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Assessing the impact of AOGCMs uncertainty on the risk of agricultural water demand caused by climate change

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Abstract: A major future challenge and limiting factor for future water resource management and planning is climate change and drought conditions and their impact on agricultural water demand. Many models have targeted climate change predictions for temperature, rainfall, and evapotranspiration and have led to future estimation of water demand for agriculture. However, uncertainty and risk analysis are normally not considered in future water demand estimations. The main objective of this study is to quantify the impact of climate change on agricultural water demand and productivity and better understand the uncertainty and risk involved in using several Atmospheric-Ocean General Circulation Models (AOGCMs) to predict future temperature and water demand.

As a case study, the Zayandeh Rud basin, located in the central part of Iran, has been chosen because of its importance for agricultural and food security. The main growing and major crops are wheat, barley, sugar-beet and potato. Future temperatures have been retrieved from the IPCC database, which include AOGCMs climate change data sets. These data sets cover the whole world in a pixel-wise manner. Seven AOGCMs from the IPCC Third Assessment Report, including CCSR NIES, CGCM2, CSIRO MK2, ECHAM4 GFDL R30, HadCM3 and NCAR DOE PCM, with A2 emission scenario have been used to project the future temperatures for the study area for two different time periods (210-2039 and 2070-2099). According to the ranges of temperature resulted from these models, one thousand samples of temperature time series for these two periods are produced for uncertainty and risk analysis of water demand.

Preliminary results indicated that there is a significant increase in future temperatures, especially for the second period, ranging from 3-8.1°C, 3.1-8.2°C, 3-6.9°C and 2.3-6.5°C, respectively for the four seasons (spring, summer, autumn, and winter) compared to the base period (1971-2000). As a result, a volume of about 173 and 230 MCM/year will be required to meet the water demands, considering probabilities of 50% and 25% respectively for this period. Also, the responses of each crop to drought/increasing temperature are different; for example, potato is more tolerant for temperature variability. Finally, Considering the uncertainty of these climate models to estimate increasing temperature in future, adaptation strategies are required to mitigate the future impact of increasing future agricultural water demand (especially for the period of 2070-2099).

Keywords: *climate change, Atmospheric-Ocean General Circulation Models (AOGCMs), uncertainty, crop water requirement, Zayandeh Rud irrigation network*

1. INTRODUCTION

The average temperature of the earth's surface is increasing due to greenhouse gas (GHG) emissions, as the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007a) projects that global average temperatures will be higher by 1.8–4.0°C compared to the base period average (best estimate, likely range 1.1–6.4°C) while it was about 0.76°C during the last century. Also, changes in the average of climate variables, changes to the magnitude, character and spatial distribution of extreme rainfall may have serious social and economic implications (IPCC, 2007a) around the world. Without doubt, this phenomenon, called 'climate change,' will impact water and agricultural sectors, which are the most important ones for developing countries considering food security and climate change issues (Elmahdi et al., 2008). For example, in Iran, the agricultural sector is the main water consumer and, therefore, studying and evaluating the climate change impact and its uncertainty on agricultural sector is essential. Numerous studies about climate change have investigated its impacts and adaptation measures (e.g. Cuculeanu et al., 1999; Jones and Page, 2001; Varanou et al., 2002; Payne et al., 2004; Rosenweig et al., 2004; Quinn et al., 2004; Joyce et al., 2006; Massah, 2006; Maize et al., 2008; Elmahdi at al., 2008). The common step that should be considered in all of these studies is climate data simulation (such as temperature and precipitation) for future. The most reliable and common instruments for obtaining projections of future global climate change are the fully-coupled Atmospheric-Ocean General Circulation Models (AOGCMs). Although it is a common practice to use a single GCM, over-reliance on a single GCM could lead to inappropriate planning or adaptation responses to climate change. Therefore, emphasis must be placed on using multiple models as far as possible to avoid inappropriate planning or adaptation responses (Wilby and Harris, 2005).

Rosenweig et al. (2004) studied the implications of climate changes in crop water demand and water availability for the reliability of irrigation for many case studies, taking into account changes in competing municipal and industrial demands, and explored the effectiveness of adaptation options in maintaining reliability. The results showed that only one case study area can readily accommodate an expansion of irrigated land under climate change, while the other areas would suffer decreases in system reliability if irrigation areas were to be expanded. Thus, changes in water demand will require timely improvements in crop cultivars, irrigation and drainage technology, and water management. Another related research has been carried out by the California Climate Change Center; the goal was to begin to understand the potential impacts of climate change and adaptation to global climate change and to evaluate the utility of various tools in refining this understanding in the future. With no adaptation, lack of sufficient surface water to meet elevated evaporative demand for irrigated crops led to a dramatic increase in groundwater pumping and a coincident decline in simulated groundwater levels. As for the Zayandeh Rud basin, considered in the present study, the impacts of climate change on main crops yields under HadCM3/ A2 and B2 for two periods of 2020s and 2080s have been investigated (Massah and Morid, 2005). Results showed a dramatic yield reduction and increase in coefficient of variation for the major crops production. To cope with this phenomenon, different strategies, such as change in cropped area, change in cropping pattern, trans-basins projects and decrease in domestic water demand, were investigated.

From the above discussion, it is clear that there are many studies that have investigated the climate change impacts and different adaptation strategies to reduce the negative impacts of climate change; at the same time, in most of these studies, the related uncertainty has been ignored and only sensitivity analysis (use of artificial scenarios) or system vulnerability, by using one or a few of AOGCM scenarios, has been investigated (Alexandrov et al., 2004; Brouyere and Dassargues, 2004; Fowler and Kilsby, 2004). However, ignoring the uncertainty at different stages of climate change impact assessment can result in less certainty in final system outputs. It is also widely acknowledged that a significant source of uncertainty is the disagreements between different GCMs over regional climate changes (Jenkins and Lowe, 2003). Impact assessments have widely examined the consequences of climate change but have been less able to attach likelihoods to those outcomes. Pervasive uncertainties have limited most assessments to using only scenarios that represent alternative futures without being able to determine which of those futures may be more likely. However, the use of likelihoods in climate change assessments is emerging (Roger, 2003). Following up on this, the present study aims to quantify and evaluate the impacts of climate change on agricultural water demand and productivity for main staple crops of the Zayandeh Rud river basin in Iran. Unlike most other related works,

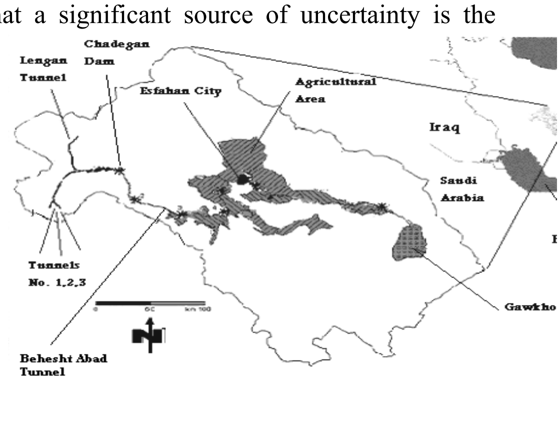

Figure 1. Location of the Zayandeh Rud basin

this study aims to assess and better explain the uncertainty and risk involved in using several models (AOGCMs) to predict future temperature and water demand, which are considered as significant sources of uncertainty (Jenkis and Lowe, 2003) and to produce probabilistic information of agricultural water demand for the periods in the near-term (2020s) as well as in the long-term (2080s).

2. STUDY AREA: ZAYANDEH RUD IRRIGATION NETWORKS

The Zayandeh Rud basin is located in the central part of Iran (Figure 1). The area of the basin is about 42,000 km^2. The agricultural sector is the main water consumer in the basin, using more than 80% of the available water resources. Wheat, rice, barley and potato are the main staple crops in the basin. Numerous factors, including continued growth of urban population, development of new agriculture lands and rapid increases in industrial demands, have caused water shortages since a half century ago. In addition to the internal changes and activities that are presently going on in the basin or are foreseen for the future, there is an important external factor due to climate change. With the global climate change and its effects on regions around the world, climate in this basin may also change significantly and impact the water resources. Mean annual temperatures from the station located in the upper sub-basins (most of the water resources in the basin is derived from upper sub-basins) show a positive linear trend, a possible indication that the Zayandeh Rud basin will see significant changes in meteorological variables in the future, especially in the long-term (e.g. 2070-2099), and thus the basin will face more drastic changes.

3. CONSTRUCTION OF CLIMATE SCENARIOS

To better estimate crop water requirements considering the direct relationship between temperature and potential evapotranspiration (Et$_c$), different temperature scenarios should be evaluated as a first step.

3.1. AOGCMs and Emission Scenarios

Atmospheric-Ocean General Circulation Models (AOGCMs) are the most comprehensive tools for estimating the response of climate to radiative forcing. The basis of these models consists of describing the physical processes taking place in the climate system and the dynamics of climate variables as a function of different internal or external changes. IPCC has presented different emission scenarios (IPCC, 2007b). According to Massah (2006), A2 scenario has the critical condition for the present case study of the Zayandeh Rud basin, and thus was used herein. The A2 scenario corresponds to pessimistic future with higher population growth, lower GDP growth, and fragmented and slower technological change (Nakicenovic and Swart, 2000).

3.2. Downscaling

There are also many techniques available for downscaling GCM outputs to the specific region or study area of interest, for discriminating between mean changes and changes in climatic variability and for ensuring consistency between climate change and non-climatic scenarios. Inverse Distance Weighting (IDW) was chosen to be used in this study. The points were weighted during interpolation, such that the influence of one point relative to another is a function of inverse distance. For performing IDW mean monthly temperatures of the study area (see equation 1) using the AOGCM grid (the above 7 models), which their coordinates has projected in Cartesian coordinate system (Cressie, 1993):

$$Z^*(x_j) = \frac{\sum \frac{Z(x_i)}{(h_{ij} + s)^p}}{\sum \frac{1}{(h_{ij} + s)^p}} \qquad (1)$$

where $Z^*(x_j)$ is the estimated value for location j, $Z(x_i)$ is the measured sample value at point i, h_{ij} is the distance between $Z^*(x_j)$ and $Z(x_i)$, s is the smoothing factor and ρ is the weighting power (common value is 1-5). However, in the present study, we used 0.1 and 3 for s and ρ respectively, as per the recommendations by Massah (2006). A relatively straightforward and popular procedure for rapid impact assessment involves the use of "change factors" (CFs). First, a baseline climatology is established for the site or region of interest. Depending on the application, this might be a representative long-term average, such as 1971–2000, or an actual meteorological record, such as daily maximum temperatures. Second, changes in the equivalent temperature variable for the GCM or Regional Climate Model (RCM) grid box closest to the target site are calculated; for example, a difference of 2.5ºC might occur by subtracting the mean GCM temperatures for 1971–2000 from the mean of the 2050s. Third, the temperature change suggested by the

GCM (in this case, +2.5ºC) is simply added to each day in the baseline time series (Diaz-Nieto and Wilby, 2005). This process is shown by following equation:

$$T_i = T_{i,obs} + \Delta T \tag{2}$$

Where, $T_{i,obs}$ observed temperature for month i in base period, T_i temperature time series for month i in future period, ΔT long term monthly average temperature change which can calculate as following:

$$\Delta T = \overline{T}_{i,GCM,fut} - \overline{T}_{i,GCM,base} \tag{3}$$

where $\overline{T}_{i,GCM,fut}$ is the long-term (30 years, such as 2010- 2039) monthly average temperature for month i in the future period simulated by AOGCM with A2 sceanrio for two periods include: 2010-2039 and 2070-2099 for temperature (columns ΔT in Table 1).

4. CALCULATION OF MAXIMUM WATER REQUIREMENT

For calculating crop evapotranspiration, the crop coefficient approach was used (FAO Irrigation and Drainage Paper 24; Doorenbos and Pruitt, 1984). In this approach, ETc, is calculated by multiplying the reference crop evapotranspiration, ETo, by a crop coefficient, Kc. Most of the effects of the various weather conditions are incorporated into the ET_o estimate. Therefore, as ET_o represents an index of climatic demand, K_c varies predominately with the specific crop characteristics and only to a limited extent with climate. This enables the transfer of standard values for K_c between locations and between climates. This has been a primary reason for the global acceptance and usefulness of the crop coefficient approach and the K_c factors developed in the past studies. Calculation of ET_0 has been done by FAO Penman-Monteith equation (Doorenbos and Pruitt, 1984) for base period but, as producing all of the necessary inputs of this equation wasn't possible for future periods, the relationship between temperature and reference evapotranspriation that has been earned from base period data was used in those times.

Table 1. Average of monthly temperature changes (°C) and corresponding weights of AOGCMs for periods of 2020s and 2080s.

month	NCAR			ECHAM4			CCSR			HADCM3			CSIRO			CGCM2			GFDL		
	WEIGHT	ΔT 2020S	ΔT 2080S	WEIGHT	ΔT 2020S	ΔT 2080S	WEIGHT	ΔT 2020S	ΔT 2080S	WEIGHT	ΔT 2020S	ΔT 2080S	WEIGHT	ΔT 2020S	ΔT 2080S	WEIGHT	ΔT 2020S	ΔT 2080S	WEIGHT	ΔT 2020S	ΔT 2080S
Jan	0.26	0.6	2.1	0.08	1.5	5.2	0.04	1.6	6.0	0.08	0.4	2.9	0.09	0.7	3.8	0.33	1.3	4.8	0.12	0.0	2.2
Feb	0.19	0.7	1.8	0.07	1.4	4.4	0.03	1.7	6.3	0.07	0.8	2.9	0.06	0.4	3.8	0.51	2.2	5.0	0.07	0.8	2.6
Mar	0.31	1.4	3.0	0.06	1.4	4.4	0.03	0.6	7.1	0.08	1.5	4.3	0.06	1.1	4.6	0.41	2.4	5.2	0.06	1.3	2.0
Apr	0.58	1.5	3.5	0.04	1.2	4.2	0.02	1.4	7.8	0.1	1.7	5.0	0.05	0.9	5.2	0.19	1.2	3.9	0.03	0.3	2.0
May	0.39	0.5	2.8	0.06	0.6	4.8	0.04	2.6	8.2	0.15	1.8	6.5	0.1	1.1	6.0	0.2	1.6	4.8	0.06	0.4	3.3
Jun	0.55	0.6	3.0	0.05	0.9	5.1	0.04	1.9	8.2	0.1	1.7	6.3	0.11	1.1	5.4	0.11	1.8	6.2	0.05	0.6	3.8
Jul	0.84	0.6	2.7	0.02	1.5	6.3	0.01	1.9	8.5	0.03	1.7	6.2	0.05	1.2	5.4	0.03	2.6	6.2	0.02	1.5	5.1
Aug	0.95	0.5	3.2	0.01	2.0	6.8	0	1.9	8.0	0.01	1.4	6.1	0.02	0.7	4.8	0.01	1.8	5.9	0	0.7	5.5
Sep	0.48	1.0	3.3	0.05	1.8	7.2	0.04	2.2	8.0	0.11	1.5	5.3	0.18	1.0	4.9	0.1	1.1	5.2	0.05	1.6	6.0
Oct	0.55	0.9	3.5	0.05	1.8	6.6	0.03	2.0	7.7	0.07	1.6	4.5	0.11	1.6	5.4	0.15	1.9	5.5	0.04	2.0	4.9
Nov	0.32	0.6	3.2	0.07	1.4	5.5	0.04	1.0	6.6	0.14	1.5	4.3	0.11	1.3	4.0	0.26	0.4	4.6	0.07	1.3	4.4
Dec	0.85	0.2	2.4	0.01	1.3	5.1	0.005	1.4	6.4	0.01	1.0	3.4	0.02	1.6	4.8	0.07	1.8	4.7	0.03	1.4	2.6

In this regard, neural networks and regression methods were used and, after necessary considerations, regression relationship with R^2= 0.84 was accepted. Figure 2 shows the monthly average of reference evapotranspiration for the base and the future periods. The crop coefficient, K_c, is basically the ratio of the crop ET_c to the reference ET_o, and it represents an integration of the effects of four primary characteristics (crop height, albedo (reflectance) of the crop-soil surface, canopy resistance and evaporation from soil) that distinguish the crop from reference grass. As the K_c for a given crop depends on the growing period, the crop coefficient curves for the initial, mid and late seasons were calculated for every crop.

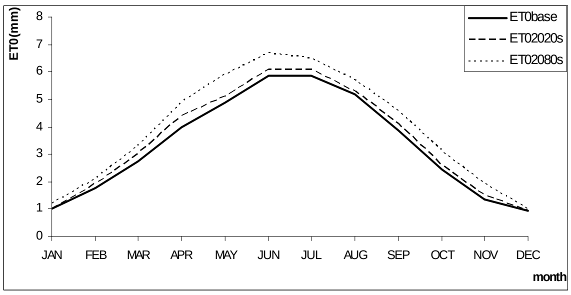

Figure 2. Monthly average of reference evapotranspiration of the Zayandeh Rud basin for base and future periods.

5. UNCERTAINTY AND ASSESSMENT

Describing uncertainty honestly is an important part of communicating science in a balanced way and is essential to maintaining trust between scientists and the broader community (IPCC Workshop on Uncertainty and Risk, 2004). Climate change assessment is dominated by uncertainty, affecting the choice of method and the confidence that can be attached to the results. In order of decreasing certainty, a result can be expressed as a central prediction, as a central prediction with error bars, as a known probability distribution function, as a bounded range with no known probability distribution, as a bounded range within a larger range of unknown possibilities, as individual scenarios with plausibility, and as a hypothesis with unknown levels of plausibility (OECD, 2003). In this study, for showing uncertainties due to use of different AOGCMs models, a bounded range with known probability distribution has been used. In every month, by comparing AOGCMs, ranges for monthly future temperature changes were quantified with an upper and lower limit. For producing probability distribution of these ranges Mean Observed Temperature-Precipitation (MOTP) method was used, following the study by Massah (2006):

$$W_i = \frac{(1/\Delta T_{ij})}{\sum_{j=1}^{N}(1/\Delta T_{ij})} \tag{4}$$

where W_i is the weight of each model in month i, ΔT_{ij} is the difference between average of temperature simulated by AOGCM j in month i base period from corresponding observed value. The result of this process is shown in columns *WEIGHT* in Table 2.

Table 3. K_c Values according the 50% cumulative probability in the period of 2070- 2099.

month / crop	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
wheat		0.56	0.56	0.56	0.58	0.86	1.13	0.98	0.43			
barely				0.55	0.7	1.1	1.15	1	0.38			
Sugar- beet					0.4	0.4	0.58	1.04	1.14	1.11	0.85	0.7
potato					0.42	0.43	0.79	1.14	1.15	0.93		

Table 2. Yearly water requirement in future periods (mm/day) with the Cumulative probability of 25%, 50%

	ET base	ET 2020S		ET 2080S		ET 2020S/ET base		ET 2080S/ET base	
		%25	%50	%25	%50	%25	%50	%25	%50
Wheat	480.87	539.89	512.17	611.49	578.58	1.12	1.07	1.27	1.20
barely	443.59	495.53	478.70	554.43	540.91	1.12	1.08	1.25	1.22
Sugar-beet	833.07	939.98	866.92	1043.10	951.88	1.13	1.04	1.25	1.14
potato	630.29	682.50	664.79	775.30	734.66	1.08	1.05	1.23	1.17

Risk can be defined in several ways, but is broadly defined as a combination of the likelihood of an outcome or event and some quantitative measure of the consequences of that outcome or event. Many analyses of risk consider a simple product of probability and consequence and in that sense are used broadly in decision making for environmental and other issues (Manning et al., 2004). Haimes (2004) has defined risk as an amalgamation of two constructs: one, probability, is a mental, man-made construct that has no physical existence peruse; and the other is severity of adverse effects. Risk evaluation relates to the following triplet risk assessment questions posed by Kaplan and Garrick (1981): i) What can go wrong?; ii) What is the likelihood that it would go wrong?; iii) What are the consequences?

6. RESULTS AND DISCUSSION

6.1. Risk Analysis of Reference Crop Evapotranspiration and Crop Coefficient (Kc)

By using 1000 monthly temperature time series samples, monthly ET_0 samples for future periods were calculated and compared those of the base period to calculate the cumulative probability of changes in reference crop evapotranspiration (ET_0) for future periods. Figure 3 shows the cumulative probability distributions for reference evapotranspiration. For example, for April with probability of 25%, up to 0.48 and 1.12 mm per day is expected for increase of ET_0 for the periods of 2010- 2039 and 2070- 2099, respectively. In this manner, for the probability of 50%, these changes would be up to 0.34 and 0.91 mm per day. There are two types of likelihood for future events that are both measured in terms of probability: i) event-based probability, where the likelihood of recurring events is estimated (e.g. floods, droughts and temperature extremes); and ii) the probability of a specific outcome, which is measured over a range of future uncertainty (Kirono et al., 2006). In the present study, the second type of probability was used to describe the future state of climate change under the different AOGCMs outputs. To this end, Monte Carlo methods (repeated random sampling) were employed to stochastically generate probabilistic estimates of future temperature change and its impacts on reference evapotranspiration increase.

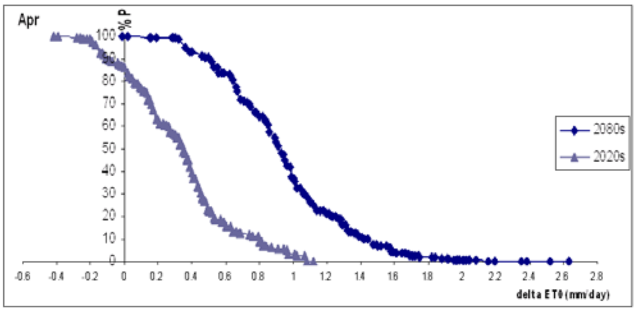

Figure 3. Cumulative probability distributions for monthly reference evapotranspiration periods.

By using SIMLAB software (Giglioli and Saltelli, 2003), long-term monthly average temperature change (ΔT) (see eq. 3) were randomly sampled and repeated 1000 times by distribution for 2020 and 2080 to get an adequate sampling density over the projected range of uncertainty. Then by using equation 2, simulations samples were used to calculate monthly temperature time series samples that were used as inputs of crop water requirement model to calculate monthly evaporation reference evapotranspiration changes in periods of 2010-2039 and 2070-2099. Having calculated the cumulative probability distributions for ET_0, discrete probability (25%, 50% and 75%) of ET_0 was used to calculate Kc. For obtaining relative humidity, its regression relationship with ET_0 in base period was used. Also, for wind speed its amounts in base period was considered. The value of K_c for every crop used in this study and every month in future periods was calculated (Table 3).

6.2. Risk of Change in Water Requirement

By using the results of ET_0 and K_c, water requirement of dominant crops of the basin was calculated for the risk of 25% and 50% probabilities for the future periods as well as the base period. The yearly water requirements for the future periods are presented in Table 2. According to these results, for the risk of 25%, the average increase of 8-12% and 23-27% is expected in water demand for different crops during the periods 2010-2039 and 2070-2099. For the risk of 50%, this increase would be 4-8% for the first period and 14-22% for the second period. In some studies, such as the one by Steinemann and Cavalcanti (2006), an increase of 10% in demand has been introduced as a trigger for system stress. If this trigger were to be accepted here, for the probability of 50%, there would not be any stress regarding water requirement increase for the period 2010-2039 in the system and so it would not need any special adaptation strategies; however, for the probability of 25%, all of the crops except potato would face the risk of increase of 10% in demand. Climate change causes an increase in water requirement of wheat for 2010-2039 by about 67 and 35 MCM/year based on the present irrigation area for the probability of 25% and 50%, respectively. For the period 2070-2099, for both the probabilities, most of the crops would face the risk of 10%-27% increase in water requirement (110- 150 MCM/year). This will necessitate use of adaptation strategies.

7. CONCLUSION

The aim of this study was to quantify the impact of climate change on agricultural water demand and productivity and to better understand the uncertainty and risk involved in using several Atmospheric-Ocean General Circulation Models (AOGCMs) to predict future temperature and water demand of the Zayandeh Rud irrigation networks in Iran. The following key inferences can be drawn from this study:

- With consideration of monthly temperature change scenarios for future periods, most impacts would be for the period 2070-2099, with the seasonal changes showing increases of 3-8.1, 3.1-8.2, 3-6.9 and 2.3-6.5^{0}C, respectively, for spring, summer, autumn and winter.
- Weighting of AOGCMs shows that, among the seven models considered, CGCM2 has the maximum weight for simulating temperature of winter months and NCAR for other months of a year.
- The probability of water requirement will be increased when approaching the end of this century. This increase would be 8% and 22% for the periods 2010-2039 and 2070-2099, respectively. Based on the current areas of basin’s irrigation networks, this increase can cause an increase of water demand by about 60 MCM/year in the first period and 180 MCM/year in the second period for the crops considered.
- There is also a high risk of reduction of the streamflow in the Zayandeh Rud. Therefore, both demand increase and supply decrease would be expected in the basin, which would lead to a high stress in the basin.
- Changes in crop patterns can be considered as one of the more useful adaptation strategies to climate change. Results showed that potato, as a source of carbohydrate, could have more resistance to climate change, and perhaps because of this the year 2008 has been called the ‘Potato year’ (Potato, 2008).
- Some other adaptation strategies, such as change of planting date and reservoir operation management, are currently being investigated.

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