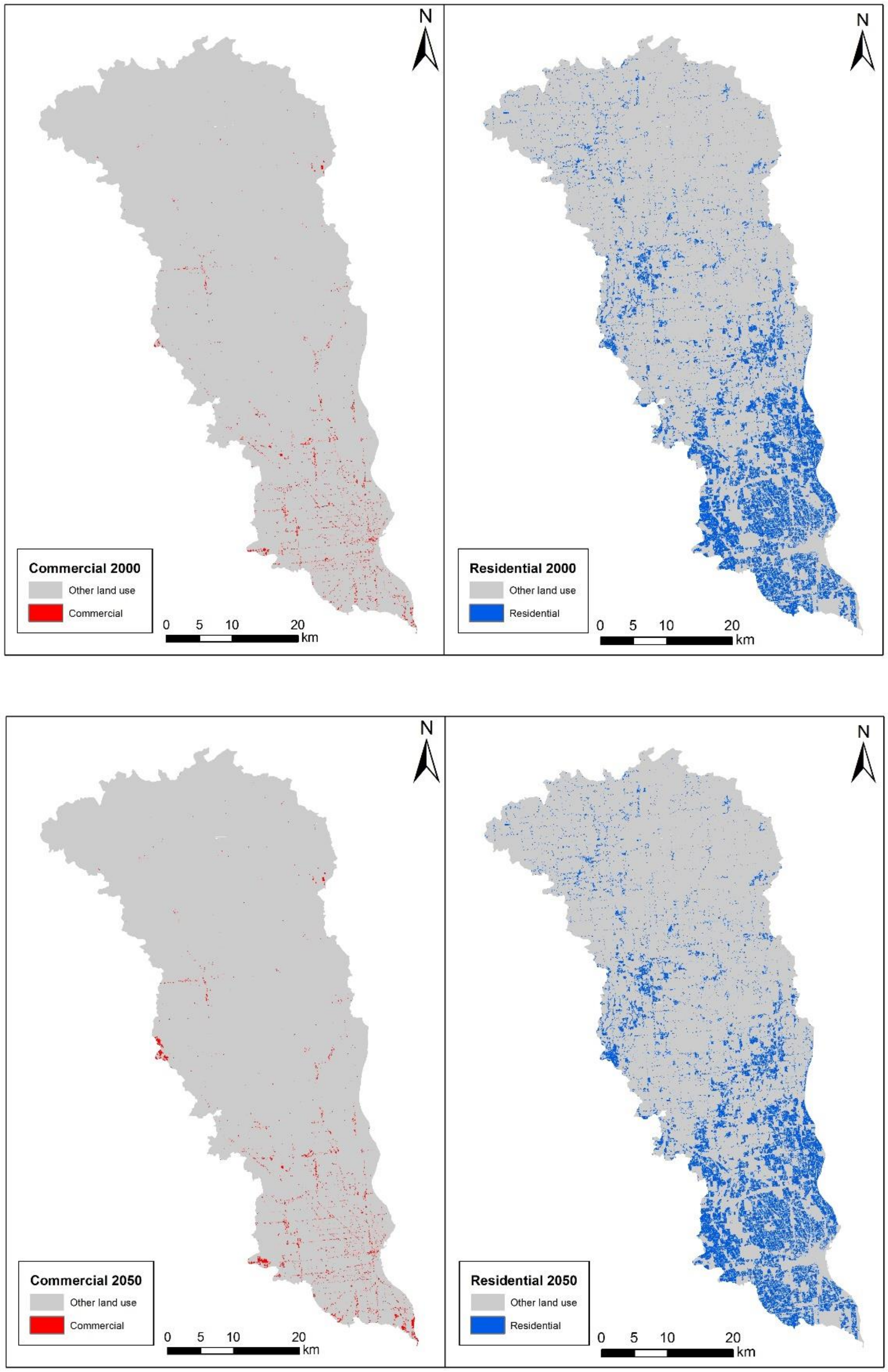
Appendix C: U.S. Geological Survey streamflow measurement sites, in descending order of latitude

Site number	Site name	Latitude (N), longitude (W)	Elevation above sea level (m)	Drainage area (km^2)
04086600	Milwaukee River near Cedarburg, WI	43°16'49", 87°56'30"	199.1	1 572.12
04087000	Milwaukee River at Milwaukee, WI	43°06'00", 87°54'32"	185.0	1 802.63
04087120	Menomonee River at Wauwatosa, WI	43°02'44", 87°59'59"	191.6	318.57
04087159	Kinnickinnic River @ S. 11th Street @ Milwaukee WI	42°59'51", 87°55'35"	179.4	48.69

Appendix D: NLCD land cover class and aggregated land cover for the study

Land cover code in NLCD	**Land cover class in NLCD**	**Land cover for the study**
11	Open Water	Water
21	Developed, Open Space	Developed
22	Developed, Low Intensity	
23	Developed, Medium Intensity	
24	Developed High Intensity	
31	Barren Land (Rock/Sand/Clay)	Barren
41	Deciduous Forest	Forest
42	Evergreen Forest	
43	Mixed Forest	
52	Shrub/Scrub	Shrubland
71	Grassland/Herbaceous	Herbaceous
81	Pasture/Hay	Planted/Cultivated
82	Cultivated Crops	
90	Woody Wetlands	Wetlands
95	Emergent Herbaceous Wetlands	

Appendix E: Simulated residential and commercial lands for 2000 and 2050



Appendix F: GCMs used for climate scenarios in the study

	Institute and country	Model name
cccma_cgcm3_1	Canadian Center for Climate Modelling and Analysis, Canada	The Third Generation Coupled Global Climate Model
cnrm_cm3	Centre National de Recherches Meteorologiques, France	Coupled Global Climate Model version 3
csiro_mk3_0	Commonwealth Scientific and Industrial Research Organisation, Australia	Mark 3.0
csiro_mk3_5	Commonwealth Scientific and Industrial Research Organisation, Australia	Mark 3.5
gfdl_cm2_0	Geophysical Fluid Dynamics Laboratory, USA	Coupled Model, version 2.0
giss_model_e_r	Goddard Institute for Space Studies, USA	Model E/Russell
miub_echo_g	Meteorological Institute, University of Bonn, Germany	ECHO-G = ECHAM4 + HOPE-G
mpi_echam5	Max-Planck-Institut for Meteorology, Germany	ECHAM model, Version 5
mri_cgcm2_3_2a	Meteorological Research Institute, Japan	Coupled General Circulation Model, Version 2.3.2a

CURRICULUM VITAE

EDUCATION

Ph.D. Geography, University of Wisconsin-Milwaukee, USA 2019/05

Dissertation title: *A Conceptual Modeling Framework for Hydrological Ecosystem Services and its Application to the Impacts of Climate Change and Urban Expansion*

Adviser: Dr. Woonsup Choi

M.S. Geography, University of Tennessee, Knoxville, USA 2012/08

Thesis title: *Assessing the performance of the AnnAGNPS model for ungauged small watersheds – a case study of the St. Croix River watershed*

Adviser: Dr. Liem Tran

B.S. Agricultural Resources and Environment, Nanjing Agricultural University, Nanjing, China 2010/06

Thesis title: *The NDVI of Taihu lake basin calculation and mapping by making use of the small satellite of environment*

Adviser: Dr. Xiaosan Jiang

RESEARCH INTERESTS

Geographic information science, Geospatial analysis, Remote sensing, Urban environmental planning, Hydrologic modeling, Ecosystem services modeling, Decision support tool development, Climate and land use change impact study

PUBLICATIONS

Peer-reviewed journal articles:

2019 **Pan, F.,** & Choi, W. 2019. Impacts of Climate Change and Urban Expansion on Hydrologic Ecosystem Services in the Milwaukee River Basin. *Climate*, 7(4): 59. https://doi.org/10.3390/cli7040059

2019 **Pan, F. &** Choi, W. 2019. A Conceptual Modeling Framework for Hydrologic Ecosystem Services. *Hydrology*, 6(1): 14. doi: 10.3390/hydrology6010014

2018 **Pan, F.**, Choi, W. & Choi, J. 2018. Effects of urban imperviousness scenarios on simulated storm flow. *Environmental Monitoring and Assessment*, 190: 499. https://doi.org/10.1007/s10661-018-6874-1

2017 Choi, W., **Pan, F.**, & Wu, C. 2017. Impacts of climate change and urban growth on the streamflow of the Milwaukee River (Wisconsin, USA). *Regional Environmental Change*, 17(3), 889-899. doi: 10.1007/s10113-016-1083-3

PRESENTATIONS

Conference presentations

2017 **Feng Pan,** Woonsup Choi. A Coupled GIS Modeling Framework for Hydrologic Ecosystem Services. *AWRA Annual Water Resources Conference*, Portland, OR November 5-9

2016 **Feng Pan,** Woonsup Choi. Impacts of Climate Change and Urban Growth on Streamflow and Sediment Export: Milwaukee River Basin, Wisconsin. *AWRA 2016 Summer Specialty Conference on GIS & Water Resources IX,* Sacramento, CA, July 11 - 13

2015 **Feng Pan,** Woonsup Choi. Impacts of Climate Change on Hydrological Processes and Uncertainties from Climate Models in the Milwaukee River Basin, Wisconsin. *Annual Meeting of the Association of American Geographers*, Chicago, IL, April 21-24.

2014 **Feng Pan,** Woonsup Choi. The Influence of Different Methods for Estimating Impervious Surface Cover on Model-simulated Streamflow of the Milwaukee River Basin. *AWRA Wisconsin Section*, Wisconsin Dells, WI, March 13-14.

2012 **Feng Pan**. Assessing the performance of the AnnAGNPS model for ungauged small watersheds – a case study of the St. Croix River watershed. *Annual Meeting of the Association of American Geographers*, New York, NY, February 24-28.

REVIEWER SERVED

Journal article peer reviewer

SAGE Open Journal

Water — Open Access Journal

TECHNICAL SKILLS

Hydrologic and water quality modeling: Numerical modeling of hydrometeorological prediction, water quality sampling and analysis, non-point source data analysis, land use/land cover change and best management practices (BMPs)/low impact development (LIDs) assessments, Total Maximum Daily Load (TMDL) and watershed implementation plan development.

GIS, Remote Sensing, and Hydrologic Models: ESRI ArcGIS, QGIS, ENVI, EDARS IMAGINE, SWAT, HSPF, AnnAGNPS

Statistical Analysis: Matlab, SPSS, R

Programming Languages: Python, Java, C, ENVI IDL

TEACHING EXPERIENCES

2013-2019	**Teaching assistant**, Department of Geography, University of Wisconsin-Milwaukee GEOG120: Our Physical Environment

PROFESSIONAL MEMBERSHIPS

2010-Present	Association of American Geographers (AAG)

HONORS AND AWARDS

2015-2017	Graduate Student Travel Award, Graduate School, UWM ($400/yr)
2014	Second Place, Student GIS Project Competition, GIS Council, UWM ($200)
2014-2018	Mary Jo Read Fellowship, Department of Geography, UWM ($2500/yr)
2013-2014	Mary Jo Read Fellowship, Department of Geography, UWM ($5000)
2010-2016	Mary Jo Read Travel Award, Department of Geography, UWM ($1000/yr)