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Impact of climate change on the monthly runoff of a semi-arid catchment: Case study Zarqa River Basin (Jordan)

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Abstract

In this paper, the long-term hydrological responses (runoff and actual evapotranspiration) of a semi-arid basin to climate changes were analyzed. This basin is the Zarqa River (Jordan). The climate changes were imposed with twelve hypothetical scenarios. Two of these scenarios were based on the predictions of general circulation models (GCMs), namely the Hadley and MPI models. The other ten scenarios are incremental scenarios associated with temperature increases by +2C and +4C and changes in precipitation of 0%, +10%, +20%, -10%, and –20%. These scenarios were used as a basis for observing causal relationships among runoff, air temperature, and precipitation. The Surface-Infiltration-Baseflow (SFB) water balance model that was developed by Boughton (1984) was used for observing these causal relationships. Firstly, areal precipitation and potential evapotranspiration of the basin are estimated based on the observed meteorological and hydrological data. The monthly runoff simulations are then predicted through the application of the SFB model. Seven years of meteorological and hydrological data are used for calibrating the model, and another Seven years of the record are used for model validation. The global optimization technique known as Shuffled Complex Evolution (SCE) method is used to obtain the optimal parameters of the SFB model. The model performed well for the Zarqa River for which the coefficient of determination was 0.78. The average monthly runoff from the model compared well to the observed average runoff. The error of the observed and simulated streamflow is within acceptance limit and found to be around 18 percent. The model performance in the validation stage is reasonable and comparable to those of the calibration stage. Both sets of climate change scenarios resulted in decreases in monthly runoff. Differences in hydrological results among all climate cases are due to wide range of changes in climate variables.

Key words: Climate change, Optimization, Rainfall-runoff modeling, Incremental scenarios, Calibration, Validation.

INTRODUCTION

Global patterns of climate change, predicted by General Circulation Models (GCM) forecast a global temperature increase of 1.5^o to 4^o C with a doubling of the current CO_2 concentration [1, 2]. Climate change has impacts on water resources, and subsequently, on the sustainability of our environment. Climate changes due to increased atmospheric CO_2 and other trace gasses affect the water supply for municipal, industrial and agriculture uses [3, 4, 5].

Lettenmaier et al. [6] indicated that the most important impacts of global warming would be those associated with changes in runoff and groundwater recharge. They also indicated that in areas with rain-dominated hydrology, it is possible to use simple water balance models to estimate the sensitivity of runoff to changes in precipitation and evaporation.

In the last 10 years, monthly water balance models have been used to explore the impact of climatic change [7]. For example, Gleick [8] reviewed various approaches for evaluating the regional hydrologic impacts of global climatic change and presented a series of criteria for choosing among the different methods. He concluded that the use of monthly water balance models appears to offer significant advantages over other methods in accuracy, flexibility, and ease to use. Gleick [8] also developed and tested a monthly water balance model for climatic impact assessment for the Sacramento basin.

Water balance models have been developed at various time scales, e.g. hourly, daily, monthly, and yearly and to varying degrees of complexity. Francini and Pacciani [9] presented a detailed review on monthly water balance models. They grouped the monthly models according to their principal objectives and their input data requirements. Conceptual rainfall-runoff models are those based on the water balance equation. Well known examples of this type of models include the Sacramento Model [10], and variable infiltration capacity hydrological model (VIC-2L) [11]. These models are useful tools in hands of engineers in charge of water resources projects. These models are critical tools for estimating the peak discharge and runoff volume of floods. Usually, the traditional use of monthly water balance models has been to investigate the importance of different hydrologic variables in diverse basins. Monthly water balance models have also been used in snowmelt simulation; climate change assessment; flow forecasting and water project design; and flow record generation in ungauged basins.

In this study, the Zarqa River System, a major surface water system, was selected to reflect actual changes to the existing water resources of Jordan. The monthly runoff for the Zarqa River basin, was assessed through the application of the

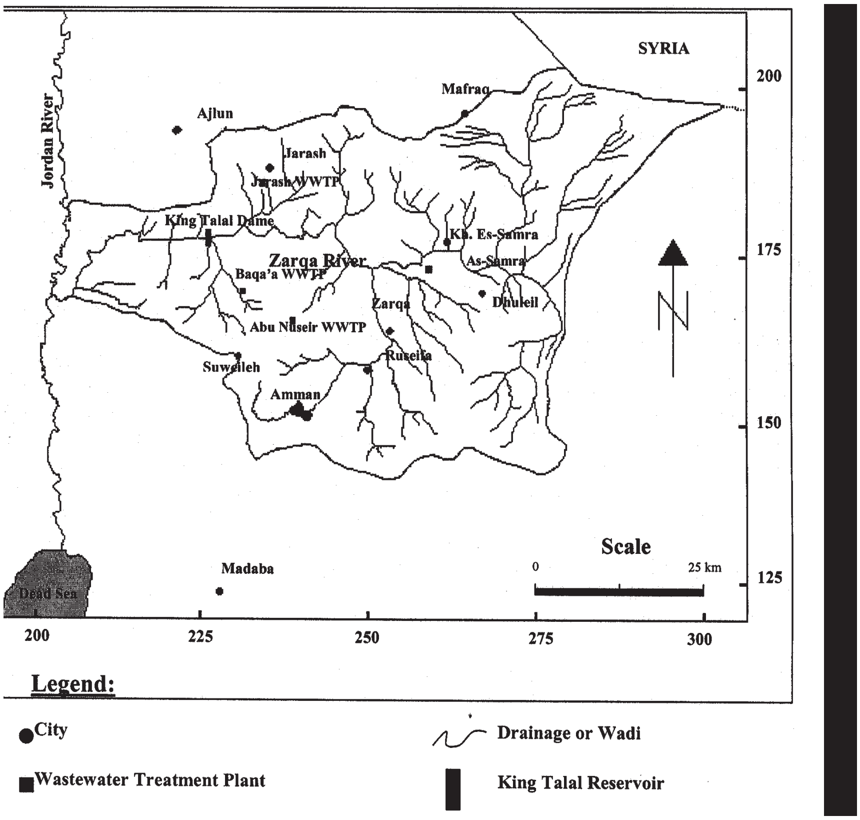

Figure 1. Zarqa River Basin

Surface-infiltration-Base flow (SFB) water balance model. Areal precipitation and evapotranspiration of the basin are estimated based on the observed meteorological and hydrological data. The SFB model has been selected due to its simplicity, which requires 5 parameters to be found by calibration. This model has also been applied previously for climate change studies.

The model was calibrated using meteorological and hydrological records from the period 1981-1988, with data from 1988-1995 used for validation. The global optimization technique known as Shuffled Complex Evolution method of Duan et. al [12] is used to estimate the model parameters. The sum of square differences between the observed and simulated runoff is used as an objective function. Then, the generated climate-change scenarios either those of the GCMs or the incremental scenarios were used as input for the SFB model to assess the impact of climate change on the water budget components of the Zarqa River basin.

Study Area Description

The Zarqa River basin with an area of 3300 km^2, is located in northeastern part of Jordan (Figure 1). Basin altitudes vary between 350 below and 1100 m above mean sea level. The eastern part of Zarqa River System is high desert plateau. Toward the west, the basin changes to a highland and then becomes progressively steeper until it reaches the Jordan valley. The basin is covered sparsely with shrub type vegetation. A variety of crops are planted along the river.

The streamflow of Zarqa river basin is the inflow to the King Talal Dam (the second largest dam in Jordan). The dam is located about 42 km northwest of Amman and impounds a reservoir of about 86 Million Cubic Meter (MCM). The average annual precipitation in the western part of the basin reaches about 400 mm, while in the eastern part it rarely exceeds 150 mm. The bulk amount of precipitation falls in the winter season (i. e., between October to May). The beneficiaries of the Zarqa River basin include households, business entities, industries and farmers.

SFB Model Description

The model selected in this study is the water balance Surface Infiltration Base Flow model (SFB) (Figure 2) which was developed by Boughton[13].

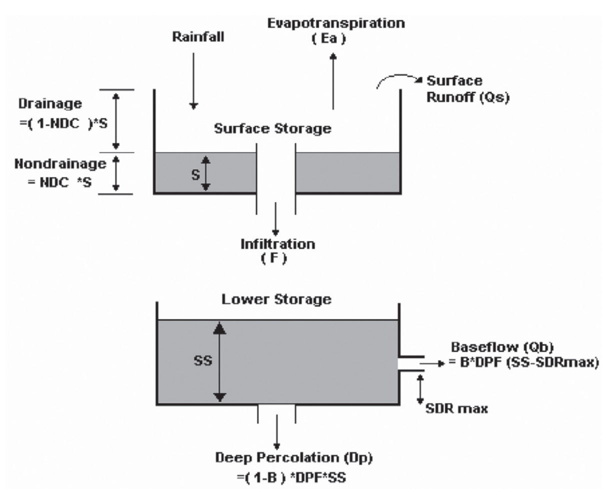

Figure 2. Schematic representation of the SFB model (after Sumner et al., 1997)

This model has been used in a number of studies that focus on the assessment of the impact of climate change. It has also been used extensively in Australia as a means of estimating monthly stream flow from rainfall and potential evapotranspiration. In addition, this model is used for both small and large basins [14, 15, 16,17].

The model requires five parameters to be calibrated. These parameters are: the surface storage capacity of the basin (S), the daily infiltration capacity (F), which controls percolation from surface store to groundwater, the base flow parameter (B), which determines the portion of the daily depletion of groundwater that appears as base flow, and the Non-Drainage Component (NDC), which represents the fraction of the upper storage that is non-draining and the deep percolation factor (DPF) which determines the fraction of depletion from the lower storage. The other model parameters are considered fixed as recommended by Boughton [13]: The maximum limiting rate of evaporation (E_{max} = 8.9 mm/day); and a base flow threshold for the lower store (SDR_{max} = 25 mm) which mean there has to be at least 25 mm of water in the lower store before any base flow occurs.

The model operates on a daily time step, with inputs of daily rainfall and daily potential evaporation. The model runs as follows: incident rainfall begins to fill the surface store, which is depleted each day by evaporation, at the potential rate when the non-drainage component is full. When the non-drainage component of the surface store is not full, then an actual rate of evapotranspiration (ET) is the potential evaporation.

Surface runoff (Q_s) occurs when the surface store is full and is described as

$Q_s = P - F \tanh (P/F)$ ....(1)

In which P is the rainfall excess remaining after the surface store is filled. The lower store is depleted by deep percolation (D_p) and baseflow Q_p which are calculated as

$D_p = (1-B)\ DPF\ SS$ ....(2)

$Q_p = B\ DPF\ (SS - SDR_{max})$..(3)

Where $SS \geq 0$ is the depth of water in the lower store.

The non-drainage component is depleted each day by evapotranspiration. When this component is full, evaporation occurs at the potential rate (E_{pot}). Otherwise, the actual evaporation rate is determined by

$E_a = \min \{ E_{max}\ s/(NDC \times S); E_{pot})$.....................................(4)

where $s \geq 0$ is the depth of water in the non-drainage component of the surface store.

Model Application

The SFB model is applied to simulate the monthly water balance for Zarqa River (Jordan). The SFB model runs on a daily time step. The most important part of the input data is the rainfall data (mm), and potential evapotranspiration (mm). The output of the model is the estimated runoff (mm) and the evaporation (mm). The model input of areal precipitation for the period 1981 to 1995 of the Zarqa River basin was calculated using the Thiessen method. Six daily rainfall stations were selected for the Zarqa River. Three daily meteorological stations were used in the computation of the area potential evaporation. The monthly streamflow data were obtained from the Ministry of Water and Irrigation. The stream flow data were adjusted by subtracting the effluents of the wastewater treatment plants upstream of the New Jarash Bridge Station.

The SFB model has of five unknown parameters (*S, F*, *B, NDC* and DPF). These parameters are estimated through model calibration by fitting the outputs of the model to the observed output at the basin. In this study, a global optimization scheme called the Shuffled Complex Evolution (SCE) method, is employed to obtain the optimum set of the model parameters by minimizing the sum of square differences between the observed and simulated runoff. The SCE method is a global optimization scheme was developed by Duan et al. [12]. The shuffled complex evolution (SCE) method includes four concepts: 1) it combines probabilistic and deterministic approaches; 2) clustering; 3) systematical evolution of a "complex" in the direction of the global improvement; and 4) competitive evolution. A detailed description of the method is given by Duan et al [12]. In short, the SCE method starts with a "population" of points distributed randomly in the feasible space. Then, the population is divided into several "complexes", where each complex has 2n+1 points (n is the dimension of the problem). Each complex is then allowed to "evolve" in a manner that is based on an extension of the simplex local search algorithm. After a number of steps, the complexes are "shuffled" together and new complexes formed such that the information gained separately by each complex is shared. The shuffling and the evolution procedures are repeated until the optimization criteria are satisfied [12]. This method has been recently employed in calibrating several hydrological models by Summer et al [15].

Two statistical criteria will be used to judge on the degree of success reach by application of the SFB model for the selected basin: the percentage error between observed and simulated total runoff, and the coefficient of determination (R^2).

Calibration Results

The calibration period extend from 1981-1988. During the calibration stage several runs were conducted to check for the most appropriate initial soil storage required by the model. In addition, several independent calibration runs are conducted to select the best seed random generator for the SCE optimization method. It is found that the inappropriate selection of the seed random generator may lead to different local minimum. At least 10 independent runs are performed and the run, which resulted in the optimum objective function, has been selected. In the calibration period from 1981-1988, the relative bias ($\Delta V\%$) was less than 18% and the R^2 values for the Zarqa River was 0.78. The calibration results obtained in this study are with the ranges obtained by Nathan and McMahon [18], in their applications of the SFB for about 33 basins located in New South Wales and Victoria, in south-eastern Australia. Figure 3 shows the observed and simulated monthly stream-flow for the Zarqa River for the calibration period.

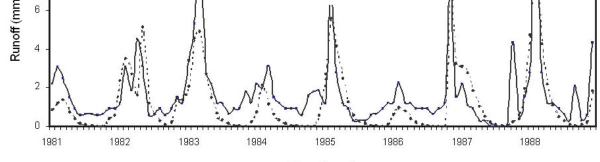

Figure 3. Observed and simulated monthly runoff for Zarqa River (Calibration period 1981-1988)

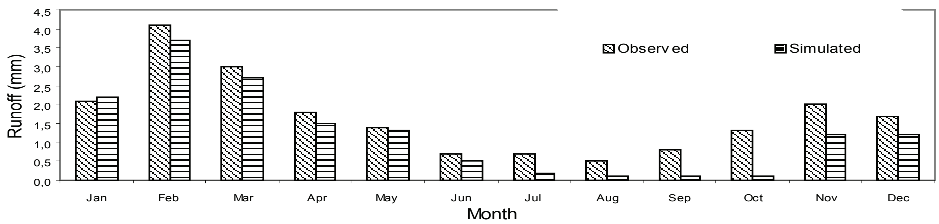

Figure 4a. Mean Monthly observed and simulated runoff for the calibration period 1981-1987

The model performed with different degree of success in terms of matching the observed peak flow and time to peak for the tested basin. The observed and simulated mean monthly runoff for the calibration period is shown in Figure 4a.

The model performance for the rainy months (October – May) was better than those of dry months (June to September). In the dry months, the flow in the river is mainly baseflow which came from groundwater springs which difficult to measure its amount in an accurate manner due to the uncontrolled uses of this flow in the upstream of the basin and due to the difficulties encountered in measuring the low flow season.

Validation Results

The optimum parameters obtained in the calibration stage were used to simulate monthly runoff for the validation period. Validation is performed for the period 1988-1995. For the validation stage, the correlation coefficient was found to be 0.65 and the relative bias was approximately 30%. The hydrograph is under predicted but the but the shape of the hydrograph remains almost the same. Figure 4b shows the observed and simulated mean monthly flows for the validation period.

5. Climate Change Scenarios

Forty years (1960-2000) of historical climate data were used to develop a baseline climate scenario (Table 1) for the Zarqa River basin. The mean annual temperature is 17.2°C, annual mean minimum temperature is 11.1°C, and annual mean maximum temperature is 23.3°C. Mean annual rainfall is 273.6 mm. The monthly variations of these parameters are given in Table (1).

Twelve climate change scenarios representing the possible average climatic conditions around year 2040 were developed. Ten of these scenarios are incremental scenarios suggested as potential scenarios of climate change. These incremental scenarios are associated with two-temperature change of +2°C, and 4°C. Along with each of these temperature changes, changes in precipitation of 0%, +10%, +20%, -10%, -20%.

The other two scenarios were based on the monthly temperature and precipitation projections from two climate change experiments performed using coupled ocean atmosphere General Circulation Models (GCMs). The experiments are Hadley Center model known as HadCM2 [19] and Max Planck Institute (MPI) model run known as ECHAM4 [20]. The HadCM2 experiment was performed in the Hadley Center in 1994/95 [21]. Both the atmospheric and ocean components of the coupled model had a grid spacing of 2.5° latitude by 3.75° longitude. This experiment comprises of two simulations: a) a one thousand year long control simulation with atmospheric greenhouse gas (GHG) and aerosol concentrations set to 1990 level; b) a perturbed simulation in which the atmospheric concentration of GHG is as observed between 1860 and 1990, and from 1990 to 2100, it is increased by 1% per year. In the ECHAM4 experiment, performed in Hamburg in 1995, the horizontal resolution of the atmospheric model was 5.6 latitude by 5.6 longitude and the ocean model was 2.8 by 2.8. The observed historical GHG forcing was applied from 1860 to 1990, followed by an annual increase corresponding approximately to 1% per annum [22].

The output of these models have been retrieved and extracted from the IPCC Data Distribution Center for climate change studies. The monthly temperature and precipitation from the Hadley and MPI models simulation of current conditions (1xCO_2) were compared with observed data (1960-2000) . In Fig (5) the Hadley model output temperature for the current run is in a good agreement with mean monthly temperature for the Zarqa River basin, while the MPI tends to over estimate the baseline temperature.

Temperature and precipitation adjustment statistics for both the Hadley and MPI model were used for construction of climate change scenarios for the Zarqa River basin. Adjustment statistics for difference between scenarios with doubling CO_2 levels by 2040 and scenarios using current CO_2 levels for the MPI and Hadley models are presented in Table (2) .

6. Application of climate change scenarios

The generated incremental and GCMs climate change scenarios were used as a basis for observing causal relationships among runoff, air temperature, and precipitation for Zarqa River basin using the SFB rainfall-runoff model. The goal was to determine how possible changes in the quantity and timing of runoff from changing climate would affect Zarqa River System.

Changes in runoff differ according to the climate change scenarios applied. Generally, using incremental and GCM scenarios, it was found that serious effects could be expected in basins with currently low total precipitation. Basins with high precipitation appear to be relatively less sensitive. Significant changes could therefore be expected in basin with medium and low runoff. Similar results in the Middle east region was noticed by Bou-Zeid and El-Fadel (2002)[23].

The effect of increasing air temperatures alone is shown in figure (6). The runoff decreases as temperature increases. The timing of the peak flow is not changed but the magnitudes of these peaks are reduced. The effect of adding or subtracting

20 percent of precipitation alone to the observed record was as expected. Greater precipitation translated into higher runoff volume during winter. The opposite phenomena occurred when precipitation amounts were reduced 20 percent.

The percent changes of annual mean runoff as a function of temperature and precipitation changes are shown in Figure (7). The largest change in annual runoff occurred when combining a +4°C temperature change with a –20% change in precipitation. These results are similar to those reported by other researchers in the Middle East [23]. For the most critical incremental scenario (+4°C and –20% precipitation), the mean annual runoff is predicted to decline by approximately 70% of the current level. For the incremental scenarios with temperature change from +2°C to +4°C and precipitation reduced by 10%, the annual runoff is predicted to decease by between 40 to 60%. With decreasing precipitation the effect could be critical, particularly during long and extreme droughts. For incremental scenarios with temperature changes from +2°C to +4°C, and precipitation increased by 10%, the annual runoff is predicted to decrease by between 10 to 30%. For example, for the incremental scenario with +4°C and 10% increase in precipitation, the runoff will decrease by about 30%. The annul runoff in the Zarqa River basin will increase by approximately 20% under the incremental scenario in which the temperature increases by 2° C and precipitation increases by 20%.

The temperature and precipitation changes as predicted by the Hadley and MPI models revealed that the mean annual runoff will be reduced by approximately to 12% and 40% respectively. Annual average values do not fully describe runoff changes for climate change scenarios; the annual distribution for various climate change scenarios should also be considered. Figure (8) presents the dynamic changes in mean monthly runoff at the Zarqa River basin for observed conditions (baseline scenario) and Hadley and MPI climate change scenarios.

7. Summary and Conclusions

The impact of the climate change on the monthly runoff of the Zarqa River basin (Jordan) was evaluated using the Surface-inFiltration-Baseflow (SFB) conceptual rainfall runoff model, and application of climate change scenarios (GCMs and incremental scenarios). Seven years of meteorological and hydrological data were used for calibrating the model. The global optimization technique known as shuffled Complex Evolution (SCE) method was used to obtain the optimal parameters of the SFB model. The model performed well for the Zarqa River for which the coefficient of determination was 0.78. The average monthly runoff compared well to the observed runoff. The error of the observed and simulated streamflow is within acceptance limit and found to be around 18 percent. The model performance in the validation stage is reasonable and comparable to those of the calibration stage.

The climate changes were imposed with twelve hypothetical scenarios. Two of these scenarios were based on the predictions of general circulation models (GCMs) namely Hadley and MPI models. The other ten scenarios are incremental scenarios associated with temperature increased by +2C and +4C and changes in precipitation of 0%, +10%, +20%, -10%, and –20%. These scenarios were used as a basis for observing causal relationships among runoff, air temperature, and precipitation. Both sets of climate change scenarios resulted in decreases in monthly runoff. Also, the timing of the peak flow is not changed but the magnitudes of these peaks are reduced. Differences in hydrological results among all climate cases are due to wide range of changes in climate variables. For example, the GCM scenarios for 2x CO2 obtained from the Hadley and the MPI models resulted in similar possible future river flows. Both models showed that the increase in temperature would reduce the monthly runoff for the rainy season except for April (no change) and May (increase). The overall trend indicated that mean annual runoff will be reduced by approximately 12% (for the Hadley Model) and 40% (for the MPI model).

The largest change in annual runoff (reduced by 70% of the current level) occurred when combining a +4°C with a –20% change in precipitation. These results are similar to those reported by other researchers in the Middle East. For the incremental scenarios with temperature change from +2°C to +4°C and precipitation reduced by 10%, the annual runoff will be deceased from about 40 to 60%. With decreasing precipitation the effect could be critical, particularly during long and extreme droughts. However, for incremental scenarios with temperature changes from +2°C to +4°C, and precipitation increased by 10%, the annual runoff shows a decrease from 10 to 30%. The annul runoff in the Zarqa River basin will increase to approximately 20% under the incremental scenario in which the temperature +2°C and precipitation increased by 20%.

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Table (1) Baseline climate scenario for Zarqa River basin

	Climatic variable			
Month	Mean Temp (^oC)	Min Temp (^oC)	Max Temp (^oC)	Rainfall (mm)
Jan.	7.8	3.3	12.3	62.7
Feb.	8.9	4.0	13.8	54.4
Mar.	11.0	6.0	17.1	49.3
Apr.	16	9.4	22.7	13.6
May	20.5	13.2	27.6	2.7
June	23.8	16.8	30.7	0.07
July	25.2	18.6	31.9	0.0
Aug.	25.4	18.6	32.2	0.0
Sep.	23.6	16.6	30.6	0.08
Oct.	20.3	13.6	26.9	8.3
Nov.	14.4	8.8	20.0	26.7
Dec.	9.5	4.9	14.1	51.3
Annual	17.2	11.1	23.3	273.6

Table (2): Statistical adjustment for difference between 2xCO_2 and current (1xCO_2) as estimated Hadley and MPI models for Zarqa River basin.

Month	Hadley Model		MPI Model	
	Temperature Difference	Precipitation Ratio	Temperature Difference	Precipitation Ratio
January	1.43	0.73	1.04	1.07
February	0.98	0.84	0.49	0.64
March	1.29	1.05	0.37	1.28
April	0.71	1.28	1.17	0.91
May	0.31	1.5	1.37	1.77
June	0.95	---	2.29	---
July	0.31	---	2.26	---
August	0.5	---	2.74	---
September	0.8	---	2.51	---
October	1.11	0.87	2.91	1.37
November	0.52	0.79	1.94	0.88
December	1.16	0.7	1.21	0.83
Average	0.85		1.63	

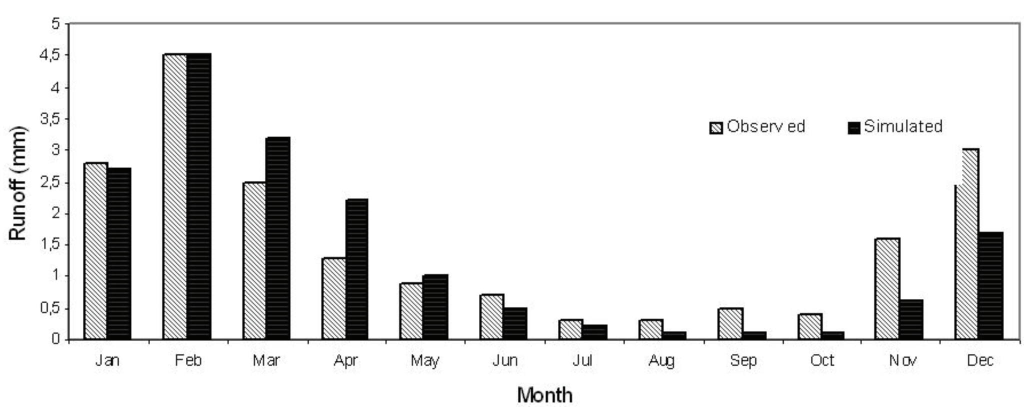

Fig. (4b): Mean monthly observed and simulated runoff for the validation period 1988-1995

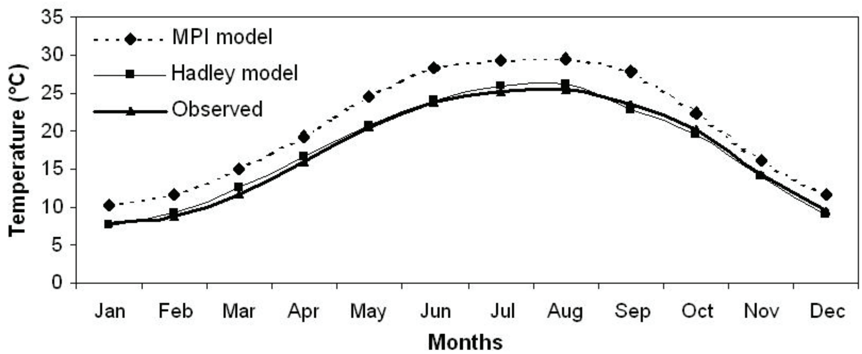

Fig. (5): Comparison of baseline 1960-2000 average mean monthly temperature and 1× CO_2 GCM scenarios for Zarqa River Basin

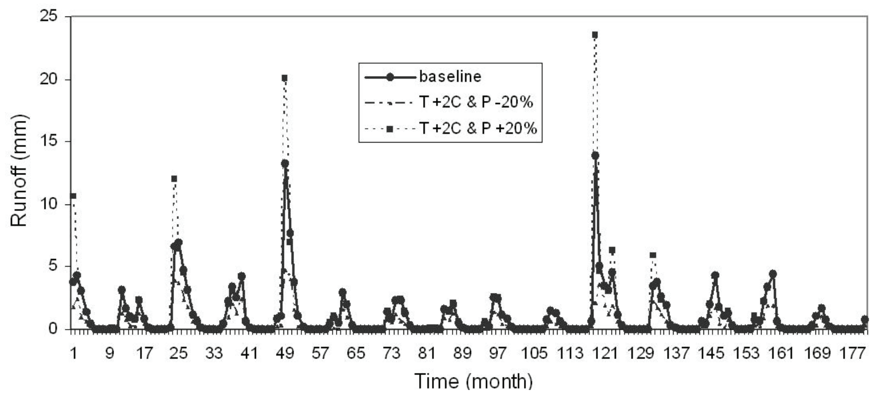

Fig. (6): Simulated monthly runoff under two incremental scenarios:

1) Temperature increased by 2°C and precipitation reduced by 20%;

2) Temperature increased by 2°C and precipitation increased by 20%.

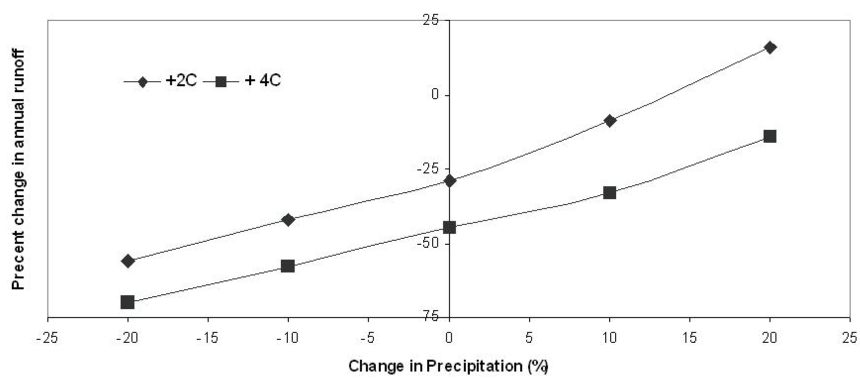

Fig (7) Annual runoff changes under the different incremental scenarios

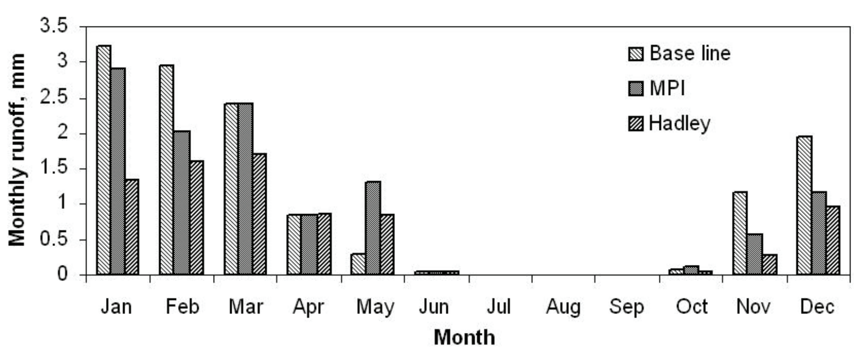

Fig. (8) Comparison between baseline mean monthly runoff and those simulated under generated climate change scenarios of Hadley and MPI models