CLIMATE CHANGE AND WATER AVAILABILITY MODELS

Applying Climate Change Predictions

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Abstract:

The impacts of climate change on various Earth systems are of concern to many scientists. The official water availability model of Texas, the Water Rights Analysis Package (WRAP), simulates water availability for assigning new water rights as well as making adjustments to existing water rights. As part of its simulation process, WRAP is able to predict and manage the state-wide water availability. Because climate change is closely related to hydrological processes, being able to predict or model the results of climate change on the state's water supply systems is important. This paper analyzes how climate change predictions can be incorporated into WRAP to model possible future results of climate change.

TABLE OF CONTENTS

Introduction

Freshwater has always been valuable. This is due to humans' dependence on water for cleanliness, recreation, lifestyle, and especially life itself. However, the value of clean freshwater appears to be increasing due to many factors related to water availability. These include:

- **Increases in population –** With global population now greater than six billion, and continuing to grow, needs for ever-more freshwater are likewise growing.
- **Urbanization –** Along with increased population is the rapid urbanization of communities and ways of life. As more and more people live in closer proximity to each other, needs for sanitation—provided by freshwater—will continue to increase.
- **Increasing wealth –** As resources are better handled and technological advancements are applied to ways of life, the possibility and realization of wealth is increasing in many places worldwide. With increased wealth comes increased demand for clean water. This clean water is used to supplement a more wealthy way of life, as indicated by what many consider basic needs—clean water, high standards of sanitation—as well as what may be classified as frivolity—swimming pools and other water recreation, car washing, etc.
- **Aquifer Depletion –** Increases in population in arid areas correlates to overuse of surface water, necessitating, in many cases, turning to groundwater for needs. When groundwater withdrawal exceeds recharge, depletion results.
- **Pollution –** Water pollution in underdeveloped countries seems to be the norm. While development of countries and areas continues, the pollution of the past, in many cases, remains and has to be dealt with. Furthermore, when neighboring countries have differing standards on pollution without common consensus, pollution problems seem to be greater than in other areas (e.g. consider possible pollution differences between two situations: where many countries share borders to a water body, and where a water body lies within a single government entity. History shows that pollution in the shared body will be greater than in the autonomous.).[1]
- **Climate Change –** The climate has a close relationship to the water cycle. As climate change occurs, there will be corresponding changes to the hydrologic cycle—for better or worse. Typical discussions on climate change focus on changes in temperature and abundance of greenhouse gases. Both of these factors will affect water quality and quantity in ways that are currently being explored and discussed.

With the many variables which influence water—including water quality, water quantity, and water availability—comes significant uncertainty of what the future will hold. With such a high reliance on clean water, it is imperative to have an understanding of, and a feel for water availability in the future—both immediate and long-term. This paper explores current and future water availability, particularly regarding climate change predictions and their impact on water availability modeling and the associated hydrological information used in such modeling.

Water Availability in Texas

Recent history in the state of Texas has shown, in a very real way, an interesting shift in water availability understanding.

Texas suffered a particularly hard year of drought in 1996. This drought was widespread and affected many Texans in major ways. In the midst of this drought, government decision-makers realized that the tools necessary to make decisions were not at their disposal. As is typical with droughts, the cause, duration, and frequency (possibility of recurrence) were unknown. Closely related to this was the concept of water availability. By definition, droughts are closely related to water availability—especially the lack thereof. Feeling a responsibility for the citizens of Texas, the incumbent governor was concerned that the state officials had no way of knowing how much water was available; nor did they have any predictions of when water would be available. This drought was associated with both a lack of water and a lack of understanding of water availability.

The year following this awakening drought, the Texas legislature passed Senate Bill 1, or the "Water Bill." This bill changed the way that many aspects of water planning were performed. These changes were facilitated by the implementation of new technological advancements, including use of geographical information systems (GIS). A significant area of change was in the digital monitoring and record keeping of water rights as part of the implementation of a state-wide water availability model. Water right data and historical flow and evaporation data for the states waters are used in this model to determine reliabilities of water resources as a prediction of water availability. As a result of the Water Bill, the Water Rights Analysis Package (WRAP) became the state's official water availability model.[2]

Armed with a water availability model, the environmental agency for the State of Texas, the Texas Commission on Environmental Quality (TCEQ), uses historical flows and water right scenarios to manage not only new water right applications, but overall water availability for the state of Texas. Thus, the state decision- makers can feel much more comfortable knowing that water availability for the state is being monitored and modeled. However, typical use of WRAP water availability modeled results are based solely on past and current conditions with no consideration of future climate change effects. With such an importance having been placed on water availability knowledge, it seems reasonable to consider the effects of a changing climate as this may affect water availability in a major way.

Water Rights Analysis Package

In order to address climate change effects on water availability models, it is necessary to first establish an understanding of their processes. This section uses the Water Rights Analysis Package to establish a knowledge base for water availability models. Upon this foundation, a discussion is added on how WRAP or other water availability models can be used with climate change modeling results to prepare for possible future scenarios.

Dr. Ralph Wurbs of the Texas Water Resources Institute (at Texas A&M University) developed the suite of modeling programs called the Water Rights Analysis Package. WRAP is a computer program that digitally manages water rights. This replaces the older method of tracing lines on maps to determine various relationships and properties of water rights.[3] WRAP is a public domain software package with input data available from TCEQ for all twenty-three river and coastal basins in Texas which simulates surface water withdrawals at about 10,000 issued water permit locations in Texas using monthly time steps and an approximately fifty year planning period (1940 – late 1990s).[4]

As discussed previously, WRAP is also able to take historical data to predict reliabilities of water and water rights. These reliabilities can be used in water availability analyses to give an indication of how much water is or will be available under various conditions. Thus, TCEQ is better able to approve of additions or changes to the existing water rights in Texas, after completing a modeled scenario which indicates the impacts on existing water rights and the overall water availability of the state. Of the many components of the WRAP model, the two most applicable to climate change analyses are naturalized flows and reservoir evaporation.[5]

Naturalized Flows and Reservoir Evaporation

WRAP uses historical flow data as part of its input. This flow data comes from locations that have a flow measuring device, a gage, that records flow measurements. One of WRAP’s purposes is to model various scenarios of differing uses or demands on Texas’ waters. Historical flow data inherently has within it the effects of the water users at the time of the flow measurement(s). Using this data as-is will, thus, not be sufficient in future analyses because the flow knowledge base is tainted, if you will, by past use. Therefore, it is necessary to obtain a prediction, through calculations, of the naturalized flows, or rather, the flows that would have existed without human intervention or use. In other words, naturalized flows are measured flows that have been adjusted to remove anthropogenic effects of both management and use (e.g. reservoirs, diversions). These can both be calculated and applied to locations with gages as well as those locations without measurement devices. This is accomplished through the use of algorithms.

Algorithms

The following equation gives an introduction to the algorithm process that is at the base of WRAP's naturalized flows.[6] This equation is shown in color to better distinguish the various components and relate them to the depiction of a flow scenario, as shown in Figure 1.

$$NF = GF + \sum D_i - \sum RF_i + \sum EP_i + \sum \Delta S_i$$

Where:

NF naturalized flow
GF gaged flow
D water supply diversions upstream
RF return flow upstream
EP reservoir evaporation minus precipitation
DS change in storage in upstream reservoirs

This method goes hand in hand with the definition of naturalized flows given earlier: naturalized flows are measured flows that have been adjusted to remove anthropogenic effects of both management and use (e.g. reservoirs, diversions). The terms of the naturalized flow equation are shown graphically in Figure 1 as a typical water resources schematic (with the solid circle being the gaged flow location and the triangle being a reservoir), where the colored terms of the equation coincide with the objects in the figure.

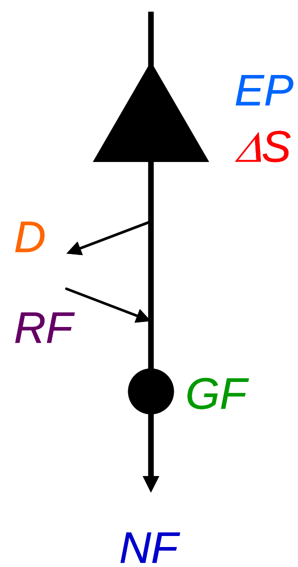

Figure 1. Schematic for Naturalized Flows

Listed as one parameter in the naturalized flow equation, reservoir evaporation can be a major anthropogenic influence. Often overlooked, reservoir evaporation remains a major "user" of water in that a deceptively large amount of water escapes reservoirs through evaporation. While evaporation rates from water surfaces vary depending on such things as temperature, incoming energy (typically solar), humidity, etc. it is not difficult to imagine a reservoir which loses as much water to evaporation in the summer as it does to the water it releases. This simple example serves to illustrate that evaporation can be a major factor to be accounted for.

The GF term, gaged flow, in the naturalized flow equation is somewhat limiting for use in WRAP. WRAP simulation results are for many geographic points which are not necessarily gaged flow points. Naturalized flows, calculated from gaged locations, can be distributed to ungaged locations using the Drainage Area Ratio (DAR) method.[6] The DAR is a method where ungaged flow is distributed according to drainage area proportionality, as follows:

$$Q_{ungaged} = R_{DA} Q_{gaged}, \quad R_{DA} = \frac{DA_{ungaged}}{DA_{gaged}}$$

Where:

- Q_i naturalized flow at either gaged or ungaged site
- R_{DA} drainage area ratio
- DA_i drainage area

The DAR equation uses the naturalized flow, as calculated using the naturalized flow equation (or some other method), and the respective drainage areas to obtain an approximation for the naturalized flow at an ungaged location.

In addition to the DAR method, WRAP has an option, internal to the program, for distributing flows using the related but more generic equations:

$$Q_{ungaged} = a\left(Q_{gaged}\right)^b + c, \quad a = \left(\frac{DA_{ungaged}}{DA_{gaged}}\right)^{N_1}\left(\frac{MP_{ungaged}}{MP_{gaged}}\right)^{N_2}\left(\frac{CN_{ungaged}}{CN_{gaged}}\right)^{N_3}\left(\frac{Other_{ungaged}}{Other_{gaged}}\right)^{N_4}$$

Where:

- Q_i naturalized flow at either gaged or ungaged site
- DA_i drainage area
- MP_i mean precipitation
- CN_i curve number
- $Other_i$ some other parameter
- b, c coefficient provided by user (default are 1 and 0, respectively)
- N_i coefficient provided by user (default is 1)

Clever manipulation of these equations provides the ability to fit the data that is available. For example, the *N* coefficient could be set to zero in a case where certain parameter(s) were not available. It is plain to see that the DAR equation is a version of this more generic equation with coefficients chosen wisely.

The coefficients provided in the more generic equation provide significant freedom in calibrating the model against measured flow, say, for further regional use. This would require computations outside of WRAP, but such may prove useful in specific studies.

Incorporating naturalized flows and reservoir evaporation, successfully in the WRAP model, results in a base hydrological system without anthropogenic effects. This is a data starting point where different use scenarios can be modeled on top of the naturalized flows, resulting in uniformly applicable results. In addition, the use of calculated naturalized flows allows for comparisons of areas that are significantly built up (meaning have many human effects) with analyses in natural, untouched areas.

Modeling Climate Change

Climate change and global warming impacts and sources are currently a hot topic for discussion and debate. Regardless of the camp prescribed to, the common consensus seems to be that climate change is occurring and has continued to occur throughout natural history, whether resulting from natural cycles, anthropogenic effects, or any combination of the possibilities. Due to the high likelihood that climate changes will affect water resources and water availability in the near future (within fifty years), it is necessary to discover ways of either adjusting current water availability models or creating new models. To stay within the scope of this paper, discussion will remain centered on the Water Rights Analysis Package, Texas' official water availability model, and its abilities to implement climate change predictions.

Currently, no changes have been made to WRAP or the water availability modeling process used by TCEQ to incorporate or reflect climate change. Despite the present static state of the models, climate change predictions can be applied to the input data previously discussed, namely, naturalized flows. Thus, after naturalized flows have been calculated, which are a main input to the model, they can be adjusted to mirror expected flows under the climate change regime. This is a technical way of taking the historical flow data, converting it naturalized flows, and then virtually applying climate change effects to the historical data to then predict reliabilities and availabilities for expected future climate changed conditions. Because WRAP has no interface for inputting climate change parameters or even changing the naturalized flows uniformly within the modeling program, such must occur outside of WRAP. Furthermore, additional models must be used to obtain climate change predictions.

The discussion on manipulating naturalized flow data will be placed aside for now as climate change models are discussed.

Climate Change Models

> Essentially, all models are wrong, but some are useful.
>
> *George Box, industrial statistician*

The Intergovernmental Panel on Climate Change (IPCC) is a scientific body commissioned to explore the results and risks of climate change from an anthropogenic point of view. While the IPCC does not perform nor monitor climate change research or data, it does gather peer-reviewed research and data from the scientific community at large and presents its findings in a unified and generally respected format.[7] In fact, the IPCC was awarded the Nobel Peace Prize in 2007, shared equally with Al Gore, "for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change."[8]

In their Climate Change 2007 document, the IPCC reported findings on climate change which included statements of low likelihood of climate change being the result of only natural (nonanthropogenic) causes, of global temperatures rising between 1.1 and 6.4 °C in the next century, of sea levels rising between 18 to 59 cm, and that an increase in heat waves with heavy rainfalls as well as increases in droughts and cyclones.[9] These are the combined results of many models. Due to space and time limitations, this paper will examine few models with the understanding that the results of other models can be applied in similar fashion as the results of the models discussed, from a WRAP point of view.

In a paper discussing the incorporation of climate change in WRAP, Dr. Ralph Wurbs, creator of WRAP, presents research findings of using climate change predictions in WRAP. Specifically, the paper outlines the use of two tools: the Soil and Water Assessment Tool (SWAT), and the Canadian Centre for Climate Modelling and Analysis Global Circulation Model (CCCma GCM). These two models were used by Wurbs for climate change analyses in WRAP; they are briefly explored here, yet it is mentioned that output from many global circulation models could be used.

Soil and Water Assessment Tool

In a thorough analysis of the Soil and Water Assessment Tool[10], Gassman outlines functions of SWAT as well as discussing its strengths and weaknesses.[11] In its essence, SWAT is a watershed modeling tool which is used by professional, educational, and governmental organizations. This model is useful in predicting the effects that land management practices have on water, sediment, and agricultural uses in ungaged hydrological systems. This is done through modeling inputs, including weather, hydrology, soil temperature, soil properties, plant growth, nutrient presence, use of pesticides, presence of bacteria and pathogens, and land management. Examples of such data include daily precipitation, maximum and minimum temperature, solar radiation, specific humidity, wind speed, and evapotranspiration. In addition, case specific input data can include orographic precipitation and snowmelt, including lifting condensation level analyses, climate change effects on standard inputs, and forecasted weather patterns.

The analyses of SWAT are applied to parts of watersheds, called hydrologic response units, which are classified by homogeneous soil characteristics, land use, and management style. These analyses can include climate change impact studies which are modeled within SWAT through properly accounting for changes in climatic inputs (due to climate change), and accounting for the effects of increasing atmospheric carbon dioxide concentrations (including effects on temperature, precipitation, and plant development and transpiration).

Canadian Centre for Climate Modelling and Analysis GCM

The Canadian Centre for Climate Modelling and Analysis (CCCma) is a division of Canada's meteorological service's Climate Research Branch. The CCCma performs research in atmospheric and climate change modeling, among other things. Flato et al. described that the global circulation model (GCM) of the CCCma is a coupled atmosphere-ocean dynamics model.[12] This combination of models—atmospheric and oceanic—created a basis for performing climate simulations of the past and present, and also projects the future climate. Such an advanced model has many handles or controls (input or modeled parameters). These include: specific humidity, precipitation, soil moisture, cloud scheme (cloud cover), moist convection, radiative heating, global mean surface temperature, carbon dioxide concentration, sea level pressure, ocean circulation, sea ice, snow, and seasonally frozen soil moisture, and more.

The CCCma GCM is an enormously complex model. This is not a toy model that resides on a personal computer and allows for user input and perfunctory manipulation of data. Rather, this GCM requires many supercomputers working together for multiple months to create the 100 years of projected data. Despite the time and effort required, this model's data is available for download from the official CCCma website.[13] Once obtained, the output data can be used for detailed analyses or for use in other models or modeled results. In this way, the sharing of knowledge, or model output, may benefit others in their analyses.

Other Models

Many of the main body of climate or global circulation models can be listed. However, as more and more attention is placed on climate change—rightly so—and its impact and influence on future conditions, including water availability, it is expected that more and more models will surface. The complexity of the existing and future models will vary widely. These will range from the simple energy balance models to the very complex coupled global circulation models. Despite the differences in complexity, and even in input parameters, useful models will rise above the modeling world clamor and prove useful for many interested scientists, thus fitting into George Box's "useful" model classification. When this occurs, the output of these models may be used to perform meaningful analyses that may shape the way that decision-makers make decisions, or the way that policies are set and enforced. At the end of the day, data is data and what is done with it is what matters.

Climate Change and WRAP

Many useful climate models exist. The output of these can be used to balance or adjust the input of other models that do not have explicit climate change modeling capabilities. WRAP is one such model. With an understanding having been established of WRAP's processes, as well as a brief introduction to two models, SWAT and CCCma GCM, attention is turned to the implementation of output data from these in WRAP for climate change water availability analyses. The results will show how Texas' water availability modeling system can be used in conjunction with climate change.

As discussed, WRAP analyses are based, in part, upon historical flow data which is converted, where necessary, to naturalized flows at gaged and ungaged sites. Data tables of monthly naturalized flows for approximately fifty years are used in WRAP to obtain the water availability modeled results. While it is true that WRAP has no internal means of reflecting climate change—there is no way to set climate change parameters within WRAP and have the modeled results encapsulate climate change—the results of the Canadian climate model, CCCma GCM, can be used in conjunction with SWAT to obtain values that can be further manipulated and used in WRAP. While this is a multi-step process, the results are useful in arriving at a water availability climate change modeled scenario. The elementary steps of this process, employed by Wurbs (2005) for his water availability and climate change work, follow:

1. Precipitation and temperature modeled results for 2040-2060 are retrieved from the CCCma GCM results: one set reflecting climate change, one without climate change.
2. The GCM modeled data is used to alter SWAT input which is used as a representation of 2050 climate.
3. SWAT is invoked with this data as well as historical data to produce sets of daily streamflow values. These values are used to adjust WRAP inputs of monthly naturalized flows. Furthermore, SWAT output is used in the adjusting of WRAP reservoir evaporation rate values.
4. The WRAP model is run with the historical and climate changed data, and results are used to assess possible future water availability.

It is through the above process that the results from many models are combined in a harmony of simulation to produce results that have meaning for the future water availability of Texas. Conducting these steps provides useful information to decision-makers as the future is prepared for. Please note, though, that while these steps reflect the research Wurbs (2005) performed in his analysis for incorporating climate change in WRAP for Texas' water availability model, other models can likewise be used if sufficient input/output parameter harmonies exist.

Conclusion

The SWAT and CCCma GCM models were used with WRAP to carry out a climate change analysis for Texas' water availability modeling system. Nevertheless, any combination of trusted models can be used in similar fashion. Thus, the symphony that is water availability modeling may be made more full and meaningful through the incorporation of different modeling systems. This paper has discussed how two models can be used in concert with WRAP for climate change, yet any other scenario or situation could likewise be modeled and applied for Texas' water availability analyses, given the proper models and input are available.

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