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Optimization and simulation of a multiple reservoir system operation

Seyed Jamshid Mousavi, Abbas Gholami Zanoosi and Abbas Afshar

ABSTRACT

Dynamic programming (DP) optimization and HEC-5 simulation models were developed for planning the long-term operation of the Karoon-Dez multireservoir system in Iran. The well-known dimensionality problem associated with DP was controlled using a heuristic approach to narrow the required search algorithm within the state space of DP. HEC-5 as a common and widely available computer program for studying reservoir systems regulation was also used to simulate operation of the Karoon-Dez system with water supply and hydropower generation objectives. HEC-5 is able to consider flood control, hydropower generation and conservation purposes. Both the DP and HEC-5 models were applied to the Karoon-Dez system consisting of six reservoirs; five reservoirs in series parallel to a sixth one. The results obtained by the HEC-5 and DP models were analysed and compared. The results show that, although the DP results were better than those of HEC-5 in terms of meeting system operating targets and energy generation, HEC-5 as a simulation model demands much less computer time and memory, making it attractive for practical use.

Key words | dynamic programming, HEC-5, multireservoir operation, optimization, simulation

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INTRODUCTION

Dimensionality, stochasticity and nonlinearity are the main sources of complexity involved in the optimization of a multireservoir operation problem. Dimensionality is mainly due to the large number of state and decision variables associated with each reservoir in the system. Stochasticity is an important characteristic of a water resources system caused mainly by the random nature of stream flows, the imprecision of the forecasts and the uncertainties in water or energy demands. Reservoir operation is also a multipurpose problem with non-linear and non-convex functions such as hydropower generation and penalty functions defined for water supply shortages, making it more challenging. Labadie (2004) presents a state-of-the-art review of optimal operation of multireservoir systems.

Three major modelling approaches that have been widely used for the optimization of multireservoir operation problems are linear programming (LP), non-linear programming (NLP) and dynamic programming (DP). A comprehensive review on the methods used in reservoir systems operation can be found in Yeh (1985). LP has been extensively used in reservoir operations problems. Among the LP algorithms, application of the interior-points methods (IPM) to large-scale reservoir operations problems has recently shown promising results (Seifi and Hipel 2001). NLP has had less applicability in optimizing multireservoir operations because NLP techniques are slow, iterative and difficult in the explicit consideration of uncertainty features. Fletcher and Ponnambalam (1998) presented a new approach for the stochastic control of multireservoir systems in which the reservoir operations information can be derived from an NLP solution. Since a reservoir system operation is a sequential decision-making process, DP would provide a good framework for optimizing the decisions. It can also take into account the nonlinearity of the objective function as well as detailed characteristics of the real system.

Application of the DP technique in water resources systems has been reviewed by Yakowitz (1982). However, the main shortcoming of DP is the exponential increase in computational burden and memory requirements as the number of state variables increases. This problem is known as the ‘curse of dimensionality’. Thus, the applicability of DP is limited to the systems with very few reservoirs. Several DP-based methods such as incremental DP (IDP) (Hall *et al*. 1969), discrete differential DP (DDDP) (Heidari *et al*. 1971) and IDP with successive approximations (IDPSA) (Larson 1968; Trott and Yeh 1971) have been developed to overcome this limitation. Another approach applied to multireservoir systems is aggregation/decomposition (A/D) techniques using DP (A/D-DP) in which some type of heuristic is used to build a suitable approximate model of the original DP model. Among them, Ponnambalam and Adams (1996) proposed a heuristic algorithm, namely, multilevel approximate DP (MAM-DP) extending the A/D-DP of Turgeon (1980, 1981).

The aforementioned complexities in optimization models have made simulation models attractive to deal with multireservoir systems operation. Although simulation models are unable to find the best solution strategies among existing ones, they are much easier to implement and are thus suitable for dealing with large-scale systems, with the ability to consider detailed representations of them. It is usual to build a simple model of the real problem to be solved using an optimization model as a screening tool and then performing further detailed analysis via simulation. There are several simulation models developed for tackling multireservoir systems operation, among which HEC-5 (US Army Corps of Engineers 1982) is one of the best, in terms of flood control, hydropower generation and conservation purposes. In this paper, the operation of the Karoon-Dez multireservoir system in Iran is examined using DP and HEC-5. DP has the advantage of using heuristics rules to make the search algorithm of the model more efficient. The paper consists of six sections. The next section describes the Karoon-Dez system used as the case study. Then, DP formulation of the system operation is presented. Computational issues regarding the DP model are discussed. The penultimate section covers the HEC-5 simulation model. The results obtained from the application of the methods to the Karoon-Dez system are explained, followed by a summary and conclusions.

SYSTEM DESCRIPTION

The case study on which the model is built is the Karoon-Dez system. This system is located in the southwest region of Iran, carrying more than one-fifth of the surface water available in the country. The total area of these basins is about 45,000 km^2. The system is composed of six reservoirs and seven sub-basin reaches as shown in Figure 1. There are five cascade reservoirs on the Karoon River in series: Karoon4, Karoon3, Karoon1, Godarlandar and Gotvand, and one reservoir on the Dez river. Karoon1, Godarlandar and Dez are in operation and Karoon4, Karoon3 and Gotvand are under construction. Generating hydropower is an important purpose of the Karoon-Dez system operation, with a total of 6,520 MW of installed capacity. Table 1 gives some information about the dams and the hydroelectric power plants (HPPs) in the system. There are other reservoirs under study that will not come into operation in the near future; hence they are not considered in this paper. Godarlandar, with 200 million cubic metres (MCM) of active storage capacity, has a much smaller capacity than the other reservoirs, functioning as a run-of-river HPP.

The Karoon and Dez Rivers join together at a location called Band-e-Ghir and form the Great Karoon River. This river passes the city of Ahwaz and flows into the Persian Gulf. Average annual streamflows to the Dez and Karoon reservoirs are 8,500 and 13,100 MCM, respectively. These two rivers supply water for the domestic, industrial, agricultural and agro-industrial sectors. The major use of water in these basins is for irrigation. These two rivers also supply water for domestic demands in the neighbouring cities and towns as well as for the industrial units in the area such as steel industries and thermal power plants. According to Figure 1, there are seven reaches in the system, but no water demand has been considered for reaches 1 to 4. Water demands associated with the other reaches are summarized in Table 2.

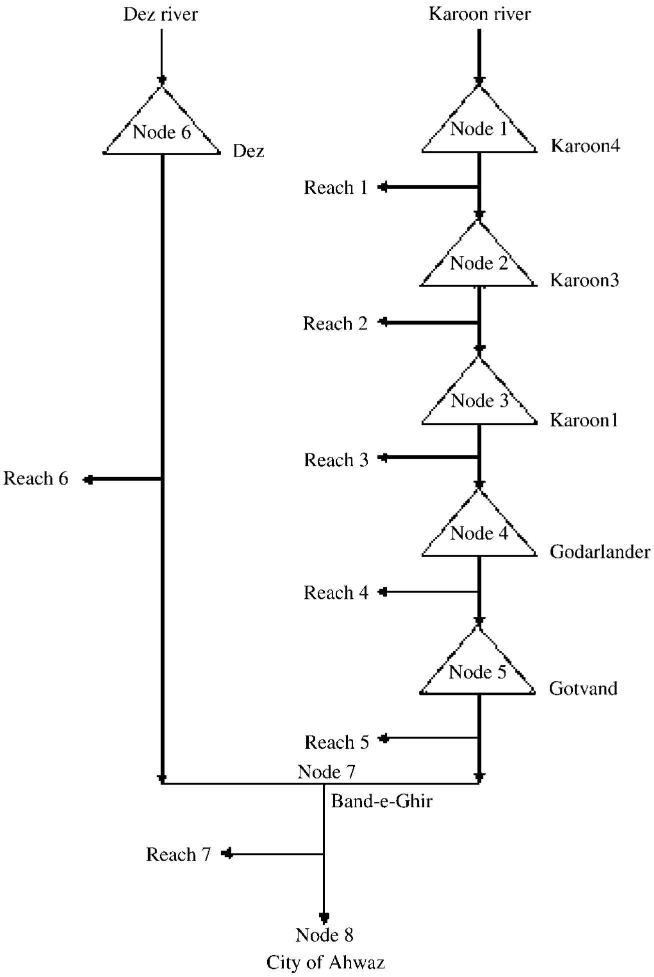


Figure 1 | A schematic representation of the Karoon-Dez reservoir system.

DYNAMIC PROGRAMMING MODEL

The DP formulation used for optimizing the system operation is represented in this section. The following notations are used for the model:

T	number of time periods
t	each time period; $t = 1,K,T$
i	index of the reservoirs; $i = 1,K,6$
j	index of the reaches of consumption; $j = 1,K,7$
$S_i(t)$	storage volume of reservoir i at the end of period t
$S_i^{\min}(t)$	minimum allowable storage volume of reservoir i at period t
$S_i^{\max}(t)$	maximum allowable storage volume of reservoir i in period t
$R_i(t)$	total release volume from reservoir i in period t
$R_i^{\min}(t)$	minimum release required downstream of reservoir i in period t
$R_i^{\max}(t)$	maximum allowable release from reservoir i in period t
$B_j(t)$	water remaining downstream of reach j in period t
$B_j^{\min}(t)$	minimum environmental flow required downstream of reach j in period t.
$\alpha_j(t)$	percentage of the demand supplied to reach j in period t

Table 1 | Dams and their HPP specifications in the Karoon-Dez system

Dam name	Normal water level (m)	Minimum operating level (m)	Plant factor (%)	Type of turbine	Installed capacity (MWh)	Average tailwater level (m)
Dez	350	290	49.0	Francis	520	176
Karoon1	532	500	49.0	Francis	1000	369
Gotvand	224	209	48.0	Francis	1000	84
Godarlander	369	364	20.8	Francis	1000	220
Karoon3	840	800	23.0	Francis	2000	645
Karoon4	1025	996	19.1	Francis	1000	845

Table 2 | Water demands in different reaches of the Karoon-Dez system

	Month											
Reach	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
5	275	264	284	319	307	223	126	114	76	74	128	231
6	465	543	681	748	737	636	421	286	138	135	183	329
7	968	9066	8492	1008	1054	743	554	516	353	3059	439	808

$\alpha_j^{\min}(t)$ minimum water supply requirement in reach j in period t

$dem_j(t)$ water demand of reach j in period t

$Int_j(t)$ natural tributary inflow to reach j in period t

$I_i(t)$ total inflow to reservoir i in period t

$E_i(t)$ evaporation loss from the reservoir i in period t

$PW_i(t)$ hydropower energy generated by reservoir i in period t

$Edem_i(t)$ energy demand defined for HPP i in period t

c_t loss due to shortage in meeting energy demand in period t

$f_t^*(S_1(t),S_2(t),S_3(t),S_4(t),S_5(t),S_6(t))$ optimal return (energy generated) from the beginning of the first period to the end of period t where reservoir storage volumes at the end of period t are $S_1(t)$, $S_2(t)$, $S_3(t)$, $S_4(t)$, $S_5(t)$, and $S_6(t)$, respectively.

Objective function

The main purposes of the operation of the Karoon-Dez system are meeting water supply and water quality requirements and maximizing hydropower generation. The first two purposes, providing a minimum flow for water quality requirements downstream of reach 7 where the city of Ahwaz is located, and meeting water supply requirements, are considered in the constraints and the third in the objective function. The objective function of the DP model is represented by a recursive function as follows:

$$f_{t+1}^*(S_1,S_2,S_3,S_4,S_5,S_6) = \min_{S_t} \{c_t + f_t^*(S_1,S_2,S_3,S_4,S_5,S_6)\} \quad (1)$$

where:

$$c_t = \sum_{i=1}^{6}(Edem_i(t) - PW_i(t))^2 \quad where \quad Edem_t(t) \geq PW_i(t) \quad (2)$$

s.t:

The constraints of the optimization model are detailed below.

Flow equations constraints

The basic dynamics of the Karoon-Dez reservoir system are described by the following flow equations:

$$S_1(t) - S_1(t-1) + R_1(t) + E_1(t) = I_1(t) \quad (3)$$

$$S_i(t) - S_i(t-1) + R_i(t) - [R_{i-1}(t) - dem_{i-1}(t) \cdot \alpha_{i-1}(t)] + E_i(t) = Int_i(t) \quad \text{for } i = 2,\mathrm{K},5 \quad (4)$$

$$S_6(t) - S_6(t-1) + R_6(t) + E_6(t) = I_6(t) \quad (5)$$

Total inflow to each reservoir i, $I_i(t)$, and the water remaining at the end of reach j, $B_j(t)$, are calculated as:

$$I_i(t) = B_{i-1}(t) = R_{i-1}(t) + Int_i(t) - dem_{i-1}(t) \cdot \alpha_{i-1}(t) \quad \text{for } i = 2,K,5 \tag{6}$$

$$B_i(t) = R_i(t) + Int_i(t) - dem_i(t) \cdot \alpha_i(t) \quad \text{for } i = 5,6 \tag{7}$$

$$B_7(t) = B_5(t) + B_6(t) + Int_7(t) - dem_7(t) \cdot \alpha_5(t) \tag{8}$$

Simple bounds on variables

The storage and release variables are subject to lower and upper bounds imposed by physical or technological constraints:

$$S_i^{\min}(t) \le S_i(t) \le S_i^{\max}(t) \tag{9}$$

$$R_i^{\min}(t) \le R_i \le R_i^{\max}(t) \tag{10}$$

Furthermore, the minimum environmental flow downstream of reach j is as follows:

$$B_j(t) \ge B_j^{\min}(t) \tag{11}$$

A minimum water allocation is required in each reach to meet the municipal and domestic needs. Thus,

$$\alpha_j(t) \ge \alpha_j^{\min}(t) \tag{12}$$

Here, the water demand centres are located downstream of the Gotvand and Dez reservoirs and no water demand is defined for reaches 1 to 4. The minimum environmental flow is only considered for the last reach and before the city of Ahwaz as $B_7^{\min}(t) = 200$ MCM.

COMPUTATIONAL ISSUES

Due to the dimensionality problem, the model described above can only be solved with a limited number of grid points, not representing the actual continuous storage volume of each reservoir. For example, if 20 storage levels are selected as the grid points for the reservoirs, there are 20^{12} possible transitions to be evaluated at each stage of the DP model. Managing this huge number of transitions within an acceptable computer time even with the high speed computers available seems to be very difficult, if not impossible.

The fundamental idea used in this study to resolve this problem is that many of these 20^{12} transitions may result in an infeasible release volume, at least from one of the reservoirs in the system. In other words, at least one of the reservoir releases may not fall within its acceptable range [$R_{\min}$, $R_{\max}$]. Although these infeasible solutions would not be chosen as optimum solutions by assigning a large penalty to them, they take significant time within the search procedure performed in each stage of DP.

Let k_1 to k_6 be the state of the storage volumes of the six existing reservoirs at the end of each stage (i.e. time period) and let j_1 to j_6 be the state of the reservoirs' volume at the beginning of that period. The forwards recursive function (Equation 1) finds the set of best initial storage volumes $\{j_1^*, j_2^*, j_3^*, j_4^*, j_5^*, j_6^*\}$ for reservoirs 1–6, which maximizes the objective function for all possible scenarios of final storage volumes $\{k_1, k_2, k_3, k_5, k_6\}$ in each time period. Saving the optimal solutions to be used in the next time period and proceeding forwards up to the final stage, followed by back tracing the optimal solutions to the first stage, gives the set of optimal storage volumes resulting in maximum hydropower generation over the planning horizon.

Suppose that indexes k_1 and j_1 are assigned to the most upstream reservoir (i.e. Karoon4) of the reservoirs in series, k_2 and j_2 to the next downstream reservoir (Kaoron3), and so on up to k_6 and j_6. Consider reservoir number 3 (Karoon1) in this system. Let the release volume be zero or negative for an arbitrary combination of (k_1, k_2, k_3, k_4, k_5, k_6, j_1, j_2, j_3, j_4, j_5, j_6). From the continuity equation:

$$R_3(t,j_3,k_3,I_3(t)) = S_3(t,j_3) + I_3(t) - S_3(t+1,k_3) - E_3(t,j_3,k_3) \le 0 \tag{13}$$

Since transition from initial state j_3 to final state k_3 has resulted in a negative release, then for the same $I_3(t)$, all transitions from j_3 to higher storage levels would certainly result in negative releases as well. Therefore, one may write:

$$R_3(t,j_3,m_3,I_3(t))\leq 0 \;\forall m_3\geq k_3 \quad (14)$$

On the other hand, all the transitions from a lower initial state ($m_3<j_3$) to k_3 would result in lower evaporation ($E_3(t, j_3, k_3)$) in Equation (13). We realized that, for our case study, the decrease in evaporation is less than the decrease in initial storage because evaporation depends on both initial and final storages, where the final storage has not been changed. Therefore, the release volume would become more negative, hence:

$$R_3(t,m_3k_3,I_3(t))\leq 0 \;\forall m_3\leq j_3 \quad (15)$$

Other infeasible transitions can be inferred by further consideration. In Equation (13), for constant j_3 and k_3, any reduction in inflow to reservoir number 3 (i.e. $I_3(t)$) will end up in a more negative release volume from the reservoir. Note that the inflow itself depends on the release volume $R_2(t)$ from upstream reservoir as:

$$R_2(t,j_2,k_2,I_2(t))=S_2(t,j_2)+I_2(t)$$
$$-S_2(t+1,k_2)-E_2(t,j_2,k_2) \quad (16)$$

Thus, we can conclude that every transition from j_2 to a storage level higher than k_2 (hence also from every storage level lower than j_2 to k_2) would result in a reduced value of $R_2(t)$. A lower value of $R_2(t)$, in turn, causes a reduction in $I_3(t)$, yielding a more negative value for $R_3(t)$, if j_3 and k_3 are not changed. This implies that $R_3(t)$ not only depends on j_3 and k_3, but also on j_2 and k_2 and, hence, on j_1 and k_1. Therefore, in addition to the transitions mentioned in Equations (14) and (15), infeasible transitions would happen for the following situations as well:

$$R_3(t,j_1,k_1,j_2,m_2,j_3,k_3)\leq 0 \;\forall m_2\geq k_2 \quad (17)$$

$$R_3(t,j_1,k_1,m_2,k_2,j_3,k_3)\leq 0 \;\forall m_2\leq j_2 \quad (18)$$

$$R_3(t,j_1,m_1,j_2,k_2,j_3,k_3)\leq 0 \;\forall m_1\geq k_1 \quad (19)$$

$$R_3(t,m_1,k_1,j_2,k_2,j_3,k_3)\leq 0 \;\forall m_1\leq j_1 \quad (20)$$

Similarly, if the release from reservoir number 3 exceeds its upper bound $R_3^{\max}(t)$ for the scenario (j_1, k_1, j_2, k_2, j_3, k_3) of state space, then many other infeasible transitions can be identified violating inequality number 10. It should be noted that $R_3^{\max}(t)$ is controlled by the outlet works' capacities and the safe capacity of the downstream river. These infeasible transitions can be summarized as follows:

$$R_3(t,j_1,k_1,j_2,k_2,j_3,m_3) \;\forall m_3\leq k_3 \quad (21)$$

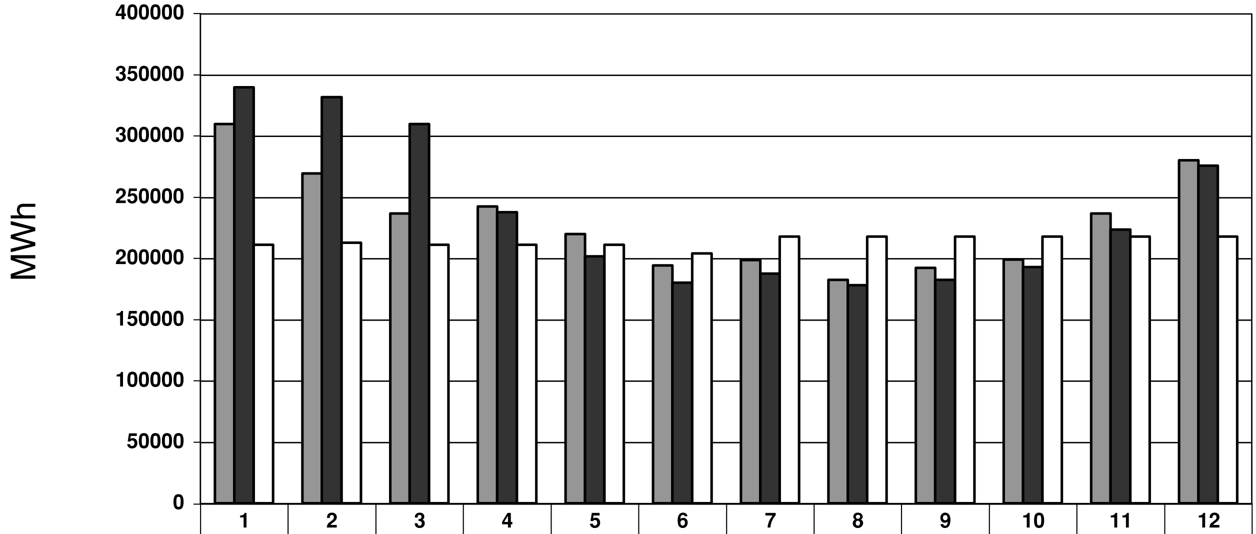
$$R_3(t,j_1,k_1,j_2,m_2,j_3,k_3) \;\forall m_2\leq k_2 \quad (22)$$

$$R_3(t,j_1,m_1,j_2,k_2,j_3,m_3) \;\forall m_1\leq k_1 \quad (23)$$

This defines the infeasible transitions at reservoir number 3, but this would be the case for any other reservoir *i* of the system. However, the dimension of the equations will differ depending on the number of reservoirs located upstream of reservoir *i*. Therefore, once an infeasible transition occurs in any stage, many other infeasible transitions can be recognized which may be overlooked in subsequent computations. More details on this approach are presented elsewhere (Mousavi and Karamouz 2003). This procedure was applied to the problem addressed in this study to reduce the computational time required for solving the DP formulation presented above.

THE SIMULATION MODEL

To simulate the operation of the described system, the HEC-5 (US Army Corps of Engineers 1982) computer program, which was developed at the Hydrologic Engineering Center (HEC) of the corps of engineers, was used. HEC-5 is designed to simulate the sequential operation of a reservoir-channel system with a branched network configuration. The program is useful in selecting the proper reservoir releases throughout the system. Reservoirs can be operated to minimize downstream flooding, evacuate flood control storage as quickly as possible, provide for low-flow requirements, and meet hydropower and diversion requirements. The last two requirements are of concern in this study. Hydropower requirements can be defined for individual projects or for a system of projects. Pump-storage operation can also be simulated. Reservoir storage allocation for various project



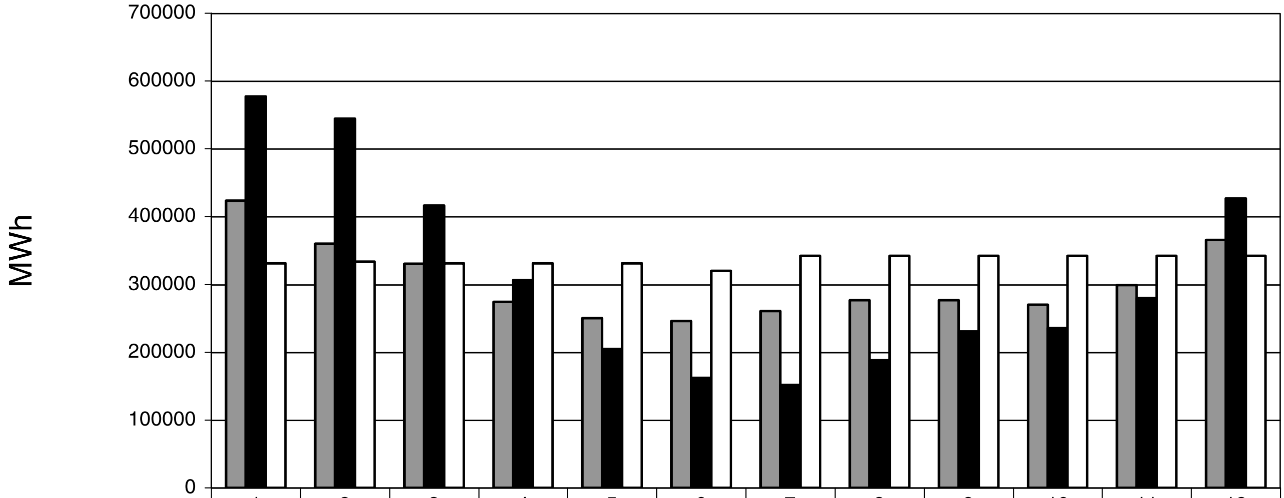
	1	2	3	4	5	6	7	8	9	10	11	12
Energy generated(DP)	309652	269327	236698	242569	220023	194252	198669	182366	192221	198963	236656	280065
Energy generated(HEC-5)	339780	331547	309841	237696	201532	179994	187549	178037	182455	192765	223573	275664
Energy demand	210974	212713	210974	210974	210974	203942	218007	218007	218007	218007	218007	218007

Figure 2 | Monthly average energy generated by DP and HEC-5 compared with monthly energy demand at Dez HPP.

purposes is specified by reservoir target storages or elevations. Reservoirs are balanced using these levels as much as possible if they are operated together for a common downstream target such as low flow requirements or are part of a power system. The program can determine the amount of seasonally varied conservation storage to satisfy all specified yields on the project including hydropower. The maximum dependable energy and flow requirements and dependable capacity can be determined automatically while still meeting all other project demands.

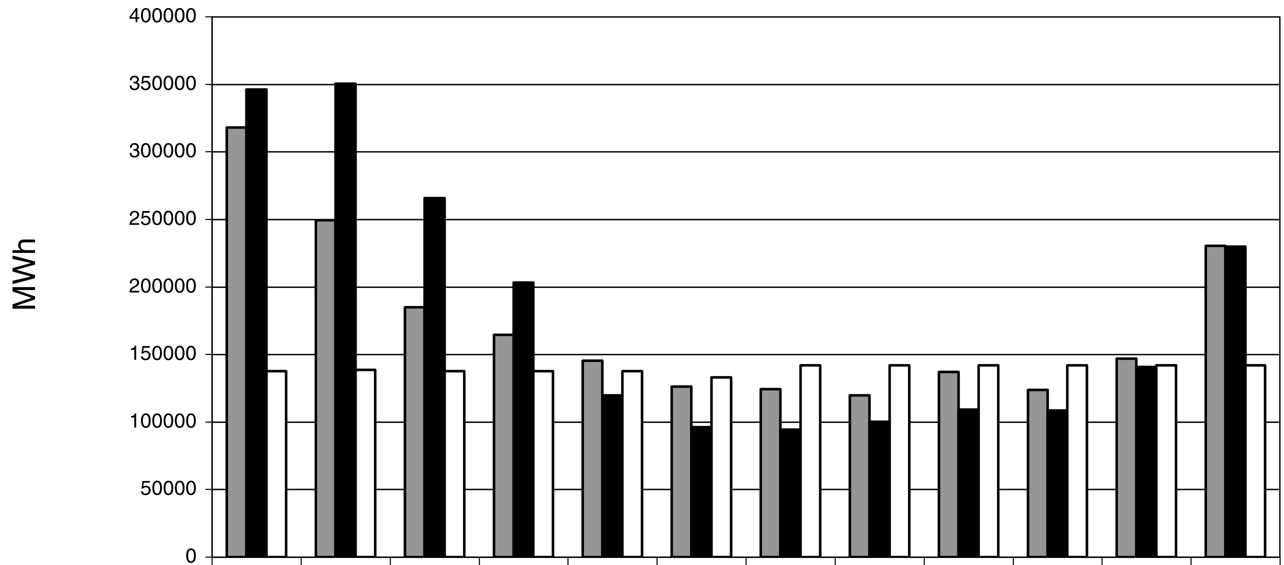
The simulation of hydropower reservoirs by HEC-5 normally consists of simulating the operation of individual power reservoirs based on producing user specified firm energy requirements for the power system or user requirements at each site or both. If system firm energy is requested, the program allocates the energy requirement to each project designated in that system for each time period based on current reservoir level and energy generation potential. The program determines the reservoir release required to produce the specified energy using the available head and efficiency for the current period. The monthly at-site power requirement can be specified as a plant factor for each month as done in this study.

The power plant efficiency at the installation defaults to 0.86 throughout the range of operating heads unless the efficiency is specified by input as some other constant or the power plant efficiency is specified to vary with the reservoir storage or head or reservoir release or both head and release. In this study, the default value is adopted. The hydraulic losses can be a constant or can be a function of the average reservoir release. The maximum penstock discharge capacity can be input to ensure that the computed power release does not exceed this value. The minimum penstock discharge capacity can also be input to indicate the discharge below which no power can be produced. The maximum and minimum power heads may also be input to indicate when no power can be produced. In this study, constant hydraulic losses are used for each project and all other information regarding maximum and minimum penstock discharge capacities as well as minimum and maximum operating levels are known based on the HPP's characteristics, predetermined in the design stage for each HPP.



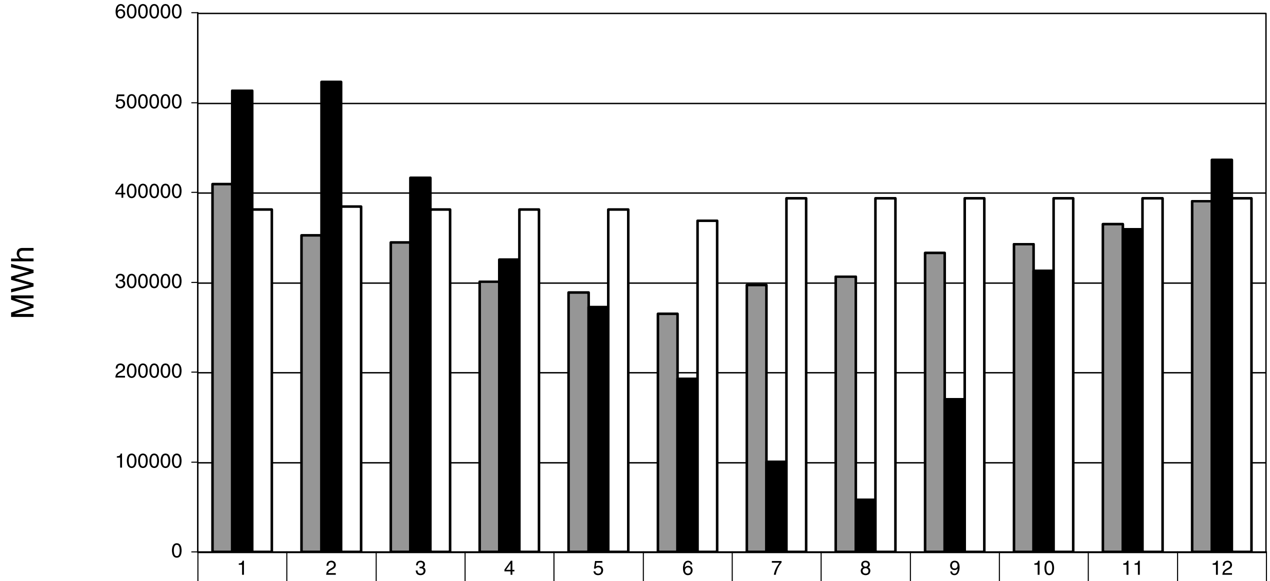
	1	2	3	4	5	6	7	8	9	10	11	12
Energy generated(DP)	423989	360315	330446	274753	250627	246272	260684	276729	277005	270073	299425	365599
Energy generated(HEC-5)	577257	544771	416497	306245	204652	162381	151603	188077	230813	235584	280165	426644
Energy demand	331200	333930	331200	331200	331200	320160	342240	342240	342240	342240	342240	342240

Figure 3 | Monthly average energy generated by DP and HEC-5 compared with monthly energy demand at Karoon4 HPP.



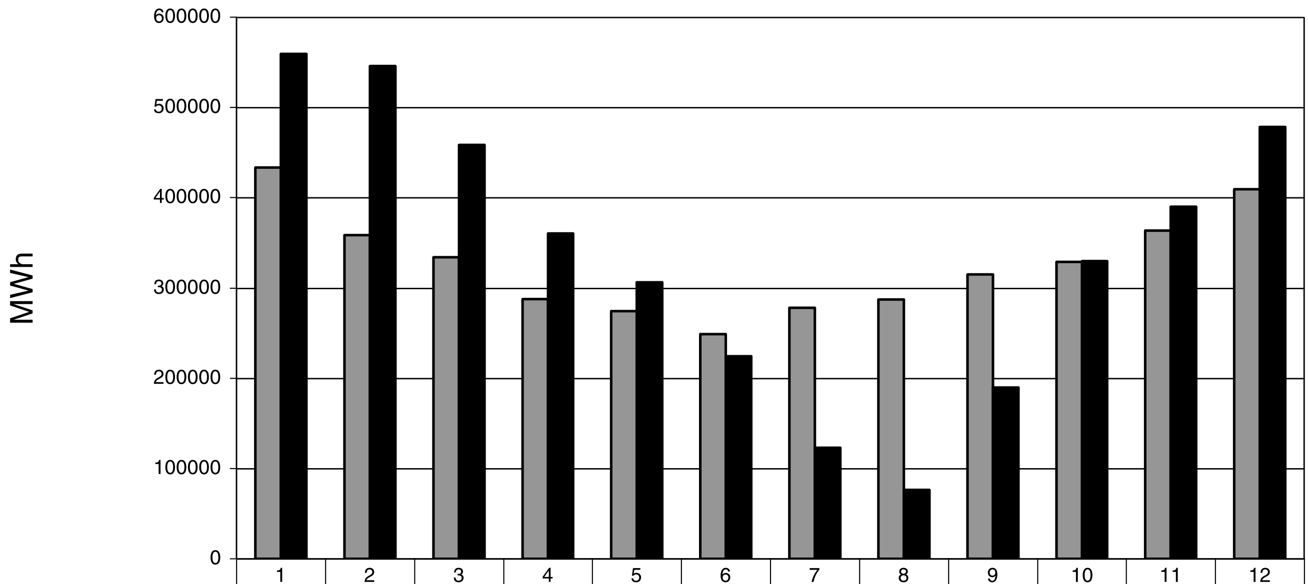
	1	2	3	4	5	6	7	8	9	10	11	12
Energy generated(DP)	318068	249434	185061	164651	145264	126110	124241	119689	136997	123766	147041	230609
Energy generated(HEC-5)	346164	350382	265737	203147	119739	96282	94252	100349	109190	108432	140717	229761
Energy demand	137520	138653	137520	137520	137520	132936	142104	142104	142104	142104	142104	142104

Figure 4 | Monthly average energy generated by DP and HEC-5 compared with monthly energy demand at Karoon3 HPP.



	1	2	3	4	5	6	7	8	9	10	11	12
Energy generated(DP)	409285	352107	344469	300862	288602	264963	296863	306361	332778	342649	364954	390170
Energy generated(HEC-5)	513009	522981	416132	325412	272520	192649	100350	57785	169854	312635	359380	436279
Energy demand	381034	384174	381034	381034	381034	368323	393725	393725	393725	393725	393725	393725

Figure 5 | Monthly average energy generated by DP and HEC-5 compared with monthly energy demand at Karoon1 HPP.



	1	2	3	4	5	6	7	8	9	10	11	12
Energy generated(DP)	433330	358386	333943	287546	274175	248784	277974	287410	315015	329002	363819	409577
Energy generated(HEC-5)	559419	546032	458527	360463	306465	224269	122917	76392	189798	329947	390141	478464

Figure 6 | Monthly average energy generated by DP and HEC-5 at Godarlandar HPP.

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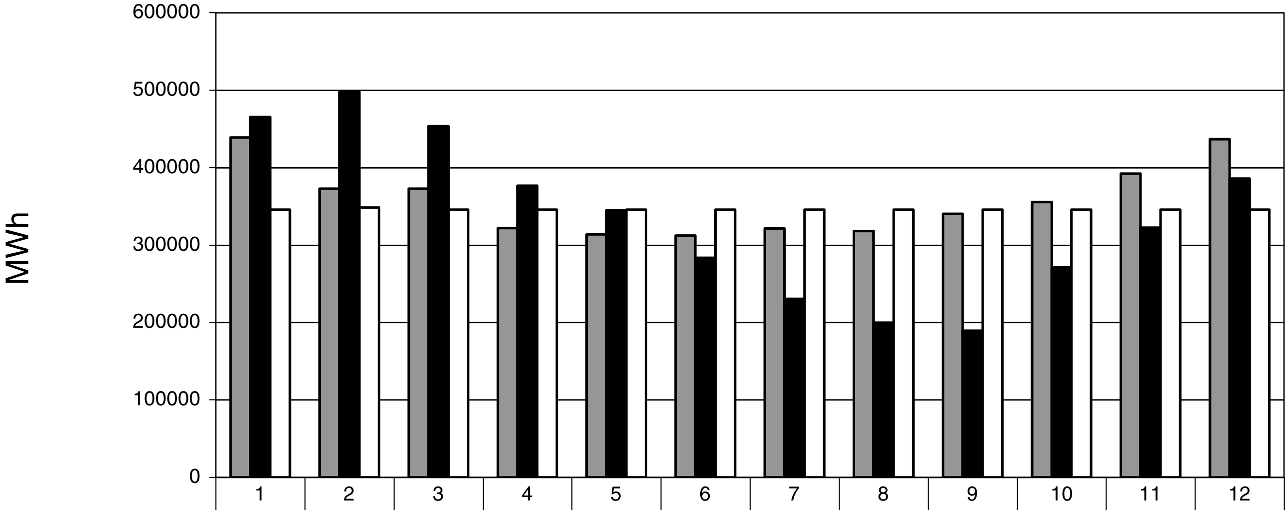

	1	2	3	4	5	6	7	8	9	10	11	12
Energy generated(DP)	438774	372513	372580	322025	313588	312132	321332	318040	340216	355230	392496	436759
Energy generated(HEC-5)	465260	498304	453491	376762	344690	283684	230562	199673	189147	271829	322265	385761
Energy demand	345600	348448	345600	345600	345600	345600	345600	345600	345600	345600	345600	345600

Figure 7 | Monthly average energy generated by DP and HEC-5 compared with monthly energy demand at Gotvand HPP.

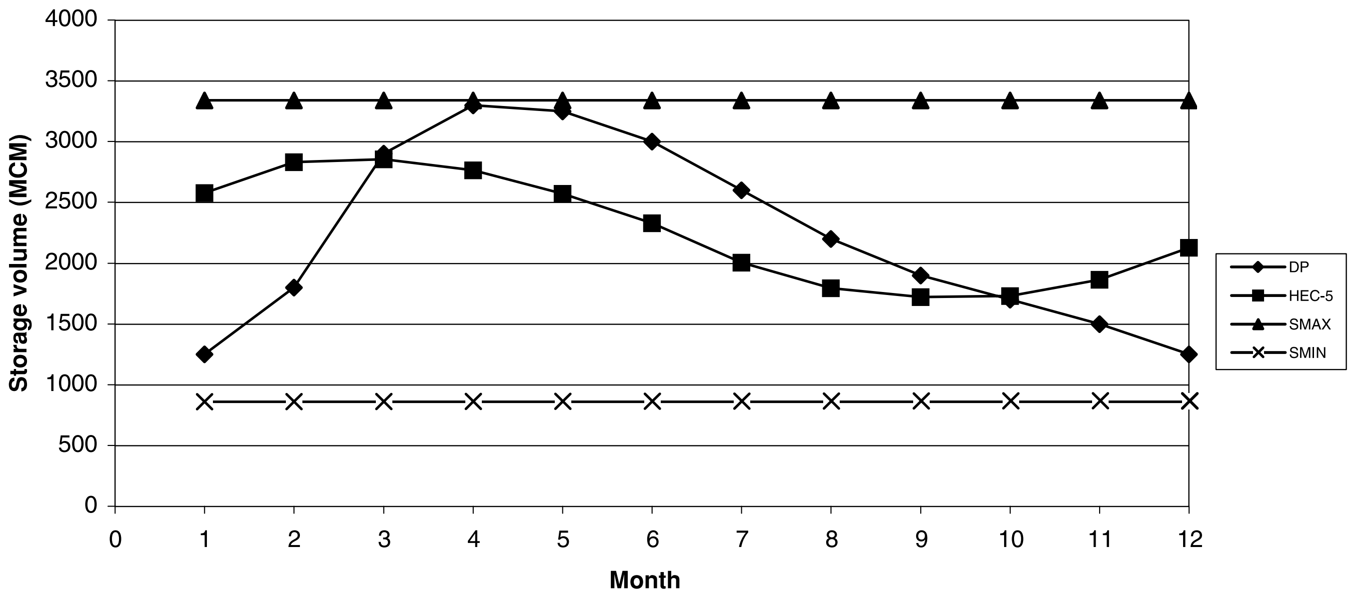

Figure 8 | Monthly average storage volume at Dez reservoir.

The individual reservoirs modeled in the power system must include projects with power drawdown storage, but can also include run-of-river projects such as Godarlandar in the Karoon-Dez system (i.e. reservoir number 4). The HEC-5 program system power routines calculate the individual reservoir releases required to generate the user specified system power energy for each time period while balancing the reservoir levels to the

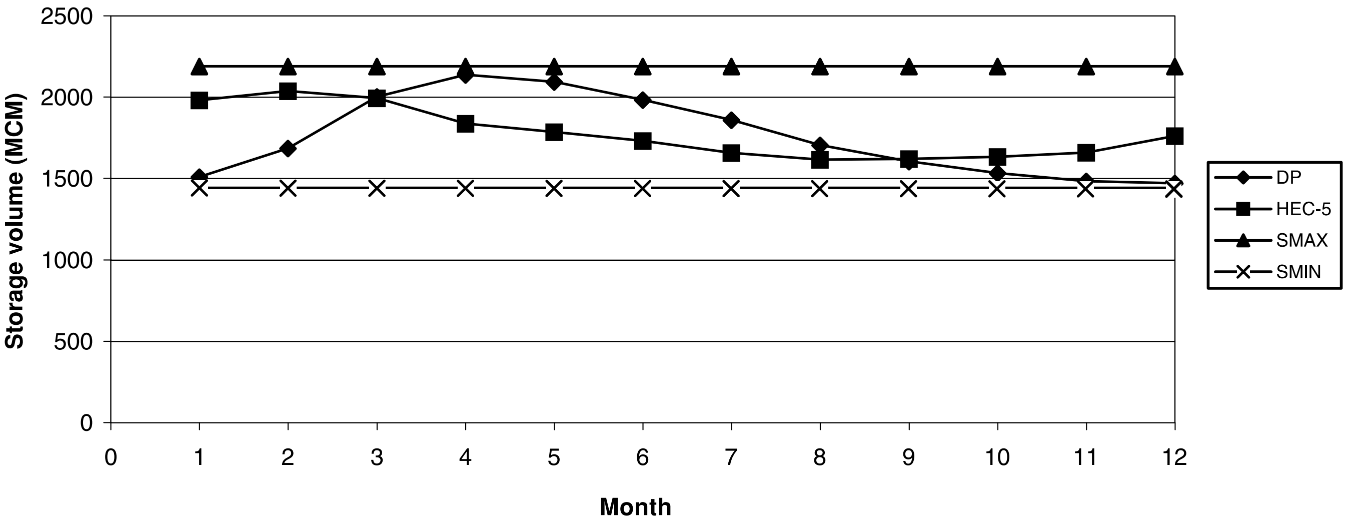

Figure 9 | Monthly average storage volume at Karoon4 reservoir.

maximum extent possible and observing all requirements and constraints on the individual reservoirs. The Karoon-Dez system was simulated using the HEC-5 capabilities as explained above and the results of the experiment are compared with those of DP in the next section.

RESULTS

Long-term planning of the Karoon-Dez system operation was studied using DP optimization and HEC-5 simulation models. Both models were examined with the main objective of minimizing the sum of deviations from demanded energy. Both models use 40 years of historical inflow series of the Karoon-Dez system with monthly time steps. For a pre-defined energy demand for each HPP site, the results obtained by DP and HEC-5 model are presented and compared. Figures 2 to 7 compare the results of DP and HEC-5 in terms of monthly average energy generated where meeting hydropower demands is selected as the main objective of the system operation. Monthly average energy generated by each HPP is also given in tables associated with those figures. Figures 8 to 13 show the average monthly variation of storage volume for reservoirs 1–6.

What can be seen from the above-mentioned figures is that DP performs better than the HEC-5 model in meeting the system's energy demand. For example, as can be seen from Figure 2, there are some shortages in meeting energy demand in the Dez HPP in months 5 to 10, where the inflow to the system is low. However, the shortages in the DP model are lower than those resulting from HEC-5. In fact, DP could preserve more water in the reservoir during months with higher inflow, to meet energy demand (firm energy) during dry months. This results in lower secondary energy, which is in excess of demand. This result is compatible with what is seen in Figure 8 in which the Dez storage volumes resulting from the DP model are higher than those of the HEC-5 model in the dry months 5–10, while they are lower in months with high inflow. The same conclusion may be more or less extended to other reservoirs of the system. It should be noted that Godarlandar (reservoir number 4) has a very small active storage capacity, not enough for monthly regulation. It functions as a run-of-river HPP and hence no energy demand has been defined for Godarlandar HPP. As can be observed in Figure 12, both in DP and HEC-5, the Godarlandar reservoir is at its full normal storage capacity each month; hence the energy generated in this HPP is controlled by release from its upstream reservoir (i.e. Karoon1).

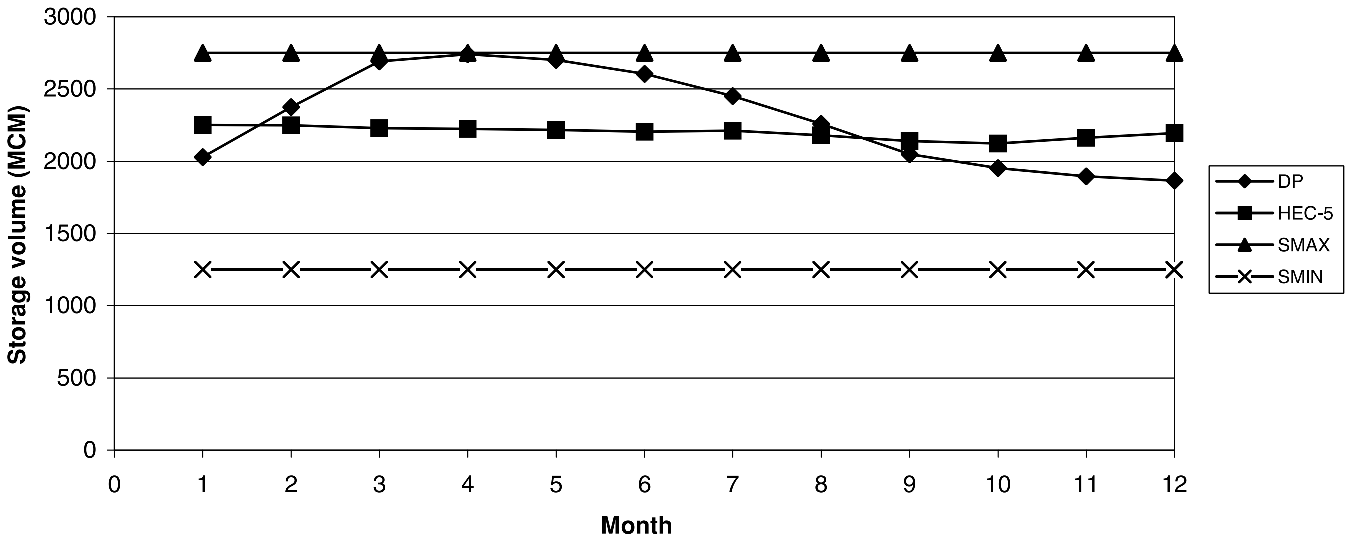

Figure 10 | Monthly average storage volume at Karoon3 reservoir.

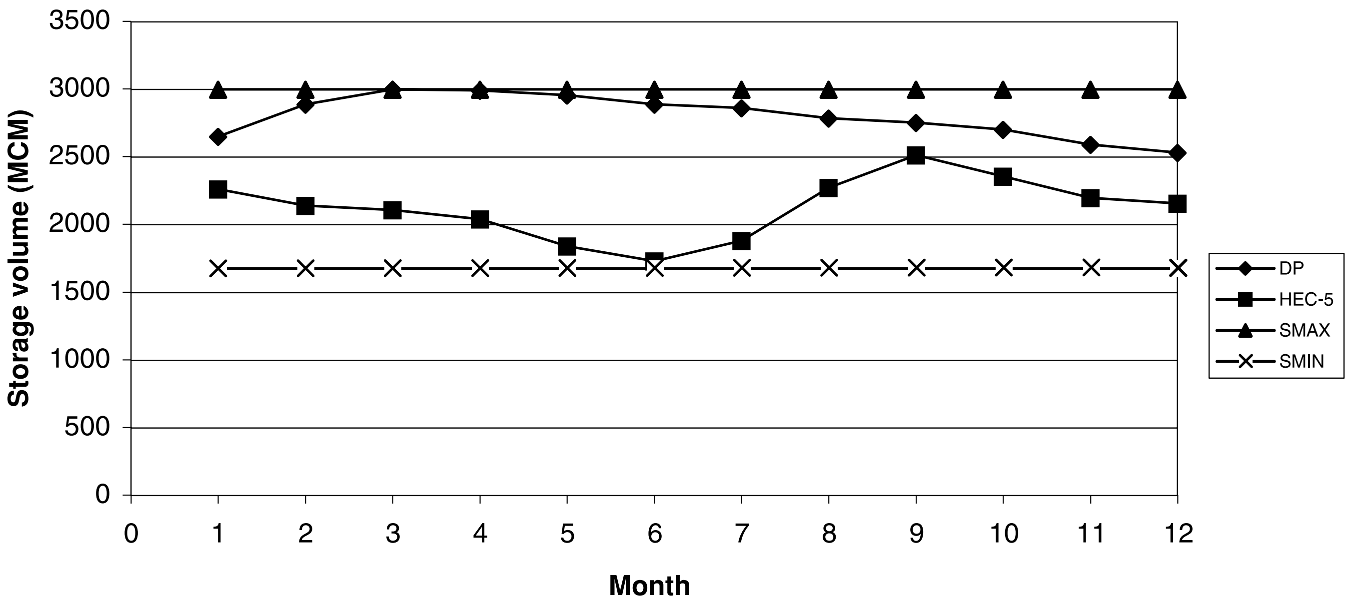

Figure 11 | Monthly average storage volume at Karoon1 reservoir.

To show the reliability of meeting energy demands and to deal with the frequency of different levels of energy generated, the monthly energy duration curves were derived for all HPPs; due to lack of space only two of them are presented here. Figures 14 and 15 show the energy duration curve for Karoon4 HPP in months 3 and 9 as a typical wet and dry month, respectively. As can be seen from Figure 14, more than 95% of the time, energy generated by HEC-5 in month 3 is higher than energy demand while the frequency is about 88% for the DP model. However, in Figure 15, which is associated with a dry month, the energy generated by the DP model is greater than that of the HEC-5 model. In fact, a significant amount of energy generated by HEC-5 in a wet month is in

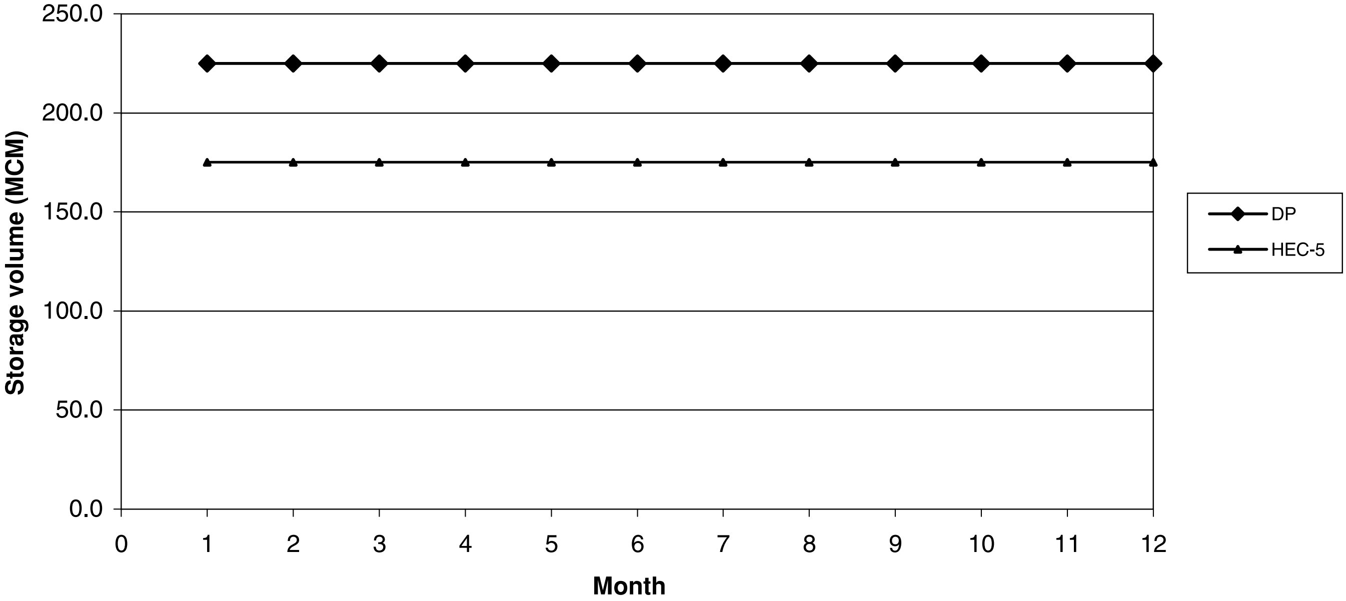

Figure 12 | Average monthly variation of storage volume at Godarlandar reservoir.

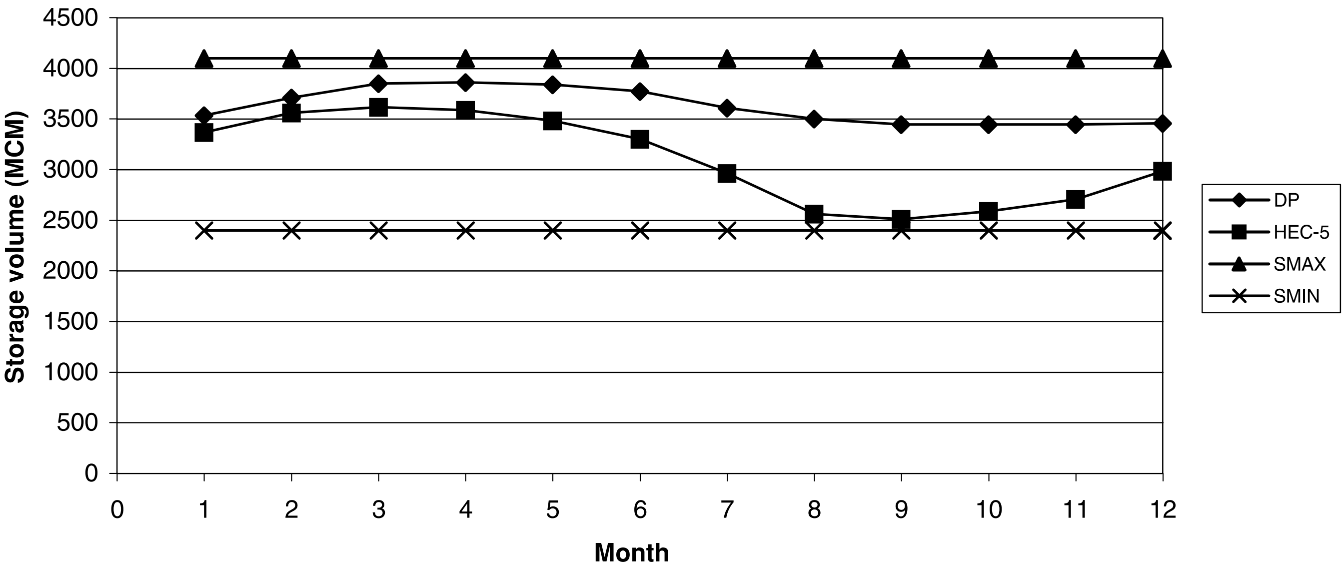

Figure 13 | Average monthly variation of storage volume at Gotvand reservoir.

excess of what is demanded (i.e. secondary energy), while DP decreases this type of energy to save the potential for firm energy generation in dry months. DP attempts to prevent severe energy shortages, as its objective is to minimize the sum of squared shortages over the planning horizon.

In terms of the water supply objective, Table 3 reports the results of meeting water demands in consumption areas (reaches) of the system in each month obtained from DP and HEC-5 results. It is seen that there are some shortages in meeting irrigation water demand in the last reach (reach 7) during 2 months of the summer in which

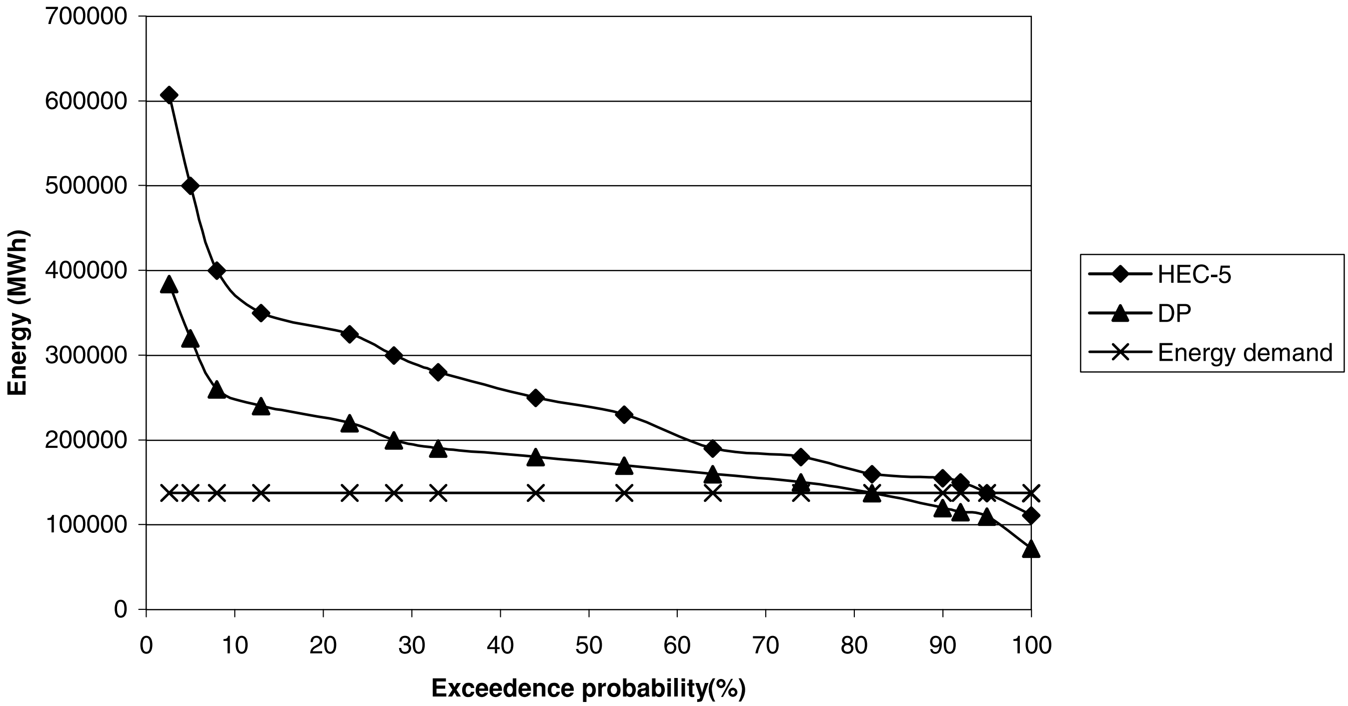

Figure 14 | Energy duration curve of Karoon4 HPP in month 3.

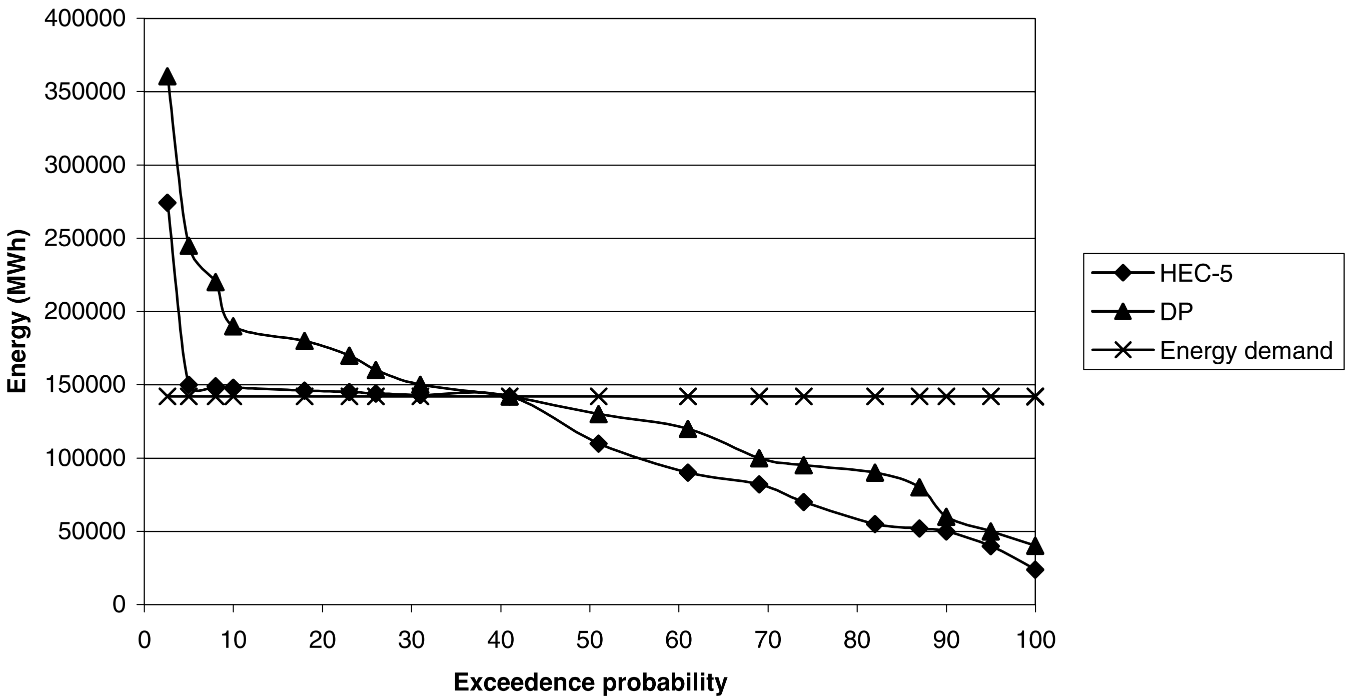

Figure 15 | Energy duration curve of Karoon4 HPP in month 9.

Table 3 | Average percentage of demand satisfaction in each reach

	Reach 5		Reach 6		Reach 7	
Month	DP	HEC-5	DP	HEC-5	DP	HEC-5
1	94	100	94	100	94	97
2	94	100	100	100	100	95
3	94	100	100	87	97	87
4	94	100	98	82	76	66
5	100	100	80	76	66	54
6	100	100	70	67	62	54
7	95	95	100	54	88	76
8	100	82	100	75	100	76
9	94	92	100	82	100	88
10	100	100	100	100	100	100
11	100	100	100	100	100	100
12	100	100	100	100	100	100

water demand is high while inflow to the system is low. However, the DP results are slightly better than the HEC-5 results. These results are obtained under the assumption that the primary objective of the system operation is hydropower generation rather than meeting water demands. In fact, the trade-off between energy and water supply objectives has not been assessed in this work; this may be necessary in a more detailed study.

SUMMARY AND CONCLUSIONS

A DP model was formulated to tackle the optimization of the Karoon-Dez multireservoir system operations in this study. This system includes six reservoirs with the primary and secondary objectives of hydropower generation and water supply, respectively. To overcome the dimensionality problem associated with multireservoir DP models, heuristic rules were used to recognize infeasible storage combinations. To check the performance of the optimization model, the system was simulated using well-known HEC-5 simulation model. The long-term operation of the Karoon-Dez reservoir system was then assessed by use of the DP and HEC-5 models and their results were compared.

It was found that the DP model performs better than the HEC-5 simulation model in meeting the system's energy demand. The energy generated by HEC-5 in months with high inflow is more than that generated by DP. However, a significant part of that energy is in excess of the energy demanded (i.e. secondary energy) whose value is cheaper than firm or dependable energy. DP attempts to prevent severe shortages in meeting the defined energy demands and hence is able to increase the amount of energy generated in low flow seasons. This is achieved by reducing the secondary energy generated in high flow seasons. In terms of water supply purposes and reliability of meeting water demands, it was seen that DP performs slightly better than HEC-5. However, in terms of computational burden and the computer time needed for solving such a problem, using HEC-5 is much more attractive than using DP. The computer time required for executing the DP model developed for the Karoon-Dez problem is approximately 2 hours while HEC-5 solves the problem in less than a minute.

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