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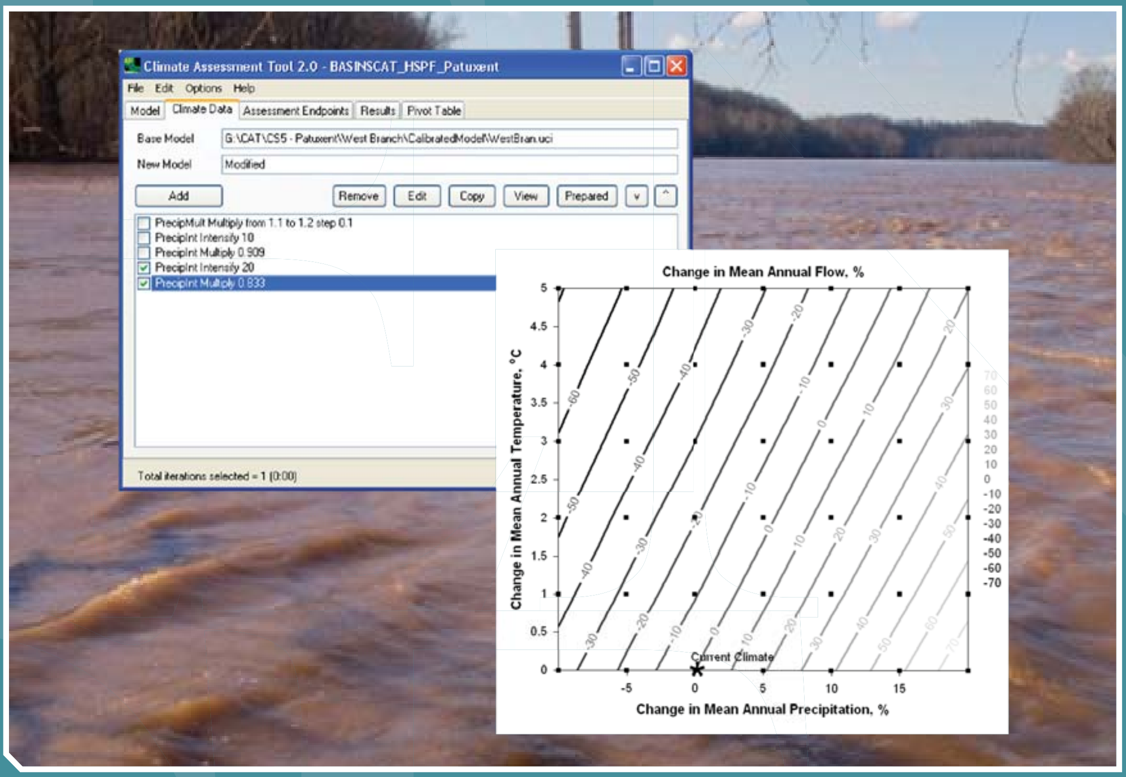
BASINS and WEPP Climate Assessment Tools (CAT): Case Study Guide to Potential Applications



United States Environmental Protection Agency
Office of Research and Development, National Center for Environmental Assessment

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

National Center for Environmental Assessment
Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

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LIST OF ABBREVIATIONS

ARS	Agricultural Research Service
BASINS	Better Assessment Science Integrating Point and Non-point Sources
BMP	best management practice
CAT	Climate Assessment Tool
CC-#	climate change scenario
CMIP3	Coupled Model Intercomparison Project Phase 3
cfs	cubic feet per second
cms	cubic meters per second
EMC	event mean concentration
ET	evapotranspiration
FB	forest buffer
GB	grass buffer
GCM	global climate model
GIS	geographic information system
HRU	hydrologic response unit
HSPF	Hydrologic Simulation Program-FORTRAN
HUC	Hydrologic Unit Code
I	intensity
IPCC	Intergovernmental Panel on Climate Change
LULC	land use land cover
NARCCAP	North American Regional Climate Change Assessment Program
NB	no buffer
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEA	National Center of Environmental Assessment
NLCD	National Land Cover Data
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resource Conservation Service
NSE	Nash-Sutcliffe Model Efficiency Coefficient
ORD	Office of Research and Development
PB	percent bias
PET	potential evapotranspiration
R^2	coefficient of determination
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
TGICA	Task Group on Data and Scenario for Impact and Climate Assessment
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
UMRB	Upper Mississippi River Basin

LIST OF ABBREVIATIONS (continued)

USDA	U.S. Department of Agriculture
U.S. EPA	U.S. Environmental Protection Agency
V	volume
USGS	U.S. Geologic Survey
WEPP	Water Erosion Prediction Project

FOREWORD

Climate change poses significant challenges to water resources and the Environmental Protection Agency's (EPA) National Water Program (NWP). EPA Office of Water's *NWP 2012 Strategy: Response to Climate Change* addresses climate change in the context of our water programs. The Office of Water is committed to working with the Office of Research and Development, other water science agencies, and the water research community to further define needs and develop research to support implementation of the 2012 Strategy, including providing the decision support tools needed by water resource managers.

The modeling tools discussed in this report result from collaborations between EPA's Office of Research and Development (ORD) and Office of Water (BASINS CAT) and the US Department of Agriculture's Agricultural Research Service (WEPPCAT). The tools were developed to facilitate the use of existing, widely used models for conducting scenario-based assessments of climate change effects on water systems. To support the use of these tools, this report illustrates how the tools can be applied in a variety of climatic and land use settings to gain an improved understanding of system sensitivity, vulnerability, and the potential effectiveness of management practices.

The EPA Office of Water thanks the authors, reviewers, and entire project team for their effort in preparing this report. We look forward to continuing our collaboration as we strive to meet the challenge of understanding and responding to climate change.

Karen Metchis, Policy Advisor for Climate Change
U.S. EPA Office of Water

PREFACE

This report was prepared by EPA's Air, Climate and Energy (ACE) research program, located within the Office of Research and Development (ORD). The ACE research program is designed to address the increasingly complex environmental issues we face in the 21st century. The overarching vision of ACE is to provide the cutting-edge scientific information and tools to support EPA's strategic goals of protecting and improving air quality and taking action on climate change in a sustainable manner.

EPA and partners recently developed two Climate Assessment Tools (CATs) that facilitate scenario-based assessments using existing, widely used models in EPA's Better Assessment Science Integrating point and Nonpoint Sources (BASINS) modeling system and USDA's Water Erosion Prediction Project (WEPP) model. This report presents a set of short case studies designed to illustrate potential application of these tools to address different questions about the effects of climate variability and change on water and water quality. The final report reflects a consideration of comments received on an External Review Draft report dated November, 2011 (EPA/600/R-11/123a), provided by an external letter peer review and a 30-day public comment period.

AUTHORS AND REVIEWERS

The National Center for Environmental Assessment (NCEA), Office of Research and Development, was responsible for preparing this final report. An earlier draft report was prepared by AQUA TERRA Consultants, under EPA Contract EP-C-06-029.

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EXECUTIVE SUMMARY

Climate is changing. During the last century, the global average temperature increased 1.4°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, 2008).

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 (multidecadal) future climate at the local and regional scales needed by decision makers (Sarewitz et al., 2000). It is therefore not possible to know with certainty the future climatic conditions to which a particular region or water system will be exposed. Water resources in many areas are also vulnerable to increasing water demand, land-use change, and point-source discharges. Climate change will interact with these and other stressors in different settings in complex ways.

Scenario analysis using computer simulation models is a useful and common approach for assessing vulnerability to plausible but uncertain future conditions and guiding the development of robust climate adaptation strategies (Lempert et al., 2006; Sarewitz et al., 2000; Volkery and Ribeiro, 2009). A barrier to conducting this type of analysis is the effort required to create and run meteorological inputs representing different climate change scenarios for different water models. EPA and partners recently developed two assessment tools, Better Assessment Science Integrating point and Non-point Sources (BASINS) Climate Assessment Tool (CAT) and Water Erosion Prediction Project (WEPP) CAT, to facilitate the use of existing, well known models in EPA's BASINS system (Hydrologic Simulation Program-FORTRAN [HSPF], Soil Water Assessment Tool [SWAT], Storm Water Management Model [SWMM]) and USDA's WEPP model for conducting scenario-based assessments. The tools provide flexible capabilities for creating and running user-specified 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 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 case studies designed to illustrate how these tools can be used to address a range of different questions about the potential implications of climate change on water and watershed systems. 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. The six case study assessments are:

- Streamflow and water quality sensitivity to climate change in the Raccoon River, Iowa, using BASINS CAT with the SWAT
- Urban stormwater sensitivity to rainfall change and effectiveness of management in the Upper Roanoke River, VA, using BASINS CAT with the SWMM
- Agricultural sediment yield sensitivity to climate change and management practices in Blue Earth County, MN, using WEPPCAT
- Streamflow and water quality sensitivity to changes in precipitation amount, frequency, and intensity in the Tualatin River, OR, using BASINS CAT with the HSPF
- Streamflow sensitivity to dry weather events in Sespe Creek, CA, using BASINS CAT with HSPF
- 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

The issue of climate change is complex and will challenge water managers to incorporate diverse, uncertain, and often conflicting information about future climate change into water resources decision making. Results of these case studies illustrate important differences in the sensitivity of different streamflow and water quality endpoints to changes in specific climate drivers. An awareness of these differences highlights the need for tools like BASINS CAT and WEPPCAT which can be used to increase understanding of system behavior, identify how we are most vulnerable, and to guide management decisions for reducing risk. It should be noted, however, that case studies in this report use preexisting models and may not represent all local management and other factors in full detail. Case study results should thus be considered qualitative and heuristic rather than absolute.

1. INTRODUCTION

There is growing concern about the potential effects of climate change on 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 typically 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 a risk of harmful impacts to these and other components of water resources management designed using historical data (Milly et al., 2008).

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, p.2). 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 watershed response to climate change will vary in different locations depending on the specific types of change that occurs and the attributes of individual watersheds including physiographic setting, land use, and human use and management of water. Effects 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, 2008). In addition, water resources in many areas 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 resource management may not be adequate to cope with the changes.

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 (multidecadal) future climate at local and regional scales relevant to water managers (e.g., municipality, drainage basin; 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. This type of information can also be valuable for assessing the implications of plausible future climate conditions, to identify how we are most vulnerable, and guide the development of robust strategies for reducing risk (Sarewitz et al., 2000).

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 potential range of expected climate changes characteristics. Scenario analysis using computer simulation models is a common approach for assessing vulnerability and evaluating the effectiveness of adaptation measures (Lempert et al., 2006; Volkery and Ribeiro, 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 used to support management decision making. Several excellent references are available discussing the use of scenarios to assess climate change impacts (e.g., see IPCC TGICA, 2007; WUCA, 2010; Brekke et al., 2009; U.S. EPA, 2011; Brown, 2011; Johnson and Weaver, 2009). A barrier to conducting this type of analysis is the level of effort required to create meteorological inputs representing multiple future climate change scenarios to drive water models.

EPA and partners recently developed two assessment tools, the BASINS CAT and the WEPPCAT, to facilitate scenario-based assessments using well known, existing models in EPA's BASINS modeling system, and USDA's WEPP model, respectively. The tools provide flexible capabilities for creating and running climate change scenarios to address a 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 investigate 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 HSPF watershed model (Johnson and Kittle, 2006; Imhoff et al., 2007; U.S. EPA, 2009a). With the release of BASINS CAT Version 2 in 2012, CAT capabilities will also be available with the SWAT and SWMM models.

WEPPCAT was released in 2010 in partnership with the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) (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 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 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 climate assessment tools when used with different models. BASINS CAT and WEPPCAT provide users with capabilities for adjusting historical meteorological data to create climate change scenarios to assess hydrologic and water quality response to climate change using the BASINS and WEPP models. The case studies in this report illustrate a number of these capabilities. Finally, case study simulations convey information about the potential response of watersheds in different parts of the nation to future changes in climate, land use, and management practices. It is important to note, however, that all case studies use preexisting models and may not represent all local management and other factors affecting hydrologic and water quality endpoints in full detail. Results should, thus, be considered qualitative and heuristic rather than absolute. The specific case study locations were selected to leverage the availability of existing models and to represent a range of physiographic, hydrologic, and climatic conditions.

The intended audience of this report is water scientists, engineers, managers, and planners with a basic knowledge of water and watershed modeling interested in using models to conduct scenario-based assessments of the potential effects of climate change on water and watershed systems. 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. More generally, the approaches for creating and using scenarios as described in this report and implemented with the BASINS CAT and WEPPCAT tools are readily transferable for use with any environmental model. We hope that the information in this report can stimulate 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 section 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 CAT: Supporting Documentation and User's Manual" (U.S. EPA, 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 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 user-selected 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; 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 pollutant loading application (U.S. EPA, 2007). The main interface to BASINS is provided through MapWindow, a nonproprietary, open-source Geographic Information System (GIS). The GIS provides a framework for linking BASINS modeling tools with environmental data (see Figure 2-1).

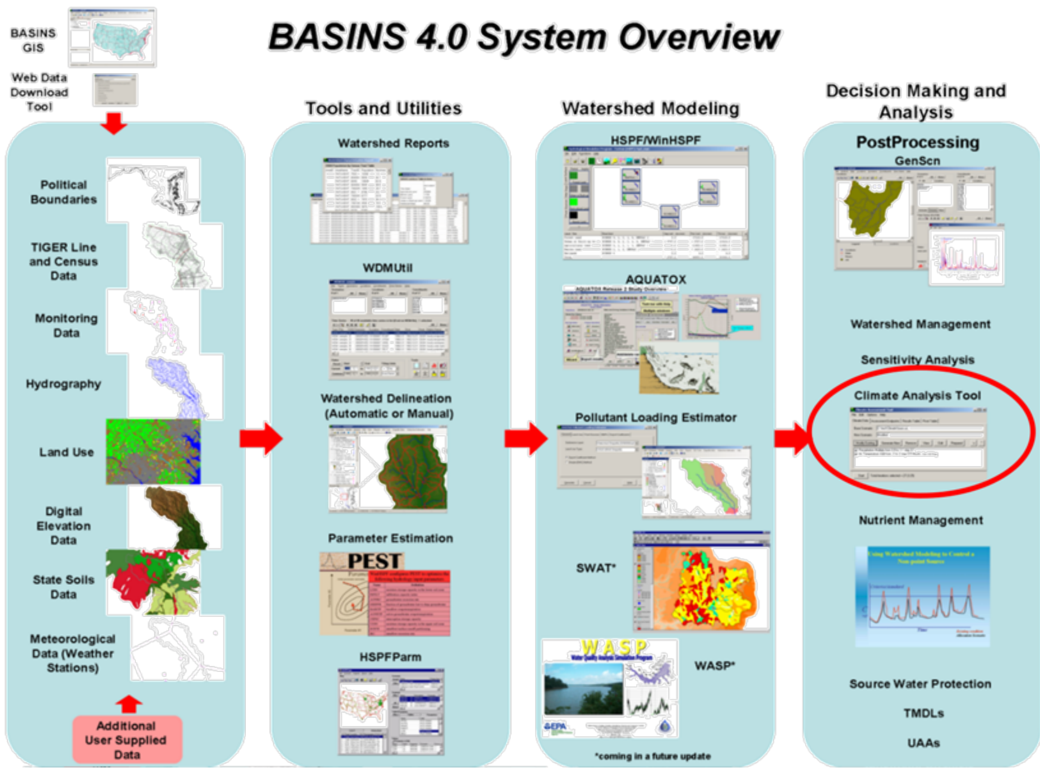


Figure 2-1. Overview of the EPA BASINS 4 modeling system (U.S. EPA, 2007).

BASINS CAT is not a stand-alone model. BASINS CAT is a plug-in available for use with pre-existing, calibrated BASINS models. Specifically, BASINS CAT does the following: (U.S. EPA, 2009a):

- provides a flexible, pre-processing capability for creating meteorological time series representing user-specified changes in climate for input to BASINS models using the change factor approach (see Table 2-1);
- manages new meteorological data so that it is properly formatted for input into BASINS models; and
- provides a post-processing capability for calculating user-specified streamflow and water quality endpoints from BASINS model output (see 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 simulations.

Modifying historical precipitation records	•Apply a multiplier to each value within selected months in a multiyear record •Apply multiplier to each value within selected years in a multiyear 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 multiyear record •Add or subtract from each value within selected years in a multiyear 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
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 and frequency events based on model output time series (e.g., 7-day average low streamflow with a 10-year return period,100-year flood, 2-year flood) • Export BASINS CAT time series data as text (ASCII) files

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.

BASISN CAT does not provide explicit capabilities for creating land-use change or management scenarios. Creation of land-use change and management scenarios as part of a BASINS CAT analysis is done by adjusting land-use and/or management definitions in input files used by the watershed model selected for the analysis.

In BASINS CAT Version 2 (released in 2012), climate assessment capabilities are accessible for three BASINS models: HSPF, SWAT, and SWMM. These three 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 as to which model is most appropriate for a given assessment. The following is a brief summary of the three 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 (http://www.epa.gov/ceampubl/swater/hspf/; 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.

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.

Processes simulated 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 (ET), 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.

Selected HSPF model strengths include (Shoemaker et al., 2005):

- model setup can be simple or complex, depending on application, requirements, and data availability;
- capable of simulating land and receiving water processes;
- a variety of simulation time steps can be used, including sub-hourly to 1 minute, hourly, or daily; and
- enables user-defined model output options by defining the external targets block.

SWAT

SWAT is a 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 runoff, sediment, and agricultural chemicals (nutrients and pesticides) from a watershed (Neitsch et al., 2005). In addition, the model includes capabilities and functionality to assess a wide variety of impacts of alternative management practices and land-use changes (Gassman et al., 2007). 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 and pond/reservoir routing. 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.

Selected SWAT model strengths are as follows:

- physically based model can be used to evaluate the relative impact of changes in management practices, climate, and vegetation on water quality or other variables of interest;
- required minimum data for running simulations are commonly available;
- ability to simulate crop and plant communities and provide crop yield and plant biomass; and
- computationally efficient allowing simulation of very large basins or a variety of management strategies without excessive investment of time or money.

SWMM

The SWMM 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 best management practices (BMPs) for reducing wet weather pollutant loadings, generating nonpoint source pollutant loadings for waste load allocation studies, and designing control strategies for minimizing 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 subareas. Overland flow can be routed between subareas, 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.

Some key SWMM strengths are as follows:

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

Introduction to WEPPCAT

The WEPP is a process-based (mechanistic) model, available as a desktop model or through a web-based interface, for simulating soil erosion and sediment yield from agricultural areas (see Figure 2-2). WEPP can be used to assess how soil erosion rates are impacted by precipitation events, soil type, vegetation type, topography, and number of commonly applied BMPs for reducing soil loss. Simulations can be run at the hill slope or watershed scale (Flanagan et al., 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 et al., 1995). Recent developments allow forested land cover, such as forested riparian buffers, to be represented in WEPP.

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 and sediment yield using the WEPP model. WEPPCAT was developed by the USDA ARS in partnership with EPA ORD and is available for use at http://typhoon.tucson.ars.ag.gov/weppcat/index.php (see Figure 2-2). 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.). WEPPCAT outputs include mean annual runoff, soil loss, and sediment yield. Users can also generate spatial sediment loss data and sediment particle size profiles.

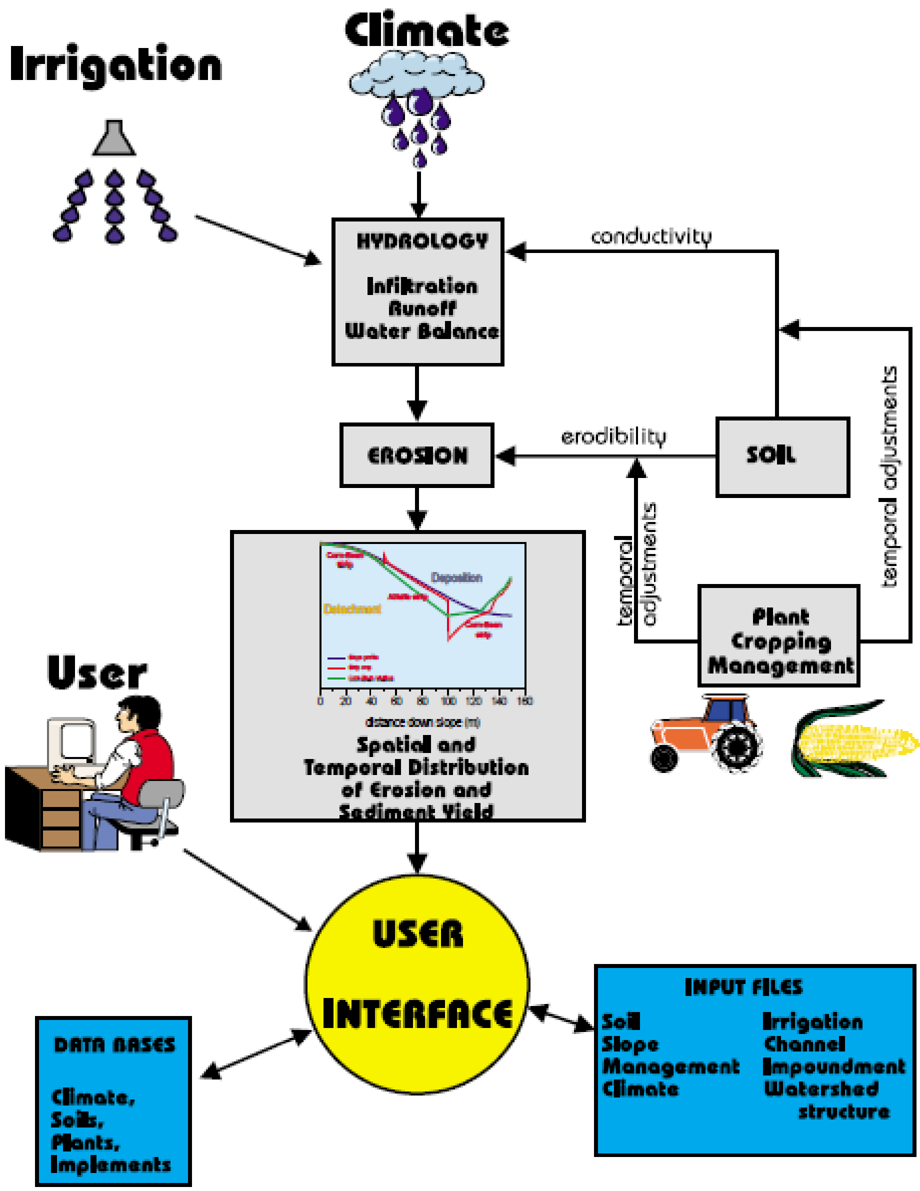


Figure 2-2. Overview of the WEPP modeling system (from Flanagan et al., 1995).

WEPP uses the stochastic weather generator Cligen to generate daily meteorological data as input to simulations based on monthly statistics from National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) weather stations (http://www.ars.usda.gov/Research/docs.htm?docid=18094). Cligen outputs include daily time series for precipitation (including storm parameters such as peak intensity), temperature, solar radiation, and wind. WEPPCAT provides a capability to create climate change scenarios by adjusting Cligen parameters to represent potential future changes in temperature and precipitation. Available adjustments include increases and decreases in mean monthly temperature, precipitation volume, and the number of wet days (i.e., the transition probabilities of a wet day following a dry day, and a dry day following a dry day). These adjustments can be made either uniformly for all months of the year, or individual adjustments can be made to specific months or seasons 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%. Adjustments in precipitation intensity are made by applying the user determined increase to the largest 5% of events, and simultaneously decreasing precipitation in the lower 95% events by the same volume. This adjustment can only be made to all events across the entire year, and is accomplished by altering the standard deviation of the distributions of daily precipitation used by the climate generator. 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 Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate database. Modifications are made by selecting precipitation values or elevations for areas surrounding the selected weather station. All WEPPCAT simulations are based on 100 years of daily meteorological data generated using Cligen. WEPPCAT results are average values based on 100 years of simulation output.

3. CASE STUDIES

3.1. INTRODUCTION

This section presents a series of six case studies designed to illustrate selected capabilities and approaches for conducting scenario-based assessments using BASINS CAT and WEPPCAT (see Table 3-1). The case studies include applications of four different watershed models; encompass a range of spatial and temporal scales; include climate change, land-use change, and management scenarios; and evaluate hydrologic and water quality endpoints of concern.

The scenarios used in each analysis were determined by available information and the goals of a specific assessment activity. Multiple scenarios were employed to capture the full range of underlying uncertainties associated with future climate, land use, and management practices on water resources. Three different types of climate scenarios were employed: synthetic scenarios, analog 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% could be applied in various combinations to create nine different climate change scenarios (IPCC TGICA, 2007). Analog 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 analogs) or from a different geographic location (spatial analogs). Model-based scenarios are developed using output from climate modeling experiments that simulate the response of the climate system to changes in greenhouse gas emissions and other climatic forcing.

Non-climatic watershed stressor scenarios, included land-use change and water resource management practices, were considered in much the same way as climate change. Land-use scenarios were based on a range of context-dependant information such as population growth, land-use regulations, and economic factors, among other things. The management scenarios were designed to explore the effectiveness of existing practices in the context of climate change adaptation. 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.

The 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 preexisting, 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 preexisting 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, IA, 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, North American Regional Climate Change Assessment Program (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 two stormwater management strategies under precipitation change scenarios developed in PART A
3.4	Agricultural sediment yield 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 vs. 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 the use of BASINS CAT with a SWAT watershed model to assess the sensitivity of streamflow and total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) loads to potential climate change in an agriculturally-dominated watershed.

PART A is a general sensitivity analysis using a matrix of climate change scenarios based on multiple combinations of potential temperature and precipitation changes within a user-defined range. Climate change scenarios were created by increasing historical mean annual temperatures +0 to +5°C by increments of 1°C and adjusting mean annual precipitation volume −10 to +20% by increments of 5%.

PART B evaluates more detailed scenarios created using BASINS CAT to represent climate model projections. 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 adjusting average monthly precipitation volumes from one climate model projection to assess the influence of different seasonal distributions of observed changes on pollutant loading and streamflow.

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 United States, 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, and it is possible these changes 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, fertilizer application, public policy, pollution abatement technology, etc.).

In this case study, a SWAT model of the Raccoon River in IA, a subbasin 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 assessed 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 specified range*** feature to assess potential changes to mean annual streamflow and TN, TP, and TSS loadings. 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 investigates how seasonal changes to precipitation volume and temperature can impact monthly and mean annual streamflow and TN, TP, and TSS loads. Spatial variability of climate change was also represented by applying distinct adjustments to temperature and precipitation data from the two NCDC weather stations included in the model. The BASINS CAT ***months/years*** adjustment feature was used to develop the climate change scenarios based on simulations for four 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 (see Figure 3-1). It contains 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 forested areas (see Table 3-2).

Water Model Setup
A preexisting, calibrated SWAT model of the Raccoon River was extracted from a previous modeling effort investigating the impacts of ethanol corn production in the UMRB (U.S. EPA, 2010). The Raccoon River SWAT model uses the 2001 National Land Cover Data (NLCD, http://www.mrlc.gov/nlcd2001.php) and 2004−2006 Cropland Data Layer (http://www.nass.usda.gov/research/Cropland/metadata/meta.htm) for the land use coverage, and the USDA-Natural Resource Conservation Service (NRCS) State Soil Geographic Database (STATSGO; http://soils.usda.gov/survey/geography/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 subwatershed 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 data sets of daily precipitation and temperature (maximum and minimum) spatially interpolated using slope, elevation, and aspect as spatial covariates. Grid cells are 4 km^2 (2 km on each side) and cover the conterminous United States.

Initial SWAT parameters for the Raccoon River model were acquired from a national database developed as part of a previous UMRB SWAT model (U.S. EPA, 2010). Additional, 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 model calibration. Calibration results for streamflow, nutrient, and sediment loads are shown in 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.

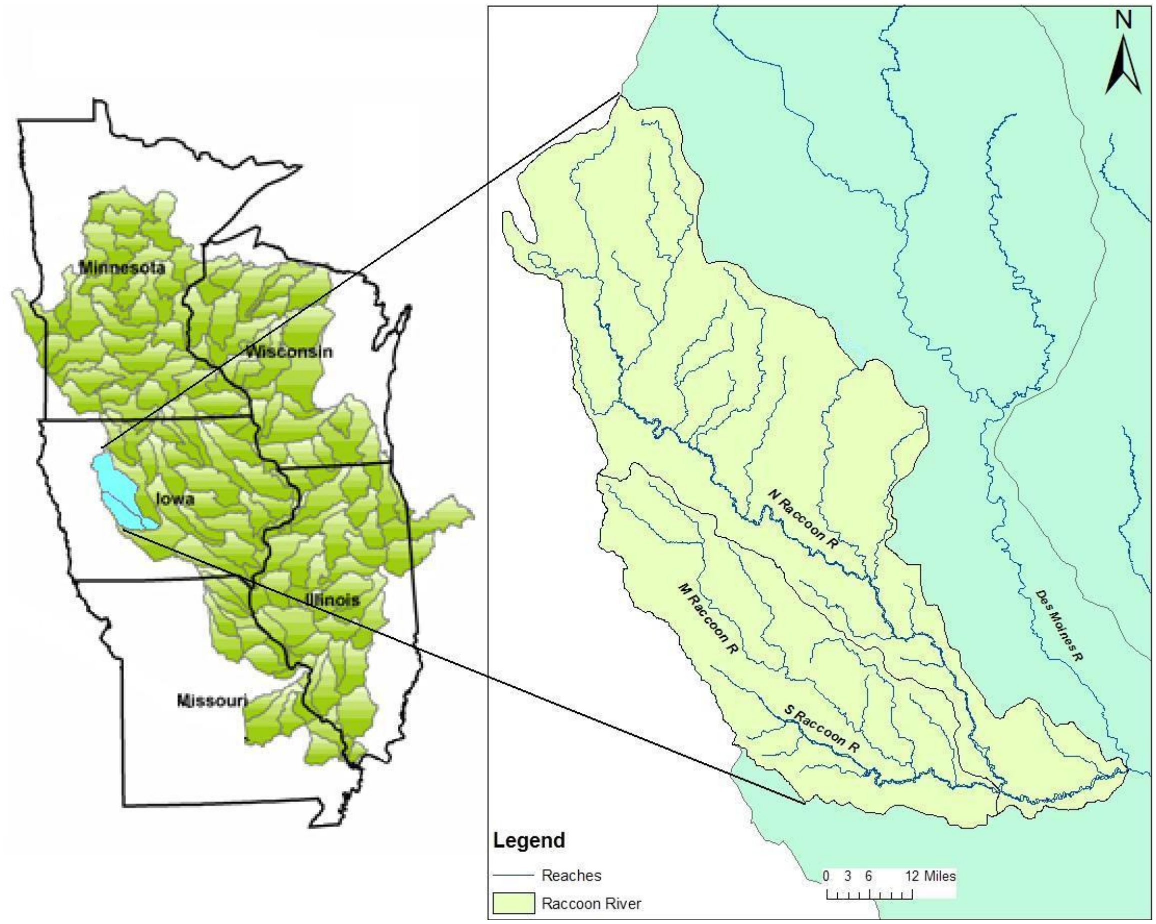


Figure 3-1. The Raccoon River watershed and major tributaries.

Table 3-2. Land-use summary for Raccoon River watershed.

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

Table 3-3. Raccoon River model calibration statistics for annual streamflow, nutrient and sediment loads. R^2: coefficient of determination; NSE: Nash-Sutcliffe Efficiency coefficient (Nash and Sutcliffe, 1970); PB: percent bias; RMSE: root mean square error.

Endpoint	Streamflow (cms)	TN (kg/ha/yr)	TP (kg/ha/yr)	TSS (kg/ha/yr)
R^2	0.93	0.93	0.90	0.40
NSE	0.99	0.47	0.49	0.07
PB	16.5	39.8	37.4	24.4
RMSE	17	24,657	2,224	3,880

PART A: Annual Sensitivity Analysis

Scenario Development: PART A

A total of 42 SWAT model simulations were completed. Climate change scenarios included 1 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 portal for accessing and visualizing summary statistics for projected future changes in temperature and precipitation at any location within the United States based on 16 GCM projections and three greenhouse gas emissions scenarios (Special Report on Emissions Scenarios A2, A1B, and B1) archived by the Program for Climate Model Diagnosis Coupled Model Intercomparison Project Phase 3 (CMIP3). Summary information is presented for two future periods: mid-century (2050s) and end-of-century (2080s).

Climate change scenarios were developed to fall within the ensemble range of projected end-of-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 ranged from −22 to +30%. Spatial variability in projected changes across the watershed was relatively small.

Climate scenarios were created using a change factor or delta change methodology (Anandhi et al., 2011). Climate change scenarios for the SWAT model were developed using BASINS CAT's ability to create ***multiple changes within specified range*** (see Figure 3-2). This feature automates the creation of multiple climate adjustments for selected variables by specifying a range of change and step increment within the range (e.g., to change temperature by 0 to 3°C by increments of 1°C). When two or more variables are selected, this feature creates scenarios reflecting each possible combination of changes for selected variables. The following adjustments were made using change factors to the Raccoon River temperature and precipitation records for 1960−2001:

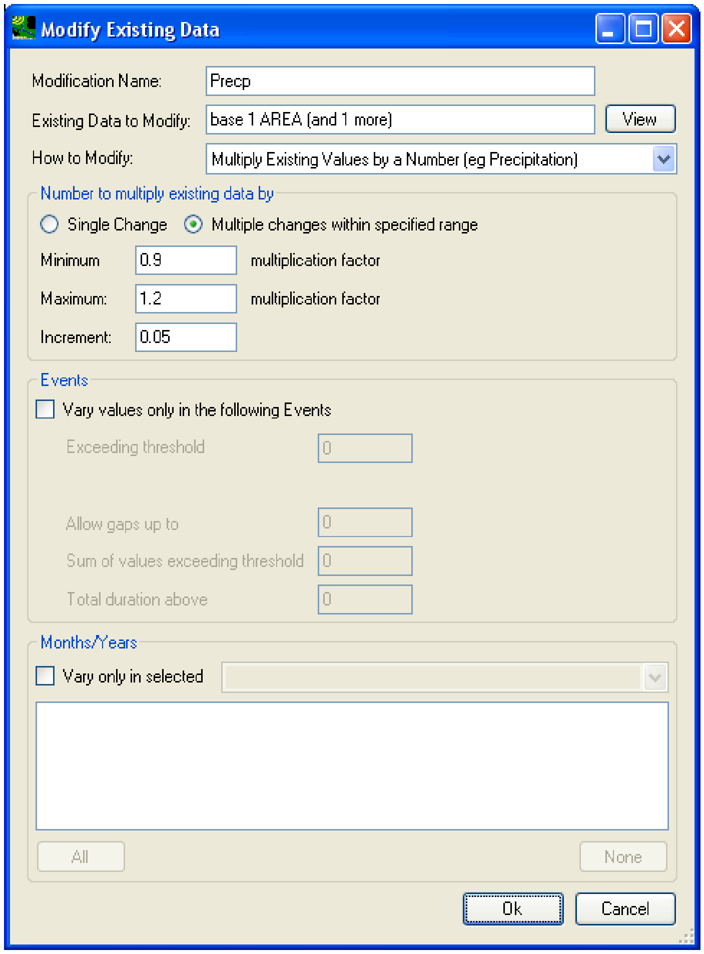


Figure 3-2. BASINS CAT option window for making multiple changes within specified range. *Modification Name* is user defined; *Existing Data to Modify* is the time series to be modified; *How to Modify* is the type of data modification*; Multiple changes within specified range* allows the user to specify the criteria for the multipliers including minimum, maximum and incremental values.

- Average daily temperatures increased by 0 to 5°C at increments of 1°C
- Average annual precipitation volume adjusted by −10 to +20% at increments of 5%

Figure 3-2 shows how the precipitation volume adjustments were made using the BASINS CAT interface. In the section labeled ***number to multiply existing data by***, the option ***multiple changes within specified range*** is selected to automate the creation of multiple scenarios within a user-specific range. The minimum and maximum multipliers within the range are defined as 0.9 and 1.2. The step increment is 0.05. BASINS CAT will, thus, create and run multiple precipitation change scenarios representing −10, −5, 0, 5, 15, and 20% change in precipitation volume.

Identical adjustments were applied to two weather stations included in the model, one located in each subwatershed. The SWAT model used the modified temperature and precipitation inputs to internally recompute potential evapotranspiration (PET) using the Penman-Monteith algorithm for simulation of each scenario. This differs from other BASINS CAT models (i.e., HSPF, SWMM) where PET is recomputed 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.

Land-use Scenarios

Land-use and land cover (LULC) data were held constant for all model runs. While it is likely that LULC in the Raccoon River will change in the future, holding it constant allowed for the assessment of potential impacts from climate change 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 SWAT model, but no adjustments were made in order to focus on potential climate change impacts only.

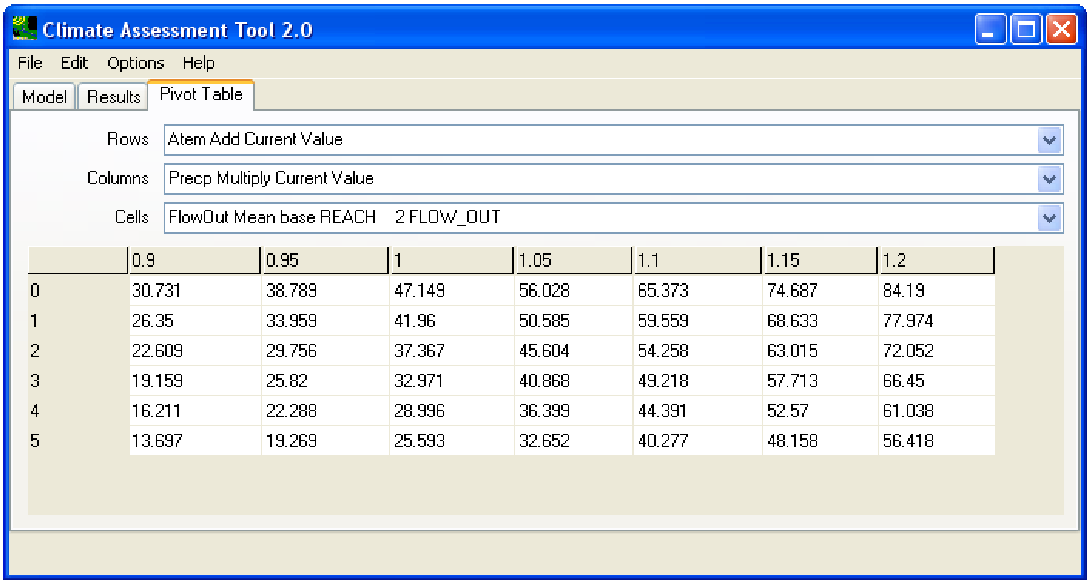
Endpoint Selection: PART A

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 largely agricultural watershed.

Results: PART A

A useful 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 (see 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. Model results for mean annual streamflow and loadings of TN (kg/ha/yr), TP (kg/ha/yr), and TSS (tonnes/ha/yr) extracted using the pivot table option are shown in Tables 3-4 to 3-7. The combination of 0% change in precipitation and 0°C change in temperature represents the baseline conditions of the model (historical climate).

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. For example, a 5% increase in precipitation and a 0°C increase in temperature resulted in a mean annual streamflow of 56 cms, while a 5% increase in precipitation with a 5°C increase in temperature resulted in a mean annual streamflow of 33 cms.



	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 window displaying results for mean annual streamflow at the outlet of the Raccoon River SWAT model in a pivot table.

Table 3-4. Mean annual streamflow (cms) for all combinations of temperature and precipitation change as extracted from the BASINS CAT pivot table. Result for the baseline condition (historical climate) is highlighted in grey in the first column.

Precipitation Change	Mean Annual Streamflow (cms)					
	Temperature Change					
	0°C	1°C	2°C	3°C	4°C	5°C
−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 TN load (kg/ha/yr) for all combinations of temperature and precipitation change as extracted from the BASINS CAT pivot table. Result for the baseline condition (historical climate) is highlighted in grey in the first column.

Precipitation Change	Mean Annual TN (kg/ha/yr)					
	Temperature Change					
	0°C	1°C	2°C	3°C	4°C	5°C
−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 TP load (kg/ha/yr) for all combinations of temperature and precipitation change as extracted from the BASINS CAT pivot table. Result for the baseline condition (historical climate) is highlighted in grey in the first column.

Precipitation Change	Mean Annual TP (kg/ha/yr)					
	Temperature Change					
	0°C	1°C	2°C	3°C	4°C	5°C
−10%	0.57	0.52	0.46	0.42	0.40	0.35
−5%	0.71	0.64	0.59	0.55	0.52	0.49
0%	0.83	0.76	0.72	0.67	0.65	0.62
5%	0.97	0.92	0.87	0.82	0.80	0.77
10%	1.12	1.06	1.02	0.97	0.96	0.93
15%	1.26	1.19	1.14	1.11	1.11	1.09
20%	1.42	1.34	1.31	1.27	1.27	1.25

Table 3-7. Mean annual TSS load (tonnes/ha/yr) for all combinations of temperature and precipitation change as extracted from the BASINS CAT pivot table. Result for the baseline condition (historical climate) is highlighted in grey in the first column.

Precipitation Change	Mean Annual TSS (tonnes/ha/yr)					
	Temperature Change					
	0°C	1°C	2°C	3°C	4°C	5°C
−10%	0.58	0.47	0.40	0.33	0.29	0.24
−5%	0.77	0.65	0.55	0.48	0.41	0.36
0%	0.98	0.84	0.74	0.64	0.57	0.51
5%	1.22	1.07	0.95	0.84	0.76	0.68
10%	1.49	1.32	1.18	1.06	0.97	0.89
15%	1.77	1.58	1.43	1.31	1.20	1.11
20%	2.08	1.87	1.71	1.57	1.46	1.35

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 (see Table 3-8). Evapotranspiration is much less sensitive to changes in precipitation than temperature. As temperature increases, evapotranspiration as expected increases, resulting in reduced streamflow and pollutant loads. For example, as temperature increases from 0 to 5°C, holding the precipitation increase constant at 5%, streamflow decreases from 56 to 33 cms, while at the same time, evapotranspiration increases from 60.5 to 69.2 cm/yr.

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 adjustment. Contours were generated by interpolation from the original 42 scenario endpoints, indicated as dots on the plot, using plotting software external to BASINS. 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.

Table 3-8. Mean annual evapotranspiration (cm/yr) for all combinations of temperature and precipitation change as extracted from the BASINS CAT pivot table. Result for the baseline condition (historical climate) is highlighted in grey in the first column.

Precipitation Change	Mean Annual Evapotranspiration (cm/yr)					
	Temperature Change					
	0°C	1°C	2°C	3°C	4°C	5°C
−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

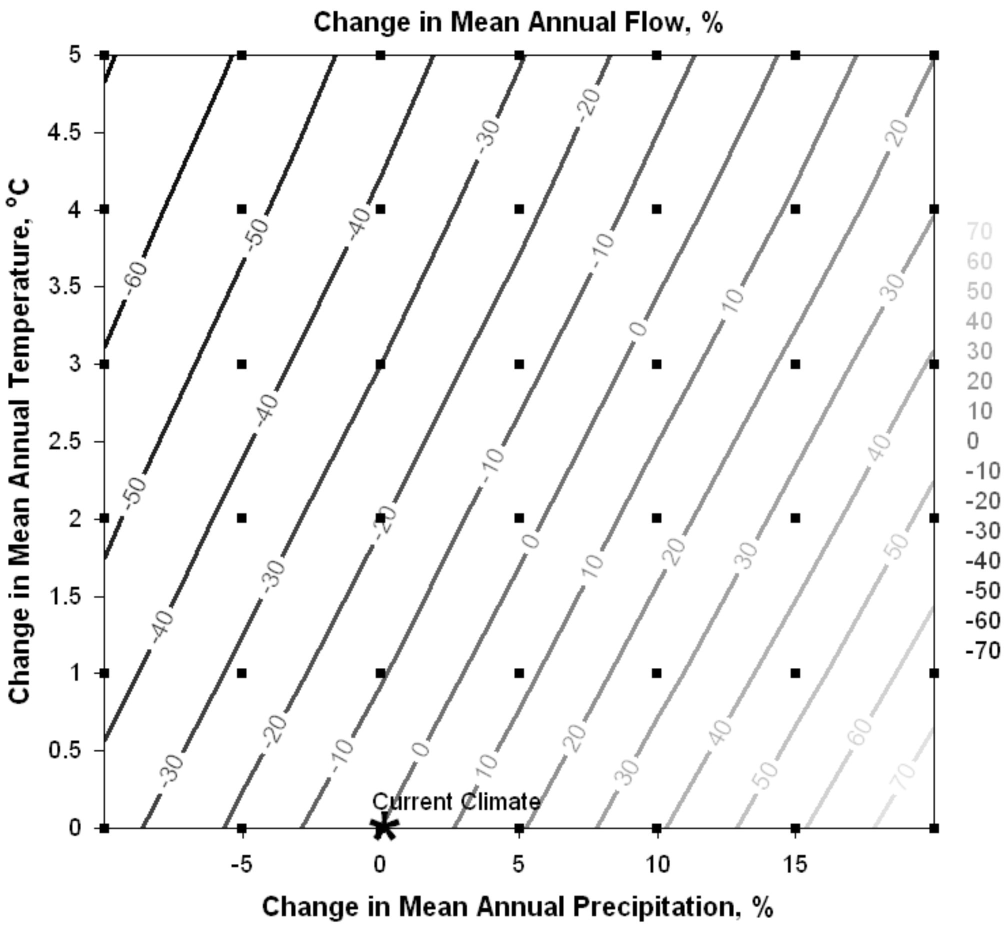


Figure 3-4. Contour plot showing percent change in mean annual streamflow for all combinations of temperature and precipitation change.

PART B: Seasonal Sensitivity Analysis

Scenario Development: PART B

A total of seven model simulations were completed. Scenarios included one baseline climate scenario and six 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 of seasonal differences in how climate changes. 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. 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, altering the timing of spring snowmelt and streamflow. BASINS CAT provides the capability to apply change factors to only selected months of the year. This capability allows scenarios representing changes that vary on a seasonal basis to be created.

For PART B, climate change scenarios were developed to investigate how seasonal changes in precipitation patterns can impact mean monthly and annual endpoint values. As in PART A, climate scenarios were developed using the change factor method. The change factors were developed using data from dynamically downscaled GCM model projections from the NARCCAP (http://www.narccap.ucar.edu). The NARCCAP model projections are a series of high resolution climate simulations developed by nesting RCMs within coarser resolution GCMs. The NARCCAP climate simulations cover 1971−2000 (baseline) and 2041−2070 (future). The change factors applied to the SWAT model weather data represented the difference in average monthly values between the baseline and the future NARCCAP simulations. The change factors were used to adjust the mean monthly values of temperature and precipitation for the entire 1960 to 2001 Racoon River weather time series.

Four climate change scenarios, CC-1, CC-2, CC-3, CC-4, were developed using four NARCCAP climate model projections (see Table 3-9). Two additional scenarios, CC-5 and CC-6, were created by applying additional adjustments to one of these NARCCAP scenarios, CC-3. Scenarios CC-5 and CC-6 each maintain the same mean annual precipitation and temperature as CC-3, but monthly precipitation values were altered to represent two different seasonal patterns of change.

Table 3-9. NARCCAP regional and global climate models used to develop climate change scenarios.

Climate Scenario	NARCCAP RCM and GCM model combinations used to develop climate change scenarios (RCM_GCM)	
CC-1	**crcm_cgcm3**	Canadian Regional Climate Model nested in the Canadian Global Climate Model version 3
CC-2	**rcm3_cgcm3**	National Center for Atmospheric Research (NCAR) Regional Climate Model version 3 nested in the Canadian Global Climate Model version 3
CC-3	**rcm3_gfdl**	NCAR Regional Climate Model version 3 nested in the Geophysical Fluid Dynamics Laboratory Climate Model version 2
CC-4	**wrfg_ccsm**	Weather Research and Forecasting Grell Model nested in the NCAR Community Climate Model version 3
CC-5	**rcm3_gfdl**	Same RCM_GCM projection as CC-3 but monthly precipitation values are adjusted to represent an alternative pattern of seasonal variability
CC-6	**rcm3_gfdl**	Same RCM_GCM projection as CC-3 but monthly precipitation values are adjusted to represent an alternative pattern of seasonal variability

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 (see Figure 3-5). Adjustments were made using monthly change factors representing the difference between baseline conditions and projected future change for each climate change scenario. Precipitation change factors were applied as multipliers to each record within a given month in the baseline precipitation time series. Temperature change factors were applied as constant degree changes to each record within a given month in the baseline temperature time series.

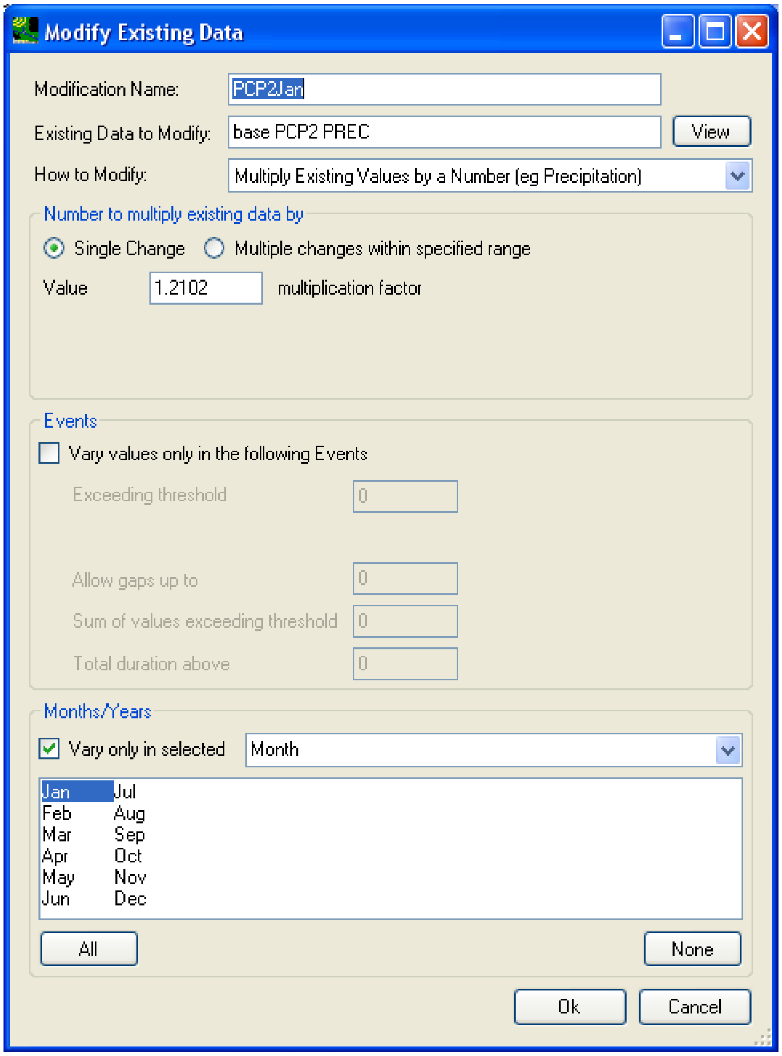


Figure 3-5. BASINS CAT window showing the modification of data on a monthly basis. *Modification Name* is user defined; *Existing Data to Modify* is the time series to be modified; *How to Modify* specifies the type of time series modification; *Single Change* under *Number to multiply existing data by* is the multiplier applied to the time series specified; the *Months/Years* adjustment specifies to which month in the time series the multiplier will be applied.

In PART A of this case study, it was assumed that the spatial variability of climate change within the study watershed was negligible, and identical change factors were applied to temperature and precipitation data from each of these locations for each scenario considered. In many cases, however, such as in large or topographically complex watersheds, spatial differences in climate change may need to be represented. 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 locations.

In PART B spatial variability was represented in all climate change scenarios by applying different monthly change factors to the two meteorological data locations used by the SWAT model, one representing the northern and the other the southern subwatersheds. 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.

Land-use Scenarios

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

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

Endpoint Selection: PART B

The endpoints for this study consisted of mean annual and monthly streamflow and loadings of TN, TP, and TSS.

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 totals for precipitation (mm), TN (kg/ha), TP (kg/ha), TSS (kg/ha), mean annual streamflow (cms), and temperature (°C) for all scenarios. All climate change scenarios have higher mean annual temperature and total annual precipitation than the baseline. However, the mean monthly precipitation and temperature values for Scenarios CC-1 to CC-4 vary in direction throughout the year compared to the baseline. The scenarios tend to have higher mean monthly precipitation in the spring (March to May) and fall (September to November), but lower mean monthly precipitation in the late summer (June to August) (see Figures 3-6 and 3-7 and Tables 3-10 to 3-13). Simulation results for scenarios representing different monthly climate adjustments (seasonal variability) illustrate a high sensitivity of streamflow and pollutant loadings to the distribution of rainfall and temperature changes within the year.

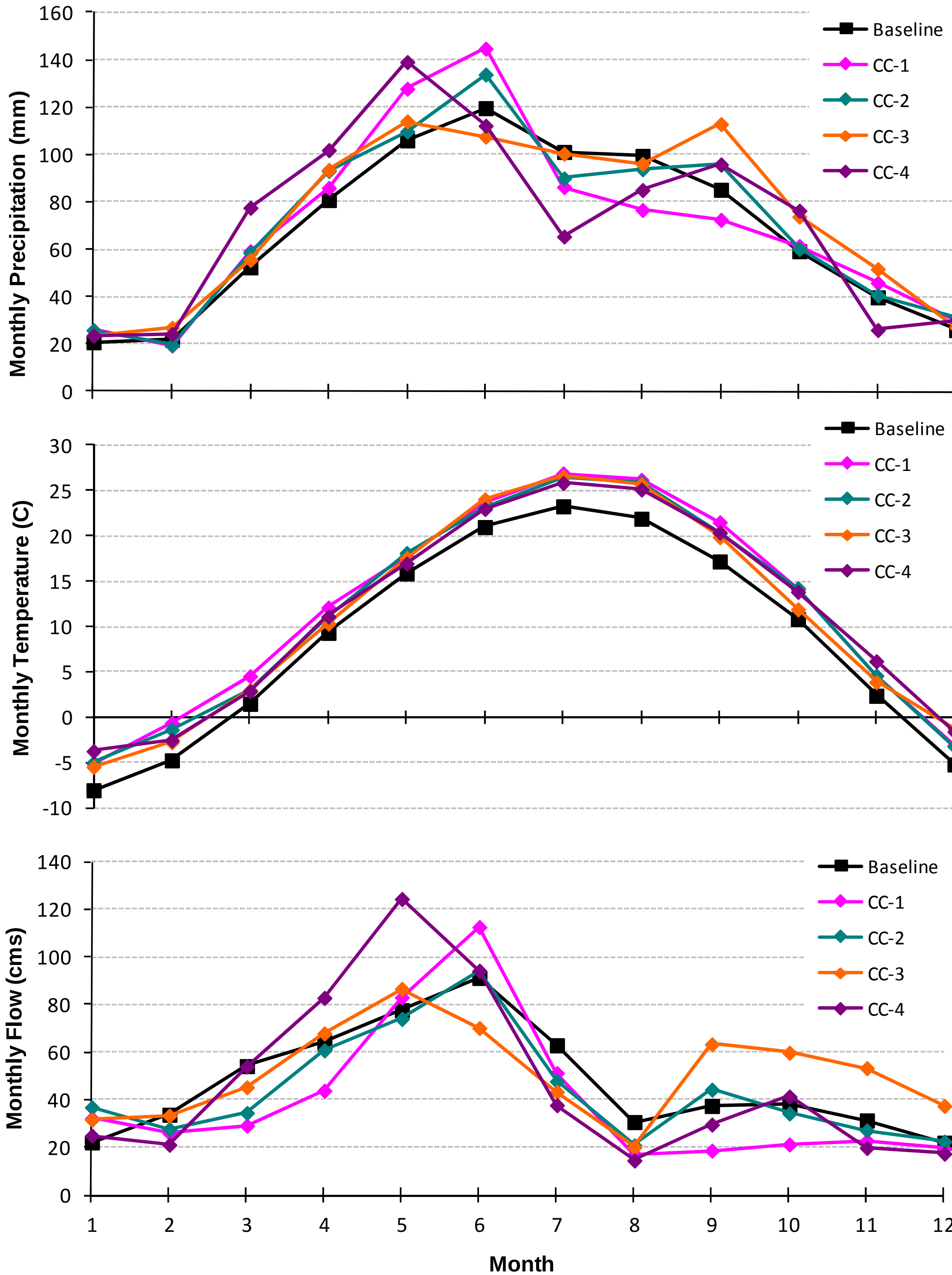


Figure 3-6. Mean monthly precipitation (mm), temperature (°C), and streamflow (cms) for the NARCCAP-derived climate change scenarios, CC-1, CC-2, CC-3, CC-4, and the baseline scenario.

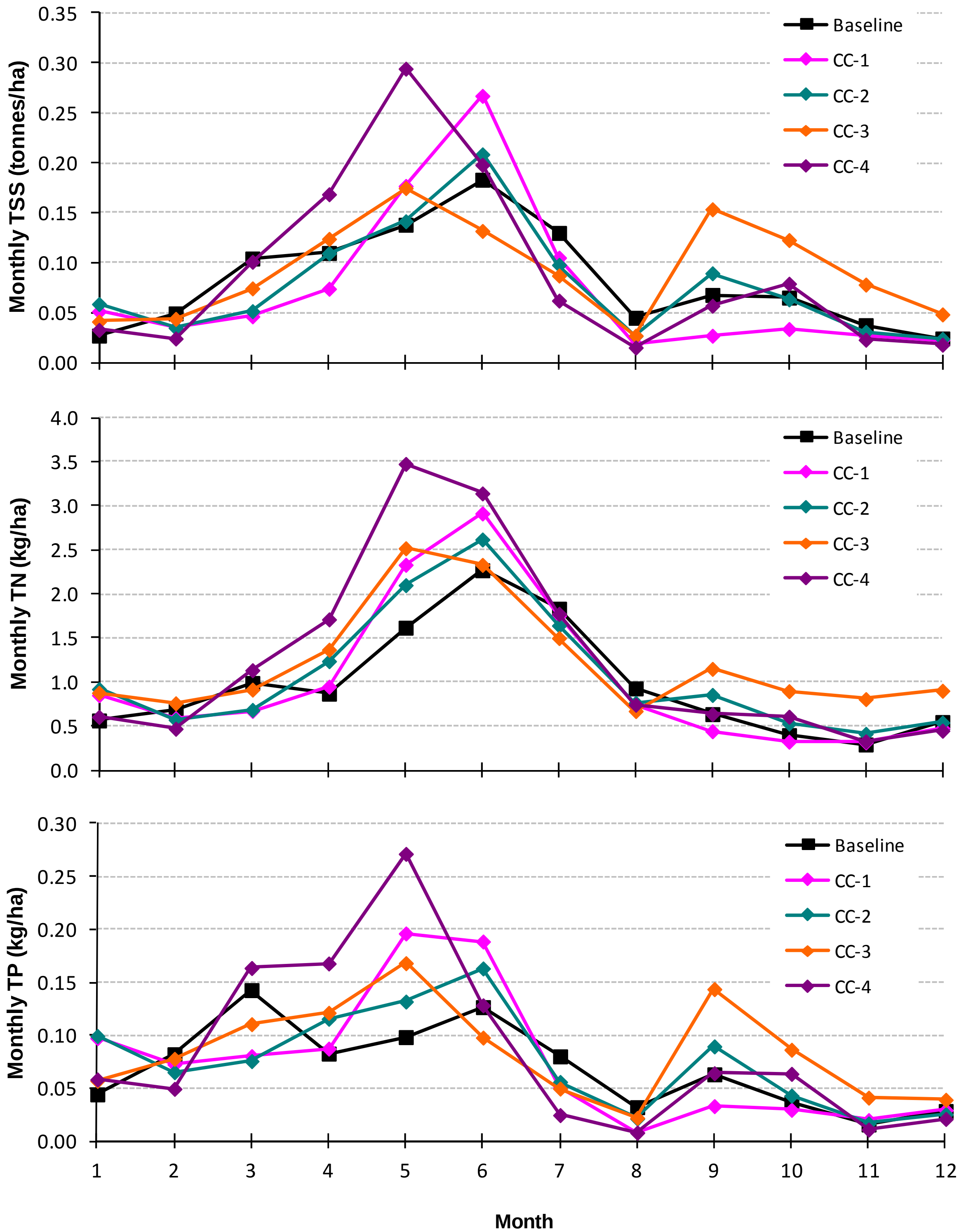


Figure 3-7. Mean monthly TSS (tonnes/ha), TN (kg/ha), and TP (kg/ha) for the NARCCAP-derived climate change scenarios, CC-1, CC-2, CC-3, CC-4, and the baseline scenario.

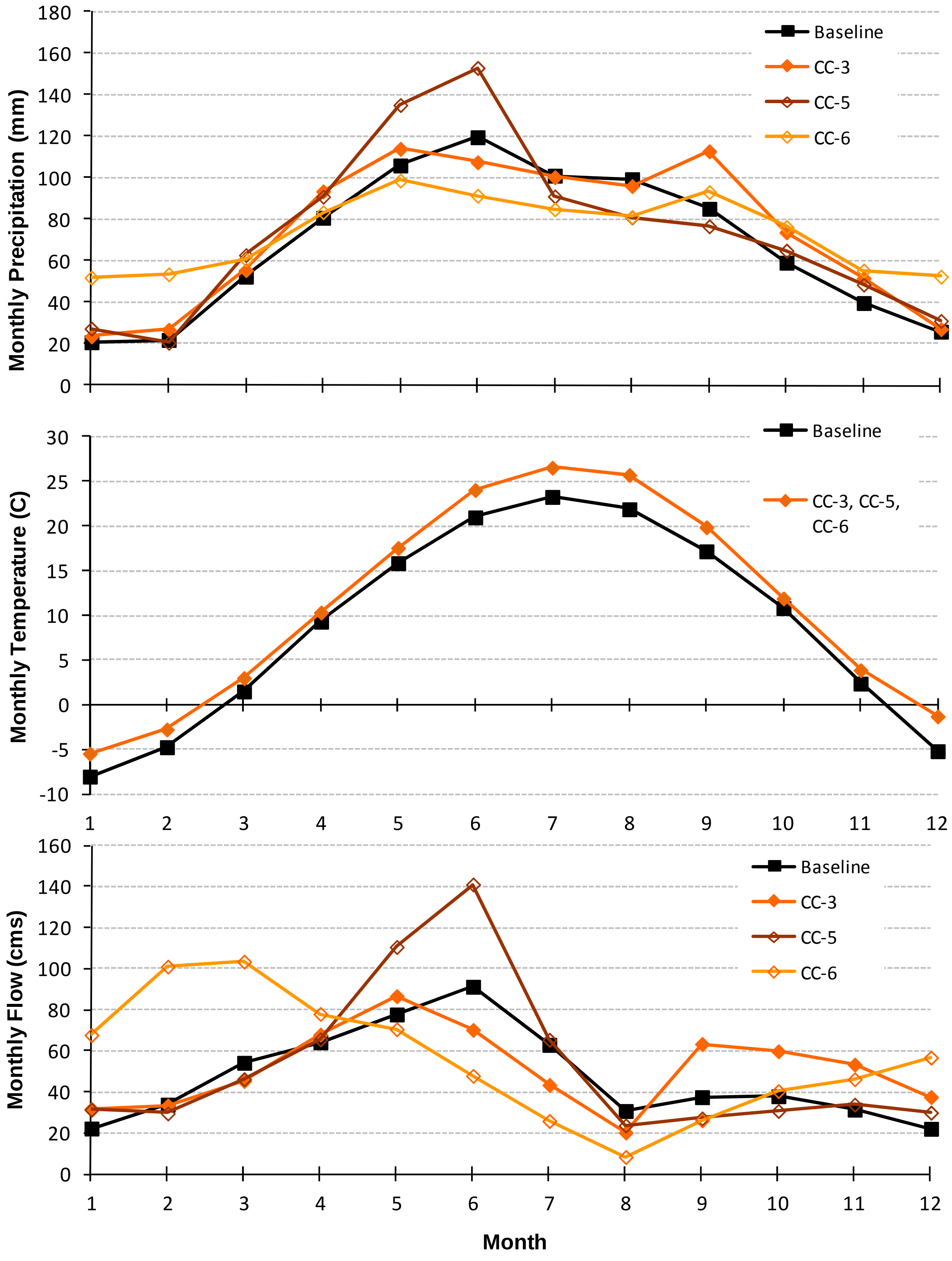


Figure 3-8. Mean monthly precipitation (mm), temperature (°C), and streamflow (cms) for the CC-3, CC-5, CC-6, and baseline scenarios. The monthly temperature was exactly the same for all scenarios since only precipitation was adjusted; therefore, CC-3, CC-5, and CC-6 are represented by the same line.

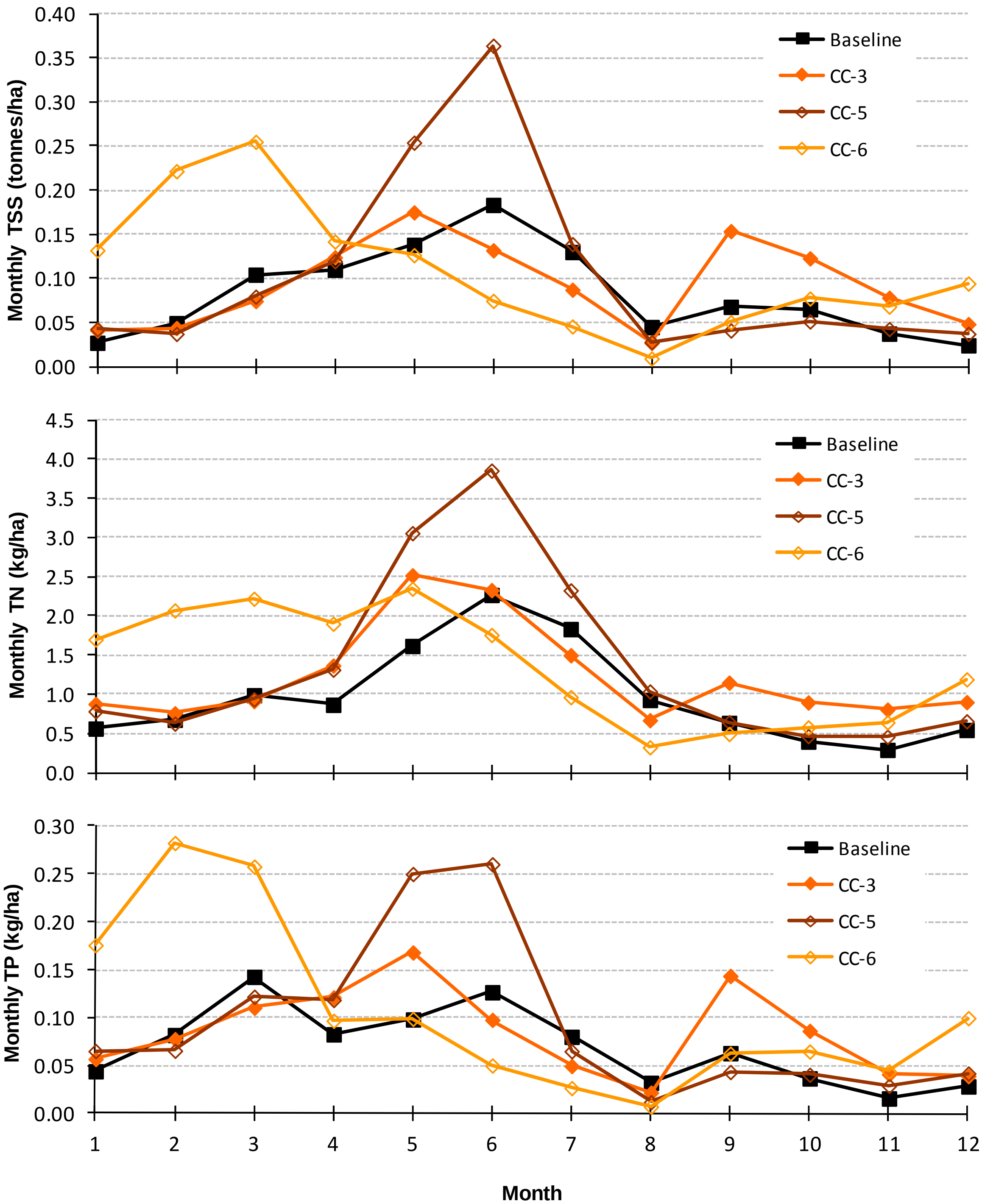


Figure 3-9. Mean monthly TSS (tones/ha), TN (kg/ha), and TP (kg/ha) for the CC-3, CC-5, CC-6, and baseline scenarios.

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	0.9	1.6	2.3	1.8	0.9	0.6	0.4	0.3	0.5	0.9
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	1.0
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	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	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	0.10	0.13	0.08	0.03	0.06	0.04	0.02	0.03	0.07
CC-1	0.10	0.07	0.08	0.09	0.20	0.19	0.05	0.01	0.03	0.03	0.02	0.03	0.07
CC-2	0.10	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	0.10	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	0.10	0.10	0.05	0.03	0.01	0.06	0.07	0.04	0.10	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	0.10	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	0.10	0.03	0.09	0.06	0.03	0.02	0.08
CC-3	0.03	0.02	0.10	0.17	0.29	0.20	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	0.10
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 annual precipitation (mm), mean annual temperature (°C), mean annual streamflow (cms), and mean annual loads of TSS (tonnes/ha), TN (kg/ha), and TP (kg/ha) for all scenarios.

Climate Scenario	Total Annual Precipitation, mm	Mean Annual Temp., °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

The influence of monthly variation in precipitation and temperature is further illustrated 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 (see Figure 3-8). 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 (see Figures 3-8 and 3-9). This scenario also had the highest mean annual streamflow and pollutant loadings, indicating potential risk from higher precipitation volumes in the winter and spring (see Table 3-14).

Summary

This study assessed the sensitivity of a predominantly agricultural watershed, the Raccoon River, to climate change. The primary BASINS CAT features used in this study were the ability to automate the adjustment of temperature and precipitation time series data for the SWAT watershed model on a monthly and annual basis, and to apply these changes spatially. 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 on a seasonal and annual basis.

The climate scenarios applied in PARTS 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 investigates how seasonal shifts in climate change (mainly in terms of varied precipitation) can affect mean monthly and annual endpoint results. Although subject to uncertainty, 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 change factors were applied to the baseline weather data of the Raccoon River watershed SWAT model. The comparison of the climate scenarios to each other and the baseline illustrates the potential effects of seasonal shifts of climate on streamflow and pollutant loadings in the Raccoon River watershed, especially precipitation as in Scenarios CC-5 and CC-6.

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

This case study illustrates the use of BASINS CAT with an event-scale SWMM model to assess the sensitivity of urban stormwater runoff and pollutant loading to climate change.

PART A evaluates stormwater runoff, nutrient, and TSS concentrations from an urban redevelopment site under a set of event scenarios. BASINS CAT was used to increase the total volume of a hypothetical design rainfall event by 10, 20, and 30%.

PART B evaluates the effectiveness of two management scenarios to meet a hypothetical stormwater goal under the same precipitation change scenarios as in PART A. The management scenarios considered in PART B were a no management (baseline) scenario, a distributed management scenario, and a centralized stormwater management scenario.

Introduction

The impacts of urban stormwater runoff on local water bodies have made it a high management priority in many cities. Impervious cover associated with roads, rooftops and compacted soil can alter hydrologic processes resulting in increased stormwater runoff, channel erosion, reduced groundwater recharge and decreased baseflow during dry weather. Stormwater runoff can also carry urban pollutants into stormwater systems and nearby streams. Urbanized watersheds generally exhibit a high sensitivity to rainfall and snowmelt events. Changes in precipitation could significantly alter stormwater runoff volumes and pollutant loading from urban environments.

PART A of this case study investigates the sensitivity of stormwater runoff from a commercial redevelopment site to precipitation change at the event scale. 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 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 management scenarios where stormwater BMPs were employed to investigate the benefits of alternative stormwater management options 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 (HUC 03010101) in southwest Virginia (see Figure 3-10; Young et al., 2009). Prior to redevelopment, the site was comprised of a few small commercial buildings and a motel. Since 2008, it has undergone 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 surfaces represent 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 tops.

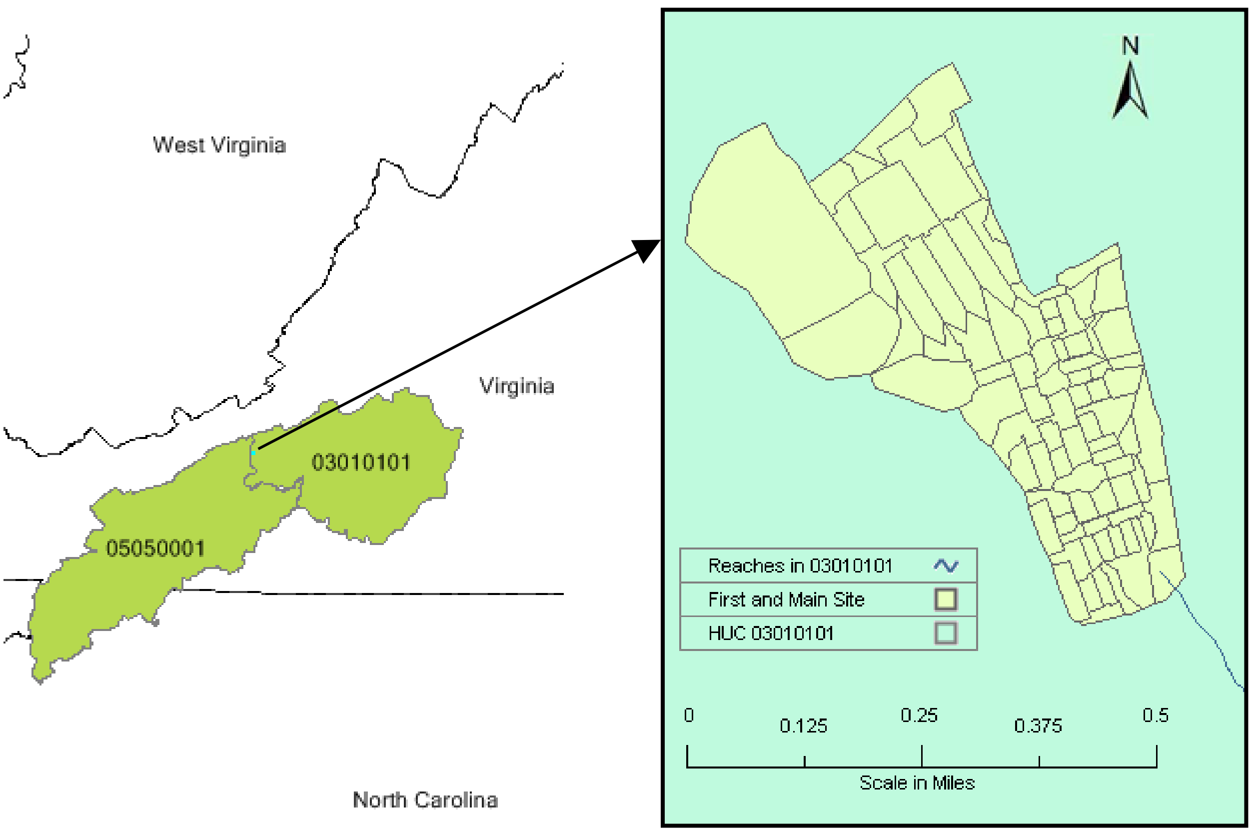


Figure 3-10. The commercial redevelopment site in the Upper Roanoke River watershed in Virginia, USA.

Table 3-15. Baseline land-use summary for the commercial redevelopment site.

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

Water Model Setup

Stormwater modeling requires consideration of individual rainfall-runoff events. A preexisting SWMM model was acquired from a previous study to evaluate an optimization tool for improving site development and stormwater BMP selection in Virginia (Young et al., 2009). The SWMM model, while capable of running on a continuous time-scale, was developed for running event-based simulations. The original study included consideration of a baseline scenario with no runoff control measures and two alternative stormwater management scenarios. The model included subwatershed delineation and hydrologic discretization of the SWMM hydraulic schematic.

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 (Soil Conservation Service) Type II storm that has a 31.7-mm/hr rainfall intensity for a 1-hour duration. The model simulation duration is 2 days with a 1-hour design event in the beginning hour of the simulation period. Temperature data were acquired from the nearby NCDC weather station in Blacksburg, VA (440766). Initial assessment of model simulations indicated that temperature was not a significant factor in determining endpoint values given the short timescale of the event. Therefore, while changes in temperature are included in climate change scenarios, results are presented only for changes in precipitation.

PART A: Runoff Sensitivity Analysis

Scenario Development: PART A

A total of four model simulations were completed. Scenarios included one baseline precipitation scenario and three 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 Climate Wizard web site. See Section 3.2 for more information on these models. Projected changes in mean annual precipitation ranged from −17 to +27%.

The climate scenarios for input to SWMM were developed using the BASINS CAT capability to create ***multiple changes within 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% by increments of 10%, 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.

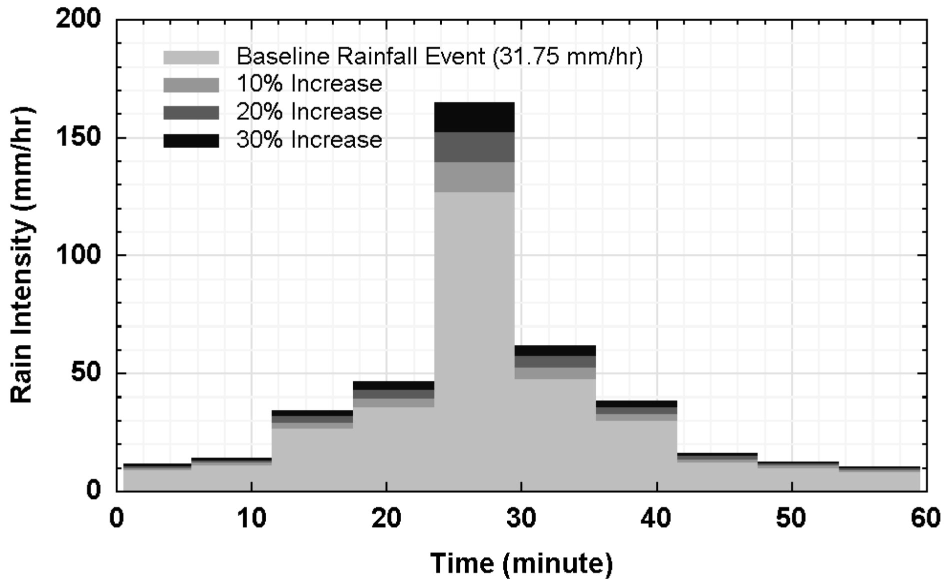


Figure 3-11. Rainfall event intensity for the baseline rainfall event and three precipitation change scenarios.

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 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 major 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 BASINS CAT ***pivot table*** capability, shows the resulting event values for the baseline and three precipitation scenarios. Precipitation depths (mm/hr) are presented as sum totals for the event, while stormwater flow rate (cms), TSS (mg/L), and TP (mg/L) 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. The flow increases of 14, 28, and 38% followed a nearly linear response to the 10, 20, and 30% increase in rainfall volume, respectively. While TSS and TP concentrations increased, the rate of increase diminished as precipitation volume increased. This response is expected 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 (mm/hr), stormwater flow rate (cms), and concentrations of TP (mg/L) and TSS (mg/L) for the baseline and three precipitation change scenarios.

	Rainfall and Endpoints			
Scenarios	**Event Rainfall Intensity (mm/hr)**	**Flow (cms)**	**TSS (mg/L)**	**TP (mg/L)**
Baseline	31.75	0.021	0.98	0.42
+10%	34.90	0.024	1.02	0.47
+20%	38.10	0.027	1.05	0.50
+30%	41.30	0.029	1.05	0.51

PART B: Management Options Assessment

Scenario Development: PART B
A total of 12 model simulations were completed. Scenarios included 1 baseline precipitation scenario and 3 precipitation change scenarios, and 3 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 alternative stormwater management options only.

Management Scenarios
A baseline scenario with no stormwater BMPs (PART A) and two scenarios representing different stormwater management strategies were included:

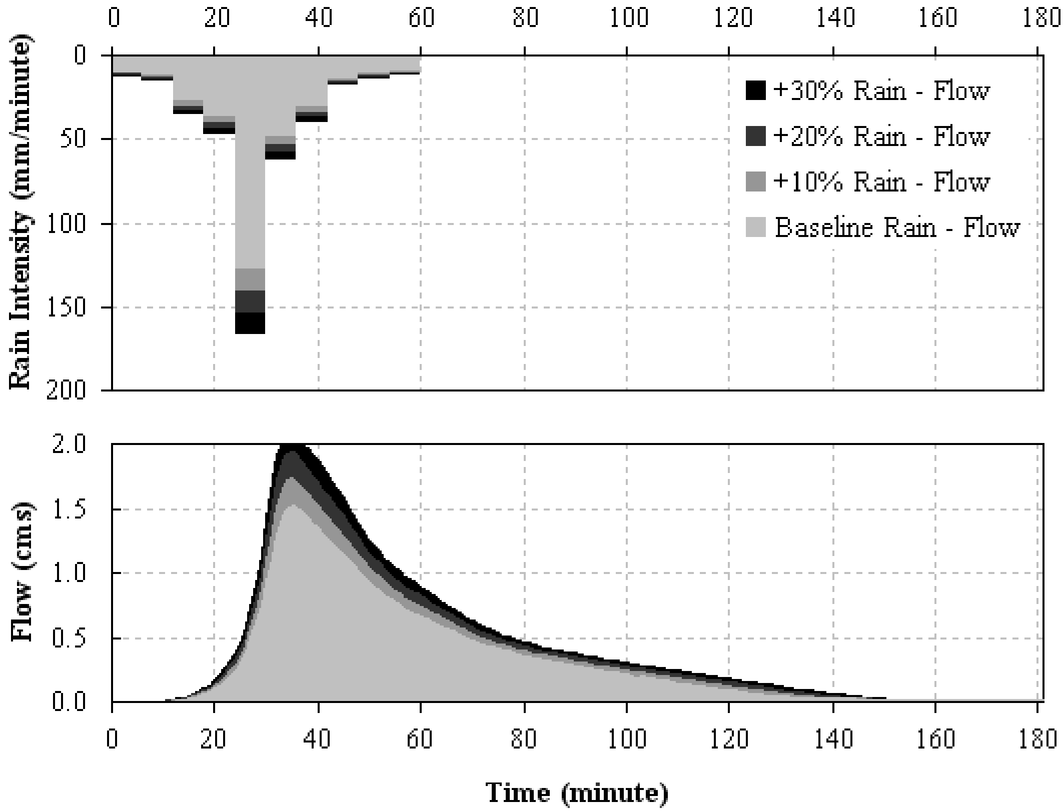


Figure 3-12. Event rainfall intensity vs. stormwater flow rate at the site outlet for the baseline and all precipitation change scenarios.

- **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 only on stormwater runoff at the redevelopment site outlet. An arbitrary management target of maintaining stormwater runoff below 0.02 cms was selected (defined as 0.7 cfs in Figure 3-13 because BASINS CAT uses the native units for the selected model, in this case SWMM uses English units) to illustrate a BASINS CAT capability for flagging simulation

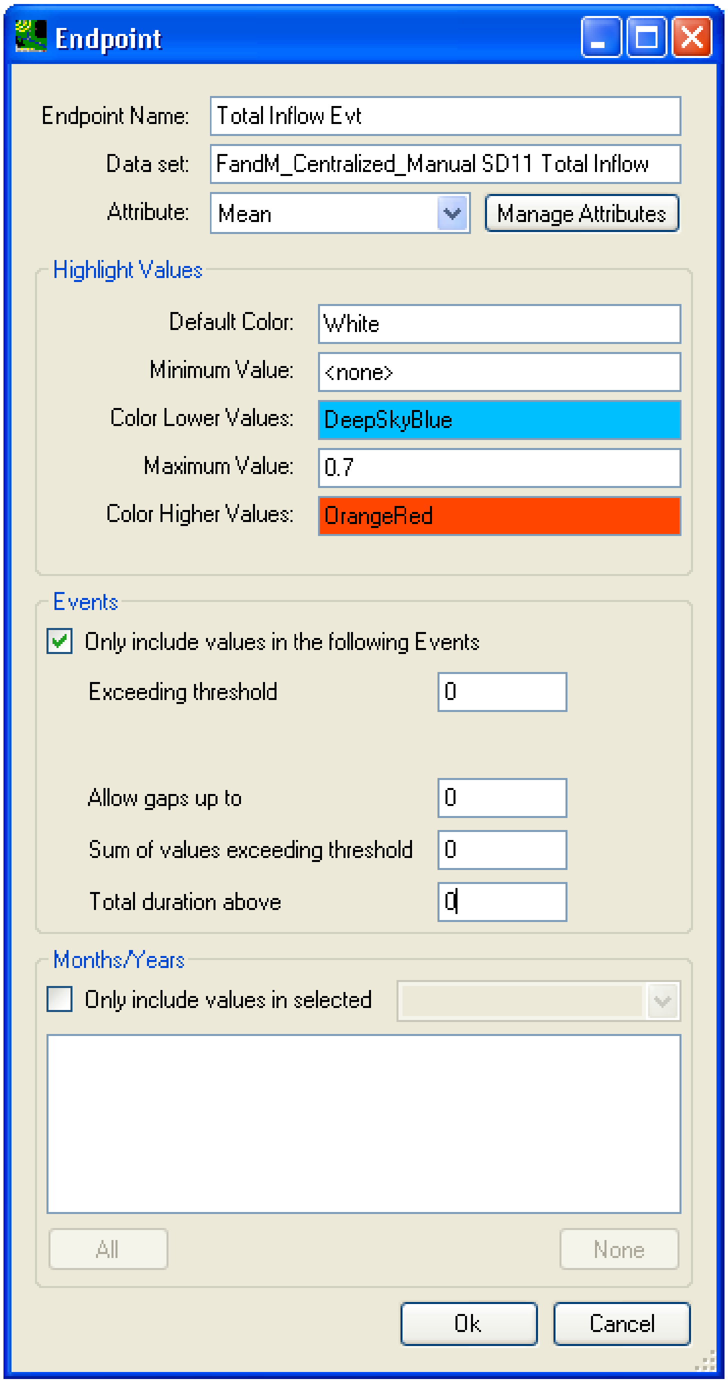


Figure 3-13. BASINS CAT *Endpoint* window where users can specify endpoints, endpoint statistics, and *Highlight Values* thresholds for color coding the results. *Endpoint Name* is user specified; *Data set* is the time series to be modified; *Attribute* is the end point statistic to be considered; *Highlight Values* indicates the endpoint threshold value used for color coding the results, in this case study, 0.7 cfs (0.02 cms).

results above or below a user-specific threshold. This capability can be useful for screening results when a large number of scenarios are evaluated. BASINS CAT allows users to specify such thresholds and color code endpoint values that exceed it using the ***Highlight Values*** option (see Figure 3-13).

Results: PART B

Changes in event rainfall intensity resulted in increased stormwater flow rates across the baseline and alternative management scenarios (see Table 3-17). The simulation results indicated that the mean flow rate at the outlet is the highest with the baseline, followed by centralized management, and then distributed management. The event rainfall dynamic and runoff hydrograph for the baseline and alternative management 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. The centralized management scenario 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 3-14) 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.

Figure 3-15 illustrates the option within BASINS CAT to display simulation results with endpoint values color-coded based on a user-specified threshold 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 rate (cms) under all precipitation change and stormwater management scenarios.

Scenario	**Baseline**	**+10%**	**+20%**	**+30%**
Precipitation (mm/hr)	**31.7**	**34.9**	**38.1**	**41.3**
Baseline (no management)	0.021	0.024	0.027	0.029
Centralized managment	0.016	0.019	0.022	0.025
Distributed managment	0.004	0.006	0.008	0.011

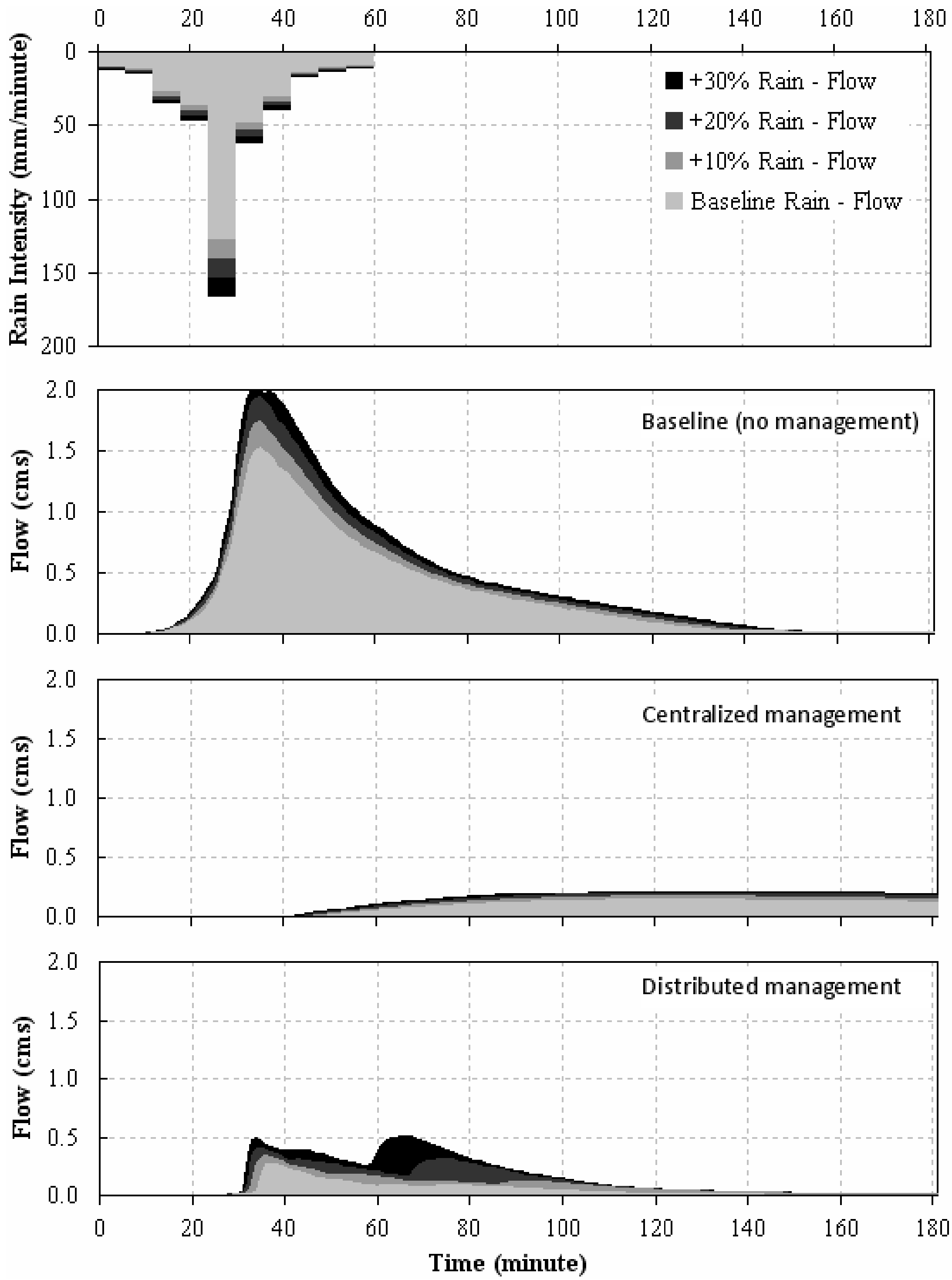


Figure 3-14. Rainfall vs. flow dynamics at the site outlet for all precipitation change and management scenarios.

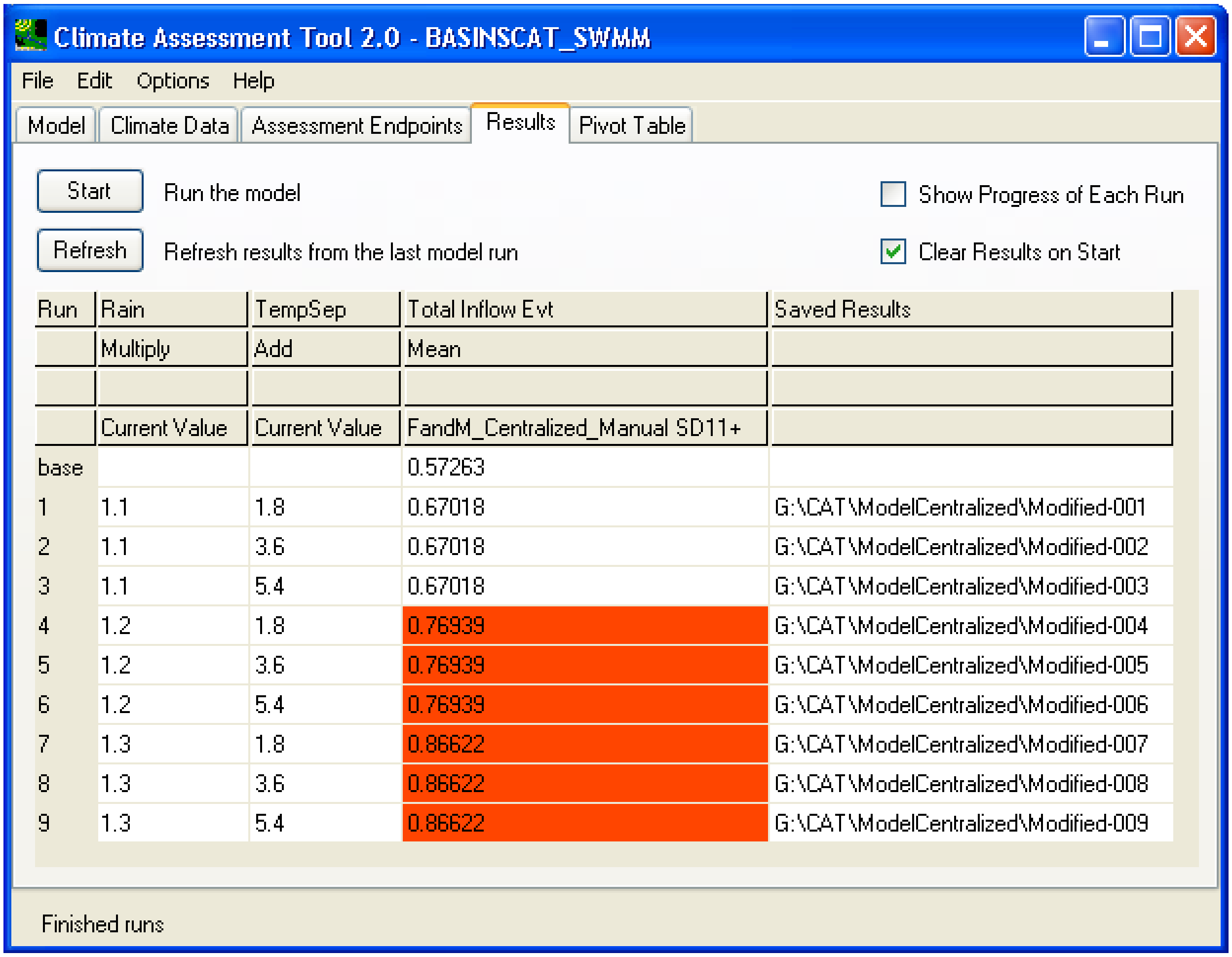


Figure 3-15. BASINS CAT window for the centralized management scenario showing the color-coded mean stormwater flow rate values that are above the specified maximum threshold defined in Figure 3-13. Temperature (TempSep) was included in the model, but it did not have an impact on the endpoints.

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 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 ***Results*** grid. This can be a very helpful feature for 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 management scenarios, baseline with no stormwater management, centralized management, and distributed management. 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 stormwater flow rate; the centralized approach resulted in the longest duration of stormwater 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. These capabilities can be an important addition to the tools used by stormwater managers to design, manage, and maintain stormwater infrastructure.

3.4. AGRICULTURAL SEDIMENT YIELD SENSITIVITY TO CLIMATE CHANGE AND MANAGEMENT PRACTICES IN BLUE EARTH COUNTY, MN, USING WEPPCAT

Case Study Overview

This case study uses WEPPCAT to conduct a sensitivity analysis of sediment yield from agricultural fields under different climate change, land use, and crop management scenarios.

In PART A, the sensitivity of soil erosion to changes in land use, crop management, and climate are evaluated. Land-use scenarios include a 30 m × 30 m field with either Lasa or Lerdal soil series with a slope of 2 or 5%. Crop management scenarios include corn spring chisel plow and soybean spring chisel plow. Climate change scenarios considered are:

- temperature increases of 0, 2, and 4°C.
- precipitation volume adjustments of −10, 0, +20%.
- precipitation intensity increases of 10%.

PART B evaluated the effectiveness of additional management practices, specifically alternative tillage practices and riparian filter strips, for reducing soil erosion under a single land use scenario and the same climate change scenarios evaluated in PART A.

Introduction

Agricultural crop production can be disruptive to soil structure, resulting in significant soil erosion during runoff events. In regions of the country where agriculture constitutes a significant percentage of land use, soil erosion can have a significant impact on water quality. Land managers often employ crop management practices to reduce agricultural impacts on surface water including cover crops, alternative tillage, and vegetated riparian filter strips that reduce soil erosion and remove sediment from runoff.

Climate change could have a significant influence on erosion processes in agricultural areas. This case study investigates the sensitivity of agricultural fields under corn and soybean production in Blue Earth County, MN, and the potential effectiveness of different crop management practices for reducing sediment yields from agricultural fields under a range of future climate change scenarios. In PART A, WEPPCAT was used to assess the sensitivity of farm fields under conventional corn and soybean 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 evaluate the potential effectiveness of alternative crop management practices, including filter strips and alternative tillage methods, for reducing climate change impacts on sediment yields.

Location Description
Blue Earth County, MN is located in the south-central part of Minnesota, one of the top producing regions of corn and soybeans in the United States (USDA, 2012a). The County is suitable for corn and soybean production given the generally flat topography, good soil quality, and ample precipitation (USDA, 2012b). Local soils are generally well drained and classified under Hydrologic Groups A and B (high infiltration and water-holding capacity) (USDA, 2012b). Topographic slopes in the County range from 0 to over 15%.

Model Setup
All WEPPCAT simulations in this case study were conducted online at http://typhoon.tucson.ars.ag.gov/weppcat/index.php. Data inputs required to run WEPPCAT include site/field characteristics (field length and width, hillslope shape, slope, and soil type), crop management, and riparian filter strip characteristics. Required meteorological inputs were acquired internally by WEPPCAT by selecting an appropriate NCDC weather station. One hundred years of daily meteorological inputs representing each climate change scenario are generated internally in WEPPCAT using the Cligen weather generator. WEPPCAT results are average values for 100-year simulations. The WEPP model does not require calibration.

PART A: General Sensitivity Analysis

Scenario Development: PART A
A total of 144 model simulations were completed. Scenarios included 1 baseline climate scenario and 17 climate change scenarios, 4 land-use scenarios, and 2 crop 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 for this region of the nation based on statistically downscaled data from 16 CMIP3 climate models acquired from the ClimateWizard web site. See Section 3.2 for more information about these data. Projected changes in temperature ranged from approximately 2°C to 7°C, and projected changes in precipitation volume ranged from approximately −23 to +33%.

Daily meteorological data for WEPPCAT simulations are generated by the Cligen stochastic weather generator using monthly weather statistics at NOAA NCDC weather stations. Climate change scenarios are created in WEPPCAT by adjusting monthly weather statistics inputs to Cligen. 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, WEPPCAT also has the capability to adjust Cligen parameters to increase the proportion of annual rainfall occurring in large magnitude events. The proportion of annual precipitation occurring in large magnitude events can be increased up to 25%. These adjustments in precipitation intensity are made by applying the user-determined increase to the largest 5% of events, and simultaneously decreasing precipitation in the lower 95% of events such that there is no or negligible net change in annual precipitation volume.

In this case study, 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 the two soil series of interest. The climate change scenarios consisted of a matrix of adjustments representing different combinations of potential changes in temperature, precipitation volume, and precipitation intensity. The meteorological data were adjusted in the following manner:

- Average annual temperature was increased by 0, 2, and 4°C
- Average annual precipitation volume by −10, 0, and +20%. These scenarios are designated as volume (V)(-10), V(0), and V(+20), respectively

Precipitation was then adjusted to assess the effects of increased event intensity (proportion of annual precipitation occurring in large magnitude events). This was accomplished by first adjusting the annual precipitation volume by −10, 0, and +20%, and then increasing proportion of annual precipitation occurring in the largest 5% of events by 10%. This scenario is designated as intensity (I)(+10)[1].

Land-use Scenarios
PART A included a total of four land-use scenarios for a 30 m × 30 m farm field. Land-use scenarios included different combinations of two Blue Earth County soil series, Lasa and Lerdal, and two uniform topographic slope gradients, 2 and 5%. The Lasa soil series is classified as Hydrologic Group A (high infiltration and water-holding capacity), and the Lerdal soil series is classified as Hydrologic Group C (low infiltration and water-holding capacity).

Crop Management Scenarios
The two crop management scenarios evaluated are corn spring chisel plow and soybean spring chisel plow. Land management options that can be represented in WEPPCAT simulations are predefined and fixed in terms of tilling, planting, and harvesting dates and methods (see Tables 3-18 and 3-19).

Endpoint Selection: PART A
The endpoints simulated by WEPPCAT are the same as the 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 of the slope minus any retained by a filter strip (if applicable).

[1] "Rainfall intensification 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 defined by the model user. In this case study, it resulted in a minor 1−2 % decrease in average annual rainfall. For example, in the V(-10) scenario, a 10% decrease in volume results in 26.8 inches of rain per year, while a 10% decrease in rainfall plus a 10% increase in rainfall intensity in the largest 5% of events 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.

Table 3-18. Soybean 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 plow 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

Results: PART A

Simulation results are shown in Tables 3-20 and 3-21 and Figures 3-16 to 3-18. Results illustrate the sensitivity of sediment yield to increases in precipitation volume and intensity. The greatest change was observed for the scenario V(+20) + I(+10), with a simulated sediment yield close to double the yield under the baseline scenario (see Tables 3-20 and 3-21 and Figure 3-16). This illustrates the synergistic effect of increasing precipitation volume and intensity on sediment yield. Results also suggest that increases in volume have a greater impact on the overall increase in sediment yield versus intensity alone. For example, under historic weather conditions (V(0)), the Lasa soil at a 2% slope under corn production yielded 4.9 tonnes/ha/yr of sediment (see Table 3-20). Increasing the precipitation volume 20% resulted in a 7.4 tonnes/ha/yr sediment yield, a 51% increase, while the combined effect of increasing the precipitation volume 20% and event intensity 10% resulted in 8.3 tonnes/ha/yr, a 69% increase (see Table 3-20).

Field slope, soil hydrologic group, and crop type influenced sediment yield under all climate scenarios. For example, as expected, a 2% slope resulted in a lower sediment yield versus a 5% slope (see Figures 3-17 and 3-18). Lasa soil also resulted in a lower sediment yield versus Lerdal, likely due to the soil properties affecting infiltration and water-holding capacity (hydrologic group classification) (see Figure 3-17). Finally, corn production resulted in a much lower sediment yield versus soybeans (see Figure 3-18).

Table 3-20. Mean annual sediment yield (tonnes/ha/yr) for corn production under conditions of changing climate[2]. Scenarios named to reflect changes in precipitation volume and intensity: V = volume, I = intensity, numerical value reflects percent change from baseline. Sediment yield values highlighted in grey indicate the baseline scenarios.

Soil Type and Slope	Temp. Increase, °C	Precipitation Scenarios					
		V(-10)	V(-10) + I(+10)	V(0)	V(0) + I(+10)	V(+20)	V(+20) + I(+10)
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

[2] See Footnote 1 for explanation of discrepancy in annual rainfall values resulting from intensity adjustments.

Table 3-21. Mean annual sediment yields (tonnes/ha/yr) for soybean production under conditions of changing climate[3]. Scenarios named to reflect changes in precipitation volume and intensity: V = volume, I = intensity, numerical value reflects percent change from baseline. Sediment yield values highlighted in grey indicate the baseline scenarios.

Soil Type and Slope	Temp. Increase, °C	Precipitation Scenarios					
		V(-10)	V(-10) + I(+10)	V(0)	V(0) + I(+10)	V(+20)	V(+20) + I(+)10
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

[3] See Footnote 1 for explanation of discrepancy in annual rainfall values resulting from intensity adjustments.

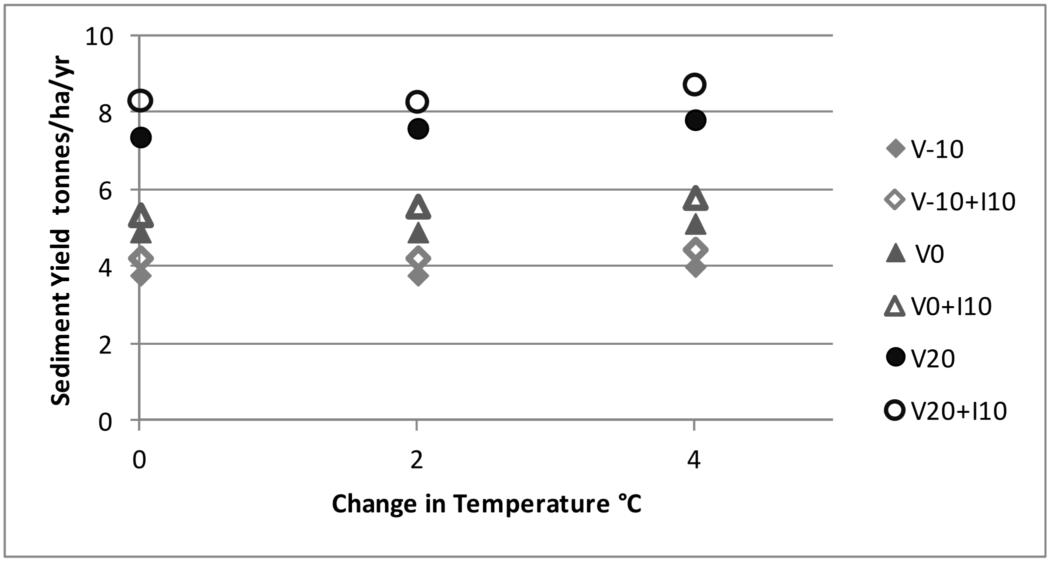


Figure 3-16. Mean annual sediment yield for Lasa soil at 2% slope under corn production for all climate change scenarios.

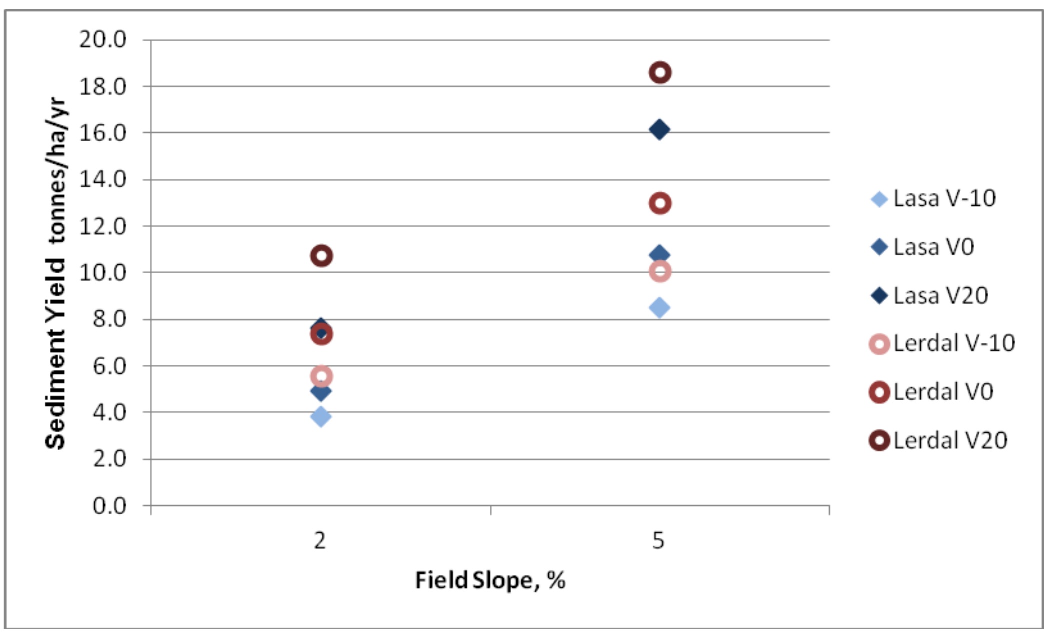


Figure 3-17. Mean annual sediment yield for the Lasa and Lerdal soil under corn production for three climate change scenarios.

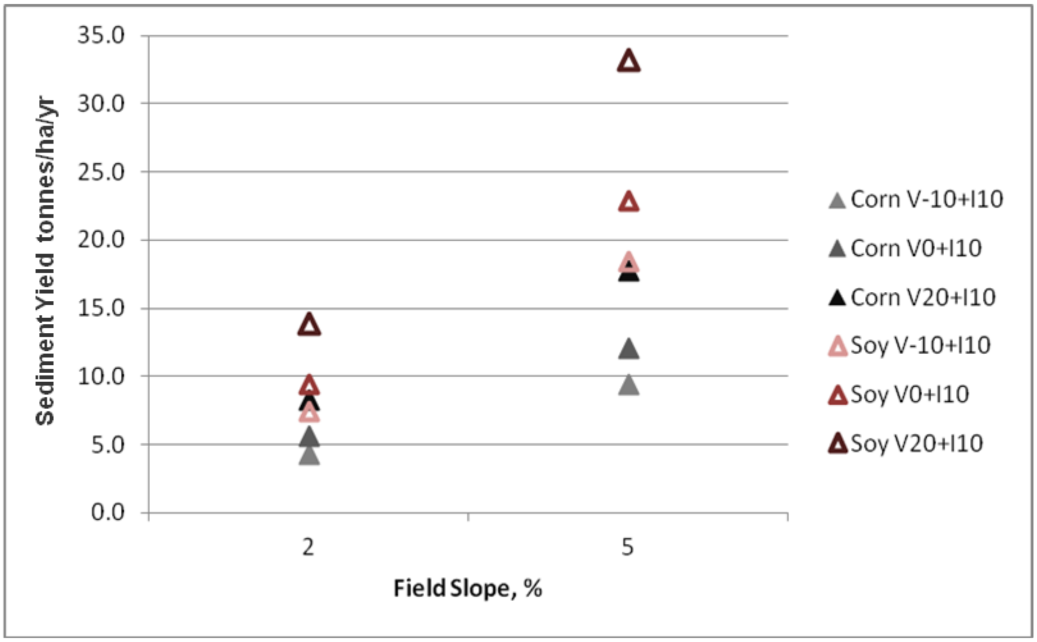


Figure 3-18. Mean annual sediment yield for Lasa soil under corn and soybean production for three climate change scenarios.

PART B: Managing Soil Erosion under Climate Change

Scenario Development: PART B

A total of 108 model simulations were completed. Scenarios included 1 baseline climate scenario, 5 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 change scenarios consisted of a matrix of different combinations of potential changes in temperature and precipitation. Mean monthly temperatures were increased by 0, 2, and 4°C. Mean monthly precipitation volumes were increased by 0 and 20%. Precipitation was further adjusted to assess the impact of increasing intensity. Similarly to PART A, this was accomplished by first increasing the precipitation volume by 20% and then increasing the intensity by 10%.

Land-Use Scenarios

PART B evaluates only one land-use scenario, a 30 m × 30 m farm field with Lerdal soil at a 5% 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 because they represent a “worst case” scenario for a field under crop production in Blue Earth County, MN based on the results from PART A.

Crop Management Scenarios
PART B was designed to assess the effectiveness of implementing additional crop management practices including alternative tillage practices and grass and forest filter strips for reducing sediment yield under a range of climate change scenarios. As a baseline, the corn spring chisel plow crop management scenario from PART A was selected. Two scenarios representing additional crop management practices were selected from a predetermined set of options available in WEPPCAT for evaluation: corn no-till and corn fall mulch till (see Tables 3-19, 3-22, and 3-23). WEPPCAT also provides the option of including a riparian filter strip to assess potential reductions in sediment yields. Six scenarios representing grass and forest filter strips 3, 6, and 9 m wide by 30 m long were also evaluated. A baseline scenario with no filter strip was also included for comparisons under each climate change scenario and tilling practice.

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
The endpoints simulated by WEPPCAT are the same as the 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 of the slope minus any retained by a filter strip (if applicable).

Results: PART B
The model simulations provide a general assessment of the potential sediment yield associated with varying degrees of climate change and different crop management options (see Table 3-24). 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 marginal returns with sediment reduction as the filter strip width increased from 3 to 9 m (see 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 and width: NB = no buffer, GB = grass buffer, FB = forest buffer, 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. Values highlighted in grey indicate baseline scenarios.

Temp (°C) Increase	Buffer	Corn Fall Mulch			Corn No Till			Corn Spring Chisel		
		V(0)	V(+20)	V(+20) + I(+10)	V(0)	V(+20)	V(+20) + I(+10)	V(0)	V(+20)	V(+20) + I(+10)
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

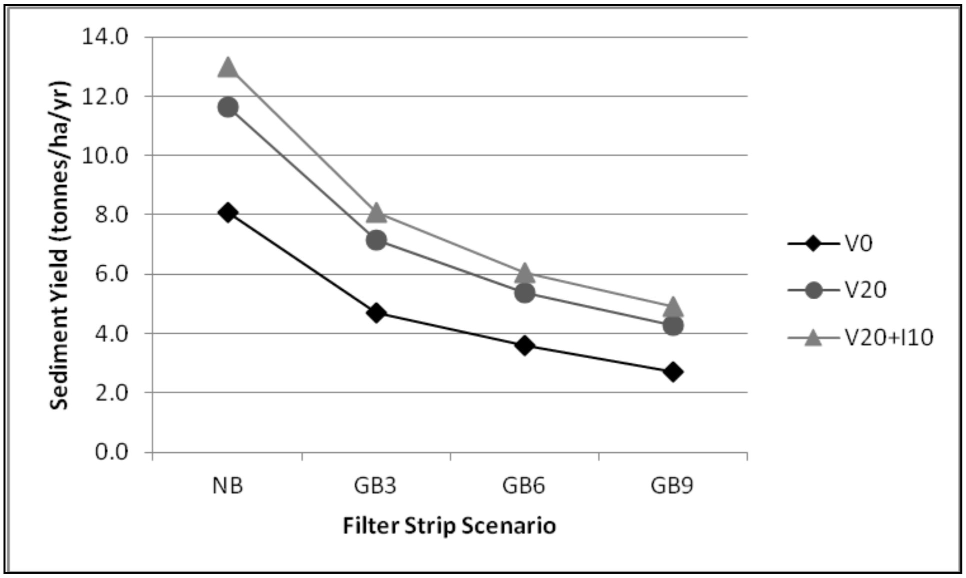


Figure 3-19. Sediment yield (tonnes/ha/yr) under corn fall mulch till with a 3, 6, and 9 m grass buffer. Buffers named to reflect cover and width: NB = no buffer and GB = grass buffer, numerical value signifies width. Precipitation scenarios named to reflect changes in volume and intensity: V = volume, I = intensity, numerical value reflects percent change from baseline.

The simulation results can be used to characterize sensitivity to climate change (see Table 3-24). For example, the simulation for a field under corn spring chisel plow and current climate conditions without a buffer resulted in a sediment yield of 11.2 tonnes/ha/yr (see Table 3-24). If climate change resulted in a 20% increase in annual rainfall (V(+20) scenario) and a 2°C increase in temperature, the sediment yield would be 18.6 tonnes/ha/yr, a 66% increase over current yields (see Table 3-24). A land owner could also use the model simulations to determine potential options for not only maintaining current sediment yield, but also identifying ways to reduce sediment yield under current and altered climate regimes. As indicated in Table 3-25, certain crop management practices and/or filter strips could meet both of these management goals. If, for example, the land owner wanted to maintain a sediment yield of 6 tonnes/ha/yr or less under the V(+20) precipitation scenario, a number of options may exist. No-till for corn production was by far the superior management practice for reducing sediment yield under the V(+20) scenario (see Table 3-25). 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 tonnes/ha/yr (see Table 3-25).

Table 3-25. Sediment yield (tonnes/ha/yr) results from a 2°C increase in temperature and a 20% increase in mean annual rainfall volume. Buffers named to reflect cover: NB = no buffer, GB = grass buffer, and FB = forest buffer, numerical value signifies width. Grayed cells signify tillage and filter strip combinations producing 6 tonnes/ha/year or less of sediment.

	Corn Fall Mulch	Corn No Till	Corn Spring Chisel
Buffer	V(+20)	V(+20)	V(+20)
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 investigate the sensitivity of sediment yields from farm fields to climate change and alternative crop management practices. WEPPCAT enables users to efficiently create and run a large number of climate change and crop management scenario combinations to assess potential changes in sediment yields. 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 under the most extreme climate change scenarios were almost double compared to the baseline 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.

PART B of this case study evaluates the effectiveness of alternative crop management options for reducing sediment yields under a range of climate change scenarios. The findings indicated that sediment yields could potentially be reduced or prevented under the most extreme climate change scenarios if certain management practices are employed. This type of information can be used to identify locations within watersheds that are vulnerable to increased sediment loading, and to develop appropriate management strategies for adapting agricultural land to climate change.

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 assess the sensitivity of streamflow, TN, and TSS loads to three different types of potential precipitation change. BASINS CAT capabilities for modifying precipitation were used to increase precipitation by 10 and 20% in the following ways:

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

All change scenarios also included a constant temperature increase of 2°C. Potential evapotranspiration was recalculated with BASINS CAT to reflect this change.

Introduction

Climate change is anticipated to result in regionally variable changes in precipitation amount, frequency, and intensity throughout the nation (IPCC, 2007). While subject to uncertainty, many regions are expected to see an overall increase in precipitation volume and average event intensity. The effects of precipitation change on streamflow and water quality endpoints will vary depending on the specific type of change that occurs and local watershed physiographic, land-use, and water management conditions.

This case study investigates the effect of different types of precipitation change on streamflow and water quality endpoints in the Tualatin River, OR, using BASINS CAT with an HSPF model. It highlights BASINS CAT capabilities for creating precipitation change scenarios representing changes in precipitation amount, event frequency, or average event intensity.

Location Description

The Tualatin River (HUC 17090010) drains 1844 km^2 in northwest Oregon and is a tributary of the Willamette River (see Figure 3-20). Land use includes densely populated areas, agriculture, and the forests of Oregon's Coast Range, Tualatin, and Chehalem Mountains. Most of the fast-growing urban population, approximately 500,000 residents, resides on 15% of the watershed's area. About 35% of the watershed is used for agriculture, and about 50% of the watershed is forested.

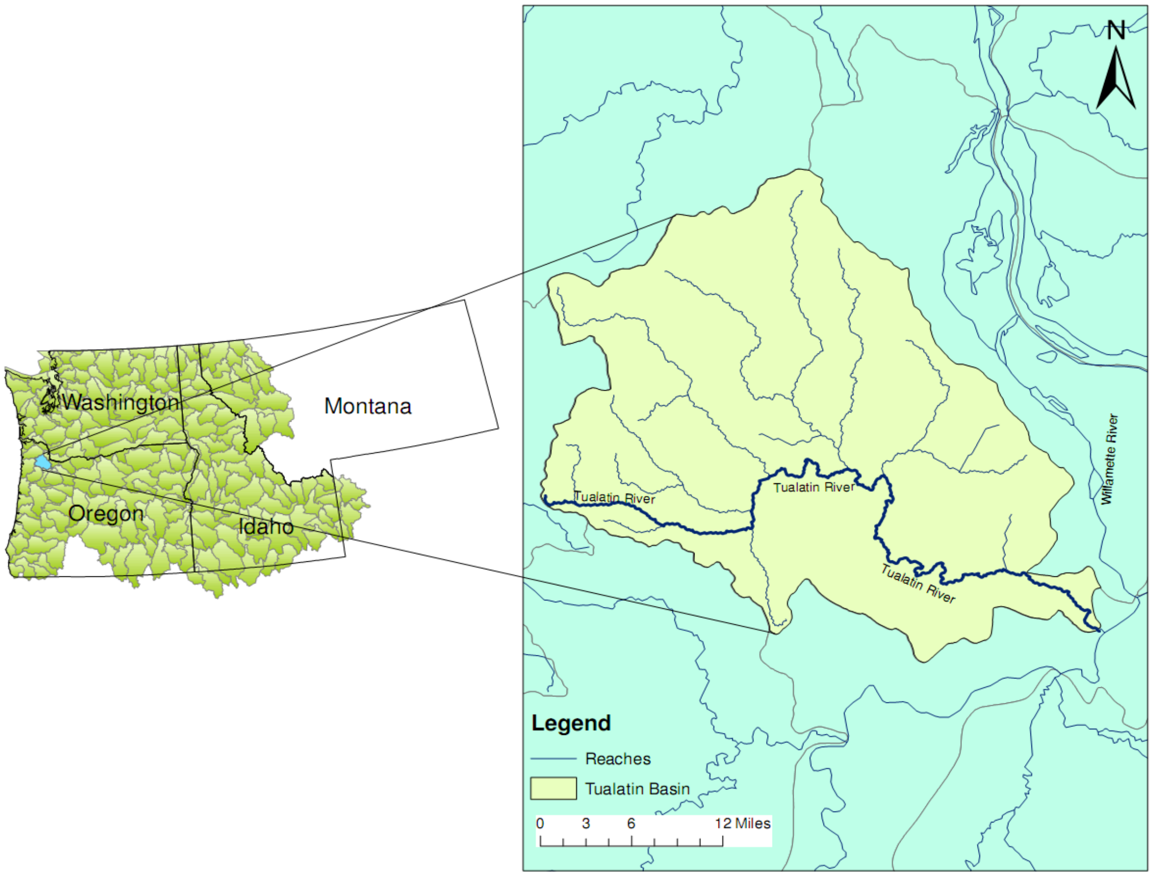


Figure 3-20. Tualatin River watershed location, Oregon, USA.

Water Model Setup

A preexisting, calibrated HSPF model of the Tualatin River was acquired from an earlier study of the entire Willamette watershed (Johnson et al., 2011). Model segmentation was based on intersections of land use, hydrologic soil group, and available NCDC weather stations. Soils data were from the STATSGO data set, and land-use was from the 2001 NLCD. Meteorological data used as input to the model were from NCDC weather stations at Beaverton (350595), Buxton (351222), and Forest Grove (352997).

The baseline model data were 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. Brief summaries of calibration and validation results are provided in Tables 3-26 and 3-27.

Table 3-26. Tualatin River HSPF model daily streamflow calibration and validation results. NSE: Nash-Sutcliffe Efficiency coefficient (Nash and Sutcliffe, 1970); E' (Garrick et al., 1978); R^2: Coefficient of Determination.

	Calibration (1995−2005)	Validation (1985−1995)
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 and validation results. Relative Percent Error is the average of observed-simulated divided by observed comparisons. Median Percent Error is the median of observed-simulated comparisons divided by average of observed values.

Endpoint Statistic	Calibration (1991−1995)	Validation (1986−1990)
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 seven model simulations were completed. Scenarios included one baseline climate scenario and six 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 temperature and precipitation changes for this region based on statistically downscaled data from 16 CMIP3 climate models acquired from the Climate Wizard web site. Section 3.2 provides additional information about these climate model projections. Projected mid-century temperature changes for this region ranged from approximately 1°C to 2.5°C, and projected changes in annual precipitation from approximately −10 to +18%.

Six climate change scenarios were created by applying change factors to baseline historical temperature and precipitation data using BASINS CAT. Each scenario included a constant temperature increase of 2°C applied to each temperature value in the baseline record. PET records were also revised using the BASINS CAT ***Penman-Monteith*** option to account for temperature changes. Six precipitation changes were created by increasing annual precipitation volume by 10 and 20% in three different ways (see Figure 3-21):

- applying a constant percent increase to all values in the baseline record using the ***Multiply Existing Values by a Number*** option (*constant increase*)
- defining events and applying a constant percent increase to all values within the largest 30% of events using the ***Multiply Large/Small Events by a Number*** option (*intensity increase*)
- randomly generating and adding values to the baseline record using the ***Add/Remove Storm Events*** option (*frequency increase*)

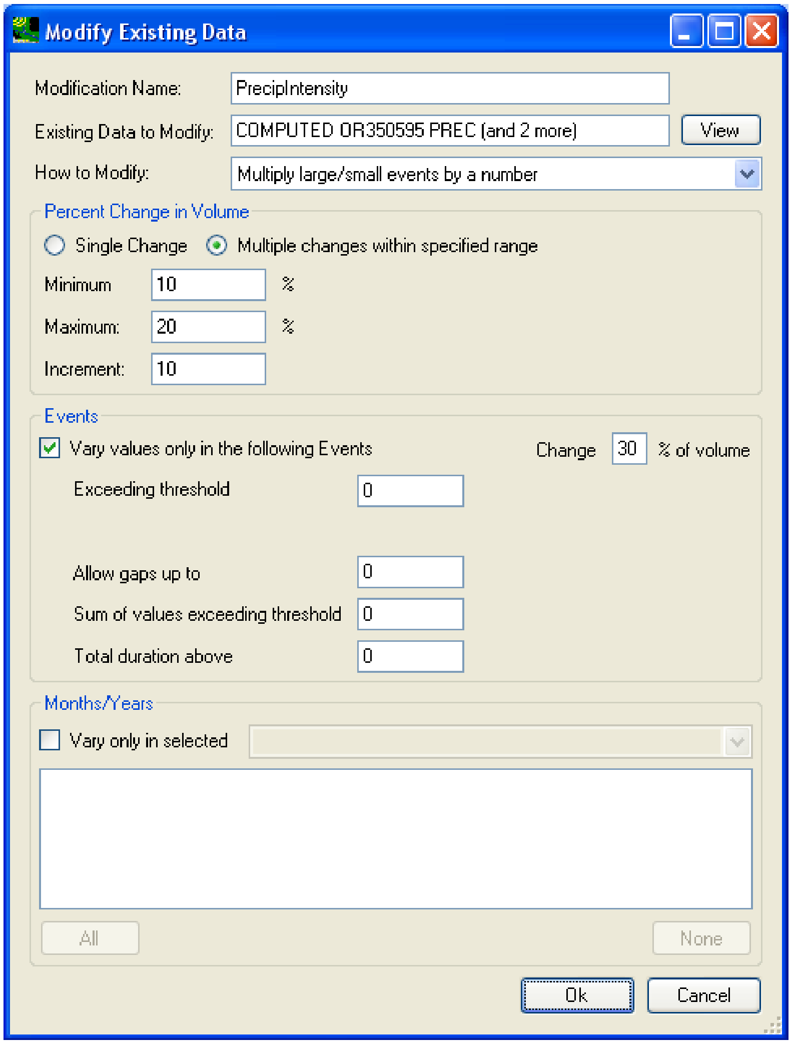


Figure 3-21. BASINS CAT *Modify Existing Data* window specifying the criteria for developing the intensity increase scenario. *Modification Name* identifies the scenario; *Existing Data to Modify* is the time series to be modified; How to Modify is the type of modification applied to the time series; Percent Change in Volume is where the range and increments of change are specified; Events is where the specific events to be modified are defined.

A time-series plot for a small portion of the modeled precipitation record for each climate change scenario is shown in Figure 3-22. The figure shows an example of how a 20% 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. The three precipitation events shown in Figure 3-22 illustrate the differences between the three methods. The event beginning on October 28, 1986 at 16:00 hours is a new event added by the frequency increase scenario. The event beginning October 29, 1986 at 0:00 hours shows the changes applied for a 2-hour event that is in the top 30% of the original record. The lowest values (light solid line) represent the frequency increase scenario, but this event is actually from the original record. The dashed line represents the constant increase scenario and is, thus, 20% 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% of events. The event on October 29, 1986 beginning at 07:00 hours is from the original record and is a small event that is increased only by the constant increase scenario. The intensity increase scenario modification does not apply because it does not fall within the largest 30% of events.

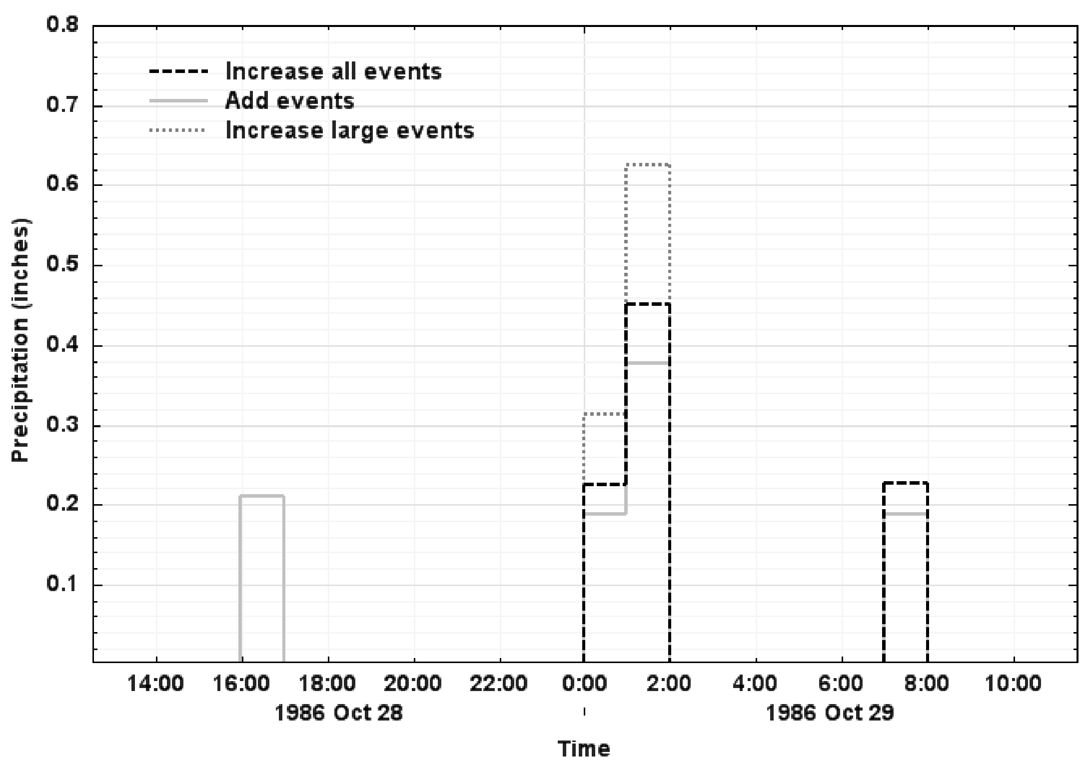


Figure 3-22. Example of precipitation event distribution for the three climate change scenarios. Legend: Increase all events = constant increase scenario; Add event = frequency increase scenario; Increase large events = intensity increase scenario.

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 to evaluate the effects of potential climate change only.

Management Scenarios
Management scenarios were not evaluated in this case study. BMPs or other management practices may have been included in the original HSPF model, but no adjustments were made to evaluate the effects of potential climate change only.

Endpoint Selection
Mean annual streamflow, TSS, and TN were selected as endpoints to evaluate sensitivity of streamflow and water quality to changes in precipitation and temperature.

Results
Simulation results for mean annual streamflow and loadings of TN and TSS are shown in Table 3-28. A key difference among the precipitation change scenarios can be seen in the depth of precipitation of the maximum precipitation event. For both the 10 and 20% increase in annual precipitation volume, the intensity increase scenario resulted in the greatest change in the size of the maximum event, followed by the constant and frequency increase approaches (see Table 3-28). A constant temperature increase of 2^{o}C was also included in all scenarios but is not shown to simplify presentation.

Table 3-28. Precipitation, streamflow and loadings of TN and TSS for all climate scenarios.

Scenario	Precipitation Volume Increase,%	Annual Precipitation, mm	Max Precipitation Event, mm	Mean Streamflow, cms	Annual Load TN, kg/ha/yr	Annual Load TSS, tonnes/ha/yr
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

Mean annual streamflow, TSS, and TN increase in all scenarios, but results suggest different sensitivities of the endpoints to the different types of precipitation change represented. Streamflow (cms) shows the largest response to the constant increase, followed by the frequency increase, and then the intensity increase scenario. Similarly, TN (tonnes/ha/yr) is less impacted by the intensity increase with more substantial, and very similar, responses from the constant increase and the frequency increase. TSS (tonnes/ha/yr) was found to be highly sensitive to the climate change scenarios but responded differently than TN and streamflow. The frequency increase scenario yielded a 14 and 35% increase in TSS (tonnes/ha/yr) for the 10 and 20% scenarios, respectively. The responses to the constant increases are more substantial (33 and 74%, respectively) and the increases in TSS (tonnes/ha/yr) in response to the intensity increases are nearly double those of the constant increase (57 and 140%, respectively). These results suggest increasing precipitation will generally increase TSS loads, however, increasing event intensity has the greatest potential impact.

Summary

This case study illustrates the sensitivity of streamflow and water quality endpoints to changes in precipitation patterns. Scenario analysis using environmental models such as those in BASINS CAT are well suited for this type of analysis. Results indicate that even if annual precipitation volume remains constant, other specific changes in how and when precipitation occurs can have a significant influence on watershed streamflow and water quality endpoints. Of particular note was the response of TSS loads to changes in proportion of annual precipitation occurring as large magnitude events (intensity increase scenario). Further analysis is required. The analysis of additional endpoints, either in the form of new constituents (e.g., TP) or hydrologic response (e.g., peak flow value) may provide further insights into 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 the severity and duration of dry weather events (meteorological drought). A relatively dry period in the historical record (1959−1961) was identified and adjusted using BASINS CAT to create alternative drought scenarios. BASINS CAT was used to increase the average annual temperatures by 2°C and alter precipitation by:

- increasing the severity of the historical dry period by adjusting annual precipitation volume during these years by 0, −10, and −20%.
- extending the duration of the historical dry period by reducing precipitation in two wet years that immediately followed the 1959−1961 dry period.
- extending the duration of the historical dry period as above and increasing the severity of drought by adjusted annual precipitation volume by −10% during these years.

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 drought impacts.

In this case study, BASINS CAT and an HSPF watershed model of Sespe Creek, CA 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 covers an area of approximately 700 km^2 in southwestern California (see Figure 3-23). 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 (see Table 3-29).

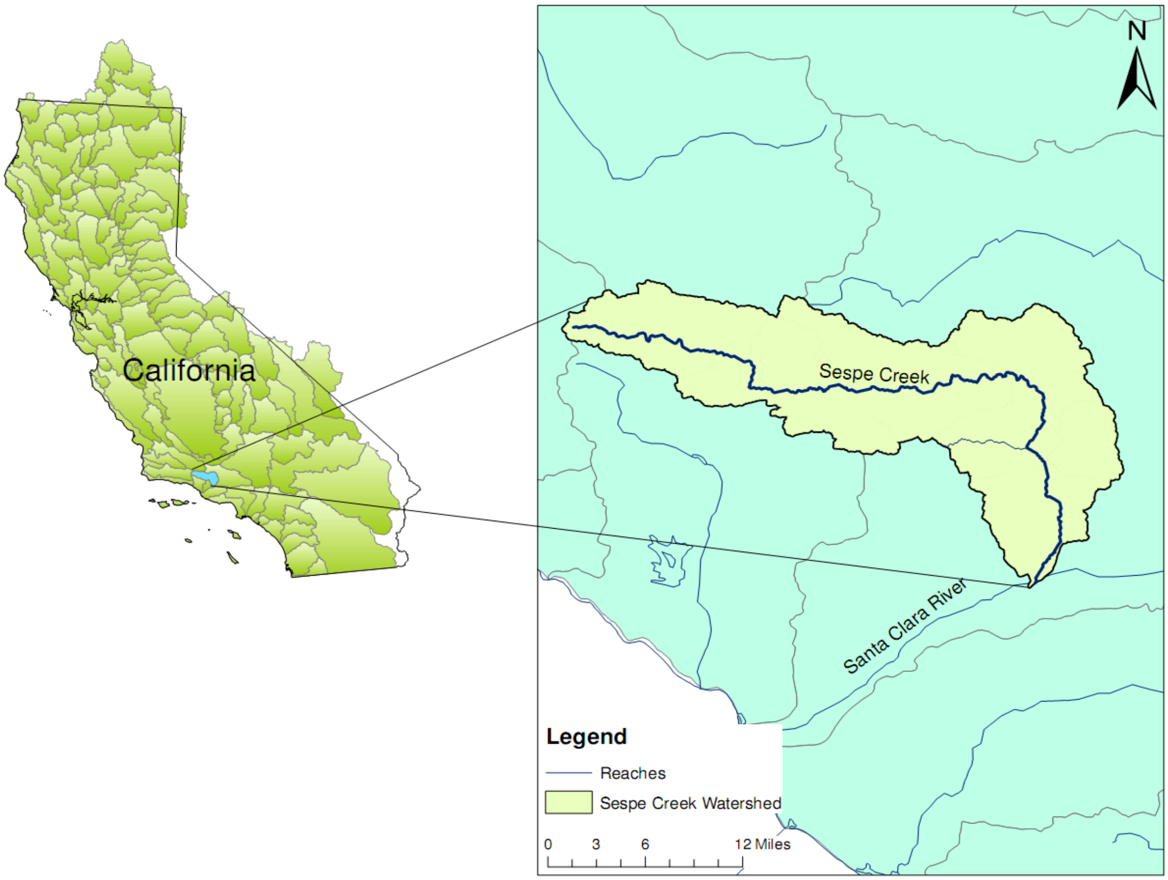


Figure 3-23. Location of the Sespe Creek watershed in California, USA.

Table 3-29. Land-use summary for Sespe Creek watershed.

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

Model Setup

A preexisting, calibrated HSPF model of the Sespe Creek watershed was extracted from a larger HSPF model of the Santa Clara River developed as part of the Santa Clara River Watershed Management effort by the Ventura County Watershed Protection District, Los Angeles County Department of Public Works, and U.S. Army Corp of Engineers Los Angeles District (AQUA TERRA Consultants, 2009). The Sespe Creek portion of the model was calibrated to historic streamflow data at the mouth of the watershed (Sespe Creek near Fillmore, U.S. Geologic Survey [USGS] gage 11113000) for the period of 10/1/1996 through 9/30/2005 and validated for 10/1/1993 through 9/30/1996. Statistical results of the calibration/validation are shown in Table 3-30.

Table 3-30. Sespe Creek HSPF model calibration and validation results for streamflow volume (normalized by watershed area). R^2= coefficient of determination.

Gage Location		Fillmore (11113000)	
		Calibration (1996−2005)	Validation (1993−1996)
Streamflow (cms)	Simulated	26.2	26.7
	Observed	27.7	24.9
Volume Error (%)		−6.1	7.0
Daily	R	0.96	0.92
	R^2	0.92	0.84
Monthly	R	0.99	0.97
	R^2	0.98	0.94
Daily Peak Difference (%)		−5.5	9.6

In the original Sespe Creek model, PET was based on observed pan evaporation data. In this case study, it was necessary to replace the observed pan data with computed PET regenerated by BASINS CAT for each climate change scenario. This was accomplished using the ***Penman-Monteith option*** for estimating PET in BASINS CAT. Model performance was validated after making this change by comparing baseline simulations from the original model to simulations using the PET generated by BASINS CAT in place of the observed pan evaporation data. Differences in total streamflow volumes were less than 1%, differences in the lowest 10% of streamflow were 3%, and differences in the highest 1% of streamflow were 2%. The original model calibration was, thus, considered acceptable for use in the case study.

Scenario Development

A total of six model simulations were completed. Scenarios included one baseline climate scenario and five 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 Climate Wizard web site. Additional information about these climate projections is provided in Section 3.2. 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%.

Five climate change scenarios were created to represent potential future changes in the severity and duration of drought (here defined as a period precipitation deficit). A period of historically dry weather in 1959−1961 was identified based on streamflow records for Sespe Creek during a baseline period, 1950−2001. BASINS CAT was then used to create scenarios of increased drought severity, duration, and combined severity and duration by adjusting observed temperature and precipitation values during and immediately following this historically dry period. The full baseline period used in all model simulations was 1952−2001. The following five climate change scenarios were created:

- Three scenarios representing increased drought severity were created by decreasing precipitation during the observed low flow period from 1959−1961 by 0, 10, and 20%. These scenarios are hereafter referred to as "Precip 0," "Precip −10," and "Precip −20," respectively.
- A scenario representing increased drought duration was created by decreasing rainfall in two relatively wet years that immediately followed the dry period, 1962−1963. Precipitation in 1962−1963 was decreased such that mean annual precipitation in these years was equal to the mean of precipitation occurring in 1961 and 1964. Precipitation in 1964 was also relatively low. This scenario, thus, represents a hypothetical drought period of 6 years, 1959−1964, and is hereafter referred to as "Duration."
- A scenario representing both increased drought severity and increased duration. This scenario was created by applying the same adjustments as in the Duration scenario together with a 10% precipitation decrease applied to all 6 years of the extended drought period. This scenario is hereafter referred to as "Duration/Severity."

A constant increase of 2°C was included in each climate change scenario to represent projected warming in this region. Temperature increases were applied to the entire baseline period, 1952−2001, used in model simulations. PET values were revised by BASINS CAT accordingly using the Penman-Monteith method.

Figure 3-24 shows the BASINS CAT window used to create the precipitation adjustments for the scenarios Precip 0, Precip −10, and Precip −20. The three fields at the top define which input records will be adjusted and by what method (i.e., "Multiply Existing Values …"). In this example, the BASINS CAT capability for creating ***multiple changes within 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.

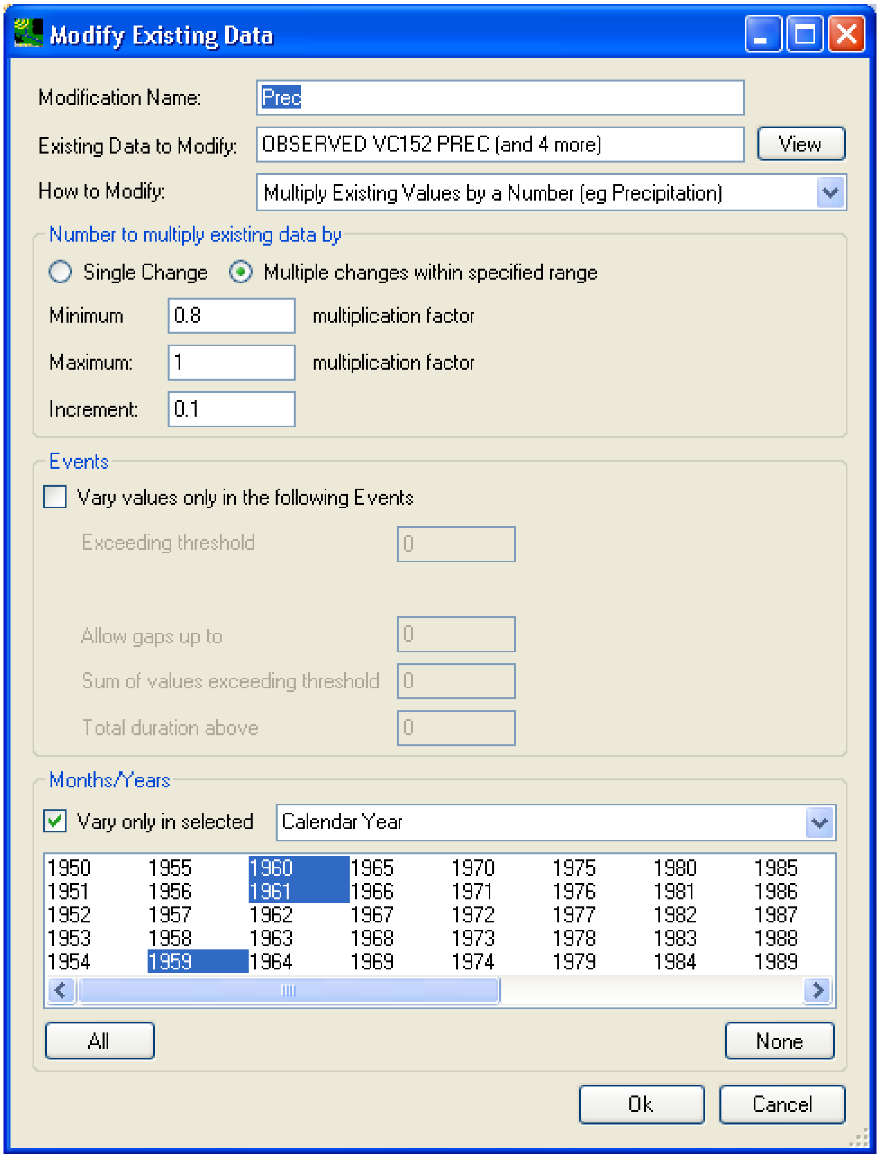


Figure 3-24. BASINS CAT window used to define precipitation adjustments for the Precip 0, Precip −10, and Precip −20 scenarios. *Modification Name* is the user defined scenario name; *Existing Data to Modify* identifies the time series to be modified; *How to Modify* defines how time series values will be adjusted; *Number to Multiply Existing Data by* indicates the number of multiplies, their range, and increment between each multiplier; *Month/Years* allows for the selection of specific years in the time series to apply the defined changes.

Land-use Scenarios
LULC was 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 was held constant to focus the analysis on the potential effects of climate change 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 to focus the analysis on the potential effects of climate change only.

Endpoint Selection
The simulation endpoints considered in this case study are mean annual streamflow and mean annual 7-day low flow. Additionally, mean monthly streamflow values from each scenario are plotted for comparison.

Results
Endpoint values for all model simulations are presented in Tables 3-31 and 3-32. Table 3-31 shows results for the Precip 0, Precip -10, and Precip -20 scenarios, and Table 3-32 shows results for Duration and Duration/Severity scenarios. Note that the values reported in each table are calculated only for the respective drought period under consideration: 1959−1961 for drought severity scenarios, and 1959−1964 for drought duration and duration/severity scenarios.

The Precip 0 scenario shows only a small decrease (roughly 5%) in streamflow resulting from a 2^{o}C temperature increase with no change in precipitation. However, combining the temperature increase with decreases in precipitation during the dry period of 1959−1961 had a significant impact on both mean flow and 7-day low flow. The Precip −10 scenario led to decreases in mean annual streamflow (cms) and mean annual 7-day low flow (cms) of 38 and 30%, respectively, from the baseline. For the Precip −20 scenario, decreases from the baseline were 62% for mean annual streamflow (cms) and 39% for mean annual 7-day low flow (cms).

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 Temperature ^{o}C	Change in Precipitation %	Mean Annual Streamflow (1959−1961) cms	Mean Annual 7-Day Low Flow (1959−1961) cms
Baseline	0	0	12.60	0.61
Precip 0	2	0	12.10	0.58
Precip −10	2	−10	7.83	0.43
Precip −20	2	−20	4.85	0.37

The Duration and Duration/Severity scenarios also impacted streamflow (see Table 3-32). In this case, reducing precipitation in 1962−1963 to represent an increased duration of drought led to decreases in streamflow relative to baseline conditions. Mean annual streamflow (cms) in the Duration scenario decreased by 61%, and mean annual 7-day low flow (cms) decreased by 43% for the extended drought period. The Duration/Severity scenario led to an additional 13% decrease in mean annual streamflow (cms) and an additional 12% decrease in mean annual 7-day low flow (cms).

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 Temperature °C	Change in Precipitation %	Mean Annual Streamflow (1959−1964) cms	Mean Annual 7-Day Low Flow (1959−1964) cms
Baseline	0	0	48.60	1.41
Duration	2	0	19.00	0.80
Duration and Severity	2	−10	12.80	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 the five scenarios (see Figure 3-25). 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 the comparable baseline values, it is notable that endpoint values from this scenario (see final row of Table 3-32) were still higher than baseline values for the original drought period (see 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, yet the early 1962 precipitation remained substantial in these scenarios (see 'Duration' and 'Duration/Severity' curves in Figure 3-25). Thus, the mean annual streamflow (cms) and 7-day low flow (cms) remained at levels above the original baseline drought (see first row of Table 3-31).

Summary

This case study illustrates the use of BASINS CAT to create scenarios for assessing the potential effects of increased drought severity and duration on streamflow. Scenarios were created by identifying a period of dry weather in the historical record, then using BASINS CAT to adjust temperature and precipitation values during and immediately following this period to represent increased drought severity, duration, and the combined effects of increased drought severity and duration.

Several BASINS CAT features were used to create the scenarios. First, the ability to modify data within specific seasonal or annual time periods allowed for precipitation changes to be applied only during drought periods. Second, the capability for creating ***multiple changes within 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.

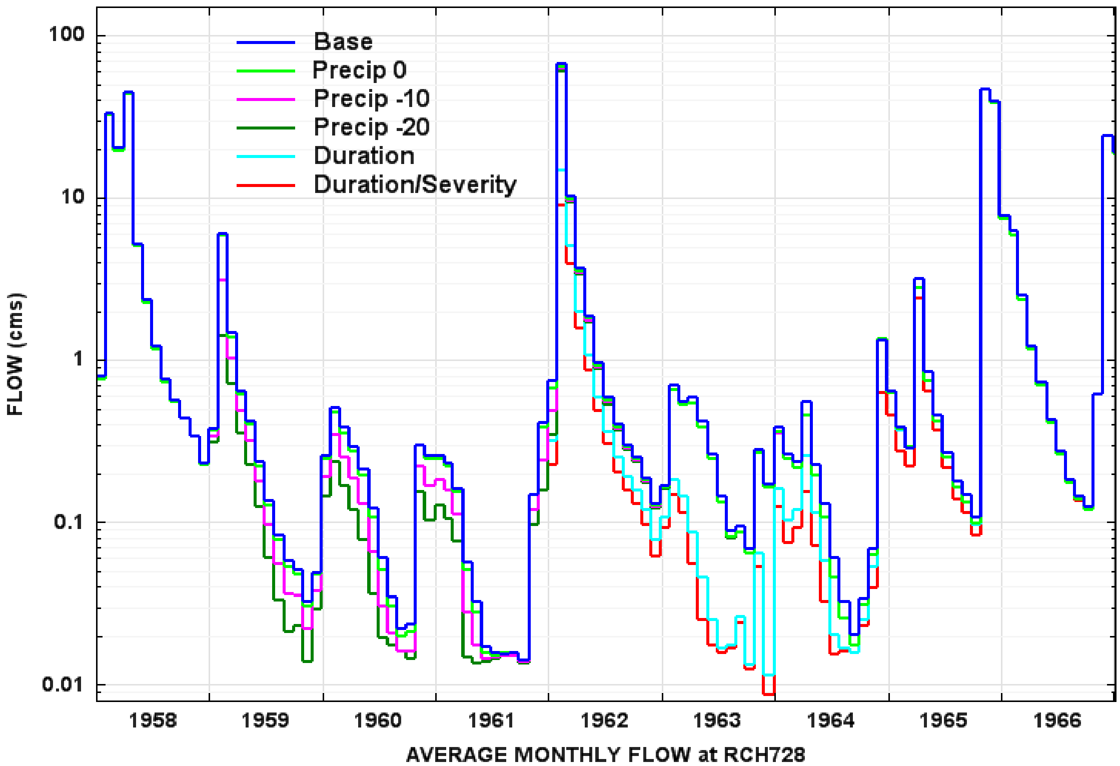


Figure 3-25. Mean monthly streamflow during drought periods for all scenarios.

BASINS CAT was used to assess changes in mean annual streamflow and 7-day low flow. In all simulations, the increased temperature and increased duration and severity of the drought period translated to decreased streamflow and 7-day low flows. This type of analyses based on a historical event can be very useful to water managers interested in exploring the potential implications of extreme events water management.

3.7. STREAMFLOW AND WATER QUALITY RELATIVE SENSITIVITY TO CLIMATE CHANGE VS. IMPERVIOUS COVER IN THE WESTERN BRANCH OF THE PATUXENT RIVER, MD, USING BASINS CAT WITH HSPF

Case Study Overview:

This case study evaluates the relative sensitivity of stormwater runoff and sediment loads (TSS) to changes in precipitation volume, changes in precipitation event intensity, and changes in watershed impervious cover using BASINS CAT with an HSPF model. The case study combines climate change scenarios created using BASINS CAT and land-use change scenarios created outside of BASINS CAT by adjusting HSPF input files. The following change scenarios were considered:

- increased precipitation volume of all events by 0, 10, and 20%
- increased proportion of annual precipitation occurring in selected large magnitude events (70^{th} percentile and greater) events by 0, 10, and 20%
- increased current watershed impervious cover of 8.6% to 15 and 25%

Introduction

Imperious surfaces in urban areas such as roofs, parking lots, roads, and sidewalks are a significant hydrologic alteration commonly resulting in impairment of local water bodies. 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.

Climate change in many parts of the nation is expected to increase the frequency and intensity of large magnitude storm events. These changes present a risk of increased stormwater runoff, pollutant loads, and flooding. In urban and suburban areas, there is also the potential for cumulative, synergistic effects on stormwater runoff resulting from the interaction of climate change and increased impervious cover associated with development. In such cases, changes in land use could exacerbate the impacts of stormwater runoff and water quality impairment on adjacent water bodies (Pyke et al., 2011). An improved understanding of these relationships can help to inform management strategies for protecting water quality and aquatic ecosystems.

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 (see Figure 3-26). Land use is mixed with significant fractions in forest, urban development, and agriculture (see Table 3-33).

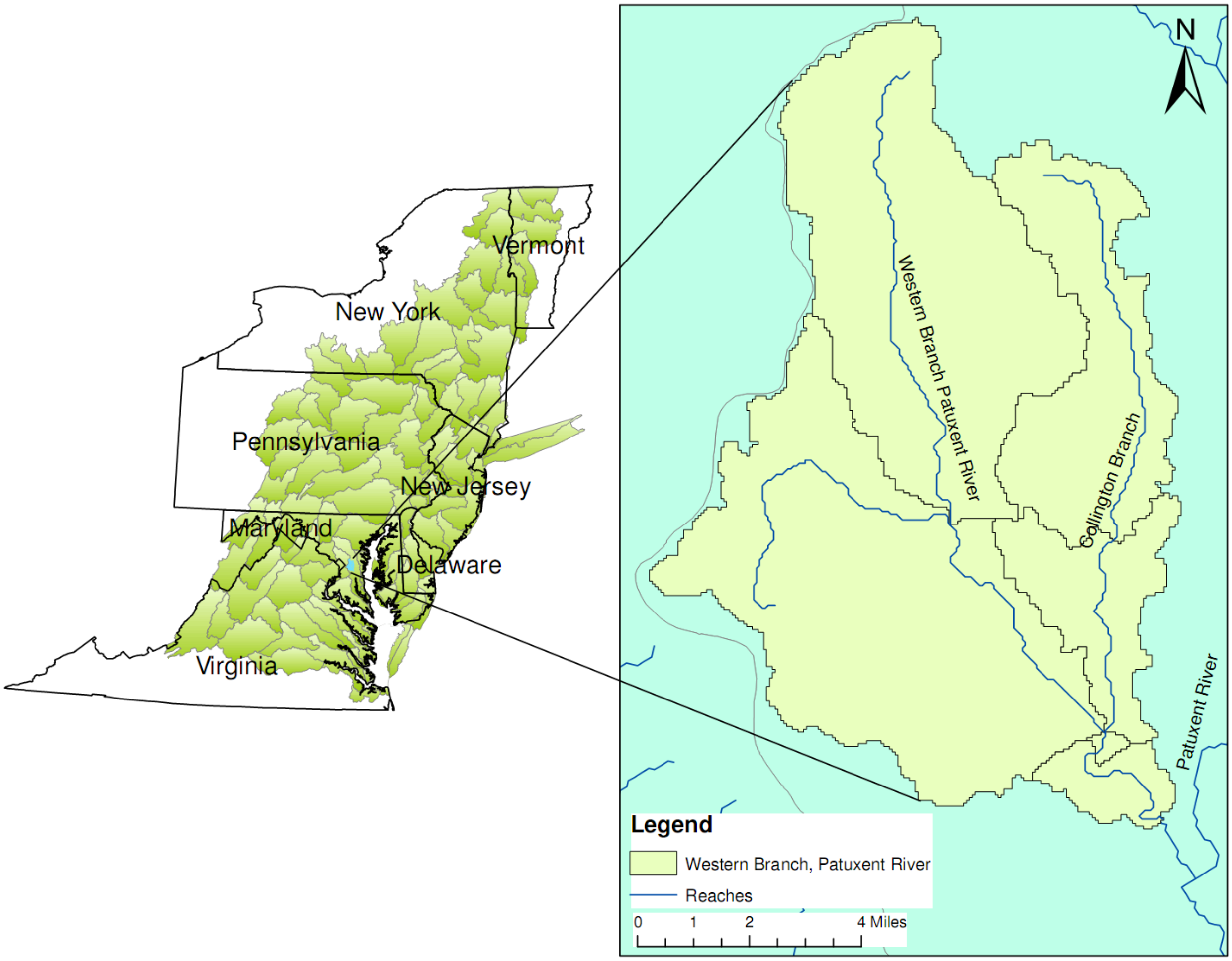


Figure 3-26. The Western Branch of the Patuxent River watershed and its location within the Chesapeake Bay watershed, MD, USA.

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
A preexisting, calibrated HSPF model of the Western Branch of the Patuxent River was extracted from a larger model of the Patuxent River watershed developed in the early 1990s for the U.S. Geologic Survey and the state of Maryland (AQUA TERRA Consultants, 1994). The

original model used GIRAS land use data. The Western Branch model used in this case study was revised to use land use data from 2001 NLCD.

Model calibration and validation were checked after making the conversion to NLCD to ensure the model would yield reasonable results. The calibration period was the same as for the original model, 10/1/1985 through 9/30/1988. The validation period was 10/1/1995−9/30/2005. Calibration and validation results are shown in Table 3-34. The overall streamflow balances are very good, with errors in total volume less than 1%, and the storm peaks are well simulated, with errors less than 6% for calibration and nearly 2% for validation.

Table 3-34. Western Branch of the Patuxent model hydrology calibration and validation statistics. NSE= Nash-Sutcliffe Efficiency coefficient (Nash and Sutcliffe, 1970); R^2= coefficient of determination.

	Calibration (1985−1988)	Validation (1995−2005)
Daily Values R^2	0.50	0.56
Daily Values NSE	0.47	0.52
Monthly Values R^2	0.74	0.81
Monthly Values NSE	0.73	0.81
% Error in Total Volume	−0.9	0.9
% Error in Storm Peaks	−5.8	2.1

Limited data were 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 (see Figure 3-27). While these checks should not be construed as a complete calibration, the model was considered acceptable for representing the relative changes across various model input scenarios, and for the primarily illustrative purpose of the case study.

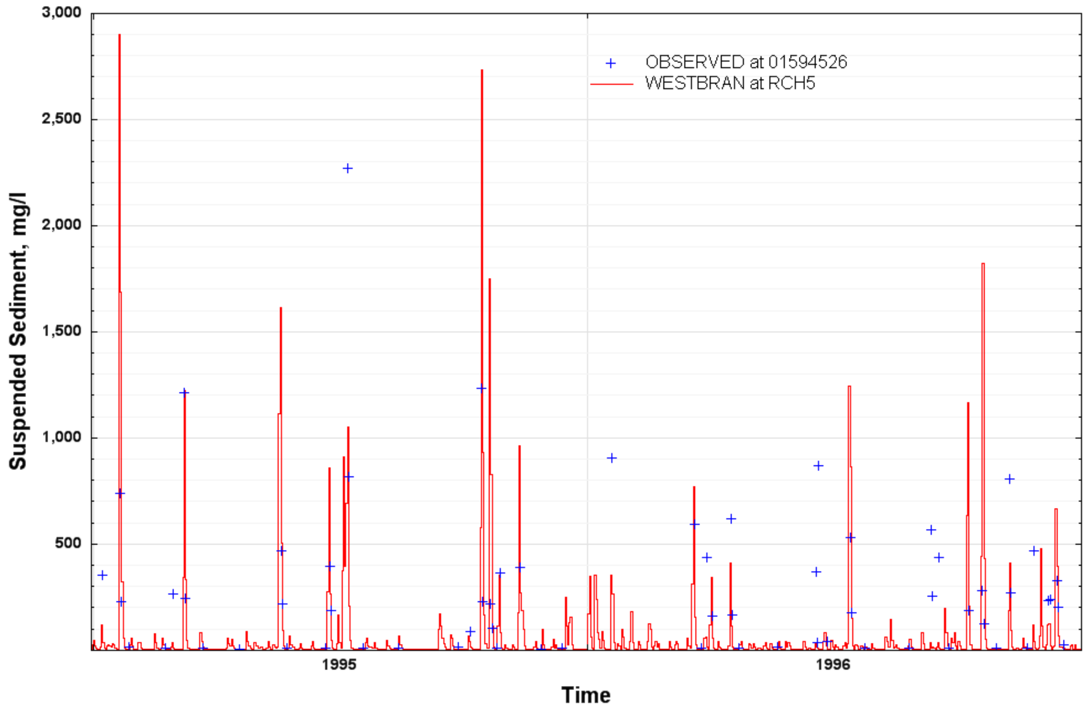


Figure 3-27. Observed and simulated TSS concentrations (mg/L) in the Western Branch of the Patuxent River watershed.

Scenario Development

A total of nine model simulations were completed' including six climate change scenarios and three land-use scenarios. Land-use scenarios represent only changes in developed land (impervious cover). No management scenarios were included.

Climate Change Scenarios

Climate change scenarios represented changes to precipitation only. No temperature adjustments were made. Precipitation change scenarios were based on an ensemble of 16 statistically downscaled climate change projections acquired from The Nature Conservancy's ClimateWizard web site (www.climatewizard.org). Section 3.2 provides additional information about these climate projections. Projected changes in mean annual precipitation in this region by end-of-century (2080s) ranged from about 0 to 20%.

A total of six precipitation change scenarios were created. Three of the scenarios represented increases in annual precipitation volume of 0, 10, and 20% (*precipitation volume* scenarios). BASINS CAT was used to adjust the magnitude of all events in the record by applying a constant percent increase to all values in the baseline record. The remaining three scenarios represented increases in the proportion of annual precipitation occurring in large magnitude events by 0, 10, and 20% (*precipitation intensity* scenarios). BASINS CAT was used to define events in the baseline precipitation record, apply a constant percent increase to all values within the largest 30% of events, and apply a constant percent multiplier to decrease all events below this threshold to create no net change in annual precipitation volume.

The creation of the scenarios was facilitated by the BASINS CAT capability for combining multiple adjustments to meteorological time series to create complex scenarios. Figure 3-28 shows the BASINS CAT window for selecting the two adjustments used to develop the 20% increase in the largest 30 percent of events (selection of *PrecipInt Intensity 20*) with no net change in annual precipitation volume (selection of *PrecipInt Multiply 0.833*).

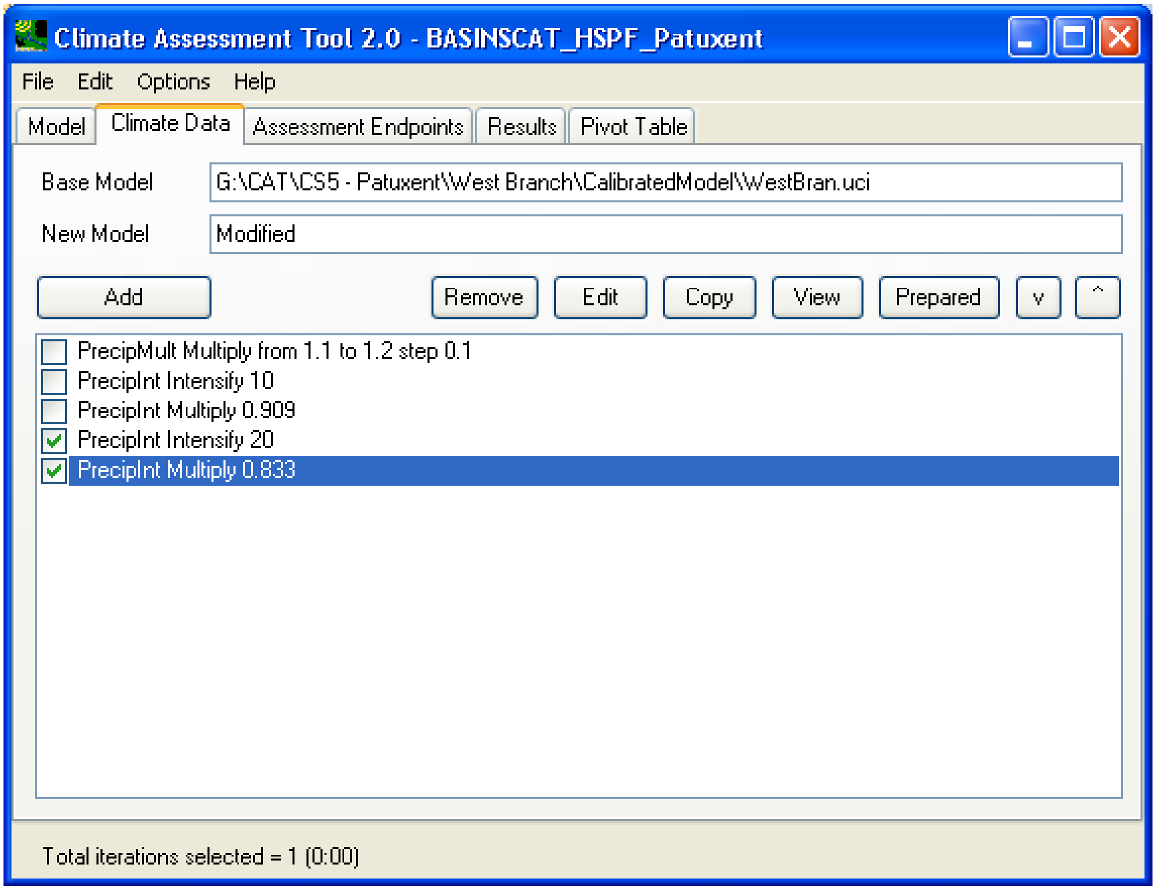


Figure 3-28. BASINS CAT window showing the selection of precipitation adjustments to create a 20% increase in the largest 30% of events with no net change in annual precipitation volume. *PrecipInt intensify 20* = increase selected events by 20%, *PrecipInt Multiply 0.833* = apply a 0.833 multiplier to events below the threshold event.

Land-use Scenarios

Three land-use scenarios were created to represent current (approximately 2001) watershed impervious cover and two potential future development scenarios with increasing impervious cover. Current impervious cover was estimated to be 8.6%. Future development scenarios assumed impervious cover of 15 and 25%.

BASINS CAT does not provide explicit capabilities for creating land-use change scenarios. The increases in impervious cover were represented in the HSPF model through a proportional decrease in each pervious land-use category. The percent increases in impervious cover were obtained by shifting land use primarily from forest and agriculture to urban, as well as by increasing in the amount of urban land that is considered impervious (i.e., increased urban density). The choice of 15 and 25% 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 (U.S. EPA, 2009b). Table 3-35 shows the percentages of each land-use category for each of the three land-use scenarios in this case study.

Table 3-35. Summary of Western Branch of the Patuxent watershed land use by category for each scenario.

Land Use Category	8.6% Impervious Cover	15% Impervious Cover	25% Impervious Cover
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 considered in this case study are mean annual streamflow and mean annual TSS loads. While not comprehensive of all impairment, these endpoints are considered representative of potential hydrologic and water quality impacts due to changes in precipitation and impervious cover.

Results
Results for mean annual streamflow (cms) and TSS loads (tonnes/ha/yr) are shown in Table 3-36. Percent changes are expressed relative to the baseline conditions: 0% increase in precipitation volume, 0% increase in precipitation intensity, and 8.6% impervious cover. Results suggest that streamflow in the Western Branch watershed is most sensitive to increases in precipitation volume. A 20% increase in overall precipitation volume leads to a 46% increase in mean annual streamflow. Increases in impervious cover also resulted in significant changes to mean annual streamflow; an increase to 25% impervious cover resulted in a 28% increase in 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.

Table 3-36. Annual streamflow and TSS load characteristics for the Western Branch of the Patuxent simulations.

Scenario	Precipitation Increase, %	Mean Annual Streamflow, cms	Change in Mean Annual Streamflow from Baseline, %	Mean Annual TSS Load, tonnes/ha/yr	Change in Mean Annual TSS Load from Baseline,%
Precipitation Volume	0	**2.81**	--	**0.056**	--
	10	**3.43**	21	**0.073**	30
	20	**4.11**	46	**0.090**	61
Precipitation Intensity	0	**2.81**	--	**0.056**	--
	10	**2.89**	3	**0.067**	20
	20	**2.97**	6	**0.078**	39
Impervious Cover	8.6	**2.81**	--	**0.056**	--
	15	**3.12**	11	**0.053**	−5
	25	**3.60**	28	**0.050**	−11

Results suggest that TSS (tonnes/ha/yr) in the Western Branch watershed is most sensitive to increases in precipitation volume. A 20% increase in overall precipitation volume led to a 62% increase in annual TSS load. A major increase in TSS load also resulted from increases in precipitation intensity. Results also suggest that TSS loads decrease with increases to impervious cover. While this could result from reductions in watershed agricultural land, this relationship is complex, and the true cause is not known.

Figure 3-29 is a simple heuristic model illustrating the relative sensitivity of stormwater runoff to changes in precipitation volume, precipitation intensity, and watershed impervious cover. Note that each scenario is presented while holding other variables constant (e.g., the precipitation intensity scenarios represent changes in precipitation intensity while holding impervious cover and precipitation volume at baseline levels). 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 in the Western Branch watershed.

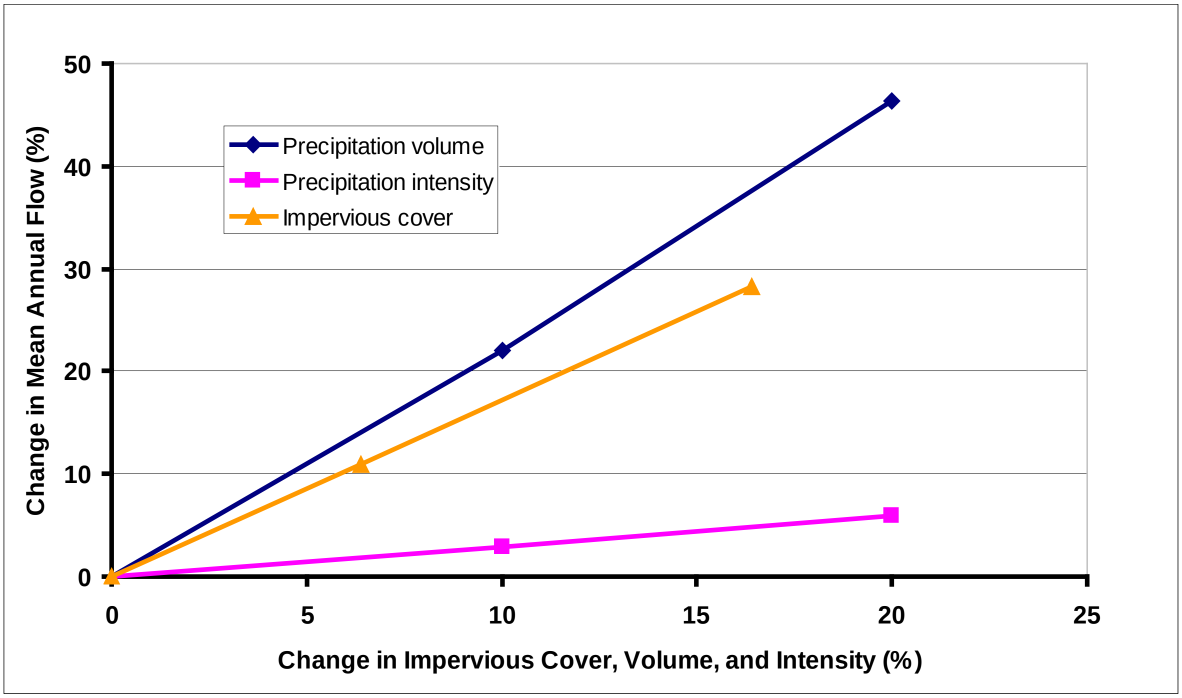


Figure 3-29. Simulated sensitivity of stormwater runoff volume to changes in impervious cover, precipitation volume, and precipitation intensity.

Figure 3-30 shows a similar comparison for TSS. 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 and is likely the result of specific land-use change characteristics included in this model.

Summary

This study assessed the relative sensitivity of streamflow and TSS loads to changes in precipitation volume, precipitation intensity, and impervious cover for a mixed-use watershed in Maryland. The primary BASINS CAT feature illustrated in this case study was the ability to create a matrix of climate change scenarios representing different combinations of potential temperature and precipitation change within user-defined ranges for input to a watershed model. This case study also illustrates the approach of combining climate change scenarios with land-use change scenarios.

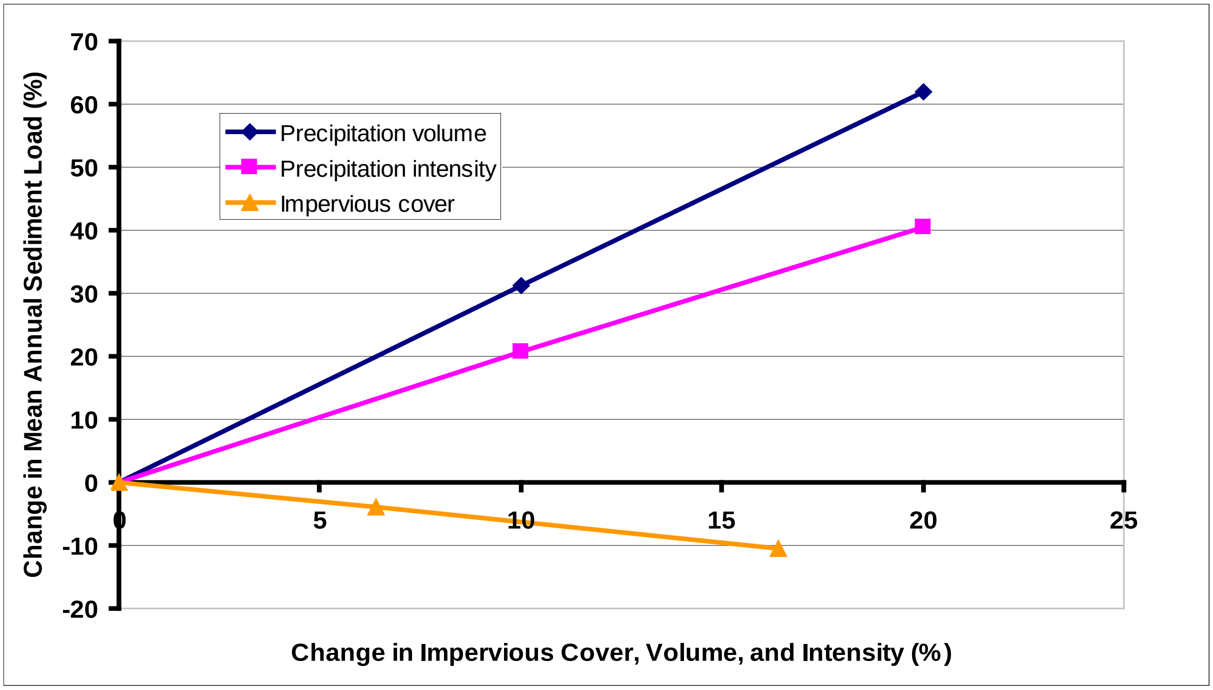


Figure 3-30. Simulated sensitivity of TSS loads to changes in impervious cover, precipitation volume, and precipitation intensity.

This case study illustrates the potential synergistic effects of climate change and urbanization on stormwater. While the scenarios applied were relatively simple, results suggest that when expressed on a constant percent basis, mean annual streamflow in the Western Branch watershed is more sensitive to changes in precipitation volume and impervious cover than to event intensity. TSS loads appear to be more sensitive to annual precipitation volume and event intensity versus impervious cover. Even relatively minor changes represented in the scenarios had notable impacts on either mean annual streamflow or annual TSS load, or both. Results suggest that improved development strategies have the potential to reduce or offset the effects of climate change. Management practices such as low-impact development that reduces impervious cover in new and existing development could be used to compensate for increased stormwater runoff associated with climate change (e.g., see http://www.epa.gov/owow/NPS/lid/).

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 analyses 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 behavior, identifying vulnerabilities, and evaluating the effectiveness of management responses to inform decision making. The tools presented in this report 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 et al., 2010; Ludwig et al., 2009; Najafi et al., 2011; Vaze et al., 2010). Further study is required to better assess, refine, and develop our current modeling and scenario development capabilities. The following discussion briefly identifies several issues, current limitations, and future needs associated with using hydrologic models for impacts assessments.

Use of a hydrologic model assumes that 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; Donigian and Love, 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, but models do not provide a complete representation of groundwater pathways including exchanges with deeper aquifers. 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.

A major component of the water budget, ET, 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, because 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.

Atmospheric carbon dioxide (CO_2) concentration has 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 that can affect water quality. Incorporation of CO_2 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.

4. CONCLUDING COMMENTS

This report is a guide to the application of two modeling tools recently developed by EPA and partners, BASINS CAT and WEPPCAT. The tools are not stand-alone models, rather they facilitate application of existing water models (e.g., HSPF, SWAT, SWMM, and WEPP) to assess questions about climate change impacts on water and watershed systems. Many communities, states, and the federal government are considering adaptation strategies for reducing the potential risks of climate change[4]. The challenges of how to incorporate diverse, uncertain, and often conflicting information about future conditions into decision making are significant. The scientific approach supported by BASINS CAT AND WEPPCAT, i.e., scenario analysis, can help inform our adaptation decisions by increasing our understanding system behavior, identifying vulnerabilities, and evaluating the effectiveness of management responses.

The six case studies in this report are designed to illustrate how BASINS CAT and WEPPCAT can potentially be used to address a range of practical, real-world questions of interest to water and watershed managers. The tools presented in this report, however, are just one step forward in building our capacity for understanding and responding to climate change. We hope that these tools can inspire and support ongoing research and applications to help meet this challenge.

[4] For examples, see: Climate Change Adaptation Task Force:
http://www.whitehouse.gov/administration/eop/ceq/initiatives/adaptation
http://www.whitehouse.gov/sites/default/files/microsites/ceq/2011_national_action_plan.pdf

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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 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 global GCMs or RCMs. Regional information and guidance about climate change can be obtained from other sources including government agencies and universities. Over time, climate change data will become more readily available as climate models are improved, new modeling experiments are conducted, new monitoring is completed, and research better reveal historical patterns of climate variability and change.

Bias Corrected and Downscaled WCRP CMIP3 Climate and Hydrology Projections
Lawrence Livermore National Laboratory/Bureau of Reclamation/Santa Clara University
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
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

National Center for Atmospheric Research, North American Regional Climate Change Assessment Program (NARCCAP)
http://www.narccap.ucar.edu/data/index.html
http://www.narccap.ucar.edu/results/index.html#climate-change

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

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

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