Bulletin of Environment, Pharmacology and Life Sciences
Bull. Env. Pharmacol. Life Sci., Vol 5 [1] December 2015: 57-65

Online ISSN 2277-1808
Journal's URL:http://www.bepls.com
CODEN: BEPLAD
Global Impact Factor 0.533
Universal Impact Factor 0.9804

ORIGINAL ARTICLE **OPEN ACCESS**

Application of SWAT Hydrologic Model to Assess the Effect of Climate on Water Balance in Catchments (Case Study)

Muhammad Reza Karaminezhad[1*],Omid Tayari[2]
[1]M.Sc. Student, Department of Civil Engineering, Kerman Branch, Islamic Azad University, Kerman, Iran
[2]Assistant Professor, Civil Engineering Faculty, Islamic Azad University of Kerman
*Corresponding author (email:Krnejad@yahoo.com)

ABSTRACT
Drastic global climate variation in the form of changes in temperature and precipitation in the last decade has become a major challenge for planners. This is because climate variations influence hydrological cycle's parameters, such as soil moisture, run-off, and as such, the available water resources. One of the ways in which to investigate the effects of climate variation on water balance is to simulate the hydrologic behavior of catchments using hydrologic models. By providing a proper simulation of a catchment areausing various scenarios for changes in temperature and precipitation rate,variation of water balance in the catchment can be estimated. The methodology was to investigate the hydrologic behavior of Sarbaz catchment in Sistan and Baluchistan Province, using SWAT (Soil and Water Assessment Tool) hydrologic model for three period scenarios: near future (2020), intermediate future (2050), and distant future (2080). The generated models were tested 30000 times in order to identify the appropriate parameters for simulation. Results reflected the possibility of achieving allowable results using the SWAT model.
***Keywords**: hydrologic modeling, climate change, SWAT, run-off*

Received 11.10.2015 Revised 19.10.2015 Accepted 02.12.2015

INTRODUCTION

Rapidly increasing population which is expected to sustain its trend in the future on one hand and improved economic conditions of a great number of people in the developed and developing countries on the other, has had a corresponding increase in the demand for the renewable water sources. This is in the background of fix resource availability at the supply side. Even if alternative sources are suggested, the economic costs of abstracting these would be prohibitive.For this reason, water supply planning becomes crucial in almost all arid regions like Iran, which is located on drought belts which are likely to experience water resource crises in a foreseeable future .Unprecedented intensification of the resource-straining industrial activities in the form of soil, water and air pollutions have undermined the environmental integrity and ecosystems. The growth of these pollutants has increased the radiation of sunlight from the Earth's surface, which in turn has been instrumental in changing the average global temperature and precipitation trends. If the emission of greenhouse gases is allowed to continue, reports IPCC, the average temperature of the Earth's surface is estimated to increase by 1 to $3.5\,^{\circ}C$ by 2100 Moreover, the legacy of such climatic change is the variation of hydrological regime the world has seen in the last few decades. To put it differently, the precipitation and surface runoff flows show an ascending trend atthe upper and central geographic latitudes while showing a descending trend at the lower latitudes. Moreover, the probabilities of recurring extreme climatic events in the forms severe floods and droughts have increased [1, 2, 3, 4].These fundamental issueshave preoccupied researchers and decision makers with the consequences of the future climate variations and the manner in which to mitigate their impact [5]. Table (1) shows the ways in which climate changes influences the parameters of the hydrology cycle such as soil moisture, groundwater quality and quantity, magnitude and duration of run-offs, and the availability of water resources.

Table (1): The effects of climate change on water resources

Potential effects of climate change on water resources	Consequences
Reduction in the average level of annual snow reserves	Probability of a reduction in the average annual water reserve Expanding challenges of reservoir management and establishment of balance between flood control and water supply
Changes in time, intensity, position, amount and form of precipitation	Probability of increased heavy floods Probability of occurrence of droughts
Long-term changes in catchment vegetation	Changes in the intensity and duration of run-offs Probability of floods and an increase in the sediments in rivers
Increased water levels in high seas	Probability of an increase in the salinity of lagoons Increased failure of dams Probability of an increase in the salinity of coastal aquifers
Increased water temperature	Probability of the loss of aquatic species with water quality variations Increased environmental water demand for temperature control
Increased agricultural and urban demands	Changes in the consumption pattern and evapotranspiration of plants
Hydropower	Probability of a decrease in hydropower levels following changes in the policy for mine harvesting

Various studies have been undertaken on water resources management in general and climate change in particular [6].

In another study, Hoffmann [7]assessed the potential effects of climate variation on river flow regimes and water resources. The study made a comparison betweenthe future and present hydrographs and assessed the spatial variability of the reaction of rivers to climate change.

By studying various climate change scenarios for the Akanagan catchment (located in British Columbia, Canada), [8] simulated the annual and spring flows for the 2050s and 2080s.

Sultani&Qorbanihave investigated the climate change model based on four decades of meteorological data drawn from the Gorgan Stations during1961 and 2000. These researchers have compared the temperature and precipitation variations using the simple linear regression method.

Javanmard and Khazanehdari used a synoptic model, factor analysis and cluster analysis methods to investigate climate changes in Iran.

Tabatabai and Husseini investigated climate variability in Semnan used statistical methods to identify the wet and dry periods, seasonal changes, monthly precipitation, and probability of seasonal/monthly precipitation. Babapour Saber investigated the changes of thermal climate in the northwest of Iran.

Jahanbakhsh and Torabistudied the nature and scale of temperature and precipitation variations and pertinent climatic elements in Iran. Elahi and Hijam studied the effect of climate change on annual runoff volumes and water resources of Imameh catchment area between 1971 and 2003. Massah examined the effect of climate change on water resources on three period scenarios using the AOGCM models under all of the existing SRES scenarios for ZayandehRud catchment: 2010-2039; 2040-2069; and 2070-2099. In addition, Javanused the HSPF model to simulate the runoffs flowing out of Qaresoo catchment and examined the effect of climate change on this flow [9, 10, 11,12,13].

THE SWAT HYDROLOGIC MODEL

An Introduction to the SWAT Hydrologic Model

SWAT (Soil & Water Assessment Tool) model is among the latest models for estimation of climate changes. This model was developed for predicting the effects of land use management on water, sedimentation, chemical agricultural factors (used in catchments with different soil types), land use, and long-term management conditions. This model is properly effective in computation terms and provides users with the possibility of long-term simulation. SWAT is a continuous model from the temporal point of view, which was not designed for simulation of individual flood scenario. The first version of SWAT was introduced to determine groundwater quality. Figure (1) depicts the hydrologic cycle in this model. This model uses the following hydrologic balance equation for simulating the hydrology cycle.

$$\Delta SW = \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \qquad (1)$$

Where,

ΔSW = Water stored in soil following the t-*th* day of simulation

R_{day}= Daily precipitation

Q_{surf}= Surface run-off evapotranspiration

W_{seep}= Water seeping from the soil profile to the unsaturated zone

Q_{gw}= Groundwater flowing into the river

Previous Research Using SWAT

Various studies have used the SWATas an analytical model. Van Liew*et al.*[14]examined the ability of SWAT for simulating river discharge and concluded that this model is capable of simulating discharge with satisfactory precision.

Chu *et al.*[15] used this model to predict the transfer of sediments and nitrate in Warner Creek catchment. Results of their investigations revealed that the SWAT model simulates annual sediments much greater than monthly sediments. However, they stated that simulation of monthly transfer of sediments in rainy months is highly flawed. Schuol and Abbaspour[16] studied the feasibility of applying the SWAT model in regions lacking meteorological data with daily time steps. The study, which was carried out in West Africa, used the monthly meteorological data to prepare daily meteorological data. Abbaspour[17] have applied the SWAT model to simulate a catchment in Swiss. The important advantage of their study was the use of a calibration method based on the uncertainty of model parameters.

Zhi*et al.*[18] investigated the effects of land use change and climate change on hydrologic cycle of a catchment area in China. They applied the SWAT to simulate the hydrologic model and found that climate variation significantly influences hydrologic cycle more than land use change.

Darren *et al.*[19] have investigated the effects of climate change on hydrologic cycle of a catchment with agricultural land use. They used the SWAT model to simulate water balance and found that different components of water balance show different levels of sensitivity to climate change.

Lironga*et al.*[20] applied 15 different climate change scenarios and the SWAT model in order to simulate water balance and showed that climate change is an underlying reason for increase in evapotranspiration.

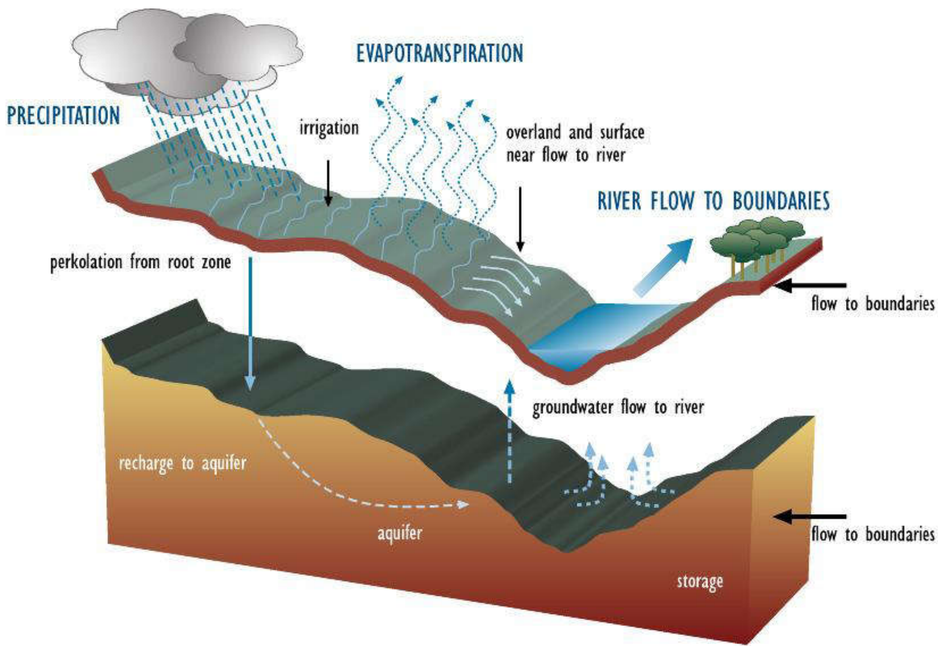

Figure (1): Illustration of the hydrologic cycle in SWAT

Saadati [21] used SWAT to study the effect of land use change on daily discharge on Kasilian catchment and reported an R^2 value of approximately 69% for the values of simulated and measured daily discharges.

Study Area

Sarbaz catchment, which is located in Sistan and Baluchestan Province, was studied in this research. As seen in the following figure, the elevation changes in this region vary between 890 and 1887 m. The study area is situated in Sarbaz County, where a kelimatologystation and a hydrology station (in the sub-catchment) are situated. Sarbazkelimatology station is located at the center of the catchment while thePiran hydrometric station is used as the outlet of the sub-catchment.

GENERATION OF CLIMATIC SCENARIOS

GCM Model

There are a whole variety of approaches that can be taken for the generation of climatic scenarios. Among these, the three-dimensional Atmospheric Ocean General Circulation Models (AOGCM) is the one that has been selected for the purpose of this study. The proposed models are based on the laws of physics, generally expressed by mathematical relations that are solved in a three-dimensional network of the Earth's surface.

One of the ways in which to simulate the Earth's climates to model the major climatic processes (the atmosphere, oceans, Earth's surface, cryosphere, and biosphere) are separately in the form of secondary models. The secondary models of the atmosphere and oceans are then paired to form the AOGCM models. After simulating the past climatic variables with the GCM models, it would be imperative to introduce the future emissions of greenhouse gases to these models to facilitate accurate simulation of the future status of the variables. For this purpose, the emissions of greenhouse gases in the emission scenarios (up to 2100) are converted to concentration and radiative forces before using them as the inputs for the GCM models.

Emission Scenario

The A2 emission scenario is employed to investigate the implications of future climate variations. The study periods were on four-phase basis of the base period (1976-2005); near future (2010-2039); intermediate future (2040-2069); and distant future (2070-2099). Table (2) presents the details of this scenario.

The file containing data on the climatic variables simulated by AOGCM is available at the IPCC website. One of the major shortcomings of the AOGCM models is their large-scale spatial and temporal computational cell resolution compared to the study area. There are different methods for generating regional climatic scenarios from the climatic scenarios of the AOGCM models. These methods are generally referred to in the literature as downscaling procedures. The Inverse Distance Weight (IDW) statistical method is employed is used in this study. The IDW method is also used on the assumption thatthe station being adjacent to the 9 cells of the HadCM3 model. The sharing of each cell is determined on the basis of the distance between the station and the center of cells.

HadCM3 Model

In this research, the output of the HadCM3 (Hadley Centre Coupled Model, version 3),prepared by Hadley Climate Prediction and Research Center (England), was used with the A2 scenario of the emission scenarios collection. The model is applied in various regions of Iran , like Khorasan, Kermanshah, Isfahan, Shahrekord provinces because of the quality and accuracy of its prediction that is comparatively claimed to yield results with a close proximity to the observational data [22,23]. Table (3) shows the general specifications of the proposed model.

Temporal Downscaling

The change factor is applied for the purpose of this research in order to downscale the research data in terms of time. In order to obtain the future time series of the climatic scenario, the climate change scenarios are added to observational values by using the following equations (1976-2005).

$$T = T_{base} + \Delta T \quad (2)$$

$$P = P_{base} + \Delta P \quad (3)$$

Where,

T_{base} denotes the time series of the monthly observational temperature in the base period, T is the temperature time series resulting from climate change in the future, and ΔT is the downscaled climate change scenario. The aforementioned parameters in relations (2) and (3), are also used for precipitation and relative moisture.

Table (2): Specifications of the A2 emission scenario in 2010 as compared to 1990 (IPCC, 1999)

Scenario specification	1990	A2
Population (billion people)	5.252	15.1
Concentration of CO_2 (ppmv)	354	834
Variation of the Earth's average temperature ($^{\circ}C$)	-	(2.1-4.4) 3.1
Global increase in sea level (cm)	-	(27-107) 62
Global GDP (10^{12}\$)	21	243

Table (3): Specifications of the HadCM3 model (IPCC, 1999: Gordon *et al.*, 2000)

Specifications	HadCM3
Spatial precision (degree) (length × width)	2.5 × 3.75
Spatial precision (degree) (length × width)	2.5 × 3.75
The periods of simulation of greenhouse gases and particulates in the past	1860-1989 CO_2 1860-1989 SO_4
Duration of simulation (year)	(control period: 240) (SRES scenarios: 1950-2099)
Simulated SRES scenarios	A1, A2, B1, B2

SWAT Model

The SWAT model calls for three major categories of information for simulation purposes, which include information layers, information files and numerical inputs (parameters). Meteorological parameters (precipitation, temperature, and half-hour rainfall intensity); Soil science parameters; land management parameters (including data on agricultural lands and water consumption); and parameters contributing to hydrologic simulations (the only method for obtaining these parameters is by calibrating the model based on the physical description of each parameter) are involved in the simulation of the SWAT model.The purpose was to estimate the variations of T_{min}, T_{max} and precipitation levels during a 90-year period. This was based on using these three parameters as required for introducing the observational time series of these parameters to the SWAT hydrologic model. This was then followed by calibrating and validatingthe model by using the SUFI-2 optimization algorithm in the SWAT-CUP. The first step in this software is selecting the parameters influencing the catchment. Table (4) presents some of the typical parameters along with their primary scopes. The results of validation and calibration (after running the model for about 30000 times) are presented in Table (5) and Figure (2).

Table (4): Some of the parameters and restrictions applied in the software

Input Parameter	Min	Max
v__SPCON.bsn	0.002	0.005
v__SFTMP.bsn	-5	5
v__CH_K2.rte	0	150
v__CH_N2.rte	0	0.30
v__OV_N.hru	0	0.80
v__SLSUBBSN.hru	10	150
v__ESCO.hru	0.01	1
v__EPCO.hru	0.01	1
v__RCHRG_DP.gw	0	1
v__SHALLST.gw	0	1000
v__GW_REVAP.gw	0.02	0.2
v__REVAPMN.gw	0	100
v__GW_DELAY.gw	0	400
v__ALPHA_BF.gw	0	1
r__SOL_ALB.sol	-0.50	0.50
r__SOL_K.sol	-0.80	0.80
r__SOL_AWC.sol	-0.30	0.30
r__SOL_BD.sol	-0.30	0.30
r__CN2.mgt	-0.40	0.040

Table (5): Results of calibration and validation

Model type	Calibration		Validation	
Variable	NS	R^2	NS	R^2
FLOW_OUT_1	0.79	8.81	0.51	0.50

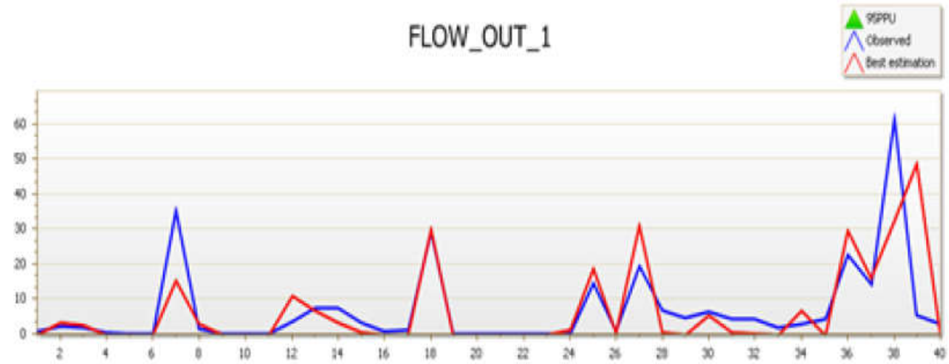

Figure (2): Results of model validation

NS (seepage coefficient) is a statistical index.The modeling can claimed to be acceptable under the scenario where the NS is higher than 0.5. R^2 denote the coefficient of determination (precision statistical index), which generally varies between 0 and 1 range. The higher proximity of the R^2 value to 1, the more desirable would be the results. In order words, the more close the R^2 value to 1, the higher the model precision and validity to simulate the real world situations. The process involved accurately-determining parametric values for the simulation and modeling. These values are shown in Table (6).

Table (6): The exact value of some of the parameters used in computer modeling

Input Parameter	Assigned Value
r__CN2.mgt	0.1512
r__SOL_BD.sol	0.0318
r__SOL_AWC.sol	-0.0834
r__SOL_K.sol	-0.2832
r__SOL_ALB.sol	-0.455
v__ALPHA_BF.gw	0.507
v__GW_DELAY.gw	168.4
v__REVAPMN.gw	13.3
v__GW_REVAP.gw	0.15986
v__SHALLST.gw	169
v__RCHRG_DP.gw	0.633
v__EPCO.hru	0.03475
v__ESCO.hru	0.92575
v__SLSUBBSN.hru	45.98
v__OV_N.hru	0.2984
v__CH_N2.rte	0.1695
v__CH_K2.rte	138.75
v__SFTMP.bsn	-3.37
v__SPCON.bsn	0.002627

RESULTS AND DISCUSSIONS

After validating the model, estimations of various climate change scenarios variations for three periods of the near future (2020), intermediate future (2050), and distant future (2080) were made on the basis of the statistical data from the study area. The results obtained for the first, second and third periods in figures are shown in tables 3, 4, and 5, respectively. As can be noted, the precipitation rate shows an incremental trend of 12.34 mm and 7.13 mm for the near future (2020) and intermediate future (2050), respectively. By contrast, the precipitation rate is anticipated to decline by 32.87 mm in the distant future (2080).

So far as the runoffs in the scenarios are concerned, an increase is initially observed in the intermediate future, whereas a decreasing trend is expected for the distant future. Although the evaporation potential is expected to have an incremental trend, actual evapotranspiration is anticipated to decline markedly in the intermediate and distant futures. Such a decline is attributed is attributed to a whole variety of factors, the most prominent of which is the significant reduction in water resources availability at global levels.

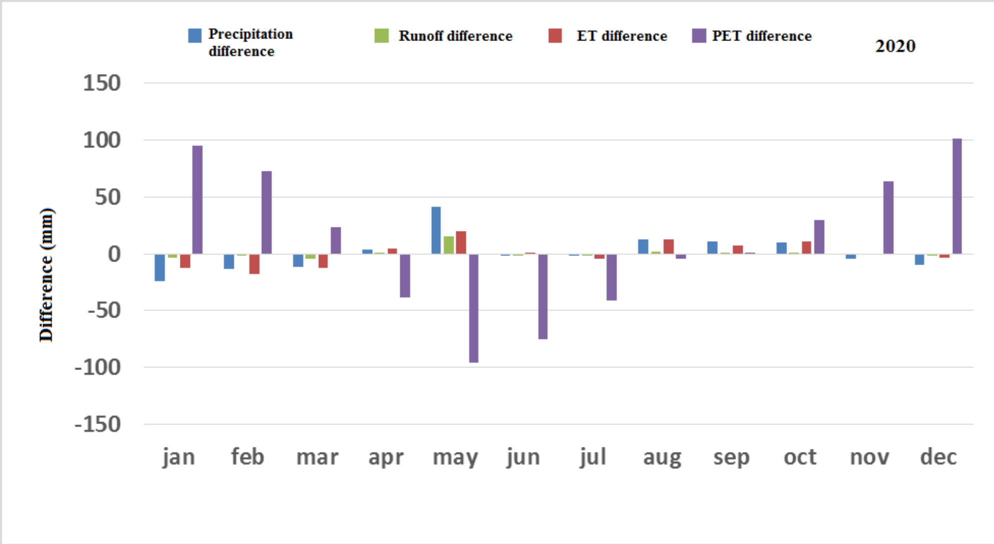

Figure (3): Variations of balance components in near future

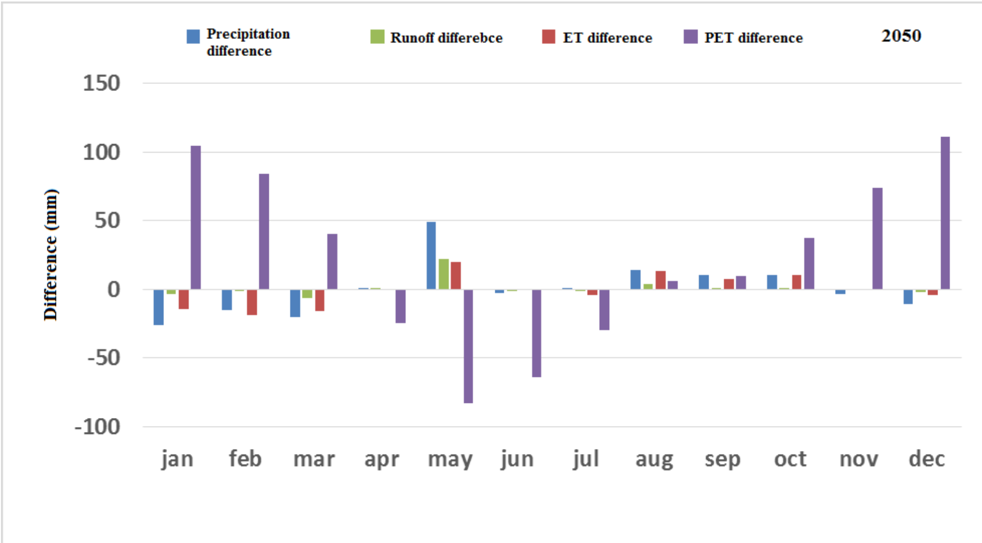

Figure (4): Variations of balance components in the intermediate future

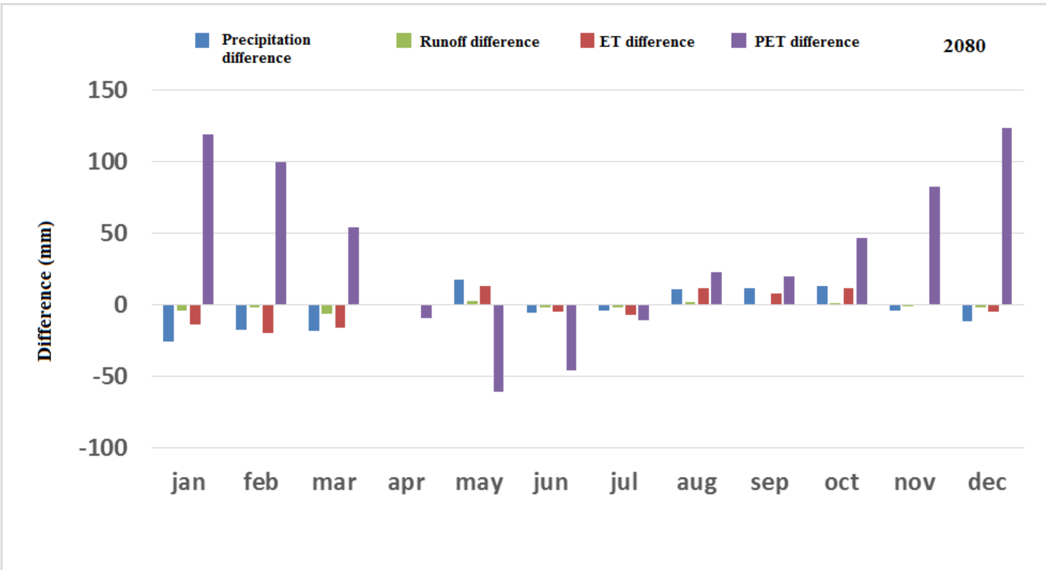

Figure (5): Variations of balance components in the distant future

CONCLUSION

The aim of this paper is to investigate the climate changes in the Sarbaz catchment area of Sistan and Baluchistan Province in Iran for three periods of near future (2020), intermediate future (2050), and distant future (2080), using the SWAT hydrologic model. Results show different ratios for various balance components in different months. Moreover, results show a drastic decline in the actual evapotranspiration rate for the intermediate and distant future, which is principally, attributed to water resources shortages. The data also suggest the likely increase in the evapotranspiration rates for all three period scenarios. The major underlying cause of such increasing evapotranspiration trend is to do with the emergence of global warming and its future implications. By and large, the results of this study seem to reflect the alarming condition and a warning shot for decision-makers to take prompt proactive measures in order to mitigate the effects of water resources shortages and the implications for arid and semi-arid region of the Middle East and North Africa. That would have to be taken seriously if one expects to fulfill the National Economic, Social and Cultural Plans. It would be particularly crucial for the highly-populous and rapidly-developing countries like Iran, to prepare herself forthe middle and long-term basis and to find means of coping with the spiraling demands made by various economic, industrial, agricultural, recreational and environmental sectors for water resources. This highlights the necessity for rational and systematic supply and demand planning and management that would not only have to look at the manners by which to boost the supply side, but simultaneously takes measures to improve demand management. Such a holistic approach to water resources management is likely to mitigate the emerging water crisis and guarantee sustainability in crop production and macro-economic development of the region.

The AOGCM models were used to define the emission scenario and the IDW method was employed to minimize the error caused by large-scale resolution of the scenario. It was found that the hydrologic models developed on the basis of the SWAT framework yield relatively higher precision in calibration and validation phase after 30000 tests. The simulation model suggests a high validity and reliability of the software for the estimation of climate changes in Iran.

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CITATION OF THIS ARTICLE

Muhammad Reza K, Omid T. Application of SWAT Hydrologic Model to Assess the Effect of Climate on Water Balance in Catchments (Case Study). Bull. Env. Pharmacol. Life Sci., Vol 5 [1] December 2015: 57-65