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Enhancing the Link between Surface and Groundwater Models for Climate Change Assessment of Water Supply and Demand in Northwest Mexico

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Abstract: The integrated use of surface and groundwater models is critical for analyzing water resources sustainability. We have applied surface and groundwater models to the Sonora River basin (SRB) in Northwest Mexico within the context of participatory modeling with stakeholders to explore alternative futures under climate change impacts. The models are used to assess the hydrologic consequences of temperature and precipitation scenarios generated through the dynamical downscaling using the Weather Research and Forecast (WRF) model for historical, near-future and far-future study periods. WRF is used to downscale two global circulation models (GCMs), HadCM3 and MPI-ECHAM5. Improved representation of surface-groundwater interactions is achieved through a calibration exercise with respect to two stream gauging stations using an automated parameter optimization algorithm. Results from the surface water model depend on the GCM, with the HadCM3 producing higher precipitation and streamflows, but comparable evapotranspiration in the future climate change scenarios as compared to the historical simulations. The MPI-ECHAM5 produces much higher rainfall and streamflows during the historical period than the HadCM3, but followed by decreases in rainfall and streamflow in the future periods. The results show that the upland recharge and channel transmission losses, and correspondingly, groundwater storages are quite sensitive to the climate change scenarios. In general, groundwater storage decreases for the historical period and increases for the far future period for the HadCM3 simulations, with the reverse occurring for the MPI-ECHAM5 simulations.

Keywords: hydrologic modeling; climate change, groundwater, surface water, Northwest Mexico.

1 INTRODUCTION

In this study, issues of water supply and demand are addressed through the use of modelling tools and long-term data sets in the SRB in Northwest Mexico with the goal of providing regional stakeholders a means to understand the full range of climate change impacts on water resources management. Specifically, we aim to create a more integrated approach to analysing water resources sustainability by enhancing the link between surface and groundwater models and potential future water supply and demand management options. Our study incorporates the HEC-HMS surface water model into a STELLA®-based water systems model. The water resources systems model includes simple groundwater balance models and allows for users to choose development and climate change scenarios and a range of water supply and demand management options.

1.1 Study Region Characteristics

The SRB is located in the central portion of the state of Sonora, Mexico, and comprises nearly 21,000 km^2 (Vivoni et al., 2007; 2010). Precipitation in the area ranges from 350 mm/year to 700 mm/year at the highest elevations (Hallack-Alegría and Watkins, 2007). The Sonora River has a northeast to southwest flow, following various mountain ranges until the final destination in the Abelardo L. Rodriguez reservoir near Hermosillo, the state capital. Currently, the Hermosillo area relies on surface water and groundwater resources from the SRB, among other sources (Scott and Pineda-Pablos, 2011). Given this reliance, an understanding of how climate change directly impacts these resources is of utmost importance in securing a sustainable water resources management plan for the future. Figure 1 shows the surface and groundwater hydrologic system, land cover, and topography of the study area. Of importance for this study is the spatial configuration of the surface water subbasins with respect to underlying aquifers.

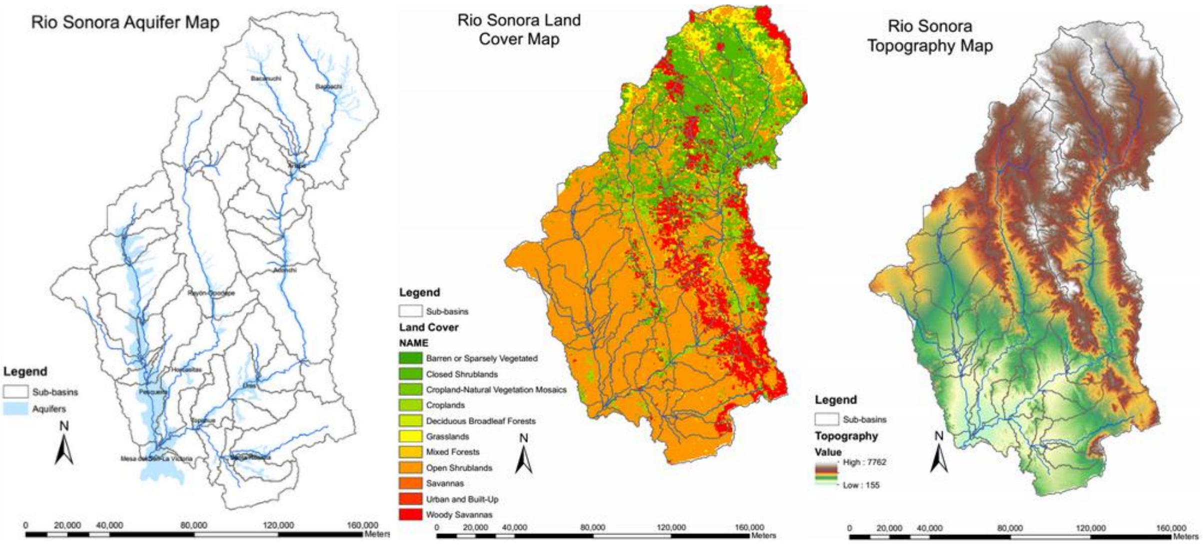


Figure 1: Rio Sonora Basin Maps

1.2 HEC-HMS Setup

The meteorological variables in the SRB derive from a ground-based network of 30 climate stations from 1980-2010, and from mesoscale atmospheric simulations from the WRF model over a historical (1990-2000), near future (2031-2040), and far future (2071-2079) periods. The ground-based network provides forcing for model calibration and validation against a set of daily, manual stream gauge measurements over the period 1980-2007. The WRF model provides downscaled hourly precipitation, solar radiation and air temperature fields at a 10 km resolution that were ultimately aggregated to a daily scale over the three previously mentioned time periods. The WRF model was used to downscale the coarser predictions of two General Circulation Models (GCM) that use the A2 high emissions scenarios, as in Robles-Morua et al. (2014). In this study, the two GCMs, HadCM3 and MPI-ECHAM5, span a range of potential future changes in temperature and precipitation.

The HEC-HMS model utilized the canopy storage method for rainfall interception, a surface depression method for initial losses, a soil moisture accounting scheme to track infiltration and losses to deep percolation, and the Priestley-Taylor approach to estimate evapotranspiration. Runoff in the channel network was routed using the Muskingum-Cunge method. The SRB was delineated into 47 individual subbasins guided by the surface topography and stream network. Model parameters were initially determined from the available soil texture and land cover information for the basin (Robles-Morua et al., 2014). Because the area of emphasis of our study is the link between HEC-HMS and the groundwater models, modelling channel transmission losses and subbasin percolation were considered of utmost importance. This enhancement modified the model calibration approach taken by Robles-Morua et al. (2014) for the SRB by increasing the losses from HEC-HMS to the underlying aquifers. Since channel transmission loss information is difficult to obtain in the SRB, existing data in the Walnut Gulch Experimental Watershed located in southern Arizona was used to derive constant loss percentages for each reach within the SRB, given similarities in climate and geology. Fractional transmission losses in the ephemeral Walnut Gulch stream network ranged from 10% to over 90% (Cataldo et al., 2004). The most commonly reported values from the Walnut Gulch study, 30% to 60% of streamflow over a given reach, were used for the SRB transmission losses.

1.3 Water Resources Systems Model Overview

The SRB water resources systems model is built with STELLA®, a system dynamics programming environment. The SRB water resources systems model has three components: (1) an underlying water balance model based on natural- and human-derived inflows and outflows and surface and groundwater storages; (2) optional historical, near-future, and far-future climate and development scenarios, and (3) options for water supply augmentation and demand efficiencies. A graphical user interface allows the user to select these options and run the model to assess water supply availability relative to demands.

Surface water discharges are obtained from HEC-HMS. The SRB is divided into 12 groundwater aquifers with separate water balances. Insufficient hydrogeologic information is available to warrant fully-discretized groundwater models for individual aquifers, but use of a single-cell groundwater model may lead to underestimation of drawdowns near well locations. Figure 2 shows the conceptual model for the aquifer water balances. Aquifers are connected laterally based on geographic proximity. Conductances between laterally-connected aquifers are calibrated with historical data and assumed initial depths to groundwater. Outputs from the groundwater balances include changes in groundwater elevations over time. Withdrawals for residential, commercial, industrial, and agricultural uses are calculated as outflows from surface or groundwater, based on historical unit demands for each category and projected changes in population and land use. Return flows are calculated for each use category and are routed as either surface water or groundwater inflows.

Users can choose from three development scenarios based on current trends or anticipated shifts in urban and rural populations and land use. Options for water supply augmentation include expansion of surface water storage and transfer facilities, reuse of industrial wastewater, desalination, and repair of distribution system leaks. Users can also choose to reduce groundwater withdrawals, given the steep declines in groundwater storage in the SRB. User-selected increases or decreases in water use efficiency for each of the water use categories are also factored into calculations of future water withdrawals.

1.4 Surface and Groundwater Model Linkages

Figure 2 represents the water balances and the interaction between HEC-HMS and the SRB water resources system model. Hydrologic fluxes shared between the models are channel transmission losses (CL), percolation (SP), and inflows into El Molinito (Q), determined by HEC-HMS. The SRB water resources systems model utilizes these predicted hydrological fluxes, along with other values, and calculates the water demand and supply for Hermosillo for the various time periods.

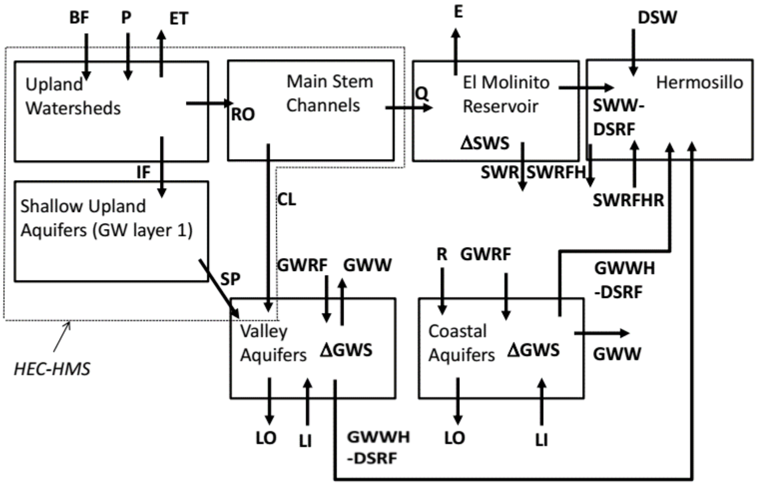


Figure 2: Rio Sonora Water Balance. Dashed line indicates the portion of the water balance calculated with HEC-HMS. Abbreviations defined in Table 1.

Table 1: Water Balance Terms

Term	Meaning	Term	Meaning
P	Precipitation onto sub-watersheds	**ΔGWS**	Change in storage in valley or coastal aquifers
ET	Evapotranspiration from sub-watersheds	**R**	Recharge to valley aquifers
RO	Runoff from sub-watersheds to main channels	**LI**	Lateral inflow into valley or coastal aquifers
IF	Infiltration from surface into upland shallow groundwater layer 1	**LO**	Lateral outflow from to valley or coastal aquifers
BF	Baseflow in the reaches within the sub-watersheds	**RFGW**	Return flows to groundwater from irrigation
SP	Percolation from upland shallow groundwater layer 1 to the valley aquifers	**Q**	Runoff from main stem channels into El Molinito reservoir
CL	Losses from main stem channels to valley aquifers	**E**	Evaporation from El Molinito reservoir
GWW	Withdrawals from groundwater aquifers used in rural areas	**SWW**	Water withdrawals from El Molinito reservoir via aqueduct
GWWH	Withdrawals from groundwater aquifers used in Hermosillo	**SWR**	Releases from El Molinito reservoir to Rio Sonora
GWRF	Return flows to groundwater from groundwater withdrawals	**ΔSWS**	Storage in El Molinito
SWRF	Return flows to main stem channels from groundwater withdrawals	**SWRFH (R)**	Return flows to surface water associated with water use in Hermosillo (recycled water)
DSRF	Flows gained from distribution repairs	**DSW**	Desalinated water from coast

2 RESULTS

2.1 HEC-HMS

Figure 3 presents a comparison of the total annual precipitation (mm) for the historical data from the ground-based network (GAUGES) and the two GCMs downscaled using WRF (Robles-Morua et al., 2014). For the historical period, there are clear biases in the climate model simulations with the HadCM3 model underestimating precipitation in the SRB and the MPI-ECHAM5 model leading to large overestimates. As a result, caution should be taken in the ability of the climate simulations to reproduce historical conditions. For both models, there are notable increases in total annual precipitation in the near and far future periods, almost two times more precipitation on average, suggesting large changes to the North American monsoon in the region. Furthermore, MPI-ECHAM5 predicts more annual precipitation than the HadCM3 GCM in both future periods.

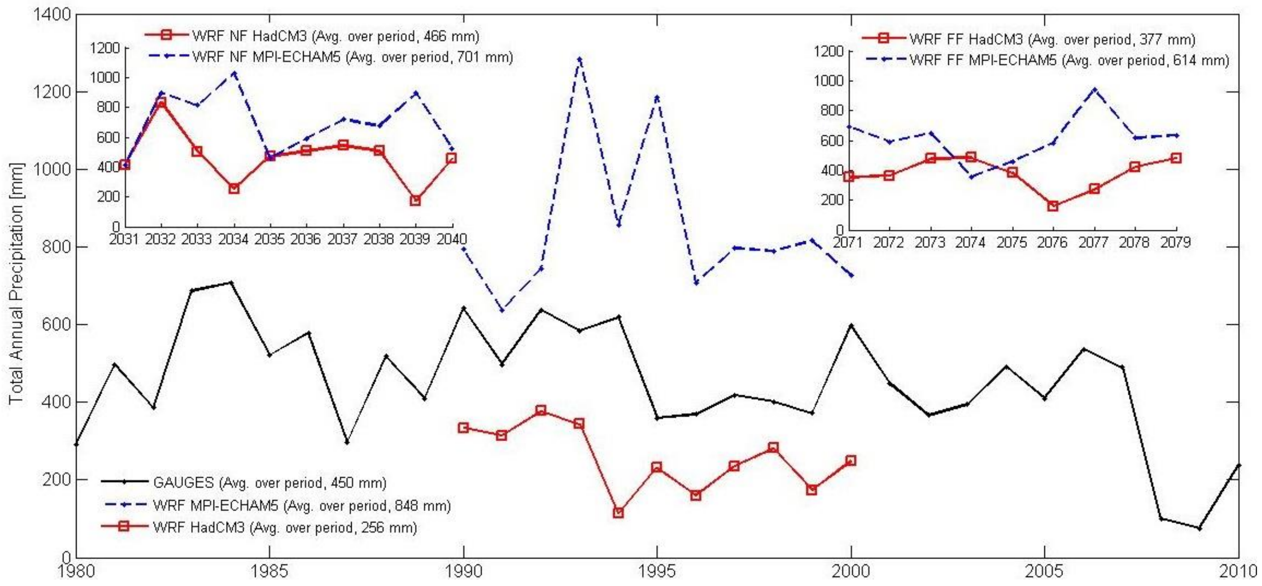
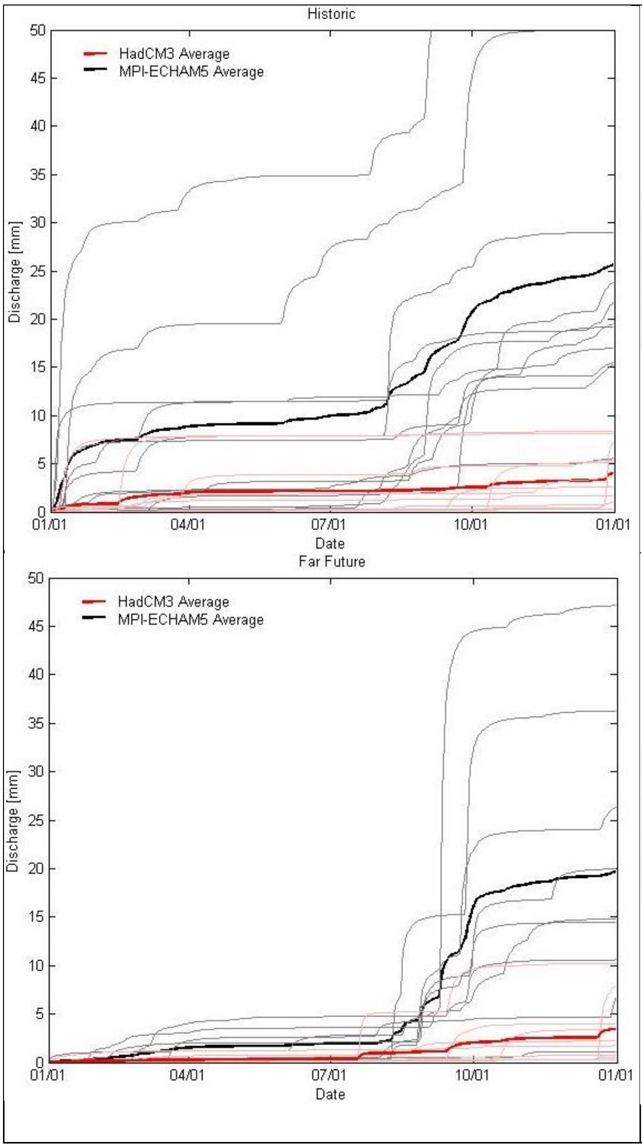


Figure 3: Annual Precipitation Comparison

Figures 4-7 are cumulative plots for the historical and far future simulations for runoff into the Abelardo L. Rodriguez reservoir at the basin outlet, evapotranspiration from all components, channel transmission losses in the stream network and groundwater percolation from individual subbasins averaged over the entire SRB. Only the historical and far future periods are shown for brevity, with results for the near future period typically lying intermediate between these cases (see Table 2). The red and black lines in the figures represent HadCM3 and MPI-ECHAM5, respectively. The bold lines are daily averages obtained over all years in each period, whereas the thin lines represent the results from individual years. Cumulative plots such as this allow quick inspection of the surface hydrology components over each period and the variations within and among individual years.

Notice the dramatic differences between the two downscaled GCM projections in the historical and far future periods. The HadCM3 boundary conditions produce considerably lower values than MPI-ECHAM5 for all surface and subsurface fluxes, a trend that follows the precipitation patterns in Figure 3. Further, the HadCM3 shows an increasing pattern of runoff, evapotranspiration, channel losses and groundwater percolation between the historical and far future period, while the MPI-ECHAM5 has the reversed behaviour, with a decrease across periods. This result suggests that regional stakeholders should recognize the considerable uncertainty in the climate change projections for the SRB. Overall, the runoff results are consistent with the prior work of Robles-Morua et al. (2014) that lacked a strong surface-groundwater exchange component. The enhancements made in this study, however, lead to higher channel losses and groundwater percolation fluxes available to the subsurface system.



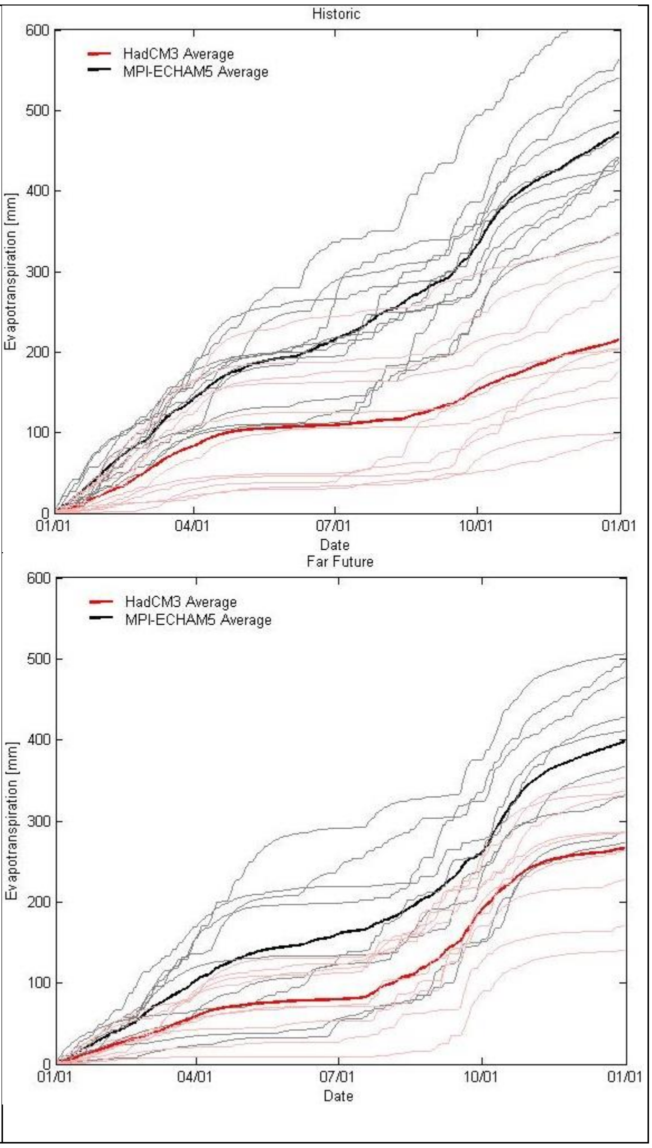
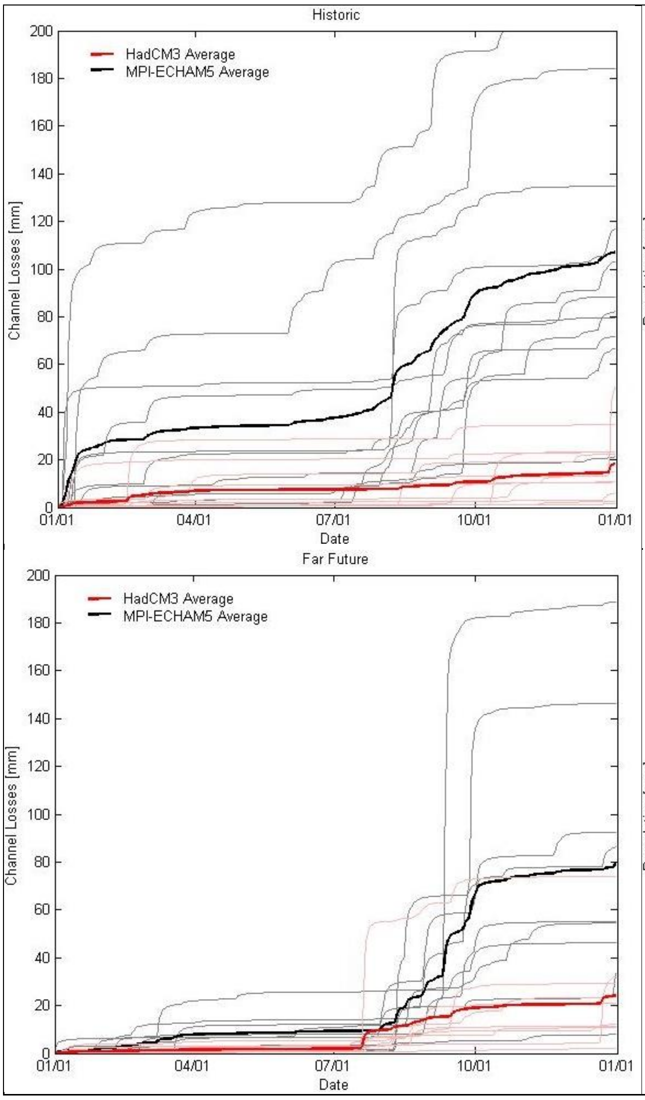


Figure 4: Runoff

Figure 5: Evapotranspiration



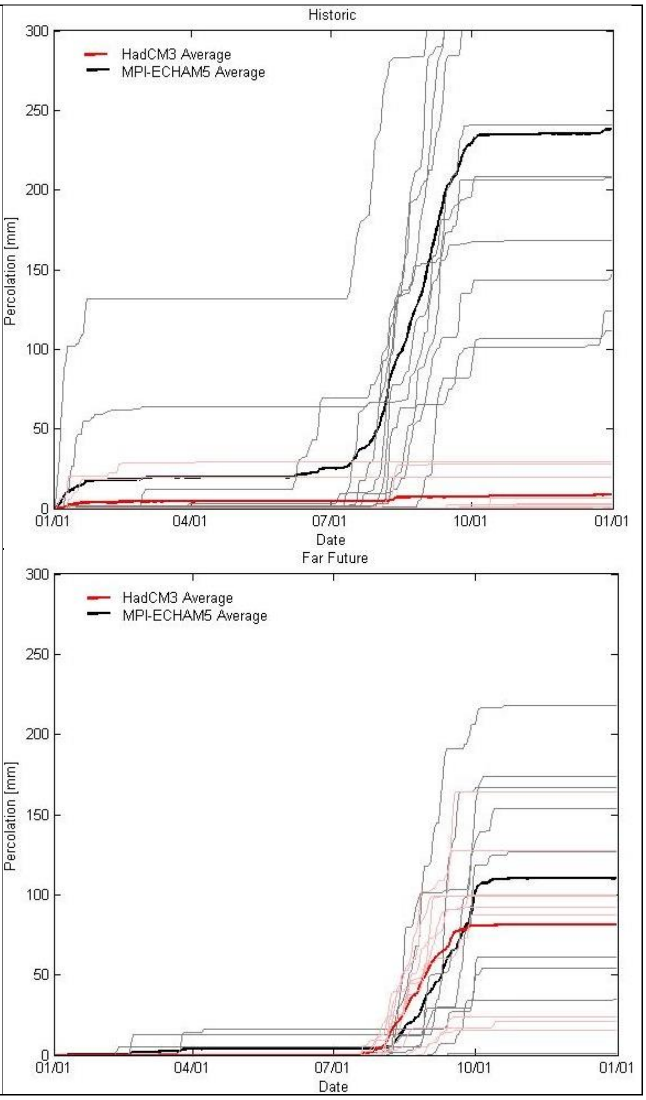


Figure 6: Channel Losses

Figure 7: Groundwater Percolation

Table 2 shows annual percipitation (P) and fractions of runoff (R), evapotranspiration (ET), channel transmission losses (TR) and groundwater percolation (L) for each period and GCM forcing. Mean annual fluxes ± one standard deviation across all years are shown. For cases where precipitation increases, the percentage lost to evapotranspiration decreases, likely due to the impact of cloud cover on radiation forcing (Hawkins et al., 2014). Small increases in runoff (2% higher R/P) are noted for higher precipitation scenarios. As a result, additional precipitation is typically lost to transmission losses and groundwater percolation, directly impacting the underlying aquifers. Groundwater percolation (L/P) is especially sensitive to the scenarios.

Table 2: Water Balance

	Historical (1990-2000)		**Near Future (2031-2040)**		**Far Future (2070-2079)**	
	HadCM3	**MPI-ECHAM5**	**HadCM3**	**MPI-ECHAM5**	**HadCM3**	**MPI-ECHAM5**
P	254.8 ± 2.9 mm	912.6 ± 1.6 mm	440.6 ± 4.0 mm	686.3 ± 1.6 mm	319.8 ± 3.1 mm	541.9 ± 1.5 mm
R/P	1.7 ± 0.1%	3.1 ± 0.1%	1.5 ± 0.0%	3.0 ± 0.1%	1.0 ± 0.0%	3.3 ± 0.1%
ET/P	87.5 ± 1.3%	58.5 ± 0.6%	66.6 ± 0.9%	63.2 ± 0.8%	74.7 ± 1.1%	66.5 ± 1.0%
TR/P	7.9 ± 0.3%	12.9 ± 0.2%	9.5 ± 0.3%	12.6 ± 0.3%	6.8 ± 0.3%	13.1 ± 0.5%
L/P	3.5 ± 0.2%	35.8 ± 0.6%	31.7 ± 0.7%	30.9 ± 0.6%	24.7 ± 0.6%	22.4 ± 0.4%

2.2 SRB Water Resources Systems Model

The results presented here focus on predicted impacts of climate change on groundwater storage. To simplify interpretation of the results, groundwater demands are kept constant for each simulation. We also only show results for the aquifers that are recharged through the channel transmission losses and groundwater percolation from HEC-HMS, obtained from individual subbasins and river reaches.

Figure 7 presents the change in groundwater elevation over the historical and far future periods and for the two different GCMs. Changes in groundwater elevations are calculated between the end and beginning of each simulation period These results show that the groundwater storages are quite sensitive to the climate change scenarios. In general, groundwater storage decreases for the historical period and increases for the far future period for the HadCM3 simulations. The behaviour over the historical period for the HadCM3 simulations qualitatively reflects trends in the RSB. The increase in storage for the far future/HadCM3 simulations is expected, since channel losses and groundwater percolation increase over this period as a result of increased precipitation, relative to the historical period.

On the other hand, groundwater storage decreases in the far future for the MPI-ECHAM5 simulations, relative to the historical period, following the trend of predicted decreases in rainfall between the far future and historical periods. In some aquifers, groundwater storage in the historical period for the MPI-ECHAM5 increases substantially relative to the HadCM3 simulations, reflecting high rainfall and coincident channel losses and percolation in the overlying subbasins. A few of the aquifers are particularly sensitive to the climate change scenarios, notably Arizpe and Santa Rosalia. These aquifers have low conductances to the aquifers immediately down-gradient, meaning that increases in recharge via inflow from up-gradient aquifers, channel losses, and percolation are slowly released to the down-gradient aquifers. In addition, rainfall in the subbasins overlying these and neighbouring aquifers varies substantially between the historical and far future periods and between the HadCM3 and the MPI-ECHAM5 simulations.

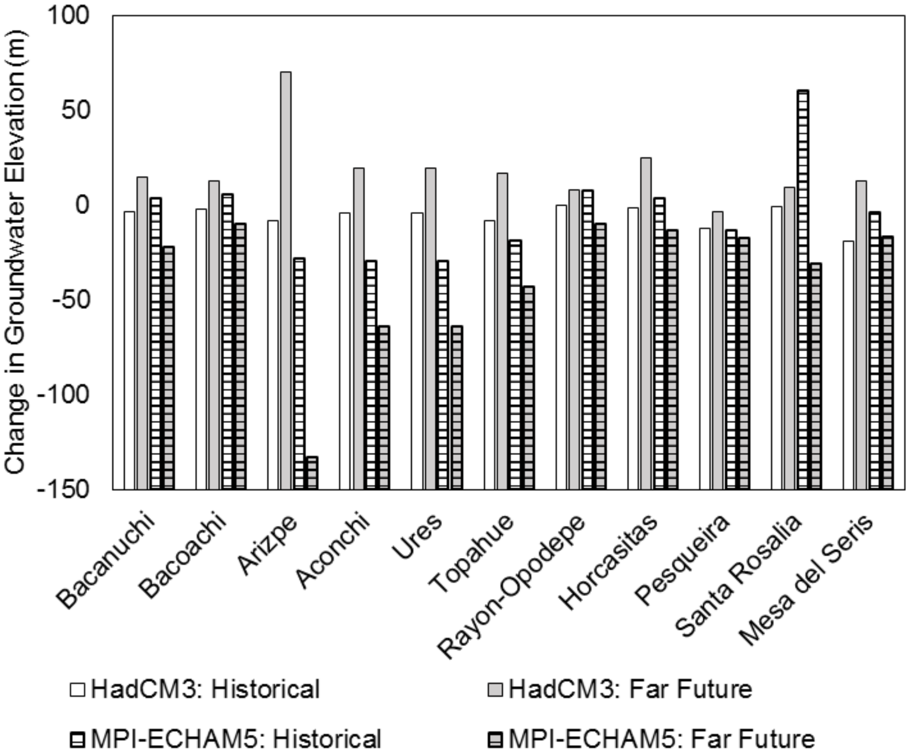


Figure 7: Changes in Groundwater Elevation over Historical and Far Future Periods and for GCM Models.

3 CONCLUSIONS AND FUTURE WORK

The results in this work indicate the surface water model has a large sensitivity to the GCM projection based on the predicted changes in precipitation. Increases or decreases in precipitation are typically translated into variations in groundwater percolation, followed by channel transmission losses. Low sensitivity is noted in the runoff or streamflow discharge reaching the Abelardo L. Rodriguez reservoir. Under these conditions, recharge to groundwater aquifers is highly variable, resulting in predictions of changes in groundwater storage that are specific to each aquifer and scenario. The behaviour of aquifers is shown to be especially sensitive to local climatic and hydrogeologic conditions. Inter-aquifer conductances are particularly important controls, but improved estimates of these parameters are needed. Given the variability in both surface water and groundwater supplies as a function of the two GCM models shown in this work, a wider range of GCM models should be tested.

Water resource managers in the SRB and Hermosillo could potentially use information provided by HEC-HMS and the STELLA® water resources system model to see how climate change impacts supply and demand. By providing the connection between the surface and groundwater models, this work will potentially provide regional stakeholders an improved means to track the impacts of climate change and alternative management scenarios on the coupled water resources. This exercise also illustrates that water resources sustainability planning needs to adequately analyze the water system as a whole through the combined use of surface and groundwater models. This interaction will give the water resource manager a full picture of the water balance within their respective watershed.

ACKNOWLEDGEMENTS

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