USE OF STELLA SOFTWARE FOR THE MODELLING OF CLIMATE CHANGE IMPACTS ON WATER BALANCE FOR THE RIO YAQUI BASIN, SONORA, MEXICO

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Abstract

Climate change in Northwest Mexico and its hydrological impact, including on water balance, water scarcity and flooding events, is a matter of great concern for the region due to its semiarid conditions. Changes in temperature, precipitation, and sea level would affect agriculture, farming, and aquaculture. The quality of water storages for human consumption may also be adversely affected.

We evaluated possible changes in precipitation and temperature for the Rio Yaqui Basin in Sonora, Mexico and assessed the impact of those changes on water runoff, evapotranspiration and aquifer recharge for the years 2010 to 2099. For this purpose, we analyzed the results of a bias-corrected and downscaled climate projection from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 3 (WCRP-CMIP3) multi-model dataset: UKMO-HadCM3 from the Hadley Centre for Climate Prediction.

The System Thinking Software STELLA 9.0.2 was used to dynamically visualize the effects of climate change on the Rio Yaqui Basin. In this software, the main components of water balance are simulated over the designated period of time with tools that include stocks and flow diagrams, causal loops, model equations and built-in functions.

Climate change projections for the Rio Yaqui Basin showed highly variable runoff behaviors, indicating the possibility of frequent droughts, alternating with years of substantial runoff.

Keywords: STELLA, modeling, climate change, hydrology

Introduction

The Intergovernmental Panel on Climate Change (IPCC) declared in 2007 that climate change would gradually modify the Earth's mean climatological conditions, and that it would cause more frequent extreme local climate events, e.g. floods and droughts. As established by Allen (2004), changes in precipitation and temperature determine the amount of water that reaches the surface, evaporates, transpires back to the atmosphere, infiltrates, runs off the land surface, and finally becomes base flow to streams. The relation between climate change and the potential for extreme runoff and flooding represents an issue of great urgency today.

According to the Fourth Assessment Report of the IPCC, global circulation models can provide reliable estimates of future climate conditions as well as the atmospheric processes that cause them, which are based on inputs such as higher emission of greenhouse gases (A2) and lower emission of greenhouse gases (B1). However, climate change conditions provided by these global circulation models have too coarse a resolution for use at regional levels or below. For this reason, downscaling processes have been developed to help improve resolution, based on dynamic statistical and empirical methodologies (Wood et al. 2002, Wood et al. 2004, and Maurer et al. 2007).

The Rio Yaqui Basin is one of the most important river basins in Sonora. Located in northwest Mexico, it covers an approximate area of 74,054 km^2, providing water for one of the most important agricultural zones in the state and the country.

Simulations generated through the System Thinking Software, STELLA, provide an adequate basis for establishing policies for the optimization of water storage during substantial runoff periods, which can then serve as water supplies during drought periods. Due to the lack of forcing data for northwest Mexico we propose the use of an empirical method.

Methodology

The archive of bias-corrected and downscaled WCRP-CMIP3 climate projections is supported by the Lawrence Livermore National Laboratory; US Bureau of Reclamation, Santa Clara University; and the US Geological Survey. This archive includes 112 downscaled projections of monthly temperature and precipitation, at 1/8 degrees resolution, and associated hydrologic conditions. Three different emission scenarios (SRES scenarios) are available for downloading: (i) A2 for technological changes and higher population growth (higher emissions path); (ii) B1 for a clean and sustainable world (lower emission path); and (iii) A1b for an equilibrated world with a balance between use of fossil and non-fossil energy (middle emission path).

For our research, we selected for use the downscaled projection of the B1 and A2 emissions scenarios from the Hadley Centre for Climate Prediction in the United Kingdom (http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/). The HadCM3 climate model is known for being one of the best in reproducing the observed climate in northwest Mexico (Arriaga, 2008).

The downscaling process consists of transforming coarse resolution climate information, or global circulation model (2°), into a finer scale (1/8° resolution) that allows definition of local impacts on the environment. There are many statistical methods available for downscaling processes but we chose the bias correction and spatial downscaling method of Wood et al. (2004) which is excellent for producing hydrologically plausible results for future climate scenarios.

For each scenario from 2000 to 2099, we determined projected precipitation and temperature. The evapotranspiration in the zone was calculated by using the Turc expression and the projected runoff and storage were based on historical rates obtained from internal reports of CONAGUA (Comision Nacional del Agua, 2004).

Finally, we present the climate change simulation in STELLA 9.0.2, with individual scripts for each subbasin in the study area: Angostura, Oviachic, and Novillo (Fig. 1).

Figure 1. The Rio Yaqui Basin

C CHANGE PROJECTIONS FOR THE RIO YAQUI BASIN

Figure 2 shows the climate change projections obtained from the CMIP3 dataset. The retrieved projection format was netCDF. It was primary analyzed in Matlab R2009a and later imported to ArcGis 9.3 software for the zonal statistical calculations.

As evident from Figure 2, there is a notable increase in temperature conditions, even for the most optimistic scenario (SRES-B1), with the exception of the Angostura River Basin. The case for increases in precipitation is not as clear as for temperature. However, the possibility of experiencing frequent periods of droughts, alternating with years of substantial runoff, is present in the Rio Yaqui Basin.

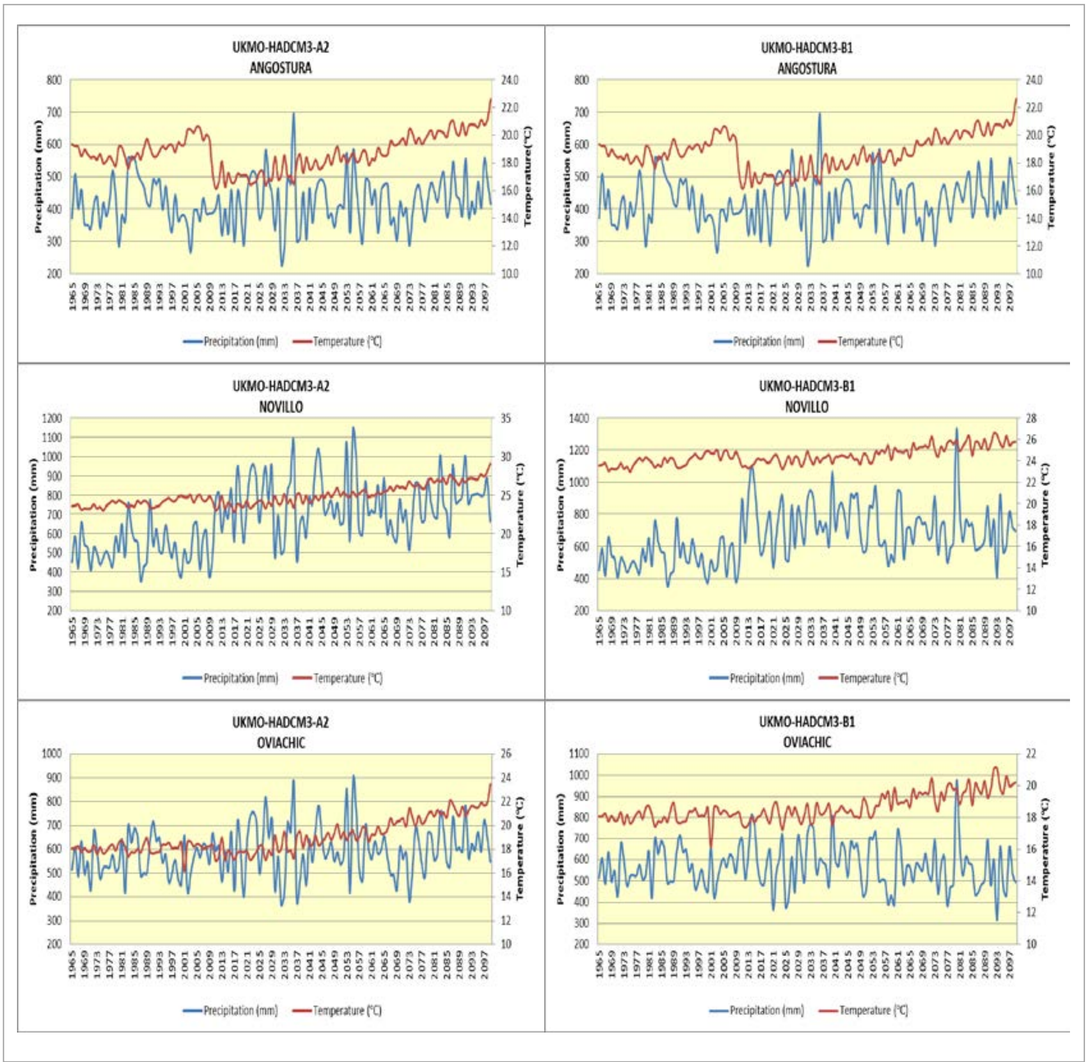

Figure 2. UKMO-HadCM3 SRES A2 and B1 for the Rio Yaqui Basin

IMPACT OF CLIMATE CHANGE IN THE RIO YAQUI BASIN

The impact of climate change on the Rio Yaqui Basin was determined using empirical methods and the software STELLA 9.0.2. The following model (Figure 3) represents the visual interface of the program and was developed using the following premises:

a) UKMO-HadCM3-A2 was used in the simulation as it represents the worst case scenario for the Rio Yaqui Basin.

b) The simulation uses historical information from 1965 to 2010, and projected information for 2011 to 2099.

c) The runoff coefficients for Angostura, Novillo and Oviachic, were obtained by correlating the historical information from water storage and precipitation in the study area (CONAGUA 1965-2010), resulting in 0.08, 0.1 and 0.03 for each sub-basin.

d) Evapotranspiration for the study area was determined by using the Turc expresion:

$$ETR = \frac{P}{\sqrt{0.9 + \left(\frac{P}{L}\right)^2}}$$

Where:
ETR=Annual evapotranspiration (mm)
L= 300 + 25T + 0.05T3
T=Temperature
P= Annual average precipitation (mm)
T= Annual average temperature (°C)

e) Given the lack of objective criteria and the difficulty of projecting water politics for the study area, the simulation uses the historical average for water transfers between dams for every year that was observed and for projections.

f) The storage in the Oviachic dam and future behavior of the system was modeled using the climate change projections for the Rio Yaqui Basin.

g) The annual outflow corresponds to the historical average of deductions from the area: Evaporation in dams and streams (529.5 hm^3), and requirements for domestic and agricultural uses (467 and 1910 hm^3 respectively).

h) Evaporation and infiltration are also considered as outflows and together account for 549 hm^3.

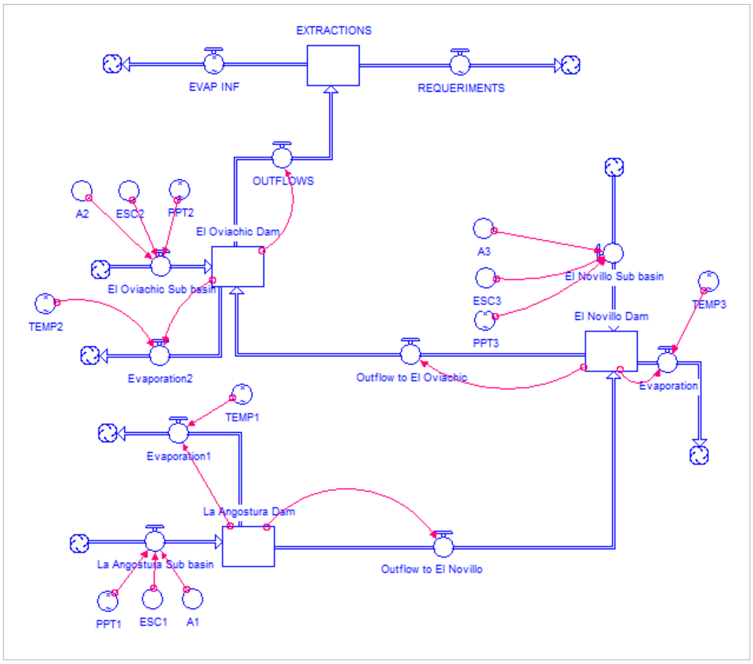

Figure 3. Climate change simulation in STELLA 9.0.2

Results

In this study, we were able to determine runoff scenarios for the Rio Yaqui Basin based on different climate change projections. The results for the calculation of runoff and water storage in the Rio Yaqui Basin are shown in Figures 4 and 5.

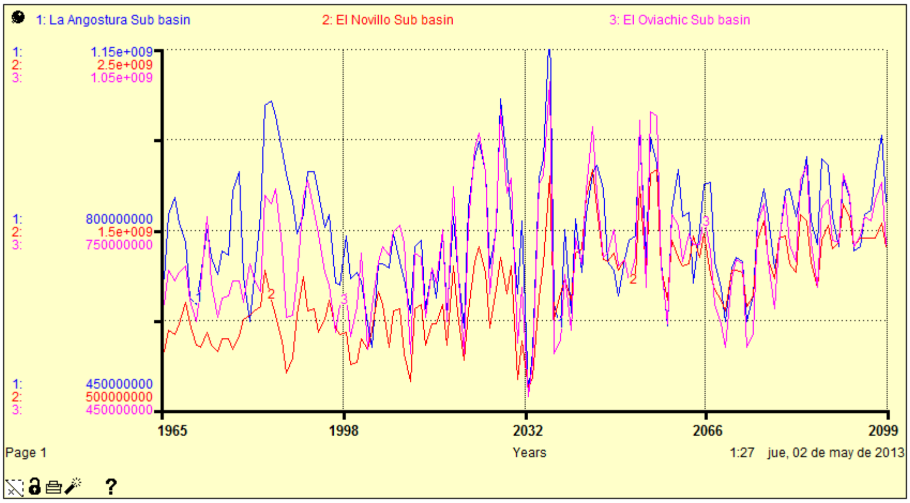

Figure 4. Projected Runoff for the Rio Yaqui Sub-basins (millions of cubic meters hm^3)

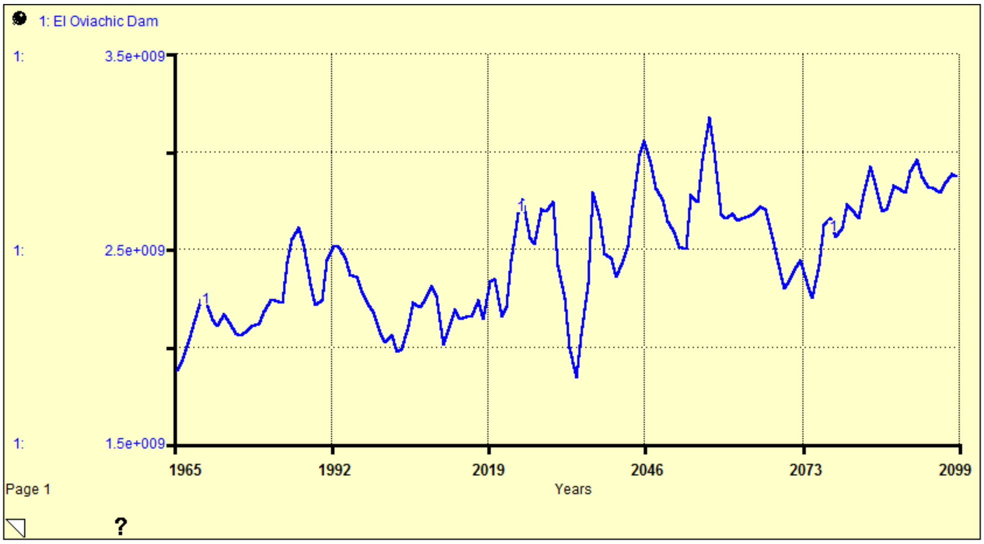

Figure 5. Water storage for the Oviachic Dam (millions of cubic meters hm^3)

Figure 4 shows the runoff resulting from the SRES A2 scenario, and although there are high water flows in some years, the periods of water scarcity are also severe.

The storage projections show a positive trend but also some annual variations (Figure 5). The historical scarcity periods of 1989, 1990, 2000, 2001, 2002 and 2003 were due to there being less rain, but also resulted from bad water management. With this simulation, potential storage deficiencies for 2034, 2070 and 2074 were identified. However, even though the water levels are projected to decrease, there will be enough water to cover the requirements of the nearby towns, provided its use is managed well. In contrast, in 2057 there is a storage projection value of 3,177 Hm^3, which is close to the maximum level that can be supported by the Oviachic Dam (3,226.7 Hm^3).

Discussion

Using the STELLA system thinking software and climate change scenarios, we developed a simple simulation for water storage for one of the biggest and most productive basins in Mexico.

According to Mendoza and y Puche (2007), the analysis and evaluation of future scenarios, even though they are uncertain, will allow early detection and the possibility of adaptation and mitigation.

Although severe, the case of water supply forecasts for the Rio Yaqui Basin is one of the least problematic for the state of Sonora. The neighboring watershed, the Sonora River Basin, has had problems with water since 1980 and future climate scenarios for the basin do not show a favorable projection. There is a government project in Sonora that aims to transport water from the Rio Yaqui Basin to the Sonora River Basin due to high water demands in the latter. Based on our study, we recommend a cautious approach to this project for the Rio Yaqui Basin as it could compromise water availability for both basins: the Yaqui and Sonora River Basins.

Recommendations for Research

We recommend modeling for every vulnerable basin. If a range of emission scenarios, climate models and runs are used in future research, results can be compared and preparation commenced for the worst case scenario.

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