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# Evaluating the water resources and operation of the Boukan Dam in Iran under climate change

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**Abstract:** The operating policies of a reservoir dam in a river basin are dependent on the upstream river's inflow. As the latter may be affected by impacts of climate change which, in turn, may alter the water supply for the various stakeholders in the basin, studies to this regard are of utmost importance to ensure the sustainable development of the future water resources in the areas. Here we present the case study of the Boukan Dam, located on the Zarrine River, highlighted as the main inflow source of Lake Urmia, which is the largest inland wetland of Iran and the largest lake in Middle East. Firstly the calibrated rainfall-runoff model SWAT is used to predict the various flow components of the Zarrine River for the historical and future periods until 2049, using downscaled input precipitation predictors of three RCP-scenarios captured from one of the projections of the CMIP5-GCM ensemble, the CESM1-CAM5-model. These streamflow scenarios are then employed in the MODSIM water management model to simulate the present-day and future available water resources of the basin and to determine the optimal operation of the Boukan Dam, based on some prioritization of the water allocation for the various water use sectors in the basin. Finally, the impacts of climate and demand changes on the dam operation are evaluated by comparing future and historical MODSIM-simulated average water budget and supply/demand ratio (SDR) for the three CESM-model scenarios. In summary, the results show that the region will face more intensive water shortages in the future, owing to climatic change and increasing demands.

**Key words:** Climate Change, SWAT, MODSIM Water Management Model, Reservoir Dam Operation, Lake Urmia, Iran

## 1. INTRODUCTION

Climate change can worsen an already existing water shortage as an additional pressure factor in some regions of the world, as it may lead to increased rainfall variability and global warming (Bates et al., 2008). Specifically, the Western Asia and Middle East countries, such as Iran, which have already been experiencing a fragile arid or semiarid environment over many decades, are most vulnerable to a changing climate, not to the least due to increasing population pressure requiring more agricultural food production (Abbaspour et al., 2009). It is thus of no surprise that the unsustainable development of agricultural demands in Iran has intensified the already existing water crisis there as an external driver.

As water resources become further stressed due to the impacts of climate change and increasing demands, it is of a strategic importance to evaluate the various components of the water resources system, such as the efficiency of reservoir dams, in order to detect the appropriate operation strategies to mitigate such hydrologic changes.

Although many studies investigated the impacts of climate change on the water cycle (i.e. Abbaspour et al., 2009), fewer studies have focused on the evaluation of the water supply of a river basin due to the impacts of climate change (Emami, 2009; Ashraf Vaghefi et al., 2015).

The wetland of Lake Urmia, as the largest inland wetland of Iran and the largest lake in the Middle East, which is mainly fed by the head waters of the Zarrine River, has been tremendously diminishing in recent years which may lead to some drastic socio-ecological repercussions in that region (Aghakouchak et al., 2015). Thus it seems undeniable that the water supply system of the lake freshwater resources and also the unsustainable development of the region should be adjusted to allow for the restoration of the lake and so, hopefully, lead to a decrease of the water stress in the basin region (Emami and Koch, 2017).

In a recent previous study of the authors (Emami and Koch, 2017), QMAP (quantile mapping)-downscaled precipitation from a projection of the CMIP5- project for a particular climatic scenario has been employed, together with SDSM- downscaled temperatures of the HADCM3 GCM-model, as input drivers for the Soil and Water Assessment Tool (SWAT), a widely used distributed rainfall-runoff watershed model (Neitsch et al., 2005), to simulate the streamflow changes of the river basin and the inflow of the dam.

The present study, as a continuation, will use this calibrated SWAT-model to predict the flow components in the historical and future periods until 2049, based on three new RCP-scenarios of precipitation captured from the latest projections of CMIP5-GCM ensemble with a better atmospheric grid resolution. This predicted streamflow will then be employed in the water management model MODSIM to simulate the present-day and future available water resources of the basin and the best operation of the dam in the wake of upcoming climate change in the basin.

## 2. DESCRIPTION OF THE STUDY AREA

The Zarrine river basin (ZRB), with an area of about 11,000 km$^2$, is located in the southern part of Lake Urmia in west Azerbaijan province between 45° 46′ E to 47° 23′ W longitude and 35° 41′ S to 37° 44′ N latitude. The river basin system contains 24 hydrometrical stations and there is one operating dam on the Zarrine River, Boukan Dam, as the biggest and most important dam of the basin, together with the diversion dam, Nouroozloo, located downstream.

The average annual temperature in the ZRB varies between 8 and 12 °C and the rainfall is situated in the range of 200 - 850 mm/a.

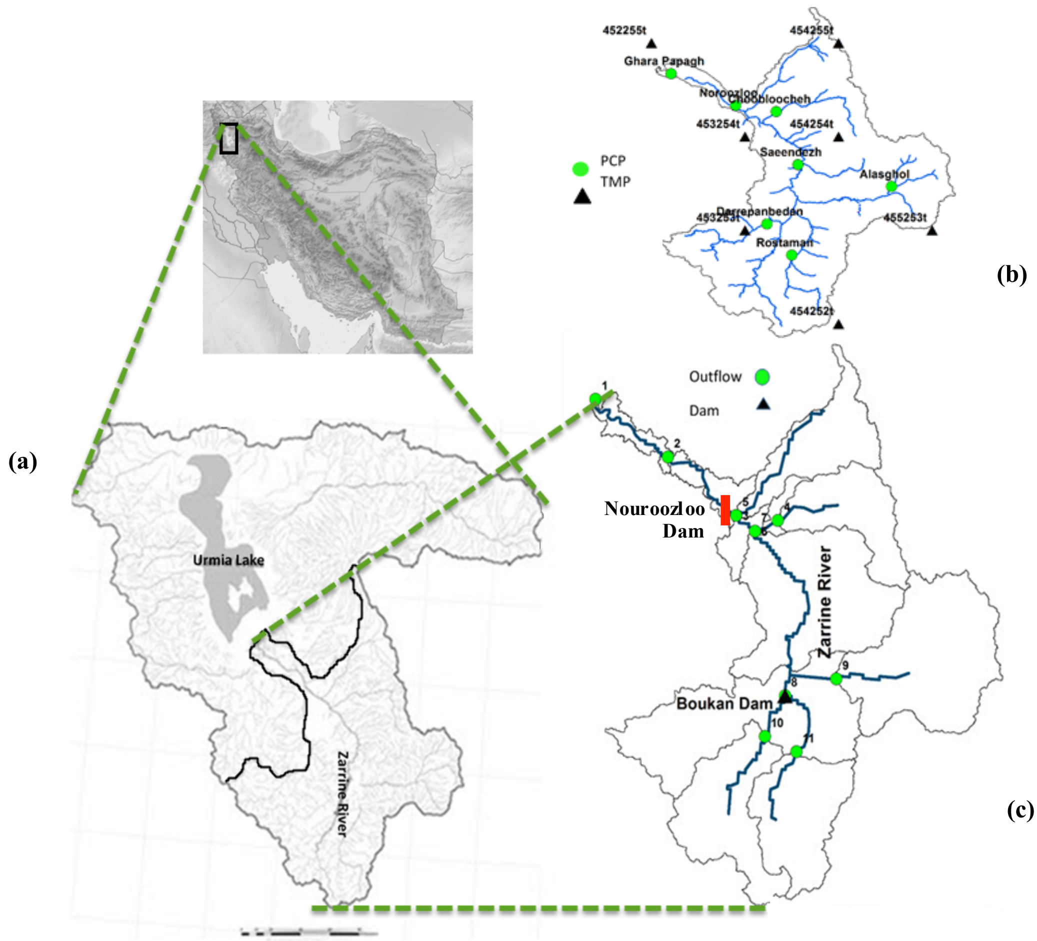


*Figure 1. Map of the ZRB in Iran (a), with sub-basins and location of climatic stations (b) and selected outlets (c)*

# 3. MATERIALS AND METHODS

### *3.1 Downscaling of climate predictors from GCM-RCP projections*

For the future prediction of the precipitation, daily predictors from five available GCM-models from the CMIP5 project series, based on their good spatial resolutions and output availability, are captured for three RCP scenarios (2.6, 4.5 and 8.5) for a 35-year period, 2015 to 2049.

These GCM-predictors are then downscaled with a non-parametric quantile mapping model (Gudmundsson et al., 2012), using robust empirical quantiles (Package QMAP in the *R*©- software environment) and provided by the "ccafs-climate" data portal (Navarro-Racines and Tarapues-Montenegro, 2015), are assessed and then the best fitted model with the lowest biases is selected for generating the future downscaled precipitation predictors for further hydrological modelling. The QMAP downscaling method removes the systematic bias of all statistical moments of the distributions of the raw GCM-predictors compared with those of the historical observations. Of course, likewise to all statistical downscaling methods, it is assumed also in this method that the historical biases will be the same in the future.

Historical and future minimum and maximum daily temperatures, also previously used in the concurrent study of Emami and Koch (2017), are SDSM- (Wilby et al., 2002) downscaled predictors from the Hadley center's HADCM3 GCM-model, as employed in the IPCC Fourth Assessment Report (AR4) for the extreme emission scenario (SRES) A2 (promoting further regional economic development) and the more benevolent B2 (with emphasis on an ecologically sustainable development). For further details the reader is referred to Emami and Koch (2017).

### *3.2 SWAT-hydrological modeling and MODSIM water resources decision modeling*

Using the downscaled climate predictors of previous section in the hydrologic model SWAT, streamflow and other relevant hydrological parameters of the ZRB, namely, the inflow into the Boukan Dam are simulated for the three climate (RCP) scenarios. Details of the setup and calibration and validation of the SWAT-model used, with some minor differences from the present application, are discussed in Emami and Koch (2017).

In the subsequent, final step, the river basin (water resources) decision model, MODSIM (Labadie, 1995), is applied to assess the impact of future predicted climatic change on the dam operation and water supply by incorporating the output of the previously modelled SWAT-streamflow as input drivers into this model.

MODSIM simulates the optimal water allocation in a river basin through a sequential solution of the following generalized network flow optimization problem, namely, a minimization of the water allocation costs, for each time period, under the constraint that the mass balance all over the network is satisfied. Mathematically this optimization problem can be cast in the following form:

$$\text{Minimize } \sum_{\ell \in A} c_\ell q_\ell \tag{1}$$

subject to:

$$\sum_{\ell \in O_i} q_\ell - \sum_{k \in I_i} q_k = 0; \textit{ for all nodes } i \in N \tag{2}$$

$$l_{\ell t} \le q_\ell \le u_{\ell t}; \quad \textit{for all links } \ell \in A \tag{3}$$

where $A$ is the set of all links in the network; $N$ is the set of all nodes; $O_i$ is the set of all links originating at node $I$ (i.e., outflow links); $l_i$ is the set of all links terminating at node $i$ (i.e., inflow links); $q_\ell$ is the integer valued flow rate in link $\ell$; $c_\ell$ is the cost weighting factor, or priority number per unit flow rate in link $\ell$; $l_{\ell t}$ and $u_{\ell t}$ are the lower and upper bound on flow in link $\ell$ at time $t$.

# 4. RESULTS AND DISCUSSION

## *4.1 Downscaled climate variables*

To predict the future daily precipitation the QMAP- downscaled outputs of five GCM-models of the CMIP5- project are evaluated for the historical period 1977 to 2005, using the quantile bias ($QB_t$), defined as the ratio of the downscaled monthly precipitation to that of the observed one above a specified percentile *t*, wherefore the 5%, 50% and 75% percentiles are usually used (Mehran et al., 2014). In addition the root mean square error (*RMSE*), and the coefficient of determination ($R^2$) are computed as further performance criteria. The results are listed in Table 1 for the RCP2.6 scenario. Similar tables were set up for the other two RCPs, 4.5 and 8.5, and are not shown here.

As can be seen from the table, CESM1_CAM5 (Community Earth System Model (CESM) with RCP #1 = RCP2.6, with the Community Atmosphere Model (CAM), version 5) has overall the best performance. As this holds also for the RCP4.5 and 8.5 precipitation scenarios, output of the model CESM, i.e. CESM1, CESM2 and CESM3, are used in the later hydrological analysis.

The results of Table 1 indicate that for all GCM-models the quantile bias $QB_t$ of the downscaled precipitation is decreasing numerically from values close to 1 at at the 25% quantile to values $QB_t$ <1 at higher (50 and 75%) quantiles, i.e. the downscaled precipitation underestimates the observed one during the historical period, particularly, for extreme precipitation. Nevertheless, as all seven stations have $R^2$ -values between 0.42 and 0.51 and RMSE between 21-56 mm/m for the CESM1-model scenario, the recorded historical precipitation in the region is rather well mimicked by the downscaled one. It should be noted that because of its high resolution (0.94º x 1.25º), all three CESM-model precipitation variants have lower bias and better performance than the MPI-ESM-LR model used previously by Emami and Koch (2017) for precipitation downscaling in the ZRB.

*Table 1. Statistical evaluation of the QMAP-downscaling precipitation performance of five selected CMIP5- GCM-models under climate scenario RCP2.6 for relative to the observations. Best model is highlighted in gray.*

| Station | Statiscal Parameter | CCCMA_CANESM2 | CESM1_CAM5 | MPI_ESM_MR | MRI_CGCM3 | NIMR_HADGEM2 | $QB_t$ | CCCMA_CANESM2 | CESM1_CAM5 | MPI_ESM_MR | MRI_CGCM3 | NIMR_HADGEM2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alasghol | $R^2$ | 0.29 | 0.45 | 0.39 | 0.39 | 0.42 | 25% | 1.00 | 1.00 | 0.99 | 0.99 | 0.98 |
| | RMSE | 43.5 | 36.1 | 37.1 | 36.1 | 35.7 | 50% | 0.82 | 0.81 | 0.81 | 0.79 | 0.78 |
| | | | | | | | 75% | 0.56 | 0.66 | 0.58 | 0.60 | 0.62 |
| Choobloocheh | $R^2$ | 0.41 | 0.51 | 0.43 | 0.35 | 0.52 | 25% | 1.00 | 1.00 | 0.99 | 1.00 | 0.98 |
| | RMSE | 35.7 | 30.1 | 32.4 | 34.6 | 29.2 | 50% | 0.82 | 0.84 | 0.82 | 0.79 | 0.83 |
| | | | | | | | 75% | 0.70 | 0.70 | 0.61 | 0.59 | 0.61 |
| Darre Panbedan | $R^2$ | 0.41 | 0.42 | 0.37 | 0.38 | 0.40 | 25% | 0.99 | 0.99 | 1.00 | 1.00 | 0.98 |
| | RMSE | 35.8 | 35.2 | 36.3 | 36.5 | 34.6 | 50% | 0.83 | 0.84 | 0.82 | 0.84 | 0.79 |
| | | | | | | | 75% | 0.69 | 0.66 | 0.66 | 0.60 | 0.60 |
| Rostaman | $R^2$ | 0.33 | 0.43 | 0.34 | 0.35 | 0.35 | 25% | 1.00 | 1.00 | 1.01 | 1.01 | 0.97 |
| | RMSE | 64.1 | 56.0 | 59.2 | 58.3 | 57.9 | 50% | 0.82 | 0.82 | 0.80 | 0.80 | 0.80 |
| | | | | | | | 75% | 0.60 | 0.62 | 0.61 | 0.57 | 0.54 |
| Noroozloo | $R^2$ | 0.32 | 0.45 | 0.38 | 0.30 | 0.45 | 25% | 1.00 | 1.00 | 0.99 | 1.01 | 0.98 |
| | RMSE | 33.0 | 29.0 | 30.5 | 32.7 | 28.5 | 50% | 0.80 | 0.84 | 0.83 | 0.78 | 0.81 |
| | | | | | | | 75% | 0.62 | 0.67 | 0.60 | 0.56 | 0.63 |
| Saeendezh | $R^2$ | 0.32 | 0.43 | 0.43 | 0.27 | 0.42 | 25% | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 |
| | RMSE | 33.6 | 29.1 | 28.6 | 32.6 | 28.2 | 50% | 0.83 | 0.81 | 0.84 | 0.78 | 0.80 |
| | | | | | | | 75% | 0.61 | 0.71 | 0.68 | 0.56 | 0.60 |
| Ghara Papagh | $R^2$ | 0.40 | 0.45 | 0.45 | 0.32 | 0.33 | 25% | 1.00 | 1.00 | 0.99 | 0.99 | 0.97 |
| | RMSE | 22.3 | 21.0 | 20.7 | 22.5 | 22.9 | 50% | 0.83 | 0.84 | 0.82 | 0.82 | 0.78 |
| | | | | | | | 75% | 0.65 | 0.68 | 0.63 | 0.52 | 0.53 |

### 4.2 Impact of climate change on inflow of the dam and reservoir operation

For evaluating the impact of climate change on dam operation, the downscaled climate variables are applied to the calibrated SWAT-model to simulate the future inflow of the dam changes in the time period of 2019 to 2049, as the downscaled predictions of the CMIP5-scenario models CESM1/2/3 start from 2015 and the SWAT- model uses a warm-up period of 4 years.

Fig. 2 shows the SWAT-simulated inflow of the dam for the historical and future time periods using the downscaled precipitation of the scenario-models CESM1, CESM2 and CESM3. Each of the latter were run with both A2- and B2- temperature scenarios – with only minor differences - and the average of two computed for the final evaluation of the dam's inflow as shown in the figure. One can notice from Fig. 2, that the future inflow of the more extreme CESM2- model scenario is lower than that of CESM1 (as well as CESM3). On the other hand, the inflow fluctuations of CESM1 are stronger than those of the other two models. Compared with the average annual streamflow into the dam of the historical reference period, that of the future CESM1- and CESM3-scenario will be increased by 33 and 14%, respectively, but reduced by 8% for the CESM2-scenario. Moreover, the average maximum monthly inflow will increase by 3% for CESM1, but will decrease by 27 and 3% for CESM2 and CESM3, respectively.

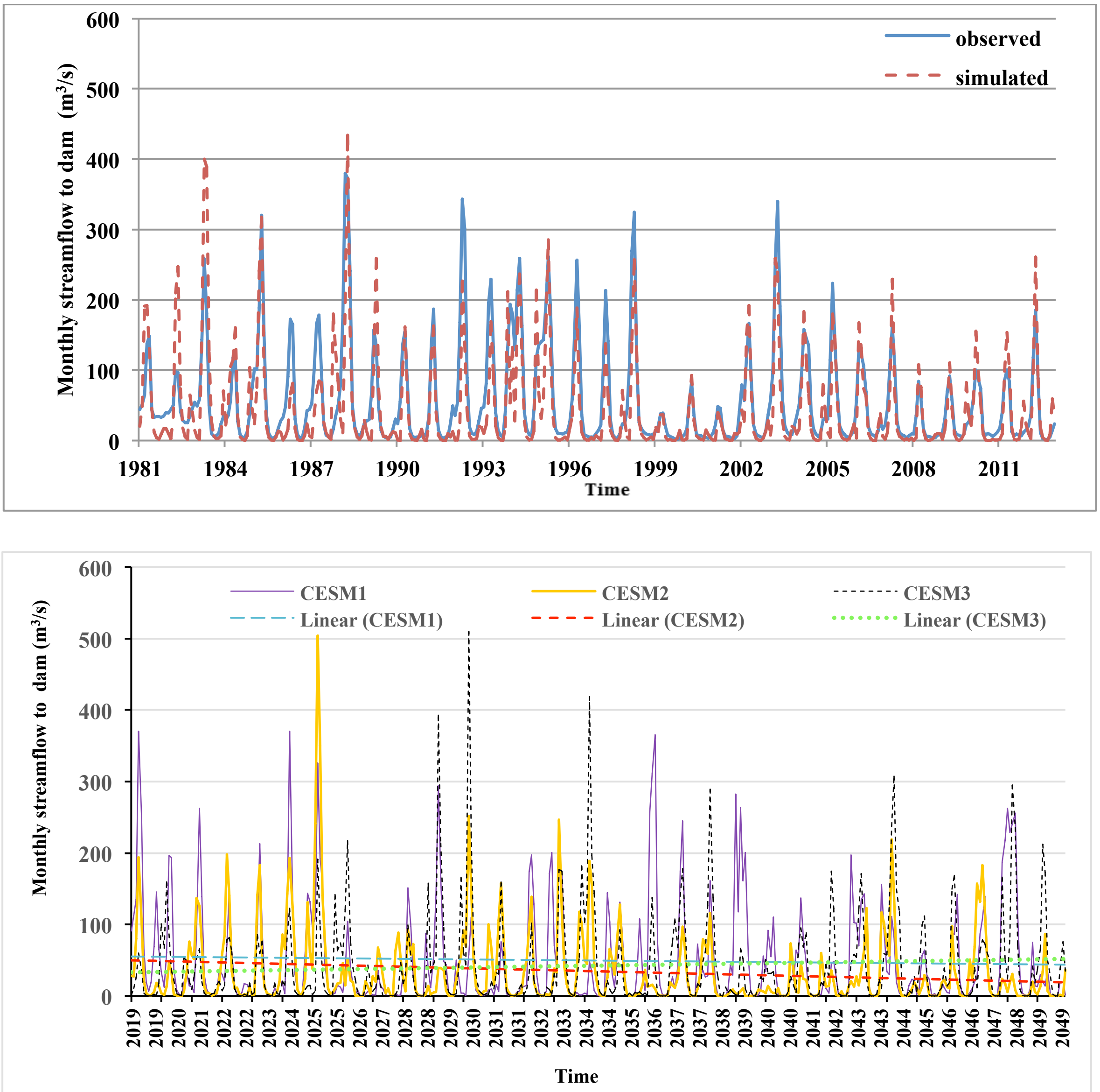


*Figure 2. Observed and SWAT-simulated streamflow (inflow of the Boukan Dam) for historical period 1981- 2012 (top) predicted inflows of the dam for CESM1( RCP2.6), CESM2 (RCP4.5) and CESM3 (RCP8.5), with linear trend (bottom)*

### *4.3 MODSIM simulated optimal water allocation*

Finally, the water management of the Boukan Dam for optimal water allocation in its downstream areas are modelled by means of MODSIM, using the schematic water network structure as sketched in four panels of Fig. 3 and the SWAT-simulated streamflow to the dam and from the tributaries along the Zarrine River as input.

Fig.3 depicts the various SWAT-MODSIM simulated annual, cumulative inflow and outflow water volumes for the different demand categories - which are in order of decreasing priority: potable (Pot), industrial (Ind), environmental (Env), fishery, agricultural (Agr) demands and filling the reservoir - along the ZRB- network for the historical (1981 to 2012) and the three future (2019 to 2049) CESM-model scenarios, discussed previously. Also indicated are the average annual water demands for the corresponding simulation periods, wherefore values of the future demands, which sum up to a total increase of 21% - mainly due to a doubled drinking water demand, and a 5% agricultural demand growth, together with a gradual increase of water demands in other sectors (Fesenduz fishery and Legzi pumping transfer) - were taken from Iran ministry of Energy administration reports. Assumptions in all these MODSIM-models include constant removal from the - already nowadays stressed - groundwater aquifers and, depending on the agricultural section, a 5 to 10 % return flow from irrigation demands to the subsurface.

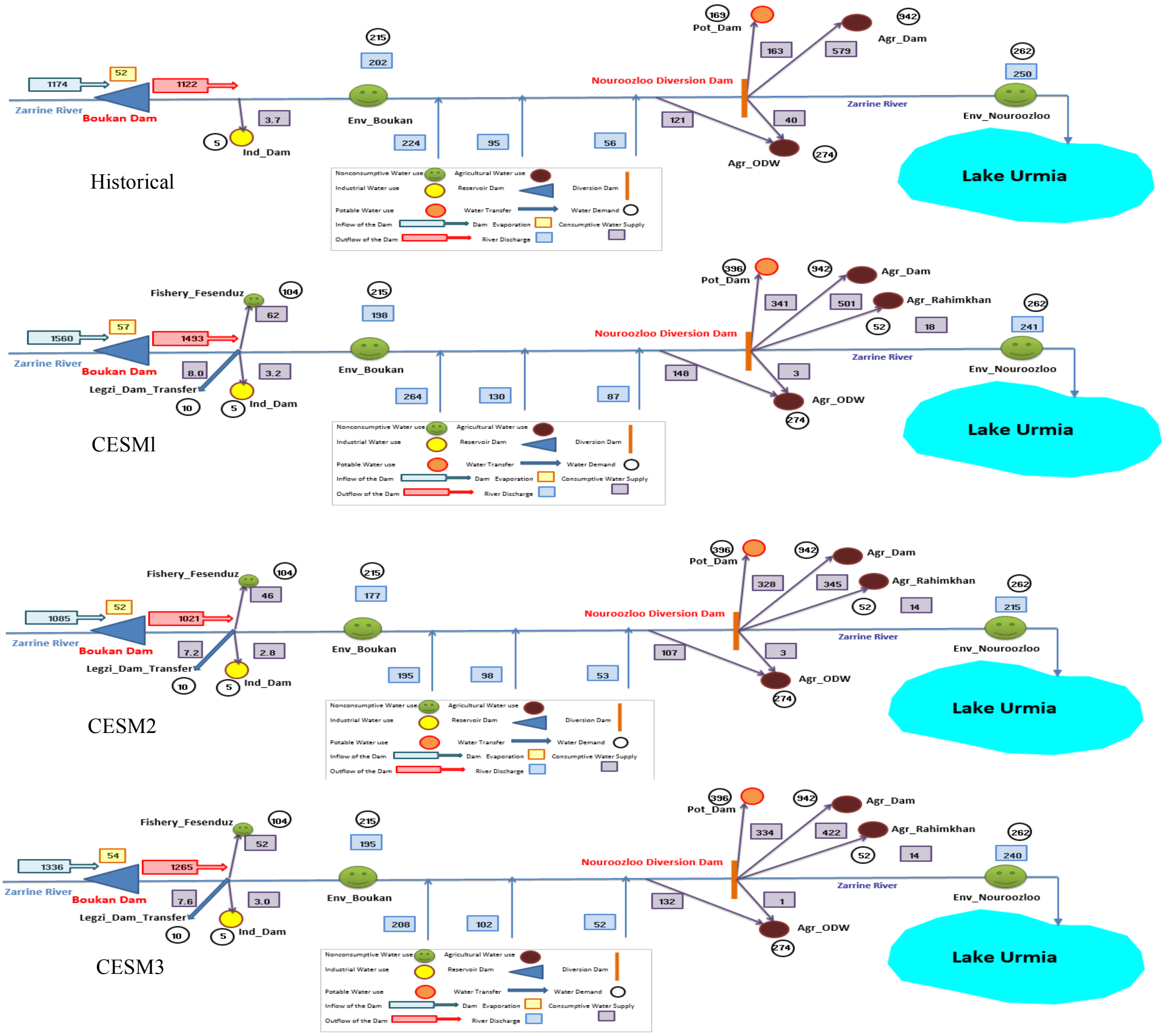


*Figure.3. MODSIM- water use network of the ZRB starting with the Boukan Dam and ending at Lake Urmia, with annual volumes (MCM) of different water demand sectors and MODSIM-simulated supplies for historical (top) and future period for climate prediction scenarios of CESM1, CESM2 and CESM3.*

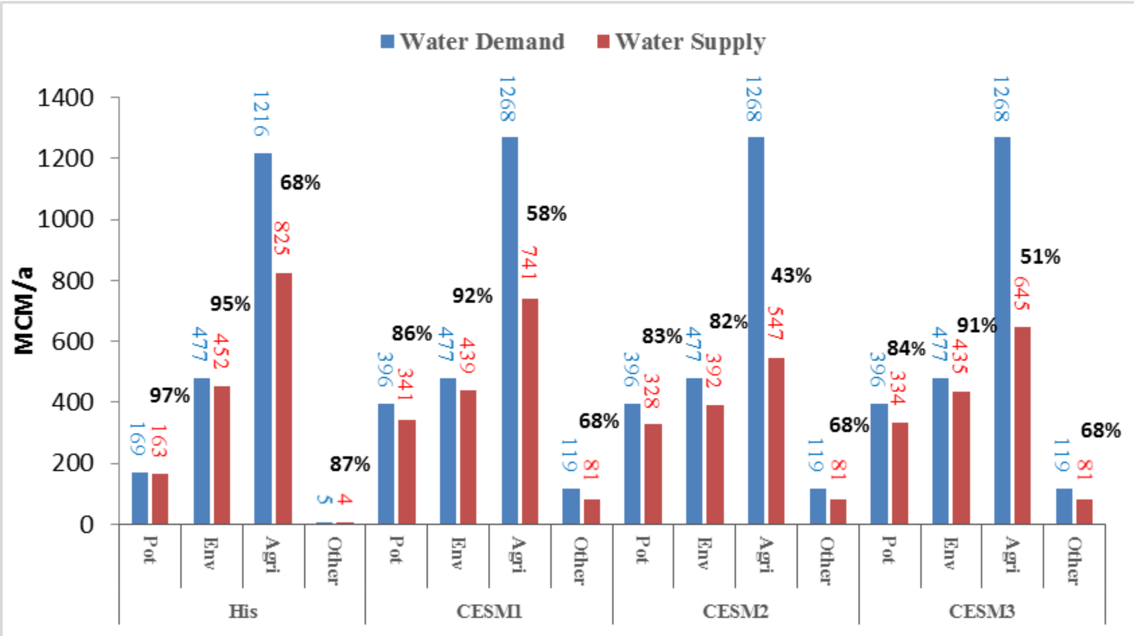


*Figure 4. Barplots of the total ZRB- water annual demands (MCM/a), the corresponding MODSIM – simulated supply and the corresponding supply/demand ratio SDR (in percent) for the various water use sectors, as for the historical and the three future climate scenarios.*

The MODSIM- simulated annual water budget numbers indicated in Fig. 3 for the different water sectors for the historical period and the three future model scenarios unveil that on average the future available water resources predicted with the CESM1- (RCP2.6) and CESM3 (RCP8.5) scenarios will increase, but decrease for the CESM2 scenario (RCP4.5). More specifically, the inflow and outflow of the dam in the CESM1 and CESM3 scenarios will rise by 33% and 14%, respectively. For CESM1, the inter-basin flows will, in addition, also increase by 28%, while they will experience a 3% decrease for CESM3. In contrast, for the CESM2-model scenario, inflow and outflow of the dam as well as the inter-basin flows will all fall by 9%.

The separate water demand/supply components along the ZRB network as depicted in Fig. 3 and discussed above, are accumulated for the totality of the ZRB in Fig. 4. From these values the ratio of water supply to demand, SDR, has been computed and listed as well. Thus, one can notice from Fig. 4 that the total basin SDR in the various water use sectors will be decreased in the future as follows: For potable water, it will decline from historic 97% to future 83-86%, depending on the scenario; for the agricultural demands it will drop from 68% to 43-58%; and for other types of demands it will dip by 19%, while SDR of the environmental water rights will drop by 3% - 13%.

In conclusion, all three climate scenarios investigated, indicate growing water resource deficits in the ZRB in the future, with the CESM2- scenario showing the strongest and CESM1 the weakest adverse effects. And because increasing water demands are another significant contributing factor to this upcoming water crisis, there will be the necessity for limiting the development of future demands and/or having recourse to an alternative water planning, such as a hedging rule or a deficit irrigation plan for the region.

## 5. CONCLUSIONS

The impact of changing climate on inflows and operation of the Boukan Dam in the ZRB is investigated using a basin-wide hydrologic model (SWAT), in conjunction with a water management model (MODSIM). The hydrological model is driven by downscaled (quantile mapping) climate predictors from the CESM_CAM5 GCM, with three future scenarios, RCP2.6, RCP4.5 and RCP8.5. Although both the RCP2.6- and RCP8.5- scenario models predict an optimistic increase of the future available water in the basin, this increase cannot cover the future growth of the demands. Very pessimistic is the RCP4.5 – scenario model which predicts even a decrease of the future inflow to the Boukan Dam. This peculiar result may hint of some uncertainties in the GCM model prediction of the precipitation.

The water allocation optimization results by means of MODSIM using the historical prioritization of the various water use sectors, together with a gradual increase of the demands, indicate an endangerment of the water supply for the drinking water sector and of the environmental rights, as the most important priorities; with the water crisis further exacerbated by the development of agricultural and other demands.

This study also shows that the add-on of a water management model to a hydrological model results in a powerful simulation tool that is able to serve for sustainable river basin management and the output can be used further to support better water decision making systems.

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