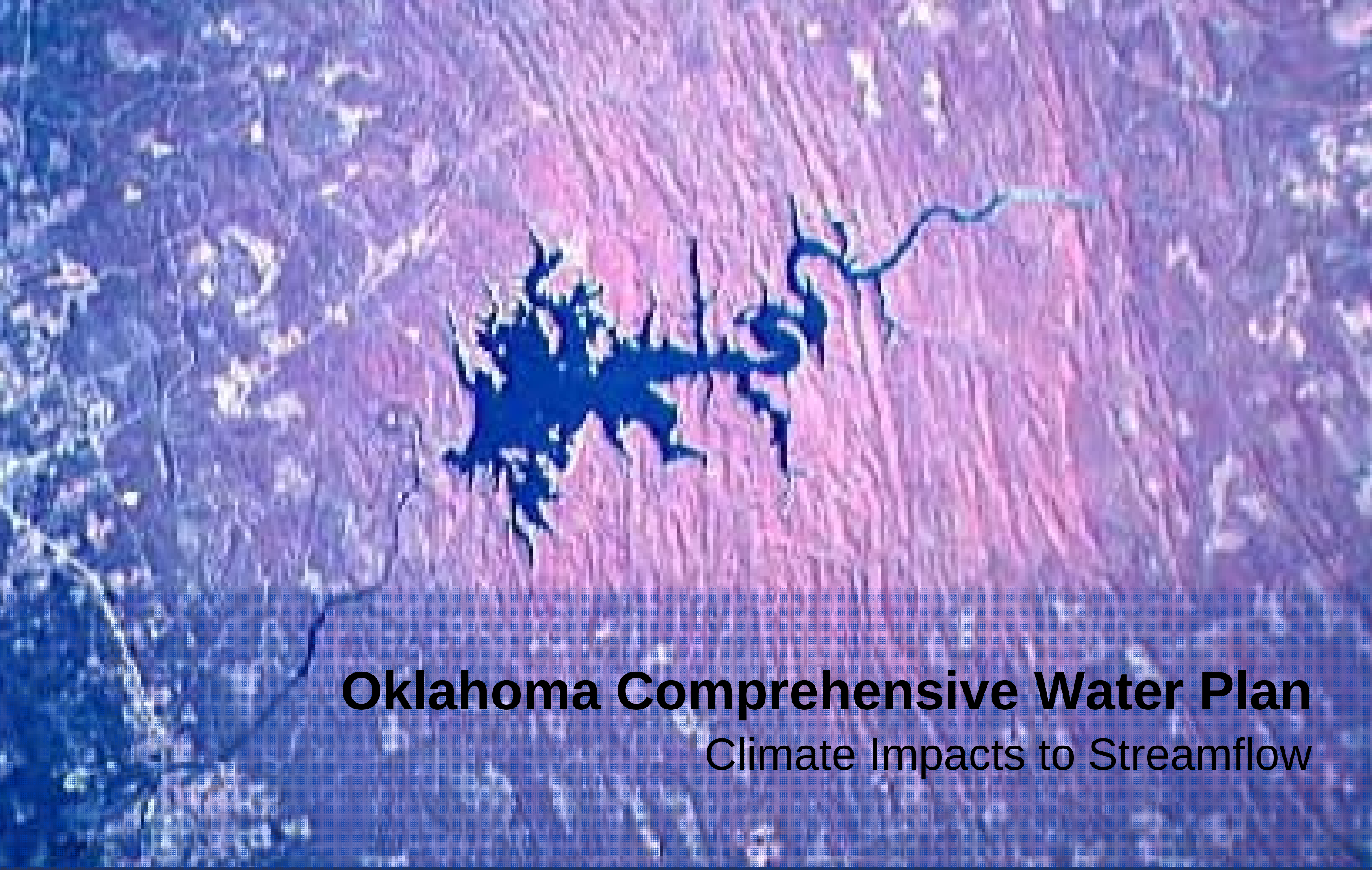

Oklahoma Comprehensive Water Plan

Climate Impacts to Streamflow

REPORT

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1.0 INTRODUCTION

In 2006, the Oklahoma Legislature appropriated funds for an update of the Oklahoma Comprehensive Water Plan (OCWP), to be completed in approximately five years. Implementation of the Comprehensive Water Plan involves policy development informed by technical studies. Technical studies consist of four principle elements: current and projected water demands; water supply availability; public water supply assessments; and technical studies in support of water resources management. The foundation of the technical studies are the estimates of water supply and water demands, including projections of future water use, which inform an assessment of the adequacy of future water supplies.

In the OCWP process, the adequacy of future water supply is evaluated using an analysis tool that compares projected demands to physical supplies for each of 82 delineated stream basins. This tool will assist with the detailed examination of demands and supplies, identification of areas of potential water shortages, and evaluation of potential water supply solutions.

In recent years, significant national and international scientific efforts have been undertaken to understand and characterize the potential implications of climate change on water resources. A wide range of models and assumptions are being used by the scientific community to estimate future temperatures, precipitation quantities and patterns, and other factors affecting water supply. While there remains significant uncertainty in the potential range of climate change impacts, particularly with regard to changes in precipitation, a sensitivity analysis of the possible effects of climate change were undertaken as part of the OCWP technical studies. By assessing sensitivity of potential impacts on both water supply and water demand from projected changes in climate, the OCWP is providing some insights into the degree to which the balance of water supply and water use might change should those projections hold true. This report describes the methods used to project the sensitivity of surface water supplies at each of the 82 OCWP basin gauging locations to a set of representative scenarios of future climate conditions. Analyses of demands and shortages under climate change are documented separately.

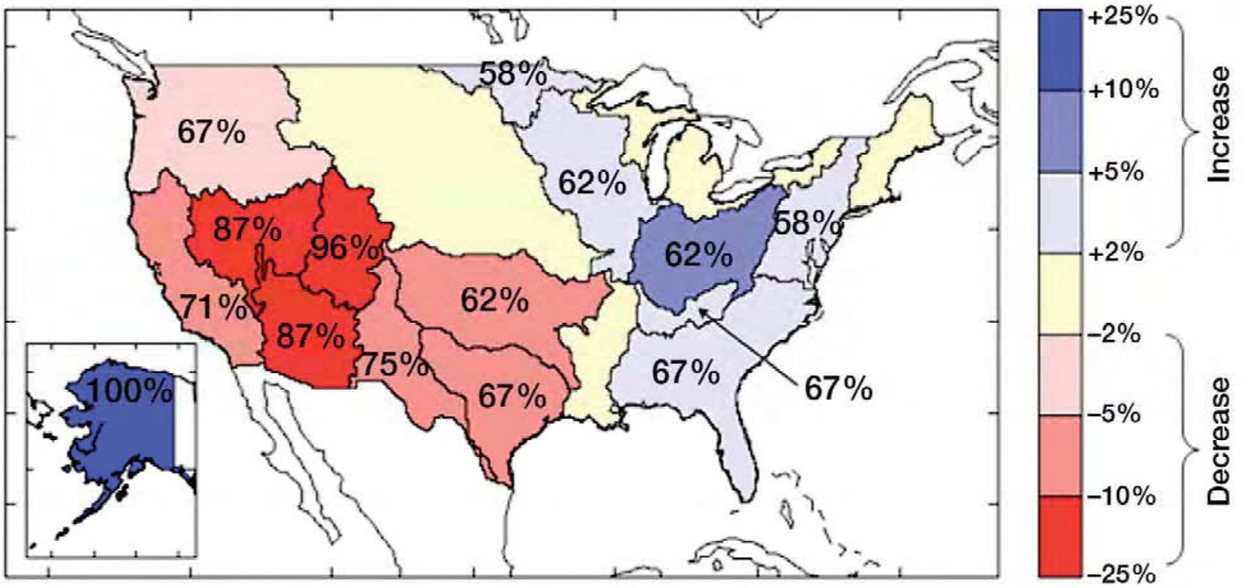
2.0 BACKGROUND

Over the last four decades climate scientists have developed a theoretical framework and observational evidence to indicate that the average temperature of the earth is increasing and that part of this increase can be attributed to emissions of greenhouse gases generated by human activities (IPCC, 2007). Modern climate simulation models, referred to as Global Climate Models (GCM, also referred to as general circulation models) have been used to develop quantitative projections of future changes in air temperature, precipitation and other climate variables based on scenarios of future emissions of greenhouse gases. These models show a consensus that globally averaged temperatures will increase, but that the amount of projected temperature increase will vary with latitude and will not be evenly distributed seasonally. Increases in global average temperature will increase evaporation, resulting in a larger average loss of surface moisture back to the atmosphere. As a result, global average annual precipitation will also increase, although the models do not show a consensus about the spatial and temporal distribution of changes in precipitation. Projections of precipitation are particularly uncertain in the middle latitudes and in the interior of continental land masses, such as the geographic setting of Oklahoma. In the American southwest and southern Great Plains, some models will project an increase in precipitation while other models will project a decrease in precipitation. There is also considerable disagreement regarding the seasonality of precipitation changes. Current difficulty in projecting changes in precipitation in these regions reflects both the evolving state of knowledge about atmospheric processes and the spatial and temporal resolution of the models used as compared to the size and duration of thunderstorms and thunderstorm complexes, both of which provide much of the annual precipitation in the southern Great Plains.

Increased temperatures over continental land masses will increase evapotranspiration from the land surface, with the result that, if precipitation does not change, streamflows will be reduced. If precipitation decreases, reductions in streamflow will be even greater, while increased precipitation can offset higher evaporation and lead to unchanged or even increased streamflows.

Hydrologic analyses have been used to estimate the effect on streamflow of projections of increased temperature and changes in precipitation. Two recent studies have assessed model projections of future conditions for the American southwest, including Oklahoma. Milly et al. (2005) reported that roughly two-thirds of model projections indicated a 5% to10% reduction in streamflows in the Arkansas and Red River basins as shown in Figure 1 (CCSP, 2008; Milly et al., 2005).

Figure 1: Projected Changes in Runoff



In Figure 1, the color indicates the average projected change in runoff while the numbers represent the percent of the 24 models that agreed with the direction of the mean change. For the Arkansas River Basin the expected change in runoff is a decrease of between 5% and 10%, and 62% of the models agree that a decrease in runoff is expected. For the Red River Basin the expected change in runoff is also a decrease of between 5% and 10% and 67% of the models agree that a decrease in runoff is expected.

Seager et al. (2007) also suggest that a there is a broad consensus among climate models that changes in atmospheric circulation will cause additional drying in a region of the American southwest that includes Oklahoma.

Both the Milly and Seager studies examined a relatively small number of GCM runs and were conducted at the scale of the GCM models. When interpreting the results of those studies, it is important to note that the results of detailed hydrologic modeling of a large number of statistically downscaled projections do not support the level of agreement they reported for the Upper Colorado River Basin. Harding et al. (2010) conducted detailed hydrologic modeling in the Upper Colorado River Basin (that portion of the basin above Lees Ferry, Arizona) based on 112 statistically downscaled climate projections from 16 GCMs and the B1, A1B and A2 SRES scenario. They report that about 30% of the projections result in estimates of future streamflow that show either no change or an increase in flow, as compared to Milly et al. (Figure 1) who report 96% agreement on future drying. Some of the differences in results may be attributed to methodological differences and some to the fact that Milly et al. looked at fewer projections (24 projections using 12 GCMs and the A1B SRES scenario), but the difference in scale of the analyses may also be significant given the complex topography of the Colorado River Basin (Milly used the native GCM grid scale while Harding et al. used data downscaled to 1/8th degree.) It is reasonable to expect that detailed hydrology modeling in Oklahoma may also show more ambiguous results than Milly et al., but it is also reasonable to expect that those differences will not be as dramatic as is the case for the Upper Colorado River Basin because the topography in Oklahoma is more homogeneous and because snowmelt provides a much smaller fraction of the streamflows in Oklahoma.

The objective of this study is to estimate the sensitivity of streamflows at each of the 82 OCWP basin gauging locations to projected climate change. The OWCP basins within the State of Oklahoma range in area from under a hundred square miles to a few thousand square miles, whereas GCM grid cells cover an area on the order of 40,000 square miles. At the scale of the OCWP basins, the use of a detailed hydrology model is an appropriate approach. This type of analysis involves the following information and analyses:

1. Emissions scenarios. Projections of future changes in climate attributed to human activity rely on projections of future concentrations of greenhouse gases (GHG), which in turn depend on current concentrations and future rates of GHG emissions. GHG emissions depend, in complex ways, on socio-economic development, technology, demographics and politics. The Intergovernmental Panel on Climate Change (IPCC) has developed a number of "storylines" of future global conditions, which are used as the basis for estimates of future GHG emissions. These storylines are documented in the Special Report on Emissions Scenarios (SRES, Nakicenovic et al., 2000) and are often referred to as SRES scenarios. The IPCC did not assign a likelihood to the SRES scenarios—all are considered equally probable "alternative images of how the future might unfold" (Nakicenovic et al., 2000, Technical Summary). From the four SRES scenario "families" (A1, A2, B1, B2), only the B1, A1B (a member of the A1 family) and A2 scenarios have been used as the basis for projections on many GCMs. These have

come to be known, respectively, as the “low”, “medium” and “high” emissions scenarios, based on their impact on climate conditions in the year 2100.

2. Global Climate Simulation. More than 20 global climate models are currently being developed, operated and maintained by national meteorological services, climate research centers and universities around the world. These models have been used to develop quantitative projections of future changes in climate variables including temperature and precipitation based on the SRES emissions scenarios. Each GCM is different, but many contain similarities in their conceptual approach and may even share simulation methods and codes. A single GCM will be used to generate many projections, each of which differ by the SRES scenario used to force the GCM, but also by the way in which the model run is initialized and constrained.

3. Downscaled Climate Projections. GCMs operate on a grid that may range in scale from 100 to 200 miles on a side, and their output is provided at this same resolution. While each GCM grid cell covers from 10,000 to 40,000 square miles, a substantial watershed might cover a few hundred to a several thousand square miles, and many tributaries drain considerably smaller areas. Before GCM output can be used for analysis of local conditions, or for local hydrologic modeling, it must go through a process called *downscaling*, which relates the large scale GCM data to detailed terrain and observed climate conditions. *Statistical downscaling*, as its name implies, uses statistical models to relate simulated climate on a large scale to local conditions on a small scale. *Dynamical downscaling* utilizes higher resolution climate models (regional climate models, or RCMs) to derive smaller-scale information. GCM projections also contain bias, which is exhibited as systematic error in replicating observed conditions, and these biases are usually removed during statistical downscaling with an *ex post* calibration process referred to as *bias correction*.

4. Hydrology Modeling. A hydrology model is used to translate observed or projected weather data (e.g., precipitation, temperature, wind, etc.) into estimates of runoff or streamflow. A wide variety of hydrology models are available, differing in their conceptual approach to simulation and by the scale at which they are appropriately applied.

All measurements contain uncertainty, and estimates of future conditions are more uncertain than measurements. This is clearly demonstrated by our day-to-day experience with such things as weather and financial forecasts. Each element of the four elements of a climate impact analysis set out above contains its own degree of uncertainty. These individual uncertainties do not add up in a straightforward way, but they do interact and each added element does increase the overall uncertainty of the final estimate of impact. Wilby and Harris (2006) found that the greatest uncertainty arose in climate impact studies from the climate models themselves, followed, in order, by the downscaling method, the hydrology model structure, hydrology model parameters and finally by the uncertainty in future emissions scenarios. The approach adopted for this work is intended to make this uncertainty as apparent as possible, so as to allow well-informed judgments regarding future water resources planning.

3.0 APPROACH

This work used climate models and hydrology models to estimate the sensitivity of runoff in Oklahoma to projected climate change. The work was anchored to an historical weather record that served as a baseline. As describe below, this baseline weather record was adjusted to produce projected weather records that reflected projected changes in climate, which were in turn estimated from the output of GCMs. The historical weather record and the projected weather record were each run through a hydrology model and the results compared with each other to estimate changes in runoff. These changes were scaled to compensate for some of the bias inherent in the hydrology model resulting in a set of adjustments to runoff, which were used in the OCWP process to develop estimates of historical flow records that reflect a range of future climate conditions.

3.1 Time Frames for Projection of Future Conditions

The OCWP process evaluates future water use every decade beginning in 2010 and extending to 2060; a subset of these projected future water use scenarios, 2030 and 2060, were identified for evaluation of the impact of projected future climate.

3.2 Hydrology Modeling Approach

A hydrology model was used to quantify the sensitivity of runoff to changed climate conditions. This sensitivity was expressed as a set of changes in runoff that were estimated by comparing simulated runoff based on the historical weather record with simulated runoff based on an adjusted weather record that reflects projected changes in climate. This approach compensates for some of the unavoidable bias inherent in any hydrology model. The hydrology model and its application are described in this section. Development of the weather records is described in subsequent sections.

This work employed a physical process-based hydrology model, the Variable Infiltration Capacity (VIC) macro-scale hydrology model. The VIC model is a distributed (gridded) macro-scale (regional-scale) physical hydrology model with several applications to climate change studies and successful application to numerous basins around the world (Wood et al., 1992; Liang et al., 1994; Liang et al., 1996; Lohmann et al., 1998a; Lohmann et al., 1998b, Christensen et al. 2004; Christensen and Lettenmaier, 2007). The VIC model has three main components, (i) a component to model land-surface (e.g., evapotranspiration), (ii) a sub-surface modeling component (e.g., infiltration and baseflow) and (iii) a routing model that simulates transport to points on a flow network. Distinguishing characteristics of the VIC model include the representation of the following (Nijssen et al., 2001; Wood et al., 1992): (1) sub-grid variability in land surface vegetation classes; (2) sub-grid variability in the soil moisture storage capacity; (3) modeling of baseflow as a nonlinear recession; (4) spatial sub-grid variability in precipitation; (5) energy balance modeling of snow dynamics; and (6) modeling of evapotranspiration based on energy transfer and aerodynamic resistance.

The VIC model operates on each grid cell independently. The scale of the grid cells may be varied depending on the application, but in this work the model was constructed on a 1/8° spatial resolution, which is at the latitude of Oklahoma City is a rectangle roughly 11 km by 14 km. In this work the VIC model was run on a daily time step. The routing model was not used in this application rather runoff was aggregated by stream basin and to a monthly time step.

The VIC model uses a separate set of vegetation and soil parameters for each grid cell. The soil and vegetation parameters used in this work were developed during the North American Land Data Assimilation System (NLDAS) project (Mitchell et al., 2004) and later updated for seasonal forecasting application documented in (Wood et al., 2006). This parameter set is gridded at a spatial resolution of 1/8 degree.

Resources were not available to develop the naturalized flows for each of the 82 stream basins defined in the OCWP process, which would be required in order to develop a refined calibration of the model parameters. Accordingly, the hydrology model was used to estimate the sensitivity of streamflow using the delta approach which is described more fully below.

3.3 Calculation of Impacts to Streamflow

The estimated sensitivity of runoff to projected climate change was quantified by making two runs of the hydrology model, one that used the historical weather record (the baseline case) and a second that used a projected weather record (the projected case; as is described below, these two records are the same length and each month in the projected record corresponds to the same month in the historical record.) For each month in the historical record the sensitivity of runoff to climate change is expressed as the ratio between the runoff simulated using the projected record and the runoff simulated using the historical record.

The sensitivity to runoff was not sufficient for this work, because the objective of the work was to develop a set of additive adjustments to historical observed streamflows that would represent the incremental impact of projected climate conditions on those observed flows. Hydrologic models will represent the impact of changed climate on runoff and hence natural streamflows and are usually calibrated to those streamflows to reduce bias. In this work a *post hoc* calibration approach was used where the simulated baseline natural flows were adjusted to reflect the same long-term average annual flow as the observed flows, after some of the observed flows were adjusted to compensate for significant influences. This adjustment was calculated as the scaling ratio between the average annual observed flow and the average annual simulated baseline flow over the period 1951 through 1960, that portion of the historical period when man-caused depletions and operational impacts should be at their lowest. Prior to making this adjustment, some of the observed flows had been adjusted to compensate for the significant impact of imports, exports and spring inflows. The same scaling ratio was applied to the simulated projected flows. Following these *post hoc* adjustments, the absolute impact of projected climate could be represented by the difference between the adjusted simulated projected flow and the adjusted simulated baseline flow

The time series of additive adjustments to observed streamflows was the final product of his work. These adjustments were subsequently used to develop estimates of climate-impacted historical flows as part of the OCWP process, which is documented elsewhere.

3.4 Climate Projections and Downscaling

For each of the two projection time frames, five climate scenarios were developed as described in the following section. The scenarios were developed from a set of readily-available downscaled projections obtained from the bias-corrected and spatially downscaled WCRP CMIP3 Climate Projections archive (WCRP CMIP3, 2009) described by Maurer et al. (2007). The archive contains 112 statistically downscaled and bias-corrected projections of monthly temperature and precipitation, with each projection consisting of an overlap period of 1950 through 1999 and a projection period of 2000 through 2099. The WCRP archive was developed jointly by the Bureau of Reclamation, Santa Clara College and the Lawrence Livermore National Laboratory. WCRP-CMIP3 archive has been developed using peer reviewed methods (Maurer et al., 2002) and is currently being used by the Bureau of Reclamation and many other entities for climate change impact analyses.

The 112 projections in the WCRP-CMIP3 archive originate from runs of 16 GCMs using the B1, A1B and A2 scenarios of future greenhouse gas emissions, as shown in the following table.

Table 1: Downscaled CMIP3 Projections

	SRES Scenario			
	a1b	a2	b1	Total
GCM	Number of Runs			
bccr_bcm2_0	1	1	1	3
cccma_cgcm3_1	5	5	5	15
cnrm_cm3	1	1	1	3
csiro_mk3_0	1	1	1	3
gfdl_cm2_0	1	1	1	3
gfdl_cm2_1	1	1	1	3
giss_model_e_r	2	1	1	4
inmcm3_0	1	1	1	3
ipsl_cm4	1	1	1	3
miroc3_2_medres	3	3	3	9
miub_echo_g	3	3	3	9
mpi_echam5	3	3	3	9
mri_cgcm2_3_2a	5	5	5	15
ncar_ccsm3_0	6	4	7	17
ncar_pcm1	4	4	2	10
ukmo_hadcm3	1	1	1	3
Total	39	36	37	112

The impacts of different GHG emissions scenarios do not begin to diverge substantially until roughly the middle of this century, so differences between projected conditions under particular SRES scenarios are less significant over the time frames used in the OCWP planning process.

3.5 Developing Weather Inputs

For the OCWP planning process, AMEC elected to use the Ensemble Hybrid-Delta (HDe) method used by the Bureau of Reclamation to evaluate reservoir storage yields in parts of Oklahoma (Brekke, et al., 2010). Four considerations are important when using GCM projections to assess the impact of future climate on water supply: changes in sequences of annual conditions, changes in mean conditions (e.g., precipitation and temperature), changes in seasonal patterns of conditions, and treatment of the disagreement (uncertainty) among GCM projections. In AMEC's judgment, the HDe method provides the best balance in addressing the four considerations discussed above. These considerations are described in the remainder of this section and the HDe method is described in the following section.

The variability of streamflows, specifically the arrival sequences of wet and dry years and particularly the nature of wet or dry spells, is an important factor in the reliability of a water supply system. Accordingly, the representation of the year-to-year sequences of flow is an important factor when assessing impacts on water resources systems. Different approaches are available to represent year-to-year variability of streamflows in a climate change impact analysis.

The variability of future, climate-impacted streamflows could be taken directly from the simulated future climate, using a calibrated hydrologic model forced with the output from a GCM. However, there is some evidence that GCMs may not have significant skill predicting year-to-year variability of precipitation outside the tropics (Lau et al., 1996, Wood, et al., 2004, Tebaldi, et al., 2008) and are not reliable for predicting changes in variability (Tebaldi et al., 2008), so less faith is placed in simulations by GCMs of changes in variability than in changes in mean conditions (IPCC, 2001).

A second choice is to represent the change in mean future climate conditions and the change in the seasonal pattern of climate condition using GCM output while representing year-to-year sequencing and variability based on the observed record (Wood et al., 2004, IPCC, 2001). In this work, the annual sequences of precipitation and temperature were taken from the historical record and information about the impact on mean and seasonal patterns of precipitation and temperature was obtained from GCM outputs.

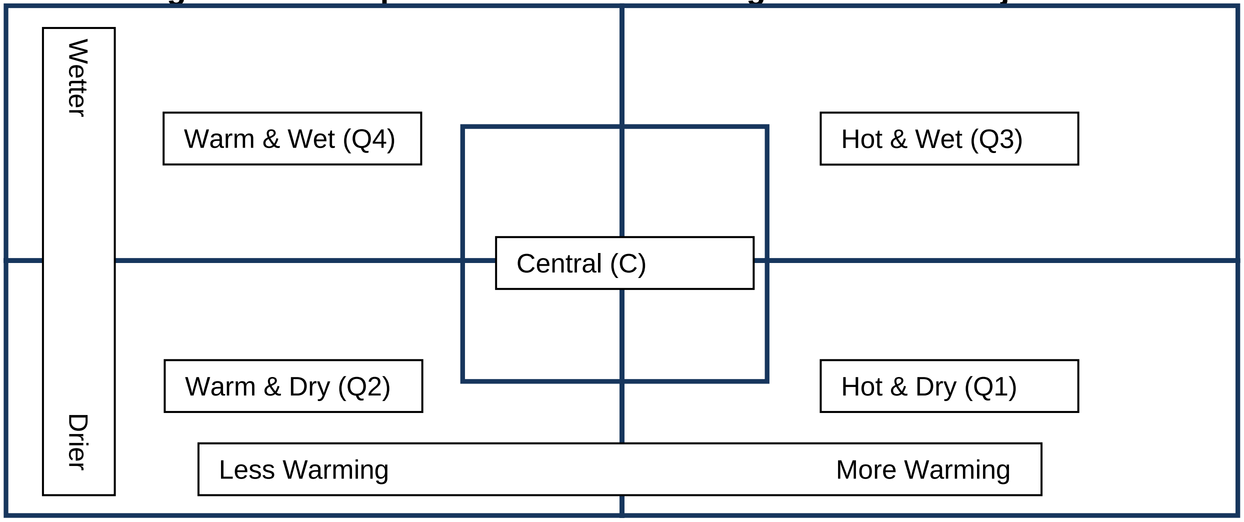
A number of methods have been developed to combine information from the historical record with information from GCMs. Of these the "delta" method may be the most commonly used (Hamlet and Lettenmaier, 1999). The delta method involves two steps: In the first step, the projected change in a climate variable (e.g., temperature or precipitation) is determined by comparing the model projection of future climate at some specified time in the future against the simulation of the historical climate (during the *overlap period*) in the same projection. In the second step, this change in the climate variable is applied uniformly to the observed record of that variable. The delta method is applied on a monthly basis to represent how the seasonal pattern of climate is projected to change. For example, if a climate projection indicates that precipitation will increase in January by 2%, every value of precipitation for January in the historical record would be increased by 2% to create a climate-impacted scenario. Temperature would be treated similarly, but an offset instead of a percent change would be used.

The projected changes in climate conditions may be different between wet years and dry years or between cooler years and warmer years. One shortcoming of the delta method is that it reduces this variability of projected change to a single mean value. In addition, selection of a particular projection to represent all or part of the range of future climate conditions can introduce bias due to substantial disagreement between different projections. The ideal solution would be to evaluate hydrologic impacts from all available projections, but due to the computational cost of detailed hydrologic modeling, this is not usually practical. Accordingly, methods that rely on "consensus" across an ensemble of projections have been developed. The HDe method adopted for this work is such a "consensus" approach and is described below.

3.6 Development of Composite Climate Scenarios

The OWCP team determined that five composite climate scenarios would be used to characterize future climate conditions at each time frame—four that represent the range of projected conditions and a fifth that represents the central tendency of the projection conditions. The five composite climate scenarios were developed by categorizing each of the 112 projections in the CMIP3 archive by its mean projected change in precipitation and temperature at the future time frames as compared to the simulated conditions during the overlap period. (This change in a climate variable is referred to as an *anomaly.)* Figure 2 illustrates conceptually the designation of the climate categories in terms of temperature and precipitation anomalies. Precipitation anomalies are expressed as a percentage while temperature anomalies are expressed as an offset in degrees Celsius.

Figure 2: Conceptual Illustration of Categorization of Projections



Temperature and precipitation anomalies were calculated for a rectangular region covering the majority of the state of Oklahoma. Table 2 shows the extent of this area.

Table 2. Coordinates of Representative Region

Extent	Coordinate
North	36.9375 N
South	34.1875 N
East	94.5625 W
West	99.9375 W

There are five areas delineated in Figure 2, four quadrants and a central rectangle, designated as "hot and dry" (Q1), "warm and dry" (Q2), "hot and wet" (Q3), "hot and dry" (Q4), and "central" (C). The boundaries between the wet and dry and warm and hot conditions are set at the median value of changes in precipitation and temperature, respectively. The bounds of the central rectangle are set at the 25th and 75th percentiles of precipitation and temperature. Each projection is categorized by the area in which it falls. Projections that fall within the central area are also included in the category associated with the quadrant in which they fall. Thus, some projections are used in two categories.

The abbreviations used for the categories (Q1, Q2, Q3, Q4 and C) are meant to provide some indication of the ordering of the scenarios that result from the categorization of the projections in terms of impact on runoff. For example, the hot and dry scenario (developed from projections that fall into the hot and dry category, as described below) will have the greatest tendency to reduce runoff and will thus fall into the lowest non-exceedance quantile of impacts. Accordingly it is designated Q1, for the first quantile. The warm and wet scenario will have the least tendency to reduce runoff (and may lead to increased runoff) and is thus is designated as Q4. The central area is intended to characterize the central tendency of the projections and is designated as C. The warm and dry and hot and wet scenarios fall roughly into the second and third non-exceedance quantiles based on work done in the Colorado River Basin and are therefore designated C2 and C3, respectively.

Figure 3 and Figure 4 are plots of the temperature and precipitation anomaly for each of the CMIP3 projections in 2030 and 2060, respectively.

Figure 3: Categorization of Projections for 2030

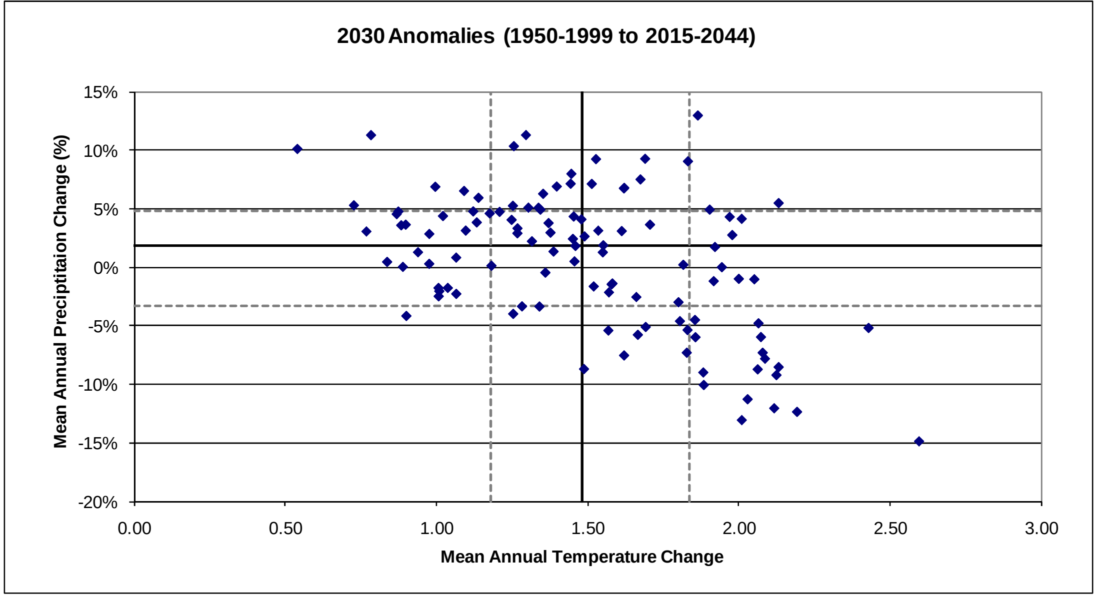
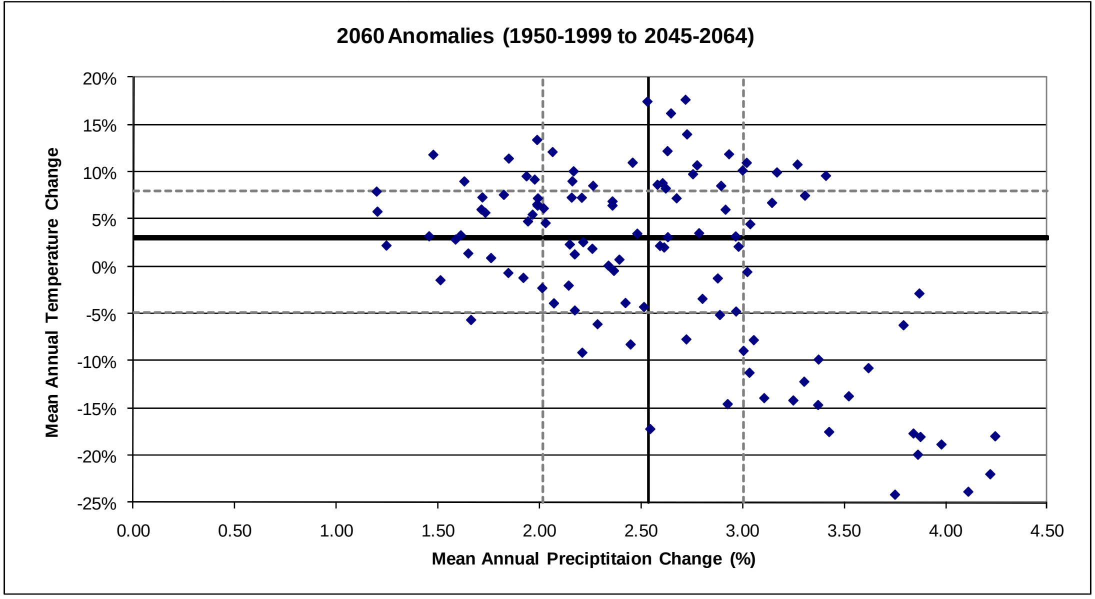


Figure 4: Categorization of Projections for 2060



For each category of climate projections (i.e., those contained in one of the regions depicted in figures 3 and 4), a composite “consensus” climate change scenario was developed using the HDe method. Climate models project different seasonal distributions of changes in temperature and precipitation. In order to preserve the model-to-model differences in seasonality the consensus climate is developed on a monthly basis.

The HDe method operates on the projections contained in one climate category (corresponding to one composite climate scenario), one grid cell, one climate variable (i.e. precipitation or temperature) and one month of the year at time. For each category, grid cell, climate variable and month of the year, the method proceeds as follows:

1. Construct the population of historical climate variables. For the historical record, pool all of the values for the selected climate variable for the selected month. If the historical record spans 40 years there will be 40 values in this population for each month.

2. Construct the population of simulated historical variables. This population is made up of the simulated values of the selected climate variable for the selected month from the overlap period for all projections in the category. A collection of projections or values of this sort is referred to as an *ensemble.* These values are simulated by the GCMs and correspond, conceptually, to the historical values. However, a GCM will not simulate the same sequence or the identical distribution of values as was observed. If there are 30 projections in the ensemble, then the number of values will be 30 x 50 or 1500 values for each month (there are 50 years in the overlap period.)

3. Construct the population of simulated projected variables. This population is made up of the simulated values of the selected climate variable for the selected month from projection period for all projections in the category. The projection period is that period in the future for which

projected impacts are sought. For this work, the projection periods are 2015 – 2044 (representing 2030 conditions) and 2045 -2075 (representing 2060 conditions). If there are 30 projections in the ensemble, then the number of values will be 30 x 30 or 900 values for each month (there are 30 years in a projection period.)

4. Determine empirical frequency distributions for each population. A non-exceedance probability is calculated for each value in each population. For example, sort the simulated projected population by value in increasing order, and assign a plotting position to each value using the equation $P = p/(n+1)$, where P is the plotting position, p is the position in the sequence (counted from the lowest value, beginning at 1) and n is the total number of values, 1500 in this example. Do the same for the historical and simulated historical populations.

5. Adjust historical values. Each monthly value in the historical record is adjusted according to the projected change (the anomaly) estimated for its plotting position. For each value in the historical population, determine the value that falls at the same plotting position in both the simulated projected and simulated historical population. These values are estimated using linear interpolation when the historical plotting position falls between two plotting positions in either the simulated historical population or the simulated projected population. The adjustment is calculated by subtracting the simulated historical value from the stimulated projected value, and is added to the historical value. After this calculation is made for each value in the historical record, the population is ordered by calendar year to produce a time series of adjusted historical values. In this way, the projected changes are associated with year/months of like type, e.g., wet year/months or cool year/months. This preserves more of the variability of the simulations while also incorporating information from all the projections in the ensemble.

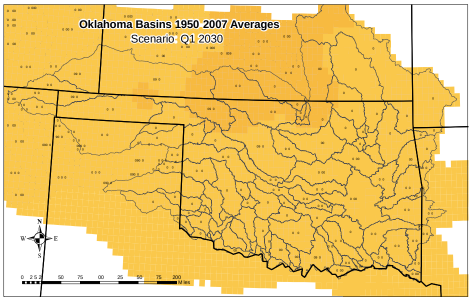
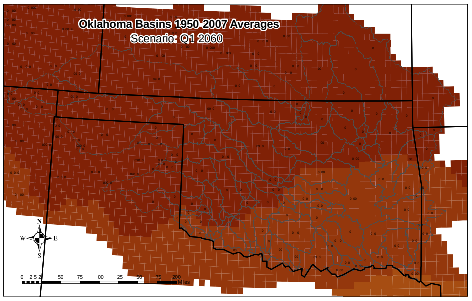
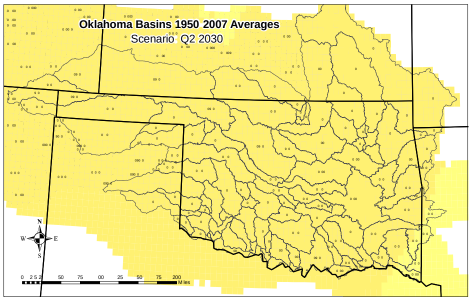
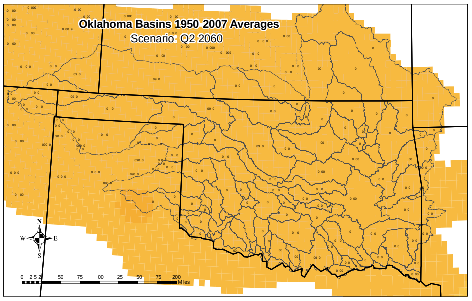
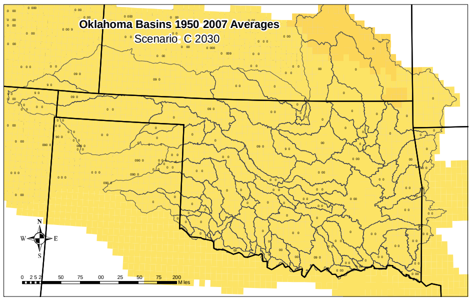
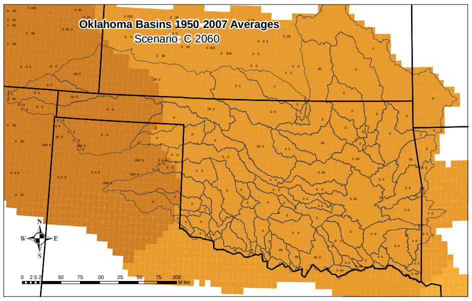
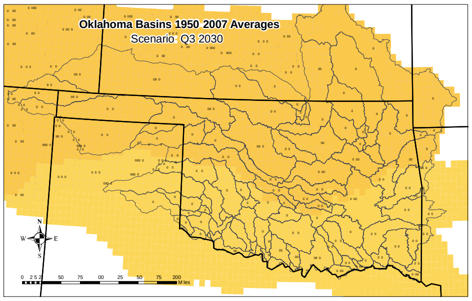
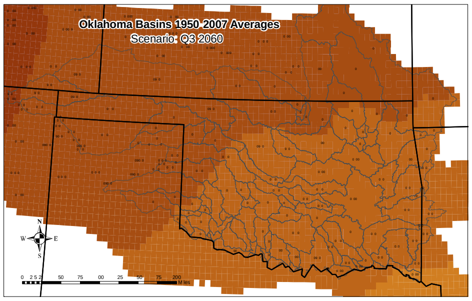
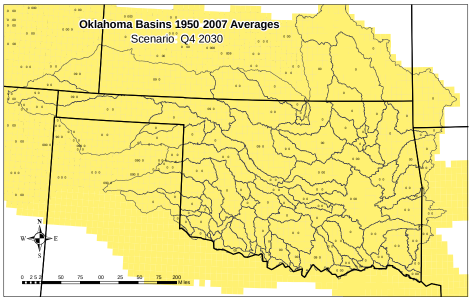
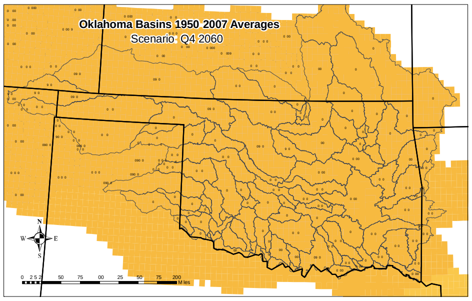
This process is repeated for each grid cell, climate variable, month of the year, composite climate scenario and projection period. The result is one time series of adjusted historical climate variables for each grid point for each of the composite climate scenario (five each for 2030 and 2060 in this work).

Historical daily weather was represented by a set of daily gridded observations at the LDAS spatial resolution of 1/8th degree (Wood, 2010.) For details on the development of this data set the reader is directed to Maurer et al. (2002). The historical data include daily total precipitation, daily maximum temperature, daily minimum temperature and wind. Projections of future climate conditions were obtained from the WCRP CMIP3 archive (WCRP, 2009). The projected climate data consist of monthly values of average precipitation and average temperature. Only temperature and precipitation from the historical data were adjusted. Precipitation was adjusted using a scale factor. Both maximum and minimum temperatures were adjusted using the same offset. In the VIC model, solar radiation is estimated based on the daily temperature range and dew point is estimated based on the daily minimum temperature, so adjusting maximum and minimum temperature by the same amount means that modeled solar radiation will be unchanged from the observed case, and relative humidity will be increased from the observed case. The WCRP CMIP3 Climate Projections archive reportedly will be refined to include maximum and minimum temperature (and possibly incoming shortwave solar radiation) when the CMIP5 projections become available.

4.0 RESULTS

Figures 5, 6 and 7 (below) show projected changes in average annual temperature, average annual total precipitation, and average annual runoff for the five composite climate scenarios for each of the two projection time frames, 2030 and 2060. Figures 5 and 6 display results for climate variables at the 1/8° resolution of the climate data and the hydrology model. The regular boundaries of changes in climate variables apparent in some parts of Figures 5 and 6 are artifacts of the downscaling process and the classification boundaries used in the mapping. Figure 7 shows the impact on average annual runoff for each of the 82 stream basins.

Figure 5: Projected Changes in Average Annual Temperature

	2030	2060
Q1		
Q2		
C		
Q3		
Q4		

Legend

Temperature
Change in degrees
Celsius

- ▨ 0.80 - 1.00
- ▨ 1.01 - 1.20
- ▨ 1.21 - 1.40
- ▨ 1.41 - 1.60
- ▨ 1.61 - 1.80
- ▨ 1.81 - 2.00
- ▨ 2.01 - 2.20
- ▨ 2.21 - 2.40
- ▨ 2.41 - 2.60
- ▨ 2.61 - 2.80
- ▨ 2.81 - 3.00
- ▨ 3.01 - 3.20
- ▨ 3.21 - 3.40
- ▨ 3.41 - 3.60

Figure 6: Projected Changes in Average Annual Total Precipitation

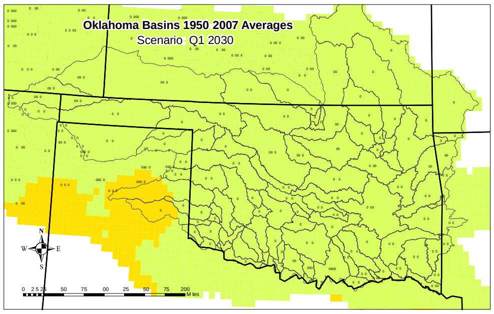
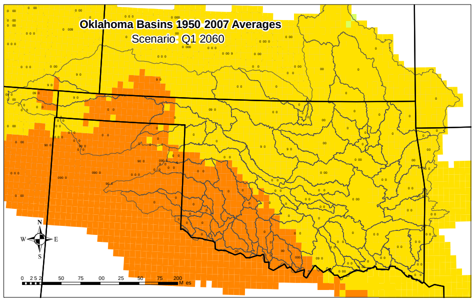
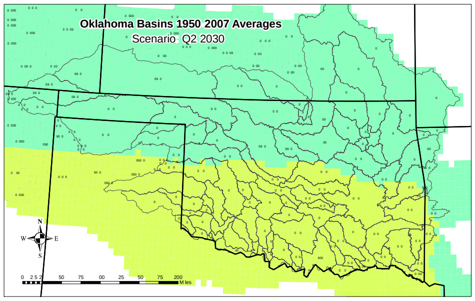
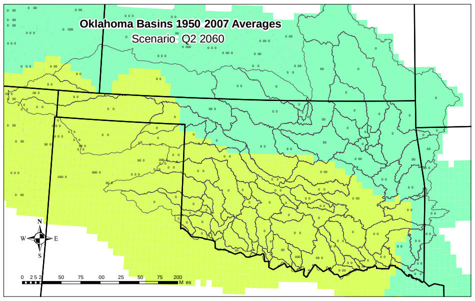
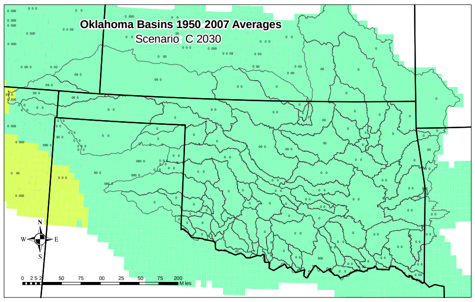
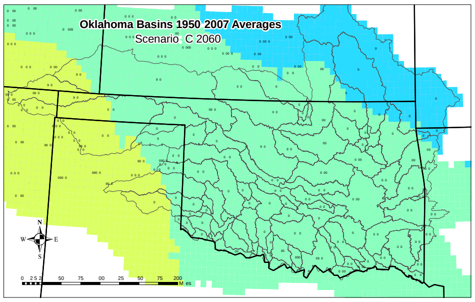
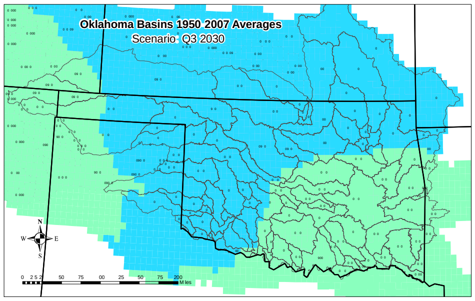
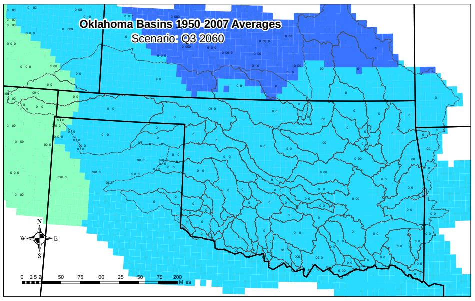
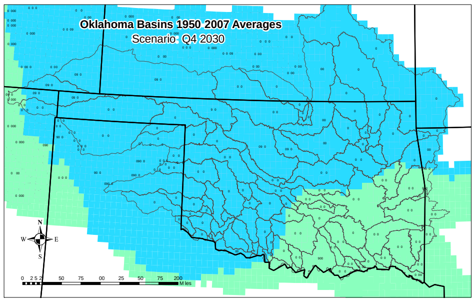
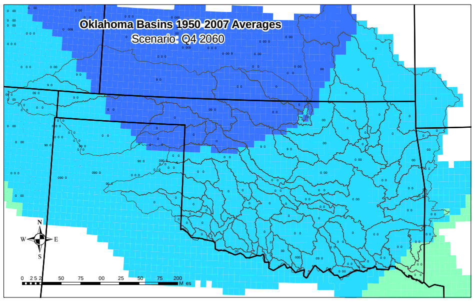
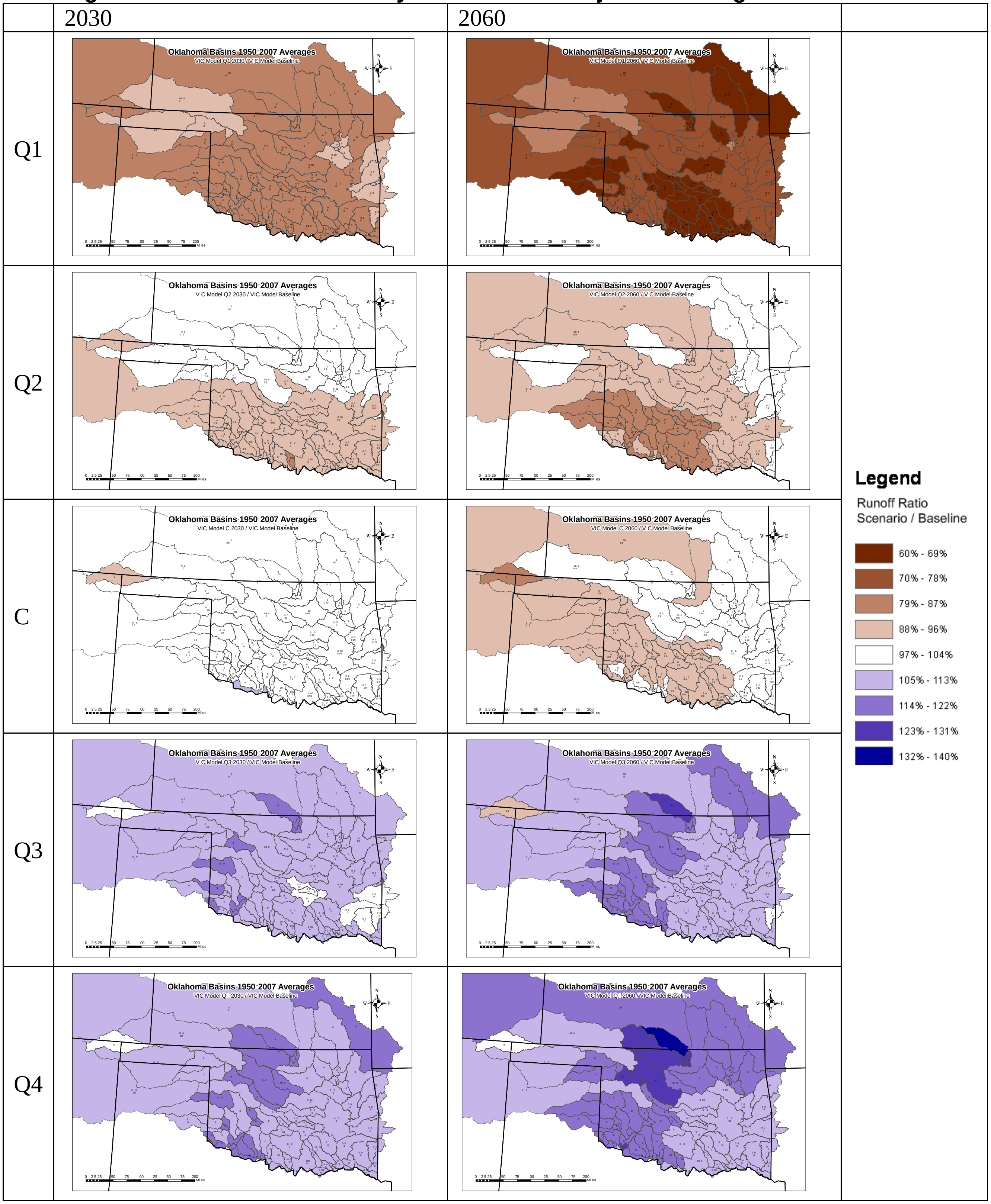
	2030	2060	
Q1			
Q2			
C			**Legend** Precipitation Ratio Scenario/Baseline 🟥 80% - 85% 🟧 86% - 90% 🟨 91% - 95% 🟨 96% - 100% 🟩 101% - 105% 🟦 106% - 110% 🟦 111% - 115% 🟦 116% - 120%
Q3			
Q4			

Figure 7: Estimated Sensitivity of Runoff to Projected Changes in Climate



Tables 3 and 4 show the average sensitivity of runoff to projected climate conditions for each of the 82 stream basins for 2030 and 2060 respectively. Sensitivity is expressed as the ratio of projected simulated runoff to the baseline simulated runoff. The baseline simulated runoff is estimated by running the hydrology model against the gridded observed climate. A ratio of 1.0 indicates no change, ratios below 1.0 indicate a projected decrease in runoff and ratios greater than 1.0 indicate a projected increase in runoff.

Projections of future climate conditions are uncertain. As a practical matter, uncertainty in climate projections manifests in disagreement between individual projections of future climate conditions and impacts. There are 112 statistically downscaled projections of future climate conditions (monthly average temperature and precipitation) in the WRCP CMIP3 downscaled archive In Oklahoma, all of those projections indicate that temperature will increase. However, those same projections contain more uncertainty about precipitation, with some projecting decreases in precipitation and some projecting increases. Uncertainties about both future temperature and future precipitation carry over into estimates of future runoff.

Wilby and Harris (2006) found that when attempting to project future runoff, the greatest uncertainty in climate impact studies arose from the climate models themselves, followed, in order, by the downscaling method, the hydrology model structure, the hydrology model parameters and finally by the uncertainty in future emissions scenarios. The approach adopted for this work has attempted to make the uncertainty in climate projections (the uncertainty arising from the emissions scenarios, the climate model structure and the boundary conditions of the climate model runs) apparent through the use of five composite climate scenarios. However, additional uncertainty is introduced into this analysis by the downscaling method, the hydrology model structure and the hydrology model parameters and those uncertainties were not quantified in this study.

Table 3: Estimated Sensitivity of Runoff to Projected Changes in Climate, 2030

Basin	C	Q1	Q2	Q3	Q4	Basin	C	Q1	Q2	Q3	Q4
10100	0.99	0.86	0.95	1.05	1.05	**11801**	1.01	0.81	0.91	1.13	1.14
10201	0.99	0.85	0.95	1.05	1.06	**11802**	1.02	0.83	0.92	1.15	1.13
10202	0.99	0.86	0.94	1.04	1.07	**20101**	1.00	0.89	0.96	1.05	1.07
10203	0.98	0.87	0.95	1.04	1.05	**20102**	0.98	0.87	0.95	1.04	1.06
10301	0.99	0.83	0.92	1.05	1.07	**20201**	0.99	0.87	0.95	1.05	1.07
10302	0.99	0.86	0.93	1.04	1.06	**20202**	0.99	0.86	0.94	1.05	1.07
10411	0.98	0.82	0.91	1.05	1.06	**20300**	0.99	0.85	0.92	1.05	1.07
10412	0.99	0.83	0.90	1.05	1.07	**20400**	1.00	0.87	0.96	1.07	1.10
10420	0.98	0.82	0.89	1.05	1.07	**20510**	0.98	0.83	0.90	1.05	1.08
10500	0.98	0.81	0.90	1.05	1.06	**20520**	1.02	0.83	0.93	1.11	1.15
10601	0.98	0.81	0.89	1.05	1.05	**20531**	1.00	0.81	0.96	1.14	1.16
10602	0.98	0.82	0.89	1.05	1.06	**20532**	1.00	0.87	0.98	1.09	1.11
10700	0.98	0.81	0.89	1.06	1.06	**20533**	1.00	0.85	0.97	1.11	1.13
10810	0.98	0.82	0.88	1.06	1.08	**20540**	1.00	0.91	0.99	1.05	1.06
10821	0.98	0.82	0.88	1.06	1.09	**20611**	0.97	0.82	0.88	1.04	1.07
10822	1.01	0.82	0.90	1.09	1.13	**20612**	0.98	0.81	0.88	1.06	1.09
10831	1.02	0.80	0.90	1.12	1.14	**20620**	1.00	0.82	0.90	1.08	1.11
10832	1.02	0.79	0.91	1.13	1.15	**20630**	0.97	0.83	0.93	1.06	1.09
10833	1.02	0.82	0.92	1.12	1.13	**20700**	0.99	0.83	0.91	1.06	1.09
10840	1.00	0.81	0.93	1.14	1.14	**20801**	0.97	0.82	0.88	1.04	1.07
10900	0.99	0.82	0.88	1.07	1.08	**20802**	0.97	0.81	0.88	1.04	1.07
11000	0.99	0.79	0.86	1.09	1.10	**20910**	1.00	0.83	0.95	1.11	1.14
11100	1.01	0.82	0.88	1.10	1.11	**20920**	1.02	0.84	0.96	1.13	1.16
11201	1.04	0.85	0.90	1.12	1.13	**20930**	1.00	0.88	0.99	1.07	1.09
11202	1.01	0.83	0.89	1.11	1.12	**20940**	0.93	0.85	0.94	0.98	1.02
11203	1.01	0.83	0.89	1.11	1.11	**21011**	0.98	0.79	1.00	1.14	1.16
11311	1.03	0.85	0.91	1.12	1.13	**21012**	0.98	0.78	1.00	1.14	1.16
11312	1.01	0.83	0.91	1.11	1.13	**21013**	1.00	0.78	1.02	1.17	1.21
11321	1.02	0.84	0.91	1.12	1.14	**21020**	1.01	0.84	1.01	1.13	1.17
11322	1.03	0.86	0.92	1.13	1.14	**21100**	0.99	0.84	0.96	1.09	1.12
11400	1.04	0.85	0.91	1.13	1.15	**21200**	0.97	0.82	1.00	1.07	1.10
11511	1.04	0.81	0.91	1.14	1.17	**21301**	1.02	0.90	0.99	1.09	1.10
11512	1.03	0.83	0.91	1.14	1.14	**21302**	0.99	0.84	0.98	1.10	1.12
11513	1.02	0.82	0.92	1.13	1.13	**21401**	1.01	0.87	0.98	1.10	1.12
11514	1.02	0.82	0.91	1.14	1.12	**21402**	0.99	0.84	0.99	1.10	1.12
11521	1.02	0.81	0.91	1.13	1.14	**21511**	1.01	0.87	0.97	1.08	1.10
11522	0.98	0.79	0.89	1.13	1.12	**21512**	1.01	0.87	0.98	1.09	1.11
11601	1.04	0.86	0.94	1.13	1.13	**21520**	1.00	0.84	1.01	1.11	1.13
11602	0.99	0.81	0.88	1.13	1.10	**21601**	1.01	0.87	0.99	1.09	1.11
11701	1.04	0.85	0.94	1.13	1.14	**21602**	1.01	0.84	1.02	1.11	1.14
11702	1.04	0.85	0.93	1.15	1.14	**21700**	1.00	0.88	0.98	1.06	1.09

Table 4: Estimated Sensitivity of Runoff to Projected Changes in Climate, 2060

Basin	C	Q1	Q2	Q3	Q4	Basin	C	Q1	Q2	Q3	Q4
10100	0.99	0.72	0.96	1.06	1.05	**11801**	0.93	0.66	0.84	1.18	1.19
10201	1.00	0.71	0.97	1.05	1.05	**11802**	0.93	0.70	0.86	1.17	1.18
10202	0.99	0.72	0.94	1.06	1.06	**20101**	1.01	0.76	0.97	1.07	1.07
10203	0.99	0.74	0.96	1.04	1.04	**20102**	0.99	0.74	0.95	1.05	1.06
10301	0.97	0.68	0.91	1.07	1.08	**20201**	1.00	0.73	0.96	1.07	1.08
10302	0.98	0.72	0.93	1.06	1.07	**20202**	0.99	0.72	0.94	1.07	1.09
10411	0.96	0.66	0.90	1.07	1.08	**20300**	0.97	0.70	0.91	1.07	1.09
10412	0.96	0.68	0.88	1.07	1.10	**20400**	1.00	0.73	0.94	1.09	1.13
10420	0.95	0.66	0.87	1.07	1.10	**20510**	0.95	0.69	0.87	1.08	1.12
10500	0.96	0.64	0.89	1.07	1.07	**20520**	0.96	0.70	0.89	1.15	1.20
10601	0.95	0.64	0.87	1.07	1.08	**20531**	0.94	0.67	0.90	1.16	1.23
10602	0.94	0.66	0.87	1.07	1.09	**20532**	0.95	0.76	0.94	1.11	1.15
10700	0.95	0.65	0.88	1.08	1.09	**20533**	0.94	0.73	0.92	1.13	1.17
10810	0.93	0.66	0.84	1.08	1.12	**20540**	0.95	0.82	0.96	1.06	1.08
10821	0.93	0.68	0.84	1.08	1.13	**20611**	0.93	0.66	0.84	1.06	1.10
10822	0.93	0.68	0.84	1.12	1.17	**20612**	0.93	0.66	0.83	1.10	1.14
10831	0.92	0.66	0.83	1.15	1.19	**20620**	0.94	0.68	0.86	1.11	1.15
10832	0.92	0.65	0.84	1.16	1.19	**20630**	0.89	0.71	0.88	1.05	1.11
10833	0.93	0.70	0.86	1.14	1.17	**20700**	0.96	0.68	0.88	1.08	1.13
10840	0.91	0.68	0.86	1.14	1.18	**20801**	0.93	0.67	0.84	1.06	1.10
10900	0.95	0.65	0.86	1.09	1.12	**20802**	0.92	0.66	0.84	1.06	1.11
11000	0.92	0.61	0.82	1.11	1.15	**20910**	0.98	0.69	0.91	1.15	1.21
11100	0.95	0.66	0.85	1.13	1.17	**20920**	0.98	0.71	0.92	1.16	1.23
11201	0.98	0.70	0.87	1.16	1.20	**20930**	0.96	0.78	0.96	1.10	1.13
11202	0.95	0.69	0.85	1.14	1.18	**20940**	0.84	0.72	0.90	0.94	1.04
11203	0.96	0.68	0.86	1.14	1.18	**21011**	1.00	0.65	0.93	1.19	1.25
11311	0.97	0.71	0.87	1.15	1.20	**21012**	1.00	0.63	0.93	1.20	1.25
11312	0.94	0.71	0.85	1.13	1.17	**21013**	1.01	0.62	0.95	1.24	1.32
11321	0.95	0.71	0.86	1.14	1.19	**21020**	1.00	0.70	0.96	1.18	1.25
11322	0.96	0.72	0.87	1.16	1.20	**21100**	0.99	0.69	0.92	1.12	1.18
11400	0.97	0.70	0.86	1.17	1.22	**21200**	0.95	0.69	0.94	1.10	1.16
11511	0.94	0.66	0.83	1.22	1.24	**21301**	1.03	0.79	0.98	1.12	1.14
11512	0.94	0.69	0.85	1.18	1.20	**21302**	1.00	0.69	0.94	1.13	1.17
11513	0.94	0.70	0.85	1.16	1.18	**21401**	1.03	0.72	0.97	1.13	1.16
11514	0.94	0.70	0.85	1.17	1.18	**21402**	1.01	0.69	0.95	1.13	1.17
11521	0.93	0.67	0.84	1.17	1.20	**21511**	1.01	0.73	0.96	1.10	1.14
11522	0.87	0.66	0.83	1.12	1.15	**21512**	1.02	0.73	0.97	1.11	1.14
11601	0.96	0.73	0.88	1.18	1.18	**21520**	1.03	0.69	0.98	1.15	1.18
11602	0.88	0.67	0.83	1.13	1.14	**21601**	1.03	0.72	0.98	1.11	1.14
11701	0.95	0.72	0.87	1.18	1.19	**21602**	1.04	0.69	1.00	1.16	1.18
11702	0.96	0.72	0.88	1.21	1.19	**21700**	1.02	0.74	0.99	1.09	1.10

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