Interbasin Water Transfer: Economic Water Quality-Based Model

Mohammad Karamouz, F.ASCE1; S. Ali Mojahedi2; and Azadeh Ahmadi3

Abstract: The interbasin water transfer project is an alternative to balance the nonuniform temporal and spatial distribution of water resources and water demands, especially in arid and semi-arid regions. A water transfer project can be executed if it is environmentally and economically justified. In this study, the feasibility of two interbasin water transfer projects from Karoon River in the western part of Iran to the central part of the country is investigated. An optimization model with an economic objective function to maximize the net benefit of the interbasin water transfer projects is developed. The planning horizon of the model is 23 years (the length of historical data); and it is solved using genetic algorithm. In order to consider environmental impacts of water transfer projects, a water quality simulation model has been used. Then, an Artificial Neural Network model is trained based on the simulation results of a river water quality model in order to be coupled with the optimization model. The outputs of the optimization model are the value of economic gain of the sending (Karoon) basin to offset the loss of agricultural income and environmental costs. The optimal polices for water transfer during the planning horizon has been generated using the coupled simulation-optimization model. Then, operating rules are developed using a K Nearest Neighborhood model for the real-time water transfer operation. The results show the significant value of using the proposed algorithm and economic evaluation for water transfer projects.

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Author keywords: Interbasin water transfer; Water quality simulation; Genetic algorithm; Economic assessment; Artificial neural network; K Nearest Neighborhood.

Introduction

Iran is located in an arid and semi-arid region of the world. It has a nonuniform temporal and spatial distribution of water resources and water demands. There is enough water in some basins while in some other basins there is water scarcity. The periodic droughts and water deficits cause the migration of the inhabitants in certain regions. In addition, considering the rate of the increasing population and the improving economy, it is necessary to have long-term planning to balance the supply and the demands distribution.

The interbasin water transfer project is an alternative to balance the nonuniform temporal and spatial distribution of water resources and water demands. Transferring water from an area may cause a variety of negative impacts, social and environmental impacts. But a water transfer project can be executed if it is environmentally and economically justified. When water is intended to be used in another basin, water rights could be traded for financial resources. In the national arena, water is equity for all. Equity for those who are in need of water and do not have access to water and those who actually have the water rights and may have a surplus that is wasted in a variety of ways. To analyze the above issues, tangible and intangible costs and benefits should be evaluated.

Several investigators have emphasized the need for economic and environmental assessment of interbasin water transfer plans. Lund and Israel (1995) presented the application of multi-stage linear programming for estimation of the least-cost integration of several water marketing opportunities with water conservation and traditional water supplies. Draper et al. (2003) developed an economic based optimization model for California’s major water supply system. They noted that optimization models driven by economic objective functions are practical for assessing the development project. Feng et al. (2007) developed a decision support system (DSS) for assessing the social-economic impact of China’s South-to-North Water Transfer project. The DSS provides decision support through simulation with an embedded water computable general equilibrium model. Gupta and Zaag (2008) have assessed the interbasin water transfers from a multidisciplinary perspective, and attempted to answer whether such transfers are compatible with the concept of integrated water resources management and the criteria for assessing such transfers. Matete and Hassan (2005) developed an analytical framework that can be applied to integrate environmental sustainability aspects into economic development planning in the case of exploiting water resources through interbasin water transfers.
In this study, the proposed optimization model with considerable computational complexity due to a high number of decision variables and nonlinear behavior of objectives and constraints are solved with the use of a genetic algorithm (GA) method. In the last decade, more attention has been given to soft computing techniques, such as evolutionary algorithms (EA) and in general particularly GA in particular. Burn and Yulianti (2001) have shown the capabilities of GAs for identifying solutions to classical waste-load allocation problems. They showed that GAs provide a rather robust and noninferior solution for deterministic waste load allocation in low flow conditions. Cai et al. (2001) combined GAs with linear programming approaches to solve a set of complicating constraints. The results show that the GA is capable of finding quality solutions to the problems at a reasonable run time. Kerachian and Karamouz (2006) used an algorithm combining a water quality simulation model and a stochastic conflict resolution GA-based optimization technique for determining optimal reservoir operation rules.

In this paper, an economic and environmental evaluation of water basin transfer projects is developed. Two water transfer projects in the central part of Iran, Solegan to Rafsanjan (Case A) and Koolrash III to Zayandeh-Rud (Case B) are considered as the case studies. These two interbasin water transfer projects have the same basin (origin) as the source of providing water. An economic model is developed to optimize the benefit for evaluating the quantity of the water to be transferred and the variation in quality of the remaining water. The GA method is used to solve the optimization model for determining the flow rate to be transferred in each month. The constraints include the system capacity (tunnels), average inflow to the diversion reservoirs, continuity equation, and water allocation to the monthly demands.

The paper is organized as follows: the methodology is presented in “Methodology” followed by case study characteristics in “Case Studies.” The water quality simulation model and its results are presented in “Simulation Model of the Karoon River (Sending Basin).” The optimization model formulation of interbasin water transfer is given in the “Structure of the Optimization Model” section. The results of optimization models and developed operating rules are presented in section 6. Finally, a “Summary and Conclusion” is given.

### Methodology

In this study, an optimization model with an economic objective function for water basin transfer projects has been developed and the environmental impacts of water transfer from the river headwater are considered. The proposed model of water transfer is based on attaining the maximum benefits with the minimum cost. Therefore, costs and benefits for each basin (sending basin and receiving basins) are estimated. The benefits include an increase in the agricultural production, decrease in pumping costs (receiving basin) and increase of water release in the receiving basin. The costs include an increase in the dredging cost and a decrease in hydropower energy generation. Most importantly, the decrease in the agricultural production in the sending basin, capital investment and the operation and maintenance (OM) costs of water transfer projects implementation as well as the treatment costs to maintain the water quality standards in the Karoon River (sending basin). The water quality variation is determined through a coupled Artificial Neural Network (ANN) model in the optimization model. The ANN model is developed using the results of the water quality simulation model for the Karoon River. The Qual2k software developed by the U.S. Environment Protection Agency (U.S. EPA) is used to simulate the water quality on a monthly time scale. The GA-based optimization model determines the monthly water allocation to the receiving basins in each month considering the benefit and cost analysis. Fig. 1 shows the proposed algorithm of optimization model for interbasin water transfer project. By using the results of the optimization model, operating rules are generated using a K Nearest-Neighborhood (KNN) model. The operating rules are used to develop a working operational scheme for real time operation using a KNN model.

### Case Studies

Fig. 2 shows the location of sending and receiving basins. Namely, one sending basin in Khuzestan (in the western part of the country) with two receiving basins including Rafsanjan plain in Kerman and Zayandeh-Rud River basin in Isfahan (in the central part of the country) are considered as case studies. One of the water transfer projects is from Solegan in the Karoon River to the Rafsanjan plain (here is called receiving Basin 1). Rafsanjan is located in the central part of Iran and has an area of 12,421 km² located between 54°, 52" and 56°, 34" longitudes and 29°, 51’ and 31°, 31’ latitudes. This region is classified as an arid area. Rafsanjan has hot summers and dry winters. Average annual rainfall is about 90 mm. The major objective of this water transfer project is to supply water demand to the Rafsanjan agriculture plain for production of pistachio, an exclusive and expensive product (over $7/kg in a local market for dried pistachio). The Water Transfer project from Solegan to Rafsanjan is designed for supplying an average of 250 MCM per year.
Second water transfer project is the water transfer project from Koohrang III Tunnel to the Zayandeh-Rud Reservoir (here is called receiving Basin 2). The objective of this water transfer project is supplying water demand to the Zayandeh-Rud Reservoir. The reservoir inflow includes natural river inflow and inflow from the first and the second Koohrang Tunnels, with an annual average of 1,600 MCM. The inflow to the reservoir will increase with the construction of the third Koohrang Tunnel called Koohrang III in this study. This water transfer project is designed for transferring an average of 250 MCM per year (Karamouz et al. 2007).

Simulation Model of the Karoon River (Sending Basin)

Lower part of the Karoon River, the largest river in Iran, with more than 450 km of length is subject to major impacts from water transfer projects. This part of the river supplies the water demands of 16 cities, major industrial and agroindustrial establishments (water demand of about 1 billion m³), and about 700,000 ha (1 ha = 10,000 m²) of agricultural lands. In the lower part, Karoon River water pollution due to increasing water withdrawal and wastewater discharge to this river has already endangered the aquatic life of the river. The affected study area (from Gotvand Dam to Darkhoein Station) and different components of water resources including the pollution sources are shown in Fig. 3 (Karamouz 2004). This part of the river is considered to evaluate how the water transfer projects are altering the river water quality.

Water Quality Simulation Model of the Karoon River

The basic equation of water quality simulation models developed in this study is based on a one-dimensional advection-dispersion mass transport equation, which is numerically integrated over space and time for each water quality constituent, using Qual2K software, developed by the U.S. EPA (2004).

Based on the available data from the existing monitoring systems, total dissolve solid (TDS) or electric conductivity (EC), biochemical oxygen demand (BOD), and dissolve oxygen (DO) are the selected water quality indices. Using the available data for 12 years (1992–2003) from the existing monitoring system, the monthly water/wastewater quality and quantity data of the first ten years was used for calibration and the past two years for validation.

The results of the simulation model show that BOD and DO concentrations do not violate the water quality standards along the river. This is because of the carrying capacity of the river for handling BOD. TDS concentration increases along the river due to domestic, agricultural and industrial wastewater discharges. Therefore, only TDS variation along the river is simulated to incorporate in the optimization model. The Qual2k simulation model is used taking into account the available data for 33 years along the river for generating more data to train and test the ANN model.

Estimation of EC (TDS) Variable Using the ANN Model

In this study, an ANN model is developed to estimate TDS variable at the water quality control point (Ahvaz City). Since the input-output relation is easy to formulate in the neural network models, it can be considered as a simple expression of input-output computations in any descriptive or optimization models.

The ANN model has been used for the examination of different types of multilayer perception (MLP) architectures. The inputs are the index of month (shows the physical and climate conditions), discharge, and TDS in headwater (Gotvand Dam). From 396 produced data points, 300 data points (about 75% of available data) have been used for training and the remaining data are used for the testing of the ANN model. Eq. (1) estimates TDS variable at Ahvaz City using the ANN model

\[
TDS2 = Purline(w2 \times \{\tan \text{sig}[w1 \times (m, Q, TDS1)] + b1\} + b2)
\]

where \(m\) = index of the month; \(Q\) = discharge, TDS1 and TDS2 are water quality characteristics in headwater and control point in downstream, respectively. The best ANN model, a MLP, includes three layers with 3, 5, and 1 neurons respectively, and minimum error in the testing period (RMSE = 0.10899). The characteristics of the ANN model including weights and biases in each layer (\(w_1, w_2, b_1,\) and \(b_2\)) are presented in Table 1. This ANN model is placed in the optimization model to simulate the TDS variation.

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Fig. 2. Iran’s major watersheds and the close-up of the three basins, the sending basin, and two receiving basins
Structure of the Optimization Model

The main objective of the proposed model is to maximize the difference between the associated benefit and cost

Maximize \[ Z = \sum_{k=1}^{3} \sum_{t=1}^{12} \sum_{y=1}^{23} \text{Benefit}_{k,t,y} - \sum_{m=1}^{5} \sum_{t=1}^{12} \sum_{y=1}^{23} \text{Cost}_{m,t,y} \]  

Subject to

\[ \text{Benefit}_{1,t,y} = \sum_{t=1}^{12} \sum_{y=1}^{T} \left( V_{2,t,y} \times \bar{CPD} \times \bar{P} \right) \]  
\[ t = 1, \ldots, 12, \quad y = 1, \ldots, T \]  

\[ \text{Benefit}_{2,t,y} = \sum_{t=1}^{12} \sum_{y=1}^{T} \left( \frac{V_{2,t,y} \times H_{b} \times H_{r}}{\eta \times 0.102} \right) \times P_{p} \]  
\[ t = 1, \ldots, 12, \quad y = 1, \ldots, T \]  

Fig. 3. Different components of the water resources including the pollution sources system in the sending region, Khuzestan Province (Karamouz 2004)
Table 1. Characteristics of Developed ANN Model

<table>
<thead>
<tr>
<th>Input 1</th>
<th>Input 2</th>
<th>Input 3</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0527</td>
<td>-2.862</td>
<td>0.4839</td>
<td>1.1844</td>
</tr>
<tr>
<td>-1.2519</td>
<td>1.7258</td>
<td>-0.4438</td>
<td>0.1956</td>
</tr>
<tr>
<td>2.5331</td>
<td>0.3893</td>
<td>0.6885</td>
<td>0.2642</td>
</tr>
<tr>
<td>2.0273</td>
<td>-0.3184</td>
<td>0.4429</td>
<td>-0.1923</td>
</tr>
<tr>
<td>-0.1577</td>
<td>0.5079</td>
<td>-2.3933</td>
<td>-0.358</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\text{Benefit}_{t,y} = \sum_t \sum_y \left[ F(R_{2,t,y}) - F(R_{1,t,y}) \right] y = 1, \ldots, T \quad (5)
\]

\[
F(R) = \begin{cases} 
-1.88 \times R^2 + 2603.5 \times R & t = 10, 11, 12, 1, 2, 3 \\
-0.759 \times R^2 + 419.5 \times R & t = 4, 5, 6, 7, 8, 9 
\end{cases}
\]

\[
R_{2,t,y} = I_{t,y} + I_{3,t,y} + S_{t,y} - S_{t+1,y} 
\]

\[
R_{1,t,y} = I_{t,y} + S_{t,y} - S_{t+1,y} 
\]

\[
\text{Cost}_{t,y} = \sum_t \sum_y \left[ \left( V_{1,t,y} + V_{2,t,y} \right) \times \text{CPD}_{t,y} \times \text{PC}_{t,y} \right] 
\]

\[
= \sum_t \sum_y \left[ \left( V_{1,t,y} + V_{2,t,y} \right) \times \text{CPD}_{t,y} \times \text{PC}_{t,y} \right] 
\]

\[
t = 1, \ldots, 12, y = 1, \ldots, T \quad (6)
\]

\[
G(Q) = -7 \times 10^{-4} \times Q^2 - 1.355 \times Q + 745.9 
\]

\[
\text{Cost}_{2,t,y} = \sum_t \sum_y \left[ \left( G(Q - (X_{1,t,y} + X_{2,t,y})) \right) - G(Q) \right] 
\]

\[t = 1, \ldots, 12, y = 1, \ldots, T \quad (7)
\]

\[
\text{Cost}_{3,t,y} = \sum_t \sum_y \left[ \left( L(Q) - L(Q - (X_{1,t,y} + X_{2,t,y})) \right) \right] 
\]

\[t = 1, \ldots, 12, y = 1, \ldots, T \quad (8)
\]

\[
L(X) = 0.0788 \times X^2 - 20.703 \times X + 4000 
\]

\[
\text{Cost}_{4,t,y} = \sum_t \sum_y \left[ \text{Phc}_{t,y} \right] 
\]

\[t = 1, \ldots, 12, y = 1, \ldots, T \quad (9)
\]

\[
\text{Cost}_{5,t,y} = \sum_t \sum_y \left[ \left( \text{CP}_{t,y} - \text{CS}_{t,y} \right) \right] 
\]

\[t = 1, \ldots, 12, y = 1, \ldots, T \quad (10)
\]

\[
X2 \min_{t,y} \times DS_{t,y} \leq X2_{t,y} \leq X2 \max_{t,y} \times DS_{t,y} 
\]

\[t = 1, \ldots, 12, y = 1, \ldots, 1 \quad (11)
\]

where \(t\)-index of the month; \(y\)-index of the year; \(T\)=number of optimization years; \(m\)=index of the cost; \(k\)=index of the benefit; \(i\)=interest rate; Benefit_{1,t,y}=benefit of the agriculture productions in month \(t\) of year \(y\); Benefit_{2,t,y}=benefit of the decreasing pumping costs in Rafsanjan plain in month \(t\) of year \(y\); Benefit_{3,t,y}=benefit of the water releasing of the Zayandeh-Rud Dam in month \(t\) of year \(y\); Cost_{1,t,y}=cost of the decreasing agriculture production in the Karoon basin in month \(t\) of year \(y\); Cost_{2,t,y}=cost of the increasing dredge actives in month \(t\) of year \(y\); Cost_{3,t,y}=cost of the hydropower generation reduction in month \(t\) of year \(y\); Cost_{4,t,y}=capital and OM costs in month \(t\) of year \(y\); Cost_{5,t,y}=cost of the water treatment in critical points in month \(t\) of year \(y\); \(V_{1,t,y}, V_{2,t,y}\)=optimal transferred water volume from Kooorghang III to Zayandeh-Rud and from Solegan to Rafsanjan in month \(t\) of year \(y\), respectively (MCM); \(X_{1,t,y}, X_{2,t,y}\)=optimal transferred discharge from Kooorghang III to Zayandeh-Rud and from Solegan to Rafsanjan in month \(t\) of year \(y\), respectively (cms); \(\text{CPD}_{t,y}\)=\(\text{PC}_{t,y}\)=average price of crops in Rafsanjan and Khuzestan plains ($/Kg$); \(Hb\)=depth of water table in Rafsanjan Plain (m); \(Hr\)=total duration of pumping from groundwater in the month (hr); \(P_p\)=price of electricity needed for water pumping ($/KWh$); \(n\)=pumping efficiency (%); \(F(R)=\)benefit function of water released from Zayandeh-Rud Dam in month \(t\) of year \(y\); \(R_{1,t,y}, R_{2,t,y}\)=release function from Zayandeh-Rud Dam with and without considering inflow from Kooorghang III Tunnel in month \(t\) of year \(y\), respectively; \(I_{t,y}\)=inflow to Zayandeh-Rud Reservoir in month \(t\) of year \(y\) (MCM); \(I_{3,t,y}, I_{4,t,y}\)=inflow to Kooorghang III and Solegan Dams in month \(t\) of year \(y\), respectively (MCM); \(S_{1,t,y}, S_{2,t,y}\)=storages of Zayandeh-Rud and Solegan Dams at the beginning of month \(t\) of year \(y\) (MCM); \(Q\)=headwater discharge in Karoon River (cms); \(G(Q)=\)cost function of dredging; \(L(X)=\)benefit function of the hydropower energy generation; \(\text{Phc}_{t,y}\)=cost of instruction and maintenance interbasin water transfer projects in month \(t\) of year \(y\); \(\text{CS}_{t,y}\)=standard values of water quality indices in the river in month \(t\) of year \(y\); \(\text{CP}_{t,y}\)=values of water quality indices in the control point in month \(t\) of year \(y\); \(\text{ANN}=\)simulation model of water quality indices in control points (ANN model); \(Pt\)=water treatment cost due to water quality exceeded the standard value; \(C\)=values of water quality indices in the headwater; \(X_{1}\min_{t,y}, X_{1}\max_{t,y}\)=minimum and maximum transferred discharge from Kooorghang III in month \(t\) of year \(y\), respectively (CMS); \(X_{2}\min_{t,y}, X_{2}\max_{t,y}\)=minimum transferred discharge from Solegan in month \(t\) of year \(y\) respectively (CMS); and \(D_{K,t,y}, D_{S,t,y}\)=percentage of monthly water allocation from Kooorghang III and Solegan considering monthly demand in month \(t\) of year \(y\), respectively. Eqs. (3)–(16) are classified and explained.
in the cost-benefit analysis based for the receiving basins (1 and 2) and sending basin as follows.

**Solegan to Rafsanjan Water Transfer Plan in the Rafsanjan Region (Receiving Basin 1)**

Eq. (3): The benefit gained from water transfer to Rafsanjan is due to increased agricultural products obtained from the crop per drop coefficient (CPD) multiplied by transferred volume of water and price of products.

Eq. (4): the benefit from the reduction in pumping cost multiplication of transferred volume of water, pumping duration (hours), and average depth of ground water level and division by pumping efficiency. Eq. (14): the total the annual cost of Solegan to Rafsanjan water transfer project that includes initial investment, OM costs during the operating period. The annual and monthly costs of the project for a period of 30 years are $30.3 and $2.23 million considering 10% interest rate and the initial investment of $102.5 million.

**Koohrang III to Zayandeh-Rud Water Transfer Plan in Zayandeh-Rud Basin (Receiving Basin 2)**

Eqs. (5)–(8): The benefit of water transfer to Zayandeh-Rud Dam obtained from the difference between water values before and after the project. Since Zayandeh-Rud basin is affected by sever drought during 1990s, the benefit of water transferring is estimated based on drought damages reduction. The benefit-release functions are obtained using Eq. (6) for the first (fall and winter) and the second (spring and summer) seasons, respectively (Araghinejad 2005).

The annual and monthly costs of the project for a period of 30 years are $10.8 and $0.903 million considering 10% interest rate and the initial investment of $102.5 million.

**Karooon Basin (Sending Basin)**

Eqs. (12) and (13): the cost of decreasing in hydropower generation in dams located along the Karoon River. These values are estimated based on the hydropower generation function (Rabei et al. 2004) through the production of less hydropower generation due to water transferring based on the price of electricity.

Eqs. (10) and (11): the dredging cost is estimated for before and after the transfer project using the proposed cost function by Zahiri and Korestani (2004). The base flow at the control point (Ahvaz City) is considered as 250 cm (cubic meter per second). Eq. (9) presents the reduction in the benefit of agricultural production considering of the amount of water transferred from the sending basin (Karooon basin).

Eqs. (15) and (16): the removal cost of the excess total dissolved solids (TDS) from associated standard value after water transfer. The TDS variation in control point is estimated using the ANN model. The standard value for TDS is considered as 1,200 mg/lit. The removal of TDS is carried out using evaporation ponds that is suitable for the climate condition in the study area.

Other constraints of water transfer model are as follows: Eqs. (17) and (18): the continuity equations of Koohrang III’s and Solegan Dams considering their minimum and maximum storage volumes and river discharge during the planning horizon. Eqs. (19) and (20): the allocation range of transferred discharge in a given month is calculated by multiplying the monthly demand percentage during the planning horizon by the minimum and maximum figures of the transferred water.

The proposed model is solved using the GA method. In the GA setting, the structure of decision variables as genes of a chromosome along the Karoon River is shown in Fig. 4. In this study, there are two decision variables in each month, which are the transfer flows from Koohrang III and Solegan Tunnels. The optimization period is 23 years (1981–2003); therefore, each chromosome has $23 \times 12 \times 2 = 552$ genes. After trial and error, the best parameters of the GA model, crossover and mutation probabilities are considered 0.8, 0.01, respectively, with 100 chromosomes in each generation.

**Results**

The results of the optimization model are presented in quantity and quality issues in following sections. The effects of the Solegan water transfer project in restoration of the Rafsanjan aquifer are evaluated. Finally, water transfer operating rules for real time operation are developed using the KNN model.
Water Quantity Assessments

The optimal monthly discharge is determined using the optimization model subject to the model constraints. Fig. 5 shows the variation of fitness value in different iterations of the GA model. As it can be seen, the fitness value has an increasing slope, up to 600 iterates, and after that the objective function levels off. It has some rapid jump until the 300th iterations and after that it converges toward a minimum of $57.4 million.

Fig. 6 shows the optimal monthly discharges of transferred water from the Koohrang III and Solegan Tunnels in 276 months (23 years). These figures show that in the last three years of optimization period, the water demands are not supplied completely due to hydrological drought in the case study area.

Fig. 7 shows the annual benefits and costs of the water transfer projects for different components of objective function and Table 2 shows percentage of these values during the planning horizon. The maximum benefit is related to agricultural production in the Rafsanjan plain (receiving Basin 1) which is due to the high value of crop products. The minimum benefit is related to the decrease in the pumping cost. The maximum costs are due to decreasing agricultural production in the Khuzestan plain (sending basin) and environmental costs resulted from changing water quality in the Karoon River. As shown in Table 2, the present value of the net benefit over 23 year time horizon is about 130 million dollars. Therefore, the cost per cubic meter of water is about $0.38.

In order to evaluate the effects of agricultural price and CPD coefficient on the net benefit, sensitivity analysis has been done. The variations of the objective function versus agricultural price and CPD variations are shown in Fig. 8. As shown in this figure, if the market price falls below 96% of the selected price in the sending and receiving basins, the transfer projects will not be economical. These projects are economically justified if the agricultural CPD coefficient (kg of production per cubic meter of water use) falls below 0.58. Currently the average production level (CPD) is 0.7 kg/m³ in Iran (0.6 is assumed for the basins in this paper) and the international norm is above 1 kg/m³. Therefore, the project seems to remain economically feasible if the rate goes up and market fluctuations will not affect its fate, significantly.


Table 2. Present Values of the Benefits and Costs and Their Percentage in Objective Function (Million Dollars): (a) Solegan; (b) Koohrang III; and (c) Karoon

<table>
<thead>
<tr>
<th>Agricultural benefit (a)</th>
<th>Water transfer benefit (b)</th>
<th>Agricultural cost (c)</th>
<th>Dredging cost (c)</th>
<th>Hydropower generation cost (c)</th>
<th>Pollution reduction cost (c)</th>
<th>Capital +OM costs (c)</th>
<th>Net benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,689.41</td>
<td>293.82</td>
<td>977.25</td>
<td>17.80</td>
<td>232.50</td>
<td>216.21</td>
<td>436.71</td>
<td>103</td>
</tr>
<tr>
<td>85.32%</td>
<td>14.68%</td>
<td>50.39%</td>
<td>0.92%</td>
<td>12.04%</td>
<td>13.35%</td>
<td>23.29%</td>
<td></td>
</tr>
</tbody>
</table>

Note: OM=operation and maintenance.

Evaluation of Water Quality Results

For assessing the effects of the transfer project on the water quality of the Karoon River, the monthly simulation model is used. This model analyzed TDS, DO, and BOD considering maximum withdrawal of transferred water from the river. The results show that water quality remains in an acceptable range (TDS < 1,200 mg/lit, BOD < 10 mg/lit) and the water transfer impacts on water quality variation are not significant. However the TDS variation could be affected by the future conditions of the river branches in upstream and the wastewater releases along the river. Therefore, the water treatment cost can be taken into account when the river water quality is critical. The comparison of water quality conditions both before and after the transfer projects implementation shows the concentration of TDS increases by 0.7 mg/lit per unit volume (1 m³) at the control point in Ahvaz.

Impact on Groundwater of Receiving Basin 1

Aquifer of the receiving Basin 1 is the source of water supply for different domestic, agricultural (97% of water demands) and industrial sectors. Due to over withdrawal of water from this aquifer, it has been classified as unauthorized aquifers for withdrawal and development. There are 1,381 wells (1,308-deep and 73-semideep) and 153 aqueducts in the region. The storage coefficient of aquifer is estimated as 0.05 and the Thiessen area of the aquifer is estimated as 4,107.91 km². The level of water subsidence is calculated using Eq. (21) as follows:

\[
\Delta h = \frac{\Delta V}{S \times A} \quad (21)
\]

where \(A=\text{Thiessen area; } \Delta h=\text{drawdown of groundwater level; } \Delta V=\text{change in aquifer volume; and } S=\text{storage coefficient.}

The results show the water table depletion will be negligible during the planning horizon (23 years) in comparison with about 11 m in the last 14 years. In the sending basin, the effect of water transfer on groundwater resources is negligible because in this region the surface water is used primarily and the aquifers are shallow and not suitable for development.

Developing Water Transfer Operating Rules

In order to develop the operating rules for water transfer, a KNN model is used. The KNN model is a nonparametric estimation of probability densities and regression functions through weighted local average of the dependent variables. For more information about KNN application see Karlsson and Yakowitz (1987), Galeati (1990), Kember and Flower (1993), Todini (2000), and Araghinejad et al. (2006).

This model gives the \(K\) most similar patterns of situation as compared to the result of the optimization model. To estimate transferred discharges for the current time step, generated patterns by the optimization model are used. The independent variables \((X_i)\) in the KNN model are the reservoir inflow in the previous month, the reservoir storage in the current month \((S_i)\), and the monthly demand \((D_i)\) and the dependent variable is the volume of transferred water discharges. The combination of independent variables is called “feature vector.” The distance of each feature vector at time \(t\) and time \(i\) is calculated based on the square root of difference between values of independent variables as follows:

\[
\text{Dis}_r = \sqrt{W_1 \times (I_r - I_i)^2 + W_2 \times (S_r - S_i)^2 + W_3 \times (D_r - D_i)^2}
\]

where \(\text{Dis}_r=\text{distance between current and observed data, and } W_j=\text{weight of independent variables optimized during the calibration period in KNN model.}

The best value of \(K\) and weights of different independent variables for two interbasin water transfer projects are shown in Table 3. The equations for estimating the volume of the water transfer are as follows:

\[
R_r = \sum_{i=1}^{K} \left( \frac{1}{\text{Dis}_i} \right) \ast R_i
\]

where \(R_r, R_i=\text{monthly estimated (r) and optimal values (i) of transferred water discharges. For the other basin (Koohrang III Tunnel), the KNN model also replicates the optimization results.}

Table 3. Best Values of \(K\) and Weights of Different Inputs in KNN Model

<table>
<thead>
<tr>
<th>Plan</th>
<th>(K)</th>
<th>(W_1)</th>
<th>(W_2)</th>
<th>(W_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solegan</td>
<td>8</td>
<td>0.1</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Koohrang III</td>
<td>7</td>
<td>0.3</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Summary and Conclusion

The impact of operation of two water transfer projects, Solegan to Rafsanjan (receiving Basin 1) and Koohe-Rud Dam from the Karoon River are investigated in this paper. The model is developed with an economic objective function considering different components of interbasin water transfer system and it is solved using GA. The water quality simulation for the sending basin using an ANN model is linked with the optimization model. In order to determine the operating rules, a KNN model is developed to be used in real time operation. The main benefit is related to the agriculture production in the Rafsanjan plain for a high value crop (pistachio). The maximum costs are for the loss of agricultural production in the Khuzestan plain and the environmental costs resulted when headwater quality in the Karoon River is altered. The results show that if the sending basin receives $0.38 per cubic meter of water transfer, it could affect the loss of agricultural income and environmental costs. The main challenge of this paper was to develop a methodology for water transfer project assessment. The results show that the water transfer projects could be economical for the case studies, but further investigation is needed to include a more comprehensive groundwater study as well as quantifying social impacts of water transfer projects.

References


