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WATER RESOURCES MANAGEMENT SCENARIO ANALYSIS IN THE KARKHEH RIVER BASIN, IRAN, USING THE WEAP MODEL

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ABSTRACT

This paper uses the Water Evaluation and Planning model (WEAP) to assess the effects of water and land resources development in the upper Karkheh River Basin (Iran) on downstream municipal, industrial and agricultural uses and on inflow to the Karkheh Reservoir. The hydrological model component of WEAP called the Soil Moisture model was calibrated for a seven-year time period (1988-1994) and validated for a three-year time period (1995-1997). Water resources development and management measures evaluated were: (1) demand management in domestic and industrial sectors; (2) reservoir operations; (3) increasing irrigation efficiency; (4) changing water allocation priorities; (5) expansion of irrigated lands; and (6) increasing groundwater withdrawals. Results showed the capability of WEAP model in water resources management scenario analysis at a river basin scale.

Key words: WEAP model, river basin simulation, water allocation, Karkheh River Basin, Simareh sub-basin

INTRODUCTION

Today's agriculture accounts for the majority of water withdrawals; hence irrigation is the dominant water use in many arid and semi-arid river basins. As populations continue to rise, irrigated agriculture will provide an increasing share of total food production to meet the growing demand. Moreover, water demands for domestic and industrial uses in developing countries grow even more rapidly than agricultural water demand. Unlike many river basins in Iran, water and land resources in the Karkheh River Basin are not fully developed and allocated yet. Considering the potential conflicts arising from competing demands of water resources systems in the near future, the planning of water resources systems in this basin requires a comprehensive and integrated approach. This approach should address the interactions within and among different systems at several spatial and temporal scales and in different points of the basin. It should also be able to aid the evaluation of different development and management strategies by involving structural and non-structural measures.

In a river basin, development and management of one part of the basin affects the land and water in other parts of the basin. The main objective of this paper is to evaluate the effects of upstream development measures on downstream demands. Also, this study intends to evaluate the functionality of the Water Evaluation and Planning (WEAP) model by considering the mentioned objective. In particular, the focus is to assess different scenarios of demand management, reservoir operation and water allocation, and construction and operation of new reservoirs. These scenarios intend to address a broad range of "what if" questions. Necessity of these management measures arises from the competitive nature of water demand in the basin. Therefore, the hydrologic effects of these measures, as well as the supply effects on demand coverage in agricultural, domestic and industrial sectors were studied. It should be noted that this study did not consider hydropower generation, environmental flow demands, and other socio-economic and environmental aspects.

The Karkheh River Basin (KRB) was one of the best options for this study since the previously mentioned measures are considered in the development plan of this basin. The KRB can be divided into three parts: (1) upper (UKRB); (2) middle (MKRB); and (3) lower (LKRB). The study area for this research was limited to the Simareh sub-basin (SSB), which is located in the MKRB. The SSB has an area of 16,411 sq km and is located in the central region of the KRB (see Figure 1). It receives tributary flows of the UKRB that ends up in the LKRB. The SSB was selected for three reasons: (1) to reduce spatial scale of the problem in the first trial of the WEAP model; (2) to use the middle location of the SSB in the KRB that reflects the nature of upstream-downstream interactions; and (3) to include the large dams under construction of the KRB in the SSB.

Karkheh Reservoir, the biggest embankment dam in the Middle East, has been recently constructed on the Karkheh River at the interface of the SSB and the LKRB. Karkheh Reservoir and its downstream irrigation and drainage network, which has not been constructed completely, are the only surface water resources of the LKRB which can be utilized to expand the irrigated area and supply the increasing water demands of other sectors. The impacts of water resources development and management measures in the UKRB on inflow to Karkheh Reservoir may give an overall picture of the impacts on the LKRB. Water resources system simulation models are needed to assess the impact of management measures in scenario frameworks. There are many simulation models at the river basin scale, such as RIBASIM, WEAP, MIKE BASIN, MODSIM, and WBalMo. WEAP was selected among them for three main reasons: (1) its integrative approach in considering hydrological processes and water allocation and management systems together; (2) its extensive usage all over the world; and (3) its free accessibility.

WEAP has a module to model hydrologic processes. The hydrological model is semi-theoretical, continuous time, semi-distributed, and deterministic. As the model is semi-theoretical, it needs calibration and verification. Agricultural water demand is computed by three methods: (1) the Soil Moisture method (the most complicated one); (2) the FAO method, which uses crop water requirement coefficients (the intermediate one); and (3) the Standard method (the simplest one). The Standard method computes the water demand as the product of activity level and water use rate for different sectors, such as, industrial, municipal, agricultural, etc. Demand for all sectors, except agricultural, can be computed only with this method. WEAP uses a one period linear programming routine to allocate resources between demands (Sieber et al., 2005a; Sieber et al., 2005b). The hydrological module of WEAP was needed for this study due to the importance of the interaction between surface and groundwater in the Simareh sub-basin, the lack of sufficient gaging stations in spite of the existence of sufficient meteorological stations, and the necessity to model irrigation demands.

WEAP has been used in many projects all over the world. Raskin et al. (1992) studied the current situation and the impacts of management strategies in the Aral Sea basin; management strategies were changing the consumption pattern, better system management, and new water resources development. Yates et al. (2005) evaluated the effects of introducing environmental priorities to water allocations in the Sacramento River basin. Levite et al. (2003) evaluated the impacts of demand management in the agricultural sector in the Olifants river basin in South Africa. Alfarra (2004) assessed the water allocation routines, types and causes of the future problems of the Naivasha Sea basin in Kenya, which is predicted to encounter some problems in the near future due to the increasing water demands in some sectors.

HYDROLOGIC MODELING

To set up the model, monthly time steps were used in hydrologic simulation for the following reasons: (1) compatibility with significant hydrologic processes time periods, (2) adherence with mid-term horizon (15 years) which has been considered in this work, and (3) existence of the data in a monthly framework. According to the Karkheh Integrated Water Plan (KIWP), the SSB is divided into five catchments: Noorabad, Eslamabad Gharb, Chardavol, Dareh Shahr, and Molab. Each catchment is divided into Hydrological Units (HUs) to make twenty HUs for the SSB. Also, the model elements, including nodes (sub-catchments, industrial and municipal demand sites, alluvial aquifers and storage reservoirs), and links (transmission from river and groundwater demand sites, transmission of runoff/infiltration to river/groundwater, return flow and rivers) were determined.

PREPARATION OF THE INITIAL DATA

The required initial data can be divided into four groups: (1) meteorological and hydrological data; (2) basin physical characteristics; (3) water demand in agricultural, municipal and industrial sectors; and (4) physical characteristics of alluvial aquifers. Meteorological data include precipitation, temperature, relative humidity, and wind speed, and hydrologic data that include stream flow and groundwater level. Missing data in a 15-year time period (1988-2002) for precipitation, temperature and relative humidity from measurements in synoptic and climatology stations were estimated by linear regression. Areal average time series for each HU was computed using the Thiessen polygon method. Missing data in the time series of stream flow measurements in five gauge stations, located at the end of each catchment of the SSB, was estimated by regression analysis. It should be added that the time series of groundwater level were available for only 2 of the 20 HUs.

The basin characteristic parameters in WEAP include land use, Leaf Area Index (LAI), Root Zone Water Holding Capacity (RZWHC), hydraulic conductivity, and flow direction. A LULC GIS layer prepared by Iran's Agro-Economic Research Institute was used for land use data. It should be noted that the LAI was initially estimated from global measurements of this parameter all over the world based on the land use data for each HU (Asner et al, 2003; Yates et al., 2005). The RZWHC was initially estimated from global measurements of rooting depth all over the world based on land use data for each HU (Canadell et al, 1996; Yates et al., 2005). The LAI and RZWHC were then calibrated for each HU. The Hydraulic conductivity of the root zone layer and the deep layer was estimated for each sub-catchment using stream flow time series analysis.

Agricultural water demand is simulated in each hydrological unit. Required parameters are crop water requirement coefficient (Kc) and soil moisture thresholds for irrigation. Soil moisture thresholds including the upper and lower limit were initially estimated and then adjusted in the calibration process by comparing observations of withdrawal for irrigation in the base year with model results. Based on the KIWP report, the municipal and industrial water demand has been considered as a constant value for the whole time period. Also, some of the physical characteristics of the alluvial aquifers including specific yield, hydraulic conductivity and maximum withdrawal were estimated based on the KIWP report (Jamab, 1999). The horizontal distance and wetted length (two other parameters) were initially estimated using a GIS layer which distinguishes flat lands from highlands in each hydrological unit. The layer was developed by the authors. Finally, the aquifer storage at equilibrium with the river and wetted depth were initially estimated and then adjusted in calibration.

MODEL CALIBRATION AND VALIDATION

The WEAP does not automatically calibrate the hydrological model; therefore the calibration must be implemented manually. Manual calibration needs experience and is time consuming. We used a seven-year period of data (1988-94) for model calibration, and a three-year period of data (1995-97) for model validation. Water withdrawal data was only available for 1993. Agricultural demand is computed by the model by considering meteorological and hydrologic conditions. To calibrate the model parameters, comparisons were made between observed and computed values for the annual average of irrigation demand and irrigation water withdrawal, stream flow, groundwater level in wells, water balance of aquifers which were computed by hydrologists for the SSB; also for irrigation water withdrawal from surface and groundwater resources, and irrigation efficiency computed by irrigation experts (Jamab, 1999). The following steps were made to calibrate the model:

1. Adjusting related parameters (irrigation thresholds and loss rate in transmission links) based on irrigation water withdrawal observations and irrigation efficiency;
2. Adjusting related parameters (hydraulic conductivity and wetted length) based on water balance of aquifers;
3. Adjusting related parameters (aquifer storage at equilibrium and specific yield) based on groundwater level in wells;
4. Adjusting related parameters (RZWHC and LAI) based on stream flow data; and
5. Repeating steps 1 to 3 due to the high sensitivity of model performance to parameters of step 4 (RZWHC and LAI).

ASSESSING MODEL PERFORMANCE

As described previously, the aim of calibration is to adjust the parameters so that the model solutions fit the observations in an optimal fashion. There are two general approaches for assessing the calibration quality; namely subjective and objective. Subjective assessment is based on a visual comparison of the simulation results with the observed data. In contrast, objective approaches are based on developing some quantitative measures of the quality of fit. To evaluate the results of the model with respect to the stream flow, two measures of error were used: Efficiency Index (EI) which represents relative error, and the Root Mean Square Error (RMSE) which represents absolute error.

Values of these measures are presented in Table 1, and stream flow results at end of each catchment are shown in Figures 2 to 6. These figures show an adequate agreement between the model's output and observed data in all catchments except for Eslamabad Gharb. Compared to other catchments, this catchment has a small hydrologic contribution to the SSB stream flow, so the model seems good enough to be used in scenario evaluation. Figures 7 and 8 show the results of groundwater level simulation compared to observations for two HUs (Eslamabad Gharb and Hasan Abad).

SCENARIO EVALUATION

The main objective of this paper is to assess the impacts of management strategies in supplying the increasing water demand at different sectors. The main management strategies are demand management, changing water allocation priorities, and water resources development. The important issue is the effect of the changes in upstream of the basin due to these strategies on downstream of the basin. For example, we should evaluate the impact of upstream water demand rise, which will result in more water withdrawal, on meeting downstream water demands. At this stage of study, we only examined the impacts of scenarios on inflow to the Karkheh Reservoir. Analysis of stream flow data at the Paypol gauge station located just below the Karkheh dam reveals that on average 5.5 billion cubic meters of water enter the reservoir per year. In this study it was assumed that the yield of the reservoir is equal to the downstream water demands.

These strategies were defined in the scenario frameworks and their impacts were evaluated in a 15-year time horizon (2006-2020) deterministically (i.e. using meteorological and hydrological data of 1988-2002). Increasing domestic water demands of urban and rural areas in the SSB in the evaluation period (2006-2020) was considered based on a linear population growth rate. Also, increasing industrial water demand was considered in the same way (Jamab, 1999). Irrigation water demand increase was considered for a 10% increase in the irrigated area (i.e. changing the dry farming to the irrigated farming). Increasing the water demand in the above mentioned sectors was considered as reference scenarios.

There are two potential alternatives for water resources development in the basin: (1) increasing withdrawal from groundwater resources; and (2) increasing the regulated surface water resources. Presently, groundwater withdrawal in many areas of the SSB is less than the safe yield and could be used further. Surface water resources of the KRB could also supply the increasing demands. There are many dams and irrigation-drainage networks under study or construction in this basin. The biggest dams of the KRB are Paalam, Kooran Boozan, Simareh, and Sazbon, which are located in the SBB.

Water demand management was also considered in both the agricultural and the municipal sectors. In the agriculture sector, increasing irrigation efficiency from 34% to 52% and in the municipal sector decreasing 7% in water consumption per capita are the targets (Jamab, 1999).

Changing priorities of water allocation between upstream and downstream of the SSB and changing priorities of water allocation between the SSB and the LKSB is examined for the sake of social equity. To assess this policy, we considered three strategies. In the first strategy, upstream usage and users have less priority compared to downstream. This reflects the basin as a usual mechanism of allocation. The second strategy is the equal priority between upstream and downstream areas. A balance between upstream and downstream is the third strategy. This scenario divides the SSB into three parts: upstream, midstream and downstream. Upstream demands have a higher priority compared to midstream, and midstream demands have a higher priority compared to downstream. Also, the LKSB has the same priority as downstream of the SSB. The necessity of assessing this scenario arises from a shortage of surface water in upstream areas.

The mentioned scenarios are summarized in Table 2. Scenario S15 is a combination of the better scenarios. After a preliminary assessment, better scenarios are determined as S1, S11, S12 and S142. Water resources system performance criteria, including reliability, resiliency and vulnerability, are selected to evaluate the scenarios. Table 3 shows the results of scenario evaluation based on these criteria in meeting the demands of different sectors of the SSB, including municipal, industrial, irrigated agriculture in high and low lands and the water demand of the LKSB (inflow to Karkheh Reservoir).

CONCLUSION

In reference scenario S1, the entire industrial sector and 97% of the municipal water demands are supplied. The study revealed that even by increasing withdrawal from groundwater resources, the demand for municipal sector was not fully meet (scenario S11). It should be noted that supplying a high portion of demands in industrial and municipal sectors is due to the accessibility to groundwater resources. It was found that the reliability of covering the irrigation demand for high lands in reference scenario is higher than low lands, which was not the same case in other scenarios. Also, the reliability of covering the irrigation demand in low land areas decreased from upstream to downstream. In increasing irrigation efficiency scenario (S12), this quantity encountered a 7% increase in high lands, and 15% increase in low lands relative to the reference scenario.

Changing allocation priorities is not recommended since it has inconsistent effects on covering irrigation demands. Operation of under-construction dams does not considerably affect agricultural demand coverage, since S141 and S142 scenarios affected only 20% of the total irrigation area of the Simareh sub-basin; however, they can considerably control inflow to the Karkheh Reservoir. Demand management and increasing irrigation efficiency were found to have important effects on water demand coverage at the Simareh sub-basin; therefore, a combination of demand management, increasing irrigation efficiency, and operation of under construction dams is recommended.

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FIGURES AND TABLES

Sub-basin	Calibration Time series		Validation Time series		Monthly average	
	EI	RMSE	EI	RMSE	EI	RMSE
Noorabad	0.95	60	0.93	63	0.95	45
Eslam abad	-0.05	20	-4.05	21	-0.71	11
Chardavol	0.96	60	0.99	32	0.99	22
Dareh Shahr	0.95	74	0.93	72	0.99	23
Molab	0.95	135	0.98	77	1.00	26

Table 1. Evaluation of the results by the indicators.

Name	Description
S1	Reference scenario - increasing water demand with business as usual allocation mechanism
S11	Increasing withdrawal from ground water resources
S12	Demand management and improving irrigation efficiency
S131	Equity in water allocation priorities
S132	Balance in water allocation priorities
S141	Operation of under construction dams assessing filling period effects
S142	Operation of under construction dams assessing long term effects
S15	Compound scenario of S1, S11, S12 and S142

Table 2. Description of development scenarios.

Scenarios	Municipal (%)	Industrial (%)	Irrigated agriculture (%)								Inflow to Karkheh dam (%)	Total average (%)	Order
			High lands				Low lands						
			up	mid	down	mean	up	mid	down	mean			
S1	97	100	61	39	84	61	53	45	80	60	33	66	5
S11	97	100	61	39	84	61	58	55	80	65	40	68	4
S12	98	100	65	47	92	68	69	69	89	75	40	74	2
S131	98	100	44	34	73	50	54	46	75	58	33	62	8
S132	97	100	61	39	84	61	53	45	53	51	40	64	7
S141	97	100	58	39	82	59	52	45	79	59	40	66	5
S142	97	100	61	41	86	63	53	47	82	61	60	70	3
S15	98	100	65	51	92	69	69	73	89	77	60	78	1

Table 3. Evaluation of the system's performance for different scenarios based on the reliability criterion.

Scenarios	Municipal (%)	Industrial (%)	Irrigated agriculture (%)								Inflow to Karkheh dam (%)	Total average (%)	Order
			High lands				Low lands						
			up	mid	down	mean	up	mid	down	mean			
S1	96	100	36	15	65	39	30	34	47	37	30	50	4
S11	92	100	36	15	65	39	31	37	49	39	44	52	3
S12	96	100	42	21	81	48	36	39	72	49	44	59	1
S131	96	100	16	15	45	25	31	24	43	33	30	44	7
S132	91	100	36	15	66	39	30	34	27	30	44	49	6
S141	96	100	17	14	45	25	30	34	38	34	11	43	8
S142	96	100	37	16	61	38	31	34	42	35	33	50	4
S15	96	100	42	22	79	48	36	58	69	54	33	59	1

Table 4. Evaluation of the system's performance for different scenarios based on the resiliency criterion.

Scenarios	Municipal (%)	Industrial (%)	Irrigated agriculture (%)								Inflow to Karkheh dam (%)	Total average (%)	Order
			High lands				Low lands						
			up	mid	down	mean	up	mid	down	mean			
S1	10	0	69	91	41	67	75	66	67	70	72	55	4
S11	10	0	69	91	40	66	67	52	64	61	72	52	3
S12	5	0	62	84	26	57	60	48	42	50	69	44	2
S131	5	0	95	96	76	89	71	78	73	74	71	63	7
S132	10	0	69	91	48	70	75	67	84	75	70	57	6
S141	10	0	99	100	73	90	76	66	77	73	72	64	8
S142	10	0	69	91	41	67	75	66	67	70	72	55	4
S15	5	0	62	82	23	56	56	43	42	47	68	42	1

TABLE 5. Evaluation of the system's performance for different scenarios based on the vulnerability criterion.

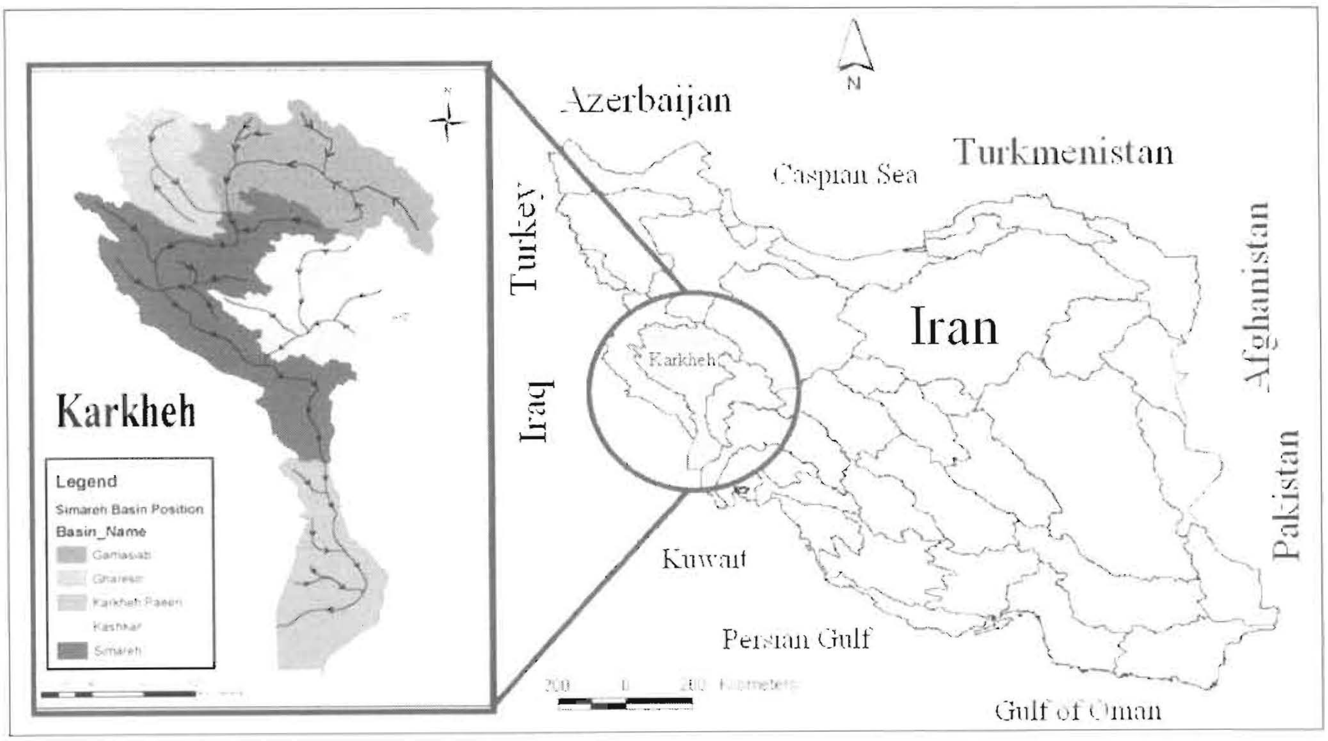

Figure 1. Simareh sub-basin's location in the Karkheh River Basin.

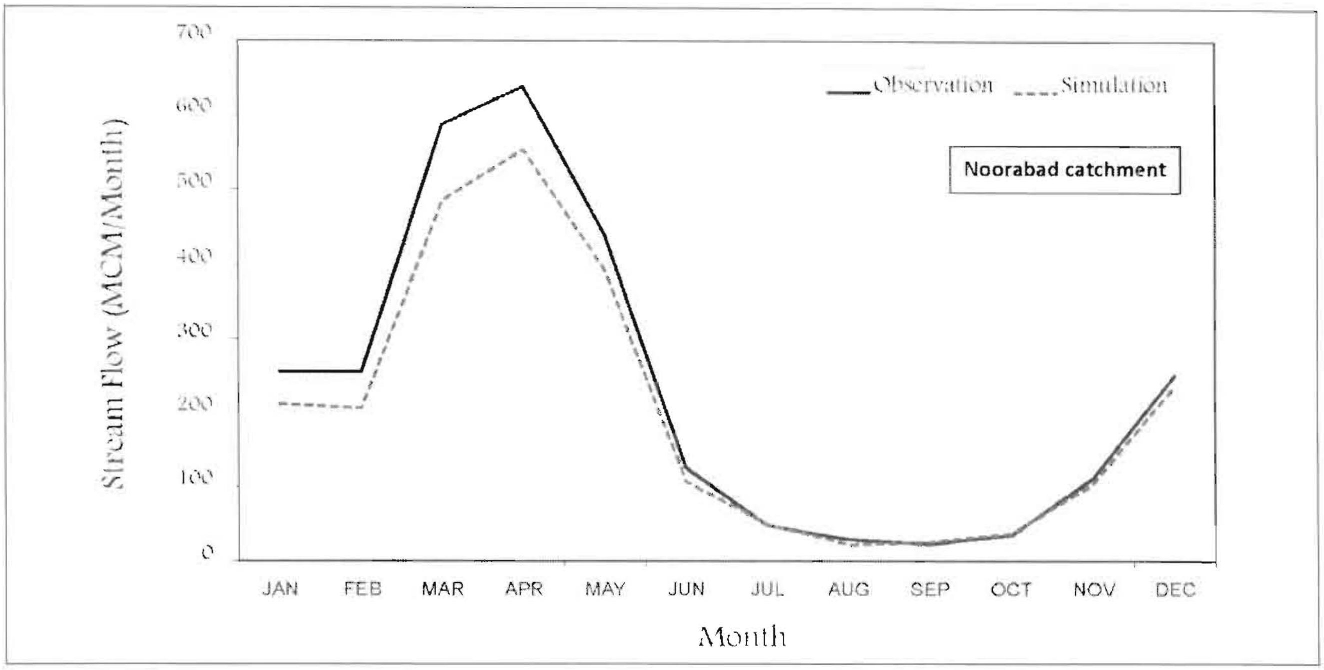

Figure 2. Streamflow at the end of the Noorabad catchment.

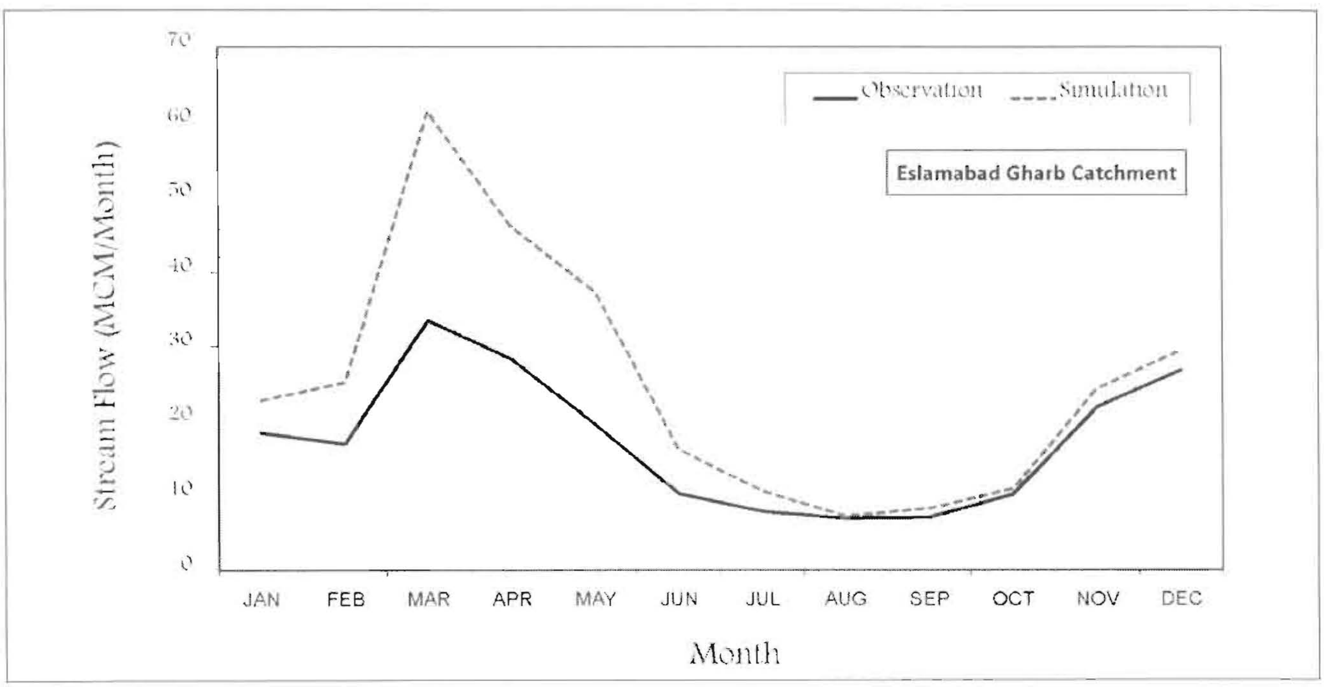

Figure 3. Streamflow at the end of the Eslamabad Gharb catchment.

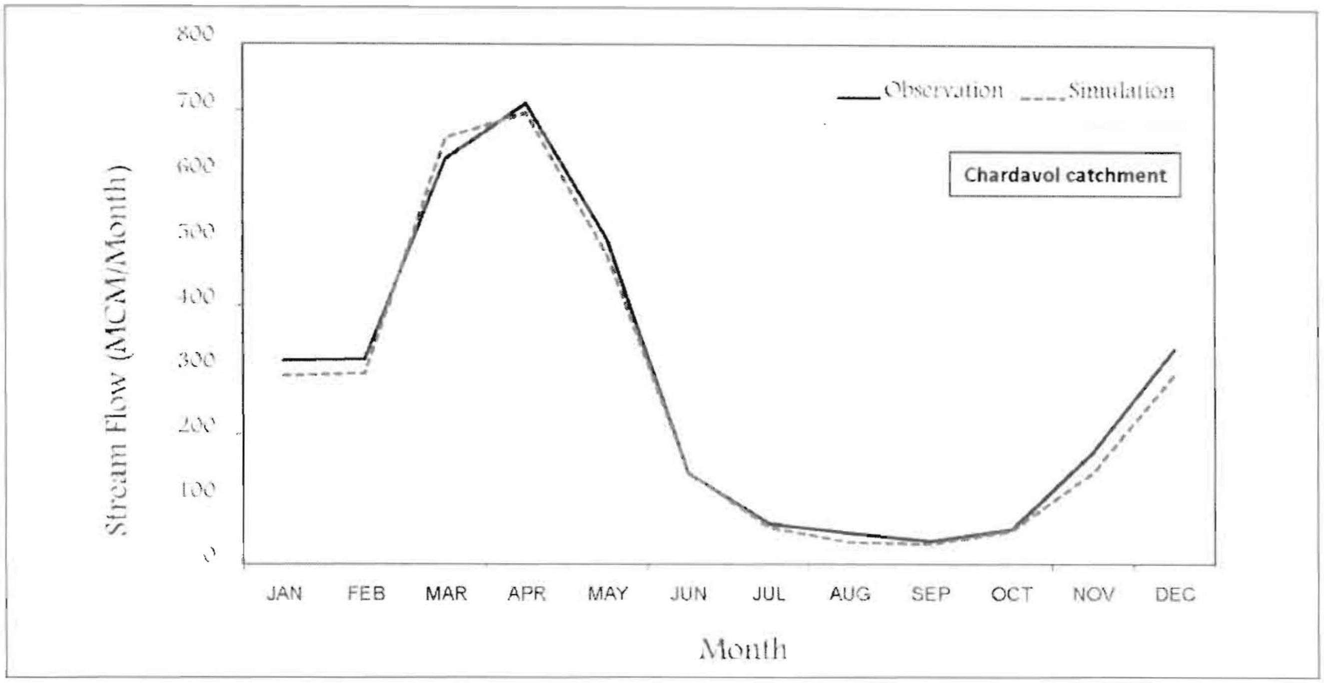

Figure 4. Streamflow at the end of the Chardavol catchment.

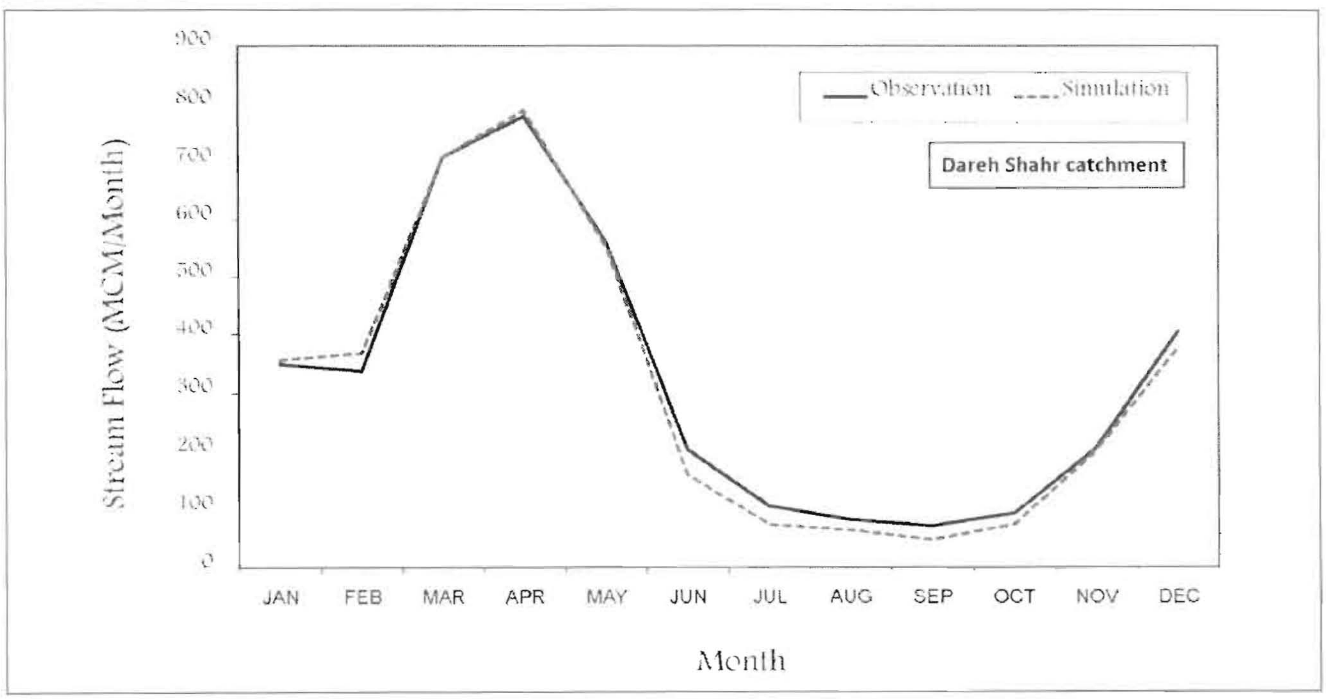

Figure 5. Streamflow at the end of the Dareh Shahr catchment.

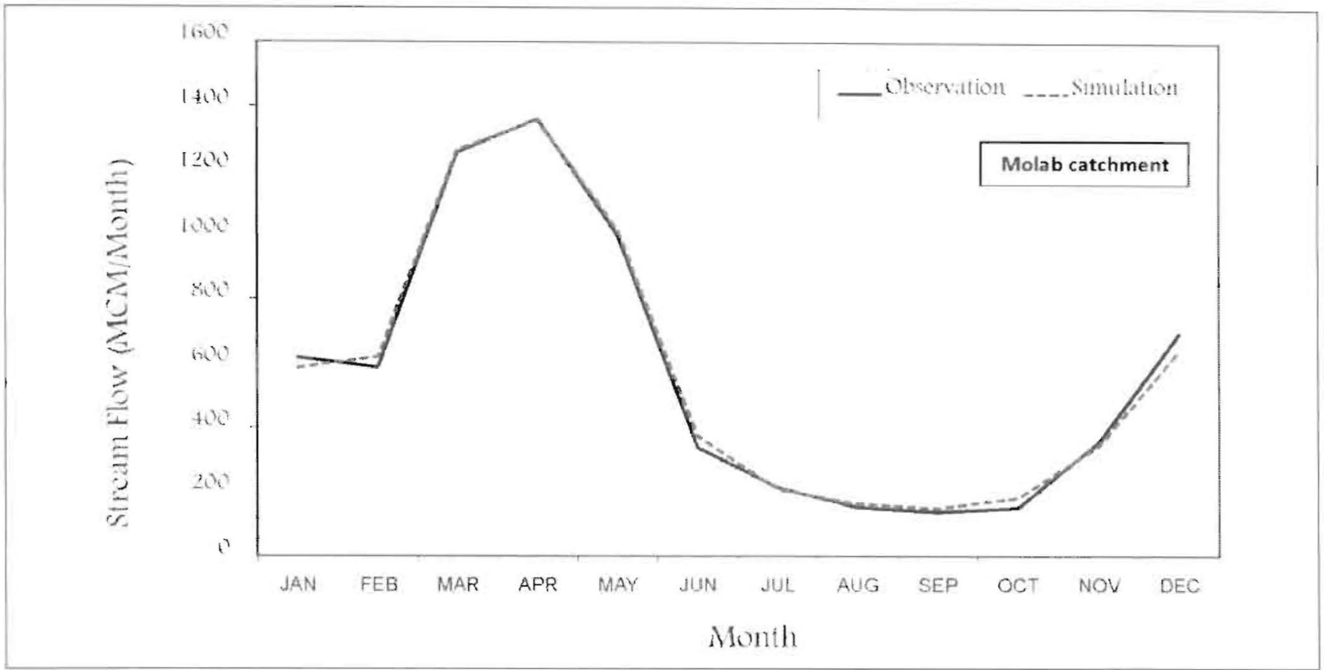

Figure 6. Streamflow at the end of the Molab catchment.

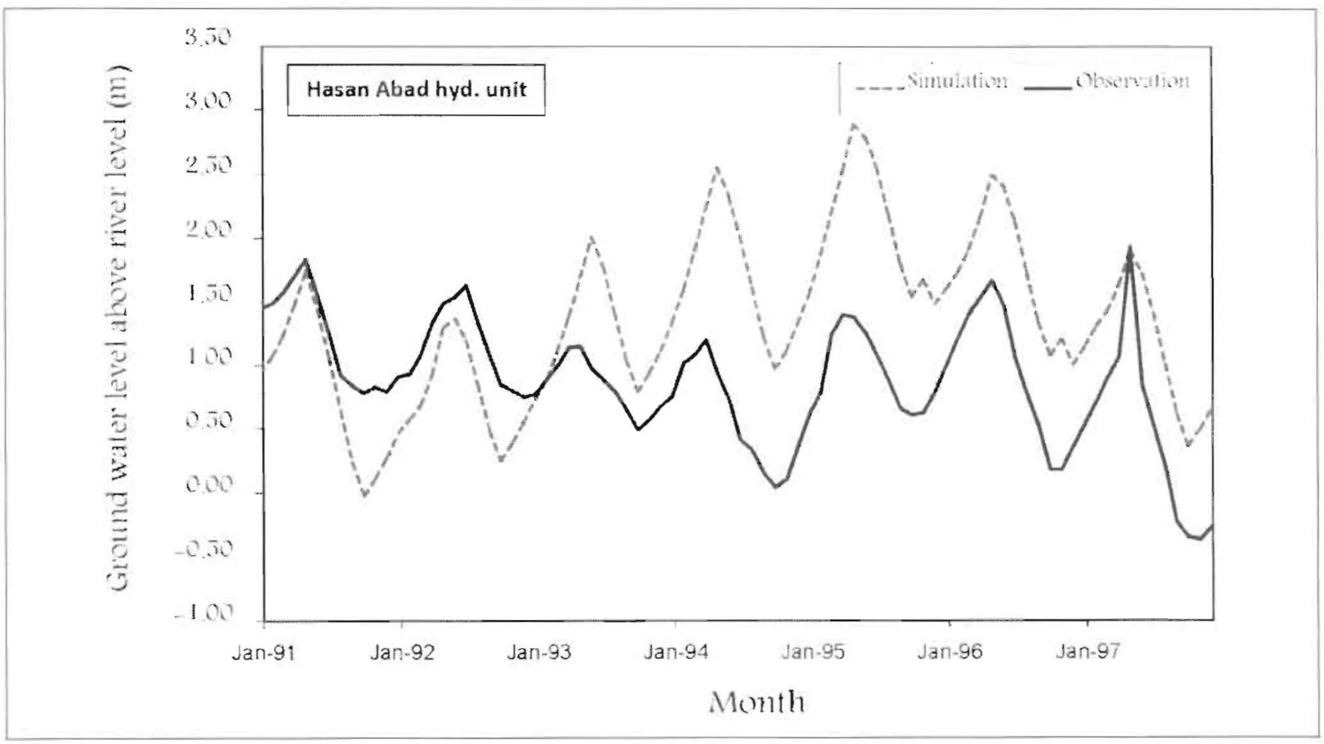

Figure 7. Groundwater level at the Hasan Abad HU.

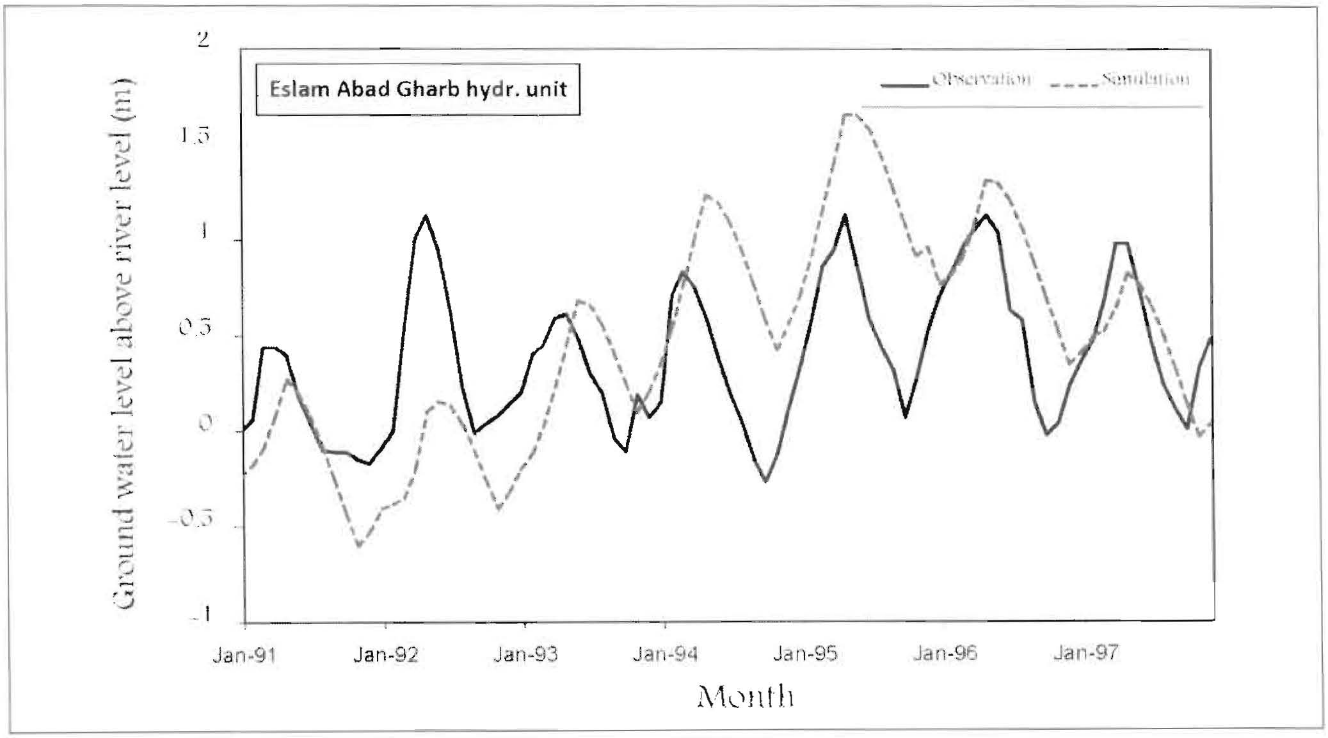

Figure 8. Groundwater level at the Eslamabad Gharb HU.