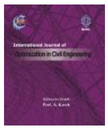
INTERNATIONAL JOURNAL OF OPTIMIZATION IN CIVIL ENGINEERING
Int. J. Optim. Civil Eng., 2016; 6(2):173-185



DRIVING OPTIMUM TRADE-OFF BETWEEN THE BENEFITS AND COSTS OF INTERBASIN WATER TRANSFER PROJECTS

A. Ahmadi Najl, A. Haghighi[*, †] and H.M. Vali Samani
Department of Civil Engineering, Faculty of Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran

ABSTRACT

The interbasin water transfer is a remedy to mitigate the negative issues of water shortage in arid and semi-arid regions. In a water transfer project the receiving basin always benefits while, the sending basin may suffer. In this study, the project of interbasin water transfer from Dez water resources system in south-west of Iran to the central part of the contrary is investigated during a drought period. To this end, a multi-objective optimization model is developed based on the Non Dominated Sorting Genetic Algorithm (NSGA-II). The optimum trade-off between the water supply benefits into and out of the Dez River basin as well as energy production is derived. Formulating the problem as a multi-objective optimization provides a better insight into the gains and losses of a water transfer project. Analyzing the case study, revealed that to reach an acceptable level of reliability for meeting the water demands it is no longer possible to generate hydropower energy with high levels of reliability.

Keywords: interbasin water transfer; multi-objective optimization; NSGA-II; reliability

Received: 12 September 2015; Accepted: 15 November 2015

1. INTRODUCTION

Many countries in Africa and Middle East are currently suffering from severe droughts and water shortages. Development and implementation of careful water resources planning and programs are highly required in these regions to manage the economic and environmental costs of water scarcity. Another challenge that countries like Iran located in arid and semi-arid regions are face with is the non-uniform temporal and spatial distribution of water resources and water demands. In the national arena, water is equity for all. Equity for those

[*]Corresponding author: Department of Civil Engineering, Faculty of Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran
[†]E-mail address: a.haghighi@scu.ac.ir (A. Haghighi)

who are in need of water and do not have accesses to water and those who actually have the water rights and may have surplus that is wasted in a variety of ways [1]. A remedy to mitigate the negative impacts of water shortage and protect the national water rights is the interbasin water transfer. In an interbasin water transfer project the receiving basin always benefits while, the sending basin may suffer. Accordingly, implementation of a water transfer project in practice is only justified when its environmental, social and economic costs for the sending basin are tolerable. Obviously, during drought periods, investigation and judgment of the positive and negative aspects of a water transfer project are much more complex and challenging. Every water transfer project has several apparent and hidden consequences that should be carefully studies and anticipated. Especially, different water users into the sending basin must be well convinced that the project would not seriously harm their yields and environment. Iran is a country with several major water transfer projects. A large amount of water is currently, and going to be transferred from Karun and Dez basins in the south-west to the central parts of the country. This study intends to investigate one of this project that transfers water from Dez River basin to the central part of the country through a multi-objective optimization model. Optimization techniques are of main tools used to investigate water resources problems. For optimum planning and management of a water resources problem, the objectives, decision variables and constraints of the problem are mathematically represented. In general, a standard simulation model is developed so that, it returns the objective function and constraint values against each given alternative of decision variables. Finally, an optimization model is applied to find the best solution that maximizes or minimizes the objective function subject to the problem constraints. In this context, several direct search methods e.g., based on genetic algorithm [2,4]; Particle Swarm Optimization [5-7]; Ant Colony Optimization [8-10] have been so far applied to the water resources problems and reservoirs operations. In most of the previous studies, the interbasin water transfer was implicitly considered in the modeling so that, the water demands in the receiving basin, outer-basin demands, are directly added to the demands in the sending basin, inner-basin demands, and benefits of the water supply were treated as a single objective function [11-13]. In fact, in these works there is no difference between the supplying water demands into and out of the basin. Some other works paid more attention to the inherent challenges raised in the water resources problems with interbasin water transfer projects. In this regard, the economic [14], environmental-economic [1,15], social-economic [16] and multidisciplinary [17] perspectives of the interbasin water transfer were investigated. All these works present an honest attempt to clarify different aspects of the interbasin water projects. However, they all are based on single objective optimization and use some prior-known information and assumptions to evaluate different perspectives of the project.

In this study, we believe that there is a serious trade-off between the benefits of satisfying water demands into and out of the basin as well as between them and the basin hydropower production. For a better decision on the amount of water to be transferred it is required to visually investigate how this trade-off happens and in which levels it becomes critical. This study deals with this issue by formulating the problem as a multi-objective optimization. In what follows, the case study, methodology and the optimization model are introduced. Then, the results are discussed and the findings and conclusion are presented.

2. CASE STUDY

Dez River is a main part of the greatest Kraun basin in south-west of Iran. This river is created from joining two main branches of Bakhtiyari and Sezar in about 40 km upstream of Dezful city in Khouzestan province. Dez dam with about 3000 MCM reservoir has been constructed on Dez River near Dezful city and has been operated since 1963 with the aims of water regulations and hydropower generation. Upon the historical data, Dez River in general, includes one-third of the total inflows to the greatest Karun basin. Accordingly, it is supposed that one-third of the total water demands in downstream of the system are satisfied by Dez River. In addition to water regulation in the Dez reservoir, this dam has a hydropower plant with 520 MW installation capacity. The Dez water resources system is also responsible to satisfy a part of environmental demands in the downstream which, implies that a pre-defined minimum flow must always exists in downstream of the system. In this study, the minimum required environmental demand is considered to be 50 m3/s for the entire simulation period. Into the basin, there are two types of water demands, first (Dez demands) are those directly withdraw from Dez River downstream of the reservoir and second (South Karun demands) are those withdraw from the greatest Karun River after joining Karun and Dez rivers. The schematic of Dez reservoir system has been shown in Fig. 1.

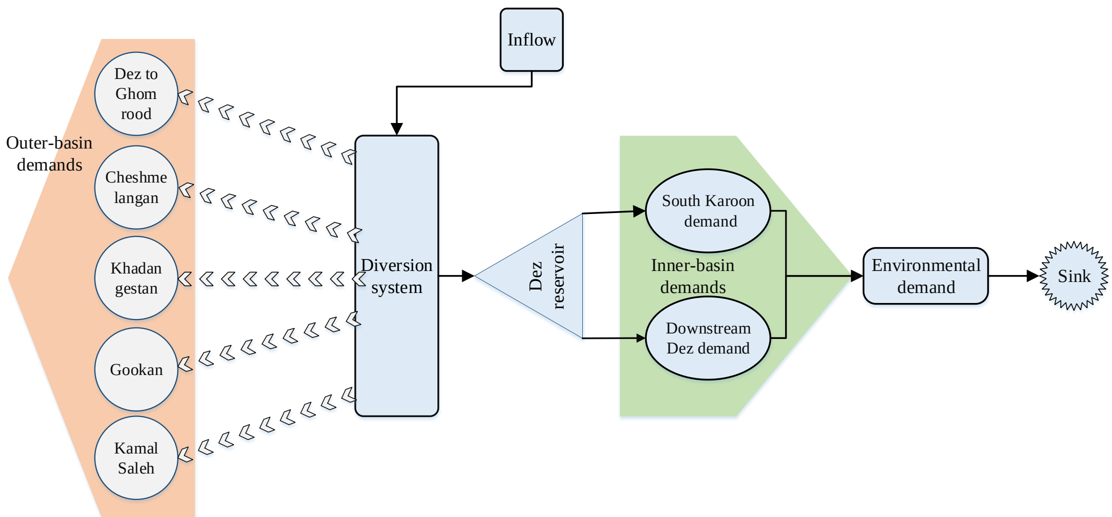


Figure 1. The schematic of Dez reservoir system

For this system, the entire Dez demands plus the one-third of the sough Karun demands are considered as the inner-basin demands lumped in the downstream of the Dez reservoir. Table (1) presents the monthly distribution of the inner-basin demands separately for each type of the aforementioned demands.

To balance the water scarcity in the country, several interbasin water transfer projects have been defined to transfer water from the upstream of the Dez reservoir to central parts of the country. Currently, there exist five main interbasin water transfer projects including; Kamal Saleh to transfer water to Arak province, Chesme Langan, Khadangestan and Gookan tunnels to transfer water to Zayandehrood River and Qomrood project to transfer water to

Qomrood River. Table 2. presents the monthly distributions of the outer-basin demands separately for each of the aforementioned projects.

Table 1: Inner-basin demands (Dez and Sougth Karun demands) in m^3/s

Month of the year	Dez	South Karun	Total (Dez+30% South Karun)
Oct.	87.41	185.9	143.18
Nov.	51.97	112.3	85.66
Dec.	25.72	75.5	48.37
Jan.	27.22	72.9	49.09
Feb.	53.52	128.4	92.04
Mar.	178.11	370.8	289.35
Apr.	173.76	347.9	278.13
May.	111.97	302	202.57
Jun.	102.5	289.2	189.26
Jul.	95.98	297.5	185.23
Aug.	176.54	411.9	300.11
Sep.	120.37	268.7	200.98

Table 2: Outer-basin demands (interbasin water transfer projects) in m^3/s

Month of the year	Qomrood	Chesme Langan	Khadangestan	Gookan	Kamal Saleh	Total
Oct.	3.4	0.3	0.5	0.5	2	6.7
Nov.	5.3	0.6	0.7	1	2.2	9.8
Dec.	7	1.2	1.1	2.2	2	13.5
Jan.	6.8	1.5	0.7	2.4	2	13.4
Feb.	8.4	3.3	0.9	4.9	2	19.5
Mar.	11.8	6	2.6	9.1	2.2	31.7
Apr.	18.1	11.8	8.2	19.9	1.9	59.9
May.	16.1	11.2	9	19.6	2	57.9
Jun.	7.5	5.7	4.5	9.9	2	29.6
Jul.	4.3	2.3	2	4	2.1	14.7
Aug.	3.6	0.9	0.9	1.5	2.3	9.2
Sep.	2.8	0.4	0.5	0.6	2.1	6.4

In the schematic of the system (Fig. 1), it is assumed that all interbasin water transfer projects withdraw water from a diversion system upstream of the Dez reservoir. Obviously, any water transfer leads to a reduction in the Dez reservoir inflow and consequently in the capacity of Dez basin in satisfying its own demands and hydropower generation. In time periods that the basin has surplus water, the water transfer projects have less negative impacts on the basin. However, during drought periods when the demands into the system already suffer from water scarcity, the water transfer projects may seriously harm the inner-basin water needs in both terms of quantity and quality. To investigate this issue for the introduced case study, a 10-year drought period is chosen from the system inflow time-history as illustrated in Fig. 2. This drought period is starting from a high water time step (on Oct. 1997) and is ending at a high water time step too (on Sept 2007). Totally, the system is intended to be simulated for 120 monthly time steps based on the described simulation period and water demands.

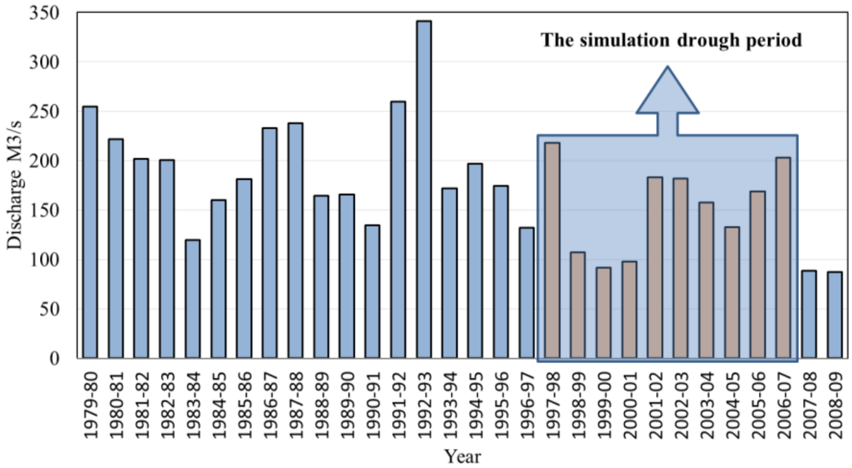


Figure 2. Time history of annual inflows to the system

3. METHODOLOGY

In schematic of the case study (Fig. 1) there are two points for regulating Dez River water. At upstream of the Dez reservoir, there is a diversion system to transfer water out of the basin to the outer-basin demands (Table 2). Also, by means of the Dez reservoir the Dez dam inflows are regulated for the inner-basin demands and hydropower generation. The releases from Dez reservoir are passed across the dam’s hydropower plant and generate energy. They are then released to the river to satisfy the downstream demands (Table 1). Clearly, any reduction in the Dez reservoir inflows because of the interbrain water transfer will influence the system performance in terms of staying inner-basin water demands and energy production. This problem becomes more serious and challenging when the system is operated in drought periods. The main question brings up here is that, in what extent a water transfer project will affect the basin performance in meeting its own demands? To answer this question, the system performance during the selected 10-year drought period (1997-2007) is evaluated in terms of the following objective functions.

$$Rel_{in} = \left(1 - \frac{\sum_{t=1}^{T} F\_in_t}{T}\right) \times 100 \tag{1}$$

$$Rel_{out} = \left(1 - \frac{\sum_{t=1}^{T} F\_out_t}{T}\right) \times 100 \tag{2}$$

$$Rel_E = \left(1 - \frac{\sum_{t=1}^{T} F\_E_t}{T}\right) \times 100 \tag{3}$$

where, Rel_{in}, Rel_{out} and Rel_E are respectively the reliability of satisfying the demands into the basin, demands out of the basin and energy production. T is the entire simulation period in month and F_in_t, F_out_t and F_E_t are the demand-period failures respectively for meeting the water demands in the basin, water demands out of the basin and the energy production. For each demand-period if the supplied water is less than the requested demand a failure is counted otherwise, the failure number is null. For the energy production, the reliability is evaluated based on the dam's hydropower installation capacity. For Dez hydropower plant, during 4 hour function of the plant if the generated energy is less than the installation capacity a failure is counted. The energy production as a function of the release from Dez reservoir and its water level is estimated in each single period as follows.

$$E_t \;= \eta\gamma R_t \; H_t \tag{4}$$

where, η is the hydropower plant efficiency, γ is water specific weight, R_t is the release from the reservoir at time step t to the hydropower plant and H_t is the reservoir storage head at simulation time step $t = 1,2, \cdots T$, in month in this study.

The above objective functions represent the system performance against any decision made on the amount of water to transfer and to release for the entire simulation period. To analyze the trade-off between these performance criteria a multi-objective problem with three objective functions is developed as the following.

$$\text{Maximize } (Rel_{in}, Rel_{out}, Rel_E) \tag{5}$$

Subject to:

$$S_{t+1} = S_t + Q_t + P_t - R_t - O_t - Tr_t \quad \text{Mass balance constraint} \tag{6}$$

$$O_t = \max\{0, (S_{t+1} - S_{\max})\} \quad \text{Spill constraint} \tag{7}$$

$$S_{\min} \le S_t \le S_{\max} \quad \text{Storage constraint} \tag{8}$$

$$R_t \ge ED_t \quad \text{Environmental constraint} \tag{9}$$

where, Tr is the amount of water to transfer out of the basin, S is the reservoir storage volume, Q is the expected inflow to the reservoir, P is effective rainfall on the reservoir, O is the spill volume, $S_{\max}$ and $S_{\min}$ are respectively the maximum and minimum storage capacities of the reservoir and ED is the environmental demand in downstream of the system.

To solve the above problem, the reservoir simulation model must be coupled to a multi-objective optimization model. In the above mathematical programming there are three objective functions having challenge with each other and, are evaluated as a function of the transferred water Tr from the upstream diversion system and the released water R from the reservoir. Accordingly, for the whole simulation period there are $2T$ decision variables. The simulation model is responsible to evaluate the objective functions $Rel_{in}, Rel_{out}, Rel_E$ as well as to satisfy the physical constraints (6-8) in each given alternative of decision variables. The performance constrain on the environmental demand (Eq. 9) must be met into the optimization model. To find the optimum values of the decision variables in context of the introduced multi-objective problem the method of NSGA-II is exploited in this study. In the following, the applied NSGA-II is described in details while, it is explained that how the simulation model is coupled with that.

4. OPTIMIZATION MODEL

The NSGA-II is a well-known multi-objective optimization method working based on the principle of Pareto optimality criterion. In general, a non-dominated sorting scheme enables the population-based optimization method like GAs to identify and promote solutions dominate other solutions. The basic notion of dominancy is defined as the following.

Solution x dominates y if both of these conditions are simultaneously met:

1. None of objectives in x is worse than in y.
2. At least one objective in x is better than in y.

Other aspects of dominancy may also be added to the above definition as Deb [18] did when developing the NSGA-II. They proposed a new operator that not only fulfils the above criterion but also, in lower levels, preserves the diversity of Pareto-optimal solutions. For handling the problem constraints, proper operators can be also added to the algorithm to make it self-adaptive. Accordingly, main steps of the NSGA-II applied to solve the problem is introduced as follows.

1- The optimization is started by generating a random population P of decision variables i.e., the water releases $R_{1\ to\ T}$ and water transfers $Tr_{1\ to\ T}$. The population is consisting of N_{pop} chromosomes containing $2T$ genes (decision variables).

2- The simulation model is run against every chromosome and the objective functions are evaluated.

3- For each chromosome, the total violation of environmental constraint Eq. (9) is evaluated as the following.

$$V=\sum_{t=1}^{T}\max(0, ED_t-R_t) \tag{10}$$

4- According to the constraint violation values, the population is divided into a feasible and infeasible sub-populations.

5- According to the notion of dominancy the feasible sub-population is ranked and, to each feasible chromosome a rank number is assigned. On this basis, the Pareto fronts from level 1 to l are formed so that, chromosomes in front 1 are dominants over those in the next fronts and, chromosomes in front l are overcome by the previous fronts.

6- All infeasible chromosomes are stored in front $l+1$.

7- It is also important to maintain a good spread of the Pareto-optimal solutions. To preserve a good diversity of solutions, NSGA-II uses an operator namely the crowded-comparison. For every chromosome in the feasible fronts, a crowding distance is measured as the distance of the biggest cuboid contacting two neighbor solutions. For example, in Fig. 3, the crowding distance associated with solution i is $a+b$. The boundary solutions (points A and B in Fig. 3) are the extremities of the front and must be emphasized more than intermediate solutions. Hence, they receive a huge crowding distance value, e.g., infinity.

8- To select the parents, a combined criterion using the binary tournament selection method is used here. From the previous steps, each chromosome has three attributes including the total constraint violation, non-domination rank number (level of Pareto front) and the crowding distance. To select each parent two chromosomes x and y are randomly selected from the population. x wins the tournament if one of the following conditions is satisfied.

i. x is feasible and y is not.

ii. x and y are both infeasible but, x has a smaller constraint violation.

iii. x and y are both feasible but x dominates y. In other words, if x belongs to a better Pareto front.

iv. x and y are both feasible and belongs to the same Pareto front but, x has a larger crowding distance.

Otherwise, y wins the tournament.

9- An appropriate crossover technique is applied to each pair to produce two children. In this study, the blend crossover method (BLX-α) proposed by Eshelman and Shaffer [19] is adopted. Accordingly, a population of new offspring F with size N_{pop} is generated.

10- Few genes in the new population F are randomly mutated.

11- The hydraulic simulation model is run against each new offspring and the corresponding objective functions and constraint violation are evaluated.

12- The parents and children populations, P and F, are merged resulting in a combined population $J = P \cup F$ with size $2N_{pop}$. J is divided into the feasible and infeasible sub-populations. The feasible population is sorted based on the non-domination criterion and, the new Pareto fronts from level 1 to l are formed. For each individual in each front the crowding distance is measured. All infeasible solutions are transferred to front $l+1$. let NF_i be the number of individuals in each front $i, i = 1,2,\dots,l+1$.

13- The new population with N_{pop} size is derived from the combined population J. First the best Pareto front, $i = 1$, is taken into account. If $NF_i \leq N_{pop}$, all individuals in front i is transferred to the new population and, the remaining $N_{pop} - NF_i$ individuals are provided by the next Pareto fronts. If $NF_i > N_{pop}$, N_{pop} individuals are selected from the current front with respect to the crowding distance criterion. In a same front, chromosomes with larger crowding distances are preferred to be chosen. It is worth mentioning that, since all parents and children participate in forming the new generation the elitism is automatically preserved.

14- The convergence criterion i.e., no further improvement in the optimal solutions, is checked. If it is not satisfied, the algorithm is continued.

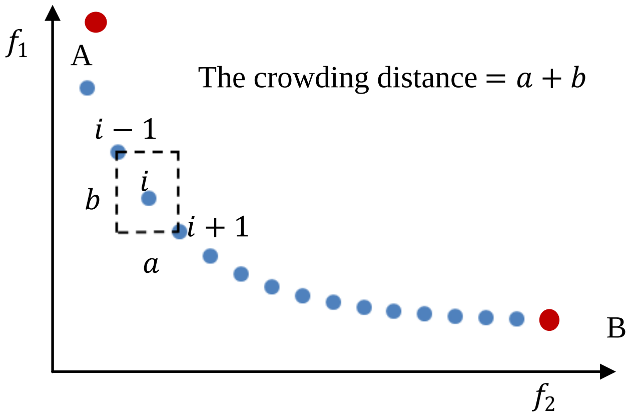


Figure 3. A Pareto front with crowding distance measurement

5. CASE STUDY ANALYSIS

In this section, the introduced optimization model is applied to the mathematical programming of the case study to investigate the trade-off between different objective functions of the problem. In this case study, there are two types of decision variables including the water transfer Tr from the upstream of the system and water release R from Dez reservoir. This case study is simulated for a 10-year drought period with monthly time steps. Accordingly, the total simulation time is 120 months. Therefore, the current optimization problem includes 240 decision variables for the whole simulation period. In tables 1 and 2 the total monthly demands respectively for the inner- and outer-basin water uses have been presented. Once a chromosome is generated by the NSGA-II and introduced to the simulation model, using the releases R from the reservoir the reliability of meeting inner-basin demands Rel_{in}, the first objective function from equation (1), as well as the reliability of hydropower production Rel_E, the third objective function from equation (3), are evaluated. Then, using the transfer water Tr values the reliability of meeting outer-basin demands Rel_{out} , the second objective function from equation (2), is evaluated. The simulation model also evaluates the violation of environmental constraint for the entire simulation period according to equation (10). For each GA chromosome, the objective function values along with the quantity of constraint violation are returned to the optimization model. To start the optimization, the NSGA-II parameters are justified through some initial trial-and-error runs. On this basis, the population size, mutation ratio and maximum generation number were decided to be 400, 0.03 and 1000 respectively. The problem was several times analyzed and the best results were obtained in context of optimum Pareto fronts. Since, the current problem has three objective functions, the Pareto fronts become three dimensional as shown in Fig. 4 representing the best obtained front.

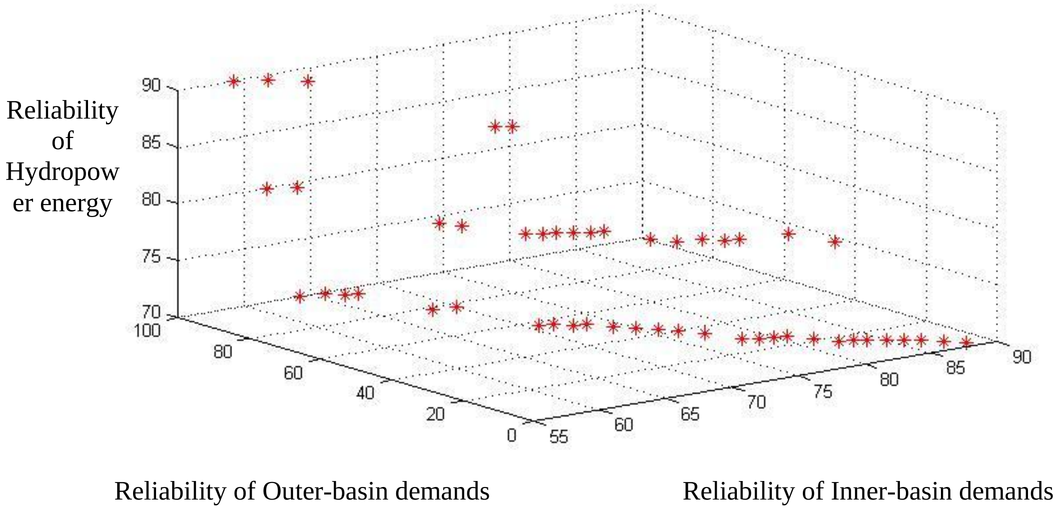


Figure 4. Three-dimentional pareto fronts

For better representing the results to discuss the trade-off between the objectives more clearly, some two-dimensional Pareto fronts are extracted from Fig. 4 and depicted in Fig. 5. In this figure, the trade-off between the reliability of satisfying water demands into and out of the basin are shown for different ranges of reliability of hydropower generation. First of all, the Pareto fronts of Fig. 5 clearly manifest that there is significant trade-off between the problem objective functions. This means that, during the selected 10-year drought period a serious challenge exists between satisfying the inner- and outer-basin demands. This challenge becomes more important when the importance of hydropower generation is taken into account. As seen in Fig. 5 by increasing the reliability of energy production not only the number of feasible solutions on the Pareto front significantly decreases but also, the trade-off between the demands reliability become very critical. For instance, to keep the reliability of hydropower generation above 90%, in the best conditions, the reliability of satisfying the inner-basin demands is about 65%. This clearly indicates that during the drought period the basin does not have enough water even for its own demands. To increase the reliability of demands satisfaction especially for water transfer projects, we inevitably have to disregard high values of reliability of energy production.

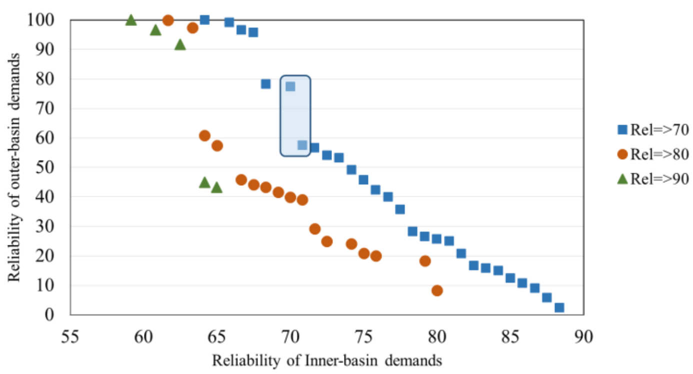


Figure 5. Two-dimentional pareto fronts

For example, we may decide to adopt above 70% or 80% reliability for hydropower generation. If so, the number of feasible decisions are much more and the extent of trade-off between the demands reliability becomes wider. For example, if it is compromised on 80% reliability of hydropower generation, the inner-basin demands are satisfied with at most 80% reliability while the outer-basin demands are satisfied with only 10% reliability. Definitely, 10% reliability has no meaning for the water users out of the basin and does not solve any problem of them. In any case, if it is decided to balance the water supply objectives with no difference between the demands into or out of the basin, a decision must be made to result in a similar reliability for both types of demands. If so, for example, when the energy reliability is considered 80% the water supply decision is a point on the corresponding Pareto front that satisfies the inner basin demands with 64% and the outer-basin demands with 60% reliability. Similarly, if we consider 70% reliability for the energy production the balanced reliability of meeting inner- and outer-basin demands are respectively 70% and 78%. Any decision from the derived Pareto fronts has its own benefits and costs for each of into and out of the basin water users. These benefits and costs must be economically, socially and environmentally investigated and finally, a decision must be made that while, it solves the problem of arid regions of the country, does not seriously damage the sending basin economy and environment. The Pareto fronts of Fig. 5 also reveals that by better management of the water uses into the basin it is possible to transfer a part of water without significant changes in supplying the inter-basin demands. For example, considering the front of 70% energy reliability, a steep drop is found in the trade-off between the demands satisfaction around the 70% reliability of inner-basin demands (highlighted in Fig. 5). This drop indicates that by only 1% reduction in the reliability of inner-basin demands (72% to 71%) it is possible to increase the reliability of outer-basin demands by 20% (58% to 78%). In fact, on top of all challenges and difference of opinions about the water transfer projects, by a good and systematic management many of the associated problems can be controlled. The proposed multi-objective optimization method facilities this importance.

6. CONCLUSION

Transferring water from a basin to another basin is an alternative for balancing water in arid regions. These projects are generally challenging and have some positive and negative issues in social, economic and environmental points of view. The approach of programming and handling the problem has a great influence on investigation of the projects' apparent and hidden consequences. This study introduced a multi-objective optimization approach for analyzing water transfer projects. A simulation-optimization model was developed based on the NSGA-II method and applied to Dez reservoir system as a case study. It was emphasized that the water transfer projects are justified only when the sending basin has surplus or at least enough water to satisfy its own demands. Otherwise, any water transfer would harm the basin water users in a variety of aspects. Hence, the consequences of water transfer projects are required to be specially investigated during drought periods. Accordingly, for Dez water resources system a 10-year drought period from its historical data was taken into account. The results of simulation-optimization clearly showed that there is a serious trade-off between the water supply objectives into and out of the basin as well as the energy production. The derived Pareto fronts provide a helpful tool for the water resources associations and managers to more carefully and realistically make decision on the development and operation of interbasin water transfer projects. Besides, it is concluded that apart from the benefits and costs of any interbasin water transfer project, a careful attention must be paid on the management and operation of the reservoirs into the basin to lessen the negative issues of water transfer projects.

REFERENCES

1. Karamouz MS, Mojahedi A. Ahmadi. Interbasin water transfer: economic water quality-based model, *J Irrig Drain Eng* 2009; **136**(2): 90-8.
2. Chen L, McPhee J, Yeh WWG. A diversified multiobjective GA for optimizing reservoir rule curves, *Adv Water Resour* 2007; **30**(5): 1082-93.
3. Louati M, et al. Application of a genetic algorithm for the optimization of a complex reservoir system in tunisia, *Water Resour Manag* 2011; **25**(10): 2387-404.
4. Jothiprakash V, Shanthi G, Arunkumar R. Development of operational policy for a multi-reservoir system in india using genetic algorithm, *Water Resour Manag* 2011; **25**(10): 2405-23.
5. Nagesh Kumar D, Janga Reddy M. Multipurpose Reservoir operation using particle swarm optimization, *J Water Resour Plan Manag* 2007; **133**(3): 192-201.
6. Shourian M, Mousavi SJ, Tahershamsi A. Basin-wide water resources planning by integrating PSO algorithm and MODSIM, *Water Resour Manag* 2008; **22**(10): 1347-66.
7. Ostadrahimi L, Mariño M, Afshar A. Multi-reservoir operation rules: multi-swarm pso-based optimization approach, *Water Resour Manag* 2012; **26**(2): 407-27.
8. Jalali MR, Afshar A, Mariño MA. Multi-Colony ant algorithm for continuous multi-reservoir operation optimization problem, *Water Resour Manag* 2007; **21**(9): 1429-47.
9. Madadgar S, Afshar A. An Improved continuous ant algorithm for optimization of water resources problems, *Water Resour Manag* 2009; **23**(10): 2119-39.
10. Kumar DN, Reddy MJ. Ant colony optimization for multi-purpose reservoir operation, *Water Resour Manag* 2006; **20**(6): 879-98.
11. Dariane A, Momtahen S. Optimization of multireservoir systems operation using modified direct search genetic algorithm, *J Water Resour Plan Manag* 2009; **135**(3): 141-8.
12. Ahmadi M, Bozorg Haddad O, Mariño MA. Extraction of Flexible Multi-Objective Real-Time Reservoir Operation Rules, *Water Resour Manag* 2014; **28**(1): 131-47.
13. Bozorg-Haddad O, et al. Development and application of the bat algorithm for optimizing the operation of reservoir systems, *J Water Resour Plan Manag* 2014; **141**(8): 04014097.
14. Draper A, Lund J. Optimal hedging and carryover storage value, *J Water Resour Plan Manag* 2003; **130**(1): 83-7.
15. Matete M, Hassan R. An ecological economics framework for assessing environmental flows: the case of inter-basin water transfers in Lesotho, G*lob Planet Change* 2005, **47**(2-4): 193-200.

16. Feng S, et al. Assessing the impacts of south-to-north water transfer project with decision support systems, *Dec Support Syst* 2007; **42**(4): 1989-2003.
17. Gupta J, P. van der Zaag. Interbasin water transfers and integrated water resources management: Where engineering, science and politics interlock, *Phys Chem Earth*, Parts A/B/C 2008; **33**(1–2): 28-40.
18. Deb K, et al. A fast and elitist multiobjective genetic algorithm: *NSGA-II.*, *IEEE Trans Evol Comput* 2002; **6**(2): pp. 182-197.
19. Schaffer LJEAD. Real-Coded Genetic Algorithms and Interval-Schemata, 1992.