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BASINS and WEPP Climate Assessment Tools (CAT): Case Study Guide to Potential Applications

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FOREWORD

AUTHORS AND REVIEWERS

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

%	percent
°C	Celsius
°F	Fahrenheit
7Q10	7-day average low streamflow with a 10-year return period
ARS	Agricultural Research Service
BASINS	Better Assessment Science Integrating point & Non-point Sources
BMP	best management practice
bu	bushel
CA	California
CAT	Climate Assessment Tool
CFM	change factor methodology
cfs	cubic feet per second
cms	cubic meters per second
CTIC	Conservation Tillage Information Center
EMC	event mean concentration
GCM	global climate model
GCRP	Global Change Research Program
GIS	geographic information system
ha	hectare
HSPF	Hydrologic Simulation Program-FORTRAN
HUC	Hydrologic Unit Code
ICLEI	ICLEI - Local Governments for Sustainability
IPCC	Intergovernmental Panel on Climate Change
km	kilometers
LULC	land use land cover
MD	Maryland
mg/l	milligram/liter
MGD	million gallons per day
mm	millimeter
MN	Minnesota
NARCCAP	North American Regional Climate Change Assessment Program
NCDC	National Climatic Data Center
NLCD	National Land Cover Data
NPS	nonpoint source
NRCS	Natural Resource Conservation Service
NSE	Nash-Sutcliffe Model Efficiency Coefficient
PB	Percent Bias
PET	potential evapotranspiration
PLOAD	Pollutant Loading Application

PRISM	Parameter-elevation Regressions on Independent Slopes Model
RCM	regional climate model
RMSE	Root Mean Square Error
STATSGO	State Soil Geographic Database
SWAT	Soil Water Assessment Tool
SWMM	Storm Water Management Model
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UMRB	Upper Mississippi River Basin
USACE	U.S. Army Corps of Engineers
USDA	US Department of Agriculture
USEPA	US Environmental Protection Agency
USGS	U.S. Geologic Survey
VA	Virginia
WEPP	Water Erosion Prediction Project
yr	year

EXECUTIVE SUMMARY

Climate is changing. During the last century, the global average temperature increased 1.4^{o}F (IPCC, 2007). Changes in the form, amount, and intensity of precipitation have also been observed, although with significant regional variability (IPCC, 2007; Groisman 2005). Climate modeling experiments suggest these trends will likely continue or accelerate throughout the next century (IPCC, 2007; Karl et al., 2009). There is increasing concern about the potential effects of climate change on water resources. Potential effects of climate change include increased risk of flooding and drought, changes in the quality and seasonal timing of runoff, loss of aquatic habitat, and ecosystem impairment (Bates et al., 2008; Karl et al., 2009; U.S. EPA, 2008a).

Many communities, states, and the federal government are considering adaptation strategies for reducing the risk of harmful impacts resulting from climate change. Challenges remain, however, concerning how best to incorporate diverse, uncertain, and often conflicting information about future climate change into decision making. Despite continuing advances in our understanding of climate science and modeling, we currently have a limited ability to predict long-term (multi-decadal) future climate at the local and regional scales needed by decision makers. It is therefore not possible to know with certainty the future climatic conditions to which a particular region or water system will be exposed. In addition, most water and watershed systems are already vulnerable to existing non-climatic stressors including land-use change, point-source discharges, and habitat loss. The potential interaction of climate change with the effects of other existing and future stressors are not well understood at the watershed scale.

Scenario analysis using computer simulation models is a useful and common approach for assessing the vulnerability of water and watershed systems to a wide range of plausible but uncertain future conditions and events, including the effectiveness of alternative management responses (Lempert, 2006, 2010; Volkery, 2009). By exploring the implications of a wide range of uncertain but plausible future conditions, we can identify how we are most vulnerable, and guide the development of management strategies that are robust across a wide range of potential future conditions and events (Sarewitz et al., 2000). To reduce the likelihood of future impacts, tools and information are needed for assessing the potential implications of potential climate change, land-use change, and management responses in specific watershed locations.

USEPA and partners recently developed two assessment tools, the BASINS Climate Assessment Tool (CAT) and the Water Erosion Prediction Project Climate Assessment Tool (WEPPCAT). The tools are each intended to facilitate application of existing simulation models for conducting scenario-based assessments. Specifically, they provide flexible capabilities for creating and running climate change scenarios to address a wide range of “what if” questions about how weather and climate could affect water and watershed systems. Combined with the existing capabilities of the BASINS and WEPP models, the tools can be used to explore the combined effects of potential changes in climate and land use on a range of streamflow and water quality endpoints, as well as the potential effectiveness of management practices for reducing impacts.

This report presents a series of short, illustrative case studies using the BASINS and WEPP climate assessment tools. Case studies are presented using BASINS CAT with the HSPF, SWAT, and SWMM water models, and using WEPPCAT with the WEPP model. Each case study presents a real or plausible issue in a specified location, and applies BASINS CAT or WEPPCAT to address or inform upon the problem. Taken together, the six case studies illustrate the use of BASINS CAT and WEPPCAT to address a range of practical, real-world questions of potential interest to water and watershed managers.

Case study simulations illustrate important differences in the sensitivity of streamflow and water quality endpoints to changes in specific climate drivers. Generally, increased precipitation resulted in increased streamflow and pollutant loads. The response to increased precipitation was found to be reduced or even reversed, however, by increased evapotranspiration that resulted from increased annual temperatures. Increased temperature combined with reduced precipitation consistently resulted in decreased streamflow. An awareness of these subtleties in the response of different streamflow and water quality endpoints to specific types of climate change highlights the need for improved understanding of system behavior, and in turn, the difficulty in developing quantitative predictions of future change.

Responding to climate change will require that information about climate change be incorporated into applicable facets of community and natural resource management and decision making. Considering climate change in the context of a broad agenda allows communities to determine how climate change risks rates against other activities and factors in the community and may also help to identify ways to adapt for climate change using existing methods.

The scientific approach supported by these tools, i.e., scenario analysis, can be useful for understanding system behavior, identifying vulnerabilities, and evaluating the effectiveness of management responses to inform management decision making. The tools presented in this report, however, are just one step forward in building our capacity for understanding and responding to climate change. Application of hydrologic models in this way has limitations, many of which are not well understood (Ghosh 2010; Ludwig, 2009; Najafi, 2011; Vaze et al., 2010). Further study is required to better assess, refine, and develop our current modeling capabilities. Further study is also required to better address the challenge of incorporating diverse, uncertain, and often conflicting information about future climate change into water resources decision making.

1. INTRODUCTION

There is growing concern about the potential effects of climate change on water resources.
Climate has a direct influence on the occurrence, distribution, and management of water resources. Changes in the amount, form, and intensity of precipitation, together with factors affecting evaporative loss such as air temperature have a direct influence on the quantity, quality, and timing of available water (Gleick and Adams, 2000). Water infrastructure is designed and operated to maintain safe and reliable drinking water supplies, flood protection, wastewater treatment, and urban drainage under anticipated climatic conditions. Climate change presents an increased risk of harmful impacts to these and other water management goals.

It is now generally accepted that human activities including the combustion of fossil fuels and land-use change have resulted, and will continue to result in, long-term climatic change (IPCC, 2007; Karl et al., 2009). The 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that “warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level” (IPCC, 2007). During the last century, the global average temperature has increased 1.4^{o}F (IPCC, 2007). Changes in precipitation patterns have also been observed, although with significant regional variability (IPCC, 2007; Groisman 2005). Climate modeling experiments suggest these trends will likely continue or accelerate throughout the next century (IPCC, 2007; Karl et al., 2009).

The effects of climate change will vary in different locations depending on the specific type of change that occurs together with the attributes individual watersheds including physiographic setting, land-use, and human use and management of water. Effects will vary in different regions of the nation but could include increases or decreases in available water supply, changes in the seasonal timing of supply, increased risk of flooding and drought, increased water temperature, changes in pollutant loading, loss of aquatic habitat, and ecosystem impairment (Bates et al., 2008; Karl et al., 2009; U.S. EPA, 2008a). In addition, in many areas water resources are stressed and vulnerable to existing, non-climatic stressors including increasing demand, land-use change, point-source discharges, and habitat degradation. Climate change will interact with these stressors in different settings in complex ways that are not well understood. Where effects are large, current water management may not be adequate to cope with the effects of climate change.

Responding to climate change is complicated by the scale, complexity, and inherent uncertainty of the problem. Despite continuing advances in our understanding of climate science and modeling, current climate models have a limited ability to predict long-term (multi-decadal) future climate at local and regional scales (Sarewitz et al., 2000). It is therefore not possible to know with certainty the future climatic conditions to which a particular location or water system will be exposed. This uncertainty should not, however, be considered a barrier to taking action. Current global and regional climate models (GCMs, RCMs) are excellent tools for understanding the complex interactions and feedbacks associated with future emissions scenarios and identifying a set of plausible, internally consistent scenarios of future climatic conditions. Historical observations and paleo records of climatic variability can also provide useful information about the type and range of changes possible in different regions of the nation. By exploring the implications of a wide range of uncertain but plausible future conditions, we can identify how we are most vulnerable, and use this information to guide the development of robust strategies for reducing risk (Sarewitz et al., 2000).

Vulnerability (to climate change) is defined by the IPCC (2007) as “the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes”. Assessing the risks and impacts of climate change (vulnerability assessment) can take many forms depending on the ecological or social resource of interest, decision context, and projected the potential range of expected climate changes characteristics.

Scenario analysis using computer simulation models is a common approach (Lempert, 2006, 2010; Volkery, 2009). A number of water simulation models are available that are capable of representing the response of watershed systems to changes in climatic, land-use, and management drivers. Many of these models, such as those currently available in EPA's BASINS modeling system (HSPF, SWAT, SWMM), are well validated and already commonly used to support management decision making. Several excellent references are available discussing the use of scenarios in assessing climate change impacts and vulnerabilities to water (e.g., see IPCC TGICA, 2007; WUCA, 2010; Brekke et al., 2009; U.S. EPA, 2011a).

In an effort to support scenario-based assessments of climate change impacts on water, USEPA and partners have developed two assessment tools, the BASINS Climate Assessment Tool (BASINS CAT) and the Water Erosion Prediction Project Climate Assessment Tool (WEPPCAT). These tools facilitate application of existing simulation models for conducting scenario-based assessments. Specifically, they provide flexible capabilities for creating and running climate change scenarios to address a wide range of "what if" questions about how weather and climate could affect water and watershed systems (e.g., how would increases in the intensity of rainfall events affect stormwater runoff, what type of climate change would need to occur to increase stream water temperatures to a level harmful to fish?). Combined with the existing capabilities of the BASINS and WEPP models, the tools can be used to explore the combined effects of potential changes in climate and land use on a range of streamflow and water quality endpoints, as well as the potential effectiveness of management practices for reducing impacts.

BASINS CAT was originally released in 2007 with EPA's BASINS modeling system version 4.0, and was originally available only with the Hydrologic Simulation Program-FORTRAN (HSPF) watershed model (Johnson and Kittle, 2006; Imhoff et al., 2007; U.S. EPA, 2009a). With the release of BASINS CAT Version 2 in 2011, CAT capabilities will also be available with the Soil and Water Assessment Tool (SWAT) and Stormwater Management Model (SWMM).

WEPPCAT was released in 2010 in partnership with the USDA Agricultural Research Service (http://typhoon.tucson.ars.ag.gov/weppcat/index.php). WEPPCAT provides an online platform for creating and running climate change scenarios to assess potential implications for soil erosion from agricultural lands using the USDA ARS Water Erosion Prediction Pilot (WEPP) model.

About This Report

This report presents a series of short case studies using the BASINS and WEPP climate assessment tools. The case studies are designed to address three general objectives. First, the case studies illustrate conceptually how scenarios based on different types of climate, land use, and management information can be used to address different questions about the potential implications of climate change on watersheds. Climate change scenarios are created based on model projections as well as historical data and past events. Land use change and management scenarios are also included to address questions related to the relative effects of land use versus climate change, and the effectiveness of management practices for reducing impacts. Second, the case studies illustrate selected capabilities of the tools when used with different models.

Finally, while the primary intent of case studies is illustrative, the results are based on real simulations in each study location. Results thus convey information about how watersheds in different parts of the nation could respond to future changes in climate, land-use, and management practices. It should be noted that due to the significant effort involved in developing new models, all simulations in this study used pre-existing models. Additionally, while all models are calibrated, efforts to validate the models were limited and models may not represent all local management and other factors in full detail. Results should thus be considered qualitative and heuristic rather than absolute.

While the climate change scenarios evaluated in this case study were relatively simple, they provide a screening-level understanding of stormwater runoff sensitivity to climate change, and the potential effectiveness of stormwater management strategies for reducing climate change impacts. Evaluation of more detailed climate change or management scenarios is also possible. The coupling of BASINS CAT and hydrologic/hydraulic models, when calibrated, can facilitate development of rapid assessment methods that provide timely and usable quantitative information. The flexible capabilities of BASINS CAT for creating and running scenarios can aide and facilitate a wide range of analyses. These capabilities can be an important addition to the tools used by stormwater managers to design, manage, and maintain stormwater infrastructure.

The intended audience of this report is watershed or water utility managers, urban and regional planners, agency officials, researchers, and other water professionals interested in conducting modeling studies of the potential effects of climate change on water and watershed systems, including the coupled effects of climate change, land-use change, and the effectiveness of management responses. The report may be of particular interest to current users of BASINS or WEPP that want to extend the scope of their modeling to include the potential effects of climate change. The intent of the information presented in this report is to stimulate further creativity and exploration of the different ways scenario analysis can be used to support management decision making.

2. BASINS AND WEPP CLIMATE ASSESSMENT TOOLS

This chapter provides a brief introduction to the BASINS and WEPP climate assessment tools. More detailed documentation of BASINS CAT is available in the document "BASINS 4.0 Climate Assessment Tool (CAT): Supporting Documentation and User's Manual" (USEPA, 2009a), and on the BASINS web page (http://water.epa.gov/scitech/datait/models/basins/bsnsdocs.cfm). More detailed documentation of WEPPCAT is available on the WEPPCAT web page (http://typhoon.tucson.ars.ag.gov/weppcat/index.php).

BASINS CAT and WEPPCAT are each intended to facilitate application of existing simulation models for conducting scenario-based assessments. The conceptual basis of these tools is simple; to provide flexible capabilities for creating and running scenarios to address a wide range of what-if questions users may have about the potential effects of climate change on water and watershed systems. It is important to note that BASINS CAT and WEPPCAT do not provide climate change data for any particular region of the United States. Rather, the tools simply provide a capability for users to create meteorological data reflecting any type of change they wish to consider. In each case, climate change scenarios are created using the change factor or delta-change approach, whereby historical meteorological data within a selected baseline period (e.g., daily temperature, daily precipitation) are adjusted to create scenarios for input to water models. These capabilities support a range of assessment goals, e.g., simple screening analysis, systematic sensitivity analysis, or assessing more detailed scenarios based on climate model projections.

Introduction to BASINS CAT

EPA's BASINS modeling system integrates environmental data, analytical tools, and watershed modeling programs to support assessments of watershed land use change, pollutant discharges, and management practices on water quality (U.S. EPA, 2001; U.S. EPA, 2007; http://www.epa.gov/waterscience/basins/). BASINS consists of four components: (1) a comprehensive collection of national cartographic and environmental databases, (2) environmental assessment tools and utilities (summarize results; establish pollutant source/impact interrelationships; selectively retrieve data; import tool, download tool, grid projector, post processor, and land use, soil classification and overlay tool); (3) automated watershed characterization reports (for eight different data types); and (4) a suite of watershed models including HSPF (Bicknell et al., 2005), SWAT (Neitsch et al., 2005), AQUATOX (Clough and Park, 2006), SWMM (Rossman, 2010) and PLOAD (U.S. EPA, 2007). The main interface to BASINS is provided through MapWindow, a non-proprietary, open-source Geographic Information System (GIS). The GIS provides a framework for linking BASINS modeling tools with environmental data (Figure 2.1).

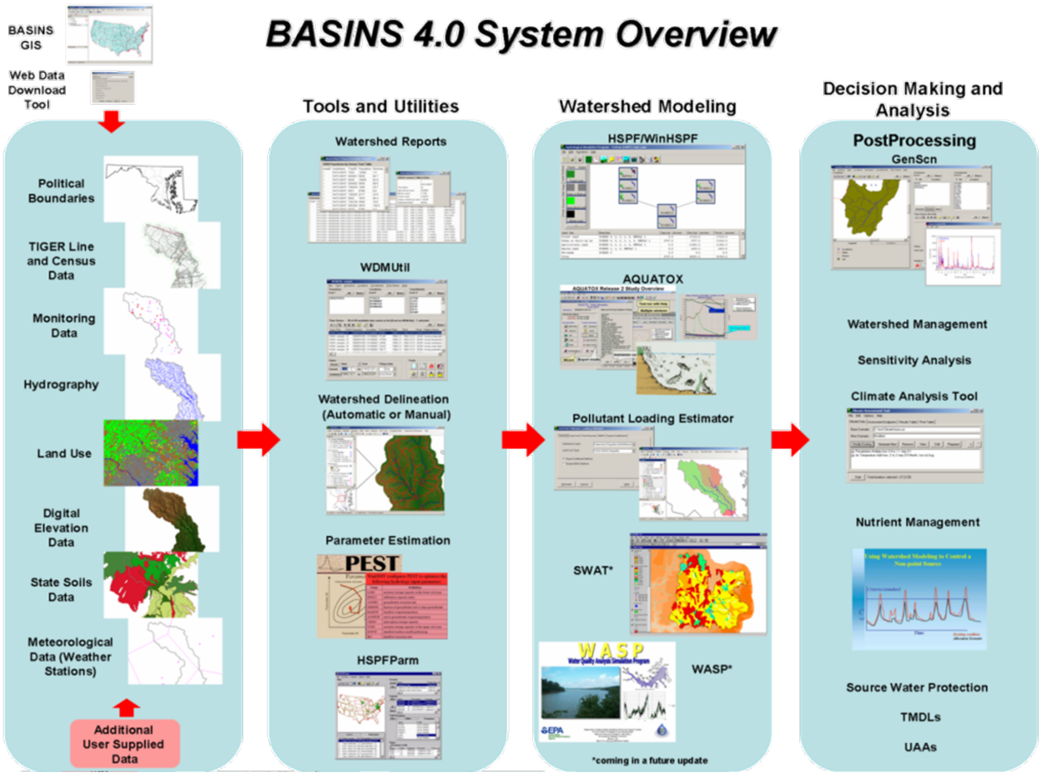


Figure 2.1. Overview of the EPA BASINS 4 Modeling System.

BASINS CAT is not a stand-alone modeling application. CAT is a BASINS plug-in available for use with pre-existing, calibrated BASINS models. Development was intended to facilitate application of existing BASINS models to assess the implications of climate variability and change. Given a pre-existing, calibrated model within BASINS, BASINS CAT provides three capabilities (U.S. EPA, 2009a).

- a flexible scenario generation capability for creating meteorological time series using the change factor approach reflecting any user determined change in temperature and precipitation for use as input to the selected BASINS model (Table 2.1);
- managing the new climate data for input into BASINS models; and
- a post processing capability for calculating management targets (endpoints) useful to water and watershed managers from model output (Table 2.1).

Table 2.1. Summary of BASINS CAT options for adjusting meteorological time series to create climate change scenarios and assess endpoint values based on model simulation outputs.

Modifying historical precipitation records	• Apply a multiplier to each value within selected months in a multi-year record • Apply multiplier to each value within selected years in a multi-year record • Represent storm intensification by applying multiplier to values (events) only within a selected size class • Represent changes in event frequency by adding or removing storm events to observed historical precipitation time series

Modifying historical air temperatures	• Add or subtract from each value within selected months in a multi-year record • Add or subtract from each value within selected years in a multi-year record
Creating complex scenarios	• Combine multiple adjustments to precipitation and temperature time series to create complex scenarios • Create spatially variable climate change scenarios for multiple locations • Create synthetic climate change scenarios within specified ranges • Export BASINS CAT climate change scenarios as text (ASCII) files
Calculating assessment endpoints	• Calculate mean, max, min, sum and other summary values from model output time series • Calculate summary values for specified range of concern in model output time series (e.g., selected months, years) • Calculate duration-frequency events based on model output time series (e.g., 100-year flood, 2-year flood)

Climate change scenarios (i.e., the adjusted meteorological time series created using the tool) are contained within the same BASINS Watershed Data Management (WDM) file with the original, historical meteorological records. In addition, BASINS CAT provides a view/export capability that can be used to display the changes resulting from a specific adjustment or save the adjusted weather record as an ASCII file.

Climate assessment capabilities are accessible for 3 BASINS models (BASINS CAT Version 2, released September, 2011): the Hydrologic Simulation Program-FORTRAN (HSPF), the Soil and Water Assessment Tool (SWAT), and Stormwater Management Model (SWMM). These 3 models provide general capabilities for application to a wide range of issues in water management. Models differ in the approaches used to represent key processes, input requirements, and endpoints simulated. It is the user's choice to determine which model is most appropriate for a given assessment. The following is brief summary of the 3 BASINS models accessible to BASINS CAT.

HSPF

HSPF is a process-based, basin-scale model that provides a comprehensive package for simulating watershed hydrology and water quality for a wide range of conventional and toxic organic pollutants (Shoemaker et al., (2005). The model simulates watershed hydrology, land and soil contaminant runoff, sediment-chemical interactions, and in-stream fate and transport in one-dimensional stream channels. It can be configured to represent all types of land uses, and offers the ability to include land use activities and potential management controls. Since its inception in 1980, HSPF has been widely applied in the planning, design, and operation of water resources systems, and is arguably one of the best verified watershed models currently available. HSPF can be applied to most watersheds using available meteorological, land use, hydrography, management, streamflow, and water quality data. The principal model outputs include streamflow runoff and mass loads or concentrations of sediment, nutrients, pesticides, and toxic chemicals at selected points within a watershed. The most recent release is HSPF Version 12, which is distributed as part of the EPA BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) system.

HSPF represents a watershed as a group of various land uses all routed to a representative stream segment. The modeling framework is defined in terms of subwatershed segments, one-dimensional stream reach segments and well-mixed reservoirs/lakes. The spatial scale for simulation uses one-dimensional, lumped parameters on a land-use or subwatershed basis. For overland flow, the model assumes onedirectional kinematic-wave flow. The receiving water bodies assume complete mixing along the width and depth.

Processes simulations for pervious and impervious land areas include water budget, sediment generation and transport, and the generation and transport of other water quality constituents. Hydrologic simulations include consideration of interception, infiltration, evapotranspiration, interflow, groundwater loss, and overland flow processes. Sediment production is based on detachment and/or scour from a soil matrix and transport by overland flow in pervious areas, whereas solids buildup and wash-off is simulated for impervious areas. HSPF also simulates the in-stream fate and transport of a wide variety of pollutants, such as nutrients, sediments, tracers, dissolved oxygen/biochemical oxygen demand, temperature, bacteria, and user-defined constituents.

Some key HSPF model strengths are as follows (Shoemaker et al., (2005)):

- HSPF can be set up as simple or complex, depending on application, requirements, and data availability.
- HSPF is one the few watershed models capable of simulating land processes and receiving water processes simultaneously.
- A variety of simulation time steps can be used, including sub-hourly to 1 minute, hourly or daily.
- The model includes capabilities to address a variable water table.
- The model enables user-defined model output options by defining the external targets block.

SWAT

SWAT is a widely applied, physically-based, watershed-scale model designed to assess long-term changes to water quality and quantity as a result of resource management and land use changes (Neitsch et al., 2005). SWAT uses a curve number approach for hydrologic simulation. It does not simulate event-based changes. Utilizing weather and soils data, and information on vegetation, topography and land use, SWAT can model the physical process associated with hydrology and sediment and nutrient transport among other things. This enables the model to be used in large watersheds as well as small ungaged streams. SWAT can also be modified for more specialized modeling.

SWAT is the result of more than 30 years of modeling investigations and research efforts conducted primarily by the USDA Agricultural Research Service (ARS) and the Texas A & M University Blackland Research and Extension Center (BREC) in College Station, Texas. SWAT is a public domain, basin-scale, continuous simulation model that operates on a daily time step and is designed to predict the nonpoint source loadings and resulting water quality impacts of water, sediment, and agricultural chemicals (nutrients and pesticides) from a watershed. In addition, the model includes capabilities and functionality to assess a wide variety of impacts of alternative management practices and land use changes. The model is physically based, computationally efficient, and capable of continuous simulations over long periods of time, ranging from days to decades. Major model components include weather, hydrology, erosion/sedimentation, soil temperature, plant growth, nutrients, pesticides, bacteria, agricultural management, stream routing and pond/reservoir routing (Gassman et al., 2007). The simulation of these components is carried out within SWAT's basic building block, the Hydrologic Response Unit (HRU). HRUs represent unique combinations of land use, soil characteristics, and management within each sub-basin being modeled.

The SWAT model has comprehensive representation of all major watershed processes. It has a particularly strong representation of agricultural land use. Hence, it is usually selected for assessing nutrient loads from agricultural dominant watersheds. The model uses GIS technology, topography, soils, precipitation, plant growth, and crop management information to form a complete deterministic representation of the hydrology and water quality of a watershed.

SWAT has gained both national and international acceptance as an efficient and reliable watershed modeling tool as demonstrated by hundreds of SWAT-related papers in the open technical literature, presentations at international SWAT conferences, and its inclusion in EPA's BASINS modeling system. Additional information regarding the development and use of SWAT can be found at: http://www.brc.tamus.edu/swat.

Some key SWAT model strengths are as follows:

- The model is physically based. Watersheds can be modeled to evaluate the relative impact of changes in management practices, climate, and vegetation on water quality or other variables of interest
- The model uses readily available inputs. The minimum data required to make a run are commonly available from various government agencies.
- The model's ability to simulate crop and plant communities and provide crop yield and plant biomass.
- The mathematical solutions within the model are computationally efficient. Simulation of very large basins or a variety of management strategies can be performed expeditiously without excessive investment of time or money.

SWMM

The EPA Storm Water Management Model (SWMM), first developed in 1971, is a rainfall-runoff simulation model that can be used to simulate runoff quantity and quality from primarily urban areas on a single event or long-term (continuous) basis (see http://www.epa.gov/ednnrmrl/models/swmm/). SWMM is commonly used to inform decisions related to stormwater management, combined sewer overflows, assessing nonpoint source pollution loads, and low impact development techniques. Typical SWMM applications include the design and sizing of drainage system components for flood control, flood plain mapping of natural channel systems, evaluating the effectiveness of BMPs for reducing wet weather pollutant loadings, generating non-point source pollutant loadings for waste load allocation studies, and designing control strategies for minimizing combined sewer overflows and sanitary sewer overflows (Rossman, 2010).

SWMM operates on time steps ranging from seconds to years. SWMM accounts for spatial variability by dividing a study area into a collection of smaller, homogeneous subcatchment areas, each containing its own fraction of pervious and impervious sub-areas. Overland flow can be routed between sub-areas, between subcatchments, or between entry points of a drainage system through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM simulates the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps.

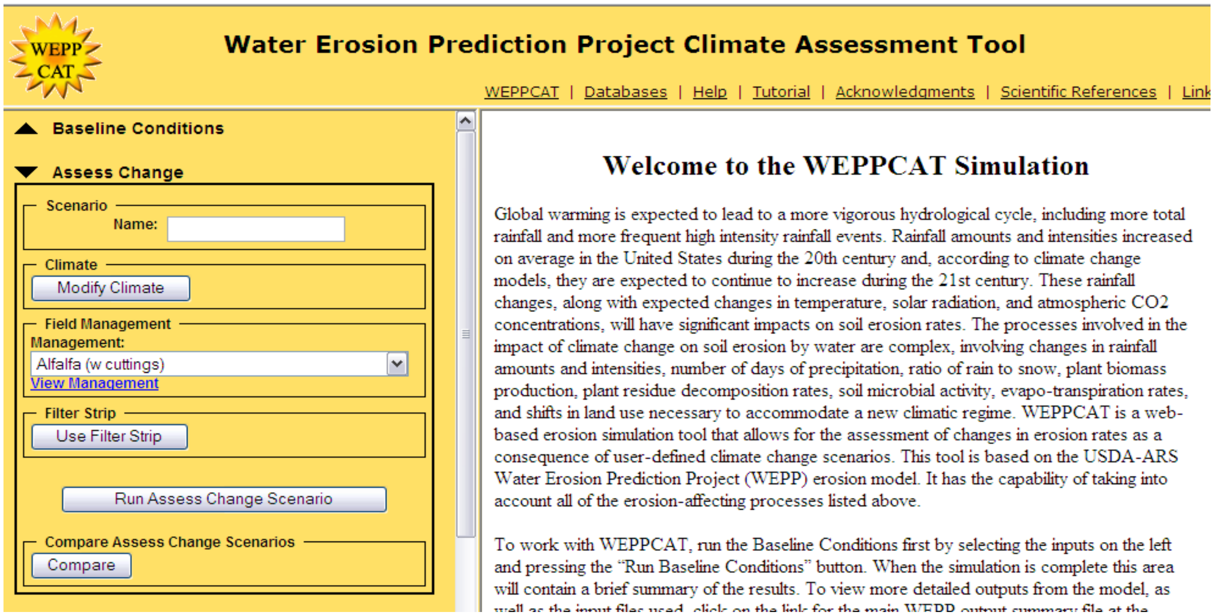
Some key SWMM strengths are as follows:

- SWMM model accounts for all hydrologic processes that produce runoff from urban areas.
- Accounts for interruption in natural stream transport network such as nonlinear reservoir routing of overland flow.
- SWMM contains a flexible set of hydraulic modeling capabilities dealing with industry standard stormwater structures such as stormwater storage, divider, pumps, weirs and orifices etc.
- Can simulate different flow regimes such as such as backwater, surcharging, reverse flow, and surface ponding.
- In addition to modeling runoff, can account for the production, transport, and treatment of pollutant loads associated with runoff.

Introduction to WEPPCAT

The Water Erosion Prediction Project (WEPP) is a process-based soil erosion model developed in the mid-1990s by the USDA Agricultural Research Service (ARS). It is currently one of the best known and validated models available for simulating soil erosion from agricultural areas. WEPP can be used to assess how erosion rates are impacted by precipitation events, soil type, vegetation type, topography and number of common best management practices (BMPs) for reducing soil loss. Simulations can be run at the hill slope or watershed scale (Flanagan and Nearing, 1995). Hill slope scale simulations are ideally suited for assessing the effectiveness of BMPs in local settings such as a specific farm field. Watershed scale applications consist of linking hill slopes via channels and impoundments (Flanagan and Nearing, 1995). Recent developments allow forested land cover, such as forested riparian buffers, to be represented in WEPP. WEPP is available as a desktop model or through a web-based interface.

WEPPCAT is an online application of the WEPP model that provides flexible capabilities for creating climate change scenarios to assess the potential effects of climate change on soil erosion using the WEPP model. WEPPCAT was developed in partnership with the USDA ARS, and is available for use at http://typhoon.tucson.ars.ag.gov/weppcat/index.php (Figure 2.2).



Management: Alfalfa (w cuttings)

View Management

Welcome to the WEPPCAT Simulation

Global warming is expected to lead to a more vigorous hydrological cycle, including more total rainfall and more frequent high intensity rainfall events. Rainfall amounts and intensities increased on average in the United States during the 20th century and, according to climate change models, they are expected to continue to increase during the 21st century. These rainfall changes, along with expected changes in temperature, solar radiation, and atmospheric CO2 concentrations, will have significant impacts on soil erosion rates. The processes involved in the impact of climate change on soil erosion by water are complex, involving changes in rainfall amounts and intensities, number of days of precipitation, ratio of rain to snow, plant biomass production, plant residue decomposition rates, soil microbial activity, evapo-transpiration rates, and shifts in land use necessary to accommodate a new climatic regime. WEPPCAT is a web-based erosion simulation tool that allows for the assessment of changes in erosion rates as a consequence of user-defined climate change scenarios. This tool is based on the USDA-ARS Water Erosion Prediction Project (WEPP) erosion model. It has the capability of taking into account all of the erosion-affecting processes listed above.

To work with WEPPCAT, run the Baseline Conditions first by selecting the inputs on the left and pressing the "Run Baseline Conditions" button. When the simulation is complete this area will contain a brief summary of the results. To view more detailed outputs from the model, as well as the input files used, click on the link for the main WEPP output summary file at the

Figure 2.2. WEPPCAT opening screen

WEPPCAT simulations are limited to the hill slope scale only. The WEPPCAT online interface allows users to input field characteristics including soil series, field size, slope steepness, slope shape, and land management (e.g., alfalfa with cutting, bluegrass with grazing, etc.). Like the parent WEPP model, daily meteorological data necessary to run WEPPCAT are generated using the stochastic weather generator Cligen. WEPPCAT outputs include mean annual precipitation, runoff, soil loss and sediment yield. Users can also generate spatial sediment loss data and a sediment particle size profile.

Baseline meteorological data for WEPPCAT simulations are generated using Cligen parameters based on observed monthly average temperature and precipitation from NOAA National Climatic Data Center (NCDC) weather stations. Climate change scenarios are created by adjusting Cligen parameters to reflect potential changes of interest to users. Available adjustments include increases and decreases in mean monthly temperature, precipitation volume, and the transition probabilities of a wet day following a dry day, and a dry day following a dry day (i.e., number of wet days). These adjustments can be made either uniformly among months of the year, or individual adjustments can be made to specific months of the year. In addition to changing precipitation volume, Cligen parameters can also be adjusted to increase the proportion of annual rainfall occurring in large magnitude events (i.e., to represent an increase in event intensity independent of changes in total annual precipitation). WEPPCAT provides a capability to increase the proportion of annual precipitation occurring in large magnitude events up to 25 percent[1]. Adjustments in precipitation intensity are made by applying the user determined increase to the largest 5 percent of events, and simultaneously decreasing precipitation in the lower 95 percent events by the same volume such that the adjustment results in negligible change in the volume of annual precipitation. This adjustment can only be made to all events across the entire year. It is currently not possible to adjust the intensity of events only in specific months of the year. Precipitation data can also be modified in WEPPCAT based on elevation using the PRISM model climate database. Modifications are made by selecting precipitation values or elevations for areas surrounding the selected weather station.

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[1] Adjustment of rainfall intensity is accomplished by altering the standard deviation of the distributions of daily precipitation used by the climate generator. This approach results in a slight change in average annual rainfall even if changes to the overall volume are not indicated in the model inputs.

3. CASE STUDIES

3.1. Introduction

This Chapter presents a series of six case studies that are designed to illustrate selected capabilities and approaches for conducting scenario-based assessments using the BASINS CAT and WEPPCAT tools (Table 3.1). Case studies are an effective way to demonstrate the utility of these tools to water managers and others interested in assessing climate change impacts on their systems. The case studies in this report encompass a range of spatial and temporal scales, climate and land-use change scenarios, and hydrologic and water quality endpoints of concern. They were designed to include applications of either BASINS CAT or WEPPCAT to assess the implications of future climate change in the context of changing land use and management responses.

Case studies vary in the way different information about climate and land use change is used to develop scenarios for exploring system sensitivity, vulnerability, and the effectiveness of management response. Climate change scenarios can be developed based on any available information about climate change. The IPCC Task Group on Data and Scenario Support for Impacts and Climate Analysis (TGICA) describes three different types of climate scenarios: synthetic scenarios, analogue scenarios, and scenarios based on outputs from climate models (see IPCC TGICA (2007) for a more complete discussion). Synthetic scenarios are created by incrementally modifying climatic attributes within a predetermined, plausible range of future change. For example, adjustments of historical temperatures by 1, 2, and 3°C and historical precipitation by 5, 10, and 15 percent could be applied in various combinations to create 9 different climate change scenarios (IPCC TGICA, 2007). Analogue scenarios are constructed by identifying a time or geographic location that has a climate similar to anticipated future conditions in the location of interest. These records can be obtained either from the past (temporal analogues) or from a different geographic location (spatial analogues). Model-based scenarios are developed using output from GCM and RCM modeling experiments that simulate the response of the climate system to changes in greenhouse gas emissions and other climate forcings. The case studies in this report illustrate applications of either BASINS CAT or WEPPCAT using each type of scenario.

Many watersheds are currently stressed by a wide range of non-climatic factors including land-use change, water withdrawals, and other factors. Water infrastructure and management also exerts a major control on observed hydrologic and water quality conditions. Climate change will interact with existing and future changes in non-climatic factors in complex ways in different locations. Understanding and responding to climate change requires consideration of climate change in a holistic context.

A critical concern is the interaction of climate and land-use change on water. Land-use change can be considered in a scenario analysis in much the same way as climate change. Land use scenarios can be based on a range of context dependant information. Future land use and land cover conditions will be influenced by population growth, land use regulations, and economic factors, among other things. Understanding the potential effectiveness of alternative management strategies is likewise a critical concern. In many areas existing infrastructure and management may be well capable of handling anticipated future hydrologic change. In other areas, a greater risk may be present requiring some further action. For example, assessing the impact of climate change on agriculture may require assessing various types of cropping practices or inclusion of best management practices as scenarios. Stormwater runoff assessments may require developing scenarios that depict community build-out conditions under current zoning or projected population growth (EPA 2009b).

Ultimately, the scenarios used in an analysis should depend on the available information and, equally important, the goals and requirements of a specific assessment activity. In each case, consideration of multiple scenarios is desirable to capture the full range of underlying uncertainties associated with future climate, land use, and management practices on water resources.

It should be noted that the primary intent of the case studies in this report is to illustrate the use of BASINS CAT and WEPPCAT in a variety of applications. All case studies using HSPF, SWAT, or SWMM were conducted using pre-existing, calibrated models. In certain cases minor modifications such as performing additional calibration were made. In each case, however, models may not represent in full detail all management practices and other factors influencing the hydrologic behavior of case study watersheds. WEPP simulations did not require a pre-existing model, and were developed independently. In addition, analysis and discussion of simulation results are brief and not comprehensive. Results should therefore not be considered absolute.

Table 3.1. Summary of case studies presented in this report.

Section	Topic	Analysis Approach
3.2	Streamflow and water quality sensitivity to climate change in the Raccoon River, Iowa, using BASINS CAT with SWAT	PART A: Assess scenarios based on different combinations of assumed temperature and precipitation change within plausible ranges of future change; changes uniform for each month of the year PART B: Assess scenarios based on downscaled climate model projections (NARCCAP) for temperature and precipitation for mid-21st century; changes vary among months of the year
3.3	Urban stormwater sensitivity to rainfall change and effectiveness of management in the Upper Roanoke River, VA, using BASINS CAT with SWMM	PART A: Assess scenarios based on different assumed changes in precipitation (single event) within a plausible range of future change PART B: Assess performance of 2 stormwater management strategies under precipitation change scenarios developed in PART A
3.4	Agricultural soil erosion sensitivity to climate change and management practices in Blue Earth County, MN, using WEPPCAT	PART A: Assess scenarios based on different combinations of assumed changes in temperature, precipitation volume, and precipitation event intensity; changes uniform for each month of the year PART B: Assess performance of land management practices for reducing sediment loss from corn fields under climate change scenarios developed in PART A.
3.5	Streamflow and water quality sensitivity to changes in precipitation amount, frequency, and intensity in the Tualatin River, OR, using BASINS CAT with HSPF	Assess scenarios based on different combinations of assumed increases in precipitation annual volume, precipitation event intensity (proportion of annual total in occurring in large magnitude events), and precipitation event frequency (number of precipitation events per year)

3.6	Streamflow sensitivity to dry weather events in Sespe Creek, CA, using BASINS CAT with HSPF	Assess scenarios based on targeted adjustments to a historical period of dry weather; scenarios represent increased severity of historical dry period, increased duration of historical dry period, and increased severity and duration of historical dry period
3.7	Streamflow and water quality relative sensitivity to climate change versus impervious ground cover in the Western Branch of the Patuxent River, MD, using BASINS CAT with HSPF	Assess scenarios based on different combinations of assumed increases in precipitation annual volume, precipitation event intensity (proportion of annual total in occurring in large magnitude events), and impervious ground cover

3.2. Streamflow and water quality sensitivity to climate change in the Raccoon River, Iowa, using BASINS CAT with SWAT

Case Study Overview

This case study illustrates two different assessment approaches, a general sensitivity analysis (PART A) using synthetic climate change scenarios and a more detailed scenario analysis (PART B) using climate model projections to assess potential climate change impacts on streamflow and total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) loads from agricultural lands using BASINS CAT with the SWAT watershed model.

In PART A, the climate change scenarios were created by increasing historical mean annual temperatures +0 to +5^{o}C by increments of 1^{o}C and adjusting mean annual precipitation volume -10 to +20 percent by increments of five percent. Land use remained constant and no management practices were assessed.

In PART B, climate change scenarios were created by applying adjustments to average monthly temperature and precipitation volumes based on projections from four regionally downscaled climate models. Two additional scenarios were created by synthetically adjusting average monthly precipitation volumes for one of the climate model projections to further explore the seasonal impacts on pollutant loading and streamflow. Land use remained constant and no management practices were assessed.

Introduction

Nutrient pollution is an ongoing water quality issue in the Mississippi River basin, leading to such problems as extensive algae growth and hypoxia in the Gulf of Mexico (Rabalais, 2001). The Upper Mississippi River Basin (UMRB), a major agricultural region in the U.S., is a significant net exporter of nutrients to the Mississippi River and Gulf of Mexico. Future climate change is projected to result in warming temperatures and changes in precipitation regimes. Specific regional climate changes are uncertain, but it is possible that changes in temperature and precipitation could influence pollutant loading in the Mississippi River Basin (Rossi et al., 2009). Managers and decision makers interested in quantifying future nutrient loads from the UMRB will likely need to consider the potential impacts of climate change in addition to other factors that impact water quality (e.g. land use, public policy, pollution abatement technology, etc.).

A watershed sensitivity study can help establish a general understanding of how climate changes may interact with the landscape and alter hydrologic processes and water quality. In this case study, a SWAT model of the Raccoon River in IA, a sub-basin within the greater UMRB, was used to simulate potential watershed response to projected climate change. BASINS CAT was used to create an array of climate change scenarios for model simulations and assess endpoints. The sensitivity of the Raccoon River was explored in two different ways:

In **PART A** of this case study, adjustments to precipitation and temperature were applied uniformly to the entire duration of the simulation using the BASINS CAT ***multiple changes within a user specified range*** feature to assess potential changes to mean annual streamflow and pollutant loadings (TN, TP, and TSS).

However, changes to climate seldom follow a definitive and uniform pattern across the year, especially for precipitation; therefore this case study was taken a step further in PART B.

PART B of this case explores how seasonal changes to precipitation volume and temperature can impact monthly and mean annual streamflow and TN, TP, and TSS loads. Spatial variability was also accounted for by applying distinct adjustments to temperature and precipitation data from the two meteorological stations included in the model. The BASINS CAT ***months/years*** adjustment feature was used to develop the climate change scenarios based on simulations for 4 RCMs, and the tool was used to assess sensitivity of endpoints.

Location Description

The Raccoon River watershed encompasses an area of roughly 9,400 km^2 in central Iowa (Figure 3.1). It is comprised of two 8-digit Hydrologic Unit Codes (HUCs). The northern portion (HUC 07100006) contains the North Raccoon branch and the main Raccoon River. The southern portion (HUC 07100007) contains the Middle and South branches which flow into the main Raccoon River at the HUC outlet. The Raccoon River watershed drains into the Des Moines River at the city of Des Moines, IA. Land use in the watershed is predominantly agricultural, with minimal urban development and forests (Table 3.2).

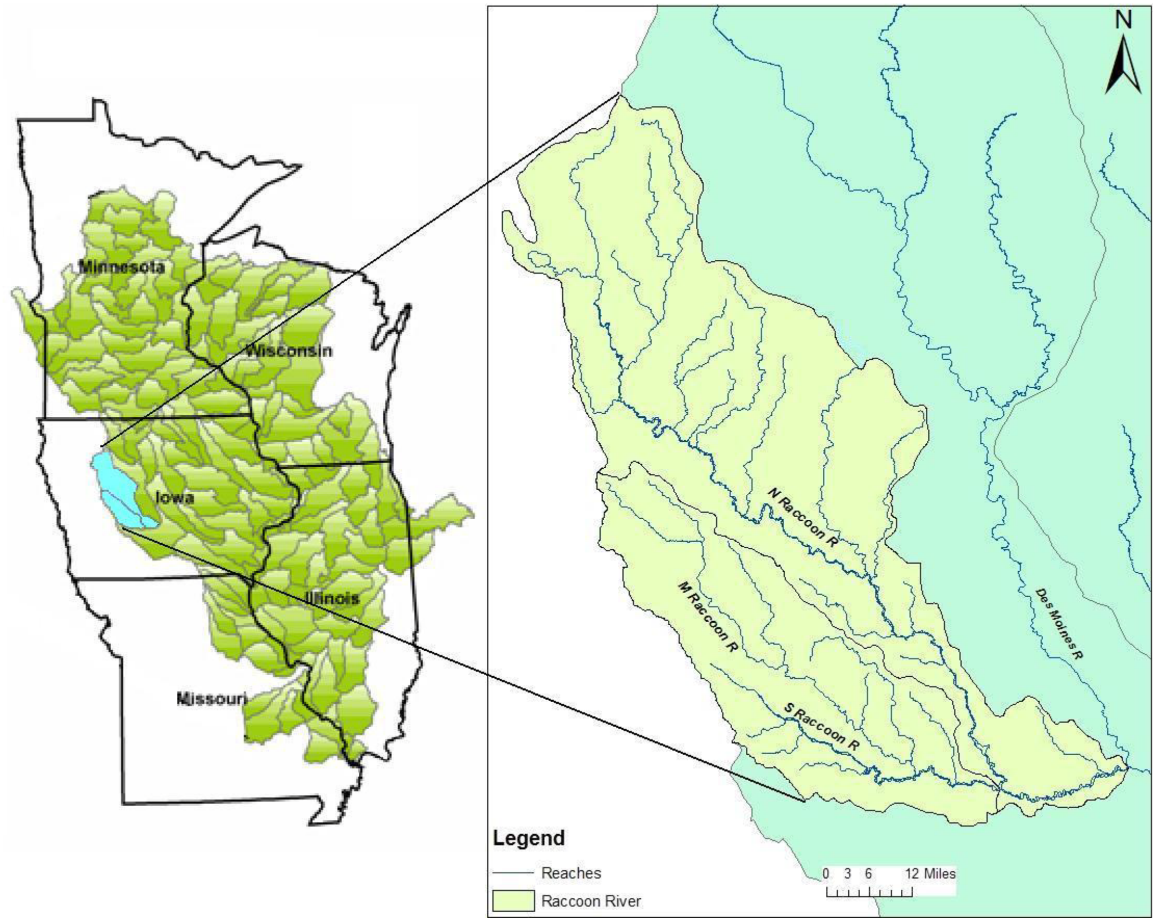


Figure 3.1. The Raccoon River watershed and major tributaries.

Table 3.2. Land use summary for Raccoon River watershed.

Land Use	Portion of Watershed (%)
Corn	42
Soybeans	33
Other Ag	13
Urban/Developed	8
Forest	2
Wetland	2

Water Model Setup

A SWAT model of the Raccoon River was identified from a previous effort investigating the impacts of ethanol corn production in the UMRB (USEPA, 2008a). A follow-on effort was performed to isolate the Raccoon River basin and improve model calibration (USEPA, 2010). The Raccoon River SWAT model uses the 2001 National Land Cover Data (NLCD) and 2004-2006 Cropland Data Layer for the land use coverage and the USDA-NRCS STATSGO for soils data. Data from the Conservation Tillage Information Center and the 1997 and 2002 USDA Census of Agriculture were used to identify the cropping rotation and management practices for the agricultural land areas. Each sub-watershed was assigned appropriate management and tillage practices. The model was set up to run using 1960-2001 weather data developed by Di Luzio (2008). These weather data, developed for modeling and assessments, are gridded datasets of daily precipitation and temperature (maximum and minimum) spatially interpolated using slope, elevation and aspect as spatial covariates. Grid cells are four km^2 (two km on each side) and cover the conterminous U.S.

Initial SWAT parameters for the Raccoon River model were acquired from a national database developed as part of a previous UMRB SWAT model (USEAP, 2010). More detailed calibration of the Raccoon River SWAT model was carried out using available streamflow, TN, TP and TSS data at the watershed outlet at Van Meter, IA. The entire 42-year simulation duration, 1960-2001, was used to conduct the calibration. Streamflow was reasonably well-calibrated while nutrient and sediment loadings showed mixed calibration statistical values (Table 3.3). The model was limited by exclusion of point sources which influences streamflow and pollutant loads. Quantitative results should therefore not be considered absolute, but rather as indicative of the relative changes resulting from the scenarios considered in this case study.

Table 3.3. Raccoon River model calibration statistics for annual results. NSE: Nash-Sutcliffe Efficiency coefficient; PB: percent bias, RMSE: root mean square error.

Endpoint	Streamflow	TN	TP	TSS
R^2	0.934	0.934	0.903	0.398
NSE	1	0.472	0.485	0.069
PB	16.5	39.8	37.4	24.4
RMSE	17	24657	2224	3880

PART A: Annual Sensitivity Analysis

Scenario Development: PART A

A total of 42 SWAT model simulations were completed. Climate change scenarios included one baseline scenario and 41 climate change scenarios. No land use or management scenarios were included.

Climate Change Scenarios

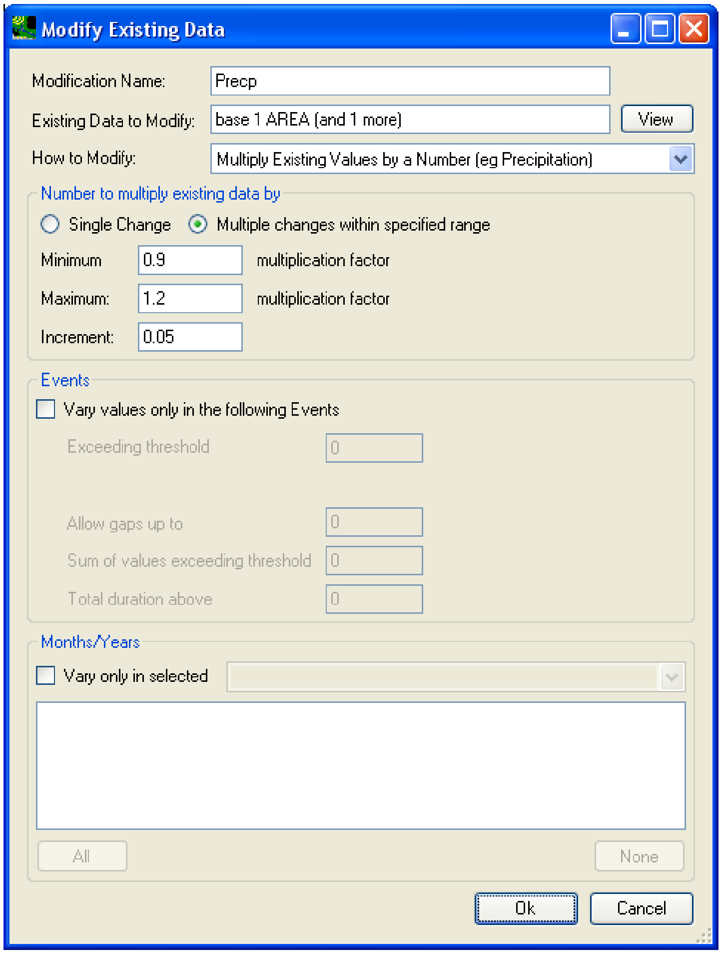
The focus of PART A was to assess the sensitivity of the Raccoon River to changes in mean annual precipitation and temperature. Information about potential future changes in temperature and precipitation in the Raccoon River watershed was obtained from an ensemble of statistically downscaled climate change data acquired from The Nature Conservancy's ClimateWizard web site (www.climatewizard.org). ClimateWizard is a user-friendly portal for accessing and visualizing summary statistics for projected future changes in temperature and precipitation at any location within the U.S. based on GCM projections archived by the Program for Climate Model Diagnosis Coupled Model Intercomparison Project (CMIP3) for 16 climate models and 3 greenhouse gas emissions scenarios (SRES A2, 1B, and B1). Summary information is presented for 2 future periods, mid-century (2050s) and end- century (2080s).

In PART A of this case study, climate change scenarios were developed to fall within the ensemble range of projected end- century (2080s) temperature and precipitation changes for the Raccoon River watershed. Projected changes in mean annual temperature ranged from approximately 2 to 6.5°C, and projected changes in annual precipitation volume from -22 to +30 percent. Spatial variability in projected changes across the watershed was relatively small.

Climate change scenarios for the SWAT model were developed using BASINS CAT's ability to create ***multiple changes within a user specified range*** (Figure 3.2). This feature automates the creation of multiple climate adjustments for selected variables by specifying a range and step increment within the range (e.g., to change temperature from 0 to 3°C by increments of 1°C). When 2 or more variables are selected, this feature creates scenarios reflecting each possible combination of changes for selected variables. The following adjustments were made to the Raccoon River temperature and precipitation records for 1960-2001:

- Average daily temperatures increased by 0 to 5°C at increments of 1°C (i.e., 0, 1, 2, 3, 4, 5).
- Precipitation volume adjusted by -10 to +20 percent at increments of five percent (i.e., -10, -5, 0, 5, 10, 15, 20).

A total of 42 climate change scenarios resulted from each unique combination of the six temperature and seven precipitation adjustments. For simulation of each scenario, the SWAT model used the modified temperature and precipitation inputs to internally re-compute potential evapotranspiration (PET) using the Penman-Montieth algorithm. This differs from other BASINS CAT models (HSPF, SWMM) where PET is re-computed external to the model by BASINS CAT, and then provided to the model as an input variable in the same manner as temperature and precipitation.



Modify Existing Data

Modification Name: Precp

Existing Data to Modify: base 1 AREA (and 1 more)

How to Modify: Multiply Existing Values by a Number (eg Precipitation)

Number to multiply existing data by

○ Single Change ● Multiple changes within specified range

Minimum 0.9 multiplication factor

Maximum: 1.2 multiplication factor

Increment: 0.05

Events

☐ Vary values only in the following Events

Exceeding threshold 0

Allow gaps up to 0

Sum of values exceeding threshold 0

Total duration above 0

Months/Years

☐ Vary only in selected

Figure 3.2. BASINS CAT option window for making ***multiple changes within a user specified range***.

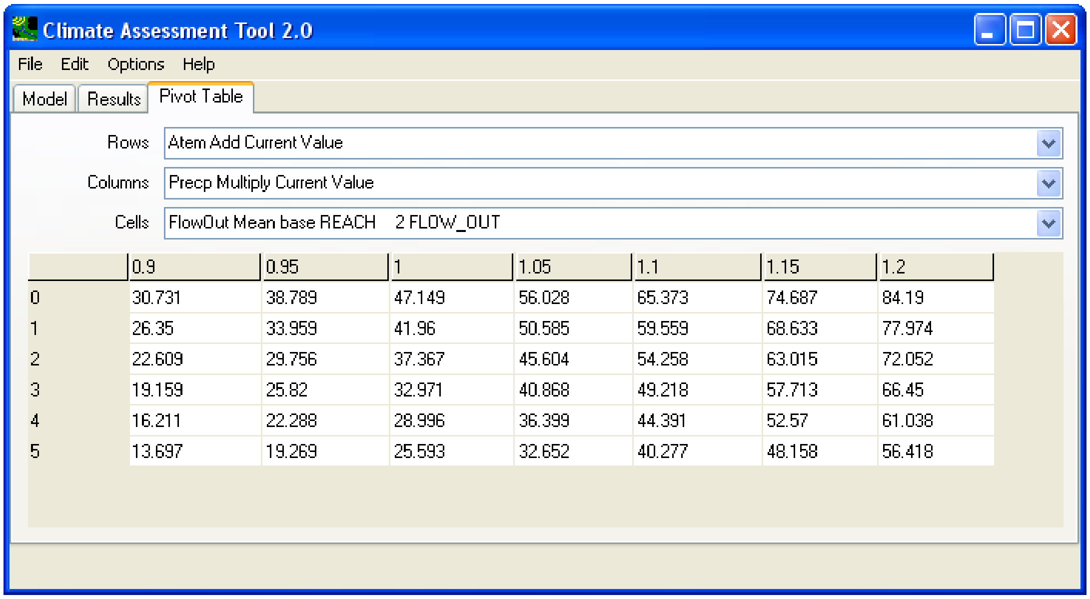
Land Use Scenarios
Land use and land cover (LULC) data were held constant for all model runs. While it is unlikely LULC in the Raccoon River will not change in the future, holding it constant allowed for the assessment of potential impacts from climate change only.

Management Scenarios
Future management scenarios were not evaluated in this case study.

Endpoint Selection: PART A
The endpoints for this study consisted of mean annual streamflow and loadings of TN, TP, and TSS. A cursory assessment of these constituents was considered appropriate given the goal of evaluating general watershed sensitivity to climate change in a highly agricultural watershed.

Results: PART A
Model results for mean annual streamflow and loadings of TN, TP, and TSS are shown in Tables 3.4 to 3.7. The combination of zero percent change in precipitation and 0^{o}C change in temperature represents the baseline conditions of the model (historical climate). An effective method for analyzing results from a series of climate scenarios created with BASINS CAT is the ***pivot table*** capability. The tool allows users to interactively build pivot tables by specifying row, column, and cell variables (Figure 3.3). The pivot tables are displayed in the BASINS CAT interface and may also be saved in a form readily available for use by common spreadsheet tools.

Results show changes in streamflow were proportional to changes in precipitation, and inversely proportional to changes in air temperature. Changes in pollutant loads were directly proportional to changes in streamflow, increasing with increases in streamflow. For example, a five percent increase in precipitation and a 0°C increase in temperature resulted in 56 cms in mean annual streamflow, while a five percent increase in precipitation with a 5°C increase in temperature resulted in 33 cms in mean annual streamflow.



Rows Atem Add Current Value

Columns Precp Multiply Current Value

Cells FlowOut Mean base REACH 2 FLOW_OUT

	0.9	0.95	1	1.05	1.1	1.15	1.2
0	30.731	38.789	47.149	56.028	65.373	74.687	84.19
1	26.35	33.959	41.96	50.585	59.559	68.633	77.974
2	22.609	29.756	37.367	45.604	54.258	63.015	72.052
3	19.159	25.82	32.971	40.868	49.218	57.713	66.45
4	16.211	22.288	28.996	36.399	44.391	52.57	61.038
5	13.697	19.269	25.593	32.652	40.277	48.158	56.418

Figure 3.3. BASINS CAT pivot table window displaying results for mean annual streamflow at the outlet of the Raccoon River SWAT model.

Table 3.4. Mean annual streamflow (cms) for all combinations of temperature and precipitation change. Baseline condition is highlighted by the box in the first column.

Precipitation Change, %	**Temperature Change, °C**					
	0	**1**	**2**	**3**	**4**	**5**
-10	31	26	23	19	16	14
-5	39	34	30	26	22	19
0	47	42	37	33	29	26
5	56	51	46	41	36	33
10	65	60	54	49	44	40
15	75	69	63	58	53	48
20	84	78	72	66	61	56

Table 3.5. Mean annual nitrogen load (kg/ha/yr) for all combinations of temperature and precipitation change. Baseline condition is highlighted by the box in the first column.

Precipitation Change, %	**Temperature Change °C**					
	0	**1**	**2**	**3**	**4**	**5**
-10	7.9	7.1	6.3	5.6	5.0	4.4
-5	9.8	9.0	8.1	7.4	6.8	6.1
0	11.6	10.9	10.0	9.2	8.6	7.9
5	13.5	13.0	12.1	11.3	10.8	9.9
10	15.4	14.9	14.1	13.5	13.1	12.2
15	17.1	16.7	15.9	15.5	15.2	14.4
20	18.9	18.6	17.8	17.5	17.3	16.6

Table 3.6. Mean annual phosphorous load (kg/ha/yr) for all combinations of temperature and precipitation change. Baseline condition is highlighted by the box in the first column.

Precipitation Change, %	**Temperature Change °C**					
	0	**1**	**2**	**3**	**4**	**5**
-10	0.6	0.5	0.5	0.4	0.4	0.4
-5	0.7	0.6	0.6	0.6	0.5	0.5
0	0.8	0.8	0.7	0.7	0.7	0.6
5	1.0	0.9	0.9	0.8	0.8	0.8
10	1.1	1.1	1.0	1.0	1.0	0.9
15	1.3	1.2	1.1	1.1	1.1	1.1
20	1.4	1.3	1.3	1.3	1.3	1.3

Table 3.7. Mean annual TSS load (tonnes/ha/yr) for all combinations of temperature and precipitation change. Baseline condition is highlighted by the box in the first column.

Precipitation Change, %	**Temperature Change, °C**					
	0	**1**	**2**	**3**	**4**	**5**
-10	0.6	0.5	0.4	0.3	0.3	0.2
-5	0.8	0.7	0.6	0.5	0.4	0.4
0	1.0	0.8	0.7	0.6	0.6	0.5
5	1.2	1.1	1.0	0.8	0.8	0.7
10	1.5	1.3	1.2	1.1	1.0	0.9
15	1.8	1.6	1.4	1.3	1.2	1.1
20	2.1	1.9	1.7	1.6	1.5	1.4

Evapotranspiration for the climate scenarios was analyzed to determine its potential role on endpoint values. BASINS CAT was used to generate a ***pivot table*** of modeled evapotranspiration from the land surface for each of the climate scenarios (Table 3.8). Evaporation from water surfaces was inconsequential and not included. Evapotranspiration is much less sensitive to changes in precipitation versus temperature, and is the likely cause of the decrease in annual streamflow and pollutant loads as temperature increases from the baseline. As temperature increases, evapotranspiration increases, and the amount of streamflow decreases. For example, as temperature increases from 0 to 5°C, holding the precipitation increase constant at five percent, streamflow decreases from 56 cms to 33 cms, while at the same time evapotranspiration increases from 60.5 cm/yr to 69.2 cm/yr.

Table 3.8. Mean annual evapotranspiration (cm/yr) for all combinations of temperature and precipitation change. Baseline condition is highlighted by the box in the first column.

Precipitation Change, %	**Temperature Change, °C** 0	1	2	3	4	5
-10	58.7	60.4	61.9	63.3	64.6	65.8
-5	59.4	61.3	62.9	64.4	65.9	67.1
0	60.0	61.9	63.7	65.3	66.9	68.2
5	60.5	62.5	64.4	66.1	67.8	69.2
10	61.0	63.1	65.0	66.9	68.7	70.2
15	61.4	63.6	65.6	67.5	69.4	71.0
20	61.8	64.0	66.1	68.1	70.0	71.7

In addition to ***pivot tables***, contour plots can provide a visual display of results from the climate scenarios, a presentation useful for climate vulnerability assessment and decision support. While BASINS CAT does not directly generate contour plots, model output can be exported as text files for use with any graphics and plotting software. Figure 3.4 is a contour plot of the simulated change in streamflow for each combination of temperature and precipitation adjustments. Contours were generated by interpolation from the original 42 scenario endpoints, indicated as dots on the plot, using DPlot software (http://www.dplot.com). The impact of warming temperatures on mean annual streamflow can be seen by moving vertically from the point labeled “Current Climate”. Similarly, the impact of changes in precipitation can be seen by moving horizontally in the plot.

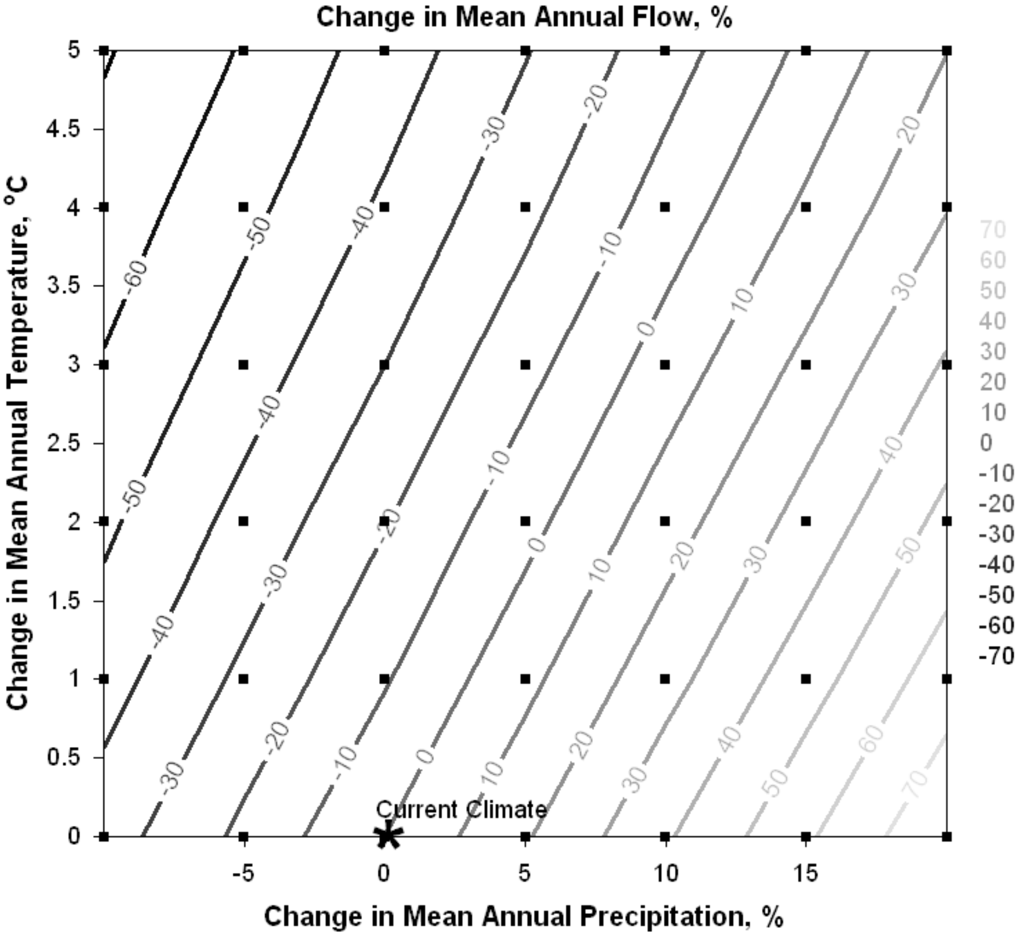


Figure 3.4. Contour plot showing percent change in mean annual streamflow for all combinations of temperature and precipitation change.

PART B: Seasonal Sensitivity Analysis

Scenario Development: PART B

A total of 7 model simulations were completed. Scenarios included 1 baseline climate scenario and 6 climate change scenarios. No land use change or management scenarios were included.

Climate Change Scenarios

In PART A, climate change scenarios were created without consideration that climate change may vary seasonally throughout the year. Adjustments were made uniformly to all temperature and precipitation values within the historical baseline period. Although not well understood, it is possible that climate change will vary seasonally throughout the year. For example, there may be increases in winter precipitation with little change during the summer months. Similarly, greater warming may occur during the winter months than summer. The effects of the seasonal timing of climate change on streamflow and water quality could be great. BASINS CAT provides the capability to apply change factors to only selected months of the year. This capability allows scenarios to be created representing changes that vary on a seasonal basis.

For PART B, the climate scenarios were developed to explore how seasonal precipitation patterns can impact mean monthly and annual endpoint values. As in PART A, climate scenarios were developed using the change factor methodology (CFM) (Anandhi et al. 2011), often called the delta change method. Scenarios were developed by adjusting the mean monthly values of temperature and precipitation for the entire 1960 to 2001 simulation period. To create climate change scenarios that reflect plausible seasonal variation of change, monthly deltas were developed using dynamically downscaled GCM model projections developed by the North American Regional Climate Change Assessment Program (NARCCAP) (http://www.narccap.ucar.edu). The NARCCAP projections are a series of high resolution climate simulations developed by nesting RCMs within coarser resolution GCMs. The baseline simulations cover 1971-2000 and the climate change simulations cover 2041-2070. The changes applied to the Raccoon River SWAT model weather data represented the difference in monthly average values between the baseline and the future simulations.

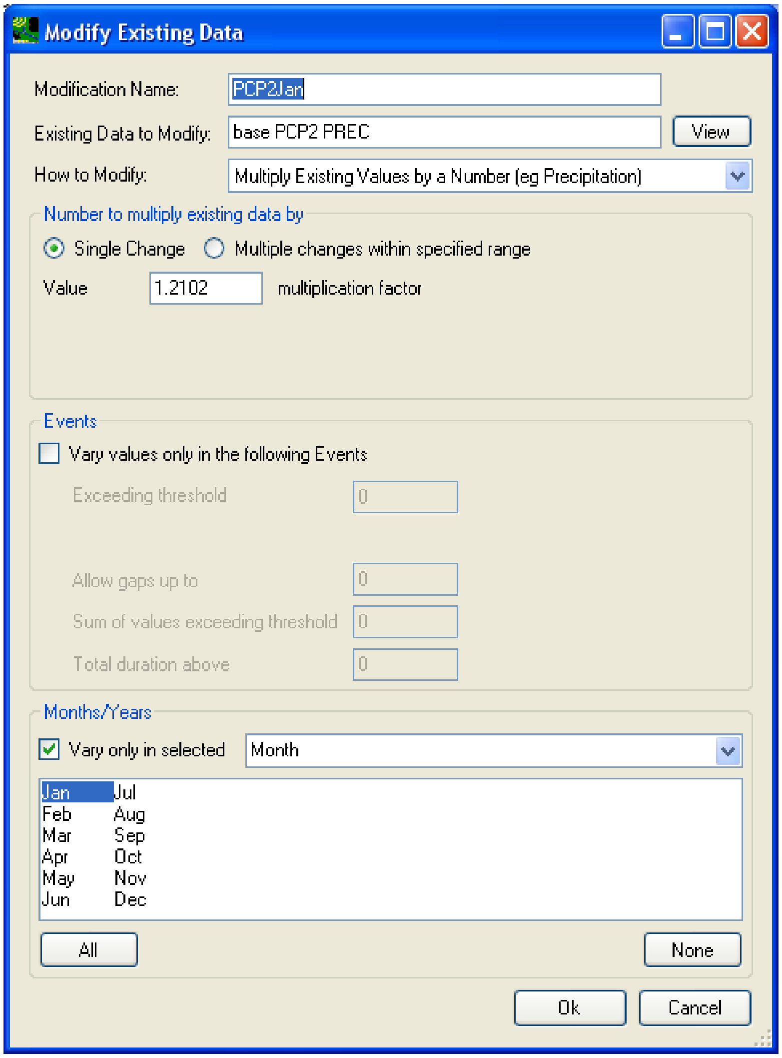
Temperature and precipitation data from four NARCCAP models were used to develop an initial set of climate change scenarios (CC-1, CC-2, CC-3, CC-4) (Table 3.9). CC-3 was further modified to create two additional climate change scenarios. CC-5 and CC-6 maintained the same mean annual rainfall and temperature as CC-3, but monthly changes were altered to represent two different seasonal patterns of changes that sum to the same net annual values.

Table 3.9. NARCCAP climate models used to develop the case study scenarios.

Climate Scenario	**NARCCAP Climate Model**
CC-1	crcm_cgcm3
CC-2	rcm3_cgcm3
CC-3	rcm3_gfdl
CC-4	wrfg_ccsm
CC-5	rcm3_gfdl_(with synthetic monthly adjustments)
CC-6	rcm3_gfdl_(with synthetic monthly adjustments)

The BASINS CAT ***Months/Years*** adjustment feature was used to modify the monthly temperature and precipitation climate data in the SWAT model for each of the simulations (Figure 3.5). Adjustments to historical precipitation are made by specifying a multiplier that is applied to each record within a given month in the precipitation time series. Temperature records are adjusted by specifying a constant degree change within a given month in the temperature time series.

PART B of this case study also incorporates consideration of spatial variability of climate change within the Raccoon River watershed. The Raccoon River SWAT model used in this case study receives meteorological input from two locations, the northern and southern subwatersheds of the Raccoon River basin (Di Luzio 2008). In PART A of this case study, identical change factors were applied to temperature and precipitation data from each of these locations for each scenario considered. This approach assumes the spatial variability of climate change within the study watershed is negligible. Conversely, spatial variability in climate change can be represented in BASINS CAT by applying different sets of change factors to meteorological data from stations in different watershed locations (e.g., in large or topographically complex watersheds). In PART B of this case study spatial variability was represented by applying different monthly change factors to data from the northern and southern subwatersheds of the Raccoon River basin. Using the BASINS CAT's ***Months/Years*** adjustment feature, adjustments were first applied to temperature and precipitation data from one location, followed by application of a different set of adjustments to data from the second location.



Modification Name: PCP2Jan

Existing Data to Modify: base PCP2 PREC

How to Modify: Multiply Existing Values by a Number (eg Precipitation)

Number to multiply existing data by

● Single Change ○ Multiple changes within specified range

Value 1.2102 multiplication factor

☐ Vary values only in the following Events

Months/Years

☑ Vary only in selected Month

Jan	Jul
Feb	Aug
Mar	Sep
Apr	Oct
May	Nov
Jun	Dec

Figure 3.5. BASINS CAT modify existing data window showing adjustment to January precipitation using the ***Months/Years*** adjustment capability.

Land Use Scenarios
Same as PART A. See Section 3.2.1.

Management Scenarios
Same as PART A. See Section 3.2.1.

Endpoint Selection: PART B
The endpoints for this study consisted of annual streamflow and loadings of TN, TP, and TSS at monthly and annual time steps.

Results: PART B
Model simulation results are shown in Figures 3.6 to 3.9 and Tables 3.10 to 3.13. The BASINS CAT ability to specify monthly time subsets for endpoint analysis was used to extract the mean monthly values. Table 3.14 presents the annual total for precipitation, TN, TP, and TSS and the mean annual streamflow for all scenarios. In general, the contrast of the various monthly climate adjustments clearly demonstrate

that the distribution of rainfall and temperature changes within a year produced significantly different outcomes in streamflow and pollutant loadings.

The simulation results as presented in Table 3.14 indicate that all climate scenarios have higher mean annual temperature and annual total precipitation than the baseline. The mean monthly dynamics for precipitation, streamflow and pollutant loadings deviate within Scenarios CC-1 to CC-4 from the baseline (Figures 3.6 and 3.7 and Tables 3.10 to 3.13). In general, the climate scenarios have higher mean monthly precipitation than the baseline in the spring and fall, but lower mean monthly precipitation in the summer. Looking at the trends in detail, it is evident that monthly differences in precipitation in combination with increased temperatures can have a significant impact on the endpoints. For example, the climate change simulations indicate higher mean precipitation in the spring versus the baseline. However, the endpoint values tend to be lower than the baseline, possibly the result of earlier plant growth and higher rates of evapotranspiration caused by warmer spring temperatures.

The influence of monthly variation in precipitation and temperature is further demonstrated by the comparisons of CC-3 and two synthetically adjusted versions, CC-5 and CC-6. All three scenarios have the same mean annual rainfall and temperature, but the seasonal distribution of precipitation is modified in CC-5 and CC-6 (Figure 3.8, top panel). The modified scenarios indicate additional potential impacts on mean monthly and annual streamflow and pollutant loads. For example, in Scenario 6, more than doubling the baseline precipitation in the winter and early spring resulted in a significant increase in all endpoints during those same months (Figures 3.8 and 3.9) likely due to reduced evapotranspiration and limited plant uptake. This scenario also had the highest mean annual streamflow and pollutant loadings, indicating potential risk from higher precipitation volumes in the winter and spring (Table 3.14).

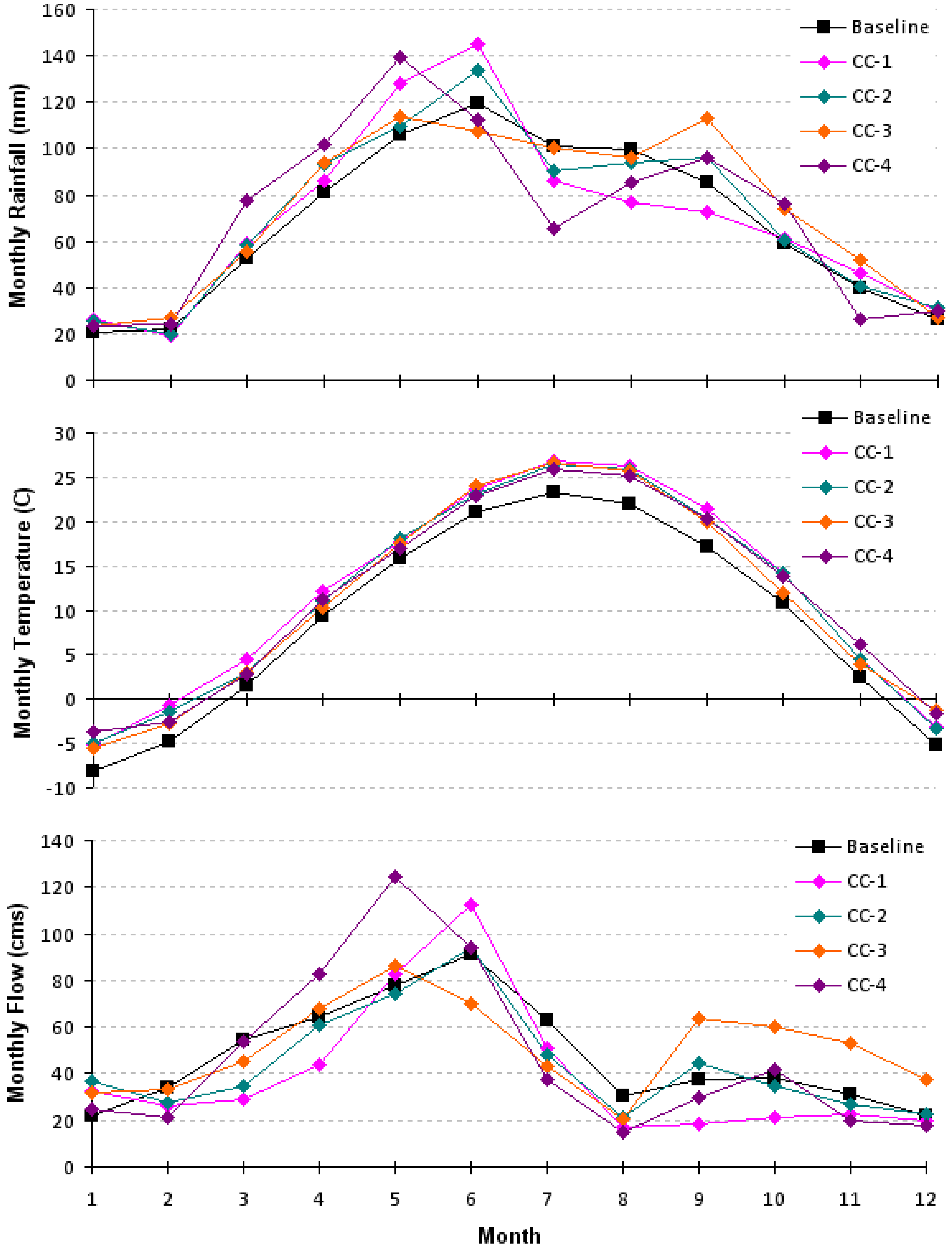


Figure 3.6. Mean monthly precipitation, temperature, and streamflow rate for the NARCCAP and baseline scenarios.

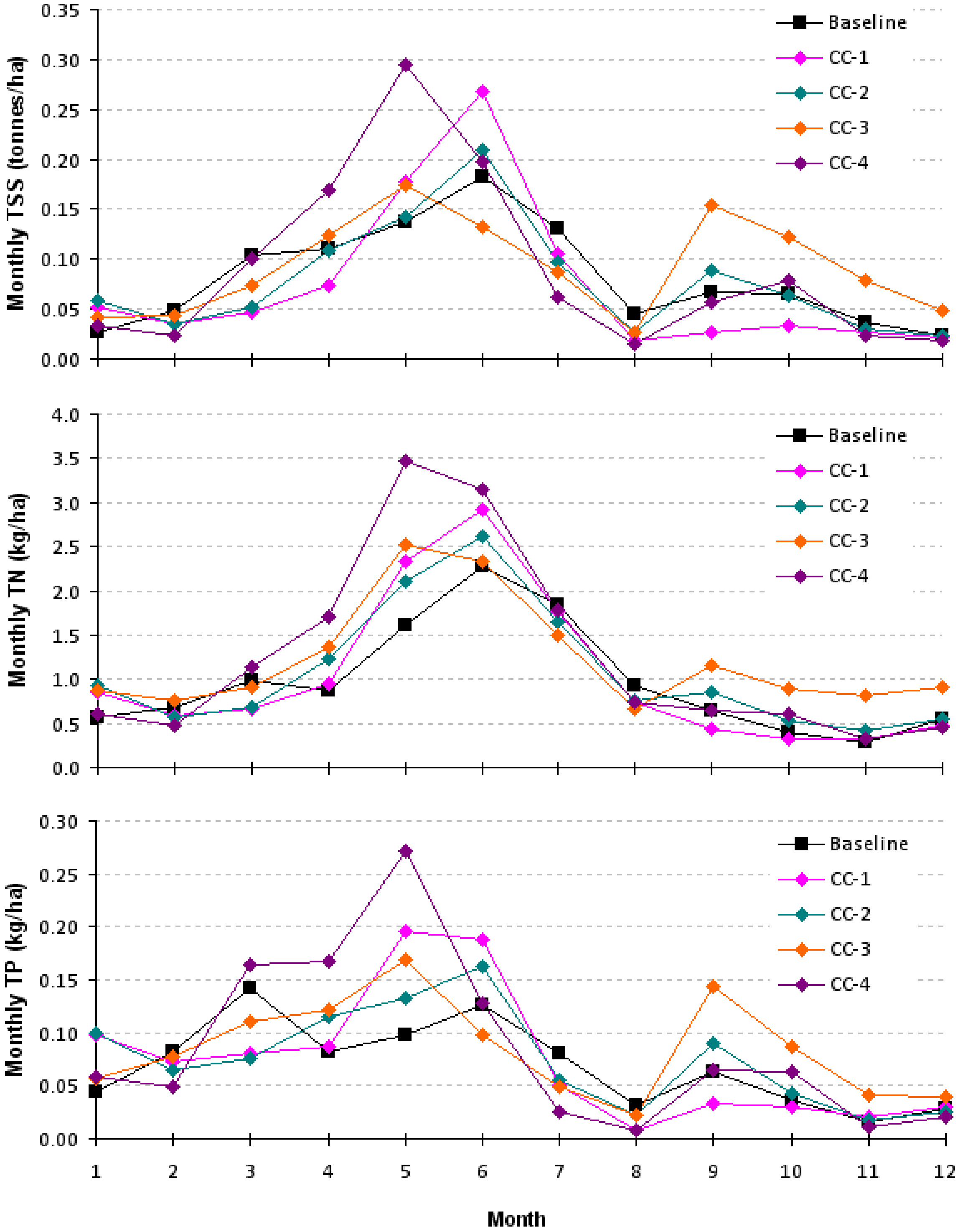


Figure 3.7. Mean monthly TSS, TN, and TP loadings for the NARCCAP and baseline scenarios.

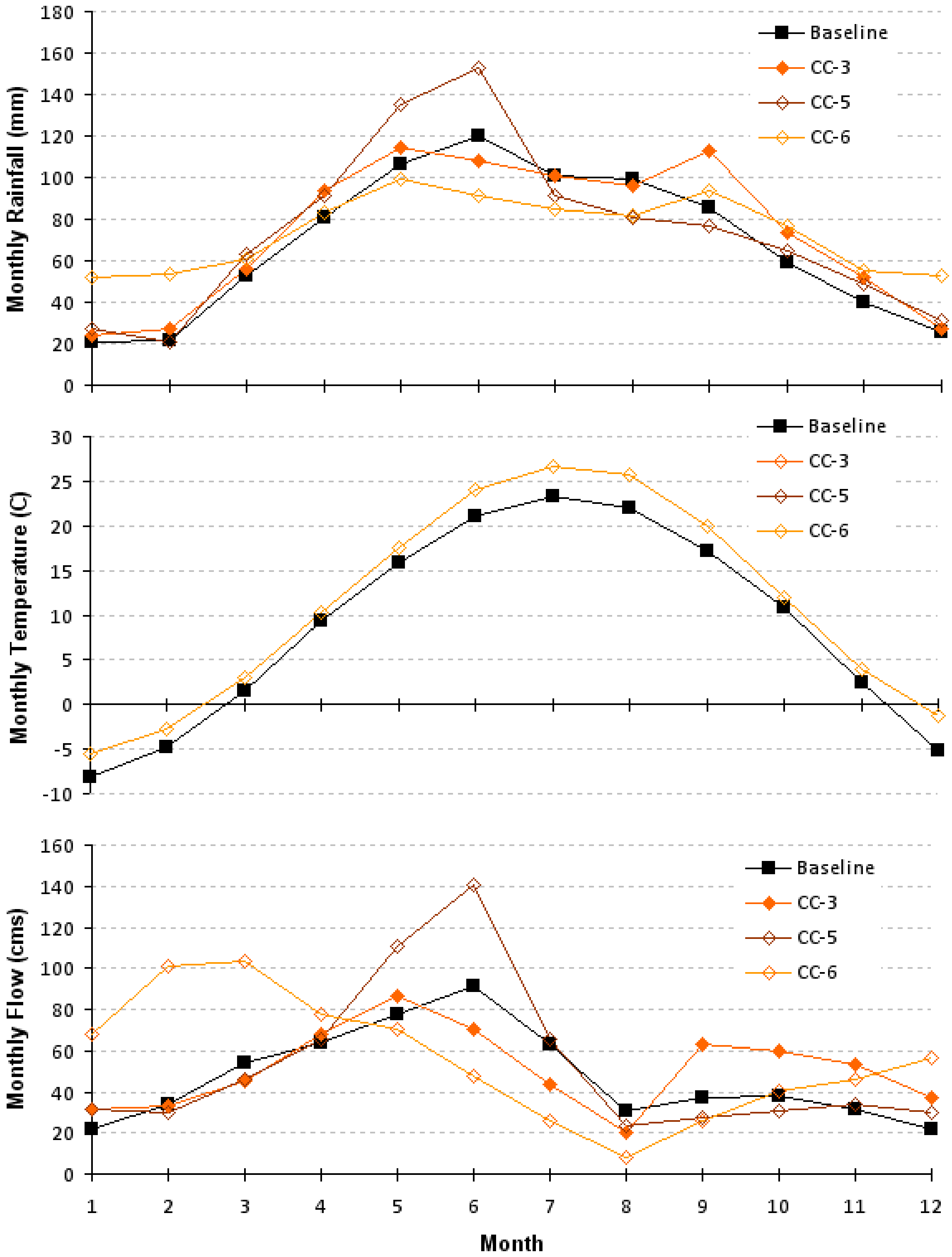


Figure 3.8. Mean monthly precipitation, temperature, and streamflow rate for the CC-5, CC-6, and baseline scenarios.

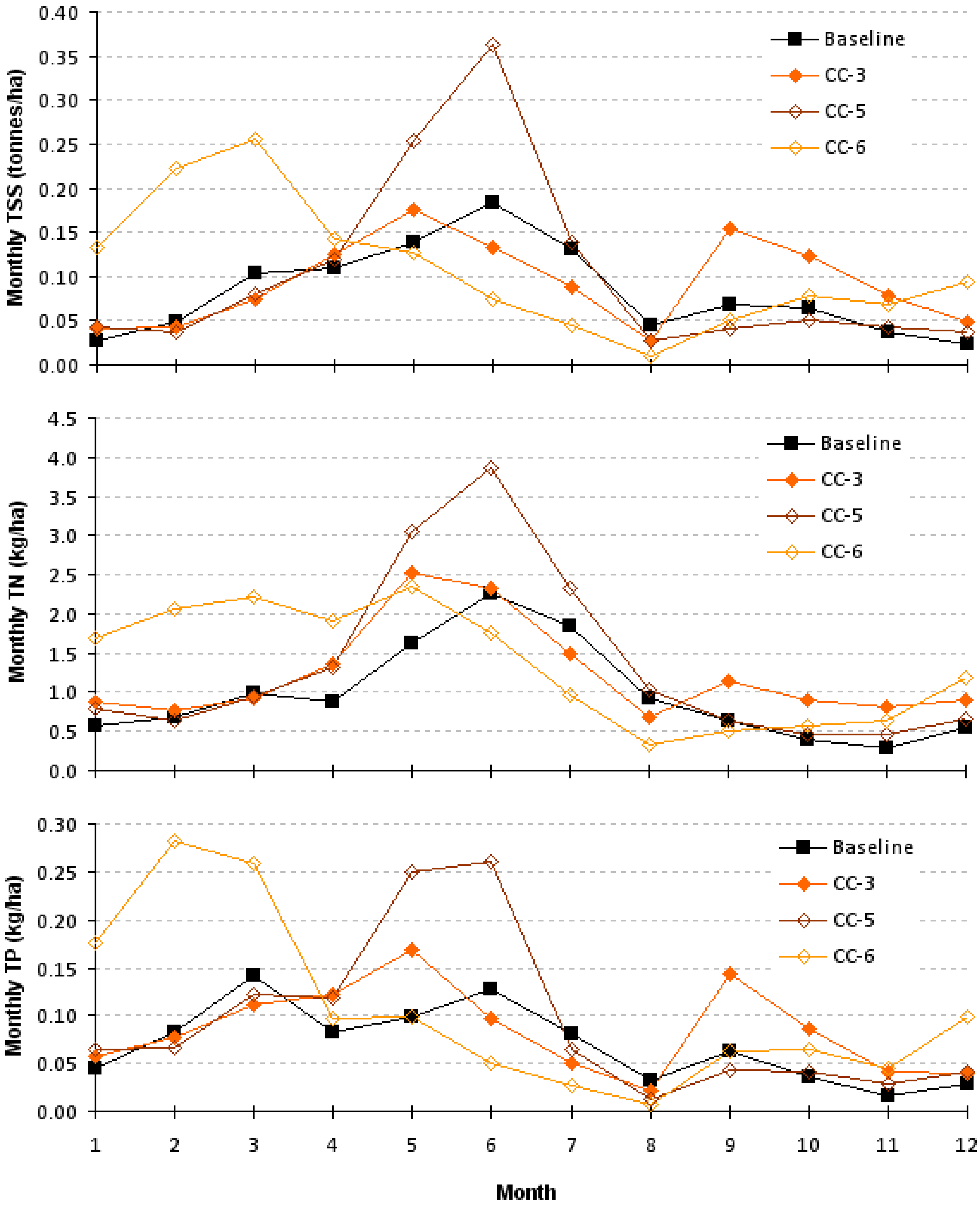


Figure 3.9. Mean monthly TSS, TN, and TP loadings for the CC-5, CC-6 and baseline scenarios.

Table 3.10. Mean monthly streamflow (cms) for all scenarios.

Climate Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
baseline	22	34	54	64	78	91	63	31	37	38	31	22	47
CC-1	32	26	29	44	83	113	51	17	19	21	23	20	40
CC-2	37	28	35	61	74	94	48	21	44	34	27	22	44
CC-3	25	21	54	83	124	94	38	15	30	41	20	17	47
CC-4	32	33	45	68	87	70	43	20	63	60	53	37	51
CC-5	31	30	46	66	111	141	65	24	27	31	34	30	53
CC-6	68	101	103	78	71	48	26	8	26	40	46	57	56

Table 3.11. Mean monthly nitrogen load (kg/ha) for all scenarios.

Climate Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
baseline	0.6	0.7	1	0.9	1.6	2.3	1.8	0.9	0.6	0.4	0.3	0.5	1
CC-1	0.9	0.6	0.7	0.9	2.3	2.9	1.8	0.7	0.4	0.3	0.3	0.5	1
CC-2	0.9	0.6	0.7	1.2	2.1	2.6	1.6	0.8	0.9	0.5	0.4	0.5	1.1
CC-3	0.6	0.5	1.1	1.7	3.5	3.1	1.8	0.7	0.6	0.6	0.3	0.4	1.3
CC-4	0.9	0.8	0.9	1.4	2.5	2.3	1.5	0.7	1.2	0.9	0.8	0.9	1.2
CC-5	0.8	0.6	0.9	1.3	3.1	3.9	2.3	1	0.6	0.5	0.5	0.7	1.3
CC-6	1.7	2.1	2.2	1.9	2.3	1.8	1	0.3	0.5	0.6	0.6	1.2	1.4

Table 3.12. Mean monthly phosphorous load (kg/ha) for all scenarios.

Climate Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
baseline	0.04	0.08	0.14	0.08	0.1	0.13	0.08	0.03	0.06	0.04	0.02	0.03	0.07
CC-1	0.1	0.07	0.08	0.09	0.2	0.19	0.05	0.01	0.03	0.03	0.02	0.03	0.07
CC-2	0.1	0.07	0.08	0.12	0.13	0.16	0.06	0.02	0.09	0.04	0.02	0.03	0.08
CC-3	0.06	0.05	0.16	0.17	0.27	0.13	0.03	0.01	0.06	0.06	0.01	0.02	0.09
CC-4	0.06	0.08	0.11	0.12	0.17	0.1	0.05	0.02	0.14	0.09	0.04	0.04	0.09
CC-5	0.07	0.07	0.12	0.12	0.25	0.26	0.07	0.01	0.04	0.04	0.03	0.04	0.09
CC-6	0.18	0.28	0.26	0.1	0.1	0.05	0.03	0.01	0.06	0.07	0.04	0.1	0.11

Table 3.13. Mean monthly TSS load (tonnes/ha) for all scenarios.

Climate Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
baseline	0.03	0.05	0.1	0.11	0.14	0.18	0.13	0.05	0.07	0.07	0.04	0.02	0.08
CC-1	0.05	0.04	0.05	0.07	0.18	0.27	0.11	0.02	0.03	0.03	0.03	0.02	0.07
CC-2	0.06	0.04	0.05	0.11	0.14	0.21	0.1	0.03	0.09	0.06	0.03	0.02	0.08
CC-3	0.03	0.02	0.1	0.17	0.29	0.2	0.06	0.02	0.06	0.08	0.02	0.02	0.09
CC-4	0.04	0.04	0.07	0.12	0.18	0.13	0.09	0.03	0.15	0.12	0.08	0.05	0.09
CC-5	0.04	0.04	0.08	0.12	0.25	0.36	0.14	0.03	0.04	0.05	0.04	0.04	0.1
CC-6	0.13	0.22	0.26	0.14	0.13	0.08	0.05	0.01	0.05	0.08	0.07	0.09	0.11

Table 3.14. Total and mean annual precipitation, temperature, streamflow, TN, TP, and TSS loads for all scenarios.

Climate Scenario	Total Annual Precipitation, mm	Temp. Annual Mean, C	Mean Annual Streamflow, cms	Total Annual TSS, tonnes/ha	Total Annual TN, kg/ha	Total Annual TP, kg/ha
baseline	813.0	8.83	47.1	0.98	11.6	0.83
CC-1	835.9	11.85	39.8	0.88	12.4	0.89
CC-2	853.5	11.61	43.7	0.94	12.9	0.90
CC-3	857.9	11.50	46.9	1.07	15.1	1.03
CC-4	884.0	11.22	51.0	1.11	14.7	1.01
CC-5	884.2	11.22	52.9	1.23	16.2	1.11
CC-6	884.3	11.22	55.7	1.30	16.2	1.27

Summary

This study assessed the sensitivity of a predominantly agricultural watershed, the Raccoon River, to climate change. The primary BASINS CAT feature demonstrated in this study was the ability to automate the adjustment of temperature and precipitation time series data for the SWAT watershed model on a monthly, seasonal, and annual basis. This allowed an array of climate change scenarios to be automatically generated and used as inputs for model simulations. The ***pivot table*** feature was used to generate endpoint result tables for all temperature and precipitation change combinations considered. This capability made it possible to quickly develop and evaluate watershed sensitivity to the climate change scenarios. In PART B, the BASIN CAT ability to report mean monthly values for endpoints was used to extract monthly endpoint outputs from the model simulations.

The climate scenarios applied in PART A and B were developed using synthetic adjustments and climate model projections. While simple, they were effective in showing that the Raccoon River watershed is indeed sensitive to changes in both precipitation and temperature. PART A presented a general watershed sensitivity analysis whereby uniform adjustments to precipitation and temperature were applied across the entire watershed and simulation time series. The results enabled the development of a contour plot, a simple guide for assessing watershed response across a range of temperature and precipitation changes. In the context of watershed management, a simple assessment such as the one presented may be adequate, providing enough detail to inform the underlying watershed management goal. This type of modeling and analysis approach can also be extended to assess the general sensitivity of land-use change or land management practices.

PART B explored how seasonal shifts in climate change (mainly in terms of varied precipitation) can affect mean monthly and annual endpoints results. While not well understood and somewhat uncertain, seasonal shifts in precipitation due to climate change are likely. Further, a shift in the timing or seasonality of climate patterns could lead to unexpected outcomes that are not visible when examining the trends at an annual scale only. To illustrate the effect of seasonal variability, monthly adjustments to precipitation and temperature in the form of delta changes were applied to the baseline Raccoon River watershed SWAT model. The comparison of the climate scenarios to each other and the baseline demonstrates the potential effects of seasonal shifts of climate on streamflow and pollutant loadings in the Raccoon River watershed, especially precipitation as explored in Scenario CC-5 and CC-6. The sensitivity of results to the seasonality of changes could have implications for management decision-making. For example, if climate change in the UMRB results in higher precipitation volumes in the winter months, higher runoff and pollutant loads are likely. Managers may have to look toward more winter cover crops or modified fertilizer application protocols.

3.3. Urban stormwater sensitivity to rainfall change and effectiveness of management in the Upper Roanoke River, VA, using BASINS CAT with SWMM

Case Study Overview

Using BASINS CAT with SWMM, this case study demonstrates a general urban stormwater sensitivity analysis (PART A), including precipitation change scenarios, to assess stormwater volumes, nutrient and TSS concentrations from an urban redevelopment site. In PART B, the ability of two management scenarios to meet stormwater goals is assessed under the same precipitation change scenarios presented in PART A.

In PARTS A and B, a rainfall event was adjusted using synthetic adjustments across a range; specifically event volume was increased by 10 to 30 percent by increments of 10 percent. Management scenarios in PART B included distributed and centralized stormwater management.

Introduction

Urbanized watersheds generally exhibit a higher sensitivity to rainfall and snowmelt events than pre-development conditions. Impervious cover alters local hydrologic processes, creating amplified runoff events and decreased baseflow in streams during periods of dry weather. Urban stormwater runoff carries pollutants from roads, roof tops, and other impervious areas into stormwater systems and nearby streams. Urban stormwater impacts on local aquatic ecosystems and public health have made it a high management priority in many cities. Changes in precipitation regimes could significantly alter stormwater runoff volumes and pollutant loading from urban environments. Water resource planners, engineers, and others engaged in stormwater management should explore the interactions of climate change with the urban environment in their planning and decision making.

PART A of this case study explores the sensitivity of stormwater runoff from a commercial redevelopment site to precipitation change at the event scale. The Storm Water Management Model (SWMM) was used to simulate the urbanized watershed’s response, and BASINS CAT was used to develop the precipitation change scenarios. The BASINS CAT capability to create ***multiple changes within a user specified range*** was used to modify rainfall event volumes, creating an array of climate scenarios for use in the model simulations. Endpoints analyzed included stormwater flow rate and event mean concentrations (EMCs) of TP and TSS at the site outlet.

PART B assessed two additional SWMM models where stormwater BMPs were employed to explore the benefits of alternative stormwater management scenarios under precipitation change. Such analysis can be a cost effective way of evaluating climate change adaptation strategies. BASINS CAT was used to develop the precipitation change scenarios and assess the results from the model simulations.

Location Description

The study site was a 0.2 km^2 commercial redevelopment project located in the headwaters of the Upper Roanoke River (HUC03010101) in southwest Virginia (Figure 3.10; Young et al. 2009). The site was previously undeveloped except for a few small commercial buildings and a motel. Since 2008, it has been undergoing two phases of redevelopment. Phase I involved the construction of a shopping mall, theater, restaurants, and stormwater detention facility in the southern portion covering approximately 0.05 km^2 of the site. Phase II called for a big-box retail development in the northern portion covering approximately 0.1 km^2 of the site. The entire site drains from the northwest to southeast corner. Baseline land use categories for the site are shown in Table 3.15. For this small urban watershed, there are three distinct land use categories: green space, impervious surfaces, and roof top. The impervious space represents any paved surface such as roads or parking lot. Green space represents any naturally occurring or manmade pervious land cover. Roof top represents all roof top surfaces, including both conventional and vegetated roof top.

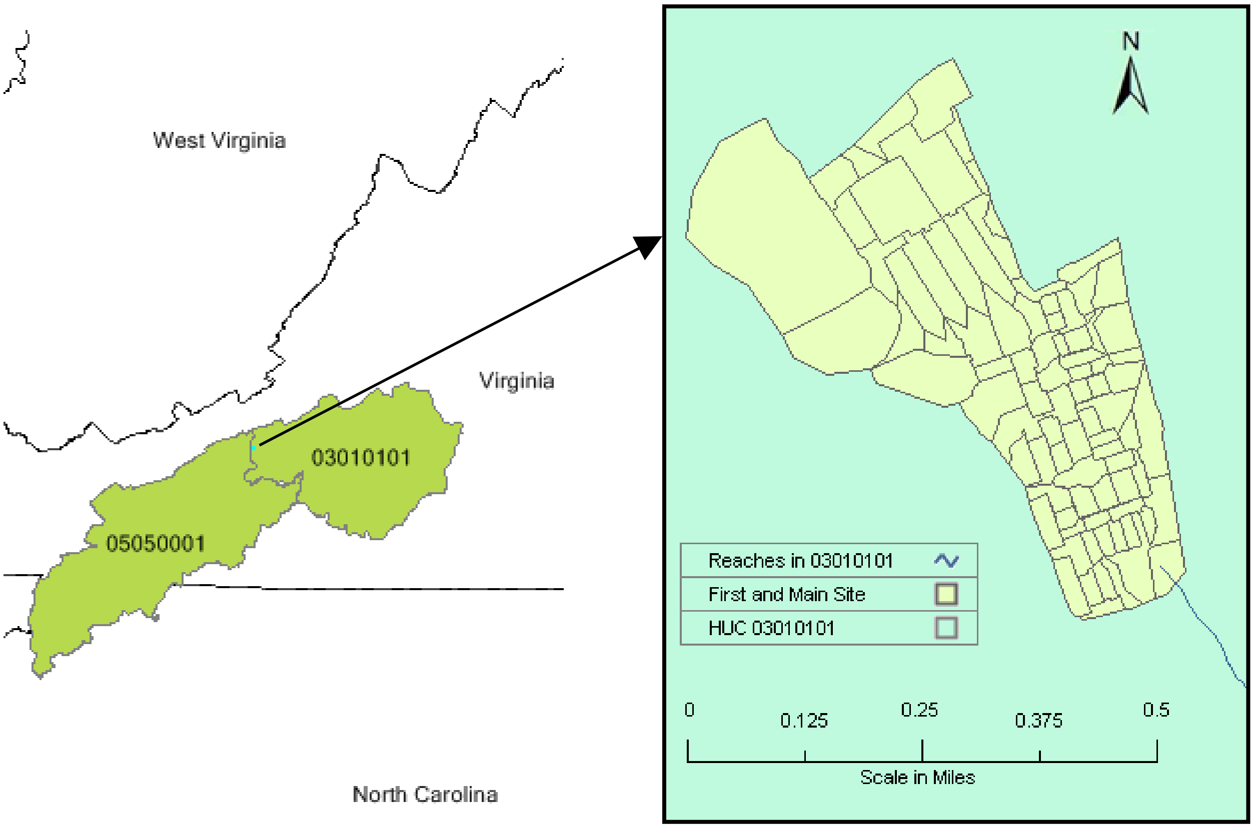


Figure 3.10. The commercial redevelopment site in the Upper Roanoke River watershed.

Table 3.15. Baseline land use summary for the commercial redevelopment site.

Land Use	Portion of Watershed, %
Green space	43
Impervious	41
Roof top	16

Water Model Setup

Evaluation of a watershed for the purpose of storm water management is commonly completed on the timescale of individual rainfall-runoff events. The SWMM model was developed for running event-based simulations, unlike HSPF and SWAT which are typically run on a continuous, annual or longer time scale (although SWMM can also be run on continuous time scales). This case study used a series of SWMM models originally developed for evaluating an optimization tool designed to improve site development and stormwater BMP selection in Virginia (Young et al., 2009). The model included subwatershed delineation and hydrologic discretization of the SWMM hydraulic schematic. In the original evaluation, two alternative stormwater management scenarios were modeled in comparison to the baseline scenario, pre-development conditions with no runoff control measures.

The SWMM model used in this case study was not calibrated; rather the baseline scenario was used as a basis against which the two alternative stormwater management scenarios were compared. The model uses a custom designed SCS Type II storm that has a 31.7 mm/hr rainfall intensity for a 1-hour duration. The model simulation duration is two days with a 1-hour design event in the beginning hour of the simulation. For this case study, temperature data were retrieved from a nearby National Climatic Data Center (NCDC) weather station in Blacksburg, VA. Initial assessment of model simulations indicated that temperature was not a significant factor given the short timescale of the event; therefore, changes to temperature were not included in the simulations.

PART A: Runoff Sensitivity Analysis

Scenario Development: PART A

A total of 10 model simulations were completed. Scenarios included 1 baseline scenario and 9 precipitation change scenarios. No land use or management scenarios were included.

Precipitation Change Scenarios

Precipitation change scenarios were developed to fall within the ensemble range of projected end-of-century (2080s) precipitation changes for this region based on statistically downscaled data from 16 CMIP3 climate models acquired from the ClimateWizard web site (see Section 3.2 for more information on these models). The ensemble range of projected change was used to establish boundary conditions for the design event adjustments. Projected changes in annual precipitation ranged from -17 to +27 percent.

The climate scenarios for input to SWMM were developed using the BASINS CAT capability to create ***multiple changes within a user specified range***. This feature automates the creation of multiple adjustments for selected variables by specifying a range and step increment within the range (e.g., to change temperature from 0 to 3°C by increments of 1°C). In this study, the design event rainfall intensity was increased 10 to 30 percent by increments of 10 percent, which together with the baseline scenario resulted in a total of four precipitation change scenarios.

The event rainfall intensity for the baseline and three precipitation change scenarios are shown in Figure 3.11. For each model run, BASINS CAT was used to generate a revised PET record based on the revised temperature record using the Hamon method (Hamon, 1961). The revised PET record was then provided as an input variable to the SWMM model in the same manner as the revised temperature and precipitation records.

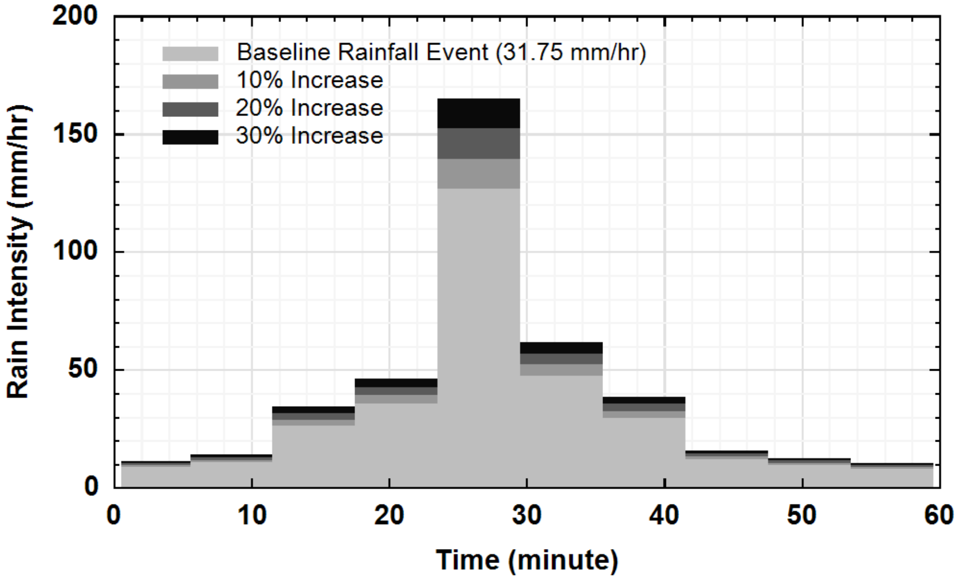


Figure 3.11. Rainfall event intensity for the baseline 1- hour rainfall event and three precipitation change scenarios.

Land Use Scenarios
Part A of this case study does not include land use scenarios. LULC was held constant to assess the impacts of precipitation change only.

Management Scenarios
Part A of this case study does not include management scenarios. Stormwater BMPs were not included to assess the impacts of precipitation change only.

Endpoint Selection: PART A

The endpoints for this study included the event mean stormwater flow rate (cms) and the EMCs of TP and TSS at the site outlet. The original study by Young et al. (2009) included TP and TSS, both reported as key pollutants in the State of Virginia. Using BASINS CAT, the endpoint time series and desired statistics at event or months/years timescales can be reported.

Results: PART A

Table 3.16, developed using the BASIN CAT ***pivot table*** capability, shows the resulting event values for the baseline and three precipitation scenarios. Precipitation values are presented as sum totals for the event, while flow, TSS, and TP are event means. The rainfall event dynamic and flow hydrograph for all scenarios are shown in Figure 3.12. The increase in rainfall volume in the simulated design storm was found to increase the flow rate and pollutant concentrations during the event. While the flow increases of 14, 28, and 38 percent followed a nearly linear response to the 10, 20, and 30 percent increase in rainfall volume respectively, increases in pollutant concentration (4, 6.6, and 6.9 percent, respectively, for TSS; 11, 18, and 20 percent, respectively, for TP) diminished as precipitation volume increased. This response is logical given that first flush of pollutants would be washed away at a much faster rate for larger events and pollutant concentrations will become diluted as runoff volumes increase.

Table 3.16. Event rainfall intensity, mean flow, and concentrations of TP and TSS for the baseline and three precipitation change scenarios.

Scenarios	Rainfall and Endpoints Event rainfall intensity (mm/hr)	Flow (cms)	TSS (mg/l)	TP (mg/l)
Baseline	31.75	0.021	0.981	0.423
+10%	34.90	0.024	1.020	0.471
+20%	38.10	0.027	1.046	0.501
+30%	41.30	0.029	1.049	0.509

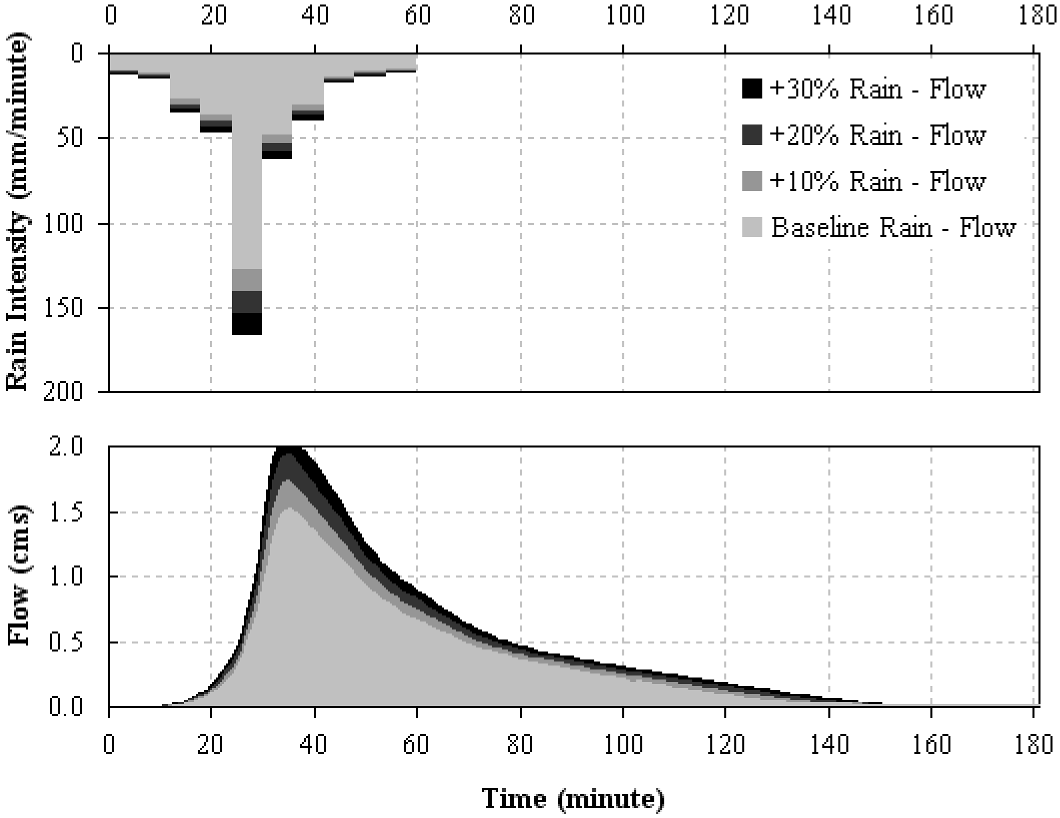


Figure 3.12. Event rainfall intensity versus runoff at the site outlet for all precipitation change scenarios.

PART B: Management Options Assessment

Scenario Development: PART B

A total of 12 model simulations were completed for this case study. Scenarios included 1 baseline and 3 precipitation change scenarios, and 3 management scenarios (1 baseline and 2 alternative management scenarios). No land use scenarios were considered.

Precipitation Change Scenarios

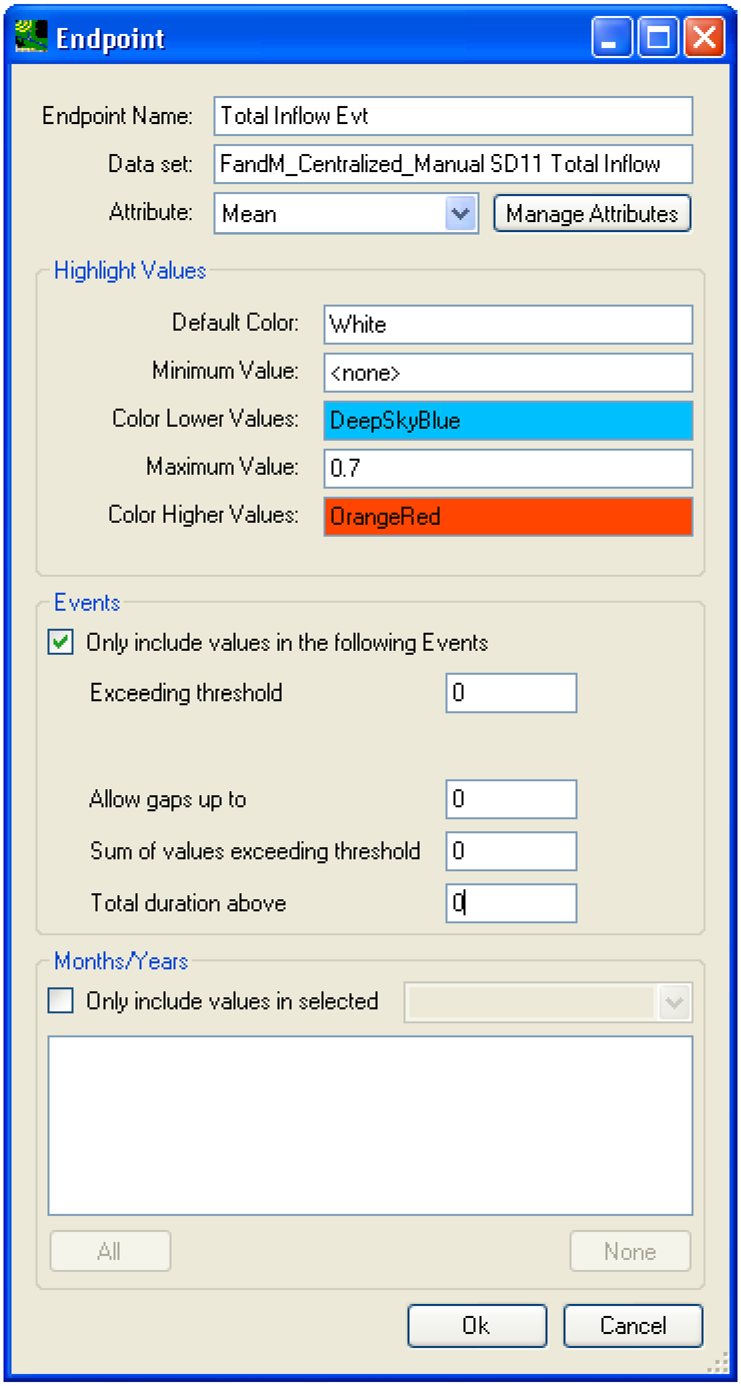
Same as PART A.

Land Use Scenarios
Part B of this case study does not include land use scenarios. LULC was held constant to assess the impacts of the precipitation change and management scenarios only.

Management Scenarios
A baseline SWMM model with no stormwater BMPs and two alternative SWMM models representing two different stormwater management strategies were included in PART B:

- Baseline: Pre-redevelopment conditions.
- Centralized management: strategy that consists of installing a small number of conventional mass storage/detention structures to collect storm runoff. These detention structures are designed to capture runoff from large drainage areas within the entire watershed and release through control structures such as weirs. Such a mass storage-delayed release approach serves both to reduce the peak flow rate and to help reduce pollutant loading in runoff through filtration and gravitational settling.
- Distributed management: strategy that consists of a large number of storage structures of low capacity, combined with infiltration structures, such as pervious pavement and green rooftops, throughout the headwater areas of the watershed. By spreading out multiple source-control BMPs throughout the whole drainage basin, this approach can achieve in-situ runoff volume reduction while minimizing pollutant movement off-site.

Endpoint Selection: PART B
PART B focused on stormwater flow from the redevelopment site outlet. An arbitrary management target of maintaining stormwater runoff below 0.02 cms (0.7 cfs in Figure 3.13) was assumed to illustrate the potential utility of this analysis for management decision making. BASINS CAT allows users to specify such thresholds and color code endpoint values that exceed it (e.g., see Figure 3.13).



Endpoint Name: Total Inflow Evt

Data set: FandM_Centralized_Manual SD11 Total Inflow

Attribute: Mean

Highlight Values

Default Color: White

Minimum Value: <none>

Color Lower Values: DeepSkyBlue

Maximum Value: 0.7

Color Higher Values: OrangeRed

Events

☑ Only include values in the following Events

Exceeding threshold: 0

Allow gaps up to: 0

Sum of values exceeding threshold: 0

Total duration above: 0

Months/Years

☐ Only include values in selected

Figure 3.13. BASINS CAT Endpoint window where users can specify endpoints, event and monthly (inter-annual) statistics, and thresholds for color coding the results.

Results: PART B

Changes in event rainfall intensity resulted in increased flows of stormwater across the baseline and two management scenarios (Table 3.17). The simulation results indicated that the mean flow at the outlet is the highest with the baseline, followed by centralized management, and distributed management. The event rainfall dynamic and runoff hydrograph for the baseline and precipitation change scenarios are shown in Figure 3.14. Increases in the design event rainfall intensity were shown to increase the flow rate in an almost linear fashion for all three management scenarios. Both centralized and distributed management helped reduce peak flow rate significantly compared to the baseline scenario with no management practices in place. The centralized scheme also prolonged flow duration (at a very low flow rate) to beyond 400 minutes after the onset of the design event (not shown in Figure) while flow essentially ended after 180 minutes for the baseline and the distributed management scenarios. The distributed management scenario utilized a series of source-control BMPs that have limited storage capacity (in contrast to the large detention structures in the centralized management scenario), which can be overcome in larger storms, leading to the delayed “second peak” in its hydrograph. Nevertheless, like centralized management, it drastically reduced the flow rate under all precipitation change scenarios.

Figure 3.15 illustrates the option within BASINS CAT to display simulation results with endpoint values color-coded based on a user-specified criterion. In this case, 0.02 cms was chosen (arbitrarily) as the ceiling stormwater flow rate above which the cell containing the endpoint value is highlighted in orange.

Table 3.17. Event mean flow (cms) under all precipitation change and management scenarios. Flow values greater than the threshold are highlighted in orange.

	Precipitation (mm/hr)			
	31.7	**34.9**	**38.1**	**41.3**
Scenario	**Base**	**+10%**	**+20%**	**+30%**
Baseline	0.021	0.024	0.027	0.029
Centralized	0.016	0.019	0.022	0.025
Distributed	0.004	0.006	0.008	0.011

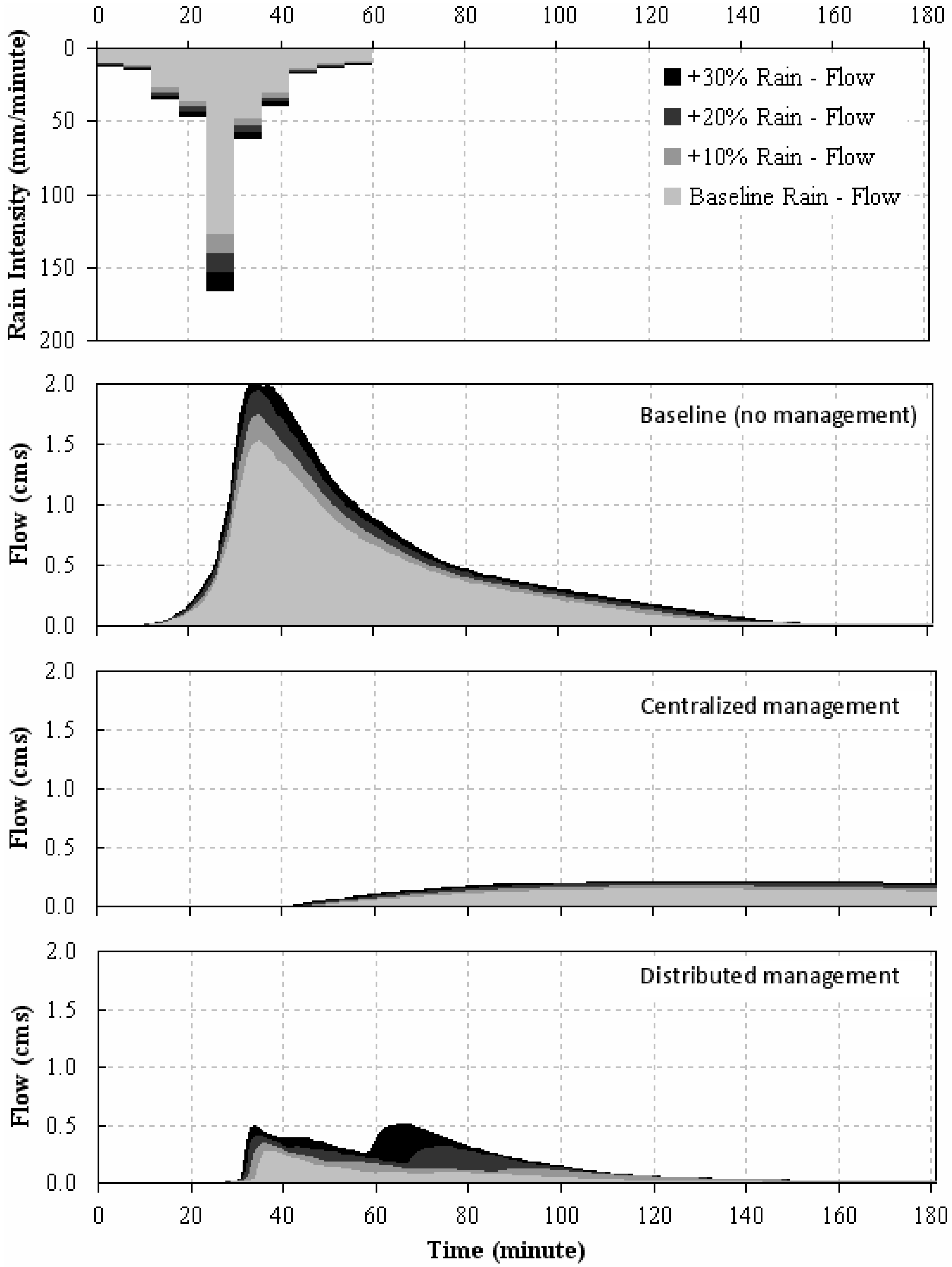
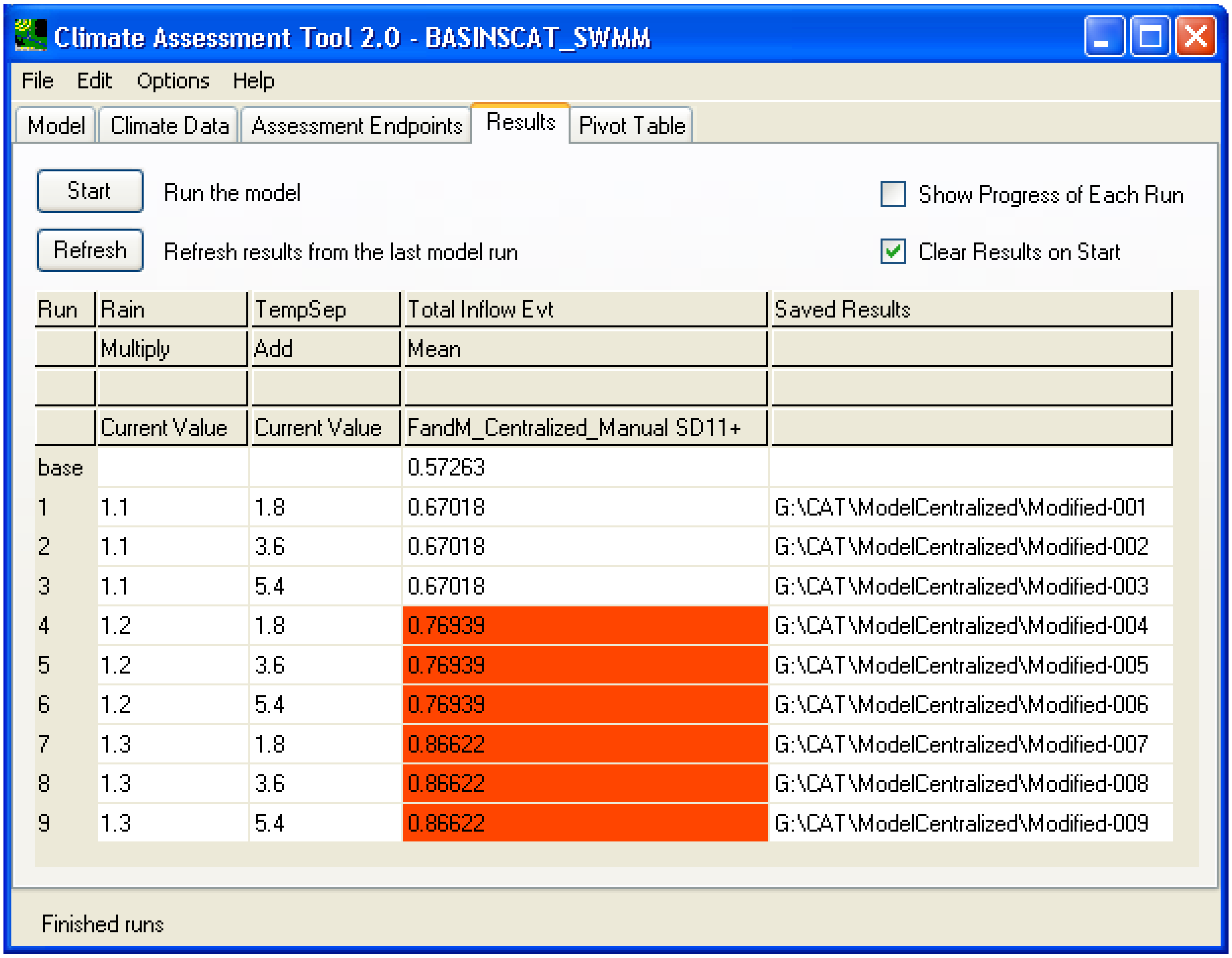


Figure 3.14. Rainfall versus flow dynamics at the site outlet for all precipitation change and management scenarios.



Start — Run the model

Refresh — Refresh results from the last model run

☐ Show Progress of Each Run

☑ Clear Results on Start

Run	Rain	TempSep	Total Inflow Evt	Saved Results
	Multiply	Add	Mean	
	Current Value	Current Value	FandM_Centralized_Manual SD11+	
base			0.57263	
1	1.1	1.8	0.67018	G:\CAT\ModelCentralized\Modified-001
2	1.1	3.6	0.67018	G:\CAT\ModelCentralized\Modified-002
3	1.1	5.4	0.67018	G:\CAT\ModelCentralized\Modified-003
4	1.2	1.8	0.76939	G:\CAT\ModelCentralized\Modified-004
5	1.2	3.6	0.76939	G:\CAT\ModelCentralized\Modified-005
6	1.2	5.4	0.76939	G:\CAT\ModelCentralized\Modified-006
7	1.3	1.8	0.86622	G:\CAT\ModelCentralized\Modified-007
8	1.3	3.6	0.86622	G:\CAT\ModelCentralized\Modified-008
9	1.3	5.4	0.86622	G:\CAT\ModelCentralized\Modified-009

Finished runs

Figure 3.15. BASINS CAT result grid window for the centralized management scenario, showing the color coded endpoint (event mean flow, cfs) values that are above the specified maximum threshold defined in Figure 3.13.

Summary

This study assessed the sensitivity of stormwater quantity and quality in a small urban watershed in Virginia to precipitation change using SWMM. The assessment utilized BASINS CAT to process adjustments to design event rainfall intensity. This allowed an array of precipitation scenarios to be automatically generated and used as input for model simulations. The pivot table feature of BASINS CAT was used to generate endpoint result tables for the precipitation changes considered. The endpoint definition dialog allows the user to specify maximum and minimum threshold values by which the resulting values can be color-coded accordingly in the result grid. This can be a very helpful feature in quickly identifying the scenarios that exceed management targets when using BASINS CAT.

PART A was a general sensitivity analysis of the baseline site conditions that indicated increasing rainfall event intensity increased both stormwater flow rate and pollutant EMCs. PART B assessed stormwater sensitivity to climate change from a management perspective. The assessment included three models representing the baseline with no stormwater BMPs, a centralized management, and a distributed management approach. Increasing precipitation resulted in an almost linear increase in stormwater flow at the outlet for all management scenarios. On an event basis, for any given rainfall intensity, the two alternative stormwater management approaches significantly lowered the peak runoff flow rate; the centralized approach resulted in the longest duration of runoff flow.

While the climate change scenarios evaluated in this case study were relatively simple, they provide a screening-level understanding of stormwater runoff sensitivity to climate change, and the potential effectiveness of stormwater management strategies for reducing climate change impacts. Evaluation of more detailed climate change or management scenarios is also possible. The coupling of BASINS CAT and hydrologic/hydraulic models, when calibrated, can facilitate development of rapid assessment methods that provide timely and usable quantitative information. The flexible capabilities of BASINS CAT for creating and running scenarios can aide and facilitate a wide range of analyses. These capabilities can be an important addition to the tools used by stormwater managers to design, manage, and maintain stormwater infrastructure.

3.4. Agricultural soil erosion sensitivity to climate change and management practices in Blue Earth County, MN, using WEPPCAT

Case Study Overview

In PART A, this case study demonstrates, using WEPPCAT with WEPP, a general sensitivity analysis of sediment yield from agricultural fields under different climate, land use, and management scenarios. PART A climate scenarios included:

- Temperature increases of 0, 2 and 4°C
- Precipitation volume adjustments of -10, 0, +20 percent
- Precipitation intensity increases of 10 percent

Land use scenarios include a 30 m x 30 m field with either Lasa or Lerdal soil series with a slope of 2 or 5 percent. Management scenarios include corn spring chisel plow and soy spring chisel.

In PART B, a subset of the PART A climate and land use scenarios were paired with a series of management scenarios including alternative tillage practices and sediment filter strips to assess these practices in the context of climate change adaptation.

Introduction

Soil loss from agricultural fields can lead to decreased productivity and impacts on adjacent water bodies. Soil erosion is affected by land use, soil characteristics, slope, and local climate. Field crop production can be disruptive to soil structure, resulting in significant erosion and soil loss during runoff events. In regions of the country where agriculture constitutes a significant percentage of land use, sediment erosion can have a significant impact on water quality. Land managers and farmers often employ management practices to reduce agricultural impacts on surface water, including cover crops, contour plowing, and vegetated riparian filter strips that remove sediment from runoff.

Climate change, including changes to temperature and precipitation patterns, has the potential to increase erosion and soil loss in agricultural areas. This case study explores the sensitivity of a field under corn and soy production in Blue Earth County, MN and the potential climate adaptation benefits of common erosion control practices including filter strips and alternative tilling methods.

In PART A, WEPPCAT was used to assess the general sensitivity of fields under conventional corn and soy production in Blue Earth County, MN to potential changes in climate. Climate change scenarios included adjustments to temperature, precipitation volume, and precipitation event intensity. PART B expanded on the analysis in PART A to explore the potential effectiveness of selected management practices for reducing climate change impacts on soil loss.

Location Description

Minnesota ranks among U.S. states as one of the top producers of corn and soy (USDA, 2010a). Blue Earth County, MN is located in the south-central part of the state, the region producing the majority of these crops for Minnesota (USDA, 2010a). The county is suitable for corn and soil production given the generally flat topography, soil quality, and ample precipitation (USDA, 2010b). Local soils are generally well drained and classified under hydrologic groups A and B. The county has a few poorly drained soils categorized under hydrologic groups C and D that developed from glacial outwash in areas with little to no slope (USDA, 2010b). Topographic slopes in the county range from 0 to over 15 percent.

Model Setup
WEPPCAT was accessed online at http://typhoon.tucson.ars.ag.gov/weppcat/index.php. User-defined model inputs include field characteristics (field length and width, shape, slope, soil type) field management, riparian filter strip characteristics, weather station for baseline meteorological data, and precipitation and temperature adjustments for creating climate change scenarios. The WEPP model does not require calibration against observed data.

PART A: General Sensitivity Analysis

Scenario Development: PART A
A total of 109 model simulations were completed. Scenarios included 18 climate change scenarios, 4 land use scenarios, and 2 management scenarios.

Climate Change Scenarios
Climate change scenarios were developed to fall within the ensemble range of projected end-of-century (2080s) temperature and precipitation changes based on statistically downscaled data from 16 CMIP3 climate models acquired from the ClimateWizard web site (see Section 3.2 for more information on these models). Projected changes in temperature ranged from approximately 2°C to 7°C, and projected changes in precipitation volume ranged from approximately -23 percent to +33 percent.

Baseline meteorological data for WEPPCAT simulations are generated using Cligen. Weather parameters are generated by Cligen based on observed monthly average temperature and precipitation information from NOAA National Climatic Data Center (NCDC) weather stations. WEPPCAT creates climate change scenarios by adjusting Cligen parameters to reflect potential changes of interest to users. Available adjustments include increases and decreases in mean monthly temperature, precipitation volume, and the transition probabilities of a wet day following a dry day, and a dry day following a dry day (i.e., number of wet days). These adjustments can be made either uniformly among months of the year, or individual adjustments can be made to specific months of the year. In addition to changing precipitation volume, Cligen parameters can also be adjusted to increase the proportion of annual rainfall occurring in large magnitude events (i.e., to represent an increase in event intensity independent of changes in total annual precipitation). WEPPCAT provides a capability to increase the proportion of annual precipitation occurring in large magnitude events up to 25 percent[2]. Adjustments in precipitation intensity are made by applying the user determined increase to the largest 5 percent of events, and simultaneously decreasing precipitation in the lower 95 percent of events by the same volume such that the adjustment results in negligible change in the volume of annual precipitation.

WEPPCAT was used to modify precipitation volume, precipitation intensity, and temperature. Baseline meteorological inputs for simulations were obtained from the NCDC Winnebago weather station given its proximity to Blue Earth County and location to the soils series of interest. The climate scenarios consisted of a series of synthetic adjustments to temperature and precipitation volume and intensity applied in combination. The meteorological data were adjusted in the following manner:

- Temperature was increased annually by 0, 2 and 4°C.
- Precipitation volume was increased annually by -10, +0 and +20 percent. (Scenarios designated as V-10, V0, and V-20, respectively.)

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[2] Adjustment of rainfall intensity is accomplished by altering the standard deviation of the distributions of daily precipitation used by the climate generator. This approach results in a slight change in average annual rainfall even if changes to the overall volume are not indicated in the model inputs.

Precipitation was then adjusted to assess the effects of increased event intensity (i.e., as defined here, increased intensity refers to an increased proportion of annual rainfall occurring in large magnitude events). This was accomplished by first adjusting the annual precipitation volume by -10, 0 and 20 percent, then increasing the intensity of the largest 5 percent of precipitation events by 10 percent. This intensity adjustment does not result in an increase in mean annual rainfall; rather it redistributes the annual volume to generate larger storms in the upper 5th percentile[3]. A total of 18 climate scenarios were included in this case study.

Land Use Scenarios

PART A included 4 land use scenarios for a 30m x 30m field. Characteristics included two Blue Earth County soils types, Lasa and Lerdal at 2 and 5 percent uniform slopes. Lasa soil is a hydrologic group A soil (high infiltration and water holding capacity) and Lerdal is a hydrologic group C soil (low infiltration and water holding capacity).

Management Scenarios

The two management scenarios evaluated are corn spring chisel plow and soy spring chisel. Land management options that can be represented in WEPPCAT simulations are predefined and fixed in terms of tilling, planting and harvesting methods (Tables 3.18 and 3.19).

Table 3.18. Soy spring chisel plow land management specifications in WEPPCAT

Date	Operation Type	Operation Name
4/5	Tillage	Chisel Plow
4/10	Tillage	Field cultivator, secondary tillage, after duckfoot points
5/10	Tillage	Planter, double disk openers
5/10	Plant-Annual	Soybeans - Medium Fertilization Level
6/10	Tillage	Cultivator, row, multiple sweeps per row
10/15	Harvest	Soybeans - Medium Fertilization Level

Table 3.19. Corn spring chisel land management specifications in WEPPCAT

Date	Operation Type	Operation Name
4/15	Tillage	Chisel Plow
4/25	Tillage	Field cultivator, secondary tillage, after duckfoot points
5/1	Tillage	Tandem Disk
5/10	Tillage	Planter, double disk openers
5/10	Plant-Annual	Corn, Jefferson IA, High production 125 bu/acre
6/5	Tillage	Cultivator, row, multiple sweeps per row
10/15	Harvest	Corn, Jefferson IA, High production 125 bu/acre

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[3] “Rainfall Intensitification is accomplished here by altering the standard deviation of the distributions of daily precipitation used by the climate generator.” (WEPPCAT 2011). This approach results in a slight change in average annual rainfall even if changes to the overall volume are not indicated in the model inputs. In this case study it resulted in a minor 1-2 % decrease in average annual rainfall. For the example, in the V-10scenario a 10 percent decrease in volume results in 26.8 inches of rain per year, while a 10 percent decrease in rainfall plus a 10 percent increase in rainfall intensity in the largest 5 percent of storms results in 26.2 inches of average annual rainfall. This difference was deemed insignificant and actually resulted in more conservative TSS loads due to a decrease in annual runoff versus the volume only adjustment in annual precipitation.

Endpoint Selection: PART A

The endpoints simulated by WEPPCAT are the same as the original WEPP model: sediment loss and sediment yield. Sediment loss is the total amount of soil displaced along the length of a field due to runoff as measured at the bottom of the slope. Sediment yield is the amount of soil displaced (sediment loss) as measured at the bottom the slope minus any retained by a filter strip (if applicable).

Results: PART A

Simulation results are shown in Tables 3.20 and 3.21 and Figures 3.16 to 3.18. Results suggest sensitivity of sediment yield to increases in precipitation volume and intensity. The greatest change was observed for the scenario V20 + I10, with simulated a sediment yield close to double the yield under the baseline scenario. This illustrates the synergistic effect of increasing precipitation volume and intensity on sediment yield. Results also suggest increases in volume have a greater impact on the overall increase in sediment yield versus intensity alone. For example, under historic weather conditions (V0) the Lasa soil at a 2 percent slope under corn production yielded 4.9 tons/ha/yr of sediment. Increasing the precipitation volume 20 percent resulted in 7.4 tons/ha/yr sediment yield, a 51 percent increase, while the combined effect of increasing the precipitation volume 20 percent and event intensity 10 percent resulted in 8.3 tons/ha/yr, a 69 percent increase.

Field slope, soil hydrologic group and crop type influenced sediment yield under all climate scenarios. As expected, a 2 percent slope resulted in a lower sediment yield versus a 5 percent slope. Lasa soil also resulted in a lower sediment yield versus Lerdal, likely due to the soil properties affecting infiltration and water holding capacity. Finally, corn production resulted in a much lower sediment yield versus soy.

Table 3.20. Mean annual sediment yield (tonnes/ha/yr) for corn production under conditions of changing climate[4]. Scenarios named to reflect changes in precipitation volume and intensity; V = volume, I = intensity, numerical value reflects percent change from baseline.

Soil Type & Slope	**Temp Increase, °C**	**Precipitation Scenarios**					
		V-10	**V-10+I10**	**V0**	**V0+I10**	**V20**	**V20+I10**
Rainfall, mm		656.6	641.9	725.2	712.95	869.75	852.6
Lasa 2%	**0**	3.8	4.3	**4.9**	5.4	7.4	8.3
	2	3.8	4.3	4.9	5.6	7.6	8.3
	4	4.0	4.5	5.2	5.8	7.8	8.7
Lasa 5%	**0**	7.6	8.5	**9.9**	10.8	14.6	15.9
	2	8.5	9.4	10.8	12.1	16.1	17.7
	4	9.4	10.5	12.1	13.5	18.2	19.7
Lerdal 2%	**0**	5.6	6.3	**7.2**	8.1	10.8	11.9
	2	5.6	6.5	7.4	8.3	10.8	11.9
	4	6.1	6.9	8.1	9.0	11.7	12.8
Lerdal 5%	**0**	8.7	10.1	**11.2**	12.6	16.4	18.2
	2	10.1	11.7	13.0	14.6	18.6	20.8
	4	11.9	13.9	15.5	17.5	22.4	25.1

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[4] See Footnote 3 for explanation of discrepancy in annual rainfall values resulting from intensity adjustments.

Table 3.21. Mean annual sediment yields (tonnes/ha/yr) for soy production under conditions of changing climate[5]. Scenarios named to reflect changes in precipitation volume and intensity; V = volume, I = intensity, numerical value reflects percent change from baseline.

Soil Type & Slope	**Temp Increase, °C**	**Precipitation Scenarios**					
		V-10	**V-10+I10**	**V0**	**V0+I10**	**V20**	**V20+I10**
Rainfall, mm		656.6	641.9	725.2	712.95	869.75	852.6
Lasa 2%	**0**	6.7	7.4	8.5	9.2	12.6	13.7
	2	6.7	7.4	8.5	9.4	12.8	13.9
	4	7.2	7.8	9.2	10.1	13.7	14.8
Lasa 5%	**0**	16.8	18.4	21.3	22.9	30.7	33.2
	2	16.8	18.4	21.1	22.9	30.9	33.2
	4	17.7	19.3	22.2	24.2	32.5	35.0
Lerdal 2%	**0**	9.4	10.5	12.1	13.2	17.9	19.5
	2	9.6	10.8	12.6	13.9	18.6	20.4
	4	10.5	11.9	13.7	15.0	20.4	22.2
Lerdal 5%	**0**	23.1	26.0	30.0	33.0	45.3	49.3
	2	23.5	26.7	30.7	34.3	46.6	51.1
	4	25.1	28.5	32.7	36.8	50.2	54.9

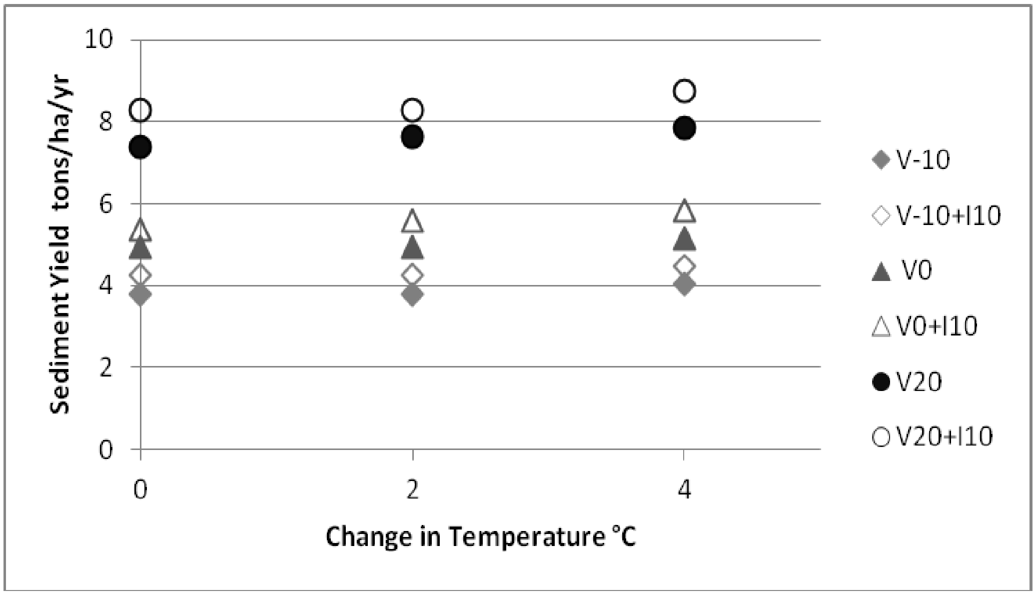

Figure 3.16. Mean annual sediment yield for Lasa soil at 2 percent slope under corn production for all climate change scenarios.

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[5] See Footnote 3 for explanation of discrepancy in annual rainfall values resulting from intensity adjustments.

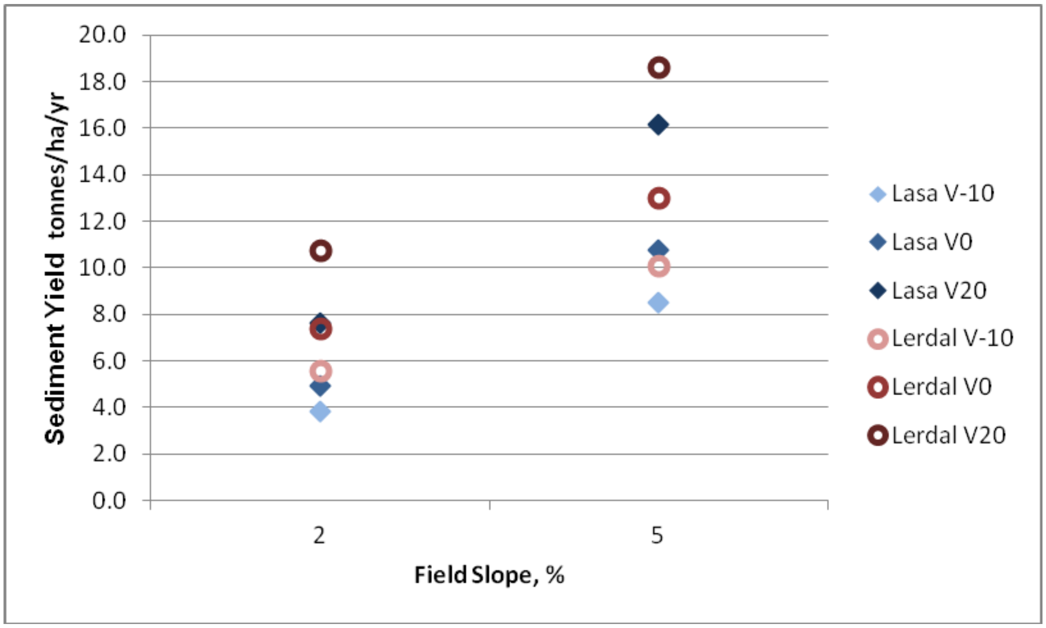


Figure 3.17. Mean annual sediment yield for the Lasa and Lerdal soil under corn production for three climate change scenarios.

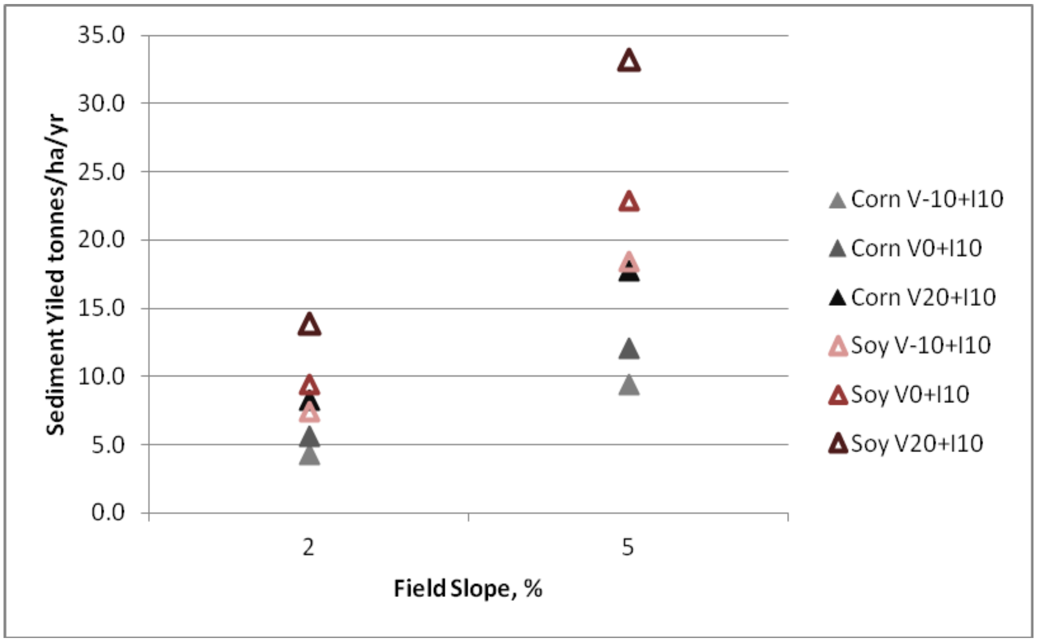


Figure 3.18. Mean annual sediment yield for Lasa soil under corn and soy production for three climate change scenarios.

PART B: Managing Soil Loss under Climate Change

Scenario Development: PART B

A total of 189 model simulations were completed. Scenarios included 1 baseline climate scenario, 9 climate change scenarios, 1 land use scenario, and 18 management scenarios.

Climate Change Scenarios
PART B used a subset of the climate change scenarios evaluated in PART A. The climate scenarios consisted of a series of synthetic temperature and precipitation adjustments. Mean monthly temperatures were increased by 0, 2 and 4°C. Mean monthly precipitation volumes were increased by 0 and 20 percent. Precipitation was further adjusted to assess the impact of increasing intensity. Similar to PART A, this was accomplished by first increasing the precipitation volume 20 percent and then increasing the intensity by 10 percent. A total of 9 climate scenarios were assessed.

Land Use Scenarios
One land use scenario was considered, a field with an area of 30 x 30 meters with Lerdal soil at a five percent uniform slope. Lerdal is a hydrologic group C soil meaning it has both a low infiltration rate and water holding capacity. This soil series and slope were selected since it represents a “worst case” scenario for a field under crop production in Blue Earth County, MN.

Management Scenarios
PAPT B was designed to assess the potential benefit of alternative tilling practices and grass and forest filter strips for climate change adaptation. The corn spring chisel plow land management scenario from PART A was selected as a baseline scenario. Two additional land management options were included, corn no-till and corn fall mulch till. The land management scenario characteristics in terms of tilling, planting and harvesting were fixed and predetermined by the WEPPCAT model (Table 3.19, 3.23, and 3.24). WEPPCAT provides the option of including a filter strip to assess potential sediment yield reductions. Grass and forest filter strips included in the model simulations were 3, 6, and 9 m wide x 30 m long. A baseline scenario with no filter strip was also included for baseline comparisons under each climate change scenario and tilling practice. A total of 18 management scenarios were assessed.

Table 3.22. Corn fall mulch till management characteristics in WEPPCAT.

Date	Operation Type	Operation Name
4/25	Tillage	Field cultivator, secondary tillage, after duckfoot points
5/5	Tillage	Tandem Disk
5/10	Tillage	Planter, double disk openers
5/10	Plant-Annual	Corn, Jefferson IA, High production 125 bu/acre
6/5	Tillage	Cultivator, row, multiple sweeps per row
10/15	Harvest	Corn, Jefferson IA, High production 125 bu/acre
11/1	Tillage	Chisel plow, straight with spike pts

Table 3.23. Corn no-till management characteristics in WEPPCAT.

Date	Operation Type	Operation Name
5/10	Tillage	Planter, no-till with fluted coulter
5/10	Plant-Annual	Corn, Jefferson IA, High production 125 bu/acre
10/15	Harvest	Corn, Jefferson IA, High production 125 bu/acre

Endpoint Selection: PART B
Same as PART A.

Results: PART B
The model simulations provide a broad picture of the potential sediment yield associated with varying degrees of climate change and land management options (Table 3.25). Generally, increases in precipitation volume and intensity and temperature resulted in increased sediment yields under all

management scenarios. Sediment yield decreased as filter strip width increased; however, there were diminishing returns with sediment reduction as the filter strip width increased from three to nine meters (Figure 3.19).

Table 3.24. Sediment yield (tonnes/ha/yr) resulting from corn production under all climate change, land use, and management scenarios. Buffers named to reflect cover; NB=no buffer, GB = grass buffer, and FB = forest buffer, and numerical value signifies width. Precipitation scenarios named to reflect changes in volume and intensity; V = volume, I = intensity, numerical value reflects percent change from baseline.

Temp (°C) Increase	**Buffer**	**Corn Fall Mulch**			**Corn No Till**			**Corn Spring Chisel**		
		V0	**V20**	**V20+ I10**	**V0**	**V20**	**V20+ I10**	**V0**	**V20**	**V20+ I10**
0°C	NB	8.1	11.7	13.0	1.3	2.0	2.0	11.2	16.4	18.4
	GB3	4.7	7.2	8.1	1.3	1.8	2.0	6.3	9.6	10.8
	GB6	3.6	5.4	6.1	1.3	1.8	2.0	4.5	6.9	7.8
	GB9	2.7	4.3	4.9	1.1	1.8	1.8	3.4	5.4	6.1
	FB3	4.3	6.3	7.2	1.3	1.8	2.0	5.4	8.5	10.3
	FB6	2.9	4.5	4.9	1.3	1.8	2.0	3.6	5.6	6.5
	FB9	2.2	3.6	4.0	1.1	1.8	2.0	2.7	4.3	4.9
2°C	NB	9.4	13.5	15.2	1.3	2.0	2.2	13.0	18.6	21.1
	GB3	5.2	7.8	9.0	1.3	2.0	2.2	6.7	10.3	11.9
	GB6	3.6	5.6	6.3	1.3	2.0	2.2	4.7	7.2	8.3
	GB9	2.9	4.3	4.9	1.1	1.8	2.0	3.4	5.4	6.1
	FB3	4.5	6.9	7.8	1.3	2.0	2.2	5.8	9.0	11.2
	FB6	3.1	4.7	5.4	1.3	2.0	2.0	3.8	5.8	6.7
	FB9	2.2	3.6	4.0	1.3	1.8	2.0	2.7	4.3	4.9
4°C	NB	11.7	17.0	18.6	1.6	2.2	2.5	15.5	22.4	25.3
	GB3	6.1	9.2	10.3	1.6	2.2	2.5	7.6	11.9	13.5
	GB6	4.0	6.3	7.2	1.3	2.0	2.2	4.9	7.8	9.0
	GB9	2.9	4.7	5.2	1.3	2.0	2.0	3.6	5.6	6.5
	FB3	5.4	8.1	9.2	1.6	2.2	2.2	6.5	9.0	13.0
	FB6	3.4	5.4	5.8	1.3	2.0	2.2	4.0	6.3	7.2
	FB9	2.5	3.8	4.3	1.3	2.0	2.2	2.7	4.5	4.9

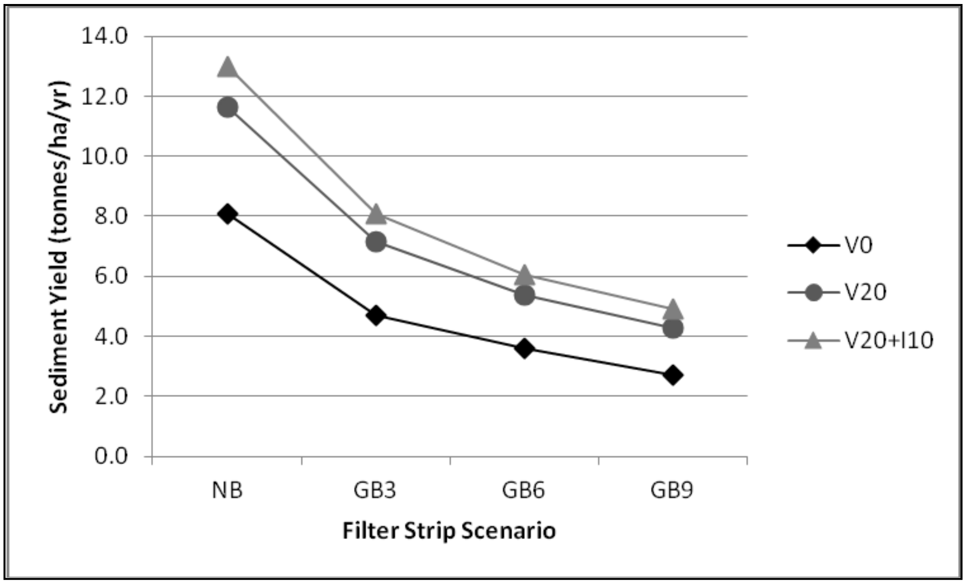


Figure 3.19. Sediment yield (tonnes/ha/yr) under corn fall mulch till with a 3, 6, and 9 meter grass buffer. Buffers named to reflect cover; NB=no buffer, GB = grass buffer, and FB = forest buffer, and numerical value signifies width. Precipitation scenarios named to reflect changes in volume and intensity; V = volume, I = intensity, numerical value reflects percent change from baseline.

The simulation results can be used to characterize sensitivity to climate change (Table 3.25). For example, the simulation for a field under corn spring chisel and current climate conditions without a buffer resulted in a sediment yield of 11.2 tons/ha/yr (Table 3.25). If climate change resulted in a 20 percent increase in annual rainfall (V20 scenario) and a 2°C increase in temperature, the sediment yield would be 18.6 tons/ha/yr, a 66 percent increase over current yields. A land owner could also use the model simulations to determine potential options for not only maintaining current sediment yield, but also to identify ways to reduce sediment yield under altered precipitation regimes. As indicated in Table 3.26, certain land management practices and/or filter strips could meet both of these management goals. If the land owner wanted to maintain a sediment yield of 6 tons/ha/yr or less under the V20 precipitation scenario, a number of options may exist. No-till for corn production was by far the superior management practice for reducing soil yield under the V20 scenario. A landowner could also maintain current tillage practices and install a 6 to 9 m forest buffer or 9 m grass buffer and reduce sediment yields below 6 tons/ha/yr.

Table 3.25. Sediment yield (tonnes/ha/yr) results from a 2^{o}C increase and temperature and a 20 percent increase in mean annual rainfall volume. Buffers named to reflect cover; NB=no buffer, GB = grass buffer, and FB = forest buffer, and numerical value signifies width. Grayed areas signify tillage and filter strip combinations producing 6 tons/ha/year or less of sediment.

Buffer	**Corn Fall Mulch**	**Corn No Till**	**Corn Spring Chisel**
	V20	**V20**	**V20**
NB	13.5	2.0	18.6
GB3	7.8	2.0	10.3
GB6	5.6	2.0	7.2
GB9	4.3	1.8	5.4
FB3	6.9	2.0	9.0
FB6	4.7	2.0	5.8
FB9	3.6	1.8	4.3

Summary

In this case study, WEPPCAT was used to explore soil erosion sensitivity to climate change by efficiently modifying weather data for input into the WEPP model. WEPPCAT enables users to run an almost unlimited number of land management-climate change scenario combinations to explore potential sediment yields. The ability to modify temperature and precipitation volume and intensity data, as well as explore the benefits of filter strips and alternate land management options were all utilized in this case study. While the model outputs are not actually predicting future conditions, they provide a useful mechanism for comparing sediment yield across a range of potential futures in order to assess sensitivity and vulnerability.

The results from PART A indicated a relatively high degree of sensitivity of agriculture land in Blue Earth County, MN to climate change. The sediment yields from fields with both Lasa and Lerdal soil were almost double compared to the baseline yields under the most extreme climate change scenarios evaluated in this study. The finding also indicated that crop type and slope play a significant role in determining sediment yield under all climate change scenarios.

In PART B, sediment management options were explored in the context of climate change adaptation. Sediment yield from a corn field under alternative land management and climate change scenarios was modeled. This type of information can help identify appropriate management practices for adapting agricultural land to climate change. The findings indicated that sediment yields could potentially be prevented or even reduced under the most extreme climate changes if management practices are employed.

3.5. Streamflow and water quality sensitivity to changes in precipitation amount, frequency, and intensity in the Tualatin River, OR, using BASINS CAT with HSPF

Case Study Overview

This case study used BASINS CAT with HSPF to explore watershed sensitivity under changing precipitation regimes with respect to flow, TN, and TSS. The BASINS CAT capability to modify precipitation patterns was employed to increase precipitation by 10 and 20 percent using the following climate scenarios:

- constant percent increase applied to all precipitation events (constant increase).
- increase applied to the largest 30 percent of precipitation events (intensity increase).
- increase in total number of annual precipitation events (frequency increase).

Temperature was increased by 2°C for all scenarios. Potential evapotranspiration was recalculated with BASINS CAT to reflect this change.

Introduction

It is projected that precipitation will be directly impacted by changes in atmospheric circulation and increases in water vapor and evaporation associated with warmer temperatures due to climate change (IPCC, 2007). While many regions are expected to see an overall increase in precipitation, there is significant uncertainty with respect to changes in local and regional rainfall patterns leading to this increase. Watershed responses to different precipitation patterns are also uncertain and will depend on land use and water management among other drivers.

In this case study, the impacts of alternate precipitation patterns are assessed using an existing HSPF model of the Tualatin River in Oregon. BASINS CAT was used to develop the climate change scenarios and assess the water quality and quantity endpoints. This study used the BASINS CAT capabilities for making adjustments to all precipitation events, precipitation events within a user specified size class, and adding new events to the precipitation baseline time series.

Location Description

The Tualatin River (HUC 17090010) drains 712 square miles in northwest Oregon, and is a tributary of the Willamette River (Figure 3.20). Land use and land cover ranges from the densely populated areas of southwest Portland, Hillsboro, Tigard and Beaverton to agricultural areas near Scholls, Gaston, Banks, Mountaindale and North Plains to the forests of Oregon’s Coast Range, Tualatin Mountains and Chehalem Mountains. Most of the fast-growing urban population, approximately 500,000 residents, resides on 15 percent of the watershed’s area. About 35 percent of the watershed is used for agriculture, and about 50 percent of the watershed is forested.

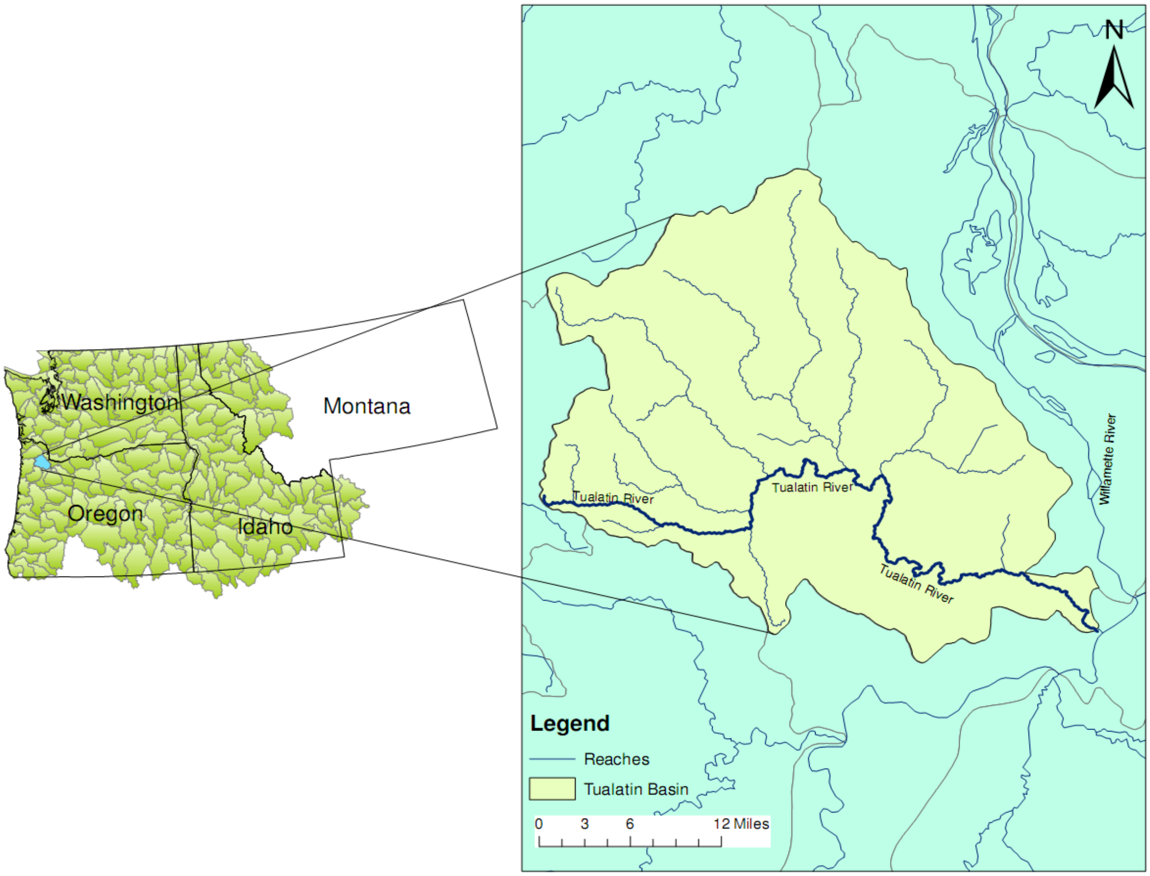


Figure 3.20. Tualatin River Watershed Location.

Water Model Setup

A pre-existing HSPF model of the Tualatin River was acquired from a previous modeling study that included the entire Willamette River (Johnson et al., 2011). Model segmentation of the watershed was based on intersections of land use, hydrologic soil group, and available NCDC weather stations. Soils data were taken from the STATSGO soil survey and LULC was based on the 2001 National Land Cover Database (NLCD). Four point source inputs were included in the model using data from the U.S. EPA's Permit Compliance System. Meteorological data (precipitation, air temperature, and potential evapotranspiration) were drawn from the BASINS4 Meteorological Database (USEPA 2007), a consistent, quality-assured set of nationwide data records disaggregated to the hourly time step typically used by HSPF. Meteorological data from three National Climatic Data Center (NCDC) weather stations (350595 – Beaverton, 351222 – Buxton, 352997 – Forest Grove) across the watershed were used as input to the model.

The baseline model data was for 1980 through 2005. A hydrology calibration period of 10/01/1995 to 09/30/2005 and validation period of 10/01/1985 to 09/30/1995 were used for the Tualatin stream gage at the basin outlet. The water quality calibration and validation periods were 10/01/1991 to 9/30/1995 and 10/01/1986 to 9/30/1990, respectively. A brief summary of calibration and validation results are provided in Tables 3.26 and 3.27.

Table 3.26. Tualatin River model daily streamflow calibration/validation results. NSE: Nash-Sutcliffe Efficiency coefficient.

	Calibration (‘95 – ‘05)	**Validation (‘85 – ‘95)**
NSE	0.799	0.811
E’	0.731	0.702
R^2	0.726	0.769

Table 3.27. Tualatin River HSPF model monthly water quality calibration/validation results. Relative Percent Error is the average of observed-simulated/observed comparisons. Median Percent Error is the median of observed-simulated comparisons/average of observed values.

Endpoint Statistic	**Calibration (‘95 – ‘05)**	**Validation (‘85 – ‘95)**
TSS Load Relative Percent Error	3	5
TSS Concentration Median Percent Error	-7.8	10
Total N Load Relative Percent Error	2	-6
Total N Concentration Median Percent Error	-16.8	-19.2

Scenario Development

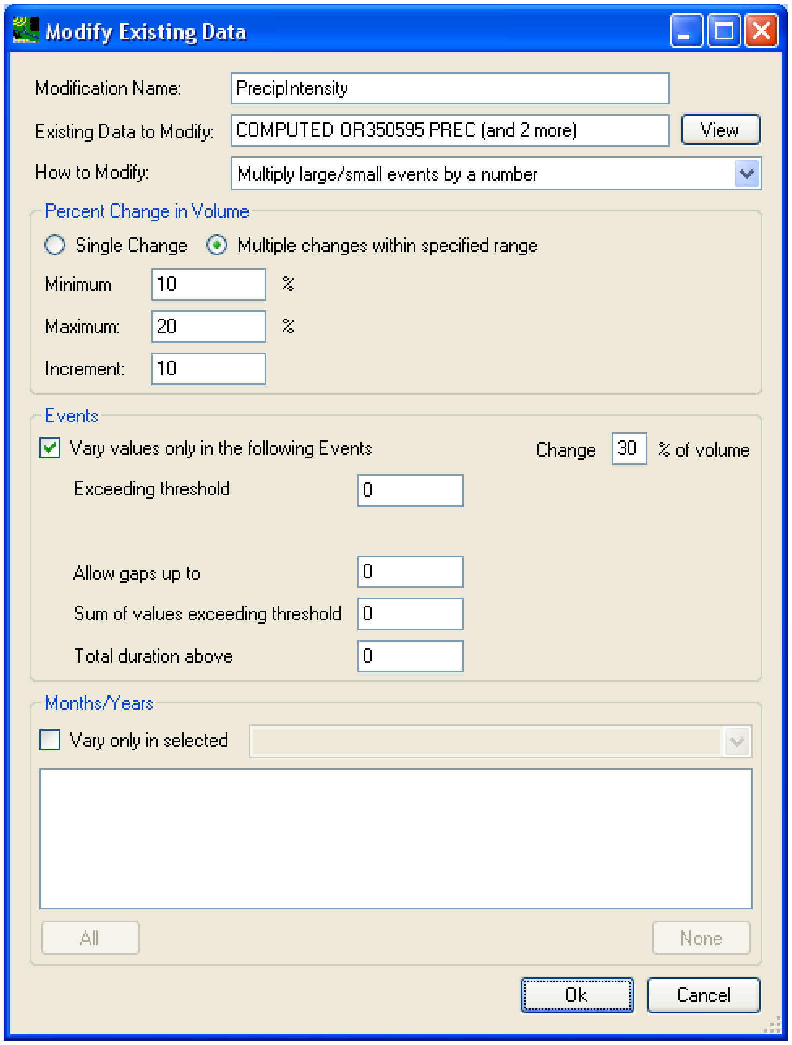
A total of 7 model simulations were completed. Scenarios included 1 baseline climate scenario and 6 climate change scenarios. No land use or management scenarios were included.

Climate Change Scenarios

Climate change scenarios were developed to fall within the ensemble range of projected mid-century (2050s) temperature and precipitation changes for this region based on statistically downscaled data from 16 CMIP3 climate models acquired from the ClimateWizard web site (see Section 3.2 for more information on these models). Projected mid-century changes in temperature for this region ranged from approximately 1°C to 2.5°C, and projected changes in precipitation ranged from approximately -10 to +18 percent.

Six climate change scenarios were created. Each scenario included an increase of 2°C applied to all daily temperature values in the baseline record. Potential evapotranspiration (PET) records were revised using the BASINS CAT ***Penman-Montieth option*** to account for temperature changes. Annual precipitation volume was increased by 10 and 20 percent using three different capabilities available in BASINS CAT: ***adjusting the magnitude of all events in the record, adjusting the magnitude of specific events, and randomly adding/deleting events to change the number of precipitation events in the record*** (Figure 3.21). The 10 and 20 percent increases in precipitation volume were applied to the baseline precipitation records in the following manner:

- constant percent increase applied to all precipitation events (constant increase).
- increase applied to the largest 30 percent of precipitation events (intensity increase).
- increase in total number of annual precipitation events (frequency increase).



Modification Name: PrecipIntensity
Existing Data to Modify: COMPUTED OR350595 PREC (and 2 more)
How to Modify: Multiply large/small events by a number

Percent Change in Volume
○ Single Change ● Multiple changes within specified range
Minimum 10 %
Maximum: 20 %
Increment: 10

Events
☑ Vary values only in the following Events
Change 30 % of volume
Exceeding threshold 0
Allow gaps up to 0
Sum of values exceeding threshold 0
Total duration above 0

Months/Years
☐ Vary only in selected

Figure 3.21. BASINS CAT window specifying increased precipitation in the top 30 percent of events.

A time-series plot for a small portion of the modeled precipitation record for each climate change scenario is shown in Figure 3.22 as an example of how a 20 percent increase in precipitation is achieved using each of the three different precipitation adjustment capabilities. The plot contains curves for each pattern change method: a dashed line for the constant increase, a dotted line for intensity increase, and a light solid line for frequency increase. Each of the three precipitation events in Figure 3.22 demonstrates different aspects of the three methods. The first event (hour 16 - 17) is a new event added by the increase in frequency method. The second event (hour 0 - 2) shows the changes applied for a 2-hour event that is in the top 30 percent of the original record. The lowest values (light solid line) represent the increased frequency method, but this event is actually from the original record. The dashed line represents the constant increase method and is thus 20 percent higher than the original storm volume. The dotted line shows the intensity increase applied to this large event, one that falls within the largest 30 percent of events. The third event (hour 7– 8) is a small event that is increased only by the constant change method. The intensity modification does not apply since it does not fall within the largest 30 percent of events.

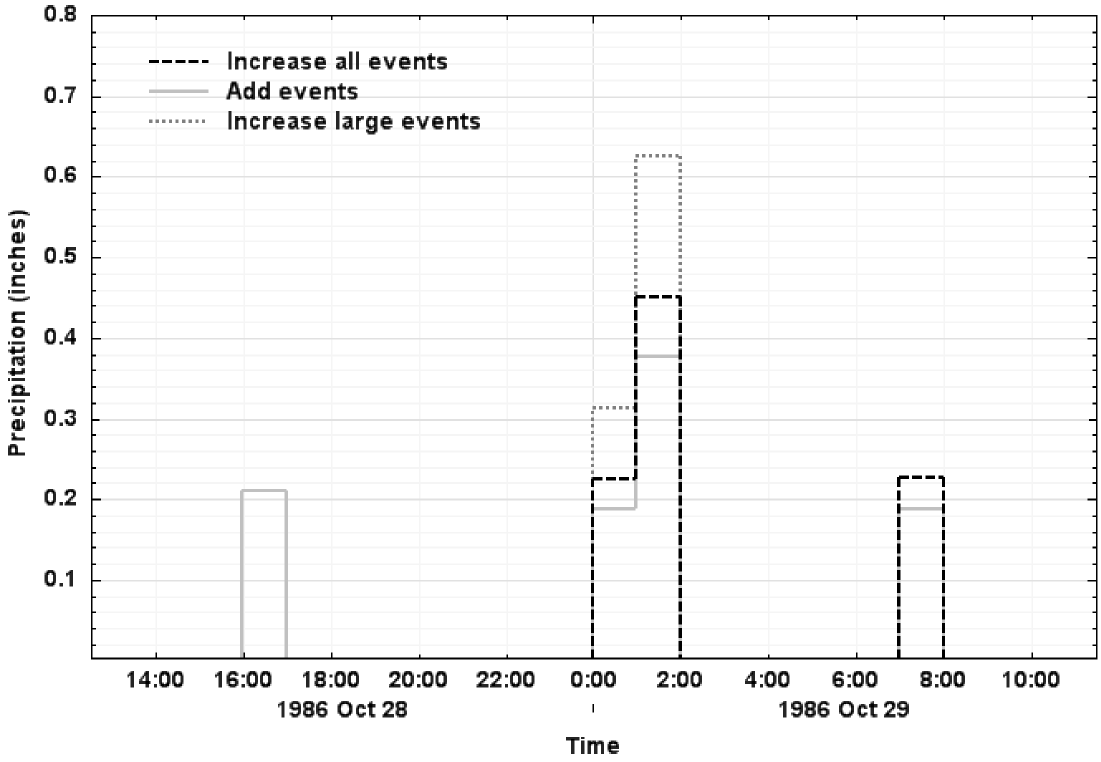


Figure 3.22. Example of precipitation event distribution for the 3 climate change scenarios.

Land-Use Scenarios

Land use scenarios were not evaluated in this case study. While it is unlikely land use in the Tualatin River watershed will not change in the future, land use was held constant in order to focus on potential climate change impacts only.

Management Scenarios

Management scenarios were not specifically evaluated in this case study. BMPs or other management practices may have been included in the original HSPF model, but no adjustments were made in order to focus on potential climate change impacts.

Endpoint Selection

Two water quality constituents, TSS and TN, and one water quantity constituent, mean annual streamflow, were selected as the analysis endpoints.

Results

Results for the selected endpoints from all model runs, including values for percent and absolute change in annual precipitation, and the maximum precipitation event during the simulation are presented in Table 3.28. The two annual precipitation volume increases, 10 and 20 percent, are consistent for the three adjustment methods, but the maximum precipitation event depths vary. Temperature adjustments are not included in the table since a constant 2^{o}C temperature increase was included in all model runs.

Table 3.28. Precipitation, streamflow, and loadings of TN and TSS for all climate scenarios.

Scenario	Precipitation volume	Annual precipitation,	Max Precipitation	Mean Streamflow,	Annual load	Annual load

	increase,%	mm	Event, mm	cms	TN, kg/ha	TSS, tonnes/ ha
Baseline	0	1,014	20.2	34.5	17.7	0.50
Frequency	10	1,115	20.2	38.4	19.3	0.57
Constant	10	1,115	22.2	39.3	19.5	0.66
Intensity	10	1,115	26.9	38.6	18.8	0.78
Frequency	20	1,217	20.2	44.2	21.5	0.67
Constant	20	1,217	24.2	45.3	21.6	0.86
Intensity	20	1,217	33.6	43.9	20.2	1.19

The model results show a significant watershed response with all three endpoints increasing under all climate change scenarios. The results also indicate that the different precipitation patterns have varying degrees of impact on the endpoints. Streamflow shows the largest response to the constant increase, followed by the frequency increase, and then the intensity increase. Similarly, TN is less impacted by the intensity increase with more substantial, and very similar, responses from the constant increase and the frequency increase.

TSS was found to be highly sensitive to the climate change scenarios, but responded differently than TN and streamflow (Figure 3.23). The frequency increases yielded a 14 and 35 percent increase in TSS for the 10 and 20 percent scenarios, respectively. The responses to the constant increases are more substantial (33 and 74 percent, respectively) and the increases in TSS in response to the intensity increases are nearly double those of the constant increase (57 and 140 percent, respectively). These results indicate that all precipitation scenarios increase TSS loads, however, increasing event intensity has the greatest potential impact.

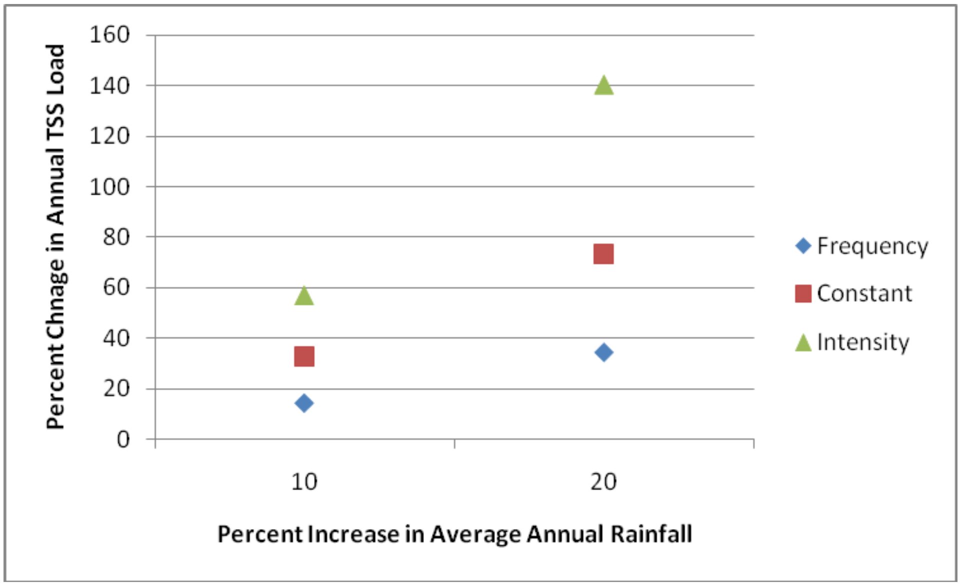


Figure 3.23. Percent change in TSS loads relative to baseline for all climate change scenarios.

Summary

This case study demonstrated three different ways BASINS CAT can adjust precipitation records to represent potential changes in climate. Mean annual volume increases of 10 and 20 percent were applied to baseline precipitation records using three different methods: constant increase of all events, increase of event frequency, and increase in event intensity of the largest 30 percent of events. Temperature was also adjusted to reflect projected changes.

This study illustrates the sensitivity of a watershed to changing precipitation patterns and highlights the variation in response to these different adjustments. The results indicate that even if annual precipitation volume remains constant, how and when it occurs makes a difference in watershed response. Of particular note was the response of TSS loads to different levels of event intensification. Given the dramatic response in TSS loading to precipitation intensity, additional scenarios could be run to further explore these relationships including more detailed analysis of TSS response to changes in specific events, and the effects of adding seasonal variability of changes (e.g., monthly)(see the Section 3.2). The analysis of additional endpoints, either in the form of new constituents (e.g. total P) or hydrologic response (e.g. peak flow value) may also provide further insights to watershed sensitivity to changing precipitation patterns.

3.6. Streamflow sensitivity to dry weather events in Sespe Creek, CA, using BASINS CAT with HSPF

Case Study Overview:

This case study used BASINS CAT with an HSPF watershed model of Sespe Creek, CA, to examine the sensitivity of streamflow to changes in magnitude and duration of dry weather events (meteorological drought). A dry period in the historical observation record was selected to create a series of climate scenarios. BASINS CAT was used to develop climate scenarios that increased average annual temperatures by 2°C and altered precipitation in the following way:

- Increased the magnitude of a historical dry period (1959-1961) by adjusting annual precipitation volume by 0, -10, and -20 percent
- Extended the duration of the historical dry period to include the years 1959-1964 by reducing precipitation in wet years that followed the 1959-1961 dry period
- Increased the magnitude and extend the duration of the dry period to include the years 1959-1964

Introduction

Managing the impacts of drought on water supply is an important goal of watershed management. Climate change in many parts of the nation could result in warmer, dryer conditions leading to increased drought risk. Responding to this challenge will require an improved understanding of the implications of climate change for drought, and the development of management strategies for reducing the impacts of drought.

In this case study, BASINS CAT and an HSPF watershed model were used to assess the sensitivity of water supply to increased severity of dry weather events (meteorological drought) in Sespe Creek, CA. In the context of this case study, we defined drought severity to include the magnitude and duration of precipitation deficit. The simulation endpoints evaluated include mean annual and low-flow streamflow statistics.

Location Description

The Sespe Creek watershed (Figure 3.24) covers an area of approximately 700 km^2 in southwestern California, with its headwaters near the Ventura-Santa Barbara county line. It flows east through relatively pristine, mountainous and remote terrain of the Los Padres National Forest. Then it bends south through a bedrock-confining gorge before widening out into a broad alluvial fan near the City of Fillmore until its confluence with the Santa Clara River. Elevations range from more than 2,000 m in the headwaters and upper reaches to about 120 m above mean sea level at the mouth. The typical hydrologic pattern includes peak flows in late winter/early spring in response to winter rains and spring snowmelt followed by very dry conditions in summer and fall. The watershed is primarily undeveloped, with dominant land uses being forest and shrub land (Table 3.29).

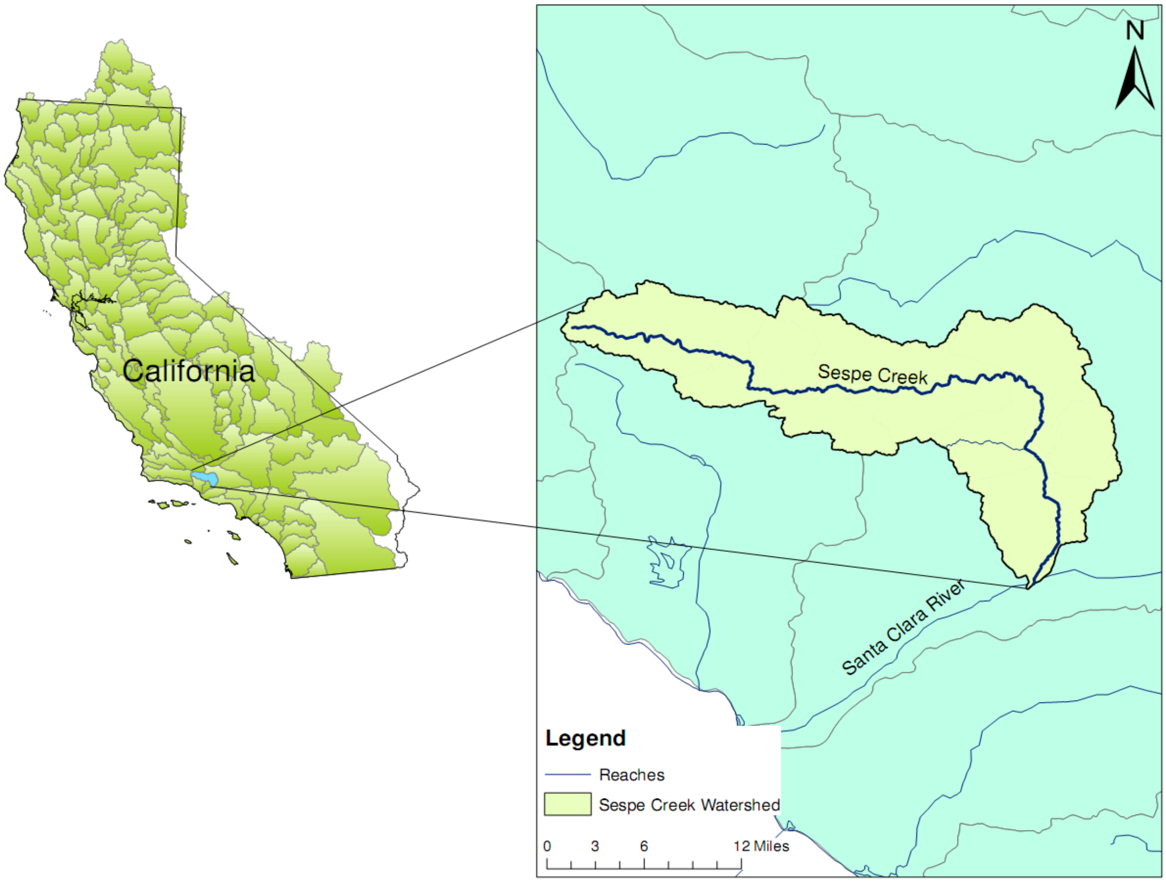


Figure 3.24. Location of the Sespe Creek watershed.

Table 3.29. Land use summary for Sespe Creek watershed.

Land Use	Portion of Watershed, %
Forest	14
Shrub	80
Open/Grassland	3
Agriculture	2
Developed	1

Model Setup

The Sespe Creek model was extracted from a larger HSPF model of the Santa Clara River (AQUA TERRA Consultants, 2009). This model was developed as part of the Santa Clara River Watershed Management effort, a joint effort by Ventura County Watershed Protection District, Los Angeles County Department of Public Works and U.S. Army Corp of Engineers Los Angeles District. As part of this effort, the Sespe Creek portion of the model was calibrated to historic streamflow data for the period of 10/1/1997 through 9/30/2005, and validated for 10/1/1987 through 9/30/1996. Statistical results of the calibration/validation are shown in Table 3.30. For this case study, the model was run for the period 1952 – 2001 in order to include a wide range of hydrologic conditions and at least one significant period of low flow.

Table 3.30. Streamflow volume (normalized by watershed area) calibration and validation results for Sespe Creek model.

Gage		**Wheeler Springs**		**Fillmore**	
		Calibration (10/1/02 – 9/30/05)	**Validation (10/1/86 – 9/30/96)**	**Calibration (10/1/96 – 9/30/05)**	**Validation (10/1/93 – 9/30/96)**
Streamflow (cms)	**Simulated**	24.9	18.3	26.2	26.7
	Observed	22.6	18.5	27.7	24.9
Volume Error (%)		9.5	-1	-6.1	7
Daily	**R**	0.95	0.91	0.96	0.92
	$\mathbf{R^2}$	0.91	0.82	0.92	0.84
Monthly	**R**	0.98	0.98	0.99	0.97
	$\mathbf{R^2}$	0.97	0.96	0.98	0.94
Daily Peak Difference (%)		4.7	3.8	-5.5	9.6

The original Sespe Creek model made use of observed pan evaporation data as the potential evapotranspiration (PET) input term required by HSPF. It was necessary to replace the observed pan data with computed PET that could be regenerated by BASINS CAT for each future simulation in order to better represent the impact of future temperature adjustments on PET. This was accomplished using the ***Penman-Monteith option*** for estimating PET in BASINS CAT. The baseline model was run using the PET generated by BASINS CAT in place of the observed pan evaporation data. Using BASINS analysis tools, results from the modified model were compared to the original. Differences in total and mean streamflow volumes were less than 1%, differences in the lowest 10% of streamflow was 3%, and the difference in the highest 1% of streamflow was 2%. The original model calibration was thus considered acceptable for use in the case study.

Scenario Development

A total of 6 model simulations were completed. Scenarios included 1 baseline climate scenario and 5 climate change scenarios. No land use or management scenarios were included.

Climate Change Scenarios

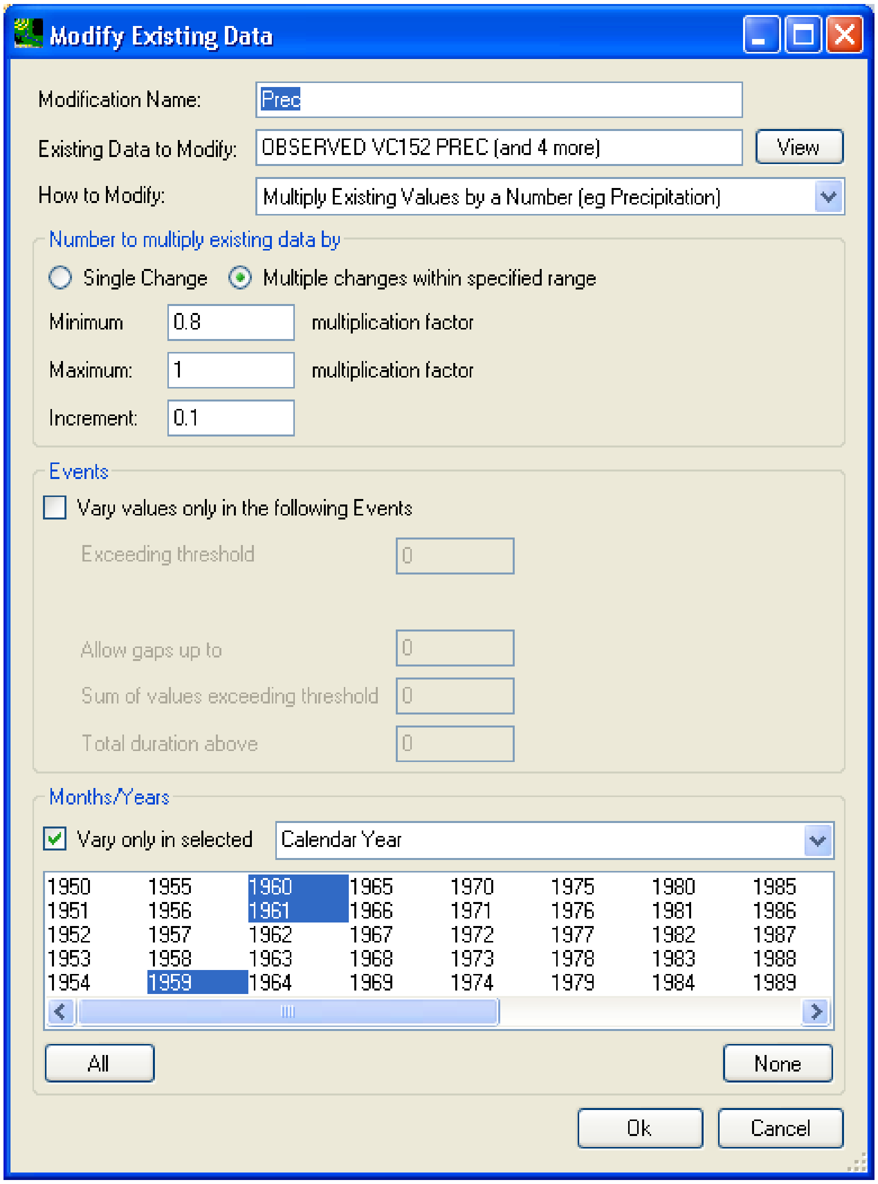
Climate change scenarios were developed to fall within the ensemble range of projected mid-century (2050s) temperature and precipitation changes for this region based on statistically downscaled data from 16 CMIP3 climate models acquired from the ClimateWizard web site (see Section 3.2 for more information on these models). Projected mid-century changes in temperature for this region ranged from approximately 1°C to 3°C, and projected changes in precipitation ranged from approximately -40 to +35 percent.

A total of 5 climate change scenarios were created to represent increased drought severity including increased magnitude and duration of precipitation deficit. Each climate change scenario included an increase of 2°C applied to all daily temperature values in the baseline record from 1952-2001 to represent projected changes in temperature for this region. Potential evapotranspiration (PET) records were revised to account for temperature changes using the Penman-Montieth method. Analysis of annual observed streamflow in Sespe Creek from 1950 to present day showed that the period from 1959 – 1961 represented a prolonged period of low flow. The first 3 climate change scenarios represented changes in the magnitude of dry weather events and were created as follows:

- Decreased precipitation by 20 percent during the observed low flow period 1959-1961, identified hereafter as “Precip -20”

- Decreased precipitation by 10 percent during the observed low flow period 1959-1961, identified hereafter as “Precip -10”
- Maintained historic precipitation during the observed low flow period 1959-1961 (thus representing the impact of the 2^{o}C temperature change only), identified hereafter as “Precip 0”

Figure 3.25 shows the BASINS CAT window used to create the precipitation adjustments in the three climate change scenarios. The three fields at the top define which input records will be adjusted and by what method (i.e. “Multiply Existing Values …”). The BASINS CAT capability for creating ***multiple changes within a user specified range*** was made to produce the three adjustments. The bottom frame defines the time of year (***Months/Years***) during which the adjustments were applied (e.g., 1959 – 1961). BASINS CAT was then used to combine these three precipitation adjustments with the temperature and PET adjustments described above to create three scenarios of varying drought severity.


Modify Existing Data

Modification Name: Prec

Existing Data to Modify: OBSERVED VC152 PREC (and 4 more)

How to Modify: Multiply Existing Values by a Number (eg Precipitation)

Number to multiply existing data by

○ Single Change ● Multiple changes within specified range

Minimum 0.8 multiplication factor

Maximum: 1 multiplication factor

Increment: 0.1

Events

☐ Vary values only in the following Events

Exceeding threshold 0

Allow gaps up to 0

Sum of values exceeding threshold 0

Total duration above 0

Months/Years

☑ Vary only in selected Calendar Year

1950 1955 1960 1965 1970 1975 1980 1985
1951 1956 1961 1966 1971 1976 1981 1986
1952 1957 1962 1967 1972 1977 1982 1987
1953 1958 1963 1968 1973 1978 1983 1988
1954 1959 1964 1969 1974 1979 1984 1989

Figure 3.25. BASINS CAT window defining adjustments to precipitation.

The fourth scenario represented increased drought duration (hereafter referred to as “Duration”). The dry period of 1959 – 1961 was followed by two years of more typical precipitation. This was followed by another dry year in 1964. The original 3-year dry period was extended by adjusting the years 1962 – 1963 to follow the trend of the years directly preceding and following them. This was done by applying a constant multiplier to all events in 1962 and 1963 such that their mean annual precipitation matched the mean annual totals of 1961 and 1964. This adjustment, combined with the temperature and PET adjustments described above, led to a simulated drought period of six years (1959-1964). The fifth and final scenario represented both increased drought severity and increased duration (hereafter referred to as “Duration/Severity”). This scenario was created using the same adjustments as in the fourth scenario to increase duration, together with a 10% precipitation decrease applied to all six years of the extended drought period to represent increased drought severity.

Land Use Scenarios

Land use scenarios were not evaluated in this case study. While it is unlikely that land use in the Sespe Creek watershed will not change in the future, land use and land cover was held constant in order to focus on potential climate change impacts.

Management Scenarios

Management scenarios were not specifically evaluated in this case study. BMPs or other management practices may have been included in the original HSPF model, but no adjustments were made in order to focus on potential climate change impacts.

Endpoint Selection

The simulation endpoints considered in this case study were mean annual streamflow and mean annual 7-day low flow. Additionally, mean monthly streamflow values from each scenario were plotted for comparison. For some analyses, endpoint values were computed only for the scenario’s period of intensified drought (1959 – 1961 or 1959 – 1964) to more clearly understand the scenario’s impact.

Results

Endpoint values for all model simulations are presented in Tables 3.31 and 3.32. Table 3.31 shows results for the drought severity scenarios, where temperature increase was applied to the entire run and precipitation adjustments were applied only to the period 1959 – 1961. Table 3.32 shows results for scenarios where the drought was intensified by increasing the duration (1959 – 1964) and then reducing rainfall during this period by 10 percent. For both tables, endpoint results are reported only for their respective drought periods as the mean annual endpoints were only minimally impacted over the length of the entire simulation period (1952 – 2001).

Results from Table 3.31 show that changing only the temperature (“Precip 0” scenario) caused only a slight decrease (roughly 5 percent) in the two endpoints. However, combining the temperature change with decreases in precipitation during the dry period of 1959 – 1961 had a significant impact on the endpoints. Decreasing precipitation by 10 percent (“Precip -10” scenario) led to decreases from the baseline in mean annual streamflow and mean annual 7-day low flow of 38 and 30 percent, respectively. For the 20 percent precipitation decrease (“Precip -20” scenario), decreases from the baseline were 62 percent for mean annual streamflow and 39 percent for mean annual 7-day low flow.

Table 3.31. Simulation results for the Precip 0, Precip -10 and Precip -20 scenarios as applied to historic period of low flow (1959-1961) .

Scenario	Change in Temp °C	Change in Precipitation %	Mean Annual Streamflow (1959-1961) cms	Mean Annual 7-Day Low Flow (1959-1961) cms
Baseline	0	0	12.6	0.612
Precip 0	2	0	12.1	0.584
Precip -10	2	-10	7.83	0.427
Precip -20	2	-20	4.85	0.374

Results in Table 3.32 also show dramatic change in endpoint values in response to the Duration and Duration/Severity scenarios. Adjusting the precipitation record for the years 1962 - 1963 (normal rainfall) to match the mean of years of 1961 and 1964 (low rainfall) and extending the dry period to 1959 to 1964 led to a significant decrease from baseline conditions for all simulated scenarios. Mean annual streamflow in the Duration scenario decreased by 61 percent and mean annual 7-day low flow decreased by 43 percent for the extended drought period. Furthering the severity of the extended drought by applying a 0.9 precipitation multiplier (Duration/Severity scenario), led to an additional 13 percent decrease in mean annual streamflow and an additional 12 percent decrease in mean annual 7-day low flow.

Table 3.32. Simulation results for the Duration and Duration/Severity scenarios as applied to the extended period of low flow (1959-1964).

Scenario	Change in Temp, °C	Change in Precipitation, %	Mean Annual Streamflow (1959-1964) cms	Mean Annual 7-Day Low Flow (1959-1964) cms
Baseline	0	0	48.6	1.41
Duration	2	0	19.0	0.80
Duration and Severity	2	-10	12.8	0.63

Using the BASINS CAT option to save input and output files for all simulations, BASINS analysis tools were used to generate a plot of mean monthly streamflow for each scenario (Figure 3.26). This plot provides further insight into the results in Tables 3.31 and 3.32. While the Duration/Severity scenario yielded the greatest decrease from baseline values, it is notable that endpoint values from this scenario (final row of Table 3.32) were still higher than baseline values for the original drought period (first row of Table 3.31). . The Duration and Duration/Severity scenarios were developed by decreasing all rainfall events in 1962 – 1963 by the same amount, the early 1962 precipitation still remained substantial and led to significantly increased streamflow (see 'Duration' and 'Duration/Severity' curves in plot). Thus, the mean annual streamflow and mean annual stream flow and 7-day low flow values for these scenarios remained at levels above the original baseline drought.

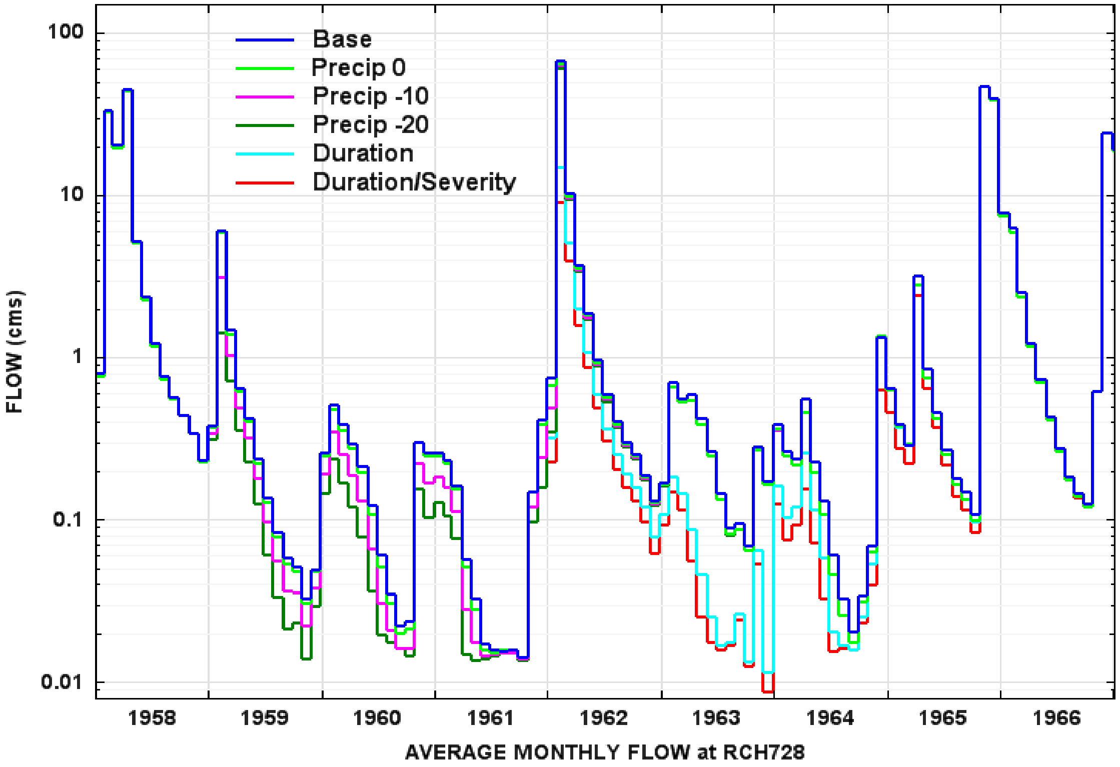


Figure 3.26. Mean monthly streamflow during drought period for all scenarios.

Summary

This case study illustrates the sensitivity of streamflow to potential increases in drought severity resulting from climate change. A baseline low flow period was selected from the historic streamflow record. This drought was then intensified in 3 different ways. First, the severity of the drought was increased by increasing the mean annual temperature and decreasing annual precipitation. The drought duration was then lengthened by reducing precipitation in two consecutive, relatively wet years occurring mid-way within the selected period of drought. Finally, these two adjustments were combined by decreasing precipitation during the entire, extended drought period. The endpoints of mean annual streamflow and 7-day low flow responded as expected with significant decreases from baseline values for all simulations.

Several BASINS CAT features were used to create the intensified drought scenarios. First, the ability to modify specific time span subsets allowed for precipitation changes to be applied only during drought periods. Second, the capability for creating ***multiple changes within a user specified range*** was used to decrease precipitation. Finally, the ability to combine adjustments was used to create the scenario where both drought duration and severity were increased. BASINS CAT was used to assess changes in mean annual streamflow and 7-day low flow in this study, but the tool has the ability to generate and report any desired duration-frequency event (7Q10, 100-year flood) or any n-day high or low flow time series percentile. BASINS CAT can also report such values for specific time periods.

3.7. Streamflow and water quality relative sensitivity to climate change versus impervious ground cover in the Western Branch of the Patuxent River, MD, using BASINS CAT with HSPF

Cast Study Overview:

This study evaluated the role of impervious cover in managing stormwater under increased precipitation volume and event intensity using BASINS CAT with an HSPF model of the Western Branch of the Patuxent River, MD. The sensitivity of stormwater runoff generation and pollutant loads, specifically TSS, was explored through a combinations of the following land use and climate change scenarios::

- watershed impervious cover of 8.6, 15, and 25 percent
- increased precipitation volume of all events by 0, 10 and 20 percent
- increased event intensity of 70th percentile and greater events by 0, 10 ,and 20 percent

Introduction

Urban and suburban development of watersheds results in increased impervious cover in the form of houses, parking lots, roads, and sidewalks. Impervious cover disrupts aspects of the pre-development hydrologic conditions which affect the health and integrity of local waterways. Many of the effects are interrelated and often difficult to quantify, but two of the most significant causes of the impairment of urban streams are increased stormwater runoff and runoff pollution.

Changes in local and regional climate may increase the frequency and intensity of heavy storm events leading to substantial increases in stormwater runoff, pollutant loads, and flooding. There is also the potential for synergy among climate and land use changes, exacerbating the impact of urbanization, leading to increases in the amount of runoff and water quality impacts on surface water. An investigation of the relationships between climate change and urbanization can provide a simple, heuristic understanding of how reductions in impervious cover could be used to compensate for increased stormwater runoff associated with climate change (Pyke et al., 2011).

BASINS CAT was used with an HSPF model of the Western Branch of the Patuxent River, MD to assess the relative sensitivity of stormwater to changes in precipitation volume, event intensity, and impervious cover. The BASINS CAT capability for creating ***multiple changes within a user specified range*** was used to create an array of climate scenarios for use as model inputs. The model simulations were used to develop a simple heuristic model for exploring land use-based climate change adaptation options.

Location Description

The Western Branch of the Patuxent River (HUC 02060006) drains an area of 230 km^2 east of Washington D.C., and is a tributary of the Patuxent River and Chesapeake Bay (Figure 3.27). Land use is mixed, consisting of agricultural, forest, barren, wetlands and urban land uses (Table 3.33).

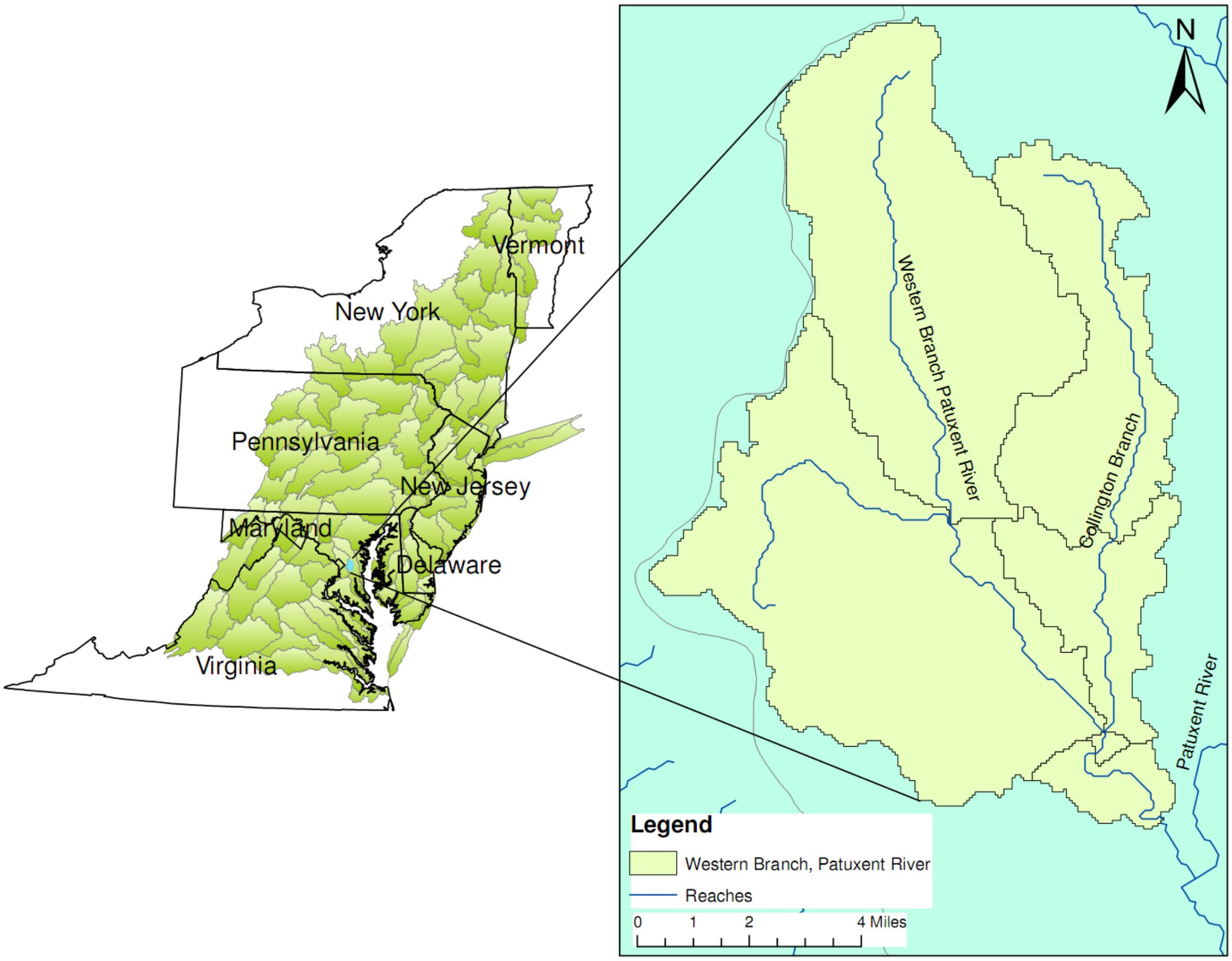


Figure 3.27. The Western Branch of the Patuxent River watershed and its location with the Chesapeake Bay watershed.

Table 3.33. Land use summary for Western Branch of the Patuxent River watershed.

Land Use	Portion of Watershed, %
Forest	39
Urban/Developed	34
Agricultural	25
Wetland	2
Barren	< 1

Model Setup

The Western Branch of the Patuxent HSPF model used in this case study is based upon a model of the Patuxent River watershed developed during the early 1990s for the USGS and the state of Maryland (AQUA TERRA Consultants, 1994) and subsequently modified for other projects. For this project the NLCD 2001 land cover was used, replacing the GIRAS land use land cover data from BASINS used in earlier versions of the model. The period from 10/1/1985 through 9/30/2005 was chosen for the simulation based on available meteorological data.

Model calibration and validation checks were performed since this case study required some modifications to the original HSPF model. The calibration and validation efforts for this case study were not as extensive as in the original full-modeling study given the scope of this project; they were completed to check that the case study model would yield reasonable results. The calibration period was kept the same as the earlier model, 10/1/1985 through 9/30/1988. The USGS gage on the West Branch has a gap in observed data in the early 1990s so that period could not be used for calibration/validation checks. Accordingly, available streamflow and meteorological datasets for the time period of 10/1/1995 – 9/30/2005 were used for model validation.

The calibration checks for streamflow show monthly R^2 values of 0.74 for the calibration period and 0.81 for the validation period (Table 3.34). The hydrology simulation for the validation period appears better than for the calibration period, which is likely a factor of the validation period being considerably longer. The overall flow balances are very good, with errors in total volume less than 1 percent, and the storm peaks are well simulated, with errors less than 6 percent for calibration and nearly 2 percent for validation.

Table 3.34. Selected Western Branch hydrology model calibration/validation statistics. NSE: Nash-Sutcliffe Efficiency coefficient

	Calibration	**Validation**
Daily R^2	0.50	0.56
Daily NSE	0.47	0.52
Monthly R^2	0.74	0.81
Monthly NSE	0.73	0.81
% Error in Total Volume	-0.9	0.9
% Error in Storm Peaks	-5.8	2.1

Limited data was available for calibrating TSS on the Western Branch, but a time series plot of the simulated and observed TSS concentrations shows that the simulation captures the overall range and distribution of TSS concentrations at the sampling location (Figure 3.28). While these checks should not be construed as a complete calibration, the model was deemed appropriate for representing the relative change across various model input scenarios.

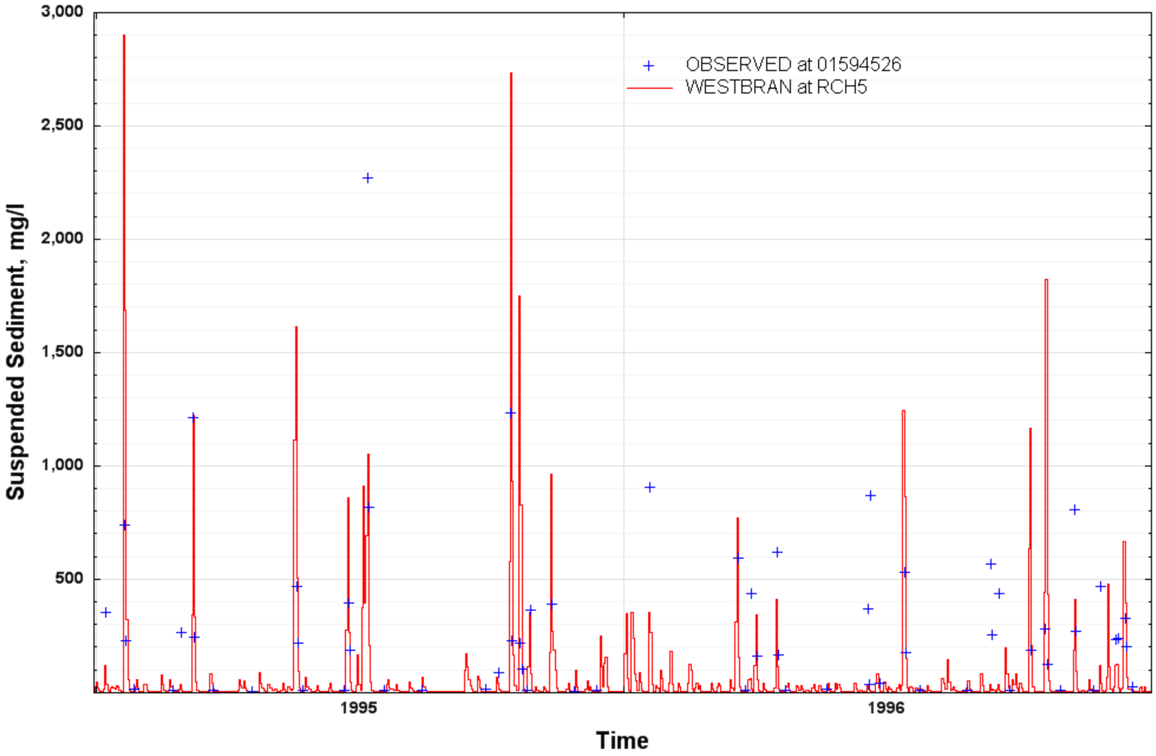


Figure 3.28. Measured and simulated TSS concentrations (mg/L) in the Western Branch of the Patuxent River watershed.

Scenario Development

A total of 9 model simulations were completed. Scenarios included 6 climate change scenarios and 3 land use scenarios. No management scenarios were included.

Climate Change Scenarios

Climate change scenarios for this case study represented changes to precipitation only. No temperature adjustments were made. Climate change scenarios were developed using an ensemble of 16 CMIP3 statistically downscaled climate models presented in ClimateWizard (See Section 3.2 for more information on these models). A plausible end-of-century range of climate change for this region was determined to be 0 to 20 percent increase in mean annual precipitation. The scenarios were developed to explore various changes in precipitation patterns. Three scenarios reflected changes in precipitation volume:

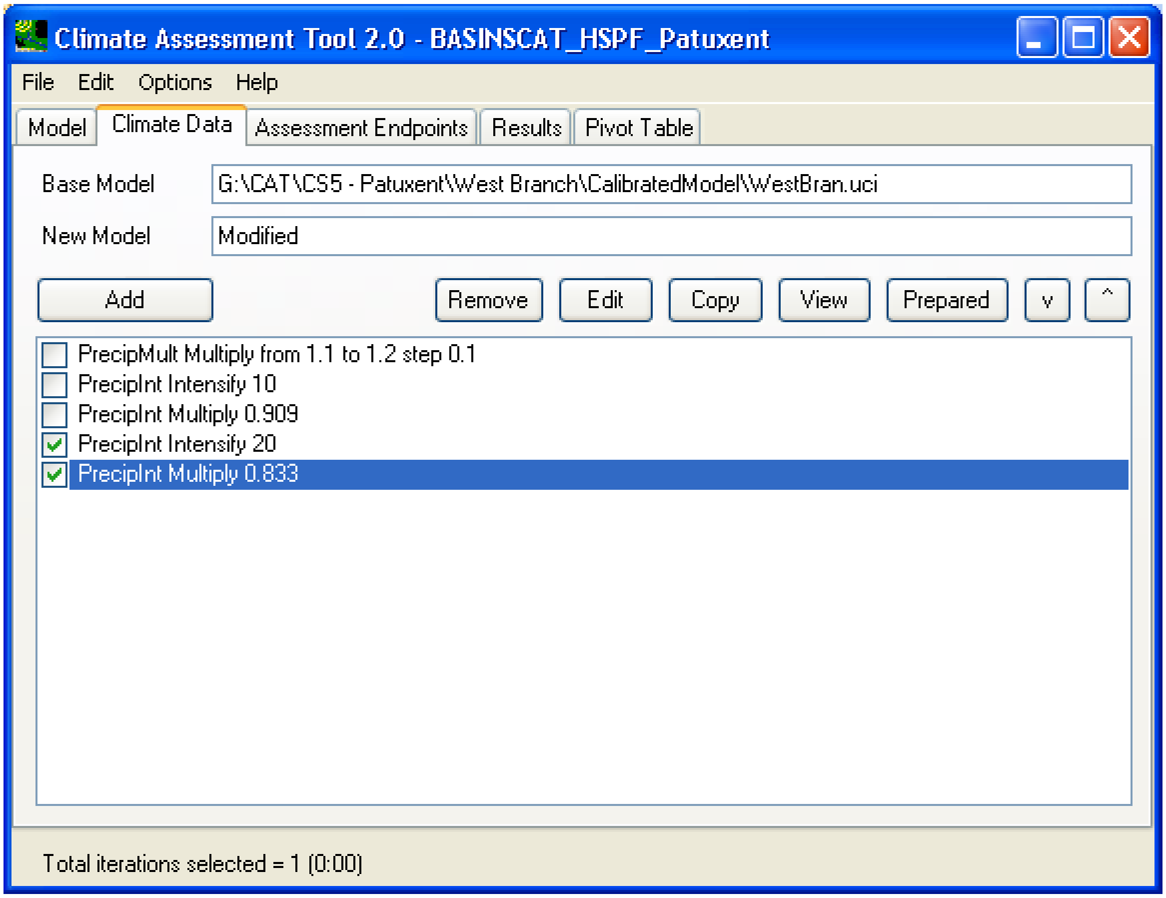
- Increase event values by 0% for all years on record
- Increase event values by 10% for all years on record
- Increase event values by 20% for all years on record

Three scenarios reflected changes in event intensity, where the proportion of annual precipitation occurring in events above the 70th percentile was increased while events below this threshold were decreased to create no net change in annual volume:

- Increase volume of events above the 70th percentile event by 0%

- Increase volume of events above the 70th percentile event by 10% and decrease volume of events below threshold event to maintain mean annual precipitation
- Increase volume of events above the 70th percentile event by 20% and decrease volume of events below threshold event to maintain mean annual precipitation

The creation of these scenarios was facilitated by the BASINS CAT capability for combining multiple adjustments to meteorological time series to create complex scenarios. Figure 3.29 shows the selection of the two adjustments used to develop the 20 percent increase in events above the 70th percentile while maintaining the same total annual precipitation. A total of 6 climate scenarios were developed.



Base Model: G:\CAT\CS5 - Patuxent\West Branch\CalibratedModel\WestBran.uci

New Model: Modified

☐ PrecipMult Multiply from 1.1 to 1.2 step 0.1
☐ PrecipInt Intensify 10
☐ PrecipInt Multiply 0.909
☑ PrecipInt Intensify 20
☑ PrecipInt Multiply 0.833

Total iterations selected = 1 (0:00)

Figure 3.29. Climate change scenario specifications in BASINS CAT.

Land Use Scenarios

Three land use scenarios were developed to simulate current watershed impervious cover and two potential impervious cover futures:

- Current percent impervious, 8.6 percent overall
- Increase the overall percent imperviousness to 15 percent
- Increase the overall percent imperviousness to 25 percent

The increases in impervious cover were obtained through a proportional decrease in each pervious land use category. These percent increases in impervious land were obtained by shifting land use primarily from forest and agriculture to urban, as well as an increase in the amount of urban land that is considered impervious (as increased urban density). The choice of 15 and 25 percent imperviousness for the future scenarios is not based on local information, but falls within the range for moderate to highly developed watersheds in the mid-Atlantic region (USEPA, 2009b). Table 3.35 shows the percentages of each land use category for each of the three land use scenarios.

Table 3.35. Summary of W.B. Patuxent land use composition by category for each land use change scenario.

Land Use	Scenario 8.6% Impervious	Scenario 15% Impervious	Scenario 25% Impervious
Forest	39	36	32
Urban/Developed	34	39	46
Agricultural	25	23	20
Wetland	2	2	2
Barren	<1	< 1	< 1

Management Scenarios
Management scenarios were not evaluated in this case study.

Endpoint Selection

The endpoints for this study consisted of average annual streamflow and mean annual TSS loads. Given the goal of assessing the relative sensitivity of stormwater to changes in precipitation volume, event intensity, and site impervious cover, a focus on streamflow is appropriate along with TSS loads since both are generally impacted as a result of these factors.

Results

Model simulation results for mean annual streamflow and TSS loads are shown in Table 3.36. Percent changes are expressed relative to the baseline conditions: 0 percent increase in precipitation volume, 0 percent increase in precipitation intensity, and 8.6 percent impervious cover. Simulations indicated that streamflow in the Western Branch watershed is the most sensitive to increases in precipitation volume. A 20 percent increase in overall precipitation volume leads to a 46.3 percent increase in mean annual streamflow. Increases in impervious cover also resulted in significant changes to mean annual streamflow. Increases in precipitation intensity did not have nearly as large an effect on mean annual streamflow as did increases in precipitation volume and impervious cover.

These simulations indicated that TSS loads in the Western Branch watershed are the most sensitive to increases in precipitation volume. A 20 percent increase in overall precipitation volume led to a 62 percent increase in annual TSS load. A major increase in TSS load was also shown resulting from increases in precipitation intensity. Results also indicated that increases to impervious cover actually decreased the annual TSS loading.

Table 3.36. Annual streamflow and TSS load characteristics for the Western Branch of the Patuxent scenarios

Scenario	Increase, %	Mean Annual Streamflow, cms	Change in Mean Annual Streamflow, %	Mean Annual TSS Load, tonnes/ha	Change in Mean Annual TSS Load (%)
Precipitation Volume	0	2.8	--	0.06	--
	10	3.4	22	0.07	31
	20	4.1	46	0.09	62

Precipitation Intensity	0	2.8	--	0.06	--
	10	2.9	3	0.07	21
	20	3.0	6	0.08	40
Impervious Cover	8.6	2.8	--	0.06	--
	15	3.1	11	0.05	-4
	25	3.6	28	0.05	-10

Figure 3.30 shows the changes in stormwater runoff associated with changes in impervious cover (holding precipitation volume and intensity constant), precipitation volume (holding impervious cover and precipitation intensity constant), and precipitation intensity (holding impervious cover and precipitation volume constant). These results, though based on limited data, suggest that when expressed on a constant percent basis, mean annual stormwater runoff is most sensitive to changes in precipitation volume, followed by changes in impervious cover and precipitation intensity.

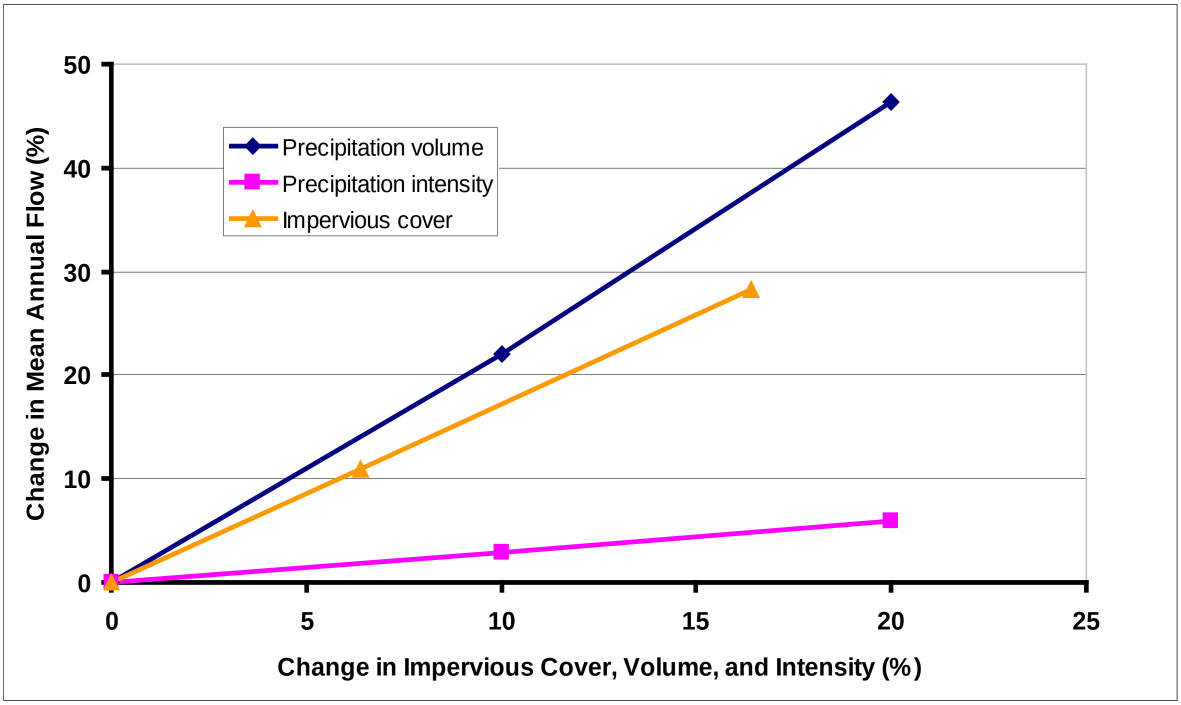


Figure 3.30. Simulated sensitivity of stormwater runoff volume to changes in impervious cover, precipitation volume, and precipitation intensity.

Similarly, Figure 3.31 shows the changes in TSS load associated with changes in impervious cover, precipitation volume, and precipitation intensity. The results suggested that when expressed on a constant percent basis mean annual TSS loads are most sensitive to changes in precipitation volume followed by changes in precipitation intensity. Mean annual TSS load is inversely related to changes in impervious cover. It should be noted that TSS loading from developed land is complex, and the relationship seen here is not universal. The observed inverse relationship in these simulations likely resulted from the conversion of primarily agricultural land to urban/suburban land. The conversion of forested land to urban/suburban is likely to increase TSS loads. Moreover, newly developed land with significant new construction and exposed soil can result in equal or greater loading than agricultural land.

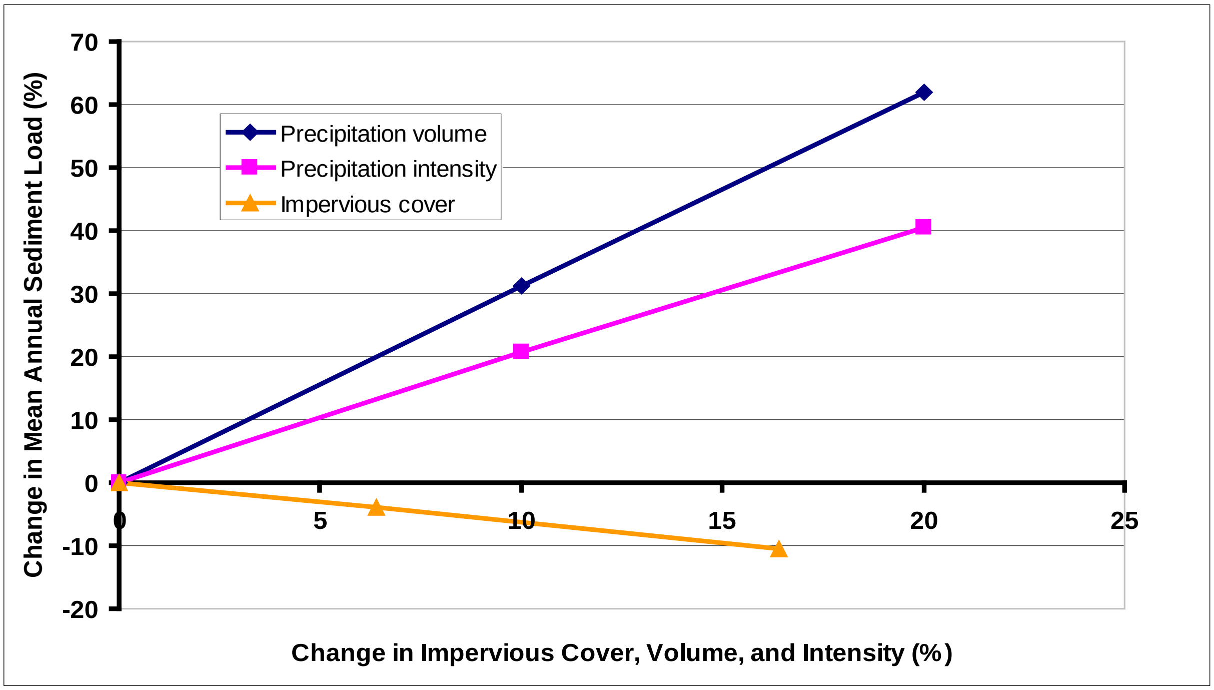


Figure 3.31. Simulated sensitivity of TSS load to changes in impervious cover, precipitation volume, and precipitation intensity.

Summary

This study assessed the relative sensitivity of streamflow and TSS pollution to changes in precipitation volume, event intensity and site impervious cover for a mixed-use watershed in Maryland. The primary BASINS CAT feature demonstrated in this study was the ability to synthetically adjust climate inputs for watershed models. This allowed an array of climate change scenarios to be automatically generated and used as input for model runs. This case study also demonstrates the approach of combining climate change scenarios with land use change scenarios. While the climate change and land use scenarios applied were relatively simple, they were effective in illustrating some basic points.

The results indicated that mean annual streamflow in the Western Branch watershed is more sensitive to changes in precipitation volume and impervious cover than they are to event intensity. In addition, TSS loads in this watershed are more sensitive to annual precipitation volume and event intensity versus impervious cover. While the most extreme changes yielded dramatic changes in endpoint results, even relatively minor changes had notable impacts on either mean annual streamflow or annual TSS load, or both. It should also be noted that while increasing impervious cover leads to higher mean annual streamflow, it may actually lead to decreased TSS loads, likely due to agricultural land being converted to urban uses.

This case study illustrates the potential synergy of climate change and urbanization with respect to stormwater runoff and water quality impacts. Management practices such as low-impact development that reduce impervious cover could be used to compensate for increased stormwater runoff associated with climate change. In short, this study illustrates an important concept for water planners: that improved development strategies have the potential to reduce or offset the effects of climate change.

3.8. Limitations of Case Study Simulations

The case studies in this report illustrate selected capabilities of the BASINS and WEPP climate assessment tools for conducting scenario-based assessment of watershed response to changes in climate, land-use, and management practices. The scientific approach supported by these tools, i.e., scenario analysis, can be useful for understanding system behaviour, identifying vulnerabilities, and evaluating the effectiveness of management responses to inform management decision making. The tools presented in this report, however, are just one step forward in building our capacity for understanding and responding to climate change. Application of hydrologic models in this way has limitations, many of which are not well understood (Ghosh 2010; Ludwig, 2009; Najafi, 2011; Vaze et al., 2010). Further study is required to better assess, refine, and develop our current modeling capabilities. The following discussion briefly identifies several issues, current limitations, and future needs associated with the use of hydrologic models for climate change impacts assessment.

Use of a calibrated hydrologic model to conduct analyses assumes that change scenarios do not alter watershed behavior in a way that invalidates the model parameterization achieved through calibration. This issue exists in any modeling analysis (Donigian 2002, 2003), but is of particular concern when considering climate change scenarios (Vaze et al., 2010). In many cases, climate change scenarios will fall outside the range of historical observations used to calibrate the model. It is reasonable to assume that at some point, large changes imposed by scenarios will affect model calibration. It is difficult to know where this point is, however, or what the implications are for results. BASINS CAT and WEPPCAT, for the most part, impose no constraints on the type and magnitude of climate changes made. Users must therefore be cautious to consider the validity of model simulations, particularly when assessing change scenarios falling outside the range of observed climatic variability.

At the decadal scale, climate change may alter groundwater storage and recharge potentially impacting streamflow and water quality. The HSPF and SWAT models contain simple representations of the shallow groundwater system, including percolation recharge, storage, discharge to streams, losses to deep aquifers, and loading of pollutants such as nitrate. While these representations are adequate for the simulation of surface water hydrology in most watersheds, the models do not provide a complete representation of groundwater pathways because exchanges with deeper aquifers are not explicitly simulated. Where these exchanges with deeper aquifers are represented in the models they are typically held constant and their sensitivity to climate change is not simulated. Thus, a complete picture of any long-term trends attributable to future climate may not be fully represented by a given watershed model. Future research is needed to better understand the long-term impacts of climate change on groundwater, and to better represent these effects in watershed models.

Evapotranspiration (ET) is a major component of the water budget that is directly sensitive to climate. ET is also strongly influenced by land cover, which is in turn influenced by climate. Changes in ET have a significant influence on the occurrence, distribution, and movement of water including soil moisture, groundwater recharge, and streamflow. The method used to calculate ET, or more commonly the reference potential evapotranspiration (PET), is thus a key process in simulating the watershed response to climate change. The models in the case studies each have one or more options for representing PET. Many watershed modeling efforts perform well with simplified approaches to estimating PET, such as the Hamon method, which depends primarily on temperature. The robustness of watershed model calibrations conducted with simplified PET is suspect under conditions of climate change, since a variety of other factors that influence PET, such as wind speed, relative humidity, and cloud cover, are also likely to change. It is advisable to use a full energy balance method for PET, such as Penman-Monteith PET (Jensen et al. 1990), yet little is known about the proper specification of climate-altered input variables such as wind and solar radiation. Further research is needed to improve these capabilities.

Atmospheric concentration of carbon dioxide (CO_2) is a direct driver of climate change. Atmospheric CO_2 concentrations have increased steadily throughout the last century. The trajectory of future CO_2 concentration will vary depending on human efforts to reduce emissions, but could plausibly exceed 500 ppm (per volume) by 2050 (compared to about 370 ppm per volume in 2000). Increases in atmospheric CO_2 concentrations effectively reduce the stomatal conductance of plant leaves, thus reducing water loss through transpiration. Limited research has been conducted on the potential effects of increased atmospheric CO_2 on ecosystems, but the initial findings indicate that when CO_2 levels increase, ET decreases (Leakey et al. 2009). CO_2 effects on plant growth could also influence nutrient uptake, litter fall, and other processes affecting water quality. Therefore, incorporation of CO2 fertilization into a model is a potentially significant factor affecting simulation of watershed response to climate change. The SWAT watershed model includes a plant growth module that can account for the effects of increased CO_2, but the other models available with BASINS CAT and WEPPCAT do not. Further research is needed to improve our understanding of how changes in atmospheric CO_2 concentrations influence vegetative processes and our capabilities in representing these processes in hydrologic modeling.

4. CONCLUDING COMMENTS

Many communities, states, and the federal government are considering adaptation strategies for reducing the risk of harmful impacts resulting from climate change[6]. Challenges remain, however, concerning how best to incorporate diverse, uncertain, and often conflicting information about future climate change into decision making. Tools and information are needed to help build capacity for understanding and responding to climate change impacts at local scale.

This report is a guide to application of two modeling tools recently developed by U.S. EPA and partners, BASINS CAT and WEPPCAT. BASINS CAT and WEPPCAT are not stand-alone models. Rather, these tools facilitate application of existing water models (HSPF, SWAT, SWMM, and WEPP) to assess questions about climate change impacts. More specifically, each tool provides flexible capabilities for creating user-specified climate change scenarios to address a range of "what-if" questions about the potential effects of climate change on water. This report presents six short case studies designed to illustrate tool capabilities. Each case study presents a real or plausible issue in a specified location, and applies BASINS CAT or WEPPCAT to address or inform upon the problem. Taken together, the six case studies illustrate the use of BASINS CAT and WEPPCAT to address a range of practical, real-world questions of potential interest to water and watershed managers.

Case study simulations illustrate important differences in the sensitivity of streamflow and water quality endpoints to changes in specific climate drivers. Generally, increased precipitation resulted in increased streamflow and pollutant loads. The response to increased precipitation was found to be reduced or even reversed, however, by increased evapotranspiration that resulted from increased annual temperatures. Increased temperature combined with reduced precipitation resulted in consistent decreases in streamflow. An awareness of these subtleties in the response of different streamflow and water quality endpoints to specific types of climate change highlights the need for improved understanding of system behavior, and in turn, the difficulty in developing quantitative predictions of future change.

Some of the most difficult questions that water and watershed managers will likely face regarding climate change involve the development of effective management responses for reducing climate risk. Case study simulations, while intended only as illustrative, suggest the potential effectiveness of climate adaption options involving practices that are readily available, easy to employ, and likely to provide benefits under a range of current and future conditions. For example, agricultural management practices such as alternative tillage practices, BMPs (filter strips) and planting different crops may be successful in reducing the impacts of climate change on sediment yields from fields. A more distributed stormwater management system that employs green infrastructure was found to be beneficial in reducing stormwater impacts under conditions of increased precipitation at event and annual time scales. Adapting stormwater management practices to climate change may be further enhanced by reducing watershed impervious cover as explored in Section 3.7. Considering climate change in the context of broad community planning will help determine how climate change risks rate against other priorities and can be incorporated into existing decision making processes.

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[6] For examples see: Climate Change Adaptation Task Force (http://www.whitehouse.gov/administration/eop/ceq/initiatives/adaptation) and Federal Agency Climate Adaptation Planning Implementation Instructions http://www.whitehouse.gov/sites/default/files/microsites/ceq/adaptation_final_implementing_instructions_3_3.pdf.

The scientific approach supported by these tools, i.e., scenario analysis, can be useful for understanding system behavior, identifying vulnerabilities, and evaluating the effectiveness of management responses to inform management decision making. The tools presented in this report, however, are just one step forward in building our capacity for understanding and responding to climate change. Application of hydrologic models in this way has limitations, many of which are not well understood (Ghosh 2010; Ludwig, 2009; Najafi, 2011; Vaze et al., 2010). Further study is required to better assess, refine, and develop our current modeling capabilities. Further study is also required to better address the challenge of incorporating diverse, uncertain, and often conflicting information about future climate change into water resources decision making.

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APPENDIX A

Selected Sources of Climate Change Information

The case studies in this report utilized climate model projections and other information to develop the climate scenarios. The information used in this report is just a small subset of the climate data currently available. Selected additional sources of climate change information, data, and guidance concerning the use of climate change data are listed below. Most sources provide climate change projections developed from climate modeling experiments using GCMs or RCMs. This is not an exhaustive list of climate data sources. Information and guidance about climate change in different parts of the country can be obtained from additional sources including government agencies and universities. Over time, additional information about climate change will become available as climate models are improved, new modeling experiments are conducted, new monitoring data becomes available, and research such as investigations of paleo-climate better reveal historical patterns of climate variability and change.

Bias Corrected and Downscaled WCRP CMIP3 Climate and Hydrology Projections
http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html

ClimateWizard
http://www.climatewizard.org

Conservation International
http://futureclimates.conservation.org/

Data Basin
http://databasin.org/

Earth System Grid gateway
http://pcmdi3.llnl.gov/esgcet/home.htm

IPCC Data Distribution Centre (DDC)
http://www.ipcc-data.org/

Lawrence Livermore National Laboratory, Program for Climate Model Diagnosis and Intercomparison
http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php

Lawrence Livermore National Laboratory/Bureau of Reclamation/Santa Clara University
http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html

North American Regional Climate Change Assessment Program (NARCCAP)
http://www.narccap.ucar.edu/data/index.html

SERVIR – Regional Visualization and Monitoring System
http://www.servir.net/

USDA Forest Service
http://www.fs.fed.us/rm/data_archive/dataaccess/contents_datatype.shtml