

Current State of Knowledge in Effects of Climate Change on Watershed Behavior

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Abstract

Global climate change will have many effects on various aspects of our lives, and in particular on watershed issues such as drought, flooding, sediment behavior, and pollution runoff. This paper will summarize these pertinent issues and relate the current state of the knowledge in this field through a detailed literature review.

Introduction

In recent years, there have been many papers published on the various potential effects of climate change on watershed behavior. These papers have spanned many topics from general hydrology to specific regional topics of interest. They have also examined the issue on a scale varying from worldwide to individual small watersheds.

Several sources state that the mean average global surface temperature increased 0.6^{o}C during the 20th century and is projected to further increase 1-3.5^{o}C during the 21st Century (Muzik 2002). It has also been stated that if the global atmospheric carbon dioxide concentration were to double, it would most likely result in a temperature rise of between 1.4^{o}C and 5.8^{o}C (Jha 2006). Such a rise in global temperature would likely result in a global increase in precipitation and evapotranspiration, leading to an increase in both extreme wet and extreme dry conditions (Jha 2006, Wurbs 2005).

The potential of an increasingly warm climate naturally leads to concern over the effects a changing climate would have on watersheds. Possible changes include changes in water temperature, runoff, streamflow, and water quality (Chang 2001). Changes to such as these would affect many important aspects such as ecological, social, and economic systems (Dibike 2004). This is especially a concern in arid and semiarid regions and in areas of higher population density where water resources must be carefully managed. Unfortunately, difficulty arises in estimating the potential effects of climate change due to two main reasons: the amount of greenhouse gases (primarily carbon dioxide) that will be present in the atmosphere at any future date is uncertain, and climatic factors are complex and often difficult to predict with any degree of certainty.

Climatic Effects of Climate Change

An increase in temperature due to climate change would likely affects many climatic factors, including precipitation, evapotranspiration, and soil moisture. Several methods have been utilized to predict climatic variation due to climate change, including applying predicted changes to specific climatic aspects, global circulation models, spatial analogue techniques, and temporal analogue techniques (Arora 2001).

Global circulation models (GCMs) are utilized in the majority of studies concerning the effects of climate change on watershed behavior. These models simulate interactions between various climatic factors, such as the amount of greenhouse gases in the atmosphere, temperature, precipitation, and evapotranspiration, and therefore can be used to model both the current climate and potential future climates (Arora 2001). Though these models are commonly used, their accuracy is limited due primarily to their coarse spatial resolution (Arora 2001). In order to attempt to correct this spatial coarseness, regional climate models or statistical downscaling methods are often used (Mohseni). When the greenhouse gas concentration is increased, GCM results generally indicate an increase in average global temperature, precipitation, and evapotranspiration accompanied by a decrease in soil moisture (Arora 2001).

Even with the uncertainty associated with climate change forecasting, general trends are apparent across various studies. Trends in precipitation and evapotranspiration and the resulting trends in soil moisture are often focused upon as that they can be used as inputs for hydrologic models.

Precipitation

The amount and frequency of precipitation in a region are often related to temperature. As temperature increases due to climate change, average global precipitation will likely increase while average over-land precipitation will likely decrease (Arora 2001). However this trend is not always true for a region, as that amount of precipitation received is also dependent on other factors such as topography.

The type of precipitation in an area at different times of the year is primarily determined by temperature. The amount of snow accumulation and the resulting amount of snowmelt is vitally important in many parts of the country in that it helps to replenish soil moisture in the spring and helps maintain normal streamflow and evapotranspiration amounts (Shelton 2001). Increased temperature due to climate change will almost certainly decrease the snow-water equivalent for many regions and also prompt an earlier snowmelt, thus potentially causing decreased streamflow and water shortages (Shelton 2001).

Evapotranspiration

Evapotranspiration (ET) is an important factor in watershed climate change studies since the rate of ET in a watershed directly affects the amount of runoff. Overall, most studies predict that evapotranspiration will increase both globally and over land as temperature increases (Arora 2001, Jha 2006). However, some studies indicate that an increase in atmospheric carbon dioxide concentration could actually decrease evapotranspiration due to an increase in stomatal closure (DeWalle 2000).

Soil Moisture

In general, as precipitation and evapotranspiration increase, soil moisture decreases (Arora 2001). The amount of moisture present in soil affects the amount of precipitation that will be absorbed into the ground instead of running into the river. Therefore, soil moisture is also an important factor in hydrologic studies.

Hydrologic Effects of Climate Change

The climate-change-induced changes in climatic variables, such as precipitation, evapotranspiration, and soil moisture, result in changes to runoff and streamflow. These two topics are directly related and are the areas where most studies on the effects of climate change on watershed behavior have focused.

Runoff

The amount of runoff in a basin directly affects the amount of streamflow in a river. Many variables have an affect on the amount and timing of runoff including the amount and frequency of precipitation, the type of precipitation (snow-water equivalent), the degree of evapotranspiration, the amount of soil moisture, land usage in the basin, etc. Several studies have been undertaken that specifically address changes in runoff due to climate change.

In 2001, a study was published detailing a climate change simulation for the Upper Deschutes Basin in central Oregon. A mesoscale atmospheric model was used to simulation a warmer and wetter climate resulting from an atmospheric carbon dioxide concentration double that of the current concentration (Shelton 2001). For this $2xCO_2$ climate, evapotranspiration was increased by 23% and the snow-water equivalent was decreased by 59% (Shelton 2001). This $2xCO_2$ climate was compared against a nine-year control climate (1951-1960), and the runoff resulting from each climate was determined through the use of a watershed model (Shelton 2001). The results indicate an average annual runoff increase of 23% and a change in the month during with the minimum and maximum runoff occur (Shelton 2001).

Also in 2001, researchers at the University of Minnesota published another report on climate change in watersheds. This case study compares the effects of two projected $2xCO_2$ scenarios on two watersheds located in different climates. The two watersheds are the Baptism River watershed in Minnesota and the Little Washita River watershed in Oklahoma (Mohseni 2001). The Baptism River watershed is heavily timbered and is located in a temperate and humid climate, while the Little Washita River watershed is predominantly pastures and agriculture with a warm and seasonally dry climate (Mohseni 2001). The two general circulation models (GCMs) used are the Goddard Institute of Space Studies (GISS) model and the Canadian Center of climate Modeling (CCC) model (Mohseni 2001). A monthly runoff model

(MINRUN96) was used to model runoff for a past historical climate and the two climate change scenarios (Mohseni 2001). The pattern resulting from the simulation shows a change in runoff that differs depending on the watershed, the season, and the amount of predicted precipitation (Mohseni 2001). Overall, the more northern Baptismal River watershed showed no significant change in annual runoff, while the more southern Little Washita River watershed showed about a 7% increase in annual runoff under both climate change scenarios (Mohseni 2001).

The Great Lakes are an important source of freshwater since ninety-five percent of all surface freshwater in the United States is located within them (Barlage 2002). Climate change could impact the supply of water within the lakes and also the amount of water being input to them by rivers (Barlage 2002). A case study was performed on the Huron River watershed in southeastern lower Michigan in order to determine the impact of climate change on runoff in a river watershed with the Great Lakes watershed. The Hadley Coupled Climate Model (HadCM2) and Vegetation/ Ecosystem Mapping Analysis Project (VEMAP) were used to determine precipitation, temperature, moisture, and solar radiation data sets which were then input into a version of the Biosphere-Atmosphere Transfer Scheme modified to include hydrologic components (BATS/HYDRO) to determine the change in runoff between a control period of 1994-2003 and a predicted future period of 2090-2099 (Barlage 2002). The model results indicated a 2.5% increase in the precipitation resulting in surface runoff due to climate change (Barlage 2002). This increase resulted from an increase in surface relative humidity due to both an increase in temperature and precipitation (Barlage 2002).

From these three case studies, it appears that an increase in temperature due to climate change will most likely result in an increase in the average annual runoff (Barlage 2002, Mohseni 2001, Shelton 2001). There may also be a change in the seasonal runoff pattern (Shelton 2001). This is, of course, still highly dependent on watershed location and other variables such as land use.

Streamflow

The amount of streamflow in a basin is directly affected by the amount of runoff, and therefore also prone to changes due to temperature and the resulting changes in precipitation, evapotranspiration, and soil moisture. Streamflow is the topic for which the most studies have been done concerning climate change and watershed behavior as that it is often of the greatest concern. Due to the sheer amount of studies on this topic they could not all be summarized in this article, however the following studies are a good representation of the work done addressing the topic.

In 2001, researchers at the Canadian Centre for Climate Modeling and Analysis (CCCma) performed a simulation on the effects of climate change on the hydrology of twenty-three major rivers throughout the world (Arora 2001). The CCCma coupled GCM was utilized to generate daily runoff values for both a control simulation and for a predicted period of increased atmospheric greenhouse gas concentration from 2070-2100 (Arora 2001). These runoff values were used to determine streamflow data for each river from which comparisons were made between results of the two simulations (Arora 2001). The results show that warmer regions (15 of 23 rivers) had a general decrease in mean annual discharge (median decrease of 32%) due to a precipitation decrease and an evapotranspiration increases, while other regions (8 of 23 rivers) had a general increase in mean annual discharge (median increase of 13%) (Arora 2001). Also middle- and high-latitude rivers showed obvious changes to the amplitude and phase of their annual flow cycle, while low-latitude rivers showed very little change (Arora 2001). As for mean annual flood magnitudes, 17 of the 23 rivers demonstrated a decrease in magnitude (mean decrease of 20%).

The Fraser River watershed was the focus of another case study published in 2002. The main goal of this study was to determine if the historic annual flow trends would be consistent under climate change scenarios generated by two GCMs (the Canadian Centre for Climate Modeling and Analysis model (CGCM1) and the Hadley Centre for Climate Prediction and Research model (HadCM2) (Morrison 2002). The predicted climate change scenarios for the period of 2070-2099 were compared against historic data (Morrison 2002). The results indicate a 5% average flow increase and an 18% decrease in average peak flow, with overall trends matching those of the historic data (Morrison 2002). Also, an increase of 1.9^{o}C was predicted for the mean summer water temperature, resulting in the potential for the water temperature to be warm enough (above 20^{o}C) to degrade the spawning success of salmon in the river.

The San Francisco estuary and its upstream Sacramento and San Joaquin Rivers watersheds are very important to the overall water supply in California and the health of the estuary itself (Knowles 2002). Researchers from the Scripps Institute of Oceanography's Climate Research Division released a paper in 2002 detailing a case study into the potential effects of climate change on this area (Knowles 2002). The Parallel Climate Model (PCM) was utilized to model a temperature increase of 2.1^{o}C by 2090, which resulted in a runoff decrease of approximately 20% from the historic data and a loss of half the average April snowpack storage resulting in an increase in winter flood peaks and smaller spring flows (Knowles 2002). These changes could result in a water shortage in this important system and a change in the water quality of the estuary (Knowles 2002).

In 2005, a case study was published analyzing the hydrologic impact of climate change in the Chute-du-Diable sub-basin of the Saguenay watershed in northern Quebec. Two different statistical downscaling methods (stochastic and regression based) were used to convert the Canadian Global Climate Model (CGCM1) data into inputs for two hydrologic models (the Swedish HBV-96 and the Canadian CEQUEAU) (Dibike 2005). The results of the two downscaling methods differ with the regression technique showing a clearer trend towards the increase of daily mean temperature values and variable precipitation values, resulting in a greater increase in mean annual river flow and earlier spring peak flows (Dibike 2005). The stochastic technique showed no obviously trend in daily mean temperature and precipitation, and resulted in a decrease in mean annual river flow (Dibike 2005). This demonstrates the variability of a study's results on the statistical downscaling method used.

A recent study examined the sensitivity of the streamflows resulting from a climate change impact study on the Upper Mississippi River Basin utilizing six different GCMs (Jha 2006). The different GCMs used to predict climate change due to a doubling of atmospheric carbon dioxide were CISRO-RegCM2, CCC (from the Canadian Centre for Climate Modeling and Analysis), CCSR (from the Centre for Climate Study Research), CISRO-Mk2, GFDL (from the Geophysical Fluid Dynamics Laboratory), and HadCM3 (from the Hadley Centre for Climate Prediction and Research). The GCM outputs were input into the Soil and Water Assessment Tool (SWAT) to obtain hydrologic results, which varied greatly with respective changes in annual mean streamflow of 51%, 10%, -6%, 38%, and 27% (Jha 2006). This variation indicates that there is still a large degree of uncertainty in climate change forecasting (Jha 2006).

Mean Annual Streamflow

The previously-detailed studies show a trend towards a decrease in mean annual streamflow. This decrease is especially prevalent in warmer regions and is a consequence of a decrease in over land precipitation and increase in evapotranspiration (Arora 2001, Jha 2006). However, some river basins show an increase in mean annual streamflow (Arora 2001, Jha 2006, Morrison 2002). Therefore, similar to other variables, the change in mean annual streamflow due to climate change is found to be highly dependent on other factors such as the location of the basin, topography, land use, etc.

Annual Streamflow Cycle

The annual streamflow cycle encompasses the seasonal changes in streamflow throughout the year. Changes in the inputs to the basin due to climate change are likely to cause changes in the amplitude and phase of the annual cycle (Arora 2001). These seasonal changes are often driven by a decrease in the fraction of precipitation falling as snow and an earlier snowmelt due to overall warmer temperatures (DeWalle 2000). Therefore, middle- and high-latitude rivers often experience an overall decease in amplitude and advance in phase, while low-latitude rivers tend to experience less of a change (Arora 2001).

Annual Maximum Discharge & Flood Frequency

The annual maximum discharge is also affected by changes in runoff amounts due to climate change. The annual maximum discharge may be found to vary in intensity and/or season of occurrence. Also the frequency of large discharges (floods) may vary due to a variation in rainfall intensity.

A case study published in 2002, examined the effect of potential climate change on flood frequencies and magnitudes in the Little Red Deer River watershed, a subalpine watershed on the eastern slope of the Rocky Mountains in Alberta, Canada. A first-order analysis of rainfall intensity was used to predict changes due to a doubling of atmospheric carbon dioxide concentration (Muzik 2002). Two possible rainfall scenarios were selected and input into the HEC-1 watershed model. It was found that a 25% increase in the mean and standard deviation of Gumbel distribution of rainfall depth for storm durations from 6 to 4 hours resulted in an almost 80% increase in the mean annual flood and a 41% increase in the 1-year flood.

From this case study it is found that climate change may result in an increase in the mean annual flood and annual maximum discharge (Muzik 2002). However, other studies indicate a reduction in annual maximum discharge and mean annual flood magnitude, along with an increase in flood frequency (Arora 2001, Morrison 2002). This discrepancy most likely results from the differences in the methods used for each case study.

Streamflow Change Accounting for Urbanization

Changes in streamflow over time are obviously not only caused by climate change. Many other factors will contribute to streamflow changes in the future including land use and urbanization.

Urbanization changes the hydrology of a basin due to an increase in impervious surfaces, decrease in vegetation, change in water usages, etc. (DeWalle 2000). Some hydrologic effects of urbanization include decreased evaporation, increased streamflow, and increased frequency and magnitude of floods.

In 2000, a study was published comparing the effects of climate change on urbanizing versus rural basins (DeWalle 2000). These basins were located in four regions of the United States and 39 basins were classified as urbanizing, while 21 basins were classified as rural. Historical streamflow, climate, and population data were collected and compared for each basin. Results of this study indicated that an increase in population density results in a roughly proportional increase in streamflow. The rural basins were found to have predicted mean annual streamflow changes of +23% to -49% depending on the climate change scenario. Streamflow in basins with greater degrees of urbanization were also found to be less sensitive to temperature changes than those with lesser degrees of urbanization.

As these studies demonstrate, the results of a study of streamflow in a watershed as affected by climate change and highly dependent on the combination of methods undertaken. Future studies will most likely continue to attempt to determine the most accurate methods for studies of this type.

Effects of Hydrology on Watershed Behavior

As the hydrology of a watershed changes due to climate change it results in many other factors being affected. Studies have been done on the effects of climate change on many of these factors including erosion, nutrient loading, and water availability.

Erosion

Increasing precipitation and streamflow often result in increased erosion in a watershed. Since climate change has been found likely to cause these increases, it is also likely to cause increased erosion. Erosion increases the amount of suspended sediment in a river thus decreasing water quality and can also cause sedimentation build up problems as the particles settle out.

A case study, performed at the Siberian Branch of the Russian Academy of Science and published in 2003, examined the influence of climate change along with human activity on erosion in the Selenga River watershed within the Yenisey River watershed in southern East Siberia (Korytny 2003). A variant of the LUCIFS model was used to project continued treads in climatic factors such as air temperature, annual precipitation, rainfall erosion index, and aridity and continentality coefficients and their influence on erosion processes. For the purpose of this study, an increase in erosion is indicated by an increase in suspended sediment load and changing river structure characteristics. Historic human activity in the region was also considered. Historically, it was found that during the 20th century an increase in erosion was found for the first two-thirds of the century, followed by a decrease in erosion in the last third. It is predicted that the trend of decreasing erosion will continue in the 21st century and result in the formation of erosion features.

This study stated a likely decrease in erosion for the Selenga River watershed as that is the present trend. However, this decrease is dependent on the specific watershed and therefore more studies should be done as to the effect of climate change on erosion in other watersheds throughout the world. Also though the study used suspended sediment loads to determine the amount of erosion taking place, it did not account for any type of sediment transport and its effects on the river.

Nutrient Loading

Variation in nutrient loading (such as phosphorus and nitrogen loading) from agricultural, urban, and industrial runoff and atmospheric deposition can have a large impact on the water quality and beneficial uses of a watershed. Increased nutrient loading can lead to eutrophication problems and deduced water quality (Chang 2001).

Previous studies have indicated a likely increase in spring and decrease in summer nutrient loads due to climate change (Chang 2001). To determine the accuracy of these claims, a study was performed for six diverse watersheds of the Susquehanna River basin in Pennsylvania to assess possible effects of climate change on nutrient loading and streamflow (Chang 2001). The Generalized Watershed Loading Function (GWLF) was utilized in predicting nutrient loading for a climate change scenario of two times the current atmospheric concentration of carbon dioxide, and land use was assumed to stay constant. Overall, the predicted future climate resulted in an increase in nutrient loads and mean annual streamflow, though one watershed demonstrated a decrease primarily due to its heavy cultivation.

In another study, climate change driven nutrient loading and water quality change due to the production of maize in twelve Chesapeake Bay Region watersheds was examined. The GWLF model was used to run several scenarios, taking into account various climate change possibilities determine from two GCMs (the Hadley Climate model for 2030 and the Canadian Climate Centre (CCC) model for 2030) (Chang 2001). Overall results vary greatly depending on the scenario, within an increase in nutrient loading occurring slightly more often than a decrease.

Overall these two studies indicate that nutrient loading will most likely be found to increase due to climate change. However this is once again highly dependent on the land use within the watershed.

Water Availability

Recently there has been a trend in published studies detailing the possible effects of climate change on water availability. This is obviously a large concern as that many areas of the world are either experiencing water shortages or managing their water carefully to prevent water shortages. Many areas use modeling software to assist in their water management, so it is becoming apparent that their software may need to be adjusted to account for future climate change and its corresponding effect on water availability.

The state of Texas currently utilizes a water-availability modeling (WAM) system for regional and state-wide planning studies for the regulation of its water supplies. In 2005, a case study investigation was conducted to determine "the potential effects of climate-change on assessments of water-supply capabilities" and "whether or how climate change considerations should be incorporated into the WAM system" (Wurbs 2005). The Brazos River Basin was chosen for the study. The geography of the Brazos River Basin varies greatly as it stretch from New Mexico across Texas to the Gulf of Mexico, with the upper basin being flat and semiarid, the middle basin being wetter with rolling hills, and the lower basin being a humid coastal plain (Wurbs 2005). The Canadian Center for Climate Modeling (CCCMA) global circulation model and Soil and Water-Assessment Tool (SWAT) watershed hydrology model were used to predict a future 2040-2060 hydrology which was input into WAM and compared with the WAM results for the 1940-1997 historic hydrology (Wurbs 2005). Generally this study found a decrease in mean streamflows due to decreased precipitation and increased evapotranspiration, however the overall effect on water availability varied throughout the basin (Wurbs 2005).

The variable results from this study and others indicate that it would be difficult to integrate climate change into water-availability modeling due to the high degree of uncertainty associated with its effects. However, if climate change proves to have as great of an effect on water supplies as many studies indicate, it many prove very necessary to undertake this integration.

Conclusions & Recommendations for Future Work

The potential effects of climate change on watershed behavior are currently topics being heavily researched. This is because of the great importance of water to life on earth and an attempt to prepare for future changes in its availability.

In reviewing the many case studies that have been performed on various aspects of climate change effects on watersheds several points become apparent. First, the degree of climate change that the earth will experience in the future is largely unknown since it depends on several hard-to-predict variables, and therefore there is a lot of disagreement between various climate change models and projections. Secondly, due to the uncertainty of the degree of climate change combined with the array of different methods for performing an assessment of potential hydrologic effects and large variation between different watershed factors (such as location, land use, etc.), it is extremely difficult to develop trends as to how climate change will affect a watershed. Finally, there is a need for more research on various aspects of this subject.

Future research is needed in several areas. More research should be done to determine the most likely manifestation of climate change and the best methods for determining its hydrologic effects. Trends should also be developed for different types of watersheds in different locations with different land usages, in order to increase the ease of apply climate change study findings to other watersheds. Increased research is also needed into the aspects of watershed behavior affected by hydrologic changes such as water availability, water quality, and sedimentation. More research into the potential effects of climate change on sedimentation in watersheds could be especially valuable as that it addresses both the water quality (turbidity) and the potentially detrimental build up of excess sediments in various locations (such as the river bed, bends, and mouth).

References

Abler, D., Shortle, J., Carmichael, J., and Horan, R. (2002). "Climate Change, Agriculture, and Water Quality in the Chesapeake Bay Region." *Climatic Change*, 55, 339-359.

Arora, V.K. and Boer, G.J. (2001). "Effects of Climate Change on the Hydrology of Major River Basins." *J. of Geophysical Research*, American Geophysical Union, Vol. 106. No. D4, 3335-3348.

Barlage, M.J., Richards, P.L., Sousounis, P.J., and Brenner, A.J. (2002). "Impacts of Climate Change and Land Use Change on Runoff from a Great Lakes Watershed." *J. of Great Lakes Research*, International Association of Great Lakes Research, Vol. 28, No. 4, 568-582.

Chang, H., Evans, B.M., and Easterling, D.R. (2001). "The Effects of Climate Change on Streamflow and Nutrient Loading." *J. of the American Water Resources Association*, AWRA, Vol. 37, No. 4, 973-985.

DeWalle, D.R. and Swistock, B.R. (2000). "Potential effects of climate change and urbanization on mean annual streamflow in the United Stats." *J. of Water Resources Research*, American Geophysical Union, Vol. 36, No. 9, 2655-2664.

Dibike, Y.B. and Coulibaly, P. (2005). "Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic methods." *J. of Hydrology*, 307, 145-163.

Jha, M., Arnold, J.G., Gassman, P.W., Giorgi, F., and Gu, R.R. (2006). "Climate Change Sensitivity Assessment on Upper Mississippi River Basin Streamflows Using SWAT." *J. of the American Water Resources Association*, AWRA, Vol. 42, No. 4, 997-1016.

Knowles, N. and Cayan, D.R. (2002). "Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary." Geophysical Research Letters, *American Geophysical Union*, Vol. 29, No. 18, 38-1 – 38-4.

Korytny, L.M., Bazhenova, O.I., Martianova, G.N., and Ilyicheva, E.A. (2003). "The influence of climatic change and human activity on erosion processes in sub-arid watersheds in southern East Siberia." *Hydrological Processes*, 17, 3181-3193.

Mohseni, O. and Stefan, H.G. (2001). "Water Budgets of Two Watersheds in Different Climatic Zones under Projected Climate Warming." *Climatic Change*, 49, 77-104.

Morrison, J., Quick, M.C., and Foreman, M.G.G. (2002). "Climate change in the Fraser River watershed: flow and temperature projections." *J. of Hydrology*, 263, 230-244.

Muzik, I. (2002). "A first-order analysis of the climate change effect on flood frequencies in a subalpine watershed by means of a hydrological rainfall-runoff model." *J. of Hydrology*, 267, 65-73.

Shelton, M.L. (2001). "Mesoscale Atmospheric 2xCO2 Climate Change Simulation Applied to an Oregon Watershed." *J. of the American Water Resources Association*, AWRA, Vol. 37, No. 4, 1041-1052.

Wurbs, R.A., Muttiah, R.S., and Feldon, F. (2005). "Incorporation of Climate Change in Water Availability Modeling." *J. of Hydrologic Engineering*, ASCE, Vol. 10, No. 5, 375-385.