Simulation Optimization for Optimal Sizing of Water Transfer Systems

Nasrin Rafiee Anzab, S. Jamshid Mousavi, Bentolhoda A. Rousta and Joong Hoon Kim

Abstract Water transfer development projects (WTDPs) could be considered in arid and semi-arid areas in response to uneven distribution of available water resources over space. This paper presents a simulation-optimization model by linking Water Evaluation and Planning System (WEAP) to particle swarm optimization (PSO) algorithm for optimal design and operation of the Karoon-to- Zohreh Basin WTDP in Iran. PSO searches for optimal values of design and operation variables including capacities of water storage and transfer components as well as priority numbers of reservoirs target storage levels, respectively; And WAEP evaluates the system operation for any combinations of the design and operation variables. The results indicate that the water transfer project under consideration can supply water for the development of Dehdash and Choram Cropland (DCCL) in an undeveloped area located in Kohkiloyeh Province.

Keywords Water transfer systems · Simulation-optimization · WEAP · PSO

1 Introduction

Unevenly distribution of freshwater over space and time, along with rapid population growth and its consequent increase in per capita water consumption has led to

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J.H. Kim and Z.W. Geem (eds.), *Harmony Search Algorithm*,
Advances in Intelligent Systems and Computing 382,
DOI: 10.1007/978-3-662-47926-1_35

an inconsistency between water supplies and demands. Managing water resources requires planning, development, distribution, and optimal consumption of water resources. Such management would be recognized as a set of technical, institutional, and legal measures, the purpose of which is to balance the water supply and demand [1].

Iran is located in an arid and semi-arid area where water supply and demand is highly uneven over the space. Water availability is subject to considerable variations in different basins. While few basins are rich in water resources, the others suffer from significant water shortages. Hence, Water Transfer Development Projects (WTDPs) could be considered in order to alleviate spatial imbalance between water supplies and demands. A WTDP or an interbasin water transfer project is defined as transferring water from a distinct catchment or river reach to another one [2]. System analysis techniques including simulation and optimization models can be used to help investigate the technical aspects of water transfer projects ([3-7]). Some studies assess water transfer projects from social and environmental prospect ([8]), and some other studies incorporate both the socio-environmental aspects of water transfers and the technical ones ([9-11]). In this study, a mixed integer non-linear programming (MINLP) model is developed to determine the design parameters of the WTDP from Bashar Basin (one of Khersan River's tributaries flowing in Karoon Basin) to Dehdasht and Choram Cropland located in Zohreh Basin in Iran. Since it is not easy to solve the model by using a gradient-based optimization algorithm, we have made an attempt to solve it by a simulation-optimization technique through the linkage of the well-known Water Evaluation and Planning System (WEAP) water allocation simulation model and the PSO algorithm.

The remainder of this paper is organized as follows: A description of the study area is given in section 2. Section 3 describes the PSO-WEAP model and its application to the problem under study. The results and conclusions are then discussed in sections 4 and 5.

2 Study Area and Problem Definition

The target of this study is Dehdasht and Choram Cropland (DCCL), which is located in Kohgilouye and Boyerahmad Province, Iran, as one of the most potential land and soil resources. In spite of the fact that DCCL is located near the Maroon and Kheirabad Rivers, farmers have not been able to divert water from these surface resources to DCCL as the land is on a relatively high terrain. As a result, farming encounters water shortages and is mostly rain fed. From groundwater perspective, the land also has limited resources [12]. Therefore, in order to supply DCCL demands, a water transfer project has been proposed to transfer water from Bashar (one of Karoon's sub-basins) to Zohreh Basin encompassing the DCCL. The project is designed to pump water from Kabkian reservoir to Sepidar diversion dam (Fig. 1.) and flowing water by gravity through a tunnel to Shahbahram reservoir in Zohreh Basin (Fig. 1.). Kabkian and Shahbahram are designed to serve as regulating reservoirs. The water regulated by Shahbahram is intended to supply agricultural water demand of DCCL. In this system, the existing Kosar reservoir with, respectively, normal and minimum storage levels of 492.8 and 74.17 MCM provides water to municipalities along the coastline of the Persian Gulf and Kohgilouye and Boyerahmad, Khuzestan, Boushehr, Fars, and Hormozgan provinces as well as the Lishtar croplands of Gachsaran [12]. There are also other environmental, industrial and agricultural demands in the system which are supposed to be supplied by available surface water resources.

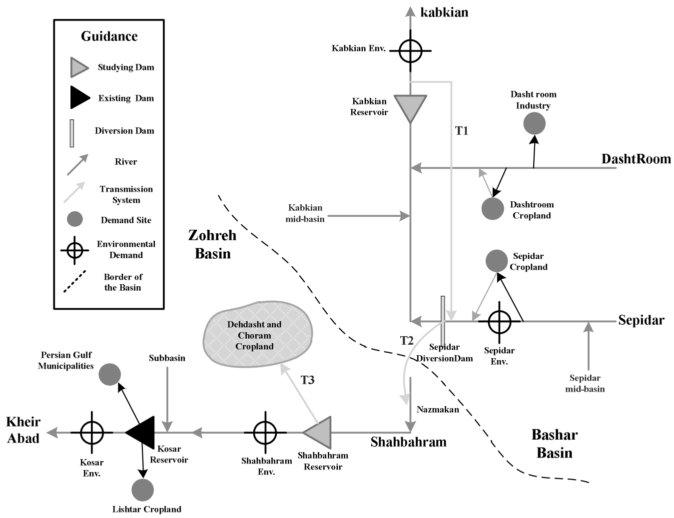

Fig. 1 Schematic representation of the system and the Bashar-to-Zoreh Basin water transfer project [12]

3 Model Description

The principal objective of this study is to develop a simulation-optimization model in order to optimize design and operation of Bashar-to-Zohreh WTDP. The motivation behind developing this model is the incapability of classical optimization methods for solving mixed integer nonlinear programs including binary variables controlling temporal reliability of water supply. Therefore, WEAP as the simulation model is linked with PSO as the optimization algorithm to construct such a simulation-based optimization tool.

3.1 WEAP Model

Developed by Stockholm Environment Institute (SEI) in 1988, WEAP is a physically based model that incorporates water supply projects and demand-side issues into a practical tool in order to assist water resources planners [13]. WEAP primarily operates based on the water balance accounting principle and can be applied to simulate either a single small sub-basin or a large scale complex basin as well as agricultural and municipal systems [13]. Even though WEAP solves several linear programs to determine the optimal allocations at a single time step, it is not capable of performing multiple time step optimization to determine the optimal decision variables. However, it can be linked to other process-based models using programming languages such as VB.net.

WEAP utilizes standard linear programs solved iteratively to calculate water allocation at each time step. The objective function of the LP is to maximize supplies to demand sites subject to supply preferences, mass balance and other constraints [13].

3.2 PSO Algorithm

First proposed by Kennedy and Eberhart [14], PSO is a stochastic evolutionary algorithm that adheres to the social behavior of bird flocks [15] to search through multi-dimensional decision spaces. Flexible operators, absence of gradients, and easily found solutions to mixed integer and combinatorial problems are some of outstanding characteristics of PSO. Providing the search space is D-dimensional, the i-th particle of the swarm is identified by the D-dimensional vector $x_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$; the best former position of this particle is identified by $p_i = (p_{i1}, p_{i2}, \ldots, p_{iD})$; the particle's velocity change is identified by $V_i = (V_{i1}, V_{i2}, \ldots, V_{iD})$, and the swarm's best particle is denoted by g. Particles of the swarm will move according to the following equations:

$$v_{id}^{n+1} = \chi\left(\omega v_{id}^{n} + c_1 r_1^{n}(p_{id}^{n} - x_{id}^{n}) + c_2 r_2^{n}(p_{gd}^{n} - x_{id}^{n})\right) \quad (1)$$

$$x_{id}^{n+1} = x_{id}^{n} + v_{id}^{n+1} \quad (2)$$

where $d = 1,2,\ldots,D$; $i = 1,2,\ldots,N$; N =size of population; ω =weight of inertia; n = number of iterations; c_1, c_2 = two positive constants called cognitive and social coefficient; χ = constriction coefficient; r_1, r_2 = random values uniformly distributed in the range [0 1] [15]. In each iteration, ω is changed according to the equation (3):

$$\omega = \omega_{\max} - (\omega_{\max} - \omega_{\min}) \times \frac{Iter}{Iter\max} \quad (3)$$

where $Iter\max$ = total number of iterations; $Iter$ = the current iteration number. Values of $\omega_{\min}$ and $\omega_{\max}$ are determined by trial and error. Like most evolutionary optimization techniques, PSO faces the problem of convergence to the local minima. Function Stretching ([15],[16]), a technique for escaping from the local minima, is used in this study to alleviate PSO's problem of local minima. This modified version is called SPSO. In the SPSO, as soon as a local minimum has been detected, a two-stage transformation will be performed on the objective function. In the first stage where G_i is produced, the original objective function (FC_i) is elevated using the equation (4). In the second stage, equation (5) is applied to stretch FC_i neighborhood upward.

$$G_i = FC_i + \gamma_1 \left\| i - \bar{i} \right\| (sign\,(FC_i - \overline{FC_i}) + 1) \tag{4}$$

$$H_i = G_i + \gamma_2 \frac{sign\,(FC_i - \overline{FC_i})}{\tanh\,(\mu\,(G_i - \overline{G_i}))} \tag{5}$$

where i = one of the local minima; FC_i = the objective function corresponding to i th particle; G_i = the first transformation function; H_i = the second transformation function; γ_1, γ_2, μ = positive constant values. The local minima located below i are not altered through aforesaid stages; therefore, the location of the global minimum remains unchanged.

3.3 PSO-WEAP Model

Given the WEAP's ability of linking with other programs, one can input the desired values of decision variables into the WEAP model in each iteration. Through coding the PSO algorithm in MATLAB environment and calling WEAP solver in the PSO algorithm, one can attempt to generate the values of variables of interest by the PSO algorithm and input them into the WEAP model. Once WEAP is performed, the objective function of the PSO-WEAP model is evaluated. The objective function is to minimize the design capacity of the proposed reservoirs and water transfer systems while maximizing the DCCL cultivable area and temporal reliability of DCCL supplies. Hence, given the components of the schematic plan illustrated in Fig. 1, the objective function (O.F) is formulated as follows:

$$\begin{aligned} O.F = Min\,(&cap_{kab} + cap_{sb} + T_1 \max + T_2 \max + (30000 - A_{\max})^2 \times \alpha \\ &+ ((100 - reliability_{choram})^2 \times \beta) \end{aligned} \tag{6}$$

where cap_{kab} = Kabkian reservoir storage capacity; cap_{sb} = Shahbahram reservoir storage capacity; $T_1 \max$ = capacity of water transfer system from Kabkian reservoir to Sepidar diversion dam; $T_2 \max$ = capacity of water transfer system from Bashar to Zohreh basin and $A_{\max}$ = maximum cultivable area of DCCL. α and β are coefficients for adjusting values of the two last terms to values of the other terms of the O.F and are determined by trial and error. $reliability_{choram}$ = reliability of DCCL supply. Temporal reliability is defined as the frequency of the periods during which DCCL is fully supplied when divided by the entire simulation periods. Temporal reliability is defined using binary variables as follows:

$$T3_t \geq Z_t \times D_t^{choram} \qquad \forall t = 1,2,\ldots,T \tag{7}$$

$$reliability_{choram} = \frac{\sum_{t=1}^{T} Z_t}{T} \tag{8}$$

where $T3_t$ = amount of water transferred to DCCL; D_t^{choram} = irrigation water demanded by DCCL; T = all periods of simulation (648 months) and Z_t =binary variable defined as:

$$Z_t = \begin{cases} 1 & \text{if DCCL is fully supplied in time period t} \\ 0 & \text{Otherwise} \end{cases} \tag{9}$$

Since we cannot call and run WEAP directly from MATLAB, , we used Excel as an interface between WEAP and MATLAB; that is, the generated-by-PSO values of variables are saved into the Excel; then, these values are called from Excel, and WEAP is executed; finally, the results are saved into the Excel and are called by PSO in MATLAB. This procedure is repeated up to the maximum number of iterations defined aiming at minimizing the objective function. The flow diagram of the PSO-WEAP model is presented in Fig. 2.

Table 1 Upper and lower bounds of decision variables

Decision Variable	Maximum	Minimum
Storage capacity of Kabkian reservoir (MCM)	201.89	14.7
Storage capacity of Shahbahram reservoir (MCM)	126.03	35
capacity of water transfer system from Kabkian reservoir to Sepidar diversion dam (cms)	9	0
capacity of water transfer system from Bashar to Zohreh Basin (cms)	18	0
DCCL's maximum cultivable area (ha)	30000	5000

Table 2 PSO parameters values

parameter	swarm	iterations	χ	ω_{min}	ω_{max}	c_1	c_2
value	20	200	1	0.4	0.9	1.5	1.5

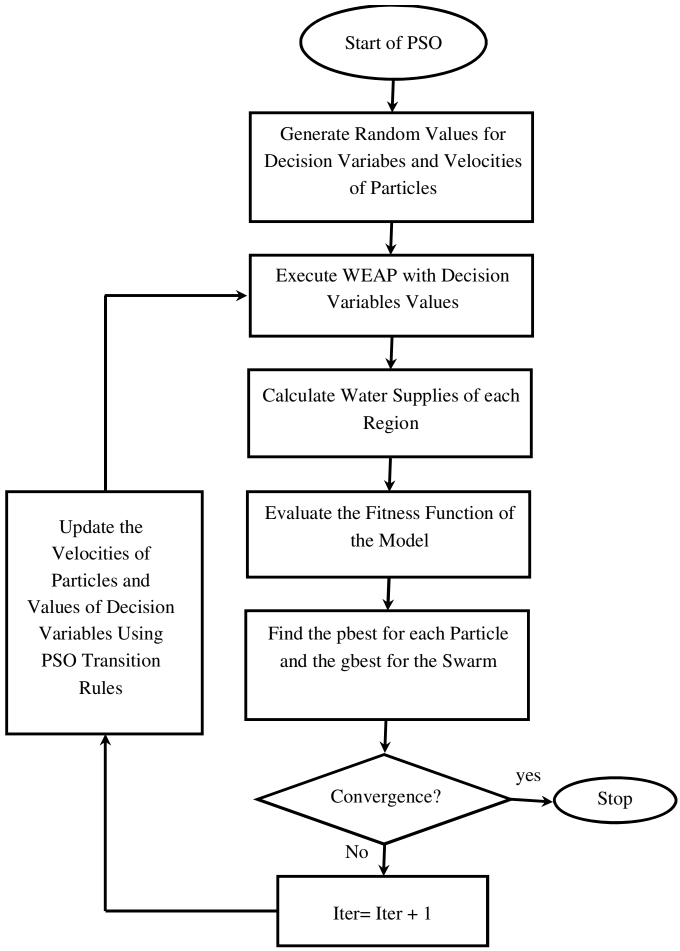

Fig. 2 The flow diagram of the PSO-WEAP model

The decision variables of the PSO algorithm are storage capacities of Kabkian and Shahbahram reservoirs, capacities of Kabkian-to-Sepidar and Bashar-to-Zohreh water transfer systems and the DCCL's maximum cultivable area. The upper and lower bounds considered for these variables are reported in Table 1 [12]. It is worth noting that in WEAP, the ordinal priorities of demands to be met were considered as environmental, municipal, industrial, and finally agricultural. Moreover, the simulation was done for a period of 54 years from 1935 to 1988. In the developed PSO-WEAP model, PSO feeds the decision variables into the inner linear programs of WEAP. Afterwards, the resulting water allocations are returned back from WEAP to the PSO where the objective function for each set of generated decision variables is evaluated. Using the PSO algorithm's evolutionary transition rules, this procedure ([1]) is continued between PSO and WEAP until the PSO objective function converges to a minimum value. The PSO parameter values are reported in Table 2.

In the first scenario, the PSO-WEAP model is applied based on its primary assumptions. The second scenario introduces other assumptions into the basic model where in addition to the capacity of storage elements, the priority numbers of the reservoirs target storage volumes are considered as operational decision variables. In other words, the priority numbers of the reservoirs target storage volumes which are fed by the PSO algorithm will be optimized by the PSO-WEAP simulation-optimization model. If the priority number of a reservoir target level becomes lower than that of the downstream demand, water will first be stored in the reservoir and the excess water will be released to the downstream. Conversely, when the number becomes higher than that of the downstream demand, water will first be released to meet the downstream demand after which the excess water will be stored in the reservoir.

4 Results and Discussions

Although reliability index is evaluated just for DCCL demand site, there are 648 integer variables in the model resulting in a relatively large scale MINLP model whose solution is difficult to obtain by classical optimization methods. Table 3

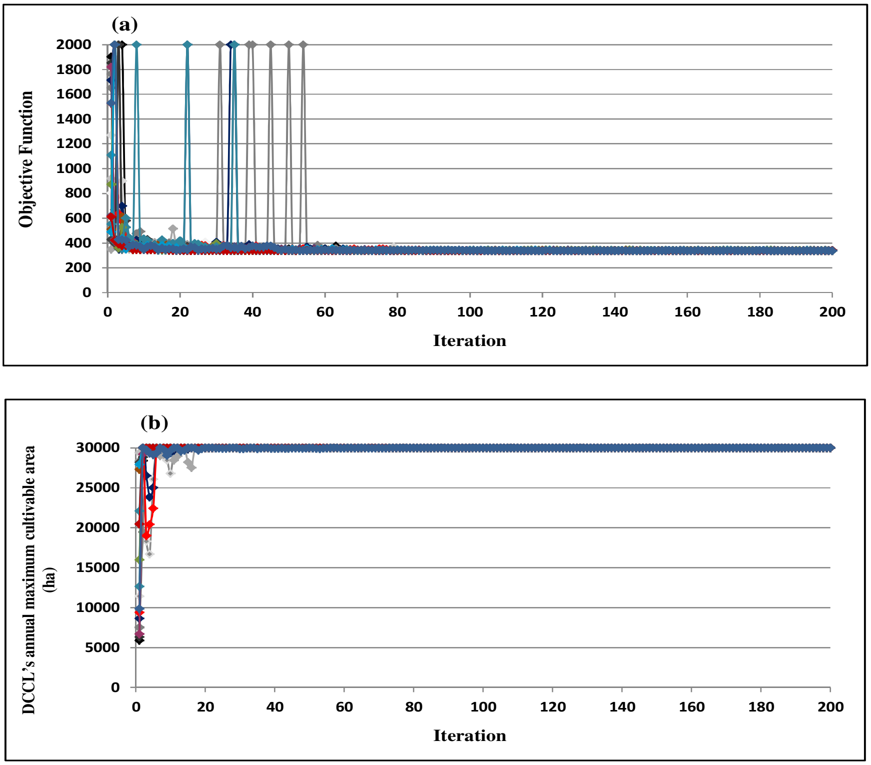

Fig. 3 Convergence trend of the PSO particles for (a) the objective function value and (b) the maximum cultivable area of DCCL

reports optimal values of decision variables of Bashar-to- Zohreh Basin WTDP obtained by the PSO-WEAP model for the first scenario. It is seen from Table 3 that the water transfer project under consideration can supply water for the development of 30,000 ha of the DCCL. Convergence curves of the particles' O.F value and the maximum cultivable area of DCCL over subsequent iterations is illustrated in Fig. 3.

Note that the O.F value goes up at some iterations in Fig. 3a which is due to function stretching; otherwise such fluctuations would not have been happened.

Table 3 PSO-WEAP model results, first scenario

Parameter	Basic scenario	Second scenario
Storage capacity of Kabkian (MCM)	57.3	53.93
Storage capacity of Shahbahram (MCM)	126.03	126.03
Capacity of Kabkian-to-Sepidar water transfer system (cms)	9	7.15
Capacity of Bashar-to-Zohreh water transfer system (cms)	9.17	7.9
DCCL's maximum cultivable area (ha)	30000	30000
Temporal reliability of DCCL demand (%)	73.92	73.46
Best objective function value of PSO-WEAP	337.54	335.92

Table 4 Volumetric and temporal reliability of water supplies to different demand sites

Demand site	Annual demand (MCM)	Volumetric reliability index (%)		Temporal reliability index (%)	
		Basic scenario	Second scenario	Basic scenario	Second scenario
Dashtroom croplands	6.95	98.2	98.2	96.76	96.75
Dashtroom industry	0.28	99.7	99.7	99.7	99.7
Sepidar lands	9.72	91.5	91.47	89.66	89.66
Dehdasht and Choram croplands (D_{DCCL})	variable	76	75.84	73.92	73.45
Lishtar lands	70.1	85.7	85.53	88.9	88.73
Persian Gulf municipals	210	95.27	95.2	90.12	89.96

In the second scenario, the increase of the number of decision variables has resulted in a larger number of function evaluations before the model convergence and therefore higher execution time of the PSO-WEAP model. It is, however, seen that the best O.F value obtained for the second scenario is almost the same as that for the basic model. This shows that optimizing the operational variables has not had a significant effect on the improvement of the model performance compared to capacity optimization of the project's storage and water transfer components. Table 4 presents the model results in terms of reliability of meeting different types of demands represented by both volumetric and temporal reliability indices.

5 Conclusions

This study was about formulating and solving an optimization model for optimally sizing the components of Bashar-to-Zohre water transfer system supplying water to Dehdasht and Choram Cropland (DCCL) area in Zohreh Basin located in Kohgilouye and Boyerahmad undeveloped Province, Iran. Considering the temporal reliability of meeting water demands, the formulation of the model was a mixed integer non-linear program, being difficult to solve by gradient-based optimization approaches. We, therefore, developed a simulation-optimization approach by linking the PSO algorithm to the well-known river basin water allocation model of WEAP. The PSO-WEAP model results indicated that the project can supply water to develop 30,000 ha of DCCL area for agricultural development. It is, however, of the utmost importance to consider socio-economic aspects of the proposed development plan, focusing on the target areas of DCCL area located in Kohgilouye and Boyerahmad undeveloped province as well as its negative effects on Karoon Basin.

Acknowledgement Mr. Jack Sieber, a senior scientist at SEI, is acknowledged for his technical help in employing WEAP.

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