POTENTIAL CLIMATE CHANGE IMPACTS ON HYDROLOGIC REGIMES IN NORTHEAST KANSAS

by

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Abstract

The Great Plains once encompassed 160 million hectares of grassland in the central United States. In the last several decades, conversion of grassland to urban and agricultural production areas has caused significant increases in runoff and erosion. Past attempts to slow this hydrologic system degradation have shown success, but climate change could once again significantly alter the hydrology. The Intergovernmental Panel on Climate Change (IPCC) studies the state of knowledge pertaining to climate change. The IPCC has developed four possible future scenarios (A1, A2, B1 and B2). The output temperature and precipitation data for Northeast Kansas from fifteen A2 General Circulation Models (GCMs) were analyzed in this study. This analysis showed that future temperature increases are consistent among the GCMs. On the other hand, precipitation projections varied greatly among GCMs both on annual and monthly scales. It is clear that the results of a hydrologic study will vary depending on which GCM is used to generate future climate data. To overcome this difficulty, a way to take all GCMs into account in a hydrologic analysis is needed. Separate methods were used to develop three groups of scenarios from the output of fifteen A2 GCMs. Using a stochastic weather generator, WINDS, monthly adjustments for future temperature and precipitation were applied to actual statistics from the 1961 – 1990 to generate 105 years of data for each climate scenario. The SWAT model was used to simulate watershed processes for each scenario. The streamflow output was analyzed with the Indicators of Hydrologic Alteration program, which calculated multiple hydrologic indices that were then compared back to a baseline scenario. This analysis showed that large changes in projected annual precipitation caused significant hydrologic alteration. Similar alterations were obtained using scenarios with minimal annual precipitation change. This was accomplished with seasonal shifts in precipitation, or by significantly increasing annual temperature. One scenario showing an increase in spring precipitation accompanied by a decrease in summer precipitation caused an increase in both flood and drought events for the study area. The results of this study show that climate change has the potential to alter hydrologic regimes in Northeast Kansas.

Table of Contents

List of Figures

List of Tables

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Chapter 1 - Introduction

Great Plains streams and ecosystems are an integral part of the diminishing North American unpolluted fresh water supply. These large systems, which once encompassed 160 million hectares, have been continually degraded by urbanization and agricultural operations (Dodds *et al.*, 2004). The result of these human impacts is an agriculturally dominated area that provides a significant portion of the food production in the U.S. Many practices have been implemented in these agricultural areas to mitigate the stream and ecosystem degradation caused by the removal of native grass and forest land. Unfortunately, there is a new potential threat that could pose an even greater risk to stream systems and freshwater supplies in these critical food producing areas. While not fully understood, many people believe that climate change will cause a significant change in local climates and ecosystems around the world (IPCC, 2007). Understanding the potential future impacts of climate change in the Midwest agricultural region has important environmental and food production concerns (Karl *et al.* 2009).

The water available for crops is one concern with future climate projections in the Midwest. A large portion of the agricultural production in this area uses rain-fed practices to provide the water inputs to produce crops. Since these operations rely on rainfall only to meet soil moisture requirements, future temperature and precipitation trends will have a significant effect on the productivity of these operations. Irrigation is also an abundant practice in this region for agricultural production because supplemental water can greatly increase yields. While these operations do not solely rely on rainfall inputs, water availability for irrigation could become a concern if a drying trend occurs in the future. Irrigation water availability problems would be compounded in such a future scenario with the conversion of dry-land operations to irrigated operations to supplement reduced precipitation.

In order to understand and plan for the adverse effects of climate change on agricultural areas, future climate scenarios need to be analyzed to determine the potential effects on water availability and quality. One way to accomplish this is with the use of a hydrologic model. A hydrologic model allows future climate scenarios to be input for an area of interest and analyzed from water quality, water quantity, soil erosion and/or plant growth perspectives. The use of hydrologic models to analyze climate change impacts is already occurring, but a better way to simulate the possible range of future climate projections is needed.

Objectives

The goal of this study is to use a hydrologic model to simulate watershed processes under future climate scenarios and analyze the resultant effects on stream hydrology. The specific objectives are to 1) identify a range of future climate scenarios based on the current knowledge and modeling capabilities of climate change, 2) implement a method to temporally downscale projected monthly temperature and precipitation changes into a daily time series, and 3) analyze the resultant effects from these time series scenarios on stream hydrology.

Outline

In this study, an in-depth analysis of the climate change projections from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report: Climate Change 2007 (AR4) and a review of previous studies using hydrologic models to assess climate change are completed (Chapter 2). From this information, future climate scenarios are developed for Northeast Kansas (Chapter 3). Monthly temperature and precipitation adjustments for these scenarios are then applied to actual temperature and precipitation statistics using a stochastic weather generator (Chapter 4). With this information, the stochastic weather generator is used to generate a continuous time series of daily minimum and maximum temperature and precipitation (Chapter 4). This data were then input into a hydrologic model to simulate watershed processes and determine output streamflow (Chapter 5). The output streamflow was analyzed to determine what effect the climate change scenarios had on the stream hydrology in Northeast Kansas (Chapter 6).

Chapter 2 - Literature Review

Understanding Climate Change Projections

The Intergovernmental Panel on Climate Change (IPCC) was created by the United Nations Environment Programme and the World Meteorological Organization to oversee and report the current understanding of climate change and its potential impacts (IPCC, 2007). The IPCC has released four assessment reports on the understanding of climate change as well as numerous other special reports and technical reports. Even though the IPCC is viewed as the leader in provision of climate change knowledge, this program does not conduct any research or monitor climate data itself. Instead, it relies on thousands of scientists from all over the world to voluntarily contribute to the work of the IPCC.

Most of the scientific group that contributes to the IPCC is comprised of government agencies, university faculty and private research firms dedicated to climate research. These researchers use sophisticated general circulation models (GCMs) to simulate atmospheric, land and sea interactions as a result of probable emissions scenarios. The emission scenarios used in these models are very detailed and consider multiple factors of climate change.

The following driving forces are considered in each emission scenario (IPCC, 2000):

- Population
- Economic and Social Development
- Energy and Technology
- Agriculture and Land-Use Emissions
- Other Gas Emissions
- Polices

With the large number of possible driving forces in climate change emission scenarios, it would be impossible for the IPCC to compare any two climate models without first establishing a standard set of emission scenarios. To satisfy the need for common scenarios, the IPCC analyzed and compared 40 different emission scenarios in the Special Report on Emission Scenarios (SRES) (IPCC, 2000). With this analysis, four distinct storylines were created as possible future climate effecting scenarios.

SRES Storyline Families

The four storyline families, A1, A2, B1 and B2, differ in regional interrelation, technology spread, regional economy, protection of local and regional environment and demographic structure change. These family classes were created by the IPCC to cover the wide range of uncertainties in future global social and economic developments and related greenhouse gas (GHG) emissions. One common misconception is that the storyline families contain a "worst case" or "best case" scenario. However, IPCC (2000) explains that "All four SRES futures represented by the distinct storylines are treated as equally possible and there is no central, business-as-usual, surprise or disaster future" (4.2.1). Even though a storyline can unfold only if the given values are emphasized more than others, the SRES made no opinions to the desirability of any one family of storyline. The SRES storylines also do not take into account policies to limit GHG emissions (IPCC, 2000). This allows for other studies to be developed to evaluate climate change mitigation measures and policies based on each family of scenarios.

The letter designation of each family relates to the economic path while the number designation relates to the regional orientation of the family. For example, B1 and B2 storylines, although to different degrees, focus on the translation of global concerns into local actions to promote sustainability in the economy. In contrast, the A1 and A2 storylines, also to different degrees, focus on sustained economic development, with higher levels of affluence throughout the world and environmental priorities perceived as less important. Also, the A1 and B1 families focus on successful economic global convergence as well as social and cultural interactions, while the A2 and B2 families emphasize an increase of diverse regional development (IPCC, 2000). These naming distinctions allow any scenario from a given family to be quickly identified and summarized by the overall driving forces behind it.

A1 Storyline Family

The A1 storyline focuses on rapid economic development in which regional income per capita distinctions decrease and eventually disappear. Other areas of focus are on commitment to market-based solutions, high commitment to education, high investment and innovation in education and technology, as well as international mobility of people, ideas and technology (IPCC, 2000). The rapid technological discovery allows resources to be produced at an increased level and increases the number of economically recoverable reserves. The increased income per capita ultimately leads to an increase in car ownership, sprawling urban areas and dense transportation networks.

Since this storyline family relies on intensive technology discovery, scenario groups are divided within the family to reflect the uncertainty in energy source development. The first scenario group within the A1 family is the A1C group. This scenario focuses technological advances in coal reserves. The second scenario group is A1G, which focuses on the advancement of oil and natural gas technology. The third scenario, A1B, focuses on a balance between different technologies and supply sources so that there is no single dominant energy source. The last A1 scenario, A1T, focuses on a shift toward renewable and nuclear energy sources (IPCC, 2000).

A2 Storyline Family

The A2 storyline features the world as a series of economic regions. These differentiated regions cause uneven economic growth with a widening of the income gap between industrialized and developing areas. As a result, people, ideas, capital and technology tend to be less mobile, which decreases the focus on global economic, social and cultural interactions. This regional focus causes self-reliance within regions for resources, technology and income. Technology change also varies between regions based on regional economy. As a result,varying energy resources between regions leads to increasing regional based energy advancements. Areas with high income, but limited resources, tend to focus on renewable and nuclear energy sources. Resource rich but economically limited regions increase their dependence on fossil fuels to meet energy demands (IPCC, 2000).

The regional view also causes people to focus on family and community life as opposed to global concerns. This leads to high global population growth. In an attempt to limit imports and keep up with growing populations, regional focus on agricultural technology advancement to meet food demands is increased. This advancement initially leads to high levels of soil erosion and water pollution, but are eventually mitigated with future advancements in high-yield agriculture (IPCC, 2000).

B1 Storyline Family

The B1 storyline is much like the A1 storyline in that focus is on a technology advanced, convergent world. However, in the B1 family the technological advancements are aimed at improved resource use and environmental protection rather than economic gain. This emphasis leads to a more balanced economy with equal, but less overall income distribution around the world. Even though the main focus of this storyline is on environmental protection, like the other scenarios, it does not include any GHG emission policies. Instead, it is a global movement by governments, media and public for a sustainable future that drives the environmental consciousness. The global alertness of environmental problems leads to a transition from conventional energy resources to cleaner gas resources and then ultimately to renewable energy sources (IPCC, 2000).

With a strong focus on solving environmental problems, this storyline leads to high environmental quality with compact cities designed for non-motorized transport and low-impact agricultural practices elsewhere. This higher quality of living leads to a low mortality rate and low population growth with global population increasing to 9 billion in 2050 and then decreasing to 7 billion in 2100 (IPCC, 2000). All of these effects add up to a significant decrease in GHG emissions and an increase in overall quality of life.

B2 Storyline Family

The B2 storyline features increased government and business environmental and social sustainability at national and local levels driven by environmentally conscious citizens. This leads to a declining trend in international institutions, but an increase in local sustainability and decision making strategies with strong communities. The technology advancement is generally high, but varies across regions. Energy systems differ between regions based on resource availability and technology advancements. The limited technology spread due to regional focuses causes the main energy systems to remain hydrocarbon based, but with a slight decrease in overall carbon intensity (IPCC, 2000).

The main focus of this storyline is on education and welfare programs. This focus leads to low mortality rates and regionally balanced incomes. Consequentially, moderate population growth is expected. The population growth along with local environmental concerns leads to a focus on urban and transportation infrastructure development as well as regional sustainable agricultural practices (IPCC, 2000). These developments result in a reduction on car dependence, urban sprawl and overall GHG emissions.

SRES Climate Change Scenarios

From the four SRES storyline families the IPCC created seven approved scenarios by breaking the A1 family into four different scenarios. These seven scenarios, shown in Table 2-1, cover a wide range of possible future changes within the climate change driving forces.

Table 2-1 SRES Scenarios and Characteristics (IPCC, 2000)

Scenario Characteristic	**A1C**	**A1G**	**A1B**	**A1T**	**A2**	**B1**	**B2**
Population Growth	Low	Low	Low	Low	High	Low	Medium
GDP Growth	Very High	Very High	Very High	Very High	Medium	High	Medium
Energy Use	Very High	Very High	Very High	High	High	Low	Medium
Land-Use Changes	Low-Medium	Low-Medium	Low	Low	Medium-High	High	Medium
Resource Availability	High	High	Medium	Medium	Low	Low	Medium
Pace and direction of Technological Change	Rapid	Rapid	Rapid	Rapid	Slow	Medium	Medium
Favoring	Coal	Oil & Gas	Balanced	Non-Fossils	Regional	Efficiency & Dematerialization	Status Quo

Even though most scientists are inclined to view one of the seven scenarios as more desirable than others, it is important to remember that each scenario has positive and negative consequences within the driving forces of the scenario. There is also no “best guess” or “worst case” scenario. It is also important to remember that due to the uncertainty of the future situation, it is probable that none of these scenarios will fully capture the complexity of future climate trends and a combination of different driving factors could result in similar results to any one of the scenarios.

As a result of the public perception of the SRES storyline families, assumptions are sometimes made about a study based on which SRES scenario is used. Since the A2 scenario is often viewed as a “worst-case scenario”, some people assume that any study using it is trying to exaggerate climate change effects. In contrast, when the B2 scenario is used, the other side of the debate often assumes the researcher is trying to show minimal climate change effects. While the researcher is probably choosing a specific SRES scenario for a reason, it is important to remember that the SRES scenarios will affect study results differently depending on what analysis parameters are used. For example, the B1 scenario might be perceived as a minimal impact scenario if population growth is used to analyze effects, but if land-use changes are analyzed, it could be considered a “worst-case scenario” due to having the highest land-use change characteristics.

Hydrologic Modeling of Climate Change

Using hydrologic models to analyze GCMs provides its own set of problems and uncertainties. The major difficulties of hydrologic modeling climate change occur with the available data from climate models. The GCM data available from the IPCC Data Distribution Centre are mostly on either an annual or monthly scale. However, daily climate input data are needed for a hydrologic model to be used. Downscaling monthly data to daily data requires applying future climate projections to historic variations and trends for the area of interest. This information gap, along with the uncertainty and complexity of future climate projections has lead to the simplification of future climate predictions for use in hydrologic models.

The most common simplification process used to simulate climate change in a hydrologic model is to reduce climate change to only temperature and precipitation effects. This approach allows easy climate representation by using future temperature and precipitation data provided by the GCMs to provide future climate trends. With this simplification, the effects of increased CO_2 concentration, solar radiation and other changes associated with climate change are assumed to have minimal effects compared to the temperature and precipitation change.

Using this approach, many studies have used monthly trends for precipitation and temperature to predict varying effects on water resources (Booty *et al*., 2005; Franczyk and Chang, 2009; Githui *et al.*, 2009; Jha *et al*., 2006; Kim and Kaluarachchi, 2009; Varanou *et al.*, 2002; Zhang *et al.*, 2007). The analysis methods used to analyze climate change effects varied between these studies according to which parameters were important for the particular region. Both Githui *et al.* (2009) and Zhang *et al.* (2007) used streamflow output from the hydrologic model to analyze the effects of climate change. Booty *et al.* (2005) based the analysis on water quality and Varanou *et al.* (2002) used a combination of water quality, surface flow, lateral flow and groundwater flow to determine climate change effects.

Climate change analysis was further extended when Franczyk and Chang (2009) added urbanization factors to the future climate scenarios. This study concluded that the runoff of combined urbanization and climate change scenarios produce amplified runoff results compared to an analysis with only one of the variables (Franczyk and Change, 2009). While land use changes are difficult to predict for the future, individual SRES scenarios have land use assumptions built into them. Since this study is focusing on agricultural areas instead of urban areas, urbanization should not be a major factor. However, in agriculturally dominated areas like the Midwest, agricultural land use and practice change may cause additional hydrologic effects to a climate change analysis.

The main concern with the previous studies that utilize hydrologic models to analyze climate change is that the variation between GCMs could result in dissimilar hydrologic analysis results if a different GCM is used to repeat the study. As a result of these concerns, hydrologic analysis has shifted more towards a sensitivity analysis approach. In Somura *et al.* (2009), a sensitivity analysis was conducted using annual precipitation variation adjustments ranging from -20% to 30% in 10% increments. Within each of the six precipitation increments, three annual temperature-increase increments of 1 ºC, 2 ºC and 3 ºC were added to form a total of eighteen different future scenarios. These scenarios were input into a hydrologic model to determine the sensitivity of river discharge and evapotranspiration (ET) to temperature and precipitation variations. This study concluded that river discharge was mostly affected by precipitation variations, but temperature did have slight effects. In addition, temperature increase did cause a significant increase in annual ET, especially during the winter months.

In Nunes *et al.* (2008), this process was taken a step further by adding CO_2 incremental increases along with precipitation and temperature. In this study, the three climate change parameters were run individually. The first four scenarios were temperature scenarios with increases of 1.6 ºC, 3.2 ºC, 4.8 ºC and 6.4 ºC. The next four scenarios made adjustments to precipitation of -10%, -20%, -30% and -40%. The final four scenarios used CO_2 adjustments of +25%, +50%, +75% and +100%. With these scenarios, biomass growth and soil erosion responses were analyzed. This analysis showed that biomass growth decreased with temperature increases, increased with higher CO_2 concentrations, and was not affected by rainfall changes. Soil erosion response did not show dependence to temperature, rainfall or CO_2 changes. Instead, soil erosion response was related to the combined effect of surface water yield and biomass growth responses. To further test these results, the three parameters were combined to form nine more scenarios. These scenarios showed that sediment yield was highly vulnerable to changes in rainfall and temperature while increased CO_2 concentration had little effect (Nunes *et al.*, 2008).

The most comprehensive hydrologic modeling analysis of climate change in North America was completed in Jha *et al.* (2006). This study used a combination of uniform shifts to conduct a sensitivity analysis for CO_2, precipitation and temperature as well as multiple GCMs to get monthly temperature and precipitation adjustments for a hydrologic analysis of the Upper Mississippi River Basin (UMRB). The sensitivity analysis resulted in the conclusion that precipitation and CO_2 shifts had a greater impact on future streamflow than temperature did. However, the impact of temperature increased as the magnitude of the change increased. The sensitivity analysis also showed that solar radiation and relative humidity changes had minimal effects on future streamflow.

Hydrologic Indices Analysis

While a hydrologic model is a great tool to help analyze climate change effects, the output of these models is somewhat limited. This study focuses on streamflow as a way to determine if hydrologic alteration occurs during future climate scenarios. Most hydrologic models are continuous and therefore produce streamflow output as a continuous series. While continuous streamflow outputs are good for visualizing hydrologic changes, it is difficult to distinguish an actual hydrologic change from natural moisture variation. Summary statistics are also available for streamflow, but this only provides the user with an average or total amount for the whole study period. For a more in-depth analysis, a way to categorize streamflow periods and analyze changes within the categories is needed. Converting the continuous streamflow data into hydrologic indices provides a perfect solution to this problem.

Using hydrologic indices resulting from streamflow data allow streamflow characteristics to be analyzed rather than trying to visually determine streamflow changes. The many different hydrologic indices also allow multiple stream characteristics to be analyzed from the general streamflow input. Indices that consider magnitude, flow variability, duration, timing, frequency and rate of change for hydrologic events are available. The magnitude category can be further broken down into high, median/mean or low flow events. The abundance of hydrologic indices can make an analysis overwhelming unless only relevant indices are analyzed. The type and number of hydrologic indices relevant to a study will vary depending on the overall goals.

In order to simplify the process of choosing relevant hydrologic indices, Olden and Poff (2003) conducted a comprehensive review of 171 different hydrologic indices to narrow down and remove redundancy in the process of choosing appropriate hydrologic indices. Their review used long-term flow records from 420 sites across the USA to highlight patterns or redundancy among the hydrologic indices. In order to accomplish this task, streams were broken down into six stream types ranging from harsh intermittent to perennial flashy. Olden and Poff (2003) found that for each stream type, between 90.5 to 97.2 percent of stream variation could be explained with three or four hydrologic indices. Since the overall goal of this study is to use hydrologic analysis to determine the effects of climate change, it is not important to completely classify the flow regimes. As a result, the hydrologic indices types described in Olden and Poff (2003) were used as a general guideline, but did not determine the final hydrologic indices used in this study.

The relevancy of hydrologic indices for climate change analysis depends on important streamflow factors in the study area. Since Kansas relies heavily on agricultural production, water availability to plants is a major factor in the area. Streamflow can be related to water availability in many different ways, such as mean monthly streamflow as well as low flow indices. Furthermore, both aquatic and terrestrial ecosystems are important for the abundant wildlife in Kansas. Aguilar (2009) applied the Olden and Poff (2003) study to ecologically relevant hydrologic indices in Kansas streams. In this study, it was determined that low flow and flood events had the most effect on aquatic ecosystems.

Another important consideration for Kansas streams is pollution control using best management practices (BMPs). In order to determine the need and effectiveness of BMPs, Kansas has developed total maximum daily loads (TMDLs) for many in-stream pollutants. Since Kansas consists of mainly rural areas, non-point source pollution (NPS) is the main cause of stream pollutants. The sources of NPS cannot be positively identified, so reducing runoff is the most efficient way to control NPS. Cleland (2002) explains that a connection between flow duration curves (flow exceedance probability curves) and TMDLs exists. Flow duration curves can be used to identify critical flow conditions for targeted pollutants. As a result, as flow exceedance probability increases, the amount of NPS entering streams generally also increases.

Through these studies, it is clear that the effects of climate change on mean monthly flow, low flow, flood events and flow exceedance probability curves will have the most effect on

Kansas streams. Hydrologic indices that show relations for these parameters will be used as an analysis tool to determine how future climate change will affect Midwest streams. As a result, future climate scenarios will also be analyzed based on their effects on agriculture, ecosystems and pollutants.

Chapter 3 - GCM Analysis and Scenario Development

The studies reviewed in the previous chapter provided a good starting position to develop climate scenarios for a hydrologic analysis of future climate trends. The first step in this process was to identify which GCM(s) to use in the hydrologic analysis. Even though the GCMs shown in Table 3-1 use the same driving forces to simulate the climate system and future climate, output data varies greatly between models. This variance is caused by different parameterization of the many factors within each model. As with any physical process, there are multiple methods/equations that can be used to calculate parameters within the model. Other differences can come with the resolution of the model used as well as multiple other factors.

Since GCMs differ in future projections of climate response to each SRES storyline, it is important to consider which model or suite of models to use before a hydrologic study can be performed. Results/implications from climate change studies will vary depending on which GCM and SRES scenario is used. In order to apply these approaches to an agriculturally dominated area in the Great Plains, an analysis of the available GCM models was completed. From this analysis, it was determined which future climate scenario approach would best fit a hydrologic study in this area.

Table 3-1 IPCC AR4 Climate Models (IPCC, 2005)

Center	Country	Center Acronym	General Circulation Model	Scenarios Available
Bejing Climate Center	China	BCC	CM1	A2, B1
Bjerknes Centre for Climate Research	Norway	BCCR	BCM2.0	A2, A1B, B1
Canadian Center for Climate Modelling and Analysis	Canada	CCCma	CGCM3 (T47)	A2, A1B, B1
			CGCM3 (T63)	A1B, B1
Centre National de Recherches Meteorologiques	France	CNRM	CM3	A2, A1B, B1
Australia's Commonwealth Scientific and Industrial Research Organisation	Australia	CSIRO	Mk3.0	A2, A1B, B1
Max-Planck-Institut for Meteorology	Germany	MPI-M	ECHAM5-OM	A2, A1B, B1
Meteorological Institute, University of Bonn	Germany	MIUB	ECHO-G	A2, A1B, B1
Meteorological Research Institute of KMS	Korea	METRI		
Model and Data Groupe at MPI-M	Germany	M&D		
Institude of Atmospheric Physics	China	LASG	FGOALS-g1.0	A1B, B1
Geophysical Fluid Dynamics Laboratory	USA	GFDL	CM2.0	A2, A1B, B1
			CM2.1	
Goddard Institute for Space Studies	USA	GISS	AOM	A1B, B1
			E-H	A1B
			E-R	A2, A1B, B1
Institute for Numerical Mathematics	Russia	INM	CM3.0	A2, A1B, B1
Institut Pierre Simon Laplace	France	IPSL	CM4	A2, A1B, B1
National Institute for Environmental Studies	Japan	NIES	MIROC3.2 hires	A1B, B1
			MIROC3.2 medres	A2, A1B, B1
Meteorological Research Institute	Japan	MRI	CGCM2.3.2	A2, A1B, B1
National Center for Atmospheric Research	USA	NCAR	PCM	A2, A1B, B1
			CCSM3	A2, A1B, B1
UK Met. Office	UK	UKMO	HadCM3	A2, A1B, B1
			HadGEM1	A2, A1B
National Institute of Geophysics and Volcanology	Italy	INGV	SXG 2005	A1B

A2 Scenario Family Analysis

In this study, only temperature and precipitation parameters are adjusted to represent possible climate change scenarios. In order to determine possible future climate, an analysis was completed to determine how different GCMs represent the A2 climate change projection for the study area. Northeast Kansas was chosen to represent a Great Plains area that has a significant amount of agricultural land. GCMs were limited to the ones that contained a historic experiment and an A2 projection for both 2050 and 2100. Only fifteen out of the twenty-four available GCMs contained all three of these simulations (historic, 2050, 2100).

Although the spatial resolution of the GCMs vary, choosing an easily identifiable study area like Northeast Kansas, simplifies determining which GCM grid cell is needed to encompass the study area. For each GCM, the grid cell with the center point closest to the National Climatic Data Center (NCDC) weather station at the Topeka Airport (COOP ID# 147007) in Northeast Kansas located at the coordinates 39º 7’ 48” N latitude and 95º 55’ 48” W longitude was chosen. Average temperature and precipitation data for each GCM were obtained for the 1961-1990 historic experiment and the 2046-2065 A2 projection for the analysis.

The analysis of these GCMs consisted of a two step process to determine how accurate the GCMs were at simulating historic trends and to see the correlation between future A2 projections between the GCMs. The first part of the analysis was completed by comparing average monthly temperature and precipitation values from the historic experiment for each GCM to the actual NCDC monthly average temperature and precipitation values over the same time period at the Topeka Airport weather station.

Figure 3-1 displays the NCDC monthly average temperature as a solid blue line. The monthly average temperatures for each of the fifteen GCMs historic runs are shown as red squares. Although mean temperature for the GCM’s historic runs are not 100% accurate, the values for all models are within a reasonable variation to the actual NCDC average for that time period.

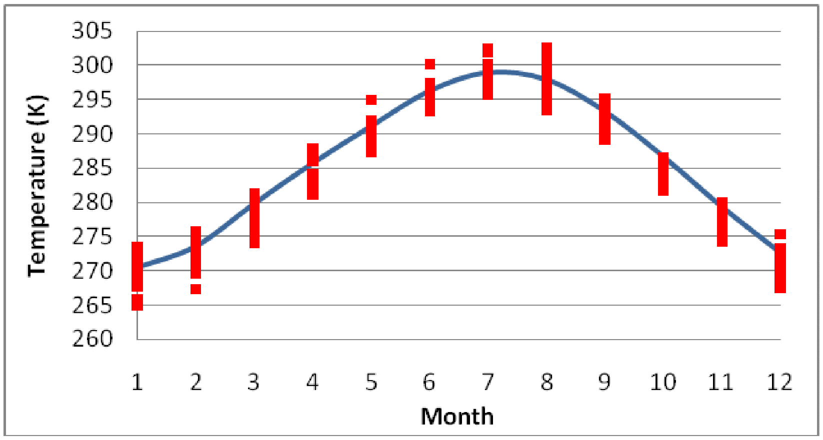

Figure 3-1 GCM Historic Simulation Temperature Comparison versus NCDC Data

The results of the precipitation historic simulation compared to the NCDC data contained more variation than for temperature (Figure 3-2). Even though variation in monthly means increased, the GCMs were still distributed around the actual monthly NCDC means. The fact that GCMs have a difficult time simulating past temperature and precipitation results is not a huge concern because the GCM future projections will be compared back to their respective historic runs to determine future monthly increases or decreases for temperature and precipitation.

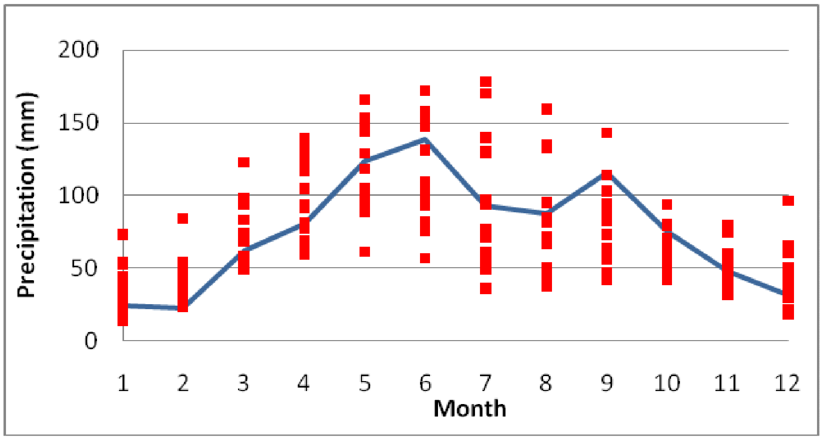

Figure 3-2 GCM Historic Simulation Precipitation Comparison versus NCDC Data

The second part of the A2 GCM analysis compared the monthly temperature and precipitation changes for each GCM to each other. This was accomplished by subtracting the mean monthly values of the historic simulation (1961-1990) from the mean monthly values of the A2 projection (2046-2064). The resultant monthly temperature and precipitation changes were then compared between GCMs to see how much variance was shown between the future projections.

Table 3-2 shows the monthly and annual average temperature change for each model. While the changes between models do not exactly match, a clear trend of temperature change throughout the year is produced. Temperature tends to increase more in the summer months than other times of the year. These GCMs show an average annual increase of between 1.3 and 4.6 ºC.

Table 3-2 A2 Average Temperature Change between 1990 and 2050 (ºC)

Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual Average**
CNRM CM3	3.5	2.9	3.1	2.5	1.5	2.9	2.7	3.6	4.2	2.8	2.4	2.1	2.9
CSIRO Mk3.0	3.4	3.8	1.7	1.5	1.9	1.1	2.2	2.6	2.0	2.9	2.3	2.8	2.3
CONS ECHOG	3.4	3.7	2.9	3.5	4.3	3.3	3.6	3.4	3.7	3.7	3.1	3.2	3.5
GFDL CM2	2.1	0.2	2.1	2.2	2.5	3.2	7.0	9.2	5.4	2.3	2.6	3.1	3.5
GFDL CM2.1	0.2	-0.2	1.3	2.0	2.4	3.2	4.9	6.0	4.7	2.6	2.5	2.8	2.7
GISS E-R	0.9	2.5	3.0	1.1	1.7	2.4	2.5	3.1	3.1	2.1	2.0	1.5	2.2
UKMO HadCM3	0.8	2.3	2.2	2.7	3.3	4.8	4.7	5.0	4.3	3.7	2.7	2.5	3.3
UKMO HadGEM1	5.9	6.0	4.7	4.9	3.6	3.8	4.0	4.2	4.1	4.3	3.8	6.1	4.6
INM CM3.0	4.9	5.0	3.4	2.8	2.3	3.1	4.5	4.5	3.7	2.4	3.6	2.7	3.6
IPSL CM4	2.6	4.5	5.5	4.1	4.1	4.1	2.4	3.2	4.0	2.6	2.9	3.2	3.6
NIES MIROC3.2medres	2.7	3.9	2.8	3.1	2.6	3.6	4.8	5.1	5.9	4.0	4.3	3.5	3.9
MPI-M ECHAM5-OM	1.7	1.3	2.5	1.7	1.7	1.5	2.6	2.9	2.4	2.5	3.1	3.6	2.3
MRI CGCM2.3.2	1.7	2.1	2.3	2.1	1.6	2.2	1.8	1.7	2.0	2.7	2.1	1.8	2.0
NCAR CCSM3	2.8	3.0	3.5	1.4	3.6	4.1	2.8	4.0	4.7	5.5	3.6	3.1	3.5
NCAR PCM	1.7	1.5	1.2	1.0	0.9	1.1	1.6	1.5	2.5	1.4	0.2	1.3	1.3

Table 3-3 shows a much different result for the precipitation analysis. Comparing the various models for given months, monthly precipitation varied from large increases to large decreases. The annual total change also showed no clear trend with changes ranging from a 148.4 mm decrease to a 146.1 mm increase.

While temperature projections varied between GCMs, they all showed an increasing trend. Precipitation data however do not show any clear trend between GCMs and varied significantly more than temperature projections. As a result of the wide precipitation variance between GCMs, the amount of change in precipitation projections should be a major factor in determining which GCM to use in a study. This increases the difficulty of analysis of climate change because the researcher not only has to choose which SRES scenario to use, but a consideration as to which GCM to rely on is also necessary.

Table 3-3 A2 Precipitation Change between 1990 and 2050 (mm)

Model	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual Total**
CNRM CM3	-3.4	-2.5	6.5	-21.3	-13.0	-1.2	-10.2	-27.9	-24.3	6.5	-6.3	5.0	-92.2
CSIRO Mk3.0	0.0	6.7	-1.6	5.4	5.0	-2.4	2.8	11.5	10.2	-10.2	8.7	6.5	42.6
CONS ECHOG	-13.3	-15.1	-0.9	-14.7	29.5	59.4	50.5	47.7	26.4	-3.7	-14.7	-5.0	146.1
GFDL CM2	29.5	-5.6	10.2	1.2	10.9	-48.6	-71.6	-44.0	-23.7	-1.2	1.2	-6.5	-148.4
GFDL CM2.1	-1.2	19.6	12.1	-2.4	36.9	-26.4	-37.8	-17.1	-16.2	-1.6	14.1	1.2	-18.7
GISS E-R	-3.7	-9.0	5.0	9.3	9.9	-7.2	7.1	-33.5	21.9	15.5	-0.9	-1.6	12.9
UKMO HadCM3	1.9	-2.2	-9.3	-6.3	10.9	-35.1	-17.4	2.5	-8.4	-6.2	5.4	10.2	-54.1
UKMO HadGEM1	2.5	-0.8	-7.4	-2.7	30.7	-3.9	-20.8	-17.1	-17.4	20.5	7.2	6.8	-2.5
INM CM3.0	13.6	15.4	22.6	24.0	17.4	-20.1	-13.0	-0.3	-8.7	-33.5	1.2	12.7	31.3
IPSL CM4	-5.3	-4.8	-0.3	-23.4	-12.1	-18.0	-0.3	-7.1	15.0	27.3	-6.3	1.6	-33.7
NIES MIROC3.2medres	8.4	13.2	14.3	-1.5	-16.4	-20.1	-27.9	-36.0	-36.0	31.6	26.1	11.8	-32.6
MPI-M ECHAM5-OM	29.5	8.1	-16.7	14.7	-4.0	12.9	-9.9	3.4	-18.0	7.4	7.5	-9.3	25.5
MRI CGCM2.3.2	11.8	16.0	19.5	3.3	1.9	-0.3	1.6	-1.6	12.9	12.1	9.9	12.7	99.7
NCAR CCSM3	0.9	-1.4	9.9	29.1	34.4	-6.6	-1.2	6.8	-2.1	-18.3	-11.7	9.7	47.3
NCAR PCM	1.2	7.3	-0.3	16.5	13.3	-6.6	-35.7	3.1	6.6	-1.2	1.2	8.4	13.8

This dilemma also causes difficulties in defending the results shown in a study because repeating a study with a different GCM will result in different results. One solution to this problem is to use the ensemble mean of all of the climate models (Brunsell *et al.*, 2010). With this approach, all available GCMs for a specific SRES scenario are combined and the mean monthly parameter changes are used as the future climate projection. By taking all available GCMs into account to produce a future climate scenario, the study can be reproduced numerous times and similar results will be found. The ensemble mean approach along with two other approaches are used in this study to develop future climate scenarios for the study area. With these climate scenarios, a wide range of future projections are developed and analyzed to determine the impacts of climate change projections in Northeast Kansas.

Climate Scenario Development

In order to develop climate scenarios, monthly temperature and precipitation adjustments are calculated by subtracting the average values of the historic run (1961-1990) from the A2 projected values (either 2046-2064 or 2080-2099) for each GCM. These adjustments are then used to adjust actual daily temperature and precipitation statistics obtained by a weather generator for the study area. In this study, three different techniques are used to develop precipitation trends for the climate scenarios. The climate scenarios are included in one of three groups that represent the method used to develop them. Once monthly temperature and precipitation adjustments were calculated, they were applied to a stochastic weather generator to produce a daily time series that was input into a hydrologic model for analysis.

Baseline Scenario Development

Instead of comparing the climate scenario hydrologic results back to actual streamflow, a baseline scenario was created. This approach helped reduce potential errors caused by the weather generator or the hydrologic model because the comparison point was developed using the same procedures as the climate scenarios. The baseline for this study was created by not adjusting monthly temperature or precipitation statistics in the weather generator. Not using any adjustment will create a climate scenario with statistics similar to current temperature and precipitation in the study area. This baseline scenario was then used as a control simulation to compare the other climate scenarios to.

Scenario Group 1 Development

The scenario group 1 approach used uniform monthly precipitation adjustments to produce climate scenarios for the study area. As shown in chapter 1, this approach has been used in many previous studies (Jha *et al.*, 2006; Somura *et al.*, 2009; Nunes *et al.*, 2008). These types of climate scenarios are generally used for sensitivity analyses where the amount of temperature and precipitation adjustment is incrementally varied between each scenario. Instead of incrementally changing the adjustment magnitude, one positive and one negative future precipitation trend were used in this study. Along with the uniform increase in precipitation, a temperature adjustment was calculated using the ensemble mean approach for the fifteen GCMs analyzed earlier.

Scenario 1a

Scenario 1a used a uniform precipitation adjustment of 10% increase for all months. The temperature adjustment for this climate scenario was an ensemble mean of all models for 2050. This climate scenario simulated a future world with an increase in precipitation and fairly uniform temperature adjustment for every month throughout the year.

Scenario 1b

Like Scenario 1a, Scenario 1b used a uniform precipitation adjustment. However, Scenario 1b used an adjustment of 10% decrease for all months. The temperature adjustment for this climate scenario was the same as Scenario 1a, an ensemble mean of the fifteen A2 GCMs for 2050. This climate scenario simulated a future world with a decrease in precipitation for every month.

Scenario Group 2 Development

The approach used in scenario group 2 was a multi-model ensemble mean approach to determine both temperature and precipitation adjustments. This approach used the mean monthly change for the fifteen A2 scenario GCMs analyzed earlier. By averaging all of the monthly adjustments for temperature and precipitation, this approach created a unified climate scenario from the A2 GCMs. This approach also limited the effect that GCMs showing very extreme changes had on the climate scenario. Since a unified future scenario is created with this approach, the results can be easily repeated with a study using the same GCMs.

Scenario 2a

Scenario 2a represented the ensemble mean temperature and precipitation adjustment from 1990 to a new level in 2050. Figure 3-3 shows the variance between GCMs for average monthly precipitation change as well as the means that were used for this climate scenario. Although there is a significant difference between the GCMs for all months, the summer months tended to have the most variance. This climate scenario lead to an increase in ensemble mean precipitation in the spring (March, April, May), fall (September, October, November) and winter (December, January, February), but a decrease in precipitation in the summer months (June, July, August).

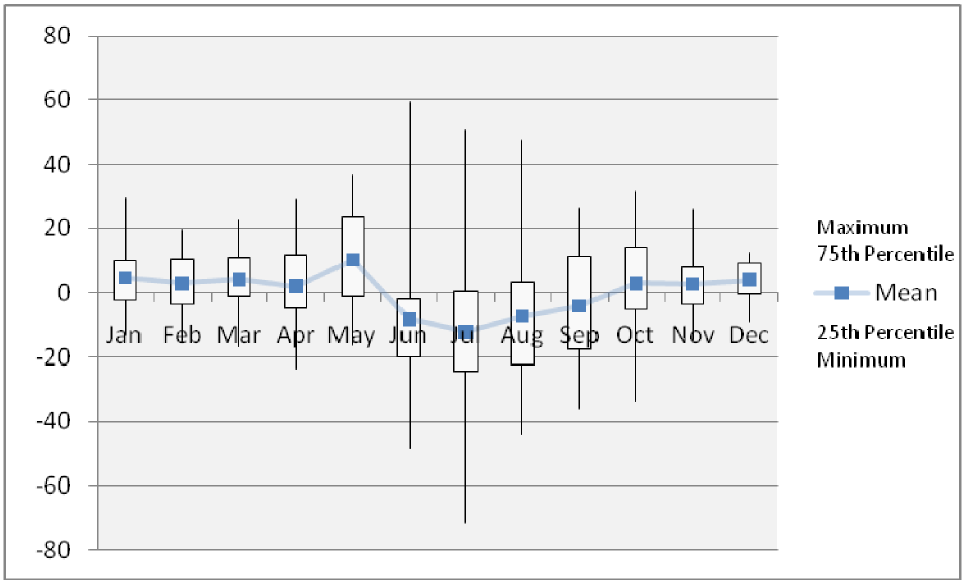

Figure 3-3 Scenario 2a Monthly Precipitation Change (mm) for GCMs from 1990-2050

Figure 3-4 shows the distribution of the GCMs for temperature. While the variances are significantly lower than the precipitation projections, the temperature projections did show a distinct increase in 2050 compared to 1990 for the entire year. The increase in mean temperature was around 2.5 ºC all year, with a slightly larger increase during the summer months. This temperature adjustment was also used in the previously established climate scenarios 1a and 1b as well as all three of the group 3 scenarios that will be discussed later.

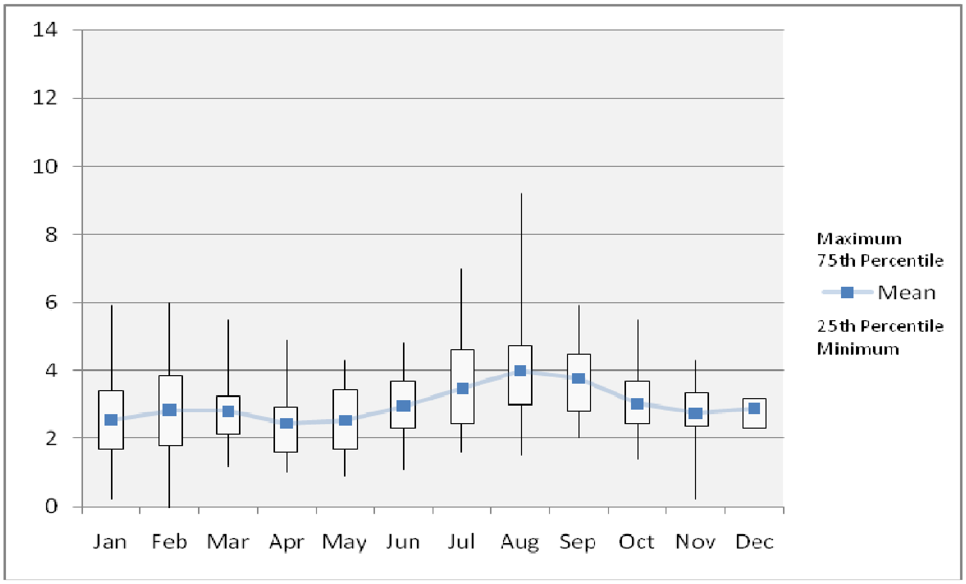

Figure 3-4 Scenario 2a Monthly Temperature Change (ºC) for GCMs from 1990-2050

Scenario 2b

Scenario 2b is similar to 2a in that an ensemble mean approach was used to determine the temperature and precipitation adjustments for a future climate scenario. Scenario 2b also used the same GCMs as scenario 2a. However, Scenario 2b used the difference in average temperature and precipitation adjustments between the historic simulation (1961-1990) and the A2 projection for 2080-2099.

Figure 3-5 shows the distribution of future precipitation shown in these GCMs. Even though the variance between GCMs for this time frame was much higher than for 2050, the mean precipitation changes show similar seasonal changes to the Scenario 2a development.

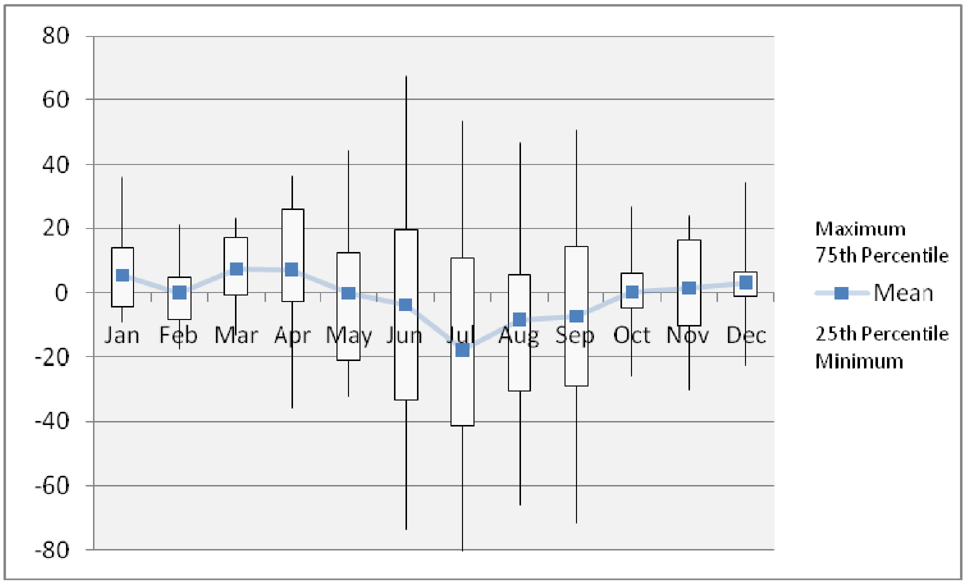

Figure 3-5 Scenario 2b Monthly Precipitation Change (mm) for GCMs from 1990-2100

The future temperature projections are shown in Figure 3-6. These projections showed a much higher mean temperature increase than in Scenario 2a. This resulted in a temperature increase of around 4.5ºC for most months except summer months which were again higher than the rest of the year with an increase of around 6 ºC. Although the differences between Scenarios 2a and 2b are not large, the almost doubling of the temperature increase should cause different results with the hydrologic analysis.

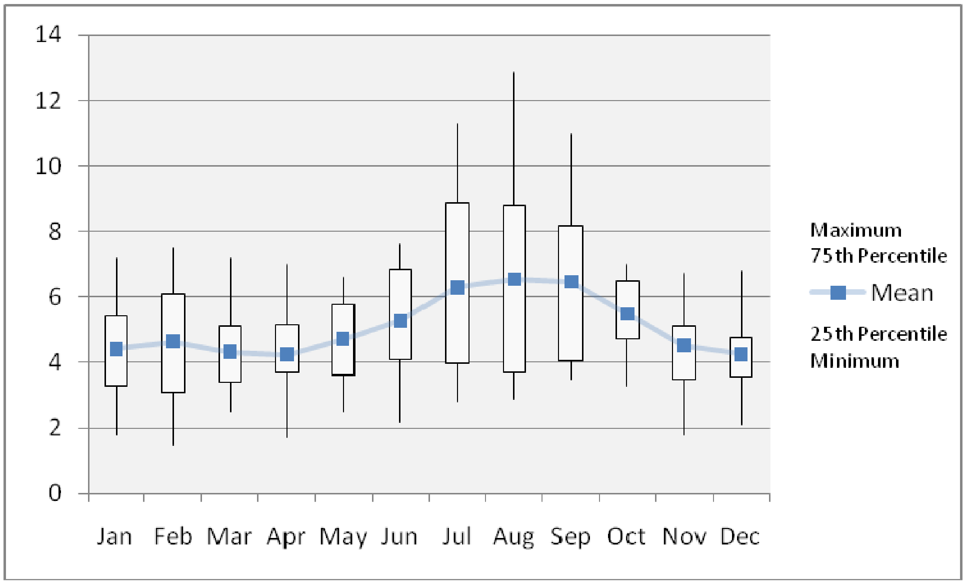

Figure 3-6 Scenario 2b Monthly Temperature Change (°C) for GCMs from 1990-2100

Scenario Group 3 Development

While the ensemble mean approach is an easy way to represent the fifteen GCMs as one unified climate scenario, if the GCMs show more than one future trend, they will not be represented in the climate scenario. In order to represent multiple future trends shown in the GCMs, scenario group 3 used a modified version of the ensemble mean approach. The ensemble mean approach was modified by grouping the GCMs that showed a common trend with other GCMs. The ensemble mean was then calculated for these groups to produce future projections.

Analyzing the temperature projections for the fifteen GCMs showed that a more consistent trend between the GCMs for temperature compared to precipitation. As a result, the modified ensemble mean approach was not used to calculate temperature adjustments. Instead, the ensemble mean of all models for 2050 was also used in the group 3 climate scenarios. Precipitation on the other hand showed three distinct trends during the spring months (March, April, May) and summer months (June, July, August) among the GCMs.

Table 3-4 displays the results of the seasonal precipitation analysis with “Wet” denoting an increase in total precipitation during the season for the 2050 period compared to the 1990 period, while “Dry” denotes a decrease. This table shows the three distinct trends between GCM precipitation projections. The models were then grouped as either showing a “Wet-Wet”, “Dry-Dry” or a “Wet-Dry” trend. Only one model (MPI-M ECHAM5-OM) did not fall into one of these three categories as it showed a “Dry-Wet” trend and was not used in any of the group 3 precipitation scenarios.

Table 3-4 A2 Model Seasonal Analysis 2050 compared to 1990

Season	CNRM CM3	CSIRO Mk3.0	CONS ECHOG	GFDL CM2	GFDL CM2.1	GISS E-R	UKMO HadCM3	UKMO HadGEM1	INM CM3.0	IPSL CM4	NIES MIROC3.2 medres	MPI-M ECHAM5 -OM	MRI CGCM 2.3.2	NCAR CCSM3	NCAR PCM
Spring	Dry	Wet	Wet	Wet	Wet	Wet	Dry	Wet	Wet	Dry	Dry	Dry	Wet	Wet	Wet
Summer	Dry	Wet	Wet	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Wet	Wet	Wet	Dry
Scenario	3dd	3ww	3ww	3wd	3wd	3wd	3dd	3wd	3wd	3dd	3dd		3ww	3ww	3wd

Three climate scenarios were developed using the ensemble mean of all models to calculate temperature adjustment and the ensemble mean of one of the model groupings to calculate precipitation adjustment. This approach allowed multiple future climate scenarios to be created from the scenario 2a GCMs that are supported by more than one GCM.

Scenario 3ww

The first modified ensemble mean climate scenario, Scenario 3ww, consisted of a grouping of all GCMs showing a “Wet-Wet” precipitation trend (Table 3-4). Of the fifteen analyzed AR4 GCMs, four of them are included in this grouping. Figure 3-7 shows the monthly precipitation distribution of these four GCMs. As expected, the monthly ensemble mean precipitation for these models lead to a large increase in average monthly precipitation during the spring and summer. Interestingly, even though these GCMs were only grouped for precipitation in spring and summer, precipitation appears to be increased in fall and winter months as well. Of all of the months, only October showed a substantial decrease in precipitation. Consequently, this GCM grouping also produced the largest annual precipitation increase compared to the other scenarios except the uniform 10% increase (Table 3-5).

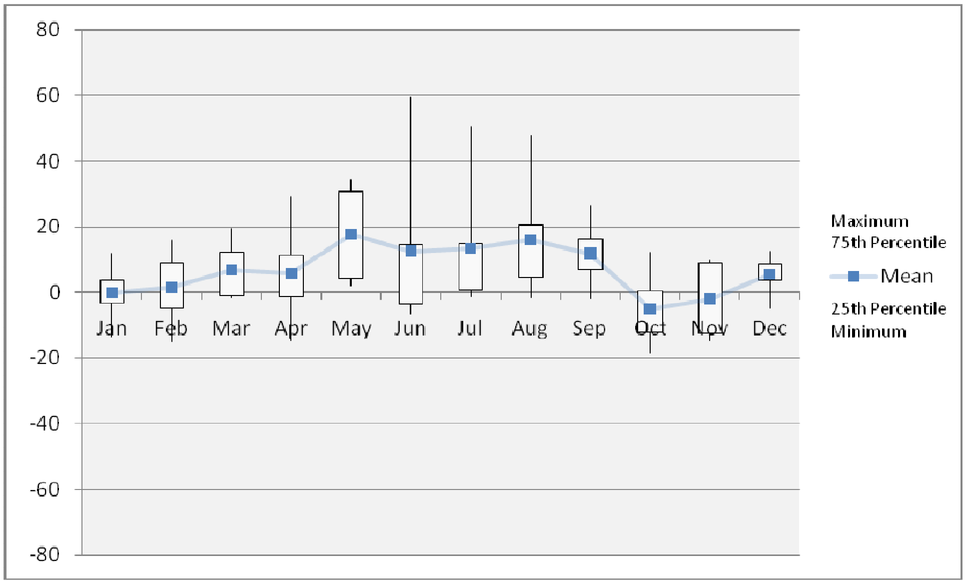

Figure 3-7 Monthly Precipitation Change (mm) of "Wet-Wet" GCMs from 1990-2050

The projections in this climate scenario produced an interesting situation for the agricultural operations in Northeast Kansas. With an increase in precipitation throughout the growing season (April-September), crops may become less dependent on irrigation input. Increased rainfall during the growing season may also provide an increase in crop yield. Aquatic ecosystems might also benefit from this increase with less frequent low-flow periods during the summer months. One downside to these positives might be an increase in runoff and erosion causing land management concerns as well as increased sediment in streams and reservoirs.

Comparing Figure 3-7 to Figure 3-3 shows the effectiveness that the modified ensemble mean approach has at decreasing the variability of mean monthly precipitation change between GCMs. This approach produced much smaller differences between 25th and 75th percentiles as well as minimum and maximum values than Figure 3-3 showed for the ensemble mean approach. For example, September showed a 75th percentile 15 mm increase and a 25th percentile of 18 mm decrease in Figure 3-3. However, the Scenario 3ww GCMs showed a 75th percentile of around a 18 mm increase and a 25th percentile of 8 mm increase (Figure 3-7).

Scenario 3dd

Scenario 3dd used the ensemble mean of the GCMs with a "Dry-Dry" precipitation trend (Table 3-4) to calculate future precipitation projections. Like the "Wet-Wet" scenarios, there were also four GCMs that contributed to the "Dry-Dry" trend. Figure 3-8 displays the statistics of this GCM grouping. These models, along with the decrease in precipitation in the spring and summer, projected an increase in precipitation in the late fall and early winter. Even with some months increasing in precipitation, this scenario produced the largest annual precipitation decrease out of all of the scenarios tested except the uniform 10% decrease in Scenario 1b (Table 3-5).

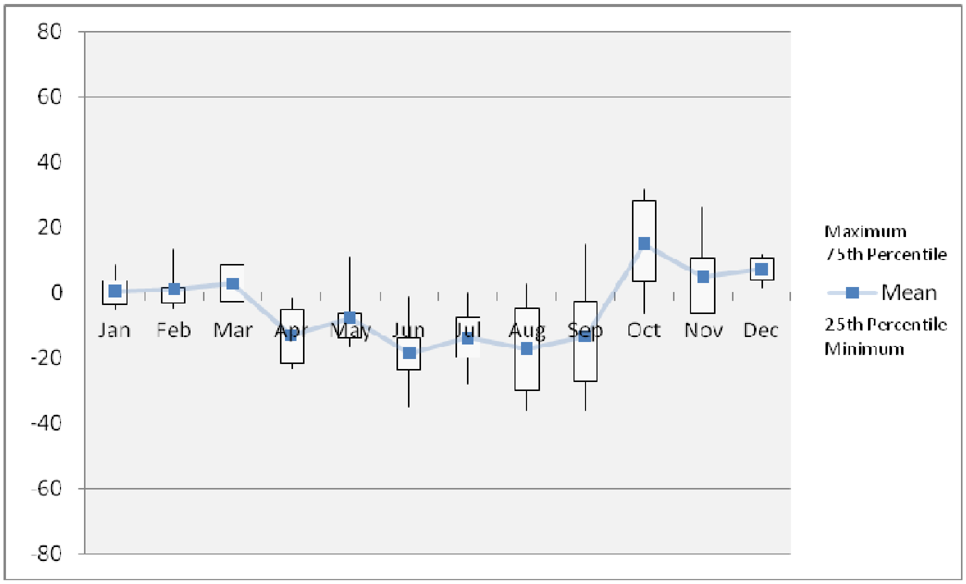

Figure 3-8 Monthly Precipitation Change (mm) of "Dry-Dry" GCMs from 1990-2050

Once again, this climate scenario provided an interesting situation for the agricultural practices in Northeast Kansas. The decreased precipitation may lead to a decrease in runoff and erosion, but adverse affects from precipitation reduction also occur. For example, the large decrease during the growing season may result in an increase in irrigation requirements. This would put additional stress on already limited unpolluted water supplies in the area.

As with Scenario 3ww, Figure 3-8 shows that the modified ensemble mean approach was also effective at reducing monthly precipitation variance between GCMs for Scenario 3dd. The spring and summer precipitation projections showed much smaller differences between GCMs, while the fall and winter month projections also demonstrated slightly less variations.

Scenario 3wd

Scenario 3wd was developed by calculating the ensemble mean monthly precipitation change of all GCMs showing a "Wet-Dry" trend in spring and summer precipitation (Table 3-4). Figure 3-9 shows the resultant rainfall distribution from the grouped GCMs. As a result of the varying seasonal precipitation trends, mean annual precipitation did not extensively change with this climate scenario (Table 3-5). Much like the climate scenarios generated in group 2, even though this scenario did not show large annual changes in precipitation, the seasonal shifts could cause considerable hydrologic alteration during the analysis.

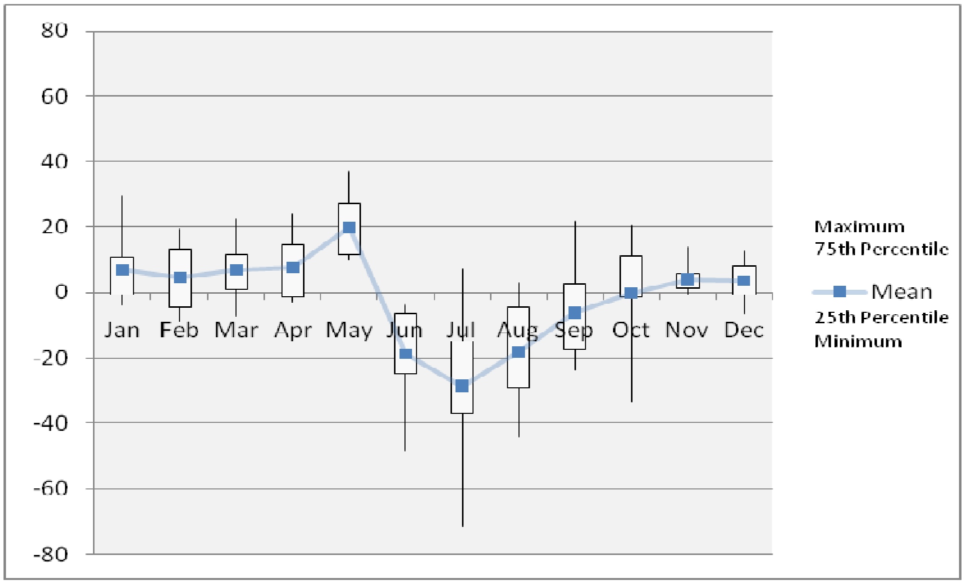

Figure 3-9 Monthly Precipitation Change (mm) of "Wet-Dry" GCMs from 1990-2050

This climate scenario is interesting for Northeast Kansas because it caused peak rainfall to shift into times of the year when ground cover on agricultural fields is at a minimum. This would result in an increase in runoff and erosion during the early part of the year. This type of climate scenario could also cause the need for increased irrigation in some areas as the summers get increasingly drier. Aquatic habitats might also come under increasing stress due to earlier floods followed by significant drought periods during the summer.

Summary of Scenarios

A baseline and seven other climate scenarios were developed using three separate development methods in this chapter. Table 3-5 shows the final temperature and precipitation adjustments for each climate scenario developed. Each of these climate scenarios provided a unique future temperature and precipitation projection for the study area. These approaches produced an efficient way to account for the wide variation in precipitation projections without modeling each GCM individually.

Table 3-5 Monthly Scenario Precipitation (mm) and Temperature (ºC) Change

	Scenario 1a		Scenario 1b		Scenario 2a		Scenario 2b		Scenario 3ww		Scenario 3dd		Scenario 3wd	
Month	Precip	Temp	Precip	Temp	Precip	Temp	Precip	Temp	Precip	Temp	Precip	Temp	Precip	Temp
Jan	2.4	2.6	-2.4	2.6	4.8	2.6	5.7	4.4	-0.2	2.6	0.4	2.6	7.0	2.6
Feb	2.3	2.8	-2.3	2.8	3.0	2.8	0.1	4.6	1.5	2.8	0.9	2.8	4.5	2.8
Mar	6.2	2.8	-6.2	2.8	4.2	2.8	7.5	4.3	6.7	2.8	2.79	2.8	7.0	2.8
Apr	8.1	2.4	-8.1	2.4	2.1	2.4	7.4	4.2	5.8	2.4	-13.1	2.4	7.7	2.4
May	12.4	2.5	-12.4	2.5	10.3	2.5	0.1	4.7	17.7	2.5	-7.7	2.5	19.8	2.5
Jun	13.9	3.0	-13.9	3.0	-8.3	3.0	-3.6	5.3	12.5	3.0	-18.6	3.0	-18.8	3.0
Jul	9.3	3.5	-9.3	3.5	-12.3	3.5	-18.0	6.3	13.4	3.5	-14.0	3.5	-28.6	3.5
Aug	8.7	4.0	-8.7	4.0	-7.3	4.0	-8.3	6.5	16.1	4.0	-17.1	4.0	-18.1	4.0
Sep	11.6	3.8	-11.6	3.8	-4.1	3.8	-7.4	6.5	11.9	3.8	-13.4	3.8	-6.2	3.8
Oct	7.6	3.0	-7.6	3.0	3.0	3.0	0.3	5.5	-5.0	3.0	14.8	3.0	-0.3	3.0
Nov	4.8	2.7	-4.8	2.7	2.8	2.7	1.6	4.5	-2.0	2.7	4.7	2.7	4.0	2.7
Dec	3.2	2.9	-3.2	2.9	4.1	2.9	3.3	4.2	5.4	2.9	7.1	2.9	3.5	2.9
Annual	90.5	3.0	-90.5	3.0	2.3	3.0	-11.3	5.1	83.8	3.0	-53.2	3.0	-18.5	3.0

While it is unlikely that the climate scenarios generated for this study area would be the same for other areas, the methods used to generate these climate scenarios can be used to generate future scenarios for any watershed around the world. The resultant climate scenarios from the group 2 and 3 development procedures are better for hydrologic analysis because they do not rely on a single GCM projection. By incorporating multiple GCM projections into a single scenario, the trends projected in the climate scenario are much easier to support.

Chapter 4 - Climate Scenario Data Generation

The resultant monthly temperature and precipitation adjustments for each scenario (Table 3-5) are applied to a stochastic weather generator to create a 105 year period of daily temperature and precipitation data. This approach only used a single adjustment for climate change for the whole time series. As a result, climate change was not an active variable during the 105 year scenario simulation. Instead, the output climate data was considered a new steady state with different monthly and annual temperature and precipitation means than the current climate.

WINDS Weather Generator

A stochastic weather generator uses statistics derived from past daily temperature and precipitation records to generate a weather time series. The weather generator used in this study is the Weather Input for Nonpoint Data Simulations, also known as the WINDS model. This model was developed at the University of Minnesota as part of the Minnesota Department of Transportation Erosion Risk Assessment Tool for Construction Sites Project (Wilson *et al.*, 2006). The WINDS model was chosen over similar weather generators because of local knowledge about the development of the WINDS model. This provided an increased understanding of the recommended uses and limitations of the WINDS model. The WINDS model is a stochastic weather generator that simulates many years of weather realization based on statistical characteristics computed from the daily or sub-daily time series of historical records. In order to accomplish this, a two step process is used (Wilson *et al.*, 2006).

The first step analyzes the historical daily weather records of the closest weather station to the area of interest out of the 208 climate stations (Figure 4-1) to obtain relevant statistical information. The statistical characteristics such as mean, standard deviation, and skew coefficient are calculated for eleven climate variables: daily minimum and maximum temperature, relative humidity, average and maximum wind speed, wind direction, solar radiation, atmospheric pressure, and precipitation depth. The mean, standard deviation and skew coefficient are computed for five-day intervals for all non-precipitation data using:

Mean: $E\left(x_j\right) = \frac{\sum_{i=1}^{n} x_{ji}}{n}$

Standard Deviation: $STDEV(x_j) = \sqrt{\frac{\sum_{i=1}^{n}\left(x_{ji}-E(x_j)\right)^2}{n-1}} = \sqrt{\frac{\sum_{i=1}^{n} x_{ji}^2-\left(\sum_{i=1}^{n} x_{ji}\right)\left(\sum_{i=1}^{n} x_{ji}\right)/n}{n-1}}$

Skewness: $SKEW(x_j) = \frac{n\sum_{i=1}^{n}\left(x_{ji}-E(x_j)\right)^3}{(n-1)(n-2)STDEV(x_j)} = \frac{n^2\sum_{i=1}^{n} x_{ji}^3-3n\left(\sum_{i=1}^{n} x_{ji}\right)\left(\sum_{i=1}^{n} x_{ji}^2\right)+2\left(\sum_{i=1}^{n} x_{ji}\right)^3}{n(n-1)(n-2)STDEV(x_j)}$

Where x_j represents the non-precipitation variable and n denotes the number of observations for the jth five-day interval (Wilson *et al.*, 2006). Each variable was then represented by cosine functions with three harmonics:

$$W(t_j) = W_{mean}\left(b_0 + b_1\cos(t_j + b_2) + b_3\cos(2t_j + b_4) + b_5\cos(3t_j + b_6)\right),\ \ t_j = 2\pi(\text{day}_j)/365$$

where *W* are the statistics of climate variable, W_{mean} is the annual mean value, and *b* represented harmonic coefficients (Wilson *et al.*, 2006). Values of the coefficients *b* are obtained using the theory for harmonic analysis and modified nonlinear Gauss method (Wilson *et al.*, 2006). The statistics for non-precipitation variables were calculated individually for each day within a year. Since precipitation climate variable is a discontinuous function with a number of events significantly less than for continuous non-precipitation variables within the same time period, a twenty-eight day interval is used for statistical characteristics represented by cosine functions presented above. Transitional probabilities of wet days given previous day is wet and wet days given previous day is dry are calculated using the same cosine fit function presented above (Wilson *et al.*, 2006).

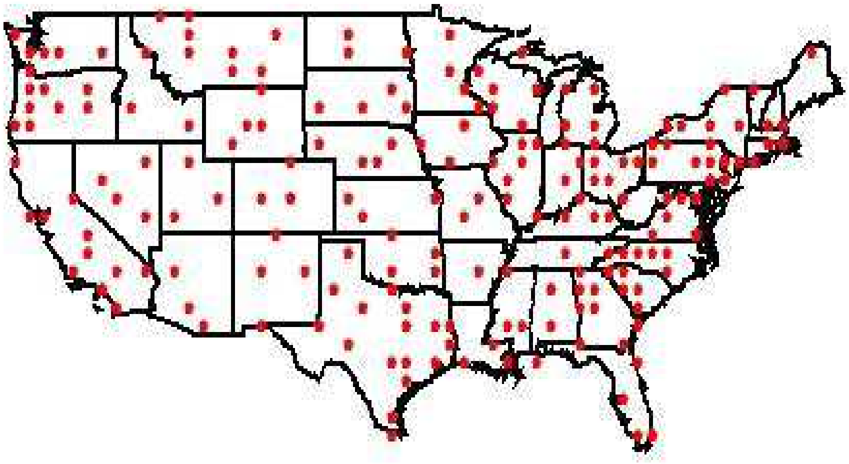

Figure 4-1 Location of Precipitation Stations Used in the WINDS Model (Wilson *et al.*, 2006)

The second step in this process uses the calculated statistics to generate a predicted time series of the eleven weather variables. Non-precipitation climate variables are represented by continuous functions, use normal probability density function, and simulated with a statistical framework of Markov processes. Discrete precipitation events are modeled using a first-order, two-state Markov chain based on a transitional probability of wet given wet days and dry given wet days (Wilson *et al.*, 2006) A transitional probability function is used to identify a rainfall event, and a log-normal probability density function distribution is used to determine the precipitation depth for that rainfall event.

Cross-correlations between non-precipitation climate variables are applied for predicting daily values. The cross-correlation maintains the fact that for any given day, maximum temperature cannot be lower than the predicted minimum temperature. This two step process allows WINDS to produce a continuous daily weather variable time series that closely resembles historical statistics. While this process is excellent at generating weather data based on historical trends, changes to the WINDS model had to be made to allow it to account for future climate change adjustments.

Methods

To allow the WINDS model to account for future climate change scenarios, the past temperature and precipitation statistics had to be modified using the adjustments calculated for each scenario in Table 3-5. The first step in this process was to obtain the historic statistics for temperature and precipitation data for the study area. Daily minimum and maximum temperature, as well as precipitation data were obtained from the weather station at the Topeka, KS Municipal Airport (COOP ID #148167) located at the coordinates 39º 04’ N latitude and 95º 38’ W longitude (NCDC, 2009).

Even though a longer time period was available for the weather station, only data from 1961 to 1990 were used to calculate the statistics. This time frame was used because it is the same time frame used in the GCM historic experiment that the climate change adjustments were calculated from. The historic statistics and cosine fits for these weather stations were calculated for temperature (Figure 4-2) and precipitation (Figure 4-3). With these data, WINDS was setup to generate 105 years of continuous daily temperature and precipitation data for each scenario.

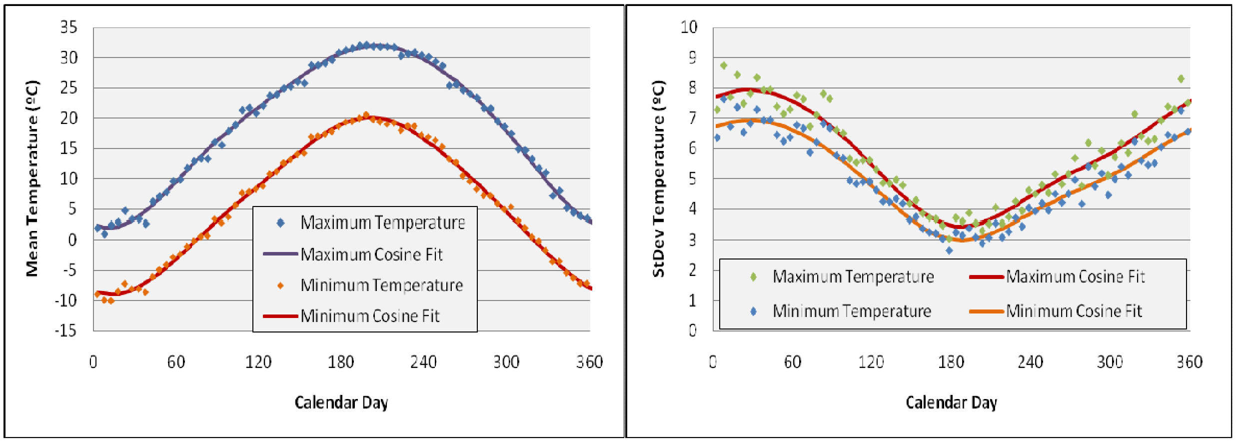

Figure 4-2 Temperature Statistics for 1961 – 1990 in Soldier Creek

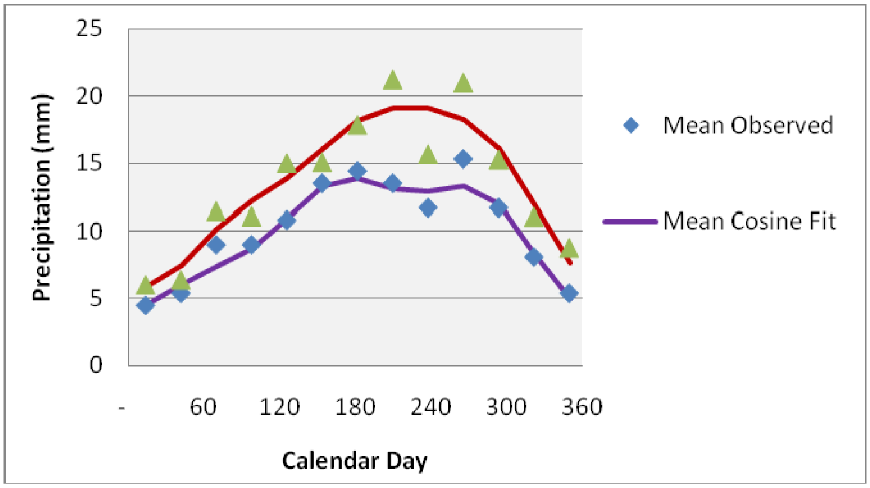

Figure 4-3 Monthly Precipitation Statistics from 1961 – 1990 for Wet Days in Soldier Creek Watershed

At each step of generating daily variables, the normalizing parameter representing annual average value of the specified variable was scaled according to the monthly shifts (Table 3-5) and a new value was generated. Standard deviations and transitional probabilities calculated based on the historical weather data were not modified in simulating future weather data. While annual scaling was not included in climate predictions, natural variability in daily values associated with standard deviations and transitional probabilities were incorporated in the model. The WINDS output produced a 105 year time series that included daily minimum and maximum temperature as well as precipitation for each of the eight scenarios.

Climate Scenario Validation

The use of past daily mean and standard deviation temperature and precipitation statistics to generate future daily temperature and precipitation values using the stochastic WINDS model, may lead to variation between actual and generated daily values. This concern was realized when producing multiple 105 year baseline scenario simulations with the WINDS model. Daily temperature mean and standard deviations continually matched actual daily statistics well. Daily precipitation mean and standard deviation statistics calculated based on 105 years of WINDS outputs, however, resulted in variations from the actual statistics.

A longer WINDS simulation period improved the results. Statistics based on 1000 years of WINDS simulation for the baseline scenario showed an R^2 of 0.99 for daily precipitation mean and an R^2 of 0.97 for daily precipitation standard deviation when compared back to actual statistics over multiple simulations. Unfortunately, the hydrologic model did not allow 1000 years of weather data to be analyzed, so a method to select a 105 year simulation that contained daily means and standard deviations that adequately matched actual statistics was developed.

For the baseline scenario, the generated mean and standard deviation for the 105 year simulation were compared directly back to the actual statistics. However, since the other climate scenarios adjust the daily mean before generation, the generated statistics cannot be directly compared back to the actual statistics. To analyze the other climate scenarios, a 1000 year simulation was completed for each. The monthly precipitation mean and standard deviation from these simulations were considered “actual” for that specific climate scenario. From there, five 105 year simulations were generated for each scenario.

The monthly precipitation mean and standard deviation from the 105 year simulations were plotted versus the actual statistics. A 1x1 line representing the 1000 year simulation statistics was also plotted. The coefficient of determination, or R^2, was calculated between the each 105 year simulation and the 1x1 line representing the 1000 year simulation statistics. A simulation was considered adequate if the mean R^2 was greater than 0.95 with the standard deviation R^2 greater than 0.80.

The results from the chosen climate scenario simulation compared to the 1000 year simulation are shown in Table 4-1. If more than one simulation was considered adequate, the simulation with the highest mean R^2 was chosen. If two adequate simulations resulted in statistically equal mean R^2, the one with the highest standard deviation R^2 was chosen. The R^2

values for the five 105 year simulation for each climate scenario are shown in the tables in Appendix A.

Table 4-1 R^2 Values for Monthly Precipitation of the Chosen Simulation

	Baseline Scenario	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b	Scenario 3ww	Scenario 3dd	Scenario 3wd
Mean R^2	0.99	0.99	0.98	0.99	0.97	0.99	0.95	0.97
Stdev R^2	0.94	0.94	0.82	0.92	0.91	0.95	0.86	0.87

Chapter 5 - Climate Scenario Hydrologic Analysis

Hydrologic models, also known as watershed models, are powerful tools that simulate the effects of watershed properties and processes on water quality and quantity as well as soil and crop quality. These models have been used to simulate the effects of watershed changes ranging from regulation efforts to conservation practice implementation. Use of watershed model results to analyze climate change scenarios is a relatively new use of these models, and suitable modeling practices are still being developed. With the development of this new use, many hydrologic models have added specific climate change simulation sub-models (Neitch *et al.*, 2005).

While these sub-models simplify climate change modeling, it is difficult to have confidence in the weather variables generated. As shown in Chapter 2, sophisticated climate models have difficulty agreeing on precipitation changes associated with climate change. The model used in this study, the Soil and Water Assessment Tool (SWAT) model, contains a climate change sub-model (Neitch *et al.*, 2005). However, this process only allowed the user to adjust CO_2 concentrations. From these changes, the SWAT model generates corresponding climate changes. The objective of this study is to analyze the IPCC GCMs, so the SWAT climate change sub-model will not be used. Instead, the temperature and precipitation data generated with the WINDS model will be input into SWAT for simulation.

SWAT Model

The SWAT model is a physically based, deterministic, continuous watershed scale simulation model developed by the USDA Agricultural Research Service (Arnold *et al.*, 1998). The SWAT version 2005 (Neitch *et al.*, 2004, 2005) was used in this study. Although there are more in-depth hydrologic based models available, the continuous nature of SWAT allows the effects of climate variables and the resultant interaction with watershed processes to be assessed over a long period of time. This is important for this study because it allows the interaction between multiple precipitation events to be analyzed along with the individual events. The SWAT model uses GIS based physical watershed inputs as well as climate data to simulate watershed processes. The SWAT model is widely used throughout the United States for assessing water resource management and nonpoint-source pollution (Gassman *et al.* 2007). One other benefit of the SWAT model is the user-friendly features that allow large watersheds to be easily modeled. SWAT is able to efficiently and accurately model large watersheds because of its ability to simplify and divide the watershed into smaller areas using a two step process.

The first step in this process is to divide the watershed into multiple sub-watersheds. These sub-watersheds are created by the model based on drainage area, but can be user adjusted. Within these small sub-watersheds, areas with similar land-use, management, slope and soil characteristics are then grouped into hydrological similar areas called Hydrologic Response Units (HRUs). This simplification process analyzes HRUs as a percentage of the sub-watershed and does not retain the spatial relationship between these areas. The HRUs are then simulated separately. The output is aggregated back into the sub-watershed scale using percentages of sub-watershed area for each HRU and applied to the outlet of the sub-watershed (Neitch *et al.*, 2005). The output from each sub-watershed is then routed through connecting sub-watersheds until it reaches the watershed outlet.

Study Area Description

In order to analyze the climate scenarios generated in Chapter 4, a watershed within the Northeast Kansas study area was identified to be the study area for the hydrologic model simulation. The watershed identified as the best candidate was the Soldier Creek Watershed (HUC10: 1027010208). This watershed was chosen because of the availability of previous hydrologic studies (Aguilar, 2009; Juracek, 2002) as well as the long historic weather and streamflow data available. The Soldier Creek Watershed covers approximately 865 km^2 (334 mi^2) in parts of Shawnee, Jackson and Nemaha Counties in northeast Kansas (Figure 5-1). The outlet of the watershed empties into the Kansas River north of Topeka, KS.

Flooding of Soldier Creek near Topeka has long been a concern (Figure 5-1). The first attempt to solve this frequent problem came in 1933 when the Northeast Drainage District of Topeka channelized the downstream reaches (Juracek, 2002). Further alteration occurred when the U.S. Army Corps of Engineers further channelized and realigned several miles of the lower portion of Soldier Creek from 1957 to 1961. During this project, the watershed outlet was moved 2.57 km (1.6 mi) further downstream away from Topeka (Juracek, 2002). As a result of these channel alterations, degradation of the channel has occurred throughout the watershed. This degradation has resulted in an unstable meandering stream with steep bank slopes.

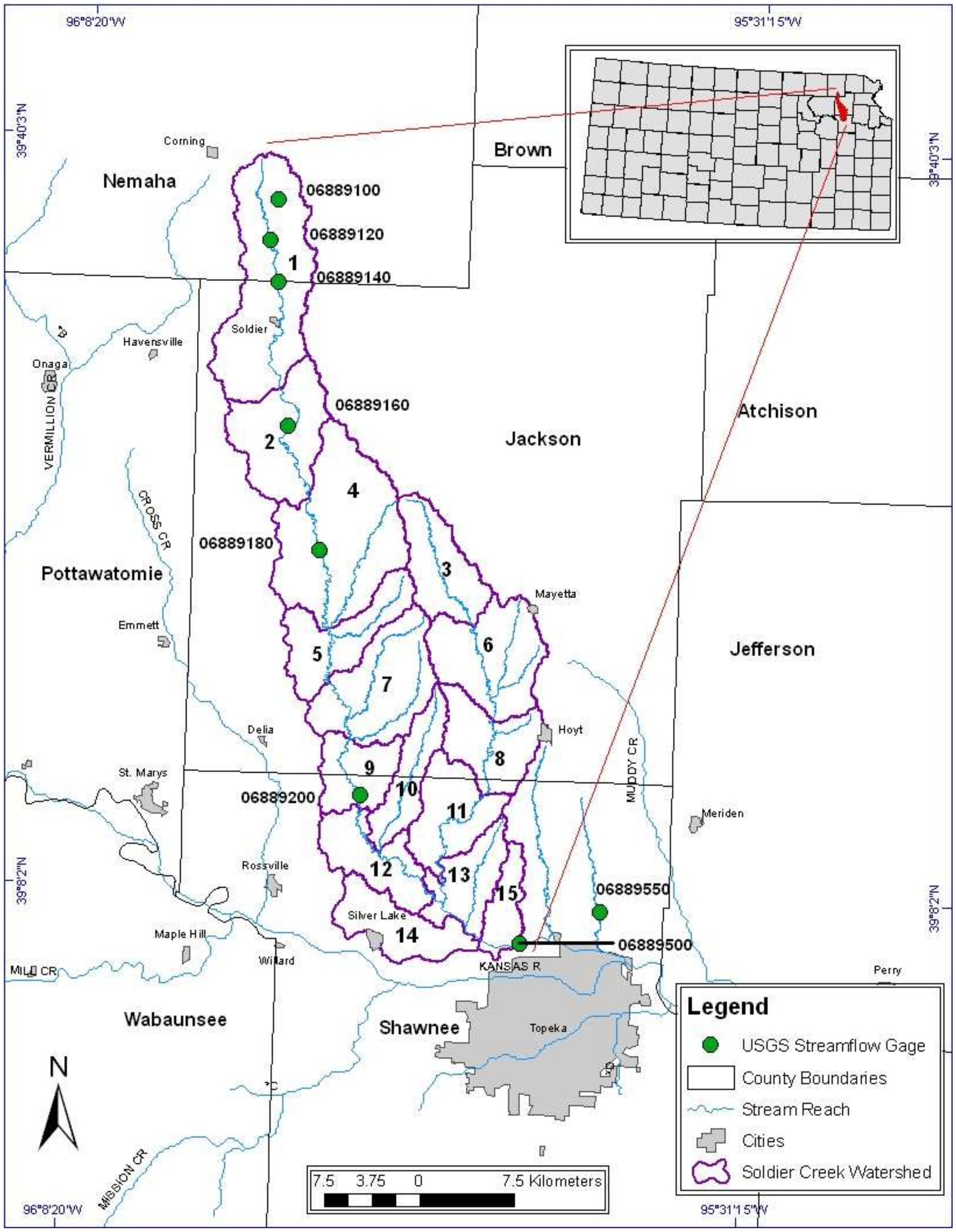

Figure 5-1 Soldier Creek Watershed Location, Sub-watersheds and Stream Gages

SWAT Model Setup

SWAT requires physical watershed inputs as well as climate data in order to simulate watershed hydrologic processes. The physical watershed inputs include topography, soil data, land-use and management operations. Climatic inputs needed on a daily time step include precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed.

Data sources were selected for this study to provide a reasonable representation of the overlapping soils, topography, land-use conditions in this watershed. The model was calibrated at the watershed outlet, and hydrologic impacts were assessed at the watershed outlet. As such, the specific spatial distribution of features in the watershed was not a primary concern. In order to assess the hydrologic impacts of climate change, the SWAT model needed to be executed many times (i.e., 100 years of simulation) to provide an adequate statistical representation of the new climatic conditions (i.e., the new 2050 or 2100 state) for each climate scenario tested. As a result, consideration of increased resolution of input data must include consideration of the potential impact on model accuracy in simulating watershed outlet response as well as the increased model processing time.

The first step in the SWAT model was to delineate the watershed and sub-watersheds. In order to accomplish this, a 30-m horizontal resolution (assumed to be about 1 m vertical resolution) National Elevation Dataset Digital Elevation Model (DEM) for Jackson, Nemaha and Shawnee counties was input into the model (USDA-NRCS, 2009). The 30-m DEM was the highest resolution data available at the time of this study. Since daily streamflow data at the watershed outlet is needed to calibrate the SWAT model, the outlet was set to correspond to the United States Geological Survey (USGS) streamflow gauging station named “Soldier Creek near Topeka” (ID # 06889500) at the coordinates 39º 6’ 0” N latitude, and 95º 43’ 29” W longitude (Figure 5-1). Using this point as the watershed outlet causes a downstream portion (approx. HUC12: 102701020808) to be cut off of the watershed for this study. As a result, the overall watershed area is approximately 769 km^2 (297 mi^2) in this study.

The model used the DEM and outlet location to calculate flow paths and the resultant stream channel which defines the overall watershed. The SWAT defined stream network was checked against the National Hydrography Dataset stream network shapefile to validate that the DEM provided enough detail to accurately define the stream. Figure 5-1 shows the watershed and fifteen sub-watersheds that were generated by SWAT using the DEM and stream outlet.

Once the watershed was defined in the model, land use, soil and slope inputs had to be determined in order to create the HRUs. The National Land Cover Dataset (NLCD) from 2001 was used to define land use in the watershed (Homer *et al.*, 2004). Because more than 65% of the watershed land cover was grassland (Table 5-1), using NLCD land cover to describe land-use in this watershed provided adequate description for all of the land-uses except agricultural – row crop areas. Tillage, fertilizer, planting and harvesting practices were added to the agricultural – row crop lands to provide additional usage data for these areas. Agricultural – row crop areas were assumed to be continuous corn for this study. This simplification does not have a large effect on runoff, but if water quality was the focus, it would have a significant impact. The land-use classification distribution is shown in Table 5-1. The Soldier Creek Watershed land-use is mainly hay (43.4%) and rangeland (22.7%), with some row crop agriculture (18.7%).

Table 5-1 Soldier Creek Watershed NLCD 2001 Land-Use Classification (KGS, 2009)

Land-Use	Area (ha)	% Watershed Area
Hay	33,386	43.4%
Rangeland	17,442	22.7%
Agricultural – Row Crop	14,429	18.7%
Forest	7,090	9.2%
Urban	3,621	4.7%
Wetland	610	0.8%
Water	421	0.5%
Total	76,999	

Figure 5-2 shows the spatial distribution of the land-use classes. Hay and rangeland are the dominant land-use types and are spread evenly throughout the watershed. Agricultural – row crop land is evenly dispersed in the northern headwaters, but concentrates towards the stream channel as the watershed progresses southward. Agricultural – row crops become the dominant land-use type in the southern tip of the watershed in the Kansas River valley.

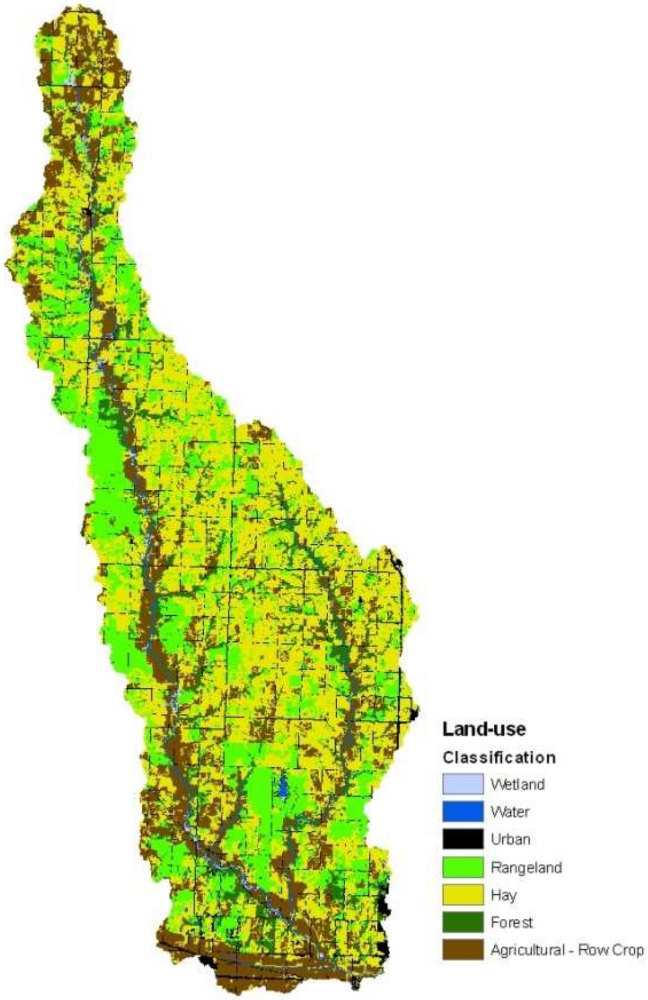

Figure 5-2 Soldier Creek Watershed NLCD 2001 Land-use Classification

The State Soil Geographic (STATSGO) soil data layer was used to represent soil characteristics in the SWAT model (USDA-NRCS, 2005). Even though higher resolution Soil Survey Geographic (SSURGO) data were available for the study area, the higher resolution SSURGO data would have greatly increased the processing time for SWAT model simulations and were not needed to support the watershed-level hydrologic response used to assess the impacts of climate variability and change in this study.

Figure 5-3 displays the soil type and hydrologic group distributions for the Soldier Creek Watershed. The upper portions of the watershed as well as the areas near the stream are mostly hydrologic soil group D. These soils have high runoff potential and restricted water movement through the soil layers (USDA-NRCS, 2007). The other large portion of the watershed contains soils in hydrologic group B. These soils are classified as having unrestricted water movement through the soil with moderately low runoff potential (USDA-NRCS, 2007).

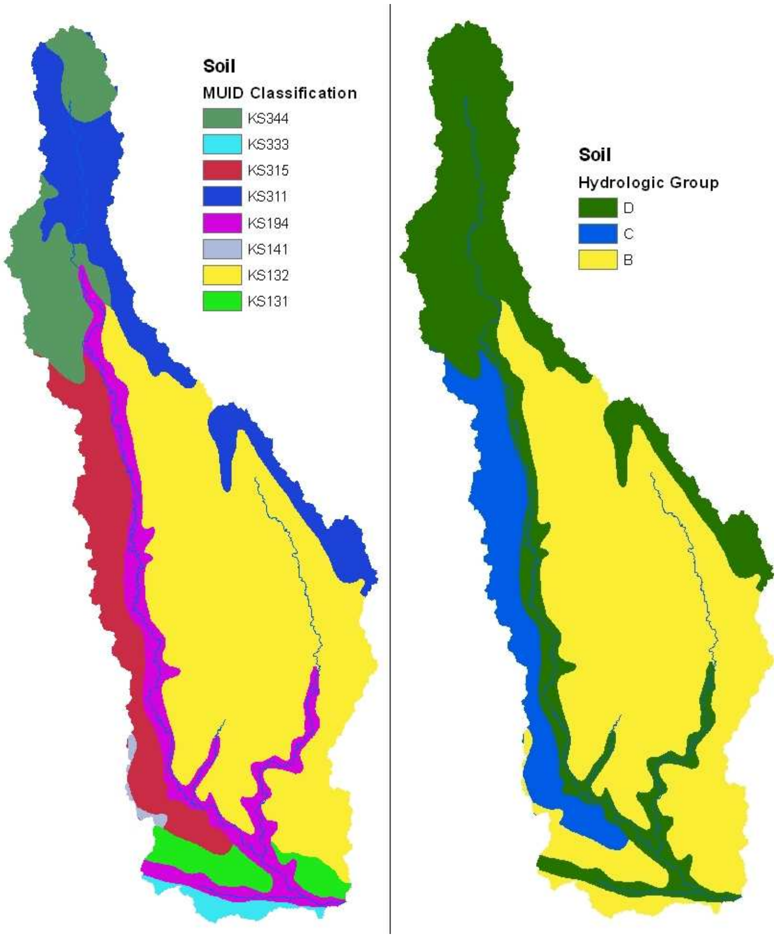

Figure 5-3 Soldier Creek Watershed STATSGO Soil Classification and Hydrologic Group

The last input needed before SWAT was able to generate HRUs was slope definitions. SWAT calculates slope data from the DEM that was input to generate the watershed and sub-watersheds. The slopes were grouped into two groups with the threshold at 3%. Most of the watershed has a slope greater than 3% (Table 5-2).

Table 5-2 Soldier Creek Watershed Slope Classification

Slope Classification (%)	Area (ha)	% Watershed Area
0-3	20851	27.1
3-53	56148	72.9

The slopes less than 3% are located mostly along the stream channels and in the Kansas River valley at the southern tip of the watershed (Figure 5-4). While a few other areas contain these gentle slopes, the other areas of the watershed are dominated by steeper slopes.

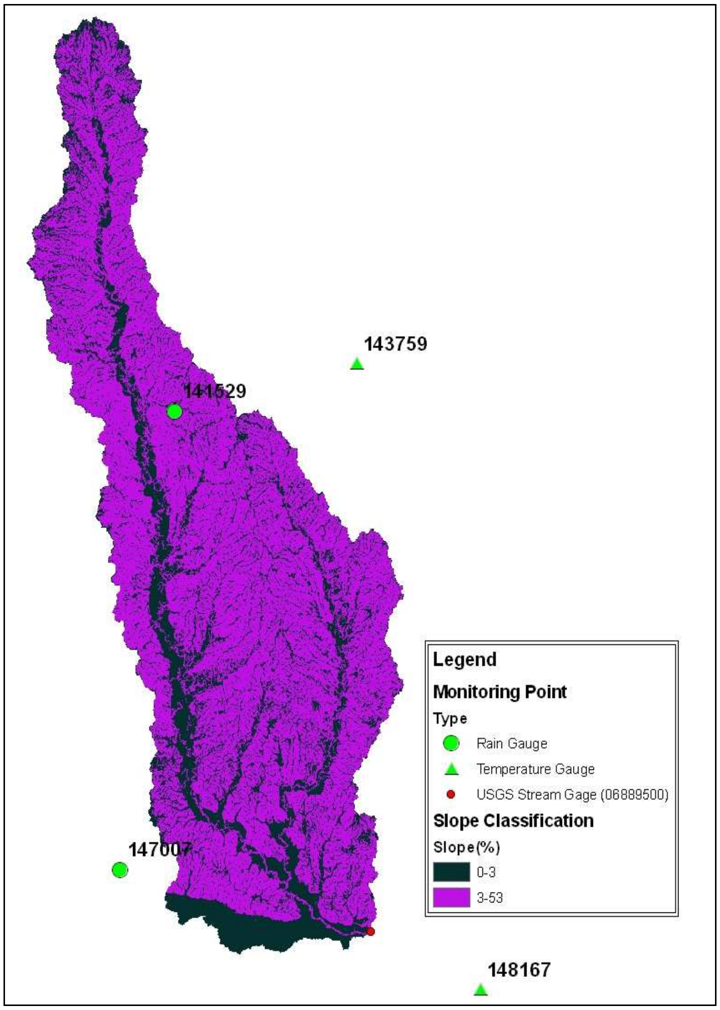

Figure 5-4 Soldier Creek Watershed Slope Classification, Weather Stations and Watershed Outlet

With all of the required data input, HRU's were generated with SWAT by grouping areas with identical land-use, soil and slope characteristics. The final step in the SWAT setup process was to enter climate data and calibrate the model for streamflow.

Calibration

In order to calibrate the SWAT model for streamflow, actual climate and streamflow data were needed. The National Climatic Data Center (NCDC) database was used to get actual climate data (NCDC, 2009). Measured daily precipitation from two weather stations (COOP ID # 141529 and 147007) were acquired from the NCDC database. Daily minimum and maximum temperature data from two different weather stations (COOP ID # 143759 and 148167) were also acquired from the NCDC database. Data from 1959 to 2008 from these four representative weather stations were input into the model (Figure 5-5). Multiple weather stations were used for both temperature and precipitation during the calibration procedures to more accurately adjust the watershed parameters. The integrated weather generator in SWAT was used to simulate solar radiation, relative humidity and wind speed for the entire watershed. Daily streamflow data was obtained from the USGS National Water Information System for the stream gage on Soldier Creek near Topeka (USGS ID #06889500) which was also chosen as the watershed outlet (Figure 5-5).

Using the NCDC weather data, the SWAT model was run from 1980 to 1990. The output streamflow from the watershed outlet was compared to the actual USGS streamflow for the same time period (Figure 5-4). Coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), and percent bias (pBias) (Moriasi *et al.*, 2007) were used to compare the simulated and actual streamflow datasets. From these comparisons, parameters were adjusted within the SWAT model in order to produce a simulated streamflow that closely resembled the actual streamflow during the calibration time period.

Alpha_BF and GW_DELAY (Table 5-3) were calculated using the SWAT Baseflow Program (Arnold and Allen, 1999). This program estimates baseflow and groundwater recharge from streamflow records. The other parameters were individually varied over the ranges in Table 5-3 for numerous repeated simulations. Each parameter was varied until an adequate adjustment value was found that produced the best streamflow statistics. Once a value was found, that parameter was held constant while a different parameter was varied. The final adjusted value for each parameter is shown in the last column of Table 5-3.

The calibration statistics for the final adjusted parameters are shown in Table 5-4. Most SWAT models are calibrated on monthly streamflow results. In Moriasi *et al.* (2007), it is determined that a monthly streamflow NSE of between 0.65 and 0.75 is considered good and a pBias less than ±10 is considered very good. This level of accuracy was easily achieved for this watershed. However, since daily streamflow is important for hydrologic indices analysis, extra calibration was used to achieve higher daily streamflow NSE. While no in-depth studies exist for daily streamflow calibration, Moriasi *et al.* (2007) also states that a NSE between 0.50 and 0.65 is considered satisfactory for monthly streamflow calibration. It is assumed that this level of accuracy on a daily scale is also satisfactory.

Table 5-3 SWAT Parameters Adjusted

Parameter	Default Value	Adjustment Range	Final Adjusted Value
SMTMP	0.5	-5 – 5	2
TIMP	1.0	0 – 1.0	0.5
ESCO	0.95	0.01 – 1.0	0.8
EPCO	1.0	0.01 – 1.0	0.1
SURLAG	4	1 – 12	2
GW_DELAY	31	0 – 500	27
Alpha_BF	0.048	0.0 – 1.0	0.08
GWQMIN	0	0 – 5000	0.01
GW_REVAP	0.02	0.02 – 0.20	0.1
REVAPMN	1	0 – 500	0.08
RCHRG_DP	0.05	0.0 – 1.0	0.1

Table 5-4 SWAT Final Streamflow Calibration Results

	R^2	NSE	pBias (%)	Median Simulated (m^3/s)	Median Observed (m^3/s)	Mean Simulated (m^3/s)	Mean Observed (m^3/s)
Daily	0.56	0.56	5.69	1.23	1.22	5.20	5.52
Monthly	0.74	0.73	5.78	2.75	2.30	5.20	5.52
Yearly	0.88	0.84	5.69	5.93	6.74	5.20	5.52

When making this judgment, it was also important to consider that the streamflow output for the various climate scenarios was not compared to measured streamflow. Instead, the future simulations were compared to the baseline scenario which was also subject to the same hydrologic modeling errors. This approach helped limit any false identification of hydrologic alteration that could have been caused by the hydrologic model.

Methods

With the hydrologic model calibrated for daily streamflow, an accurate simulation of streamflow can be obtained for the generated climate scenarios. For each of the climate scenarios developed in Chapter 3, all SWAT inputs and parameters were held constant except for the temperature and precipitation data. The final 105 year temperature and precipitation simulation from the WINDS model for each climate scenario was input. After a five year warm-up period for each climate scenario, the SWAT model was run for 100 years for each scenario. A program called Indicators of Hydrologic Alteration (IHA) was needed to convert the daily streamflow output from the SWAT model into corresponding hydrologic indices.

IHA Program

The IHA program is an easy to use program developed by The Nature Conservancy to calculate characteristics of natural and altered hydrologic systems (IHA, 2009). Since input data for the IHA program is formatted in a simple two column format containing the date and parameter value, IHA can accept any type of daily hydrologic data including streamflow, flow stages, as well as groundwater and lake levels (IHA, 2009). Once the input data are entered, the IHA program will calculate a total of 67 statistical parameters to classify the hydrologic regime (Tables B-1 and B-2). An option to either compute parametric (mean and standard deviation) or non-parametric (median and percentiles) parameters is also available.

IHA also can also be used to perform either a one period or two period analysis. A one period analysis calculates average hydrologic parameters for the entire time period. A two period analysis calculates and compares hydrologic parameters between two periods of time. Within these two analysis types, a partial year analysis can also be computed. This type of analysis would allow intra-seasonal alterations to be identified. Certain parameters within the model can also be calibrated to fit the type of analysis wanted. For example the thresholds between low flow, high flow and flood events can be changed to either a specified return interval, flow exceedance percentage or set at a certain flow value. These options allow the IHA program to be modified to analyze any hydrological system.

IHA Analysis

For this study, a two period analysis was completed to analyze the hydrologic alteration that occurred between the baseline scenario (period 1) and the climate scenarios (period 2). In order to accomplish this, the output streamflow for each future scenario was merged into a continuous time series with the baseline streamflow output. The change between the baseline and future scenarios for the hydrologic parameters shown in Table 5-5 were then analyzed to determine if future climate change projections caused a hydrologic alteration to occur.

Table 5-5 Hydrologic Parameters for Analysis (IHA 2009)

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
Magnitude of monthly water conditions	Mean flow for each calendar month	Habitat availability for aquatic organisms; Soil moisture availability for plants; Reliability of water supplies for terrestrial animals
Low flows	Low pulse count	Provide adequate habitat for aquatic organisms
	Low pulse duration	Maintain water table levels in floodplain, soil moisture for plants
Small Floods	Small flood peak	Recharge floodplain water table Deposit nutrients on floodplain
	Small flood duration	
	Small flood frequency	
Large Floods	Large flood peak	Same as small floods
	Large flood duration	
	Large flood frequency	
Flow Characteristics	Flow Duration Curve	

The hydrologic parameters in Table 5-5 were chosen because of their capacity to analyze the extreme flow conditions (low-flow, floods) as well as the normal flow conditions on a monthly (mean monthly flow) and annual (flow duration curve) scale. Each of the indices also pertains to an important ecological concern (Aguilar, 2009; Olden and Poff, 2003; Cleland, 2002) for Northeast Kansas as described in Chapter 2.

Mean flow for each calendar month is calculated by taking the average of daily streamflow for each month over the entire analysis period. A low pulse is considered when flow drops below a threshold of one standard deviation below the mean flow for the baseline period. The duration of the low pulse counts the number of days between when the flow drops below the threshold until it rises above the threshold back to a normal flow. Low flow duration is the average number of days per year that flow is below the low flow threshold. The low pulse count is the average number of times per year a low pulse is measured. The entire duration of a low flow is considered one low pulse. Flood events are calculated similarly to low pulses. A flood event is registered when flow exceeds 350 m^3/s for small floods or 600 m^3/s for large floods.

These thresholds were determined using a combination of IHA features and visual analysis of the baseline flow period. The initial flood thresholds were set by IHA to correspond with the 10% (large floods) and 20% (small floods) chance flow events for the baseline scenario. Visually analyzing the IHA streamflow output graph showed that natural breaks existed in the flood event peak streamflow. In order to capture these natural breaks, the large flood threshold was adjusted to occur at the 11% chance flow (600 m^3/s). A natural break at the 16% chance flow (350 m^3/s) was utilized as the small flood threshold.

The duration of a flood is calculated by adding the number of days between when the flood reaches the high flow threshold (greater than 75% of daily flows for the baseline) and when it recedes below that threshold. If the flood event surpasses the large flood threshold, it is classified as such. If it does not reach that threshold, but exceeds the small flood threshold, it is classified as a small flood. For this reason, a single flood cannot be both a small and a large flood.

To analyze the hydrologic alteration, both parametric and non-parametric analyses were completed for each continuous time series. The parametric analysis was used to determine the hydrologic parameters associated with each time series. The non-parametric analysis was used to determine the significance of the change between the baseline and future projections. The IHA program computes significance using a multiple step process to determine the significance count. First, the program randomly shuffles all years of input data and recalculates pre- and post-alteration medians. It repeats this process 1000 times. The significance count is the fraction of trial medians that were greater than the actual case (IHA, 2009). A low significance count shows that the difference between the pre- and post- alteration periods is highly significant. In contrast, a high significance count means there is little difference between the two periods. For simplification, the results of the significance test are reported as either highly significant, significant or not significant. This significance test is comparable to the traditional p-test (IHA, 2009).

Chapter 6 - Results and Discussion

The results from the hydrologic indices analysis for each future scenario are given below. The resultant mean monthly flow, streamflow exceedance curve and other hydrologic parameters for each 100 year future scenario were compared to the baseline scenario as well as other future projections to determine the hydrologic alteration caused by the future projections.

Scenario Group 1

Scenario group 1 contained two scenarios with uniform shifts in precipitation and the ensemble mean temperature change for the year 2050. These scenarios represent precipitation in a simplified manner that is generally used for sensitivity analysis studies. In a hydrologic study, it is easy to form expectations for these simplified precipitation scenarios. For Scenario 1a, the 10% uniform monthly increase in precipitation should cause mean and high flow indices to increase while the low flow indices should decrease. The opposite should hold true for Scenario 1b, which is a 10% uniform monthly decrease in precipitation.

Analyzing the hydrologic output, Scenario 1a showed similar results to what was expected. The streamflow exceedance curve in Figure 6-2 shows that the flow probability is increased with this scenario. Similarly, Table 6-1 shows that mean annual flow and the flood parameters also increased as expected. However, an unexpected result was observed in the mean monthly streamflow graph (Figure 6-1). This graph shows that mean streamflow increased for all months except August and November. The November mean streamflow is basically unchanged for this future scenario, but looks significant because of the way the graph is smoothed. However, the mean streamflow for August is much less for Scenario 1a than for the baseline.

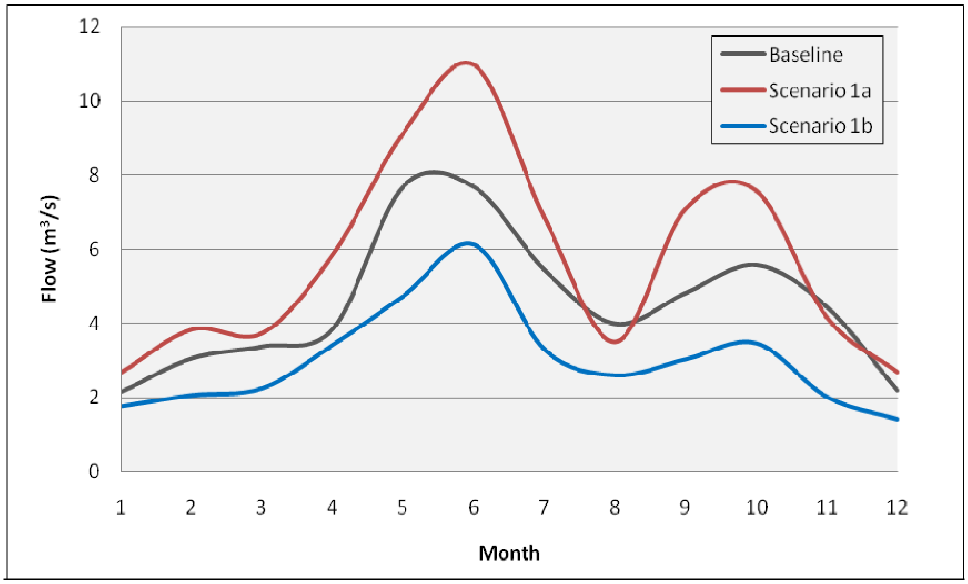

Figure 6-1 Scenario Group 1 Mean Monthly Streamflow

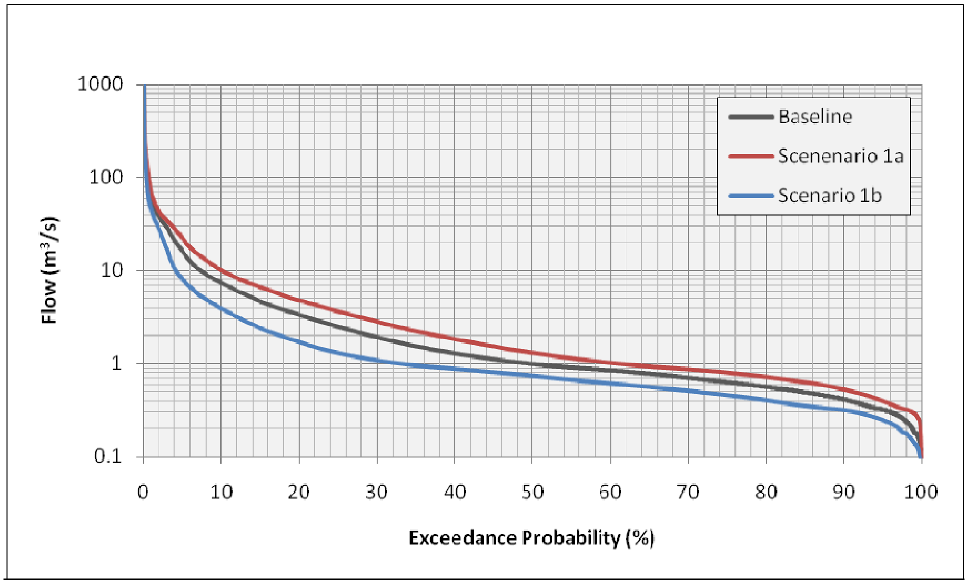

Figure 6-2 Scenario Group 1 Streamflow Exceedance Probability

Table 6-1 Scenario Group 1 Hydrologic Analysis

	Baseline	Scenario 1a	Difference	Significance	Scenario 1b	Difference	Significance
Mean Annual Flow (m^3/s)	4.5	5.6	25.1%	N/A	3.0	-33.7%	N/A
Low Pulse Count (#)	6.0	4.1	-32.4%	**	8.3	37.4%	**
Low Pulse Duration (days)	16.0	13.4	-16.6%	*	19.8	23.8%	**
Small Flood Peak (m^3/s)	434.9	443.8	2.0%	*	455.7	4.8%	**
Small Flood Duration (days)	61.7	74.2	20.2%	*	29.4	-52.3%	**
Small Flood Frequency (#/yr)	0.16	0.17	6.3%	N/A	0.11	-31.3%	N/A
Large Flood Peak (m^3/s)	777.4	838.5	7.9%	*	821.1	5.6%	-
Large Flood Duration (days)	61.4	69.2	12.6%	-	35.3	-42.5%	**
Large Flood Frequency (#/yr)	0.11	0.09	-18.2%	N/A	0.06	-45.5%	N/A

** Highly Significant, * Significant, - Not Significant, N/A Not Reported

Although unexpected, this result is caused by the temperature increase associated with this scenario. Recalling Figure 3-2, August was also the month with the highest increase in temperature for Scenario 1a. This temperature increase leads to a large increase in evapotranspiration, which offset the 10% increase in precipitation and caused a decrease in mean monthly streamflow for August.

The mean monthly streamflow for Scenario 1b (Figure 6-1) showed results similar to what was expected. Although the mean monthly streamflow decrease was not uniform, all months showed a decrease. Similarly, the streamflow exceedance probability curve in Figure 6-2 showed a decrease in flow probability. From Table 6-1, mean annual flow is considerably decreased for Scenario 1b. The low flow parameters are greatly increased, as expected.

Like Scenario 1a, Scenario 1b also has one unexpected result. This time, instead of decreasing, as was expected, both small and large flood intensity increased. However, the effect is minimal when all flood parameters are analyzed. Even though flood peaks increase, flood duration and frequency are significantly decreased for Scenario 1b. This results in floods with slightly higher peaks, but they do not last as long and are less frequent than in the Baseline Scenario.

Although some results from the scenarios in group 1 demonstrated an interesting interaction between simple climate-related ±10 uniform monthly shifts in precipitation in combination with a temperature increase, overall the results were easily predicted by analyzing the precipitation trends. While these simplified types of scenarios are good for sensitivity studies, using them alone does not give an adequate description in hydrologic studies. Using these scenarios along with climate model based scenarios in hydrologic modeling should give a more accurate portrayal of possible future climate variations.

Scenario Group 2

The ensemble mean approach used in scenario group 2 provided two unique scenarios with difficult analyses to predict. Scenario 2a uses ensemble means for temperature and precipitation results for the year 2050. Scenario 2b uses ensemble means for the same GCMs, but for the year 2100. This results in precipitation values that are comparable, but a large temperature variation exists between the two scenarios. Neither of these scenarios shows a major annual change in precipitation; both were within one percent of current annual precipitation (Table 3-5). Instead, a shift in precipitation with an increase in spring and fall and a decrease in summer months is projected.

The main difference between these two scenarios is the temperature adjustment. Scenario 2a predicted an annual temperature increase of 1.06 % while Scenario 2b projected that increase to be 1.79 %. As a result, the comparison between these two models was basically a further test of the temperature effects. As scenario group 1 showed, temperature can have a significant effect on hydrologic parameters for this watershed. As a result, the streamflow parameters should show less flow for Scenario 2b than for Scenario 2a.

The minimal increase of mean annual precipitation for Scenario 2a caused the streamflow exceedance probability graph (Figure 6-4) to remain unchanged when compared to the baseline scenario. Other hydrologic parameters were also unchanged for this scenario. Table 6-2 shows that small and large flood frequency remained equal to the baseline, and none of the parameters showed a change of over 12%. On the other hand, the mean monthly streamflow (Figure 6-3) for Scenario 2a shows a large increase in the spring followed by a considerable decrease in the summer. Even though annual precipitation totals remained within normal variation for this area, the increased precipitation in the spring followed by increased drought in the summer could cause major problems with agriculture and water resources in this area.

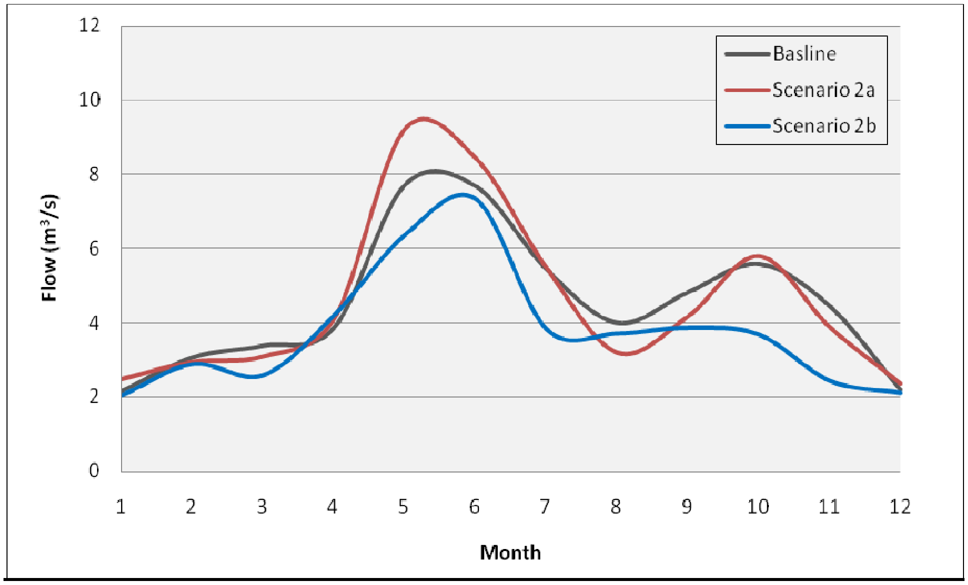

Figure 6-3 Scenario Group 2 Mean Monthly Streamflow

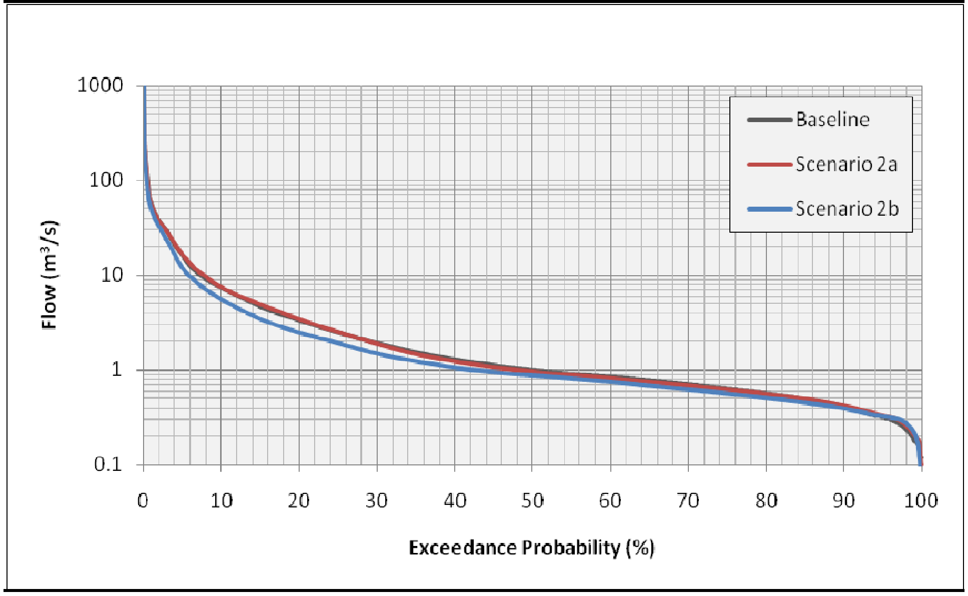

Figure 6-4 Scenario Group 2 Streamflow Exceedance Probability

Table 6-2 Scenario Group 2 Hydrologic Analysis

	Baseline	Scenario 2a	Difference	Significance	Scenario 2b	Difference	Significance
Mean Annual Flow (m^3/s)	4.5	4.6	1.5%	N/A	3.8	-17.2%	N/A
Low Pulse Count (#)	6.0	6.7	11.6%	**	7.4	24.0%	**
Low Pulse Duration (days)	16.0	14.7	-8.0%	-	14.7	-8.0%	**
Small Flood Peak (m^3/s)	434.9	448.0	3.0%	**	483.6	11.2%	**
Small Flood Duration (days)	61.7	59.8	-3.2%	*	36.4	-41.0%	**
Small Flood Frequency (#/yr)	0.16	0.16	0.0%	N/A	0.18	12.5%	N/A
Large Flood Peak (m^3/s)	777.4	861.7	10.8%	**	844.3	8.6%	*
Large Flood Duration (days)	61.4	57.6	-6.3%	*	55.4	-9.8%	*
Large Flood Frequency (#/yr)	0.11	0.11	0.0%	N/A	0.05	-54.5%	N/A

** Very Significant, * Significant, - Not Significant, N/A Not Reported

Scenario 2b also did not show a significant change in mean annual precipitation, with a decrease less than 1% (Table 3-5). However, because of the more intense temperature increase associated with the year 2100, the hydrologic analysis was much different than Scenario 2a. While most of the exceedance probability chart in Figure 6-4 remained the same for this scenario, the flow associated with probability between 4% and 48% is decreased. This shows that flows greater than 50% will remain about the same, but flows less than 50% probability are lower than for the baseline and Scenario 2a.

The mean monthly flow graph in Figure 6-3 furthers the understanding of temperature effects. Even though the precipitation change in this scenario is similar to Scenario 2a, mean monthly flows were significantly less in most months for Scenario 2b. Table 6-2 confirms this with a 24% increase in low flow counts and a 17% decrease in mean annual flow. Flood events for this scenario also showed signs of decreasing. Large flood duration and frequency are significantly decreased. Small flood frequencies and peaks are increased, but this is more of an effect of reduction in peak discharge of precipitation events that would usually cause large floods. In addition, small and large flood durations are significantly decreased for Scenario 2b.

Even though neither group 2 scenario projected large changes in future annual temperature or precipitation means, the results were much different. Scenario 2a had little effect on the baseline hydrologic indices with only a 0.93 % annual increase in precipitation and 1.06% annual increase in temperature (Table 3-5). The most disrupting change for this scenario came at the monthly scale. The increase of streamflow in the late spring and early summer, followed by the significant decrease in streamflow in the late summer and early fall will have adverse effects on agricultural production. Although crops will have adequate precipitation in the early growing stages, water stress in the late summer may lead to increased irrigation. This practice would put considerably more stress on a part of the year that already has reduced streamflow.

Scenario 2b had similar precipitation trends as Scenario 2a, but a significant increase in temperature caused additional drying effects not seen in Scenario 2a. Although the reduction in flood parameters can be viewed as positive, the adverse effects caused by reduced water availability throughout the growing season will surely outweigh it. Even though the watershed only receives 0.56 % less annual precipitation in Scenario 2b, the annual temperature increase of 1.79 % caused streamflow and ultimately water availability to significantly decrease from the baseline throughout the year.

Scenario Group 3

Scenario group 3 used a more complex development method than the previous two groups. This modified ensemble mean approach produced unique future precipitation projections by grouping climate models that had similar projection characteristics. This approach yielded three scenarios that showed vastly different precipitation projections. Scenario 3ww, which used all models that showed wet springs and wet summers should produce an increase in mean and high flow parameters with a decrease in low flow parameters. Scenario 3dd used all models that showed dry springs and dry summers. This should result in opposite effects (decreased mean and high flow parameters and increased low-flow parameters) as Scenario 3ww. The third scenario, Scenario 3wd, used all models that demonstrated wet springs and dry summers. The results of this model should be similar to the group 2 scenarios because it is a similar precipitation trend, just larger seasonal shifts.

Scenario 3ww provided a large increase in average monthly streamflow for the spring and summer months (Figure 6-5). As expected, Figure 6-6 shows that streamflow exceedance probability also increased for this scenario. The other flow parameters, shown in Table 6-3, had mixed results. The mean annual flow increased by almost 20%, and low pulse counts decreased significantly, but flood statistics showed no trend. Small flood frequency increased, as expected, but peak and duration were slightly decreased. On the other hand, large flood peak increased very significantly, but duration and frequency significantly decreased. While the flood parameters are inconclusive, the mean monthly flow and exceedance probability charts showed definite results of increasing precipitation.

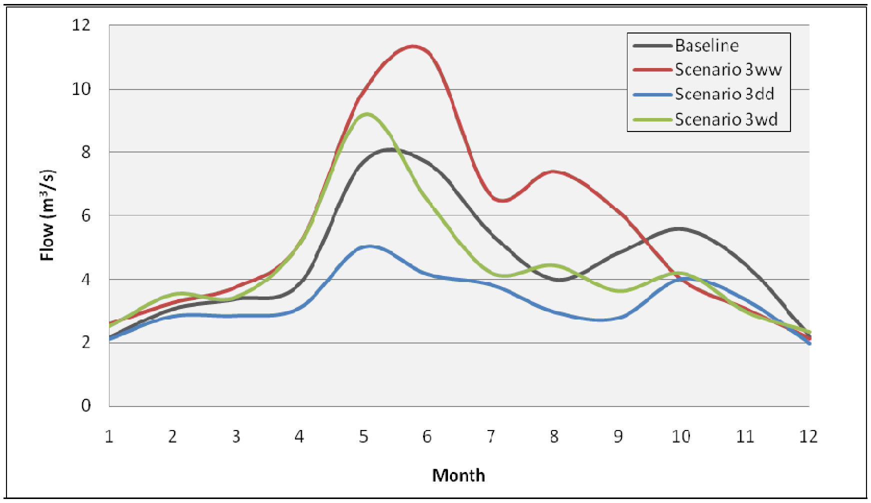

Figure 6-5 Scenario Group 3 Mean Monthly Streamflow

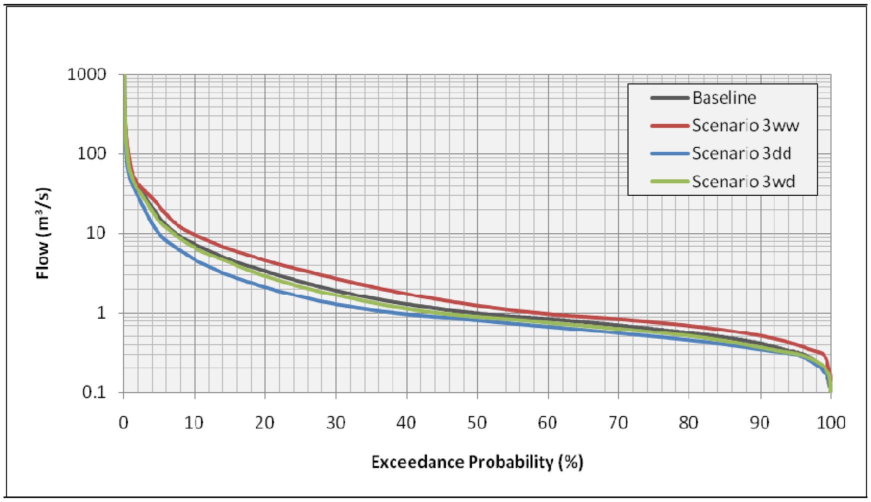

Figure 6-6 Scenario Group 3 Streamflow Exceedance Probability

Table 6-3 Scenario Group 3 Hydrologic Analysis

	Baseline	Scenario 3ww	Difference	Significance	Scenario 3dd	Difference	Significance	Scenario 3wd	Difference	Significance
Mean Annual Flow (m^3/s)	4.5	5.4	19.8%	N/A	3.2	-28.4%	N/A	4.3	-4.4%	N/A
Low Pulse Count (#)	6.0	4.0	-32.6%	**	7.8	30.6%	**	7.0	16.5%	**
Low Pulse Duration (days)	16.0	17.2	7.3%	**	16.8	5.2%	-	16.3	1.6%	**
Small Flood Peak (m^3/s)	434.9	420.8	-3.2%	*	371.3	-14.6%	**	462.2	6.3%	**
Small Flood Duration (days)	61.7	57.5	-6.9%	*	31.4	-49.1%	**	62.4	1.0%	-
Small Flood Frequency (#/yr)	0.16	0.20	25.0%	N/A	0.05	-68.8%	N/A	0.14	-12.5%	N/A
Large Flood Peak (m^3/s)	777.4	1294	66.5%	**	971.8	25.0%	**	1211	55.8%	**
Large Flood Duration (days)	61.4	51.8	-15.8%	*	41.4	-32.6%	*	55.9	-9.0%	*
Large Flood Frequency (#/yr)	0.11	0.04	-63.6%	N/A	0.05	-54.5%	N/A	0.11	0.0%	N/A

** Very Significant, * Significant, - Not Significant, N/A Not Reported

Figure 6-5 also shows that mean monthly streamflow of Scenario 3dd was notably decreased for the spring and summer months. This trend also held for the streamflow exceedance probability chart in Figure 6-6, which is much reduced. For this scenario, the other hydrologic indices in Table 6-3 also produced expected results. The mean annual flow decreased, while low pulse count and duration increased. Small flood peak, duration and frequency significantly decreased. Even though large flood peak increased, the duration and frequency of those events showed a decreasing trend. Overall, the watershed responded to Scenario 3dd as expected and showed signs of decreasing precipitation and increasing temperature trends.

The hydrologic results for Scenario 3wd were similar to the group 2 scenarios. Like Scenario 2b, the streamflow exceedance probability, shown in Figure 6-6, decreased slightly for this scenario. Figure 6-5 shows an increasing trend for spring followed by a decrease in summer mean monthly streamflow similar to Scenario 2a. The other hydrologic indices (Table 6-3) showed signs of the reduction in annual precipitation and an increase in temperature. The mean annual flow is decreased and low pulse count and duration are significantly increased. Much like the other scenarios, flood parameters showed mixed results. Small floods show an increase in peak discharge, decrease in frequency and no significant change in duration. Similarly, large floods showed an increase in peak discharge, decrease in duration and no change in frequency.

The scenarios analyzed in group 3 covered a wide range of possible future scenarios. As a result, they also provided a wide range of hydrologic alteration. While it is difficult to envision the total effect caused by these scenarios, it is clear that any one of them would have an effect on agricultural practices in northeast Kansas. The extreme precipitation increase in Scenario 3ww would decrease the water stress on crops, but would also cause increased erosion. The drying future of Scenario 3dd would reduce erosion caused by overland flow, but would put additional water stress on plant and animal communities.

Even though Scenario 3wd is a less extreme annual precipitation scenario than the other two, it could have the most effect on agricultural practices. The small annual decrease in precipitation is offset by the peak precipitation occurring earlier in the year. This shift would allow the peak precipitation to occur when agricultural fields are bare and most likely to erode. The scenario follows that up with increased drought during the summer which would yield higher water stress for the plant and animals. As these two adverse effects from Scenario 3ww and 3dd combine, Scenario 3wd becomes significantly more taxing on the agricultural community than the previous scenarios.

One other significant discovery to note is that mean monthly streamflow for the fall and winter did not significantly change for any of the group 3 scenarios (Figs. 6-1, 6-3, 6-5). This proves that most of the precipitation variation between climate models occurs in the spring and summer for this area of Kansas. As a result, the choice to group the models based on spring and summer precipitation is further validated.

Discussion

The hydrologic analysis of scenario group 1 showed that an extreme increase or decrease in precipitation would cause significant hydrologic alteration in northeast Kansas. More importantly, it also proved that temperature effects could also play a major role in hydrologic indices because for scenario 1a, mean monthly streamflow decreased for August even though precipitation increased by 10%. While these types of scenarios work well for sensitivity analyses when a gradual step-up method is used, the uniformity is unrealistic for a hydrologic analysis.

The ensemble mean approach used to develop the group 2 scenarios produced much more valuable future climate projections for hydrologic analysis. Instead of relying on an annual change in precipitation amount, these scenarios caused hydrologic alteration with monthly shifts in precipitation. These scenarios demonstrate the importance of considering monthly aspects of climate change as well as annual changes, but also demonstrated the limitation of grouping all climate model results into a single ensemble mean.

Even though the scenarios developed in group 2 did not demonstrate significant change in mean annual precipitation, significant hydrologic changes did occur in the watershed simulation. The hydrologic alterations were caused by temperature increases and precipitation distribution changes. Comparing the mean monthly streamflow, streamflow exceedance and mean annual streamflow output of these two scenarios further confirms that temperature effects do cause changes in hydrologic indices. Even though the mean annual precipitation difference between Scenario 2a and 2b was only two percent, mean annual streamflow showed an almost 19% change between the two future projections.

While the precipitation distribution shift into wetter springs and dryer summers did not cause significant changes in most hydrologic indices or the streamflow exceedance probability chart, the mean monthly streamflow chart clearly showed that other issues could occur from these scenarios. Scenario 2b showed a drying trend that would limit the water available to the agricultural crops and animals. The need to increase irrigation to support the crops will lead to an even further reduction in streamflow and water available to animals. Scenario 2a caused an increase in precipitation in the spring when fields are most vulnerable to runoff erosion. The decrease in water available in the summer months would cause similar effects to Scenario 2b, but on a smaller scale.

The third group of climate scenarios used a modified ensemble mean approach to generate 3 unique future climate projections. By grouping GCMs that demonstrated similar spring and summer precipitation trends, three ensemble climate scenarios were produced. This future climate scenario development approach proved that even though no two climate models are the same, general trends can be identified among them.

The wide range of future climate trends projected in the group 3 climate scenarios resulted in a wide range of hydrologic alteration. Scenario 3ww mostly caused increases in streamflow parameters because of the increase in precipitation for both spring and summer. Temperature appears to have little effect on the overall hydrologic alteration of this future scenario. Scenario 3dd resulted in mostly decreasing streamflow parameters. This is caused by the decrease in precipitation for both the spring and summer months. Scenario 3wd resulted in very similar results as Scenario 2a. This result was expected since both of these scenarios use the same temperature trend and similar precipitation with an increase in spring and decrease in summer.

Chapter 7 - Conclusions

In this study, the background of climate change and some hydrologic analysis techniques of climate change were reviewed. After this review, the fifteen AR4 models that contained a historic experiment as well as an A2 climate scenario projection for the years 2050 and 2100 were analyzed. Three developmental procedures were used to produce seven future climate scenarios from the fifteen models. The first group of scenarios consisted of two future projections with uniform monthly precipitation changes and an ensemble mean temperature change for all fifteen models between the historic experiment (1961 – 1990) and the 2046 – 2064 A2 projection. The second group of scenarios used the ensemble mean approach for both temperature and precipitation for all models 2046 – 2064 (2050) and 2080 – 2099 (2100) A2 projections. The third group of scenarios used a modified ensemble mean approach to group similar climate models and generate three unique future scenarios from the fifteen 2050 GCM projections.

With these climate scenarios developed, the WINDS weather generator was successfully used to temporally downscale the monthly trends shown in the climate scenarios into 105 years of daily temperature and precipitation data. This stochastic weather generator applied the developed monthly trends to the actual temperature and precipitation statistics for a weather station near the study area. With this information, WINDS was able to generate daily temperature and precipitation data that matched the future scenario statistics. In order to confirm that the 105 year simulations correctly simulated the future scenario, five 105 year simulations were compared to a 1000 year simulation of the same scenario. The 105 year simulation with the highest precipitation mean and standard deviation R^2 to the 1000 year simulation was chosen to represent the scenario in a hydrologic model simulation.

The SWAT model was setup and calibrated for the Soldier Creek Watershed in Northeast Kansas. Then, the WINDS generated scenario climate scenarios were input into the model. The watershed was then simulated for 100 years with a five year warm-up period. The daily streamflow at the outlet of the watershed was then analyzed using the IHA program. IHA generated mean monthly streamflow, streamflow exceedance probability and other hydrologic parameters to analyze if the climate scenarios caused significant hydrologic alteration to the watershed.

The scenarios developed in group 1 demonstrated that large annual increases or decreases in precipitation cause comparable fluctuations in mean streamflow parameters as well as extreme high and low-flow parameters. Although annual changes in precipitation are important, the group 1 scenarios did not take monthly precipitation shifts into account. As a result, the hydrologic impacts cannot be fully understood with the group 1 scenarios.

Scenario group 2 proved that comparable effects to the group 1 scenarios can be achieved with little change to annual precipitation totals. Scenario 2a used seasonal precipitation changes to cause a combination of the hydrologic impacts demonstrated with the first group of scenarios. This scenario caused an increase in streamflow during the spring, followed by a decrease in the summer. Scenario 2b demonstrated the importance of temperature effects on watershed processes. This scenario was able to achieve similar results as Scenario 1b, with only an 11.3 mm decrease in annual precipitation instead of a 90.5 mm decrease. These results were caused by an almost doubling of the temperature increase projected in the other scenarios.

Scenario group 3 provided a method that allows researchers to use multiple GCMs in a single future scenario without reducing all GCMs into one future trend. With this approach, three separate future trends in spring and summer precipitation were identified and simulated. Another benefit of this approach is a reduction in the monthly precipitation variability among the GCMs used to calculate future trends. These scenarios demonstrated that even though a large increase or decrease in future annual precipitation will cause hydrologic alteration, a scenario showing monthly shifts without significant annual changes could be worse. In this case, Scenario 3wd caused an increase in both extreme low-flow and high flow events where the other group 3 scenarios only negatively affected one of them.

With the uncertainty of future climate change predictions, any effort to analyze the effects should cover the whole range of the climate models. While the ensemble mean approach is an efficient way to represent all GCMs, it only produces one climate scenario to analyze future projections. The modified ensemble mean approach developed in this study provides an efficient way to represent the wide variation among GCMs. For the region used in this study, temperature trends remained consistent between GCMs. As a result, the modified ensemble mean approach was only applied to calculate precipitation trends, but could be extended to calculate temperature trends if similar variation was noticed in it.

Recommendations and Limitations

This study demonstrated the importance of temperature and precipitation changes on hydrologic indices. However, other parameters associated with climate change could also produce significant hydrologic impacts. For example, this study did not take into account the effects caused by changes in CO_2 concentration and solar radiation. These two parameters could have an important effect on the evapotranspiration in the watershed model and could increase or decrease the hydrologic alteration caused by the future scenarios. The use of different SRES scenario families would also have an effect on the results of this hydrologic study.

Intra-storm variability associated with climate change was also not considered in this study. There have been numerous studies that have shown that storm events are becoming increasingly intense, but less frequent. Easterling *et al.* (2000) explains that there is evidence of intensity change in mean and extreme events, but most observational studies are based on relatively short time periods. Storm intensity and frequency were not included in the climate scenarios developed for this study. However, as a result of the stochastic weather generator method, storm intensity is inherently increased for months demonstrating increases in total precipitation. This effect is produced by increasing monthly precipitation while keeping the same wet given wet and dry given wet daily transitional probabilities (storm frequency) shown in the actual NCDC weather station. Unfortunately, the opposite effect is caused for months showing a decreasing precipitation trend. Less total precipitation is applied to statistically similar storm frequencies causing a decrease in storm intensity. Factoring the full effects of storm intensity and frequency change into a climate change impact study could produce additional hydrologic impacts beyond monthly climate change trends alone.

This study also showed that flood parameters are just as difficult to predict in climate change scenarios as they are for current climate analyses. None of the scenarios produced a clear upward or downward trend in flood peak, duration and frequency. Therefore, if a future flood analysis is wanted, a different way to analyze it is needed. Only having one flood threshold and not breaking it down into two groups may increase the reliability of these flood parameters, but further testing is needed. It is clear, however, that even small changes in monthly climate can have significant effects on hydrologic indices for a given watershed. While the scenarios and results obtained in this study may not be accurate for other areas of the world, or even other areas of Kansas, the methods used to develop the scenarios can be universally applied to any region.

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Appendix A - Additional WINDS Output Validation Information

Table A-1 Baseline Scenario Validation

	Run 1	Run 2	Run 3	Run 4	Run 5
Mean R^2	0.95	0.99	0.99	0.98	0.97
Stdev R^2	0.84	0.94	0.90	0.80	0.70

Table A-2 Scenario 1a Validation

	Run 1	Run 2	Run 3	Run 4	Run 5
Mean R^2	0.97	0.99	0.99	0.99	0.99
Stdev R^2	0.94	0.93	0.94	0.85	0.80

Table A-3 Scenario 1b Validation

	Run 1	Run 2	Run 3	Run 4	Run 5
Mean R^2	0.96	0.97	0.97	0.98	0.97
Stdev R^2	0.68	0.76	0.81	0.82	0.73

Table A-4 Scenario 2a Validation

	Run 1	Run 2	Run 3	Run 4	Run 5
Mean R^2	0.98	0.97	0.96	0.99	0.96
Stdev R^2	0.85	0.82	0.82	0.92	0.77

Table A-5 Scenario 2b Validation

	Run 1	Run 2	Run 3	Run 4	Run 5
Mean R^2	0.98	0.97	0.97	0.97	0.97
Stdev R^2	0.85	0.78	0.79	0.91	0.81

Table A-6 Scenario 3ww Validation

	Run 1	Run 2	Run 3	Run 4	Run 5
Mean R^2	0.99	0.99	0.99	0.98	0.99
Stdev R^2	0.90	0.90	0.94	0.86	0.95

Table A-7 Scenario 3dd Validation

	Run 1	Run 2	Run 3	Run 4	Run 5
Mean R^2	0.99	0.97	0.95	0.97	0.98
Stdev R^2	0.77	0.70	0.86	0.47	0.78

Table A-8 Scenario 3wd Validation

	Run 1	Run 2	Run 3	Run 4	Run 5
Mean R^2	0.96	0.96	0.90	0.97	0.93
Stdev R^2	0.87	0.75	0.69	0.87	0.86

Appendix B - Summary of the 67 IHA Hydrologic Indices

Table B-1 Summary of IHA Parameters (IHA, 2009)

IHA Parameter Group	**Hydrologic Parameters**
1. Magnitude of monthly water conditions	Mean or median value for each calendar month *Subtotal: 12 parameters*
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means Number of zero-flow days Base flow index: 7-day minimum flow/ mean flow for year *Subtotal: 12 parameters*
3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum *Subtotal: 2 parameters*
4. Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days) *Subtotal: 4 parameters*
5. Rate and frequency of water condition changes	Rise rates: Mean or median of all positive differences between consecutive daily values Fall rates: Mean or median of all negative differences between consecutive daily values Number of hydrologic reversals *Subtotal: 3 parameters*
	Grand total: 33 parameters

Table B-2 Summary of Environmental Flow Component (EFC) Parameters (IHA, 2009)

EFC Type	**Hydrologic Parameter**
1. Monthly low flows	Mean or median values of low flows during each calendar month *Subtotal: 12 parameters*
2. Extreme low flows	Frequency of extreme low flows during each water year or season Mean or median values of extreme low flow event: • Duration (days) • Peak flow (minimum flow during event) • Timing (Julian date of peak flow) *Subtotal: 4 parameters*
3. High flow pulses	Frequency of high flow pulses during each water year or season Mean or median values of high flow pulse event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates *Subtotal: 6 parameters*
4. Small floods	Frequency of small floods during each water year or season Mean or median values of small flood event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates *Subtotal: 6 parameters*
5. Large floods	Frequency of large floods during each water year or season Mean or median values of large flood event: • Duration (days) • Peak flow (maximum flow during event) • Timing (Julian date of peak flow) • Rise and fall rates *Subtotal: 6 parameters*
	Grand total: 34 parameters