Joint Front Range Climate Change Vulnerability Study [Project #4205]

ORDER NUMBER: 4205

DATE AVAILABLE: February 2012

PRINCIPAL INVESTIGATORS:
Mark Woodbury, David Yates, Marc Baldo, and Laurna Kaatz

INTRODUCTION:
The Joint Front Range Climate Change Vulnerability Study has been a collaborative effort between water utilities along Colorado's Front Range, the Colorado Water Conservation Board, the Western Water Assessment, the Principal Investigators, and the Water Research Foundation. It has focused on developing and applying procedures for combining the results of the latest climate science with the best available hydrologic simulation capabilities to gain insight into future streamflow trends that could be expected under possible climate change. The collaborative approach allowed participants to identify and support a common assessment methodology, develop a coordinated set of evaluation tools, and combine and efficiently utilize resources rather than pursuing independent, duplicative, and more costly studies. An educational component was included and has been essential to developing the methodology, interpreting the results, and understanding needs for future research and investigation. Although the study results indicate broad variability and uncertainty about future streamflow, the results are consistent with the variability and implicit uncertainty associated with the results of the climate models that were used as inputs. The specific findings of this study point toward future research that will improve estimates and enhance understanding of streamflow response to climate change.

OBJECTIVES:
The primary objective of this study was to analyze the sensitivity of streamflow to climate change for three watersheds in Colorado and to develop streamflow sequences that represent the effects of projected climate change on a baseline streamflow. This study assesses climate change by comparing average climate conditions between two periods, which may be referred to as a "Delta" approach. Two future time periods were assessed using available climate model outputs to support near-term as well as long-term planning horizons. Each provider will be able to use these future streamflow scenarios in conjunction with its own water rights allocation (water system) model to estimate the impacts of various climate change scenarios to its current and future water supply. In addition to the climate adjusted streamflows, the output of this process is a variety of tables and graphics describing the characteristics of the streamflow response to projected climate change.

A second objective was to bring project participants together to collaborate on this study. Potential benefits of the regional collaboration include resource sharing, coordinated agreement on a study approach, development of a set of evaluation tools that can be applied throughout the region, development of consistent hydrology data available for future planning efforts, utilization of regional experts to educate the participants and ensure a scientifically robust approach, and opportunities for participants to continue working together on climate change planning. This model can provide an example for other regional collaborations.

BACKGROUND:

Colorado's Front Range Metropolitan water providers are concerned about the impact climate change may have on future water supply. Depending on the direction, timing, and magnitude of future temperature and precipitation changes, the volume of water available could increase or decrease. Additionally, peak runoff timing could change, possibly leading to water rights complications or the need for operational changes for water utilities that depend on snowmelt for water supply. To better understand the possible impacts of climate change, several Front Range providers are working together to establish the education, tools, and methodology needed to study these potential effects. This project was designed to enable entities that obtain water from the upper Colorado, South Platte, Arkansas, Cache la Poudre, St. Vrain, Boulder Creek, and Big Thompson River Basins to examine the potential effects climate change may have on these supplies. This study involved a complex integration of climate model analysis, water accounting, and hydrologic modeling.

Traditional approaches to water supply planning use historical streamflow records to simulate the operation of existing and planned water supply systems and to evaluate system reliability for meeting current and forecasted demands. This approach considers the climate to be dynamic only to the extent that variability is represented in the observed record, and assumes that discharge patterns will be stationary according to the historic record. Until recently, variability and changes in climate statistics typically have not been explicitly integrated into water resources planning processes. As climate science improves, it enables another element to be included in water supply planning—the effect of projected climate change on streamflow. One source of information that offers insight into climate impacts on future water supply is the output from global climate models (or general circulation models [GCM]) used to project the impact of greenhouse gas emissions on global climate. The study participants, in conjunction with expert guidance, identified an approach for selecting climate model runs and a method for adjusting inputs to hydrologic models based on the climate models. The hydrologic models, in turn, project the streamflow that would result under the selected climate change conditions, indicating the sensitivity of streamflow to climate change.

APPROACH:

The following approach was taken to assess the sensitivity of streamflow to climate change:

- Select specific climate projections representative of the range of outputs from multiple climate models
- Identify a climate change "signal" (the change in temperature and precipitation between a reference period and a selected future period) from each model
- Apply that climate change signal to the historical inputs for two hydrologic models for the basins noted previously
- Simulate the hydrologic response from each hydrologic model to produce time series of climate-adjusted natural runoff
- Compare the simulation of climate adjusted natural runoff with an unadjusted baseline simulation of runoff to identify potential impacts of climate change

Applying this approach to the three large-scale river basins of interest to the study participants led to the following four major tasks:

Task 1: Selection of climate model projections – A subset from a catalog of 112 available climate projections was selected to use in the sensitivity assessment. It included five projections of climate for the 30 years surrounding 2040 and five projections of climate for the 30 years surrounding 2070. The five projections were selected to represent the range of outputs of the climate models without extending to the extremes of the results. Qualitative scenario names were given to the projections (for each future period) as follows:

- Hot & Dry
- Hot & Wet
- Warm & Dry
- Warm & Wet
- Median

Task 2: Historical undepleted streamflow data development – Assessing the potential impact of climate change on water supply requires an estimate of the historical streamflow both as a baseline for comparison and also for use in calibrating hydrologic models. Streamflow sequences that have been adjusted to remove the effects of diversions from rivers, reservoir storage, reservoir releases, and agricultural return flows represent the natural streamflow of the rivers and are referred to as *undepleted* flows. The second task of this study was to compile or develop historical undepleted flows for 18 gauge locations of interest.

Task 3: Hydrologic model development – To accurately simulate the impact of climate change on streamflow using a hydrologic model requires a model that properly represents the response of the basin to the climate inputs (specifically temperature and precipitation). In an attempt to distinguish between trends attributable to a fundamental hydrologic response from trends that might be peculiar to a particular hydrologic model, two hydrologic models were selected for use in this study: the Water Evaluation and Planning (WEAP) model from Stockholm Environment Institute (Yates et al. 2005a, b), and the Sacramento model found in the National Weather Service River Forecast System (NWSRFS). The effort began with previously developed historical climate datasets and calibrated hydrologic models, where available, and then updated the model calibrations by adjusting model parameters based on a comparison of model-simulated streamflow and the historical undepleted streamflow at 18 gauge locations distributed among the three watersheds.

Task 4: Assessment of Streamflow Sensitivity to Climate Change – The analysis of streamflow sensitivity to climate change was performed in two stages. In the first stage, a simple sensitivity analysis was used to demonstrate the hydrologic simulation approach and to test the sensitivity of each model and each gauge location to a uniform temperature increase (with no change to precipitation) and to a uniform precipitation adjustment (with no change to temperature). The second stage was to perform a GCM-based sensitivity analysis to assess model response to possible climate change represented by the selected projections in which the temperature and precipitation adjustments vary spatially over the study area and temporally from month to month. In both cases, adjustments were made to the historical climate data inputs to represent climate change, while maintaining the variability associated with the historic record.

To aid in the organization and evaluation of the results of the hydrologic simulations, an automated spreadsheet tool for reviewing and analyzing the results was created. Together, the climate adjusted undepleted flows derived from both the WEAP and Sacramento model simulations for multiple GCM projections represent a sample of possible future streamflow sequences compiled and provided to the study stakeholders. The sequences will allow water resources planners in Colorado to evaluate system responses to a range of possible changes in future streamflow.

STUDY GOALS:
As these tasks were identified and defined, specific study goals emerged in an effort to enhance the potential benefits of the study and guide execution of the tasks. The following study goals were identified and achieved as part of the above tasks:

- Identify and apply a procedure for selecting multiple climate model projections (Task 1)
- Develop a consistent sequence of historical undepleted flows for the period 1950‒2005 (Task 2)
- Develop and calibrate two hydrologic models for use in computing the hydrologic response to temperature and precipitation climate changes (Task 3)
- Report on the differences in hydrologic model accuracy for water years of differing types, including wet, normal, and dry years (Task 3)
- Test and demonstrate an approach for evaluating hydrologic response to variations in climate using uniform adjustments to temperature and precipitation (Task 4)
- Simulate the hydrologic response to possible climate change in temperature and precipitation by using multiple GCM projections (Task 4)
- Evaluate the hydrologic responses to possible climate change to assess change in runoff volume, timing of runoff, spatial variability of change, elevation impacts, and hydrologic model differences (Task 4)
- Describe a clear, repeatable procedure for future use in the region or in other parts of the country (documented in this report)

FINDINGS:
The pool of 112 GCMs from which 10 scenarios were selected for hydrologic simulation showed broad variability in projected future temperature and precipitation for the North-Central region of Colorado. Though all projections showed warming, the average annual temperature changes ranged from just over 1^{o} to nearly 6^{o} Fahrenheit for the 2040 time period and from about 2^{o} to nearly 10^{o} Fahrenheit for the 2070 time period. Meanwhile, average annual percent change in precipitation ranged from -15% to +17% for the 2040 time period and from -18% to +28% for the 2070 time period.

Likewise, there are significant variations in hydrologic responses simulated from the selected GCM projections. For example, average annual change in streamflow volume for the South Platte below Henderson ranges from +33% (Warm & Wet scenario) to -35% (Hot & Dry scenario) for the 2040 period. Analysis of the change in timing for the scenarios considered indicates that the annual runoff could arrive 1 to 14 days earlier in the 2040 simulations and 7 to 17 days earlier in the 2070 simulations.

This range results from the differing average annual changes in temperature and precipitation, from the difference in the monthly distribution of those changes in each projection, and from differences in the spatial distribution of the changes. One of the most important findings of this study is that each climate projection that was considered has a unique impact on runoff volume, and in order to grasp the broad picture of future possible changes in streamflow, the range of impacts from multiple scenarios needs to be considered, as opposed to looking for a central tendency or averages of simulation results. Within this context, the following are key observations drawn from this study:

- GCM model output encompasses a broad range of projected changes to future temperature and precipitation across North-Central Colorado.
- There is substantial variability in projected future streamflow based on the range of climate model projections that were used for streamflow simulation.
- Although the results indicate both increases and decreases in annual streamflow volume, more of the climate projections that were selected resulted in decreases rather than increases.
- Where decreased annual streamflow volume is indicated for a given projection, it is a result of the computed increase in evapotranspiration due to increased temperatures, coupled with either a decrease in precipitation or else a small increase in precipitation that is insufficient to offset the increased temperature effect.
- Where increased annual streamflow volume is indicated for a given projection, it is a result of increased precipitation that is sufficient to offset the increased temperature effect for that projection.
- Spatial and temporal distribution of temperature and precipitation changes across multiple sub-basins and over the twelve-month period has considerable influence on hydrologic model results.
- The two hydrologic models responded similarly to climate change inputs in terms of both annual streamflow volume and timing of runoff.
- At the scale of the river basins evaluated in this study, there does not appear to be a consistent tendency among GCMs regarding elevation-based differences in climate change patterns. Similarly, there are no clear tendencies regarding elevation-based differences in simulated hydrologic response that are evident from the results of both hydrologic models for multiple river basins.
- While increased temperatures are shown to reduce simulated average annual streamflow, the reductions are not uniform across the study area, with the driest basins, such as those in the South Platte, experiencing the greatest percent reduction in streamflow due to warmer conditions, while the wetter basins, including the upper areas of the Colorado, show a smaller percent reduction.

STRENGTHS AND LIMITATIONS IN APPLYING THE STUDY APPROACH:
One of the strengths of the overall approach employed in this study is that it allowed a spatial and temporal climate change signal to be incorporated into the hydrologic simulation while preserving the spatial and temporal structure and variability of the historical climate. By selecting specific GCM projections to represent the climate change signal on an average monthly basis instead of using average annual temperature and precipitation adjustments, the results of this study highlight the range that can result from particular combinations of monthly distributions of temperature and precipitation change.

Several limitations in the application of the study approach became apparent over the course of the investigation. First, the study approach does not provide any insight into the potential for increased or decreased intensities of rainfall outside of the average monthly change, or for variation in the diurnal distribution of temperature increases, or for any other characteristic of the GCMs that may indicate fundamental changes in climatic characteristics beyond the average monthly change in temperature and precipitation. This was not a serious limitation for the purposes of this study, but might be important in areas where changes in peak flows are of greater interest. Any efforts to overcome this particular limitation would have to overcome the lack of GCM output available in a format that would support more detailed analysis and would have to be justified with confidence that the climate models are in fact capable of representing those changes in a meaningful way. Second, while perhaps the most important element in determining changes in annual runoff volume is the simulated response of evapotranspiration (ET) to temperature change, there are additional variables beyond temperature that influence ET that were not part of the downscaled GCM outputs and could not be incorporated into the study approach.

LESSONS LEARNED:

Two primary considerations in assessing future water availability for Front Range water providers are average annual volume and the timing of runoff. Because the water supply for these agencies is primarily stored in the snowpack, permanent changes in the timing and volume of this important resource would have major impacts on water availability and could force changes in water management strategies. The change in annual runoff volume and timing of runoff are the outputs of the study of greatest interest to the study participants and their constituents.

Runoff timing is most sensitive to temperature, due to its effect on the form of precipitation (rain or snow) and on snowmelt. Precipitation changes alone have a minor influence on runoff timing. Even changes in the timing of precipitation have little impact on runoff timing, because of the dominance of snowmelt in the annual runoff cycle, and the controlling impact of temperature on snowmelt. Because all of the climate scenarios indicate increased temperature, nearly all of the scenarios simulated indicate earlier runoff, with the effect being more pronounced in the 2070 period. While the range of projections regarding the number of days earlier that runoff will occur is broad, the tendency to earlier runoff is uniform.

Simulated runoff volume is sensitive to both precipitation and temperature change. The sensitivity to temperature change is because of the influence of temperature on ET in the hydrologic model formulations. Because all of the climate scenarios indicate increased temperature, all of the climate-adjusted runoff simulations are impacted by an increase in ET and a corresponding reduction in volume. Many of the climate projections show a slight increase in precipitation, which partially or wholly offsets the reduction in runoff caused by increased ET. Those projections that show reduction in precipitation accentuate the reduced runoff volume resulting from increased temperature. The occurrence of both increases and decreases in precipitation accentuates the spread of volume changes simulated from the selected climate scenarios.

Based on these observations, study participants may wish to prepare for the impacts of climate change on water availability with the following considerations:

- Expect runoff to occur earlier
- Consider contingency plans for both increases and decreases in average annual runoff
- Monitor evolving indicators of climate change at both global and regional scales to identify trends
- Broaden the scope of selected climate models to use in hydrologic simulation to more fully explore the range of impacts on streamflow
- Be prepared to incorporate updated climate model outputs in planning processes based on forthcoming advances in climate science
- Encourage advances in climate science that will facilitate accurate hydrologic assessment

Climate adaptation is about preparing for change and new conditions in the future. This study provides important information to water utilities and managers to aid in identifying and assessing the hydrologic response to possible climate change.

APPLICATIONS FOR WATER UTILITIES:
The methodology of GCM selection, development of adjusted historical climate sequences, and hydrologic simulation developed in this study can be widely applied to assess climate impacts on water supplies both for additional projections in the basins studied or for other locations where there is access to downscaled GCM datasets. Although applying this methodology does not require a thorough understanding of climate science, users of the methodology should be informed about the capabilities and limitations of climate science and models. An important application note is that because of the uncertainty in all of the climate models, it may be valuable and important to simulate water systems operations using multiple climate projections to reveal potential vulnerabilities specific to the hydrologic response to each projection, as discussed in the findings.

Finally, it is important for the water utility community to communicate its needs regarding developments in climate science and required outputs from the models to the climate research community so that future efforts might evolve towards methods and information most helpful in understanding and assessing local hydrologic impacts of climate change.

RECOMMENDATIONS FOR ADDITIONAL INVESTIGATION AND RESEARCH:
The findings and lessons learned from this study indicate opportunities to improve understanding of the issues surrounding hydrologic response to climate change. Additional investigation efforts should seek to better understand and assess climate variability, while refining aspects of the procedure that can help to reduce uncertainty, as discussed in the recommendations. The following specific suggestions for additional investigation and research respond to that objective.

1. Climate Model Investigation and Development – output from climate models formed the basis for the evaluation of changes in runoff volume and timing in this study. In the short term it would be helpful to develop a better understanding of the nature of precipitation projections in climate change modeling, including the degree of confidence that might be lent to them, and potential differences between models in accurately simulating precipitation

trends. It would also be helpful to investigate and apply possible methods to extract information from the climate models about changes in inter-annual and daily climate characteristics to better understand impacts of climate change on floods and droughts.

2. Additional Scenarios – This study considered just five scenarios from a dataset of 112 possible projections for analysis for each of two future periods. Using the methods and procedures developed for this study, a subsequent analysis based on a simulation of *all* of the available GCM projections would be instructive to better understand the distribution of variability among the streamflow responses to the GCMs.
3. Demand – In using the results of this study in water system models, methods and procedures could be formulated and applied to simulate the impact to corresponding climate change scenarios on demand as done by CWCB in the Colorado River Water Availability Study.
4. Evapotranspiration – A major factor in projecting reduced average annual streamflow volumes in this study is the simulation of increased ET resulting from warmer temperatures. It would be helpful to work with climate model experts to identify elements of climate models corresponding with variables that impact ET (such as wind speed, solar radiation, and relative humidity), evaluate climate model skill in predicting these variables, and determine the feasibility of extracting this information from climate models and including them in the hydrologic modeling procedure.

Many of the participants in this study began with limited experience regarding climate science, climate modeling, and how climate model outputs might be applied to hydrologic models to gain insight into changes in runoff volume and timing under the influence of climate change. Participation in this study has both broadened and deepened the understanding of the participants, and the study methodologies are developed sufficiently such that many of the suggestions for additional investigation and research noted above should now be more accessible to the participants.

MULTIMEDIA:

It was important for the study participants to have access to the complete set of results of the study for subsequent efforts. Because of the large amount of data compiled and generated and the difficulty of presenting all of the results of this study in a report, a spreadsheet was prepared as a repository and display tool for the data generated by the models. The spreadsheet was distributed to the study participants and can be made available upon request to the Foundation.

BENEFITS OF REGIONAL COLLABORATION:

Regional collaboration was a key to the success of this project and was a valuable component for a number of reasons. Instead of each participant independently embarking on a study to assess climate change impacts to its individual water systems, the collaborative approach allowed participants to work together to develop the tools necessary for an assessment, agree upon a reasonable set of climate scenarios and time periods to examine, and share both data and financial resources. This was particularly useful for Front Range utilities as their water supplies originate from many of the same sources and collaboration reduced duplication. Furthermore, because many utilities in Colorado plan for the future using historic hydrologic records, there was a common need for a hydrology model to convert GCM projections of temperature and precipitation into streamflow and this further enhanced the benefits of regional collaboration.

Another important benefit to regional collaboration on this study was the ability to draw the interest of the academic, scientific, and research communities. Members from each of these communities participated and advised the research team as the study progressed. A single utility, acting alone, would not likely attract the same attention. This partnership resulted in a strong, scientifically defensible, and rigorously reviewed approach, as well as significantly increasing participants' knowledge base through monthly education session with leading experts in climate, water, modeling, and planning. This model is one that can be continued in Colorado and duplicated in other regions of the country.

RESEARCH PARTNERS AND PARTICIPANTS:

Funding and/or technical assistance for this study was provided by the following water utilities and water agencies from the Colorado Front Range:

Participating Water Utilities:

Aurora Water
City of Boulder
Colorado Springs Utilities
Denver Water
City of Fort Collins
Northern Colorado Water Conservancy District

Participating Water Agencies:

Colorado Water Conservation Board (CWCB)
Western Water Assessment (WWA) (technical assistance)

These participants, together with others noted below who joined during the course of the study, provided overall direction for the study and collaborated through participation in educational sessions and regular project meetings.

Additional Participants

City of Westminster
City of Cheyenne Utilities
City of Longmont Utilities