Water Resour Manage
DOI 10.1007/s11269-008-9369-y

Assessment of the Impact of Potential Climate Change on the Water Balance of a Semi-arid Watershed

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Received: 19 July 2007 / Accepted: 14 October 2008

Abstract With a yearly precipitation of 200 mm in most of the country, Jordan is considered one of the least water-endowed regions in the world. Water scarcity in Jordan is exacerbated by growing demands driven by population and industrial growth and rising living standards. Major urban and industrial centers in Jordan including the Capital Amman are concentrated in the northern highlands, mostly contained within the boundaries of the Zarqa River Watershed (ZRW). The ZRW is the third most productive basin in the greater Jordan River System. King Talal Dam was built a few kilometers upstream of the Zarqa-Jordan confluence to regulate its input mostly for the benefit of agricultural activities in the Jordan Valley. Concerns regarding the sensitivity of the ZRW to potential climate change have prompted the authors to carry out the current study. The methodology adopted is based on simulating the hydrological response of the basin under alternative climate change scenarios. Utilizing the BASINS-HSPF modeling environment, scenarios representing climate conditions with ±20% change in rainfall, and 1°C, 2°C and 3.5°C increases in average temperature were simulated and assessed. The HSPF model was calibrated for the ZRW using records spanning from 1980 through 1994. The model was validated against an independent data record extending from 1995 through 2002. Calibration and verification results were assessed based on linear regression fitting of monthly and daily flows. Monthly calibration and verifications produced good fit with regression coefficient r values equal to 0.928 and 0.923, respectively. Assessment based on daily records show much more modest r value of 0.785. The study shows that climate warming can dramatically impact runoffs and groundwater recharge in

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the ZRW. However the impact of warming can be greatly influenced by significant changes in rainfall volume.

Keywords Climate change · Water management · Water scarcity · Semi-arid · Modeling · Watershed · Hydrology · HSPF · Jordan · Zarqa

1 Introduction

Jordan is a predominately desert country, where 90% of its 90,000 Km^2 receive less than 200 mm/year. With total renewable water estimated at 870 MCM/year (Millions of cubic meters per year), and a total demand around 1,000 MCM/year, Jordan has chronic water deficit that is being satisfied through unsustainable extraction of groundwater (Jridi 2005). Also, water demand is highest in the densely populated highlands, which necessitates transporting water from the lower regions at high costs.

The Zarqa River Watershed (ZRW) is located in the northern highlands of Jordan (Fig. 1). As the third largest river in the greater Jordan River System, the Zarqa River is an important resource that has been placed highly in the country's water resources development strategy. The river has been regulated since 1970 following the completion of the King Talal Dam (KTD), which impounds the river near its confluence with the Jordan River. The dam was later raised in 1987 to increase its storage capacity from 55 MCM to 86 MCM (US Geological Survey 1998). This is mostly to contain the higher runoffs experienced since 1980 due to the diversion of significant sewage flows into the river. The Zarqa River Watershed (ZRW) covers 4,000 km^2, which houses Jordan's main urban and industrial centers including the Capital Amman.

The ZRW has been the focus of several studies (Al-Abed et al. 2005; JICA 2001; Al-Shamil Engineering 2000). The watershed lies in a semi-arid region which is

Fig. 1 Zarqa River Watershed (ZRW)

expected with high confidence to experience significant reduction in precipitation and water availability under potential climate change as indicated by the Intergovernmental Panel on Climate Change (IPCC) in their recent report on climate change and water (Bates et al. 2008). These conclusions support earlier findings by leading GCM models (Ragab and Prudhomme 2002) which points to a climate change induced pattern of prolonged and severe drought in the Middle East and North Africa (MENA) region.

The IPCC report also points to the high sensitivity of semi-arid and arid regions to climate considering the already existing water stress driven by growth in urban, industrial and agricultural demands. The panel has also stressed the need for more research in the impact of climate change on ground water, which is being addressed by the current research.

The current study assesses the impact of climate change through formulating a set of alternative scenarios representing potential conditions in the basin and assess based on a physically-based model of the ZRW. The model was developed using the U.S. Environmental Protection Agency (EPA) BASINS-HSPF modeling environment. BASINS is a modeling interface designed to support the setup and calibration of a set of water and environmental modules including the Hydrological Simulation Program—FORTRAN (HSPF). The HSPF is designed to simulate the main hydrological processes that influence the spatio-temporal distribution of water, and the transport of waterborne pollutants in the basin. The HSPF is composed of several tightly integrated modules, each capturing one of several key hydrological processes (Bicknell et al. 2001).

The HSPF has been used extensively in research and operation. Albek and Ogutveren (2004) used HSPF for modeling the Middle Seydi Suyu Watershed in Turkey for the 1991–1994 water years and investigated different scenarios of climate change. The results indicate that an annual mean temperature increase of 3°C due to climate change will decrease the watershed outflows by 21%. Ackerman et al. (2005) assessed the performance of HSPF in semi-arid southern California in estimating annual, daily, and hourly flows. Burn and Band (2000) used HSPF in combination with ESRI ArcView to assess the effects of land-use change on Upper Gwynns Falls watershed, Baltitmore, USA. Radcliffe (2002) conducted a preliminary analysis of sediment sources in the Broad River watershed using HSPF. Johnson et al. (2003) compared the HSPF and the Soil Moisture Routing (SMR) models, each representing one of these mechanisms. Al-Abed and Whiteley (2002) described a GIS-based procedure for calibrating water-quantity parameters of the HSPF in modeling the Grand River watershed in Canada.

2 The Study Area

The ZRW is characterized by a Mediterranean climate with hot, dry summers and moderately cool, wet winters. Average annual precipitation varies from 400 mm in the western part of the basin to less than 150 mm in the arid eastern part (OPTIMA 2007). The bulk amount of precipitation falls in the winter season between October and May, with virtually no rain during the other months of the year. Evapotranspiration rates are quite significant with an estimated 90% of total precipitation lost to evapotranspiration. Based on class-A pan evaporation measurements, the long-term average of annual evaporation varies from less than 2,500 mm in the southwestern parts to more than 3,200 mm in the northeastern and eastern parts of the ZRW (US Geological Survey 1998). Historic averages of key climatic parameters for the record period (1970–2002) are presented in Table 1 for the basin (Al Mahamid 2005).

The soil types in the ZRW can be classified into four texture groups (clay, silty clay, silty clay loam, and silty loam). Soil layer thickness ranges from 50 to 250 cm. In certain parts of the basin soil thickness can be less than 50 cm (WAJ 2005).

The southwestern corner of the ZRW which encompasses most of Amman and Zarqa city is heavily urbanized. Agricultural activities dominate the western and northeastern parts of the basin. Agricultural land interspersed with forest and pasture lands are concentrated in the western and northwestern parts of the basin. The southern part and southeastern fringes of the basin are mainly barren arid land (Fig. 2).

Four wastewater treatment plants (WWTPs) (As-Samra, Baq'a, Jarash and Abu Nuseir) are located in the ZRW. As the largest WWTP in Jordan, As-Samra plant serves about one third of Jordan's population (US Geological Survey 1998; Rahbeh 1996). The effluent from the four WWTPs constitutes a significant input to the Zarqa, dominating the runoff during the summer season. Water impounded in the King Talal Dam is used mostly to support agricultural activities in the Jordan Valley.

3 Data and Methods

The BASINS-HSPF simulation environment was used to model the ZRW and run alternative scenarios to assess the impact of potential climate. The process was composed of first preparing the data using the BASINS tools. The preprocessed data was then used to calibrate the HSPF for the ZRW based on best fitting of daily, monthly and yearly records. Model calibration was verified using a separate data record. Sensitivity of model performance was assessed with respect to key model parameters. Alternative climate change scenarios were formulated and run through the model.

3.1 Data Processing

HSPF simulates the watershed at the level of a land segment, where hydro-meteorological conditions are considered homogeneous. Land segments drain into a stream network that eventually collects all water at the outlet of the watershed. The initial step in setting up an HSPF model is to delineate the watershed into sub-basins and process and land use data into a GIS database, specifically formatted for HSPF.

Using a BASINS utility tool, a Digital Elevation Model (DEM) for the ZRW was produced from a relief contour map (Fig. 3). The DEM along with locations of the KTD and Jarash Bridge Gauge (JBG) were used in BASINS automatic watershed delineation tools to disaggregate the ZRW into several sub-basins and define the stream network. The delineation results are stored in a special GIS database which has three main themes representing sub-basins, the stream network and the outlets as shown in Fig. 4.

Table 1 Historic averages of the climatic parameters in the ZRW (1970–2002)

Parameters	Months											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Minimum daily temperature °C	13.3	8.9	6.1	4.1	4.7	6.7	9.7	13.1	16	18	17.8	16.3
Maximum daily temperature °C	27.5	20.4	16.3	13.6	15.9	18.3	23.9	28.4	31.5	33.1	32.5	31.4
Mean daily temperature °C	20.4	14.7	11.2	8.8	10.3	12.5	16.8	20.7	23.7	25.6	25.2	23.9
Sunshine duration (h/day)	8.3	6.8	5.4	5.3	6.2	7.2	8.2	10.1	11.1	11.4	10.8	9.3
Wind speed (m/s)	1.6	1.9	1.9	1.9	2.2	2.2	2.3	2.3	2.4	2.4	2.1	1.7
Relative humidity (%)	71	73.4	81.1	82.6	81.1	73.5	65.2	59.2	59.8	63.7	68	69.3
Solar radiation MJ/m^2	4.2	6.3	11.8	18.0	26.0	33.0	31.8	27.5	22.7	14.2	7.9	4.4
Rainfall (mm)	7.3	25.1	48.9	61.8	55.1	42.9	12.8	1.9	0	0	0	0
Class-A pan (mm/d)	7.6	5.2	3.2	2.8	3.8	5.2	8.1	11	12.5	13.4	11.8	10
Potential evapo-transpiration (mm/d)	4.2	2.5	2.3	2.1	2.6	3.9	5.7	6.8	7.6	8.1	7.2	5.6

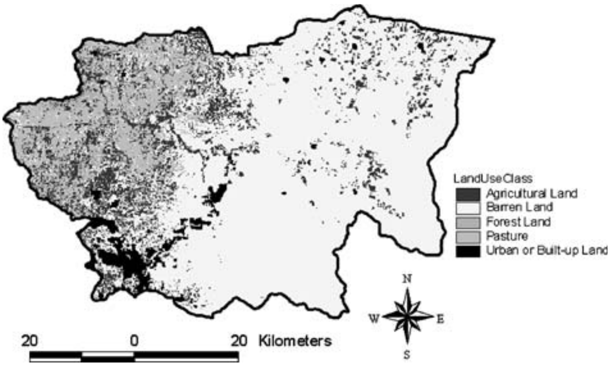

Fig. 2 Land use map of the ZRW

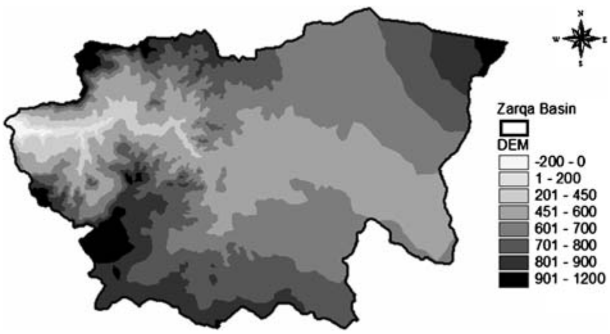

Fig. 3 A DEM map of the ZRW

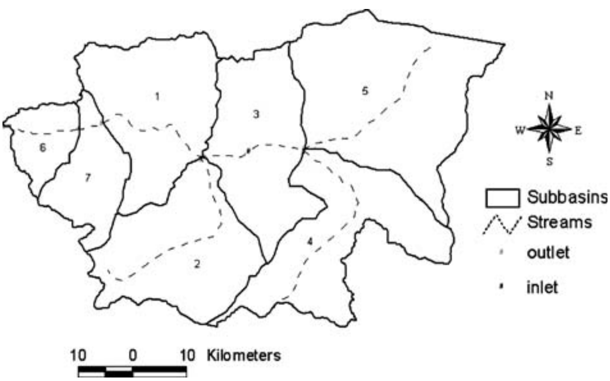

Fig. 4 The drainage area and network of the ZRW as generated by BASINS

Meteorological input is based on data from 18 rainfall stations distributed throughout the basin and two evaporation stations, one located in the eastern part of the basin, and other at the As-Samra WWTP. The Thiessen polygons approach was used to allocate data for the sub-basins.

The significant inflow contribution from the As-Samra WWTP is represented through specifying the plant effluents as input to sub-basin #3. Human-generated runoffs play an important role in augmenting stream flows in arid regions, especially during dry periods. They are generally hard to capture given their independence of natural hydrological processes (Ackerman et al. 2005).

Land use and soil data was used to estimate the percent of pervious cover, perviousness, in each sub-basin.

3.2 Model Calibration and Validation

The model was calibrated using a 15-year record (January 1, 1980 to December 31, 1994) and validated using an independent 7-year record (January 1, 1995 to December 31, 2001). The calibration period includes dry, wet, and normal flood flow years. The calibration was conducted using PEST (Automatic-Calibration parameter estimator model—Al-Abed and Whiteley 2002). The objective function was set to minimize the sum of squares of differences between simulated and measured daily flows at JBG.

The calibration process involved selecting optimal values for key HSPF parameters as listed in Table 2. Other significant parameters that represent overland flow, groundwater, ET conditions, soil moisture conditions, and forest and vegetation cover (see Table 3) are estimated using the BASINS environment based on topographic, soil and land use data.

3.3 Sensitivity Analysis

Sensitivity analysis was conducted to identify most critical model parameters. Sensitivity of a model to a given parameters measures the responsiveness of the model to a given change in the parameter. This can be assessed using the Sensitivity Index S_{I} (Lenhart et al. 2002) described as follows:

$$S_{\mathrm{I}} = \frac{y_2 - y_1}{2\Delta x} . \frac{x_o}{y_o} \tag{1}$$

Where, y is a given model output and x is the model parameter. x_o is the optimal x value obtained through calibration and y_o is the corresponding model output. y_1 is the model output obtained by decreasing x_o by Δx, while y_2 is the model output obtained by increasing x_o by Δx. The S_I for a given parameter is estimated as the slope of the line obtained through fitting a plot of $\frac{\Delta y}{y_o}$ vs. $\frac{\Delta x}{x_o}$.

3.4 Setting up Climate Change Scenarios

To assess the impact of potential climate change on the runoff in the ZRW, several scenarios representing alternative combinations of daily temperatures and rainfalls are run through the model. Table 4 shows a matrix of potential combined temperature and rainfall changes that were used to produce the climate change scenarios.

Table 2 The parameters of water budget simulation process (HSPF model—calibration period)

Name	Definition	Estimated value	Calibrated value	Units	Possible range		Function of
					Min	Max	
LZSN	Lower zone nominal soil moisture storage	6.1[a]	8.0	in.	2	15	Soil, climate
INFILT	Index of infiltration capacity	0.05	0.0324	in./h	0.001	0.5	Soil, land use
AGWRC	Base groundwater recession	0.98	0.997	None	0.85	0.999	Baseflow recession
DEEPFR	Fraction of groundwater inflow to deep recharge	0.1	0.096	None	0	0.5	GW recharge
BASETP	Fraction of remaining ET from baseflow	0.02	0.077	None	0	0.2	Riparian vegetation
AGWETP	Fraction of remaining ET from active groundwater	0	0.0018	None	0	0.2	Wetlands extent
CEPSC	Interception storage capacity	0.1	0.0212	in.	0.01	0.4	Land use
INTFW	Interflow inflow parameter	0.75	1.35	None	1	10	Soil, topography, land use
IRC	Interflow recession parameter	0.7	0.9	None	0.3	0.99	Land use, root depth

[a] LZSN estimated to be (6 for agriculture, bare, pasture and urban lands; 6.5 for forest land; 4 for water)

Table 3 The estimated water budget parameters in HSPF model using BASIN

Parameter symbol	Parameter name
LSUR	Length of the assumed overland flow plane
SLSUR	Slope of the assumed overland flow plane
FOREST	Fraction of the PLS covered by forest
KVARY	Variable groundwater recession parameter
PETMAX	Air temperature below which ET will be reduced below the input value
PETMIN	Air temperature below which ET will be zero regardless of the input value
UZSN	Upper zone nominal soil moisture storage
NSUR	Manning's n for the assumed overland flow plane
LZETP	Lower zone ET parameter; an index to the density of deep-rooted vegetation
RETSC	The retention interception storage capacity of the surface

Potential temperature increases are based on (Dibike and Coulibaly 2005), who indicated that annual global surface temperature has increased by 1°C to 3.5°C over the next century. Corresponding precipitation changes are estimated to lie between ±20% as listed in (Matondo et al. 2004).

A relationship between the temperature changes and the potential evaporation change using Priestley–Taylor method was improved and shows that Priestley–Taylor method gave 2.78% increase in potential evaporation for 1°C increase in temperature. The temperature scenario in the HSPF model is based on this relationship.

4 Results

4.1 Model Calibration and Validation

Estimated and measured runoffs are highly correlated with similar scale when compared on a monthly basis (Fig. 5). The close proximity is also evident from the monthly and yearly time series plots (Figs. 6 and 7, respectively). Monthly correlations for individual low, normal and high flow years are presented in Table 5. Modeled monthly flows are generally well correlated with measured ones during normal and high flow years. In comparison correlations are weaker during low flow years.

Model performance on estimating daily runoffs is generally lower than those for monthly and yearly volumes. Daily correlations between modeled and estimated

Table 4 Climate change scenarios

		Rainfall scenarios				
		−20%	−10%	0	10%	20%
Temp. scenarios	+0°C	✓	✓		✓	✓
	+1°C	✓	✓	✓	✓	✓
	+2°C	✓	✓	✓	✓	✓
	+3.5°C	✓	✓	✓	✓	✓

✓ applicable

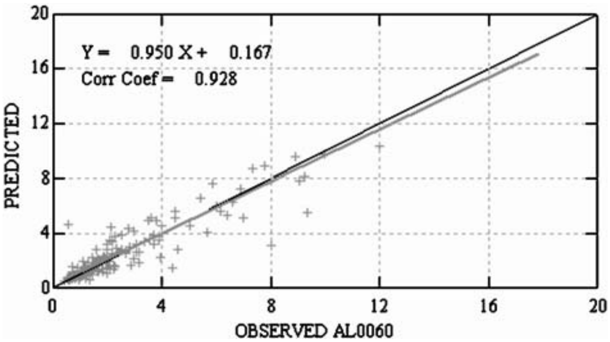

Fig. 5 Scatter plot for the monthly relationship between observed & predicted mean flow in m^3/s

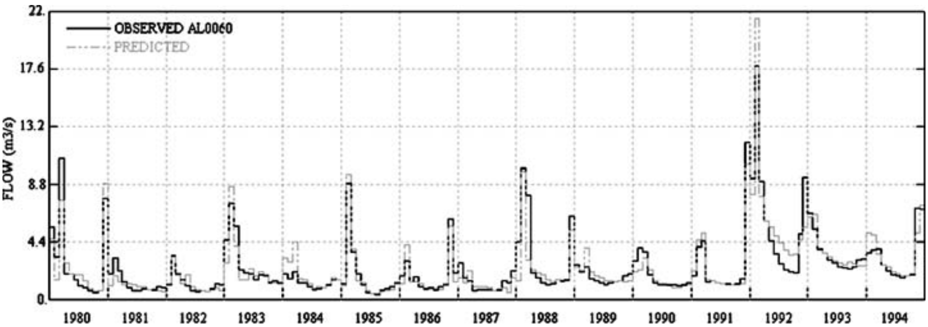

Fig. 6 Analysis plot for monthly mean flow (m^3/s)

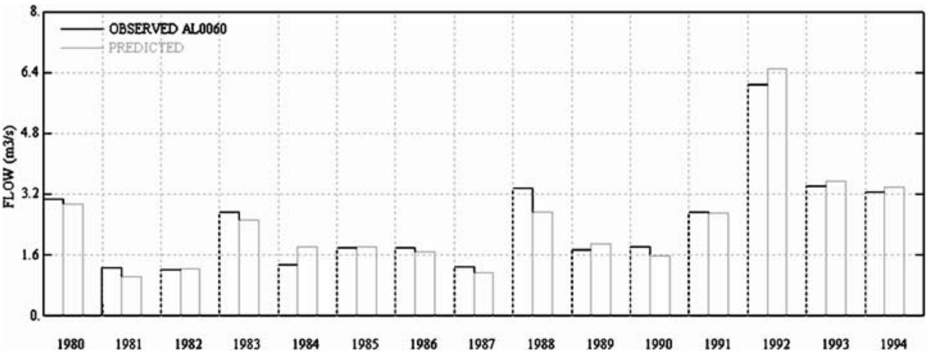

Fig. 7 Analysis plot for yearly mean flow (m^3/s)

Table 5 The evaluation of years during the calibrated period

Simulated year	Monthly correlation coefficient (R)	Simulated year evaluation
Low flow years		
1982	0.911	Good
1984	0.911	Good
1987	0.643	Poor
1989	0.742	Poor
1990	0.885	Good
Normal flow years		
1981	0.764	Poor
1985	0.997	Very good
1986	0.944	Very good
1991	0.988	Very good
1994	0.900	Good
High flow years		
1980	0.931	Very good
1983	0.913	Good
1988	0.845	Fair
1992	0.923	Very good
1993	0.944	Very good

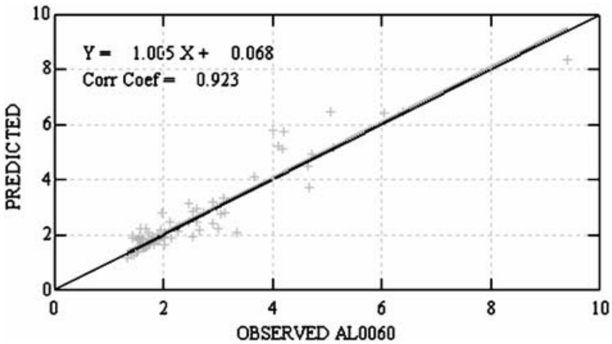

Fig. 8 Scatter plot for the seasonal relationship between observed & predicted mean flow in m^3/s

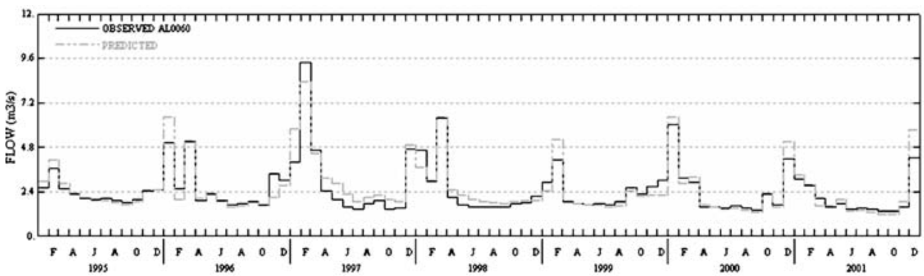

Fig. 9 Analysis plot for monthly mean flow (m^3/s)

runoff stands at an average of $r = 0.785$. However, the performance varies from 1 year to another. For example, the correlation r values for years 1982, 1991, and 1980—which represent low, normal and high flow years, respectively—are equal to 0.66, 0.925, and 0.883, respectively.

Validation of the model produced monthly runoff estimates that were highly correlated with and of the same scale as the measured ones (Fig. 8). The good

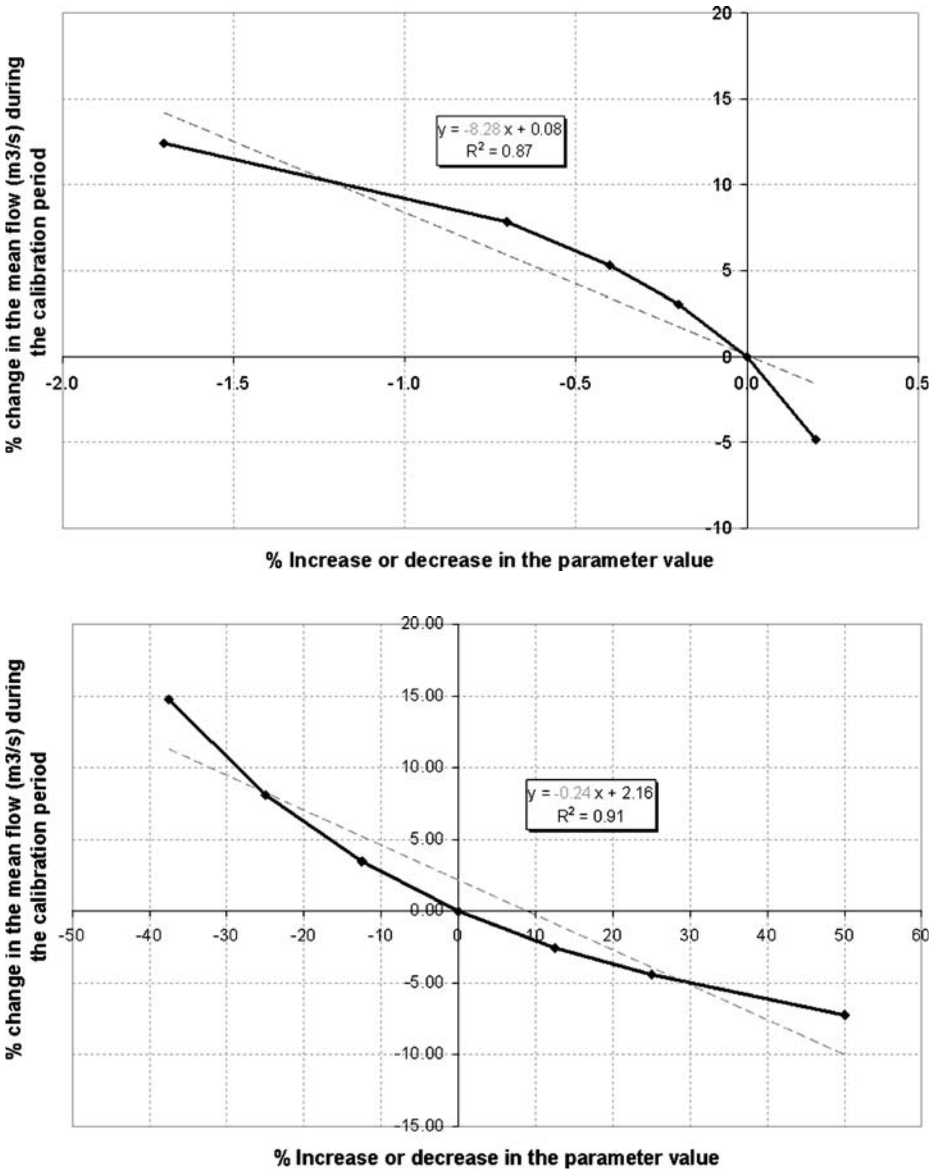

Fig. 10 Sensitivity analysis for AGWRC, LZSN, INFILT parameters

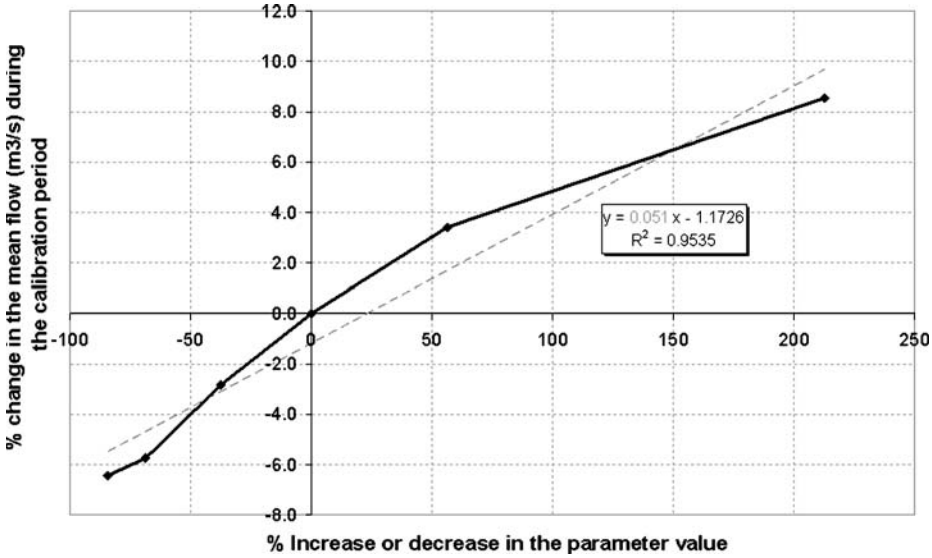

Fig. 10 (continued)

correspondence between modeled and measured monthly runoffs can be also seen in the monthly times series for the validation period (Fig. 9).

4.2 Sensitivity Analysis

The mean flow, Q_m, over the calibration period was used to measure the model response in the sensitivity analysis, i.e. $y = Q_m$. As described earlier $\frac{\Delta y}{y_o}$ was plotted against $\frac{\Delta x}{x_o}$ for selected parameters. 8 parameters were considered in the sensitivity analysis including AGWRC, LZSN, INFILT, AGWETP, DEEPFR, BASETP, IRC and INTFW. The plots of the three most sensitive parameters are shown in Fig. 10. The corresponding sensitivity indexes are presented in Table 6. The sensitivity indexes are categorized from A to E, with A representing $S_I > 1$, B representing $1 > S_I > 0.1$, C representing $0.1 > S_I > 0.01$, D representing $0.01 > S_I > 0.001$

Table 6 Sensitivity indicator and S_I category for water budget simulation parameters in HSPF

Parameter	Sensitivity indicator (S_I) (slope)	(S_I) Category
AGWRC	8.2800	A
LZSN	0.2400	B
INFILT	0.0510	C
AGWETP	0.0300	C
DEEPFR	0.0230	C
BASETP	0.0056	D
IRC	0.0043	D
INTFW	0.0015	D
CEPSC	Very low	E

and E representing 0.001 > S_I. The results show that the model is most sensitive to the parameter AGWRC and hardly sensitive to CEPSC. The model output is significantly more sensitive to AGWRC than the next most sensitive variable (8.28 to 0.24).

4.3 Impact of Potential Climate change

The impact of potential climate change was assessed in terms of corresponding changes in the mean annual flow and the mean annual groundwater recharge. The results from running the 19 climate change scenarios, specified in Table 4 through the calibrated HSPF model are presented in Fig. 11 and 12. The effect of rainfall scenarios on the peak flow was presented in Fig. 13.

Assuming no change in rainfall, higher temperatures are expected to reduce runoff by 1.2% per 1°C increase and erode groundwater recharge by triple that rate. These values reflect the increase in evapotranspiration rates expected as temperature increases. If temperature increase is accompanied with decrease in rainfall, the reduction in runoff and groundwater recharge will be obviously higher. If rainfall decreases by 10%, runoff will decrease by 12.2% with no change in temperature and decrease by 15.5% if temperature increases by 3.5°C. The impact will be much more profound on groundwater recharge. A reduction of 10% in rainfall results in a 32.3% reduction in groundwater recharge if temperature does not change and a 38.9% reduction if temperature increases by 3.5°C. The impact will be much greater for higher reductions in rainfall. A 20% reduction in rainfall would cause runoff to decrease from 20.8% to 23.6% for no change in temperature to 3.5°C increase, respectively. The same reduction in rainfall reduces groundwater recharge by 52.4%

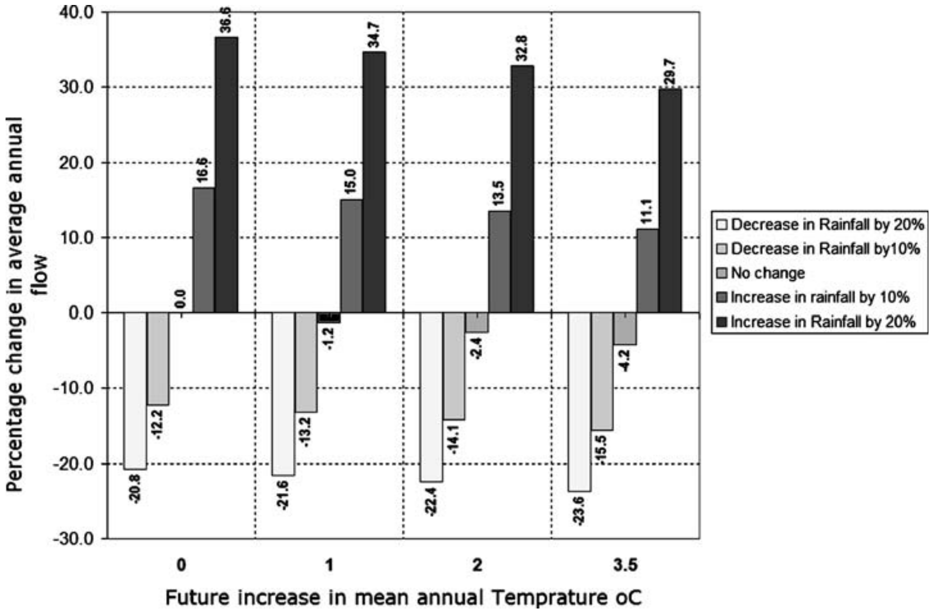

Fig. 11 The effect of climate scenarios on the mean annual flow using HSPF model

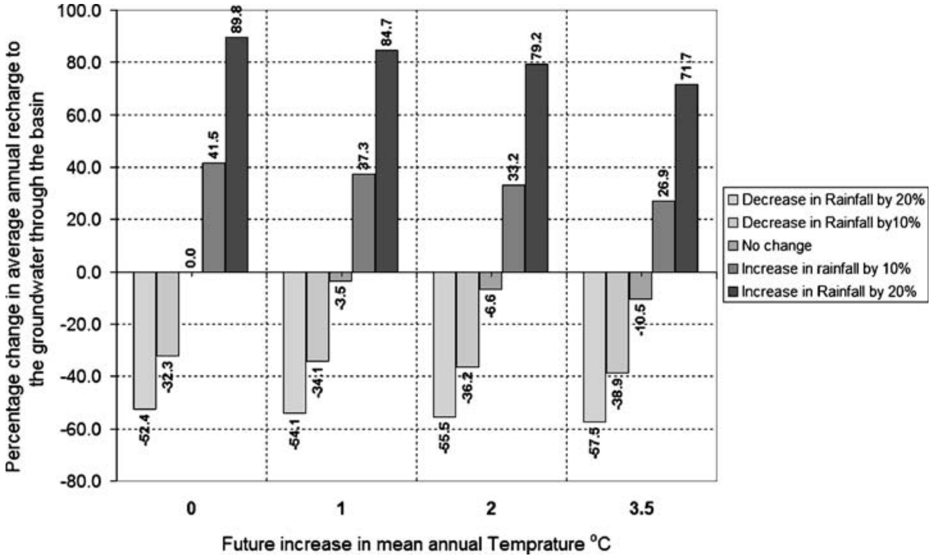

Fig. 12 The effect of climate scenarios on the mean annual groundwater recharge

under the same temperature conditions and 57.5% if temperature increases by 3.5°C. These results show that the impact of temperature increases in the range of few degrees is insignificant in comparison to the impact of 10% and higher decreases in rainfall.

Increases in rainfall are expected to produce significant increases in runoff and groundwater recharge. A 10% increase in rainfall is expected to result in 16.6% and

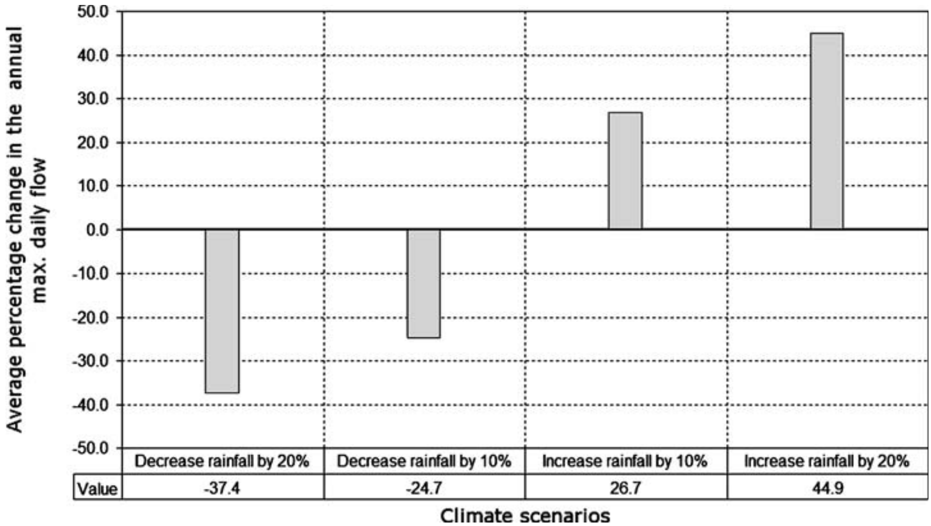

Fig. 13 The effect of rainfall scenarios on the annual maximum daily flow

41.5% increases in runoff and groundwater recharge, respectively, given no change in temperature. A 3.5°C increase in temperature would reduce these estimates to 11.1% and 26.9%, respectively. Doubling the increase in rainfall to 20% with no increase in temperature results in 36.6% and 89.8% increases in runoff and groundwater recharge, respectively. If the increase in rainfall is accompanied by an increase of 3.5°C, runoff and groundwater recharge will only increase to 29.7% and 71.1%, respectively. These results show that the impact of potential climate warming can be greatly attenuated or reversed if accompanied by gain in rainfall.

Figure 13 shows that a 20% increase in the rainfall is expected to result in 44.9% increase in the annual maximum daily flow. A 20% decrease in the rainfall is expected to result in 37.4% decrease in the annual maximum daily flow.

5 Summary, Discussion and Conclusions

The objective of the current study was to assess the impact of potential climate change on the water balance of the ZRW, which is the third most productive basin in the greater Jordan River System. The ZRW is one of the most significant water resource in Jordan, not only because of its high share in Jordan's meager water budget, but also due to being the home to the country's main urban and industrial centers, and an important water supply to the agricultural sector.

The BASINS-HSPF modeling environment was used to develop a hydrological model for the ZRW utilizing digital elevation, land use, soil, and hydro-meteorological data. The model was calibrated using a 15 year record (1980 to 1994) and validated using an independent 7 year record (1995–2001). Modeled monthly and yearly flows were well correlated with measured ones for both the calibration and validation records. Volume errors were also quite negligible. Although the model did not perform as well in estimating daily flows, the results are considered very acceptable considering the higher level of uncertainties encountered when attempting to simulate the hydrological system at short time intervals.

The model performance was more notably better during the normal and high flow years of the record in comparison to the low-yield years. This result can be partially explained by the dominance of treated sewage releases during the drier times and years. Wastewater releases are a function of the capacity of the treatment plant and anthropogenic activities, which are generally unrelated to the hydrological behavior of the basin.

An extensive sensitivity analysis was carried. It showed that the model is highly sensitive to parameters associated with the groundwater recession and the soil moisture storage to a lesser extent. This finding is not surprising considering that the stream flow in the Zarqa River is mostly driven by groundwater during the long and dry periods of the year.

Assessment of climate change impact was carried out by first formulating a set of 19 climate change scenarios representing combinations of mean annual temperature increases (1°C to 3.5°C) and decreases/increases in the rainfall in the range of 10% to 20%. The results from simulating climate change scenarios show that a climate warming, with a maximum of 3.5°C increase in temperature and no change in rainfall, have insignificant impact on the runoff. The effect on groundwater recharge is more pronounced.

Runoff and groundwater recharge would decrease significantly if the climate warming is accompanied with 10% to 20% drop in rainfall. The impact of a rainfall drop dwarfs that of temperature increase. Increases in rainfall in the range of 10% to 20% significantly increase runoff and groundwater recharge. The gain considerably outweighs the reduction induced by temperature increase.

These findings shed some light on the prospect of water losses/gains in the ZRW as a result of potential climate change, which should be carefully examined in setting up a water strategy for Jordan.

The current study is based on an incremental scenarios approach, where a spectrum of precipitation and temperature changes are applied against baseline conditions. The range of incremental values of precipitation and temperatures were selected to encompass those projected globally by the IPCC over the next century. Given the small scale of the ZRW, a more scientifically based approach could be based on downscaling output from a GCM or a regional climate model. However, no regional climate model exists for the area and the downscaling process requires technical capacity and data accessibility beyond those available to this study. More research efforts are therefore necessary to develop more realistic climate projections for Jordan at the catchment scale.

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