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Mitigating Socio-Economic-Environmental Impacts During Drought Periods by Optimizing the Conjunctive Management of Water Resources

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Abstract Multi-period optimization of conjunctive water management can utilize reservoirs and aquifer carry-over to alleviate drought impacts. Stakeholders' socio-economic and environmental indices can be used to minimize the socio-economic and environmental costs associated with water shortages in drought periods. The knowledge gap here is the evaluation and inclusion of the socio-economic and environmental value of conjunctive water management in terms of its drought mitigation capability. In this paper, an integrated water quantity-quality optimization model that considers socio-economic and environmental indices is developed. The model considers and integrates reservoir and aquifer carry-over, river-aquifer interaction and water quality with stakeholders' socio-economic indices of production, net income and labor force employment to evaluate the socio-economic and environmental value of conjunctive water management. Total dissolved solid (TDS) is used as the water quality index for environmental assessments. The model is formulated as a multi-period nonlinear optimization model, with analysis determining the optimal decisions for reservoir release and withdrawal from the river

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and aquifer in different months to maximize the socio-economic indices of stakeholders within the environmental constraints. The proposed model is used in Zayandehrood water resource system in Iran, which suffers from water supply and pollution problems. Model analysis results show that conjunctive water use in the Zayandehrood water basin reduces salinity by 50 % in the wetland and keeps water supply reduction during a drought under 10 % of irrigation demand.

Keywords Conjunctive water use · Socio-economic indices · Environmental indices · Optimization · Water quality · Water resource management · Drought

1 Introduction

Droughts are characterized by a reduction in riverbasin water resources over time and space, with negative socio-economic and environmental impacts sustaining beyond the drought period (Wilhite et al. 2007; Mishra and Singh 2010; Logar and Bergh 2013; Preziosi et al. 2013; Tsakiris et al. 2013). Optimal conjunctive use of surface and groundwater resources (Bazargan-Lari et al. 2009; Kerachian et al. 2010) is a common strategy for managing drought. Integrating conjunctive water resources system (WRS) modeling with socio-economic and environmental evaluation of WRS operation, helps assessing and mitigating the drought impacts, by optimization techniques (Rozegrant et al. 2000; Cai et al. 2003; Schoups et al. 2006; Wilhite et al. 2007; Zhang et al. 2010; Mahjouri and Ardestani 2011; Li et al. 2013; Tsakiris et al. 2013). How WRS features and interactions are modeled in conjunctive WRS management (CWRSM) influences the accuracy of the model and results significantly. CWRSM in the context of coordinating single or multiple reservoir operation, water use efficiency improvement in the agriculture sector and simple modeling of groundwater as an exogenous resource have been utilized in different studies. Simplified WRS has been integrated with economic and water quality modeling to evaluate and mitigate economic-environmental impacts of CWRSM in drought or dry periods (Karimi and Ardakanian 2010; Moeini et al. 2011; Sechi and Sulis 2010; Chang et al. 2010; Nikoo et al. 2013a, b, c). In the modeling stage of integrating different physical, economic and environmental features of WRS, simplification of the surface water or groundwater system to overcome the computational limits of numerical solutions is a common practice (Hejazi and Cai 2011; He et al. 2012; Gaivoronski et al. 2012; Georgakakos et al. 2012). However the influence of drought on both surface and groundwater resources has not been investigated by these researchers. A relevant index that has a large social impact in society is employment. Although employment is not easily modeled due to demography dynamics, multiple resources for income and migrations, ignoring it in modeling will under-estimate the impacts assigned to the impacts of drought (Krol et al. 2006).

The interactions between reservoir, surface and groundwater sources are considered in this paper to give a better perspective of the physical characteristics of a watershed system. In the integrated model a conservative contaminant is modeled to account for water quality issues associated with these watershed system components. Hydrology in terms of a monthly rainfall-runoff model is also included in the model to account for climate variability and drought in precipitation reduction. Groundwater is modeled by a tank model; wherein storage coefficient, groundwater water level, recharge from rainfall, return flows (to account for the dynamic behavior of groundwater, especially when drought results in reduced rainfall) are included. Production of farming and industry production, labor force requirements and net profit are modeled through a linear model based on the relationship between supplied water and their production. The revenue of water authorities and the municipality as the company supplying drinking water to users is considered in terms of supplied water to these companies. Labor force requirements in farming and industry is also modeled to evaluate the possible impacts of drought on employment related to labor force. This model is tested using a case study in the Zayandehrood riverbasin in Iran, which is explained in the next section. Model formulation, results and discussion as well as a conclusion of the model development and application are provided after describing the case study.

2 Case Study

Droughts have been recorded in the Zayandehrood riverbasin, Iran, since year 1051 (Heydari 2005). The cost of the last catastrophic drought in Iran during the period of 1999–2001 was estimated to be more than 4.2 billion US dollars, affecting 10 out of 28 provinces with 37 million people while reducing the country's GDP and wheat production by 12 % and 36 % respectively (Agrawala et al. 2001; FAO 2007). The Zayandehrood water resource system is located in central Iran, as shown in Fig. 1. The river has been dry for nearly 2 years from Isfahan city and points downstream, with a TDS concentration approximately 3900 mg/L at the river end. The Gavkhuni wetland is also dry with the exception of when tributary flows and local runoffs flow into it (Karimi et al. 2013; Nikoo et al. 2013b). The specifications of the Zayandehrood aquifer, socioeconomic parameters, Zayandehrood dam, TDS and return flow are presented in Table 1. Most TDS concentration is observed in groundwater and return flow from irrigation, which renders the control of water quality a challenge (Table 1). As can be seen in Table 2, industry production is 10 times more valuable as compared with agriculture production. However, agriculture gives more employment opportunity as labor force in comparison with industry. This is an important index if employment becomes a target in planning. The results of water resource system analysis in a drought condition for different scenarios are presented in the following section. The average natural recharge coefficient in the Zayandehrood water resource system is estimated to be 0.89 according to the Water Resources Atlas (Water Resources Atlas 2011). More details about the Zayandehrood riverbasin can be found in Nikoo et al. (2013a, b).

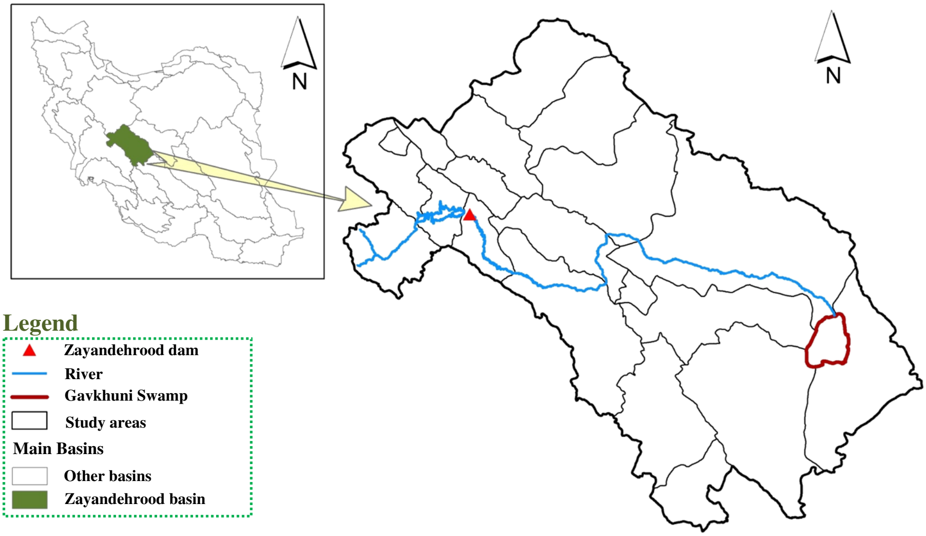

Fig. 1 Zayandehrood water resource system

Table 1 Water resources system specifications (Jamab Consulting Engineers 2005)

	Specification	Values
Aquifer	Surface area (km^2)	7451
	Mean thickness (m)	73
	Storage coefficient	0.0325
	Initial storage (MCM)	11624
	Recharge coefficient	0.89
	Initial TDS concentration (mg/L)	2132
Socio-economic	Water price ($/MCM)	68
	Groundwater maintenance cost ($/MCM)	47
	Agriculture net benefit ($/Ton)	0.4
	Industry net benefit ($/Ton)	4
	Agriculture production efficiency (Ton/ha)	5.24
	Irrigation water use (MCM/ha/year)	0.006547
	Agricultural employment (man/ha/year)	3.71
	Industrial production efficiency (MCM/Ton)	0.0000385
	Industrial employment (man/Ton/year)	0.5279
	Drinking water price ($/MCM)	650
Zayandehrood dam	Maximum storage (MCM)	1470
	Minimum storage (MCM)	438.5
	Initial storage (MCM)	970
	Initial TDS concentration (mg/L)	210
TDS and return flow	TDS concentration in river flow and runoff (mg/L)	209
	Domestic demand RTF[a] TDS concentration (mg/L)	500
	Industry demand RTF TDS concentration (mg/L)	500
	Irrigation demand RTF TDS concentration (mg/L)	1500
	Domestic demand RFF to river (MCM)	0.125
	Industrial demand RFF to river (MCM)	0.261
	Irrigation demand RFF to river (MCM)	0.15
	Domestic demand RFF to groundwater (MCM)	0.663
	Industry demand RFF to groundwater (MCM)	0.242
	Irrigation demand RFF to groundwater (MCM)	0.27

[a] RTF stands for return flow

Table 2 Average yearly socio-economic indices after analysis

Scenario	Total net benefit ($)	Total production (ton)	Total employment (people)	Agri-income ($)	Industry-income ($)	Water authority income ($)	Wastewater company income ($)
S1	18131257	5659500	3229800	537718	17260961	127604	204973
S2	18035402	5488500	3108650	469285	17260961	100183	204973
S3 (base scenario)	18156575	5659500	3229800	537718	17260961	152922	204973

3 Methodology and Model Formulation

The methodology developed, works as a tool for integrated hydrologic, socio-economic and environmental analysis at the water resource system scale. At this scale, some parameters and decision variables are considered in an aggregate manner to account for the average targets for decisions and policies over the water resource system in mitigating drought impacts. The proposed methodology is analyzed by a multi-period optimization method to take into account the pre-knowledge of future events, inflows, rainfall and demands in the current hydro-system operation. The model is used for analyzing droughts and delivering the decisions that minimize unfavorable impacts of drought. The complete hydrologic-socio-economic-environmental model is shown in Fig. 2.

Model application for drought mitigation as a part of water resources management planning is depicted in Fig. 2 and the main hydrologic processes in the water resource system are shown in Fig. 3. The interactions between river, aquifer and runoff and the direct influence of water users in terms of return flow to river and groundwater sources are also illustrated in Fig. 3. In Fig. 3 inflow, evaporation, release and storage in the reservoir are modeled by Eqs. 1 to 8. The main equations of the model are shown and explained in this section in a summarized form. Equation 1, shows the monthly time step water balance in the reservoir by inclusion of inflow at each month (*m*) and year (*y*), storage (*S*) at the start of month, release (*R*), evaporation (*E*), the inflow to the dam (*I*) and spillage (*SP*).

$$S_y^m + I_y^m - R_y^m - E_y^m - SP_y^m = S_y^{m+1} \tag{1}$$

The mass balance equation in the reservoir is given by Eq. (2) where QS and $\overline{QS}$ indicate the TDS concentration in the reservoir at the start of the month and its mean value during the course of the month. TDS modeling in water is based on a fully mixed state in the reservoir, river and aquifer within a month. Since salinity is a major problem in most water resources systems, salinity associated with TDS is modeled by:

$$S_y^m.QS_y^m + I_y^m.QI_y^m - SP_y^m.\overline{QS_y^m} - R_y^m.\overline{QS_y^m} = S_y^{m+1}.QS_y^{m+1} \tag{2}$$

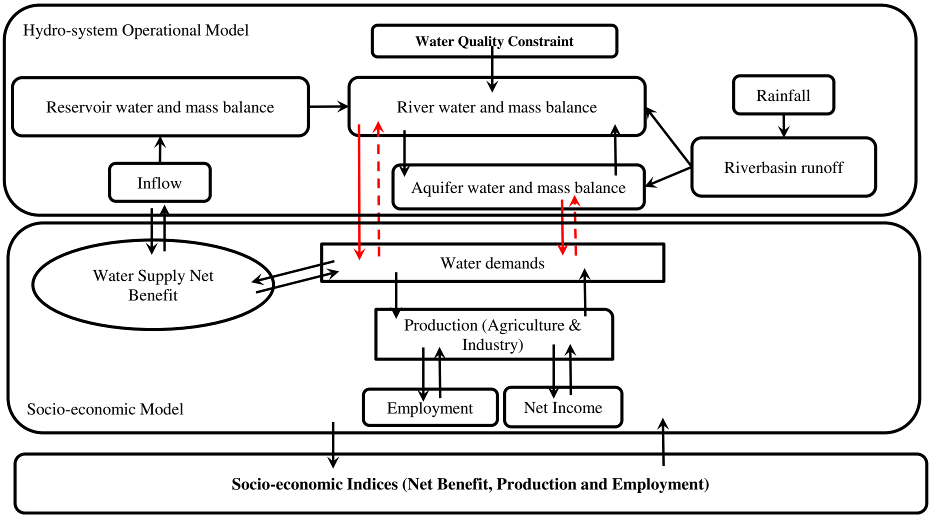

Fig. 2 Complete hydrologic-socio-economic and environmental model

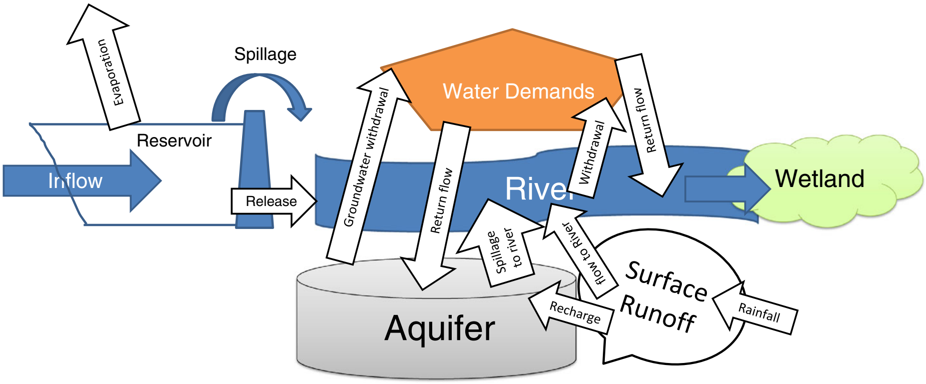

Fig. 3 Main hydrological processes in the water resource system

Equations 1 and 2 are applied for the river and aquifer with some modifications. The storage terms must be omitted from equation Eqs. 1 and 2 in the case that are applied to river. However, these equations are applied to the aquifer without any change; but for *R*, which is replaced by *GW*. Equation 3 shows the water allocation constraint in each month. QI is the TDS concentration in inflow to the reservoir. The QS is the monthly average for TDS in the reservoir. Total supplied water to irrigation (*SWIR*), industry (*SWIN*) and domestic water demand (*SWDO*) are assumed to be less than the sum of reservoir release (*R*), groundwater withdrawal (*GW*) and runoff (*RF*). Total supplied water is composed of totals deriving from groundwater and surface water for each demand type. This is not shown here, but is considered in modeling. Monthly rainfall-runoff model based on runoff coefficient is used to evaluate the surface runoff entering the river. All aquifers in the basin are modeled as a tank in an aggregate manner to account for drawdown limits in the water resource system. Drought is considered as a ratio of normal hydrologic conditions (i.e. normal hydrologic condition is considered the long-term average of rainfall).

$$SWIR_y^m + SWIN_y^m + SWDO_y^m \le R_y^m + GW_y^m + RF_y^m \tag{3}$$

In this equation, supplied water to demands must be less than the reservoir release, river flow and groundwater withdrawal, suggesting that a conjunctive water management policy is considered in the model. Water quality of inflow to the wetland, *ISQ*, is constrained to be less than a target value, TDS_{Max}.

$$ISQ_y^m \le TDS_{Max,y}^m \tag{4}$$

Equations 5, 6 and 7 show the socio-economic value of allocated water in terms of total revenue (*TREV*), total production (*TP*) in agriculture, industry and total employment (*TE*) by agriculture and industry production in the full length of the planning horizon. Revenue, production and employment of the industry and agriculture sectors are socio-economic indices that show how these sectors operate according to the amount of allocated water. These indices are linked to water through ‘crop-per-drop’ or production per unit water consumption. The cumulative objective function (Eq. 5) indicates a cumulative impact assessment in terms of socio-economic indices in the water resource system. Revenue in the agriculture sector is estimated by multiplying yearly supplied water to irrigation (*YSWI*), irrigation unit net benefit (*IUR*), in terms of dollars per ton, irrigation unit production (*IPF*), in terms of ton per ha, and irrigation unit water demand (*IAF*), in terms of million cubic meters (MCM) per ha YSWIN is the yearly supplied water to industry. Revenue is not limited to agriculture and industry but also includes income from water supply for water authorities, water and wastewater companies, and other stakeholders. Other components of Eq. 5 include the multiplication of a unit revenue term by the respective supplied water per year. *INUR* is unit revenue per industrial production measured in $/ton. *INPF* is water demand per unit production in industry measured as MCM/ton. *DMUR* is revenue obtained by a domestic water distributor (Water and Wastewater Company) in terms of $/MCM. *WP* is the average price of water for irrigation, industry and domestic water demands. *GWP* is the fee paid by water users, if they pump groundwater to the water supplier. Labor force employment in agriculture and industry in terms of production and consequently the supplied water are estimated by *IEF* measured as agriculture labor force per hectare and *INEF* industry labor force per ton per year, multiplied to supplied water as shown in Eq. 7. All the socio-economic indices were estimated based on supplied water to users in different sectors, as well as the water supplier (Karimi and Ardakanian 2010).

$$\begin{aligned} TREV &= \sum_{y}\left(\frac{YSWI_y \cdot IUR \cdot IPF}{IAF} + YSWIN_y \cdot INUR \cdot INPF\right) + \\ & YSWDM_y \cdot DMUR + \sum_{y}\left(\sum_{m} R_y^m\right) \cdot WP + \sum_{y}\left(\sum_{m} GW_y^m\right) \cdot GWP \end{aligned} \tag{5}$$

$$TP = \sum_{y}\left(\frac{YSWI_y \cdot IPF}{IAF}\right) + YSWIN_y \cdot INPF \tag{6}$$

$$TE = \sum_{y}\left(\frac{YWSI_y \cdot IEF}{IAF}\right) + YSWIN_y \cdot INPF \cdot INEF \tag{7}$$

Where YSWDM is yearly supplied water for domestic demand. Equations 5, 6 and 7 that represent socio-economic indices of stakeholders are related to supplied water by a linear relationship. They have a positive correlation with each other. Therefore maximizing one will lead to the maximization of the others so there is no need to go through a multi-objective method of optimization. In all system-wide analyses economics of the system is very important and any policy or decision that leads to better economic outputs gains more attention from decision makers. Therefore, here, *TREV* is taken as the objective function to be maximized for N-year planning horizon. The number of years (N) in planning is subject to decision makers' views, statistical length of droughts, and expected length of normal or wet years before the drought. In some practices, N is the reasonable length that could be predicted with more accuracy by prediction models ranging from 6 months to 3 years (Chen and Chiang 2005; Zhao et al. 2011; Alemu et al. 2011). This model requires calibration as well as interactions in aquifer and rainfall-runoff modeling. In other parts of the model, modeling is entirely based on a water-mass balance and hence no calibration is required. Aside from this point, the model herein is an optimization-based model; thus its validation is more meaningful than verification, because verification is mostly applicable in simulation models. Validation of this model was carried out elsewhere in several works by authors (Nikoo et al. 2013a, b).

Herein, environmental targets are imposed on the model which is employed to determine the best state under environmental constraints. According to the above statements, the resulting model is a nonlinear system of equations as shown in algebraic and symbolic model 8.

$$
\begin{array}{ll}
Max & Z = \sum_{k} c_k x_k \\
s.t. & \sum_{k,j \neq k} a_{kj} x_k x_j = b_j \\
 & \sum_{k} a'_{kl} x_k = b'_l \\
 & x_k \geq 0 \;\; and \;\; j,k,l = 1 \ldots N \\
 & a, a', b, b', c \;\; parameters
\end{array}
\tag{8}
$$

Where j, k, and l are general indices, *Z* is *TREV*, *X* are decision variables as described in Eqs. 1 to 7: *YSWI*, *YSWIN*, *S*, *R*, *SP*, *E*, *TP*, *TE*, *GW*, *ISQ*, *SWIR*, *SWIN*, *SWDO* and *QS*. Moreover, the nonlinear constraints represent components of the water quality balance equations where the other constraints are included in the linear equations.

This nonlinear system is modeled and solved in the GAMS environment. The appropriate initial point is generated by solving the quantity part of the model excluding the water quality constraints (Eqs. 2 and 4). In the next section, the results of analysis for Zayandehrood water resource system is presented and discussed.

4 Results

Soltani et al. (2008) used the scenario optimization for determining the operation rules of Zayandehrood dam. In this section, three scenarios that represent specific hydrologic conditions are analyzed. Scenario 1 (S1) represents a normal hydrologic year followed by a very dry year (very dry year means 50 % reduction of rainfall in comparison with a normal year). Scenario 2 (S2) represents a very dry year followed by another dry year. Scenario 3 (S3) represents normal hydrologic state in 2 years of planning, which is used as a benchmark for the assessment of the other scenarios. They are based on long-term mean and minimum rainfall occurring in the Zayandehrood water system for 36 years (1971–2006). The required data are obtained from engineering studies in the case study region (Jamab Consulting Engineers 2005). Nikoo et al. (2013a, b) provided more details on model verification. The base-year for these studies is 2001. Figure 4 illustrates the hydrologic scenarios considered in the analysis. The water demands at the start of the first year of analysis are taken from observed values in 2001. In the second year

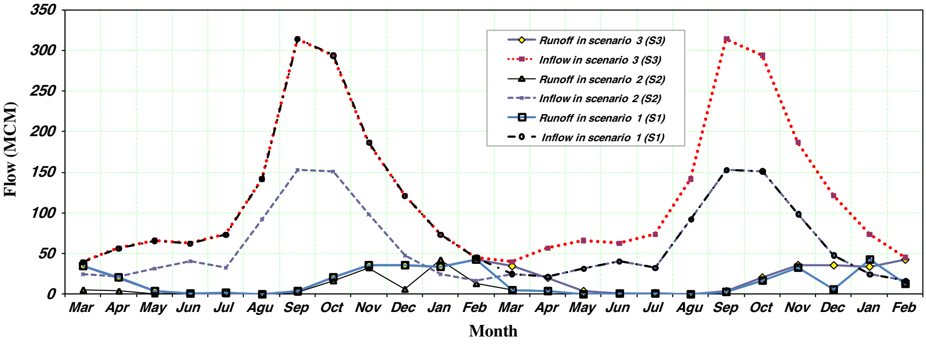

Fig. 4 Different hydrologic scenarios for inflow and runoff

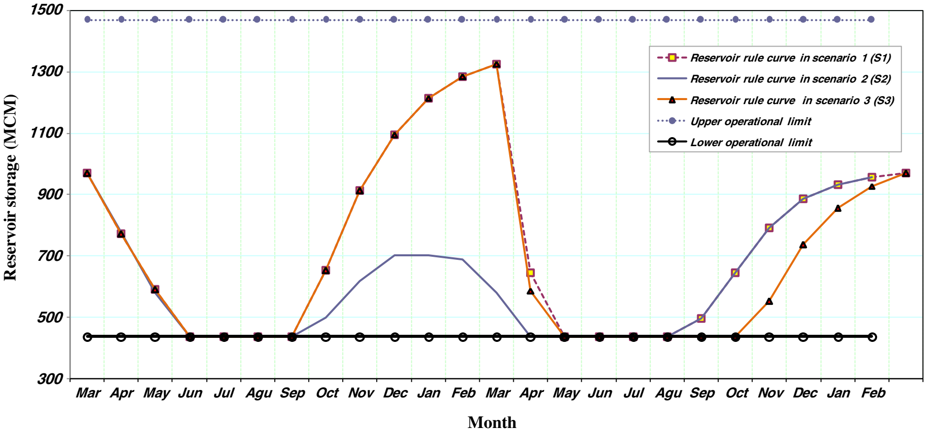

Fig. 5 Optimum reservoir storage volumes (storage rule curves) in different scenarios

of the analysis, the model is considered free to increase the water demands up to 10 % in each sector based on socio-economic returns, operational constraints and water quality constraints. This allowance for 10% increase in the second year actually shows the potential of growth and development in socioeconomic and environmental aspects of the waterbasin.

Figure 5 shows the storage rule curves in the Zayandehrood dam, indicating emptying between March to September and filling during September to March. The amount to be stored is distinctly different in scenario 2 compared to the two other scenarios. The water storage in the aquifer is in contrast to the optimum rule curve of the reservoir (Fig. 6). Indeed, reservoir and aquifer storage potentiality are coordinated for maximum efficiency by the multi-period optimization model. Socio-economic and environmental returns from conjunctive water use within the 2 years planning horizon are shown in Tables 2 and 3.

With the presence of robust predictions for the hydrological state in the next 2 years, this model shows that impacts to socio-economic indices can be kept to a minimum even if a severe drought follows a normal hydrologic year in the Zayandehrood watershed. The model can supply the wetland minimum inflow requirement and keep the TDS concentration at the inlet to the Gavkhuni swamp below the limit of 1,500 mg/L at this hydrologic condition (Fig. 7).

The objective for the results of this analysis is to show the applicability of conjunctive water management in drought management by maintaining socio-economic and environmental conditions

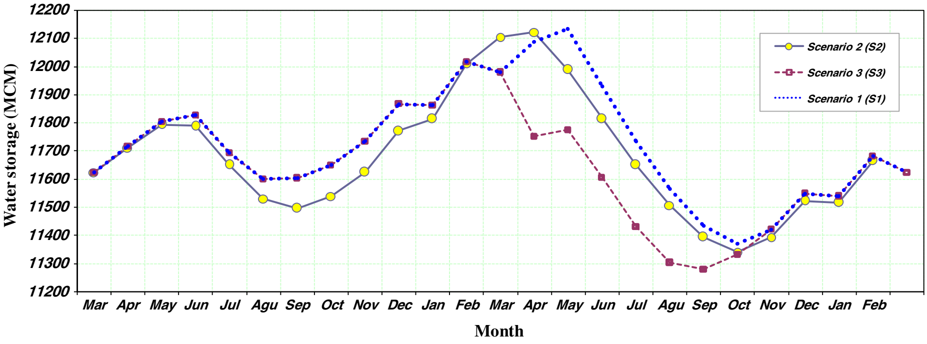

Fig. 6 Aquifer storage in each month in different scenarios

Table 3 Feasible water allocations in the water resource system

Scenarios	Water allocation (MCM) to			Resource for allocation (MCM)			Cultivated land area (ha)
	Irrigation	Industry	Domestic	Groundwater	Reservoir	River	
S1_Y1	1520	150	285	775.68	1059.27	120.79	232167
S1_Y2	1839	182	345	1622.41	1036.29	0	280923
S2_Y1	1368	150	285	609.85	1073.77	120.1	208951
S2_Y2	1564	182	345	1672.81	295.06	123.05	238840
S3_Y1	1520	150	285	775.68	1059.27	120.79	232167
S3_Y2	1839	182	345	1622.41	1780.94	0	280923

of the water resource system (or watershed at the same level with a normal hydrologic year). A relatively accurate prediction model is necessary to be included within the integrated water quantity-quality model. The other result is the possibility of 10 % development in the water resource system as shown in Table 3. The model shows that the agriculture sector must reduce its current cultivated land area up to 10 % if the system encounters a severe drought for two consecutive years. Although results are at gross level, they show that by conjunctive water management and a utilizing a relatively robust prediction model, when rainfall and inflow decreases by 50 %, water supply is reduced by a maximum of 15 % due to irrigation needs (Table 3). As a result of the assumed linear relationship between socio-economic and water supply variables (Eqs. 5 to 7), net income, production and employment are reduced by 15 % during drought conditions as compared with the base year 2001. However, domestic and industry demands, as well as environmental demand are fully satisfied. 10 % growth is considered as an exogenous constraint for irrigation, domestic and industry demands and is considered in all scenarios. Results show that based on normal year planning, 10 % growth is possible. Reservoir and aquifer in this modeling are constrained to return to their initial state, so continuation of the hydrologic state will not cause deteriorating conditions. The results indicate that water should be stored from September to March and used between March to August. The rule for aquifers differs in that water is stored in the first year while behaving more as a reservoir in the second year. Flow to the Gawkhuni wetland is well enough above the minimum requirement, due to

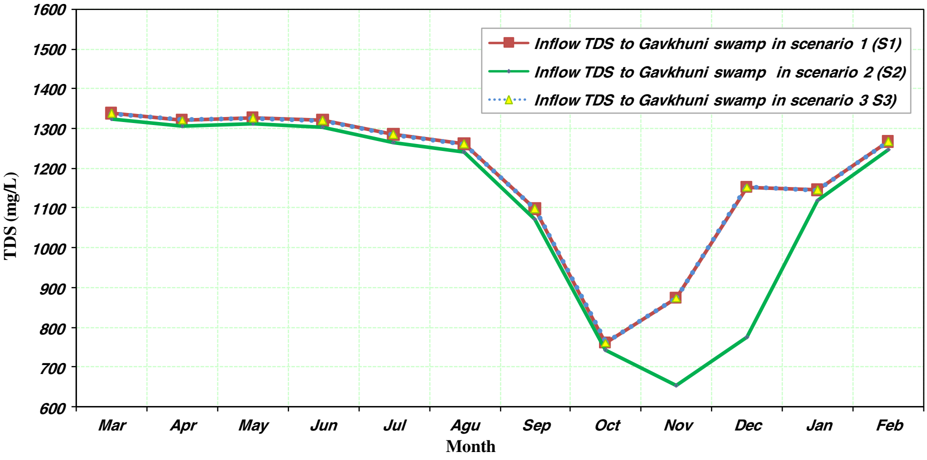

Fig. 7 TDS of inflow to the Gavkhuni swamp

return flows especially in the high-demand season. Figure 7 depicts how conjunctive water management can help water quality control in Zayandehrood River below the standard limit. Income, production and employment of the agriculture sector and water authority are reduced by a maximum of 15 % during drought periods while in 2001 production was reduced on average by 35–37 % due to drought (FAO 2007). Another important result is the TDS reduction in September to January, which is below 1,000 mg/L. It shows the potentiality of integrated management of the water resource system that increases the natural capacity of the system for water quality control. The values obtained by this analysis (Tables 2 and 3) shows meaningful improvements attainable by multi-period and integrated planning of the Zayandehrood water resource system.

5 Conclusions

In this study, an integrated hydrologic, socio-economic and environmental approach was modeled and applied to a real world case study within the context of multi-period optimization for improving the efficiency of water resources management. This was carried out through conjunctive use in accounting for socio-economic and environmental functions in terms of some simple indices such as revenue, labor forces employment, production and TDS. The model application in the Zayandehrood riverbasin indicates that meaningful improvements in water quality control of the river and water supply to the Gavkhuni swamp is possible, even during severe drought conditions. Through the use of a 2 year prediction model, the system can be operated to achieve its maximum efficiency, even when a drought occurs in the subsequent year. A prediction model is a very important requirement for such multi-period optimization. Analysis results show that the water resource system has the potential for positive socio-economic development from a water supply point of view. Conjunctive water use can reduce the TDS in the river outflow to the Gavkhuni swamp by 50 %, while providing water to it, which is critical for swamp restoration. Resources are shown to not be over-exploited in the recommended operation prescribed by the model, since all of the variables have returned to their initial conditions. This result shows the potential of a conjunctive water use strategy for Zayandehrood water resource system management, even at drought conditions. However, the model requires more development in considering other conservative and non-conservative pollutants such as nitrogen, phosphorus, heavy metals and BOD. Integrating economic and sectorial policies, such as investment for water consumption improvement practices in the agriculture sector to provide more water for socio-economic development and ecosystem demands will provide opportunities for more sustainable development in the river basin. Utilizing game theory approaches in cooperative and non-cooperative frameworks would help to identify optimum degrees of trade-off between stakeholders' values for water resources management and is recommended in the next steps of developing this work.

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