Case Study

System Dynamics Approach for Hydropower Generation Assessment in Developing Watersheds: Case Study of Karkheh River Basin, Iran

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Abstract: In many watersheds around the world where the importance of assessing a watershed as a whole is overlooked, new water resources projects are designed solely based on historic flow data. Such projects might fail to operate satisfactorily when designed without considering the uncertainties associated with future hydrologic changes. In this study, a system dynamics model (SDM) is developed to quantify the potential hydrologic impacts of future developments in parts of the Karkheh River basin, Iran, and assess their effects on hydroelectricity generation of existing and projected hydropower plants. Results indicate that upstream development could reduce future annual energy production by 254 GWh. Interbasin water transfer from the nearby Sirvan River basin to the Karkheh River basin was also investigated as a viable option to increase future energy production. Simulation results revealed that an average 88 GWh/year increase in electricity production can be achieved per 100×10^6 m^3 of annual environmental flow release out of transferred water from Sirvan to Karkheh River basin. **DOI: 10.1061/(ASCE)HE.1943-5584.0000711.** © *2013 American Society of Civil Engineers.*

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Introduction

The demand for energy has been continuously growing with the ever-increasing global population and rapid industrialization. The use of fossil fuels is becoming less attractive due to their adverse environmental impacts and the role they play in global warming through greenhouse gas emissions. Although nuclear energy appears to be more environmentally friendly, the massive 2011 earthquake in Japan revealed the hidden danger in them as well. Hydropower is a reliable and renewable source of energy to generate electricity. Due to its low environmental impacts, flexibility, and low operation and maintenance costs, hydroelectricity production is seemingly growing around the globe, especially in developing countries (Kaygusuz 2004).

As of 2010, only 1.0% of Iran's energy demand is supplied by hydroelectric powerplants, which is fairly low compared to the global average of 6.5% (BP 2011). To meet the growing demands, the Iranian Ministry of Energy is expanding its hydroelectric production capacities by building new hydropower (HP) dams, mainly in the watersheds of the Karkheh and Karun rivers (Fig. 1). Production capacity and potential energy yield of new hydropower projects in Iran are typically assessed by employing a single-reservoir reliability-based simulation model (Afzali et al. 2008) and using long-term historic streamflow data. In developing basins, such as the Karkheh River basin, where new water demands are introduced every day, and the river hydrologic regime is more and more regulated over time (due to dam construction for supplying new demands), relying on historic flow data for energy assessment is far from a holistic approach. New HP projects might fail to reach their designated goals (i.e., producing enough firm energy to meet their projected demands) when designed without considering the uncertainties associated with future hydrologic changes. To avoid the risks of failure, design policies might move toward conservative designing, which in turn prevents the hydroelectric production systems from reaching their full potential.

In this paper, a simple system dynamics model (SDM) was built to assess hydropower generation in developing watersheds in a holistic fashion. The model has been applied to the Karkheh River basin in Iran, where extensive development (three HP dams, eight irrigation dams, and more than 34,000 ha of irrigated fields) is under way. The specific research objectives are (1) to find out whether or not the newly planned HP units can meet their designated energy production goals in future when the watershed is fully developed, and (2) to assess HP generation and expansion opportunities under various realistic development scenarios. The SDM quantifies potential hydrologic impacts of future development scenarios and assesses their effects on energy generation of existing and projected HP units, all within a unit platform. Development means any future project (phenomenon) that can directly (or indirectly) affect the flow regime, such as urbanization, population growth, industrial or agricultural expansions, new HP or irrigation dams, and interbasin water transfer. The SDM contains different building blocks (subsequently called sectors) that either simulate the behavior of physical elements in the watershed (i.e., HP and irrigation dams) or estimate modified stream discharges due to the added physical elements to the system at various locations where

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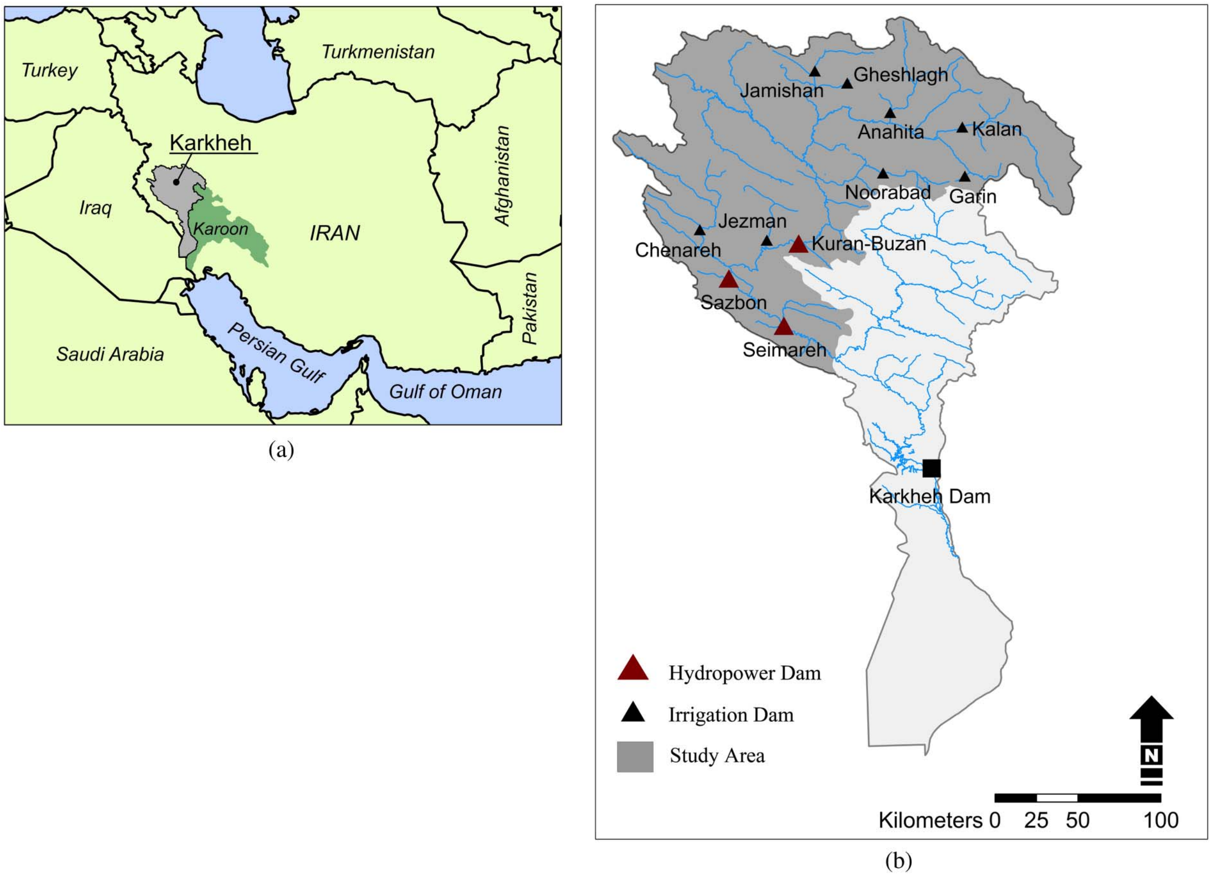

Fig. 1. (a) Karkheh and Karoon river basins located at western Iran; (b) detailed view of Karkheh River basin; the study area covers the north and western parts of the Karkheh basin; 11 dams fall in the study area, all to be constructed; Karkheh dam (not included in the model) is the only functioning hydropower dam in the basin

historic flow data are available (i.e., hydrometric stations). The main contribution of this paper is the formulation of a hydropower assessment model for developing watersheds using the system dynamics approach.

There is a long tradition of employing dynamic simulation models in water resources management owing to their complex nature (Rogers and Fiering 1986). System dynamics (SD), a framework for examining the behavior of complex systems over time (Forrester 1961), has proven to be a suitable and appropriate approach for solving complex water resources management problems. Over the last 50 years, SD applications in water resources management have deviated in many directions, focusing on such problems as regional analysis, river basin planning, urban water, flooding, and irrigation (Winz et al. 2009). The earliest applications of SDMs in water resources appeared in the late 1960s with the Susquehanna River Basin Model (Hamilton 1969), which included physical as well as socioeconomic factors. Since then, many SD applications in water resources have emerged. Simonovic et al. (1997) employed SD frameworks for water policy analysis and long-term planning of the Nile River basin. Ahmad and Simonovic (2000) developed a SDM to draft effective dam operating rules in order to minimize downstream flooding. Stave (2003) utilized a SDM to improve public understanding of water management options and the importance of water conservation in Las Vegas. Elshorbagy and Ormsbee (2006) modeled pathogen transport in a watershed using SD framework. More recently, a SD approach was employed by Karamouz et al. (2011) to develop a bargaining model for resolving disputes over water allocation among stakeholders of reservoir-river systems.

Mirchi et al. (2012) categorizes water resources SDMs into three main groups based on their underlying philosophy: (1) predictive simulation models in which an SD approach is used as a convenient tool for analyzing water resources problems and/or physical watershed processes, (2) descriptive integrated models in which an SD approach is exploited to describe the feedback structure and long-term behavioral pattern of interacting water resources subsystems (like hydrologic, ecologic, and socioeconomic subsystems), and (3) participatory and shared vision models in which SDMs are employed for promoting shared vision planning and participatory modeling of water resources among decision makers and stake holders. The SDM presented in this paper falls under the first category. A comprehensive review of SDM applications in water resources over the past 50 years can be found in Winz et al. (2009).

A quantitative SDM can be represented in the form of a stock and flow diagram, with stocks and flows being the building blocks (Ford 2010). Stocks (circle-shaped variables in Fig. 2) are any system variables that accumulate or deplete over time, such as reservoir volume behind a dam. Flows (double lines) represent the rate of change in stocks, such as inflow and outflow to and from a reservoir. Flows are accompanied by arrows indicating the direction of the flow. Sources or sinks (clouds) represent where the flow is coming from or going to outside the system boundary (Ford 2010). Connectors (single lines) show the flow of information inside the model. For example, the rate of outflow from a reservoir is partially

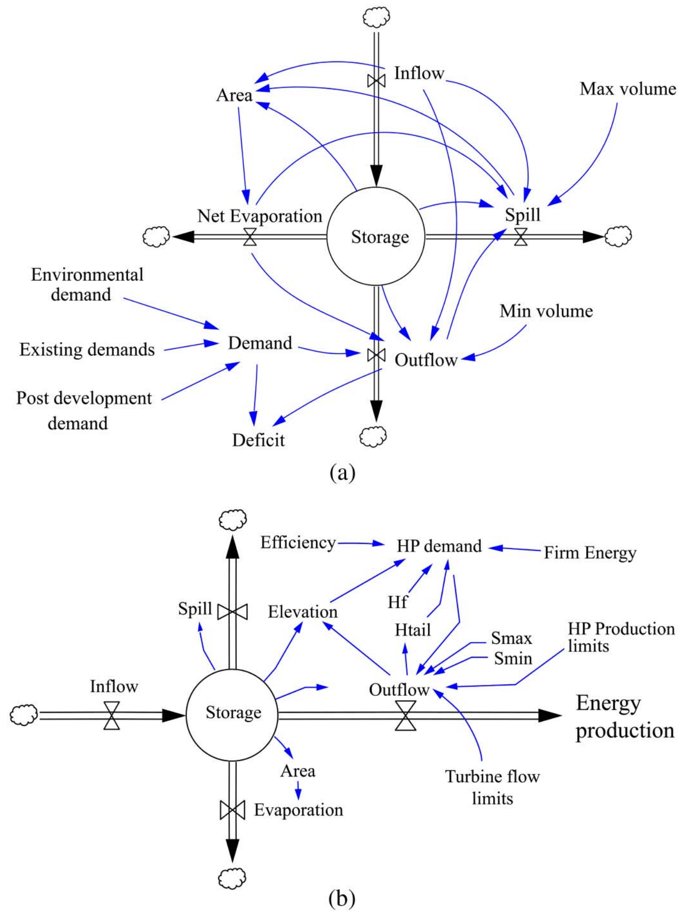

Fig. 2. (a) Depiction of the irrigation dam sector in Vensim; the embedded relationship between stock (storage) and flows (outflow, spill) is derived from the adopted operating policy; other auxiliary variables are mainly inputs to the model (like inflow and demands); (b) hydropower dam sector structure depicted in Vensim software; energy production in the HP unit is a function of electricity demand and available water for release; HP demand is the discharge necessary for generating firm energy

dependent on the demand. Therefore, demand as an auxiliary variable is linked to flow with a connector (Fig. 2). Governing equations (e.g., conservation of mass) are hidden behind the intrinsic properties of the system variables. They are presented in finite-difference expressions and solved numerically by the SD software (Elshorbagy and Ormsbee 2006).

Organization of this paper is as follows: After introducing the study area, details of the SDM structure are laid out, which is followed by a description of the future development scenarios. Subsequently, results are presented and discussed. The paper concludes with a summary and conclusions.

Research Approach

Study Area

The 900-km-long Karkheh River (Fig. 1) is the third largest river in Iran based on annual average flow. With 31 new dams to be constructed in the near future, the 51,000-km^2 Karkheh River basin is becoming one of the most rapidly developing basins in the region in terms of surface water exploitation projects. The basin's climate is best described as Mediterranean, having mild and wet winters and hot and dry summers, with mean annual precipitation ranging from 150 mm in the southern arid plains to 750 mm in the northern mountains. Annual average water yield of the basin is estimated to be approximately 8.5×10^9 m^3 (JAMAB Consulting Engineers 2006). The Karkheh River regime remained unregulated by large dams until the only hydropower dam in the watershed (Karkheh Dam) became operational in 2001 (Masih 2011). Located at the south end of the watershed (Fig. 1), the Karkheh Dam has an energy production capacity of 400 MW.

The Karkheh River terminates in the Hawr-Al-Azim swamp, an ancient remnant of the renowned Mesopotamian Marshes (Chen et al. 2011; Masih 2011). This important ecosystem has been subjected to extensive degradation and habitat loss over the past 30 years, mainly because of water diversions (for urban and agriculture use) and deterioration of water quality (Marjanizadeh et al. 2009). The Karkheh River basin has been the subject of many past studies. The latest is the work of Masih (2011), who focused on hydrological variability of the Karkheh basin and investigated scenarios of upgrading rain-fed areas for irrigated agriculture. Other important studies are by JAMAB Consulting Engineers (1999, 2006), which provide a comprehensive assessment of water resources and water balance analysis of the basin; Karamouz et al. (2006, 2008), which focus on conflict resolution over water quality and quantity allocation; and Marjanizadeh (2008), which analyze various water resources management scenarios for the current and future conditions of the basin.

This study is focused on the northern and western portions of the Karkheh River basin where most of the development will take place (Fig. 1). Presently in the study area, one hydropower dam (Seimareh) is under construction with an energy production capacity of 480 MW. The projected development (as a part of the whole Karkheh River basin development plan) includes two other HP dams (Kuran-Buzan and Sazbon), eight irrigation dams (Table 1), and more than 34,000 ha of irrigated agricultural fields, all in the midst of feasibility studies or early construction.

Before being approved by the Ministry of Energy of Iran (who oversees water resources assessment and development in Iran), all development projects must undergo extensive feasibility studies, which are carried out by semigovernmental or private consulting companies. Such feasibility studies are typically performed using historic streamflow data at the project site. In this paper, the building blocks of the entire study area's future development plan were incorporated and the river's flow regime (and consequently the HP energy production) was modeled as a whole in a dynamic framework. The ultimate goal of the study was to assess the potential effects of future developments on HP production in the Karkheh River basin.

SDM Structure

Conservation of mass is the most important governing equation in SDMs. Water quantity, as the driving factor for hydropower generation, is the primary focus of this SDM. The SDM proposed in this paper modifies the historic water balance based on new developments and simulates the HP generated at the end of each time step. The historic flow data are fed into the model at several points and the main model components (or sectors, each representing a real watershed constituent) alter the flow based on their underlying rules of operation. The SDM presented in this paper consists of three main sectors: irrigation (nonhydropower) dams, hydropower dams, and control hydrometric stations. In the sections to follow, the governing policy behind each sector is described. *Vensim DSS*

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Table 1. Characteristics of Eight Irrigation Dams Foreseen in the Development Plan of the Study Area

Characteristics	Chenareh	Jezman	Noorabad	Jamishan[a]	Gheshlagh[b]	Anahita	Kalan	Gareen	Total
Storage capacity (10^6 m^3)	116.2	37.0	83.0	62.8	50.0	24.6	45.0	60.0	478.6
Annual average inflow (10^6 m^3)	187.6	37.6	117.0	63.1	91.0	45.5	30.8	131.7	—
Existing (development) irrigation land area (10^3 ha)	5.7 (6.7)	0.1 (1.9)	0 (7.3)	2.2 (3.8)	16.6 (3.8)	0.3 (3.8)	1.8 (0)	5.6 (6.7)	32.3 (34.0)
Environmental demands (10^6 m^3/year)	34.4	5.2	21.6	6.0	4.7	9.6	6.2	27.3	—
Existing (development) irrigation demands (10^6 m^3/year)	60.0 (70.5)	0.9 (22.4)	0.0 (74.0)	20.6 (35.6)	67.5 (16.1)	2.1 (27.2)	8.1 (0)	45.1 (45.5)	204.3 (291.3)

Note: All the dams are under feasibility studies or at the early stages of construction; each irrigation dam is responsible of meeting existing and development agricultural demands in addition to environmental demands.
[a]22.0×10^6 m^3/year of existing and development irrigation demands are supplied from groundwater resources.
[b]37.2×10^6 m^3/year of existing and development irrigation demands are supplied from groundwater resources.

(*version 4.0a*), a system dynamics software package developed by Ventana Systems, was employed as the platform of this SDM.

Irrigation (Nonhydropower) Dam Sector

Water storage and release behavior of nonhydropower dams were simulated in the irrigation dam sectors of the SDM. In irrigation dams, this behavior complies with previously defined operating rules that are typically optimized based on various objectives (e.g., minimizing supply shortage, drought impact mitigation, and maximizing profit). Because such optimized release plans were missing for the study dams, the standard operating policy (SOP) was adopted (Maass et al. 1962; Loucks et al. 1981; Cancelliere et al. 1998). As hydrologic or economic uncertainties increase, which is the case for this study region, optimal operating policies converge to SOP (Klemeš 1977). In SOP (Fig. 3), the highest priority on releasing water is for immediate beneficial use (Draper and Lund 2004). For a given month t, available water for release (A_t) is defined as

$$A_t = S_{t-1} + I_t - L_t \quad (1)$$

where S_{t-1} = effective storage at the beginning of the month; and I_t and L_t = projected inflow and sum of losses (i.e., evaporation and seepage) for that month, respectively. Reservoir release (R_t) in a given month is determined based on target demand (D_t) and available water (A_t). If the available water for release is less than the delivery target ($A_t < D_t$), then all the available water is released ($R_t = A_t$). When there is no water shortage ($A_t > D_t$), the delivery target is released ($R_t = D_t$) and the excess water is stored. Reservoir will spill if maximum capacity of the reservoir is reached.

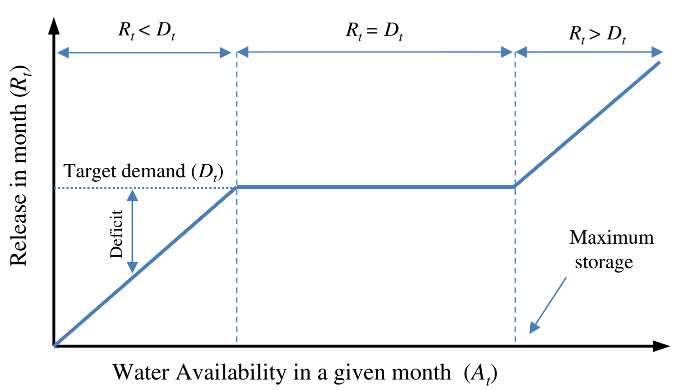

Fig. 3. SOP is the adopted operating policy for irrigation dams. In SOP, the highest priority on releasing water is for immediate beneficial use

Inputs to irrigation dam sector include inflow, dam physical characteristics (e.g., maximum and minimum storage capacities and volume-area relationship), demands, and evaporation. Historic flow data measured at hydrometric (HM) stations upstream of each dam were used as inflows to the reservoirs. Class A pan evaporation measurements acquired from nearby climatologic stations were multiplied by a correction factor of 0.55 (Hassani et al. 2008) and used for estimating evaporation losses from the reservoirs. Three types of demand were defined for irrigation dams: (1) environmental demands, i.e., amount of water that needs to be released for the sake of the downstream environment, estimated using the Montana method (Orth and Maughan 1981); (2) existing water rights, i.e., irrigation demands that are currently being pumped out of the main stream and must be supplied by irrigation dams once they become operational; and (3) projected (development) agricultural demands, i.e., the newly introduced demands due to the planned agricultural expansions downstream of each irrigation dam. The existing water rights were obtained from the Iranian Ministry of Energy. The agricultural water demands were calculated at a monthly time scale by summing the product of area covered by each crop with the corresponding monthly average water demand. Crop types, area occupied by each crop, and monthly water demands were also obtained from the Ministry of Energy. Fig. 2(a) shows the structure of a typical irrigation dam modeled in Vensim software based on the SOP theory. As mentioned previously, eight irrigation dams are foreseen in the development plan of the study area to supply irrigation water to existing and projected agricultural fields. Table 1 provides details on storage capacity, annual inflow, and demand balance of planned irrigation dams. A more detailed monthly distribution of inflow and demand mass balance is presented in Table 2.

Hydropower Dam Sector

In this sector, dam operation and energy production of HP units are simulated using a single-reservoir reliability-based simulation model, which is the commonly employed method for design and operation of HP units in Iran (Afzali et al. 2008). A brief description of the model, adopted from Afzali et al. (2008), is outlined subsequently. In this method, estimating monthly energy yield and release discharge from a HP reservoir is a multistep process. Like SOP, the highest priority on releasing water is to meet a preassigned energy demand. In other words, enough water is released in a given month to produce electricity equal to or greater than firm energy (FE). Firm energy, defined as the minimum energy guaranteed to be generated each month with certain reliability (a value assigned by design engineers), is calculated as

$$\mathrm{FE}(t) = \mathrm{IC} \times \mathrm{nh}(t) \times \mathrm{Pf} \quad (2)$$

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Table 2. Monthly Distribution of Inflow and Demands Mass Balance of Planned Irrigation Dams

	Garin				Kalan				Anahita				Gheshlagh				
Month	Inflow	Envi	Exist.	Dev.	Inflow	Env.	Exist.	Dev.	Inflow	Env.	Exist.	Dev.	Inflow	Env.	Exist.	Dev.	GW
January	5.72	0.9	0	0	2.28	0.2	0	—	3.07	0.34	0	0	5.74	0.22	0	0	0
February	5.63	1	0	0	3.03	0.31	0	—	3.65	0.43	0	0	8.16	0.35	0	0	0
March	8.74	1.13	0	0	6.14	0.52	0	—	6.7	0.64	0	0	18.2	0.7	0	0	0
April	14.52	5.27	1.81	0.72	8.57	2.55	0	—	9.87	2.61	0	0	25.36	1.11	0	0	0
May	20.64	5.97	7.69	5.6	4.89	1.59	1.59	—	7.7	2.26	0.51	6.44	16.37	0.84	8.54	1.94	0
June	20.08	4.28	11.98	10.73	1.18	0.5	0.96	—	3.8	1.32	0.44	5.55	4.72	0.4	17	3.93	9.69
July	17.02	2.92	9.38	11.8	0.42	0.12	1.7	—	1.95	0.64	0.42	5.28	1.62	0.25	12.54	3.05	6.29
August	10.62	2.13	7.66	10.33	0.26	0.05	1.45	—	1.56	0.43	0.44	5.55	0.97	0.21	11.26	3.22	8.49
September	8.56	1.78	4.42	5.53	0.2	0.03	0	—	1.38	0.35	0.19	2.45	0.76	0.13	9.02	1.96	6.96
October	7.01	0.49	2.21	0.81	0.44	0.1	0.82	—	1.3	0.12	0.15	1.93	1.24	0.11	8.22	1.89	5.75
November	6.68	0.6	0	0	1.4	0.09	1.61	—	1.91	0.17	0	0	2.94	0.13	0.92	0.13	0
December	6.44	0.83	0	0	2.05	0.18	0	—	2.56	0.26	0	0	4.93	0.2	0	0	0
Total	131.68	27.32	45.15	45.51	30.84	6.25	8.14	—	45.46	9.57	2.15	27.2	91.01	4.67	67.5	16.12	37.17

	Jezman				Noorabad				Chenareh				Jamishan				
Month	Inflow	Env.	Exist.	Dev.	Inflow	Env.	Exist.	Dev.	Inflow	Env.	Exist.	Dev.	Inflow	Env.	Exist.	Dev.	GW
January	3.94	0.25	0	0	9.14	0.83	—	0	17.5	1.54	0.89	1.05	4.96	0.44	0	0	0
February	5.46	0.33	0	0	10.58	1.02	—	0.68	20.61	1.86	0	0	6.18	0.56	0	0	0
March	7.63	0.42	0	0	21.45	1.58	—	0.88	29.39	2.53	1.13	1.33	12.4	0.99	0	0	0
April	6.03	1.56	0.03	0.67	26.02	6.71	—	5.47	30.96	9.58	5.01	5.89	16.72	1.52	0	0	0
May	3.46	1.12	0.15	3.61	17.36	4.73	—	7.44	21.83	6.94	9.22	10.84	9.64	0.95	2.49	4.3	2.65
June	1.24	0.43	0.14	3.33	4.7	1.68	—	13.82	8.22	3.19	11.79	13.87	2.32	0.27	5.03	8.69	5.36
July	0.88	0.26	0.21	4.94	2.58	1.04	—	15.08	6.82	2.03	11.95	14.06	0.97	0.1	3.9	6.74	4.16
August	0.55	0.18	0.22	5.28	3.48	1.18	—	14.99	6.21	1.7	10.97	12.9	0.66	0.06	4.12	7.12	4.39
September	0.65	0.18	0.09	2.13	2.66	0.98	—	9.57	6.77	1.63	6.85	8.06	0.59	0.05	2.51	4.34	2.68
October	1.55	0.09	0.05	1.21	3.5	0.38	—	5.86	9.27	0.6	1.41	1.65	0.77	0.23	2.41	4.17	2.57
November	2.33	0.16	0.05	1.26	6.78	0.67	—	0.2	12.47	1.13	0.73	0.85	3.1	0.37	0.16	0.28	0.17
December	3.9	0.25	0	0	8.79	0.86	—	0	17.57	1.68	0.01	0.01	4.76	0.43	0	0	0
Total	37.61	5.24	0.94	22.44	117.04	21.65	—	74	187.63	34.41	59.95	70.53	63.08	5.97	20.63	35.63	21.98

Note: Units are 10^6 m^3/month; environmental (Env.), existing (Exist.), and development (Dev.) agricultural demands are to be supplied by irrigation dams; part of the irrigation demands of Gheshlagh and Jamishan are supplied from groundwater resources (GW).

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where $FE(t)$ = firm energy yield during month t (MWh); IC = power plant's installed capacity (MW); $nh(t)$ = number of hours in month t; and Pf = plant factor, which is the fraction of a day (or month) that the powerplant is supposed to produce energy at full capacity. The actual energy produced is calculated as

$$E(t) = 2.73 \times R(t) \times [\bar{h}(t) - h_{\text{tail}}(t) - h_f(t)] \times e_p \qquad (3)$$

where $E(t)$ = generated energy (MWh) in month t; $R(t)$ = turbine release discharge at month t (1×10^6 m^3); e_p = power plant's efficiency (dimensionless); $\bar{h}(t)$ = average reservoir water level during month t (m); $h_{\text{tail}}(t)$ = average tail water head (m); and $h_f(t)$ = total head losses (m) during the month. By replacing the actual generated energy $E(t)$ with its estimate (firm energy), the turbine release discharge yields as

$$R(t) = \frac{\text{IC} \times \text{nh} \times \text{pf}}{2.73 \times [\bar{h}(t) - h_{\text{tail}}(t) - h_f(t)] \times e_p} \qquad (4)$$

In Eq. (4), $\bar{h}(t)$, $h_{\text{tail}}(t)$, and $h_f(t)$ depend on $R(t)$. Thus, Eq. (4) needs to be solved implicitly. Conventionally, it is solved iteratively. The value of $R(t)$ can be assumed initially equal to the inflow to the reservoir at month t, and $\bar{h}(t)$ is then calculated from reservoir water budget equation. Values for $h_{\text{tail}}(t)$ and $h_f(t)$ are then computed from their given relationship with $R(t)$. The relationship between $h_{\text{tail}}(t)$ and $R(t)$ usually appears as a second-order polynomial and $h_f(t)$ is generally derived from the Darcy-Weisbach friction loss equation. A new $R(t)$ is then calculated from Eq. (4) and is compared with the initially assumed value; if the difference is considerable, the procedure is repeated until convergence is established. Vensim software offers a variety of numerical approximation methods (e.g., Euler method and second- and fourth-order Runge-Kutta method) for solving implicit equations. This capability eliminates the need for coding and makes Vensim an appealing choice for simulating moderately complex physical systems. Fourth-order Runge-Kutta approximation was selected in this paper for higher accuracy.

There are some constraints that must be satisfied at the end of the simulation process. If the calculated storage at the end of the month (S_t) is outside the acceptable range ($S_{\min} \leq S_t \leq S_{\max}$), some action is required to bring it within the limits. Turbine release is increased if $S_t > S_{\max}$ to generate a secondary energy and bring S_t to its maximum capacity $S_{\max}$. Maximum energy production is also limited to the power plant's maximum production capacity and if this limit is exceeded, the excess release is spilled with no energy production. Energy production is decreased to bring S_t back to its minimum capacity if the storage falls below $S_{\min}$, consequently reducing the produced energy during that period. Using the end of the month storage to be the following month's initial storage, the procedure is repeated for each month until the very end of the simulation period. A hydropower sector modeled in Vensim software is displayed in Fig. 2(b). As indicated previously, three HP units are planned for the study area; one hydropower dam (Seimareh) is under construction and the other two (Kuran-Buzan and Sazbon) are passing final stages of feasibility studies. With these units being completed, energy production capacity of the region will be expanded by 1,133 MW. The characteristics (e.g., normal volume, installed capacity, and plant factor) of the three HP dams are listed in Table 3.

Control Hydrometric Stations Sector

Any hydraulic structure on the river and its tributaries will have an impact on the hydrologic regime. To assess such impacts, river discharges were modified at specific locations (control hydrometric stations) according to the upstream irrigation and HP dam storage and release behaviors. The modified flows, leaving these control hydrometric stations, were fed into downstream HP sectors and the energy production was then simulated. Fig. 4 depicts the location of control hydrometric stations in relation to other model components (when the watershed is completely developed, i.e., all irrigation and hydropower dams are operational). For projected agricultural developments, where groundwater (GW) is allocated for supplying part of irrigation demands (as is the case for projected farming fields downstream of Gheshlagh and Jamishan dams), that water was accounted for by adding 25% of GW irrigation volume as return flow to control hydrometric stations downstream of the fields.

Table 3. Hydropower Dams in the Study Area

Characteristics	Kuran-Buzan	Sazbon	Seimareh
Basin area (km^2)	19,904	25,524	27,886
Mean annual inflow (10^6 m^3)	2,528	3,241	3,619
Normal volume (10^6 m^3)	4,022	1,309	3,216
Installed capacity (MW)	278	375	480
Plant factor (%)	25.0	16.7	16.7
Firm energy (GWh/year)	600.0	540.0	692.4
Tunnel capacity (m^3/s)	250	360	459

Note: Seimareh Dam is currently under construction and the other two are under feasibility studies.

Simulation Period, Temporal Scale, and Model Validation

Based on available historic flow data, a 30-year simulation period (September 1963–August 1993) was selected for scenario analysis. This period contained the most complete measured flow data set amongst hydrometric stations (both control and noncontrol). Within the simulation period, 4 out of 15 hydrometric stations had gaps in observed discharge data. These gaps were filled by employing multiple linear regression models built on data from nearby hydrometric stations (R^2 values varied from 0.65 to 0.96).

Discharge data were available only at a monthly time scale; consequently, the simulations were performed at monthly temporal scale. The developed SD model can easily be adapted to finer time scales by simply changing the unit conversion parameters. Assessment of hydropower production at a monthly time scale is not uncommon in the literature (Karamouz et al. 2003). See, for

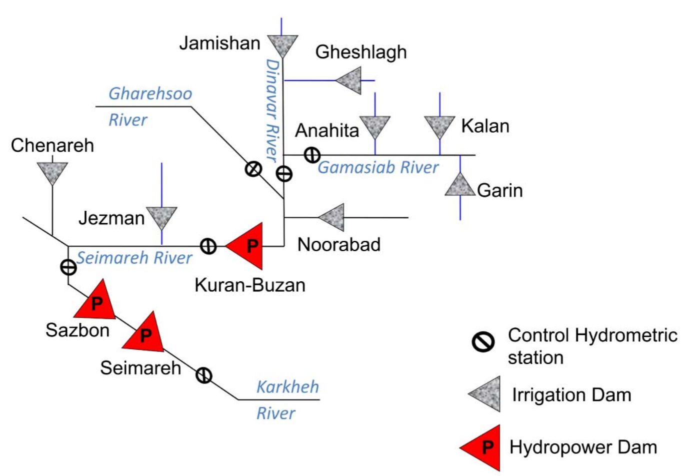

Fig. 4. Schematic view of the model components when the study area is fully developed (S_{dev})

instance, Afzali et al. (2008), Barros et al. (2003), and Cheng et al. (2008).

In the framework of SDMs, model validation is a semiformal process involving a combination of quantitative tests and qualitative behavioral analysis targeting the system's internal structure (Barlas 1996). The SDM presented in this paper considers a future state of the watershed; discharge and energy production are assessed under effects of future developments. As one would expect, no quantitative tests could be performed because there are no future streamflow data. Nevertheless, the model was validated by conducting several behavioral tests on model sectors to see if they can successfully simulate storage and release behaviors that are expected based on their adopted operating policy [details available in Sharifi (2008)].

Future Development Scenarios

Various potential development scenarios for the study area were identified and tested using the proposed SDM. The scenarios differ in the number of development elements and were selected in such a way that each represents the effects of different realistic development plans on HP generation among three HP units. Full development (scenario S_{dev}) refers to a development plan in which all eight irrigation dams are constructed and are functional (supplying existing and projected demands) in addition to the three HP dams being in operation and generating energy (as depicted in Fig. 4). On the contrary, scenario S_{null} draws a plan in which only one HP dam is functional under unmodified flow regime with no other development elements (hydropower or irrigation dams) in place. The purpose of defining S_{null} was having a reference condition to which other scenarios can be compared. Scenario S_{hydro} depicts a condition between S_{null} and S_{dev} in which only three hydropower dams are functional at a given time with no other development (irrigation dams). Scenario S_{trans} considers interbasin water transfer from the Sirvan River basin to the study area. At last, in scenario S_{Pf}, the plant factors of the hydropower units were increased to a certain limit in order to study the effects of future development scenarios on firm energy production. The last two scenarios (S_{trans} and S_{Pf}) are not complete by themselves because they do not consider any development elements. They need to be combined with prior defined scenarios (S_{null}, S_{dev}, or S_{hydro}) to form a complete scenario. The defined future development scenarios are listed and described in Table 4.

Table 4. Hypothetical Future Development Scenarios Defined for the Study Area

Scenario	Description
S_{null}	Each hydropower dam is operating solely under unmodified flow regime with no other development elements (hydropower or irrigation dams) existing in the basin.
S_{dev}	Full development in the study area with eight irrigation dams and three hydropower dams all operational.
S_{hydro}	Only three hydropower dams are operating together with no other development elements (irrigation dams) existing in the basin.
S_{trans}	Intercatchment water transfer from Sirvan basin with three different annual transfer volumes: $S_{\mathrm{trans}\text{-}a} = 300 \times 10^3\ \mathrm{m}^3$, $S_{\mathrm{trans}\text{-}b} = 500 \times 10^3\ \mathrm{m}^3$, and $S_{\mathrm{trans}\text{-}c} = 700 \times 10^3\ \mathrm{m}^3$.
S_{Pf}	Plant factors increased till reliability is reduced to 90%.

Note: Scenarios S_{trans} and S_{Pf} are not complete without being combined with other scenarios.

Results and Discussion

Energy production under various development scenarios are presented and discussed subsequently. The difference in energy generation among these scenarios stems from the changes in hydrology of the river system associated with each scenario. In accordance with the scope of this paper, rather than focusing on hydrologic modifications, the discussions were limited to differences in energy production at the HP units under various scenarios. Monthly average river discharges at the HP dam sites are provided in Table 5 for each development scenario.

Full Development (S_{dev}) versus No Development (S_{null})

Table 6 compares the energy generated based on the three scenarios S_{null}, S_{dev}, and S_{hydro}. As shown in Table 6, in all three scenarios HP units produce energy in excess of planned firm energy (Table 3), meaning that firm energy is secured at all times, even after the watershed is fully developed. Looking at each HP unit separately, S_{dev} has the lowest energy production of the three scenarios as expected (due to newly introduced upstream demands) and S_{null} has the highest. The maximum possible energy generated at S_{null} befalls when Seimareh, which is the most downstream HP dam, is functional by itself, which is far less compared to maximum (total) energy production of the two other scenarios (S_{dev} and S_{hydro}). Summing up the total energy produced by the three HP units has no physical meaning in scenario S_{null} because it was assumed that only one HP unit is operational at a time.

Comparison of total energy generated in the S_{dev} and S_{hydro} scenarios discloses the effects of upstream development (i.e., adding eight irrigation dams and over 34,000 ha of irrigated agricultural fields) on energy generation in the study area. The reduction of 254 GWh in hydroelectricity production is the consequence of upstream developments. Because all the HP units in the S_{dev} scenario are capable of producing firm energy at all times, the 254-GWh difference is in secondary energy production. The negative impact of development on energy production is intensified moving downstream. While upstream development is projected to cause 8.0% reduction in energy production of the Kuran-Buzan plant, it is projected cause a 10.2% reduction at the Seimareh plant.

Effect of Upstream Hydropower Dam Release on Downstream Reservoirs

Water is stored behind hydropower dams and is quickly released during peak energy usage times. This operational practice strongly affects the river's regime and consequently the downstream facilities. Scenario S_{hydro} was initially defined to study this effect on two hydropower storages downstream of the Kuran-Buzan Dam. As mentioned previously, in scenario S_{hydro} only three hydropower dams are functional at a given time and no other development (irrigation dams) was assumed. The Kuran-Buzan Reservoir is only affected by the river's natural flow regime, while Sazbon is influenced by Kuran-Buzan release and Seimareh is under the effect of both Sazbon and Kuran-Buzan releases.

The volume of these two storages (Seimareh and Sazbon) over time is depicted in Fig. 5 for scenarios S_{hydro} and S_{null} over the simulation period. As seen in the figure, when the Sazbon Dam is operating alone (S_{null}), a very similar pattern is repeated over time; water level rises to the maximum capacity by the end of spring and falls to its minimum toward the end of winter. The energy production can become very tenuous during drought periods when only one dam operates. On the other hand, in scenario S_{hydro}, storage mostly remains above 85% of its maximum capacity ($1.36 \times 10^9\ \mathrm{m}^3$) and it can be said that energy production is much

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Table 5. Monthly Distribution of Inflow at HP Dam Sites under Various Development Scenarios

Month	S_{null} (m^3/s)			S_{dev} (m^3/s)			S_{hydro} (m^3/s)			$S_{trans\text{-}a} + S_{dev}$[a] ($m^3/s$)			$S_{trans\text{-}a} + S_{dev}$[a] ($m^3/s$)			$S_{trans\text{-}a} + S_{dev}$[a] ($m^3/s$)		
	Kuran-Buzan	Sazbon	Seimareh	Kuran-Buzan	Sazbon	Seimareh	Kuran-Buzan	Sazbon	Seimareh	Kuran-Buzan	Sazbon	Seimareh	Kuran-Buzan	Sazbon	Seimareh	Kuran-Buzan	Sazbon	Seimareh
January	66.2	92.7	104.5	56	67.3	75.8	55.5	71.1	80.1	60.4	66.9	75.5	63.3	68.9	77	66.2	70.3	77.4
February	90.9	123.8	131.2	79.2	75.1	78.3	66.2	74.9	79.8	85.7	76.1	79	90.1	77.6	81.8	94.5	80.2	83.1
March	188	224.8	246.4	167.7	110.1	128.4	90.9	87.4	86.4	180.5	122.3	138.8	189	132.1	147.9	197.5	142.6	156.7
April	255.6	303.9	322.8	237.5	195.3	212.3	188	145.3	162.2	254.5	227.3	237.4	265.8	244.1	250.3	277	258.1	263.7
May	162.8	203.4	216.1	152.9	155.7	158.8	255.6	255.3	273	164.3	170.5	172.9	171.9	178.6	181	179.5	186	191.1
June	52.4	67.5	81.5	52.1	72	87.1	162.8	192.6	204.1	56.5	74.6	89.4	59.4	76.8	90.5	62.3	78.8	92.4
July	20.9	27.5	36.6	23.2	54.8	72.8	52.4	76.5	94.4	25.1	55.4	72.4	26.3	56.1	73	27.6	55.9	72.4
August	13	19	28	14.6	51.9	70.2	20.9	52.6	74.8	15.7	53.4	71.8	16.5	54.6	72.1	17.2	54.3	71.7
September	10.4	17.4	24.5	9.1	51.2	67.2	13	50.2	72.8	10	53.1	69.7	10.7	53.2	69.3	11.3	54.2	69.4
October	14	22	32.1	9.9	49.6	69.4	10.6	50.8	68.4	11.4	51.8	72.1	12.2	51.4	71.8	13.1	52.8	72
November	32.5	52.3	59.2	25.5	61.3	67.2	14	52.7	71.8	28	62.2	68.3	29.5	62.4	69.8	31	63.5	70.2
December	55.5	79.1	94.2	45.5	63.1	77.8	32.5	67.2	69.7	49.2	63.2	77.9	51.7	64.3	79.2	54.1	65.7	79.4
Average	80.2	102.8	114.8	72.8	84	97.1	80.2	98	111.5	78.4	89.7	102.1	82.2	93.3	105.3	86	96.9	108.3

Note: Inflows under scenario S_{null} are equivalent to natural (unmodified) river discharges at HP sites.
[a]45% of water transfer from Sirvan basin is allocated to environmental release.

Table 6. Annual Average Energy Generated (GWh/year) Based on the Scenarios of S_{null}, S_{dev}, and S_{hydro}

Scenario	Kuran-Buzan	Sazbon	Seimareh	Total
S_{null}	798	792	1,130	—[a]
S_{dev}	734	685	999	2,418
S_{hydro}	798	761	1,113	2,672

[a]Because only one HP unit is operational at a time under this scenario, summing up the total energy produced by the three HP units has no physical meaning.

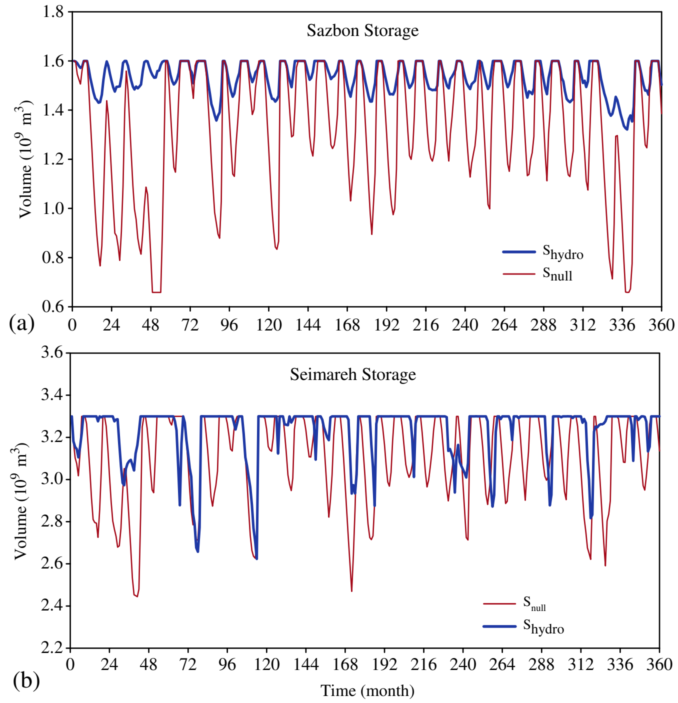

Fig. 5. Sazbon and Seimareh's storage volume variation over time for two scenarios of S_{hydro} and S_{null}; time zero is September 1963

more sustainable in this case. This effect is repeated at the Seimareh Dam, but at a lesser extent.

Implementing single-reservoir operating policies for HP dams in a multireservoir HP system (like the system of three HP units in this paper) would result in not benefiting from the gain in extra storage discussed in the previous paragraph. Application of an optimum operation policy for simulating this multireservoir system could have yielded higher energy productions. However, employing the operating policies (i.e., single reservoir models) that were assumed will be the adapted policy in the near future was attempted.

Interbasin Water Transfer

Transferring water to the Karkheh basin from the Sirvan River basin, where water is in excess due to relatively low demands, is one of the projects still being studied by the Iranian Ministry of Energy (Shourian et al. 2008). According to this project, water will be transferred to the Karkheh basin from the northwest (via the Gharehsoo River) just upstream of the Kuran-Buzan Dam (Fig. 4). The Sirvan River has an annual average inflow of 811×10^6 m^3/year at the point of diversion. The amount of transferable water was not clear at the time this study was carried out. Therefore, in this scenario (S_{trans}), three different volumes of

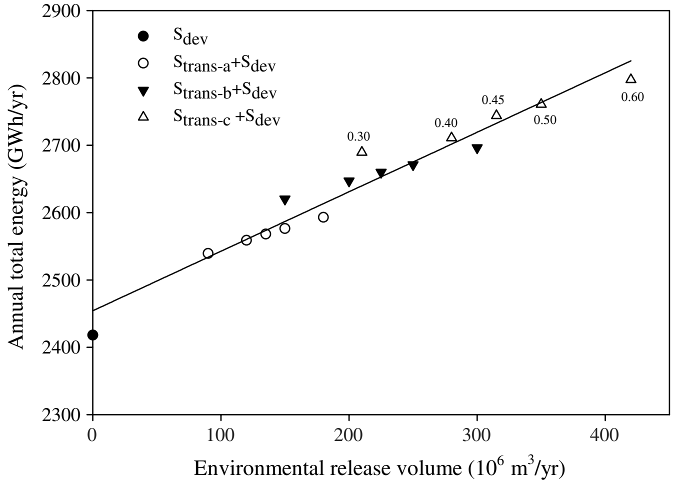

Fig. 6. Energy production (GWh/year) under different combinations of S_{trans} and S_{dev} scenarios; the numbers near the white triangles represent the fraction of total transfer volume that was allocated for environmental release in that scenario ($S_{\text{trans-}c}$); similar fractions are applied to $S_{\text{trans-}a}$ and $S_{\text{trans-}b}$; the solid line represents the best-fit linear regression line obtained between annual average electricity production and environmental flow release ($R^2 = 0.95$, slope $= 0.88$)

300×10^6 m^3 ($S_{\text{trans-}a}$), 500×10^6 m^3 ($S_{\text{trans-}b}$), and 700×10^6 m^3 ($S_{\text{trans-}c}$) were assumed for transfer annually. The assumed transfer volumes are hypothetical and thought to have monthly distributions similar to the Sirvan River flow distribution. Of the transferred water, 10% was earmarked for drinking and the rest was allocated for irrigation and environmental release (for habitat restoration of Hawr-Al-Azim wetland, located at south end of the Karkheh basin). To test the sensitivity of total power yield to this rather arbitrary allocation split, the model was run several times, each time with a different divide (environmental release = 0.3, 0.4, 0.45, 0.50, 0.6 × transfer volume). S_{trans} is not a complete scenario by itself because it does not explain any development characteristics. Therefore, it was combined with S_{dev}, which was previously defined. Fig. 6 shows the results of this scenario analysis along with S_{dev} for comparison. The horizontal axis lays out the environmental flow release for different combinations of S_{trans} and S_{dev} scenarios. Not surprisingly, the general trend shows a raise in energy production with more water allocated to the environment. Yet the most valuable outcome of this scenario analysis is an estimate on energy production increase per unit volume of water allocated for environmental release. Using all the data points on Fig. 6, a strong linear relationship is obtained ($R^2 = 0.95$) between annual average electricity production and environmental flow release. The slope of the best-fit line reveals that an average 88 GWh/year increase in electricity production can be achieved per 100×10^6 m^3 of annual environmental flow release out of transferred water from Sirvan to the Karkheh River basin.

Maximum Energy Yield with 90% Reliability

So far the only effect upstream development scenarios had on hydropower generation was the contribution of secondary energy generation. However, secondary energy is not a reliable resource due to its unpredictable nature. Electric energy cannot be stored and must be consumed the moment it is generated. Thus, there might be no use of the secondary energy depending on the generation time and demand. Yet with ever increasing energy demands, the planners might decide to increase plant factors (i.e., running the HP plants for longer durations in a day) in the future to generate more reliable firm energy rather than secondary energy. The importance of each future development scenario can be understood better if the focus is on generating more firm energy rather than secondary energy. In scenario S_{Pf}, the main objective was to determine the system's maximum production capacity and energy yield that can be achieved for a predetermined reliability. One parameter was added to each hydropower unit to calculate the reliability, and then the plant factors were increased until the reliability dropped to 90%, which is the minimum required reliability for designing powerplants in Iran. Reliability in context of this study is defined as

$$\text{reliability} = \left(1 - \frac{\text{number of failures}}{\text{number of months}}\right) \times 100 \quad (5)$$

where failure is defined as producing less than firm energy in a given month. Similar to scenario S_{trans}, this scenario also needs to be combined with one of the previous future development scenarios to be complete.

Table 7 presents the modified plant factors under different scenario combinations compared to the original allocated values by the design engineers (Table 3). The percentages of increases in plant factor relative to original allocated plant factor values act as a surrogate for an increase in firm energy production. The last column in Table 7 shows the total firm energy generated with 90% reliability

Table 7. Modified Plant Factors and Total Firm Energy Production at 90% Reliability (Scenario S_{Pf})

Scenario	Kuran-Buzan: Plant factor at 90% reliability (% increase)	Sazbon: Plant factor at 90% reliability (% increase)	Seimareh: Plant factor at 90% reliability (% increase)	Total FE production at 90% reliability (GWh/month) (% increase)
$S_{\text{Pf}} + S_{\text{null}}$ [a]	0.295 (18%)	0.191 (14%)	0.212 (27%)	— [b]
$S_{\text{Pf}} + S_{\text{dev}}$ [c]	0.270 (8%)	0.212 (27%)	0.219 (31%)	187 (23%)
$S_{\text{Pf}} + S_{\text{hydro}}$ [d]	0.295 (18%)	0.234 (40%)	0.242 (45%)	206 (35%)
$S_{\text{Pf}} + S_{\text{trans-}a} + S_{\text{dev}}$ [e]	0.292 (17%)	0.226 (35%)	0.231 (38%)	199 (31%)
$S_{\text{Pf}} + S_{\text{trans-}b} + S_{\text{dev}}$ [f]	0.308 (23%)	0.236 (41%)	0.241 (44%)	209 (37%)
$S_{\text{Pf}} + S_{\text{trans-}c} + S_{\text{dev}}$ [g]	0.323 (29%)	0.245 (47%)	0.248 (49%)	217 (42%)

[a]Single HP dam operating alone with no other development.
[b]Because only one HP unit is operational at a time under this scenario, summing up the total energy produced by the three HP units has no physical meaning.
[c]All HP dams operating with upstream fully developed.
[d]All HP dams operating with no upstream development.
[e]All HP dams operating with upstream fully developed and 300×10^6 m^3 water transfer with 45% allocated to environmental release.
[f]All HP dams operating with upstream fully developed and 500×10^6 m^3 water transfer with 45% allocated to environmental release.
[g]All HP dams operating with upstream fully developed and 700×10^6 m^3 water transfer with 45% allocated to environmental release.

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and the relative increase from the original design firm energy production capacity.

As expected, in all scenarios (except for $S_{\mathrm{Pf}} + S_{\mathrm{null}}$, which considers each dam operating individually), the plant factors of the two downstream HP units (Sazbon and Seimareh) had higher increase rates compared to Kuran-Buzan due to the positive effects of upstream HP release. Comparison of the second and third rows in Table 7 ($S_{\mathrm{Pf}} + S_{\mathrm{dev}}$ and $S_{\mathrm{Pf}} + S_{\mathrm{hydro}}$) reveals that upstream development (eight irrigation dams and new irrigation demands) reduces the capacity to increase firm energy by $228\ [= (206 - 187) \times 12]$ GWh/year. This is equivalent to energy production of a single HP unit with 105 MW installed capacity and a plant factor of 0.25. Comparison of the last three rows with the second row in Table 7 shows that at 90% reliability, firm energy generation can be increased about 116 GWh/year per $100 \times 10^6\ \mathrm{m}^3$ of annual environmental flow release.

Summary and Conclusions

In this study, an SDM was developed to predict the effects of upstream developments on hydropower generation of existing and future planned hydropower units in a basin. The proposed model was applied to the upper parts of Karkheh River basin, which is one of the most rapidly developing basins in Iran. With the use of historic data, the model was run for 30 years (September 1963–August 1993). Results showed that upstream development including construction of eight new irrigation dams accompanied by 34,000 ha of irrigated land will not affect the firm energy generation at the three downstream HP dams, but will reduce secondary energy generation by 254 GWh annually. Different future development scenarios were defined and tested using the model. It was shown that upstream HP reservoirs have positive effects on storages of downstream HP reservoirs. The implication of this is that HP generation is more sustainable in cascading HP systems. Water transfer from the nearby Sirvan River basin to the Karkheh River basin was another scenario that was explored. Simulations showed that secondary energy production can be increased by 88 GWh per $100 \times 10^6\ \mathrm{m}^3$ of annual environmental flow release out of transferred water from Sirvan to the Karkheh River basin. In the last scenario, maximum energy yield with 90% reliability was evaluated for different development scenarios, which revealed the true effects of upstream development on HP generation in the area.

This paper showed how an SD approach can be an effective framework for integrated watershed assessment. Although socioeconomic and environmental effects of the future scenarios were not explored in this study, SD provides the proper means for adding such components. Indeed, the interbasin water transfer may have significant consequences at the Sirvan River basin. The reduced flow could alter the ecosystem dynamics in that river. Further, the construction of all these dams will prevent some fish passages and therefore could jeopardize their spawning patterns. Although interbasin water transfer could benefit the wetlands at the downstream end of the Karkheh River basin, the addition of all these new dams means reduction in sediment loads. Sediment is vital for wetlands. Sediment-starved wetlands will experience subsidence, in turn causing loss of wetlands. The loss of coastal wetlands in Louisiana at the Mississippi River Delta is a perfect example to this phenomenon. If the long-term environmental consequences are not critically assessed, the short-term socioeconomic benefits may turn into big losses over the long run.

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