Climate Change Impacts on Water Resources in South Texas

Venkatesh Uddameri and Gomathishankar Parvathinathan

Water is a critical resource which is vital for the sustainable development of semi-arid South Texas. Given limited supplies and already large demands on water, the question of how changes in climate affect the state of water resources in South Texas is on everyone’s mind. The focus of this study is a preliminary investigation on how various hydrologic processes are likely to operate within the Mission River Watershed under a plausible climate change scenario. Information obtained from global climate change models indicate that the precipitation is likely to stay constant in 2100 but rainstorms are likely to be more intense. Furthermore, the region is likely to be warmer by about 4°C (7.2°F). Two water balance models: a semi-distributed event-based model covering a time period of twenty-three days following a twenty-two hour rainstorm event, and a lumped monthly water balance model were developed. Having obtained reasonable calibrations, the models were then used in a forecast mode using synthetic data representing precipitation and temperature patterns expected in the year 2100. The event-scale model results indicate that the runoff generated within the watershed will increase with higher rainfall intensification with an estimated peak flow increase of 500 cfs. The results from the monthly water balance model indicate that the projected temperature changes will cause significant increase in evapotranspiration and decreases in soil moisture content and recharge. Reductions in soil moisture may require a potential conversion from dryland farming to irrigation. The reductions in recharge are significant especially during the summer months when the groundwater withdrawals are likely to be the highest. These reductions in recharge will diminish the reliability of groundwater resources as a potential water supply source.

Water Resource Management

Proper management of water resources is an important consideration for sustainable development of South Texas. As discussed in earlier chapters, the rainfall in this semi-arid region exhibits considerable variability and erratically fluctuates between extreme droughts to hurricane-induced storms. The major inland surface water bodies, namely the Rio Grande, Nueces, and San Antonio rivers and the man-made reservoirs in them, occupy less than 2% of the vast land area (about 80,000 sq. km [30888.17 square mi]) often referred to as the South Texas (Figure 1). While average annual rainfall can exceeds 30 inches in some parts, storms tend to be high-intensity, short-duration events that lead to significant runoff and flashfloods. The region’s warm climate also causes significant evaporative losses and the potential evapotranspiration is over two times the average annual rainfall (Norwine et al. chapter 2).

Groundwater is another important component of the available water supply in the region. South Texas is largely underlain by the Gulf Coast aquifer. The western sections of the region fall under the Yegua-Jackson and Carrizo-Wilcox formations and the northern sections are underlain by the karstic Edwards aquifer. The water
availability in these aquifers varies considerably due to intrinsic geologic heterogeneity and historical use patterns. In addition, groundwater quality is also highly variable and characterized by elevated total dissolved solids (TDS), especially along the coast and in the lower Rio Grande River valley. As such, the estimated groundwater availability exhibits considerable variability as well. Doomsday scenarios of climate change notwithstanding, the high climatic and geologic variability in the region makes quantification of available water supplies an arduous task.

After being an economically under-served region for decades, South Texas is currently experiencing significant economic growth fueled by the North American Free Trade Agreement (NAFTA) and other policies. The population of the region is expected to double over the next few decades and the once agrarian and ranching economy is transforming into an industrial and service-oriented market of strategic importance. These economic and demographic shifts are going to alter the demands placed on water in years to come. The availability of water in the year 2050 as projected by the Texas Water Development Board (TWDB) as part of their state water planning process is depicted in Figure 2. As can be seen, there are several counties that are expected to fall short of their water requirements around the first half of the century. Effectual water resources management is indeed vital if future generations of South Texans are to have the same access to this natural resource as we have today.

The water demand projections are largely driven by urbanization and other social shifts and do not factor in the impacts of climate change. Given the importance of water to region’s sustainability, the central question of how climate change can alter water availability in the future is a major concern to the citizens of South Texas. The primary goal of this study is to make a preliminary attempt to address this concern based on our current understanding of plausible climate change impacts.

Caveat Lector

The only possible approach to assess the impacts of climate change on the state of water resources is through the use of sequential mathematical forecasting tools. The integration of global climate change models with physically based regional water budget models is increasingly being used to forecast and understand climate change impacts on water resources (e.g., Chaplot 2007; Jiang et al. 2007; Fiorillo et al. 2007; Burns et al. 2007 to name a few). Nonetheless, it is important to bear in mind that water balance models in general possess considerable uncertainties due to paucity of data and incomplete understanding of the various processes that affect the movement of water (e.g., Son and Sivapalan 2007). Unfortunately, this concern holds true for regional-scale models developed for South Texas as well (e.g., Chowdhury et al. 2004; Uddameri and Kuchanur 2007). These uncertainties get further exacerbated when inputs (or information) from coarse-scaled global climate change models (GCMs) are used as forcings to these regional-scale water balance models. The admonition of Neils Bohr, “prediction is very difficult,
especially if it's about the future,” holds very true for the exercise presented here. Nevertheless, it is carried out in
the spirit of Roger Bacon’s argument that, “more truth arises through error than confusion.” It is hoped that the
modeling activities pursued in this chapter will generate some initial insights that will initiate a dialogue on this
issue and foster further research that will enhance and refine our abilities to address the pressing question of how
climate change affects water resources in semi-arid South Texas.

Conceptual Model

Water Balance Modeling

The hydrologic cycle is the fundamental concept behind any water resources investigation and, as such is
used as the basis for understanding climate change impacts here as well. A generic conceptualization of the
hydrologic cycle is depicted in Figure 3. The hydrologic cycle can be studied over many different
spatial scales of interest. First, the region of interest, e.g., South Texas or Mission River Watershed, needs
to be demarcated with well defined boundaries which could be natural (e.g., watershed) or artificial (e.g.,
county boundary). This region of interest is referred to as the system of interest or simply a hydrologic
system. The hydrologic system of interest such as a watershed in turn consists of several different
compartments or sub-systems like aquifers, rivers, lakes, and reservoirs where water accumulates.

Water also leaves the terrestrial compartment due to a variety of factors such as evaporation from surface water
bodies, transpiration from plants, as well as other anthropogenic policies governing water export and import. In
addition to these inter-boundary transfers, water is also cycled between various storage pools. For example, in
highlands, water from lakes and rivers percolate into the aquifer. Groundwater discharges, also referred to as baseflows,
sustain surface water flows in lowlands even during the dry periods. The water budget is a major bookkeeping operation
where the flows into and out of the various compartments in a system are tracked. The level of spatial detail is one
measure of complexity of the water budget model. A lumped model treats the entire system of interest (watershed) as a
single homogeneous entity, while a distributed model divides the system into multiple (sub-watersheds) compartments
that are interconnected with one another. Both these approaches can be used for

Figure 3. The water cycle
studying the impacts of climate change.

Just as water budgets can be developed at a variety of spatial scales, they can also be built at different time-scales. Hydrologic processes manifest at different time-scales. In arid and semi-arid environments, precipitation occurs intermittently and over a few hours in a month. Associated events like runoff (overland flow) and infiltration (percolation into the soil) occur over several days following the rainfall. On the other hand, evapotranspiration (movement of moisture back into the atmosphere), baseflows (discharges from groundwater) moisture redistribution in the soil and recharge (discharges to groundwater) can manifest over several months following a rainfall event (Stephens 1995). Therefore, water budget models can be developed at multiple temporal scales. Models that are concerned with an individual rainfall event are called “event based models” and are well suited to study runoff characteristics following a rainfall event. On the other hand, models that simulate both wet and dry conditions are known as continuous models. Both these models provide different pieces of information to understand the impacts of climate change on water resources in a region.

Study Area

The Mission River watershed was chosen as a representative system to understand the impacts of climate change on water resources in South Texas. Mission river is a small perennial stream in the coastal bend region of South Texas formed by the confluence of Blanco and Medio creeks (Figure 4). The Mission river watershed has a catchment area of 1787.09 square km (690 square miles) that spans across Refugio, Goliad, Bee, De Witt, and Karnes Counties and drains into the Mission Bay in the Gulf of Mexico. The watershed is underlain by the Gulf Coast aquifer and the water table in the shallower unconfined aquifer is approximately 30 feet below the ground surface in the watershed. There is one gaging station 1 operated by the United States Geological Survey (USGS) near the township of Refugio, Texas (NWIS 2004). Monthly precipitation and temperature data are available since 1984 at a weather station operated by the National Weather Service (NWS) near Refugio, Texas (NCDC 2003). Measurements of other hydrologic parameters are rather scanty.

No water rights are allotted for diverting the river flows for municipal, irrigation, and industrial uses from the Mission River or other creeks in the watershed. The western sections of the watershed are mainly classified as rangeland and transitional areas and occupy roughly 15% of the watershed. The southern and eastern sections are used for agriculture (mostly dryland farming) that accounts for nearly 25%. Nearly 57% of the area has been classified as forested. The watershed has been subject to limited urbanization (about 1% urban) and does not contain anthropogenic influences from major cities. Major townships like Refugio in the watershed have maintained fairly stagnant populations in recent decades. These factors greatly minimize the impacts of urbanization on the hydrology of the watershed and make it suitable for studying long-term climatic variations without significantly introducing the confounding effects of urbanization.

Mathematical Models

Event-Scale Assessment

As stated previously water balance models can be run at several spatial and temporal scales. A semi-distributed water balance model for simulating a single rainfall event that occurred on November 3, 2002 was developed using the Soil Moisture Accounting (SMA) model available within the HEC-HMS modeling systems (USACE 2006). The composite rainfall event lasted for a period of twenty-two hours and is depicted in Figure 5. This rainfall was established using NEXRAD (Stage-II) measurements at fourteen different locations scattered over the watershed. These measurements were composited into an effective watershed scale rainfall using the area-weighted Thiessen polygon approach. In addition, spatially distributed pan evaporation rates were obtained from Texas Water Development Board (TWDB) and supplied as model inputs for mean monthly potential evaporation.

Although the SMA model is capable of running in a continuous mode, it was operated in an event mode for this analysis. The SMA model simulates a variety of processes including canopy interception, runoff, soil moisture storage, evapotranspiration from surface water and soil, and deep percolation to groundwater. The theoretical basis of the model has been described in Bennett (1998) and the model is based on concepts derived from linear control

1 Station ID: 08189500
theory. While the original SMA model is a lumped parameter model, the HEC-HMS system allows its application in a semi-distributed mode. To apply the model to the Mission River watershed, three lumped sub-models corresponding to Medio Creek, Blanco Creek, and Mission River sub-watersheds were developed. These sub-watershed models were interconnected using junction elements and outflow from each sub-watershed was routed downstream using the SCS-Lag method (Figure 6). The model was run for a total of twenty-five days at an hourly time-step for a total of six hundred time steps.

![Figure 5. Water Balance Model for November 3, 2002 using the SMA](image)

The model calibration was performed by manually adjusting tension storage and soil storage parameters which are noted to be the two most sensitive model parameters (Fleming and Neary 2004) for each sub-watershed. In addition, the soil percolation coefficient and the SCS-lag coefficient were also mildly adjusted as part of the calibration process as well. An initial estimate for the lag-coefficient was obtained from slopes and land use land cover (LULC) data using HEC-GeoHMS pre-processor (USACE 2003). The residual peak and total flow volume, i.e., the differences between the observed and predicted peak flow and total flow) were used to guide the calibration process. The hourly flow observations for the calibration were obtained from the USGS gaging station on Mission River in Refugio, Texas.

![Figure 6. Sub-watershed models](image)
Table 1. Calibration Statistics

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Figure 7. Results of Model Calibration

Figure 8. The calibration and the evaluation for hydrograph separated and model predicted runoff
The required model inputs are summarized in Appendix 1, the results of the model calibration are presented in Figure 7 and the calibration statistics are summarized in Table 1. The results indicate the model over-predicts the total flow by about 22% but does an extremely good job of capturing the peak discharge with an error of less than 0.35%. While better calibrations can possibly be accomplished by simultaneously adjusting other parameters, it is important to bear in mind that the reliability of the model decreases with increasing number of adjustable parameters. Also calibration is an inherently non-unique process (Oreskes et al. 1994) and obtaining excellent calibrations by adjusting a large number of model inputs does not necessarily imply that the model will have good predictive abilities. Therefore, a trade-off between calibration accuracy and the number of adjustable parameters needs to be maintained and evaluated in the context of the accuracy needed for the intended application. From this standpoint the calibration obtained here was deemed reasonable because the model is intended to evaluate the impacts of short-term phenomenon like alterations in peak discharges due to climate change.

**Monthly Water Balance Model**

Water balance models developed at monthly time-step offer a reasonable compromise between computational tractability, data needs, and application requirements and as such have been used for a variety of applications including climate change studies (e.g., Thornthwaite 1948; Haan 1972; Alley 1984; Xu and others 1996; Xu and Singh 1998; Wright and Xu 2000). Recently, a lumped watershed scale monthly water balance model has been developed for the Mission River watershed (Uddameri and Kuchanur 2007). The average monthly soil moisture in the watershed is the master variable in this model capable of simulating infiltration, runoff, deep percolation (recharge to groundwater), soil moisture storage and evapotranspiration. A major challenge in developing monthly water balance in semi-arid and arid watershed lies in the fact that rainfall events tend to be intermittent and occur over short durations (i.e., few hours in a month). The use of an average rainfall (i.e., total monthly rainfall averaged over an entire month) causes an over-estimation of infiltration and an under-estimation (and most times zero) runoff, which is not realistic. To overcome this obstacle, an innovative procedure was developed in that the average rainfall intensity for each month was obtained by dividing the total volume of rainfall observed in each month with an equivalent storm duration period that was obtained via calibration. Preliminary analysis of the available rainfall data indicated while the total rainfall amounts varied between months, the total number of rainfall hours varied little. As such, the storm duration was assumed to stay constant over the entire simulation period to make the model parsimonious. The equivalent rainfall duration was

![Figure 9 a. b. and c.](image-url)
obtained via calibration by matching the rainfall excess predicted by the model to the hydrograph separated rainfall excess. In addition, the field capacity, soil sorptivity, and infiltration constant were also obtained via calibration.

The observations in the time-period (1985 to 1997) were used for calibrating the model and the data from the time-period (1998 to 2002) was used to independently evaluate the model. The calibration was objectively carried using evolutionary genetic algorithms (Goldberg 1989). The mean square error was used as the calibration statistic and the calibration root mean square error (RMSE) was equal to 0.64 cm/month (0.251 in/month) while the RMSE for the evaluation dataset was equal to 1.31 cm/month (0.515 in/month). The required model inputs can be found in Uddameri and Kuchanur (2007) and are not repeated here in the interest of brevity. The calibration and the evaluation for hydrograph separated and model predicted runoff is depicted in Figure 8. The coarse temporal resolution of the model precludes it from capturing the flashiness in the streams caused due to high intensity storms. However, the model is able to better capture the more persistent low flows. The calibration and evaluation RMSE for these persistent flows are 0.591 and 0.458 cm/month (0.233 and 0.180 in/month) respectively. Therefore, this model is suitable for assessing climatic influences of persistent hydrologic parameters such as recharge, evapotranspiration and soil moisture.

Results and Discussion

Effects of Increasing Temperature – Event Scale Analysis

GCM model predictions indicate that the average temperature may increase by about 4°C (7.2°F) in the year 2100. What influence could this temperature raise have on hydrologic factors during a rainfall event? To address this question, the potential evaporation corresponding to increase in temperature was first computed using the following empirical equation developed from available temperature and pan evaporation data:

\[ PE = 0.37 \times EXP(0.299xT) \]

Where \( T \) is Fahrenheit \( (R^2 = 0.91) \) (1)

The water balance results presented in Figures 9 (a-c) depict how the rainfall is distributed between different hydrologic compartments when the climate change induces a temperature increase of either two degrees or four degrees over the baseline (current) values. The results indicate that there is a small increase in the total evaporation from soil and surface water sources which is offset by smaller decreases in the amount of runoff and interception losses. The model predictions also indicate the recharge to groundwater during the twenty-three day simulation period around the twenty-two hour rainfall event is negligible and not influenced by temperature. During the actual rainfall event, the relative humidity is nearly 100% and as the atmosphere is saturated with moisture there is negligible evaporation if any. The SMA model does not simulate evaporation when the rainfall is taking place.
The modeling results also indicate that if all other things stay the same, temperature increases are unlikely to affect flooding (peak flow and runoff) characteristics either.

**Effects of Increasing Rainfall Intensity – Event Scale Analysis**

Many climate change models predict an increase in the rainfall intensity in the twenty-second century (Meehl et al. 2005). Although this result may not be statistically significant in some GCM models, even small changes in rainfall intensity could be of great hydrologic significance. Increased rainfall intensity implies that greater amount of rainfall will be transported as runoff. In the short run, this result implies greater risk of flooding and increases in rainfall intensity will exacerbate any increased runoff due to paving of bare-soils as watersheds undergo urbanization. Increased runoff would also indicate reduced infiltration which in the long run will lead to reduced groundwater recharge and lesser availability of water. To evaluate the impacts of increased rainfall intensity, two synthetic rainfall events were constructed from the baseline case (November 3, 2002). The rainfall volume of these synthetic events was assumed to be equal that of the baseline case (3.023 cm or 1.19 inches). However, the duration of the rainfall was decreased from twenty-two hours to sixteen hours (73% duration) and twelve hours (55% duration) respectively. The synthetic rainfall events adopted for assessing the impacts of increased rainfall intensity are schematically depicted in Figure 10. The rainfall occurring between sixteen to twenty-two hours and twelve to twenty-two hours were uniformly apportioned to earlier periods (i.e., one to sixteen and one to twelve hours respectively) in these scenarios. All other parameters, including potential evapotranspiration rates were unchanged in these model runs. The hydrographs generated at the Refugio USGS gage station under these scenarios (Figure 11) indicated that the peak flow increased from nearly 4000 cfs to 4500 cfs. Also the differences in the peak flow between the 73% duration rainfall and 55% duration rainfall event were fairly small. This result indicates that an increased peak flow is to be expected with increasing rainfall intensity regardless of the magnitude of the predicted change. However, the magnitude of the change may be subject to some threshold effect (i.e., the increase peak flow may plateau off after a certain rainfall intensity).

![Figure 11. Hydrographs generated at the Refugio USGS gage station under the scenario of the rainfall occurring between sixteen to twenty-two hours and twelve to twenty-two hours](image)

Based on empirical geomorphological relationships (Leopold and Maddock 1953; Chapra 1996), this increase in the peak flow could roughly translate to an increase in water level of one to two feet in the river. Therefore increasing rainfall intensity caused by climate change has the possibility of inundating some low-lying...
areas of the watershed. Urbanization in the future is likely to enhance the impacts of this flooding and therefore future land use activities must be planned carefully to avoid potentially deleterious flooding impacts.

The water budget analysis for the three rainfall intensity conditions are depicted in Figure 12a - 12c. As can be seen, the increase in the runoff brought forth by increased rainfall intensity is compensated largely by reductions in infiltration, canopy losses, and to a lesser extent by evaporative losses. This result is again to be expected because evaporation activity is curtailed during precipitation due to saturated moisture conditions in the atmosphere. While the recharge to groundwater is not significantly affected during the rainfall event (small changes in the graphs are due to round-off), reduced infiltration implies that lesser water will be available for moisture re-distribution and diffuse recharge that occur long after the cessation of rainfall event.

**Impacts of Increasing Temperature – Long-Term Evapotranspiration Effects**

While long-term shifts in temperature may not have significant impacts on event-scale water balance, they are more likely to influence long-term hydrologic phenomenon that occur during the dry times. In particular, the impacts are likely to be more pronounced on long-term evapotranspiration as well as diffuse recharge to groundwater. The monthly water balance model used in this study uses the Thornthwaite correlation to estimate potential evapotranspiration and is driven by mean monthly temperature and average length of the day as forcings. This potential evapotranspiration is then employed to estimate actual evapotranspiration using a linear function described by Bras and Cordova (1982) and Rodriguez-Iturbe et al. (1999). The baseline (1987 to 2002) average potential and actual monthly evapotranspiration and the predicted change when the temperature in each month is raised by 4°C (7.2°F) is presented in Figure 13.

Several observations can be made from Figure 13. The potential evapotranspiration is likely to increase significantly by at least 0.1 ft/month (0.03 m/month) to over 0.175 ft/month (0.53 m/month) during summer months. However, the differences in actual evapotranspiration are not as dramatic and are about 0.05 ft/month (0.015 m/month). This small change still translates to roughly 265,000 ac-ft/yr of excess water that is lost via evapotranspiration. As a comparison, the projected water demand for the city of San Antonio for the year 2010, not 2100, is close to 230,000 ac-ft/yr and in year 2050 it is close to 360,000 ac-ft/yr (TWDB 2007).
Evapotranspiration in the watershed is primarily due to vegetation and during periods of stresses, plants do exhibit the ability to conserve water by closing their stomata through which water is lost to the atmosphere (Rodriguez-Iturbe et al. 1999). Increased periods of dryness as predicted by GCM will cause more frequent periods of stresses on vegetation and may possibly diminish the ability of some plants to quick changes (fatigue situations). Some plants may be better adaptors to these changes in stress patterns and may survive and compete better than others for available moisture. Therefore, climate changes can alter the vegetation makeup of the watershed, which in turn will affect the amount of evapotranspiration. The present analysis does not include these climate-biotic interaction possibilities, and it assumes that the vegetative makeup of the watershed is not altered significantly due to climatic and urbanization influences.

**Impacts of Increasing Temperature – Long-Term Soil Moisture Effects**

The impact of increasing temperature on soil moisture is schematically depicted in Figure 14. As can be seen, the average soil moisture in the watershed will decrease with increasing temperatures assumed to prevail in 2100. However, the changes in the soil moisture are not as significant in the later winter and spring months, i.e., the early part of the year. However, decreasing trends will start during the summer months and continue through fall and early winter months. The soil moisture will decrease by about 5% to 20% on average and, based on the simulated values, it does not appear like there will be significant critical deficits that could cause wilting of plants and other deleterious effects. However, the model results represent only a broad-brush assessment. Wilting and other soil moisture-driven stress on ecology could take place locally within the watershed. However, the decreases noted could hamper dryland farming in the watershed and increase the need for irrigation.
Figure 14. Average monthly recharge for the baseline and year 2100 conditions

Figure 15. The impact of increasing temperature on soil moisture
Impacts of Increasing Temperature – Long-Term Recharge Effects

The recharge in the monthly water balance model was computed using the Darcy-Buckhingham equation (Stephens 1995). The constitutive capillary-pressure-saturation relationships were based on the Campbell model (Clapp and Hornberger 1982). The average monthly recharge for the baseline and year 2100 conditions are presented in Figure 15 where it can be seen that the increase in temperature can have a major impact on estimated recharge. The simulation results indicate that recharge could be decreased roughly by an order-of-magnitude especially during the summer months. Groundwater resources are going to be a major source of freshwater for Texas in years to come and some plans are underway to develop groundwater in the vicinity of the watershed to meet regional demands in the near future. Urbanization of the South Texas region and this watershed in particular will also reduce recharge to the aquifer. Groundwater resources are generally considered more reliable than surface water sources in that they are not as affected by droughts and other similar vagaries of nature (Tsur 1990). However, the results obtained here indicate that this reliability could be diminished due to potential climate change effects.

Summary and Conclusions

The primary goal of this study was to develop preliminary insights aimed at addressing the pressing question about the state of water resources in South Texas based on the predicted climate in 2100. Forecasts from an ensemble of global atmosphere ocean climate change models appear to indicate that the region will be warmer by about 4.0ºC (7.2ºF) in 2100. Also, the average precipitation is not likely to vary significantly but rainstorms may be of higher intensity and shorter duration. These changes can cause alterations to both short-term (runoff) and long-term (evapotranspiration and recharge) hydrologic phenomena. The impacts of climate changes on these hydrologic processes were evaluated at the Mission River watershed in South Central Texas using a semi-distributed event-based model and a lumped monthly water balance model. These models were first calibrated for current conditions using available historical data collected both in-situ and via remote-sensing. Having obtained satisfactory calibrations, the models were then run in a forecast mode to simulate synthetic storm events and temperature conditions representative of the potential climate in the year 2100.

The results from the event-based model indicate that, for the rainfall event studied and the climate change conditions assumed, plausible increases in temperature are unlikely to cause significant changes in hydrologic variables. However, runoff generated within the watershed will increase when the same amount of rain will fall in a shorter time-period. Model results indicate that the peak flow could increase by about 500 cfs, and this increase could cause the water levels in the river to rise by about one to two feet, thereby increasing flooding and inundation possibilities in the low-lying areas of the watershed.

The results from the monthly water balance model indicate that the projected temperature changes will cause significant increase in evapotranspiration and decreases in soil moisture content and recharge. The amount of water lost via evapotranspiration is slightly higher than the current water demands of the city of San Antonio. Reductions in soil moisture will likely require a potential conversion from dryland farming to irrigation. The reductions in recharge are significant especially during the summer months when the groundwater withdrawals are likely to be the highest. These reductions in recharge will diminish the reliability of groundwater resources to supply water for various anthropogenic needs.

The total changes in the water resources within a watershed are a function of both long-term climate change and short-term urbanization. In many cases, the long-term climate change will exacerbate the deleterious urbanization impacts that take place in the short term. For example, paving of bare soils due to urbanization will increase the amount of runoff and flooding in the same way as the intensification of storms due to climate change. Similarly, increased urbanization could result in greater groundwater withdrawals and will exacerbate the effects brought forth by climate change shifts that lead to increased evapotranspiration, decreased soil moisture storage and recharge. It is important to remember that while urbanization and climate change occur concurrently, the present exercise did not model the effects of urbanization and focused on climate change alone. Uncertainties in model predictions arise due a variety of factors including limited data availability; incomplete understanding of hydrologic processes; theoretical gaps and controversies; and also due to the need to estimate certain inputs via calibration which is inherently a non-unique process. All the uncertainties in the global climate change models get imported into the water budget models, which are uncertain by themselves. Also, any insights generated from these combined
models will be affected by the uncertainties in both the climate change and water budget models. Therefore, every effort was made to obtain reasonable and reliable calibrations and site-specific inputs. A comprehensive uncertainty analysis could however not be carried out with the current scope but it is planned for the future. These limitations notwithstanding, the results provide a first glimpse of how various hydrologic processes affecting water resources in the watershed behave under a future climate scenario.

**Acknowledgments**

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Literature Cited


## APPENDIX 1

### Table 2. HEC-HM Model Parameters

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</tr>
<tr>
<td>Groundwater 1 Coefficient (hr)</td>
<td>918</td>
<td>918</td>
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<tr>
<td>Groundwater 2 Storage (in)</td>
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<td>0</td>
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<tr>
<td>Groundwater 2 Percolation (in/hr)</td>
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<tr>
<td>Groundwater 2 Coefficient (hr)</td>
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<tr>
<td>SCS Lag Time (mins)</td>
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<td>2825</td>
<td>318</td>
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