Dynamic programming model for hydraulics and water resources simulating and optimizing water transfer system (a case study in Iran)
Ramin Mansouri, Hassan Torabi Pudeh, Hojatt Allah Yonesi and Amir Hamzeh Haghiabi

ABSTRACT

Inter-basin water transfer projects have large tunnels and the cost of implementation is high. In order to cut costs, this system should be optimized. In inter-basin water transfer projects, hydraulics and water resources are equally important. For optimizing, both hydraulic and hydrologic modeling flow conditions must be considered together. In this study, four dams and three water transfer tunnels were used for transferring water from Yalan dam to Zayanderud dam (YPGZWT project) in Iran. Dynamic Programming (DP) and integrated solution of water resource and hydraulic models, developed by the authors, were used for optimizing the project. The objective of the study is the transferring of 95% of the water flow between both basins after supplying the agricultural consumption and environmental needs of their respective areas. The water level in the dam reservoirs and diameter of the tunnels were considered as the state variable and decision variable respectively in the DP model. The results showed that Yalan, Pashandegan and Gokan dams with a height of 135, 44 and 106 m, respectively, and Yalan–Pashandegan, Pashandegan–Gokan and Gokan-Zayanderud tunnel diameters, 2.812, 3.294 and 5.432 m, respectively, were the most economically optimal combination of water transferring in YPGZWT Project and the cost of this project is 350.70 million US dollars.

Key words | dynamic programming, optimization, simulation, water resources planning, water transfer efficiency

INTRODUCTION

Nowadays, water shortfalls in most countries has become a serious crisis. Therefore, the management of water resources is one of the most important actions to resolve challenges in the water crisis.

The provision of clean, fresh water is the major factor for the development of an area, city or a country's development. More than 65 countries, including Iran, are located in the world's dryland belt. This is about 41% of the world's landmass including the Sahara, the Middle East and Central Asia, which includes a population of over 2.3 billion people (Human Impact Report 2009).

The region's climates generate a wide spatial variety of hydrological regimes. As a result, the region presents a very uneven distribution of precipitation, water resources and water use. Therefore, the transfer of inter-basin water in the form of water projects for the collection, transmission and creation of appropriate quality for balanced development of human activity is necessary.
Inter-basin transfer or trans-basin diversion are (often hyphenated) terms used to describe man-made conveyance schemes which move water from one river basin to another where water is less available or it could be utilized better for human development. The purpose of such designed schemes can be to alleviate water shortages in the receiving basin, to generate electricity, or both.

White (1977) showed that the peak of the design and implementation of large projects for water in the developed countries was between 1960 and 1970. Therefore, 1970 was the turning point in the management of water resources in the world. Transfer of water from one basin to another was carried out firstly in the USA. The former Soviet Union and China also used this method to increase water basins.

Since the 20th century, many more similar projects have been completed in other countries, including Colorado – Big Thompson Project (Grigg 1996) in the USA, Tugela River to the Vaal River (Zaji Bunu 1999) in Nigeria, Sunyng River to Murray and Murumbyj Rivers in Australia (Ghasemi & White 2007), The Brazilian inter-basin Water Transfers (Andrade et al. 2011), inter-basin water transfer in India (Mahabaleshwara & Nagabhushan 2014), inter-basin water transfers at the US-Mexico border city of Nogales (Prichard & Scott 2014), Takus-Seigo – the largest hydraulic structure in Spain (Rey et al. 2015), etc.

In the water transfer system, exploiting reservoirs with hydraulic and water resources occurs at the same time, when both hydraulic and hydrologic modeling flow conditions are considered together. Due to scale of these projects and the associated costs, optimization in these projects is important. Therefore, models of planning and exploiting water transfer system are generally divided into three major parts: hydraulic simulation, hydrologic simulation and optimization.

In order to simulate the hydraulics of the transfer tunnels, hydraulic equations and methods are used. A water transfer tunnel can be analyzed by several common methods such as such as Hardy–Cross (Cross 1936), linear theory (Isaacs & Mills 1980), and Newton–Raphson (Stephenson 1984). Nowadays, commercial software such as EPANET (Rossman 2000) and optimized methods help researchers and designers with the simulation and optimization of hydraulic pressure problems. For example, an application of the genetic algorithm in the water distribution systems (Vairavamoorthy & Ali 2000, 2005), optimal design of water networks using a modified genetic algorithm (Kadu et al. 2008), differential evolution algorithm for optimal design of water distribution networks (Suribabu 2010), optimization of the water distribution networks with differential evolution (Mansouri et al. 2015).

In planning and exploiting water reservoirs model, simulation and optimization are used. First, Jacoby & Loucks (1972) combined the use of optimization and simulation models in river basin planning. Then, Loucks et al. (1981) showed that simulation models can be statistical or process oriented or both. WEAP (Water Evaluation and Planning) software (Stockholm Environment Institute ‘SEI’ 2015) is one software that is used for simulation of water resource issues.

Modelling and optimizing of water resources has attracted the interest of many researchers (e.g. Wu et al. 2009; Chau & Wu 2010; Chen et al. 2015; Gholami et al. 2015; Taormina & Chau 2015; Wang et al. 2015).

Optimization modeling in water resources management has largely been addressed in the literature. Early mathematical optimization dates back to the work of Masse (1946) for hydropower operations, and numerical optimization methods (Little 1955) for the application of stochastic dynamic programming of hydropower.

Yeh (1985) classified the models into four groups for designing and exploiting water reservoirs: Linear Programming (LP) Models, Dynamic Programming (DP) Models, Non-Linear Programming (NLP) Models, and Simulation Models.

Different optimization methods were used in the water transfer system. Tingsanchali & Boonyasirikul (2006) used the SDPR (Stochastic Dynamic Programming with Risk) procedure, which is a combination of Dynamic Programming (DP) and Stochastic Dynamic Programming (SDP) to determine the optimal operation policy of the proposed Kok-In-Nan Trans basin diversion system in Thailand. Wang et al. (2009) designed the Cooperative Water Allocation Model (CWAM) within a general mathematical programming framework for modeling equitable and efficient water allocation among competing users at the basin level and they applied this to a large-scale water allocation problem in the South Saskatchewan River Basin located in
southern Alberta, Canada. Sadegh et al. (2010) used a new methodology based on crisp shapely value games for optimal allocation of inter-basin water resources. Condon & Maxwell (2013) presented the development of a Water Allocation Module (WAM) for an integrated hydrologic model, ParFlow.

In the previous available studies in literature, the water transmission system was evaluated and optimized from the perspective of water allocation or the transfer volume for the inter-basin water transfer. In addition to hydrological and hydraulic transmission, which is a function of issues, the high cost of construction of the dam and tunnel is very important.

Torabi et al. (2016) presented the optimal designing of water conveyance from basin No. 1 to basin No. 2. In the study, water is transferred between these two dams by a tunnel structure. The purpose of the study is transferring 95% of water flow between two basins after supplying the agriculture consumption and environmental needs. Therefore, the mathematical program was developed first to solve the governing equations of water balance of the reservoir and hydraulic of the tunnel.

Torabi et al. (2016) optimized the cost of transferring water between two dams by using an innovative method. When the number of dams and water transfer tunnels increase, their method cannot be used to optimize the system because the number of unknown parameters increases with the increase in dams. Hence, the DP model was used to solve water transfer systems that contain a large number of dams and tunnels.

Therefore, in this study, the optimization and modeling of integrated hydraulic and water resources are studied. The YPGZWT project is a national project in Iran, which contains four dams (Yalan, Pashandegan, Gokan, and Zayanderud) and three tunnels (Yalan-Pashandegan (YP), Pashandegan-Gokan (PG), and Gokan-Zayanderud (GZ)). In this work, the YPGZWT project has been optimized by Dynamic Programming (DP). This optimization must be carried out when its constraints are considered and the water transfer system does not have any hydraulic problems.

In this work, three components were used simultaneously for optimizing; the first component is a water balance equation for estimating the water level in all dams, and the second component is pressure flow equation in pipe for determining all tunnels diameter and the third and final component is an optimization model (DP) for optimizing the cost of the YPGZWT project.

Optimal water resources modeling (DP), a hydraulic model (EPANET Software version 2.0.12), and water balance equations (a code developed by the authors) were used simultaneously, so that the lowest cost of inter-basin water transfer system is achieved when transferring 95% of water flow between two basins. The inter-basin water transfer cost is divided into two parts: (1) the cost of the dam (depending on the dam height) and (2) the water transfer tunnel (depending on the diameter of the tunnel). So, the aim of this paper is to find the optimal cost of these two parameters, while all the conditions are within the allowable range.

MATERIALS AND METHODS

Case study

In this study, the target area is located in the west of Iran at the longitude of 49° 42′ to 50° 13′ E and the latitude of 25° 32′ to 33° 00′ N, which is part of Isfahan watershed, Iran. In the project, four dams (Yalan Dam, Pashandegan Dam, Gokan Dam and Zayanderud Dam) and three water transfer tunnels (Yalan-Pashandegan, Pashandegan-Gokan and Gokan-Zayanderud) were used for transferring water from Yalan dam to Zayanderud dam (YPGZWT Project) (see Figure 1).

As can be seen in Figure 1, in addition to the first tunnel (YP tunnel) between the reservoirs in Yalan and Pashandegan, two lateral tunnels (Torzeh and Masir) and Sepesatan fountain exist and their water is collected in Pashandegan reservoir. Also, in addition to the main tunnel (PG tunnel) which exists between Pashandegan and Gokan reservoirs, seven rivers (Gokan, Kahangan, Patagan, Alkon, White Water, Yellow Water and Shirestan River) exist which feed into Gokan reservoir.

The tunnels are under hydrostatic pressure conditions and the elevation of the tunnel at the inlet and the outlet is equal to the dead storage of the upstream dam and the normal elevation of the downstream dam, respectively (see Figure 2).
Figure 2 shows the length of tunnels, the normal water level and dead elevation of water in all reservoirs. Tunnels are designed with two different slopes in the YPGZWT project.

All data, such as inflow to the reservoir, the volume elevation curve, precipitation and evaporation from the surface of the reservoir, for the dams were available for the period of 40 years (1970–2010) from the Regional Water Authority and Meteorological Organization, Iran.

In the YPGZWT project two different conditions of hydrological and hydraulic properties are considered. The hydrological condition depends on the height of the dam and dam reservoir, and the hydraulic condition depends...
on the hydraulics of the water transfer tunnel and its diameter and roughness.

The parameters of the transfer are simulated by a water balance equation (hydrological condition) and a pipe hydraulic equation (hydraulic condition) and then optimized by DP. So, YPGZWT project was divided into three parts, two parts are for simulation and one part is for optimization. These three parts were linked dynamically for the purpose of optimization and simulation of YPGZWT project.

**Water balance equation (hydrological condition)**

A model was developed in Visual Basic to simulate water resources. The results of the water balance model were also compared using WEAP Software. For the simulation of hydrological conditions, the general water balance equation is shown:

$$S_{t+1} = S_t + Q_{in} - Q_{Tunnel} - Q_{Agr} - Q_{Envi} - L_{Et} + P_t - S_{pt}$$  \(1\)

where \(S_{t+1}\) is the reservoir storage volume at the beginning of period \(t+1\) or at the end of period \(t\); \(S_t\) is the reservoir storage volume at the beginning of period \(t\); \(Q_{in}\) is the volume of inflow to reservoir in period \(t\); \(Q_{Tunnel}\) is the transferred volume by the transmission tunnel in the period \(t\); \(Q_{Agr}\) is the volume of water required for agriculture in period \(t\); and \(Q_{Envi}\) is the required volume of environmental needs that must be released from the dam to downstream in period \(t\); \(L_{Et}\) is the volume of evaporation and infiltration losses in period \(t\); \(S_{pt}\) is the overflow discharge (spillway) from the reservoir in period \(t\), and \(P_t\) is the volume of precipitation on the reservoir surface in period \(t\).

Changes in the inflow to the reservoir of dams during the simulation month cause variations in water level and will also change discharge tunnels accordingly. So, \(Q_{in}\) is very important and is derived from hydrological data. **Figure 3** shows average annual \(Q_{in}\) for all dams. It is noteworthy to mention that \(Q_{in}\) is used in the simulation is on a monthly basis.

Changes in the surface area and the volume of reservoir for every water surface level are required for the simulation and modeling of the basin to basin water transfer system. Therefore, the relation of volume, surface area and water level for all dams is derived from topography maps as shown in **Figure 4**.

To simulate and compute the amount of transferred water from the reservoir by the tunnel from Yalan dam to
Pashandegan dam, Pashandegan dam to Gokan dam and Gokan dam to Zayanderud dam, Equation (1) needs to be solved. In this equation, $S_t$, $Q_{in}$, $Q_{Agrit}$ and $Q_{Envit}$ are known parameters, and $LE_t$, $Q_{Tunnel}$, $Sp_t$ and $S_t+1$ are unknown parameters.

$LE_t$ is related to the evaporation losses, that is a function of water level of the reservoir at the beginning and end of period $t$ (beginning of period $t + 1$) and finally, it is directly related to the volume at the beginning and end of the month, that is specified in Figure 3 for each dam and so:

$$LE_t = f(S_t, S_{t+1})$$

(2)

This means that only the initial and final volume of the reservoir in period $t$ affects the evaporation losses. Since all dams are in the same climate regions, thus, the evaporation ($LE_t$) and precipitation ($P_t$) are assumed the same and equal. Figure 5 shows the monthly evaporation and precipitation rate.

The other unknown parameter in Equation (1) is the discharge of the tunnel which is shown by $Q_{Tunnel}$. Discharge of the tunnel ($Q_{Tunnel}$) is varied by any change in the water level of the reservoirs (upstream and downstream of the tunnel).

Therefore, the tunnel discharge depends on two characteristics: (1) hydrological characteristics such as the reservoir water level, and (2) hydraulic characteristics or physical characteristics of the tunnel such as the tunnel diameter and the wall roughness. On the other hand,
changes in reservoirs level are affected by reservoir water balance.

$S_{Pt}$ is another unknown parameter in Equation (1). This parameter depends on the volume of the reservoir and the difference between inflow and outflow. To calculate $S_{Pt}$ a model is presented with a series of assumptions.

**Pipe hydraulic equation (hydraulic condition)**

Calculation of the discharge flow of the main tunnel is not possible to do manually as the flow depends on the water level. Therefore, EPANET software was used to solve the hydraulic Equation (1) and $Q_{Tunnel}$.

EPANET is the software that is used for hydraulic calculation in pressure networks. The reason for using the software is its ability to link different codes and software.

With respect to the above conditions and restrictions in optimization and simulation of inter-basin water transfer system, none of the existing software on water resources is able to solve the above situation (hydrological condition, hydraulic condition and optimization). Therefore, to solve Equation (1), a DP model and DE algorithm were used and linked to EPANET software. The code for the DP model and DE algorithm was written in Visual Basic.

**METHODOLOGY**

Equation (1) has four unknown parameters which are $LE_t$, $Q_{Tunnel}$, $S_{Pt}$ and $S_{t+1}$. A number of assumptions are made to solve this equation. The initial assumption is that $S_{Pt} = 0$. $LE$ is a function of reservoir surface and is calculated from $S_t$. $Q_{Tunnel}$ is also calculated at the beginning of the period ($S_t$). Now there is an unknown parameter ($S_{t+1}$) in Equation (1). After specifying the $S_{t+1}$, three cases can be considered that are shown in Figure 6. It should be noted that the discharge tunnel is achieved from EPANET software.

**Case (1):** $S_{t+1} > S_{Normal}$, in this situation $S_{Pt}$ is not equal to zero, so $LE_t$ and $Q_{Tunnel}$ are calculated again at $S_t$ and at $S_{t+1} = S_{Normal}$ and the overflow of the dam ($S_{Pt}$) is determined.

**Case (2):** $S_{Minimum} < S_{t+1} < S_{Normal}$, in this case the same as Case 1, $LE_t$ and $Q_{Tunnel}$ are calculated at $S_t$ and $S_{t+1}$. The average values of $LE_t$ and $Q_{Tunnel}$ are inserted into Equation (1) and recalculated. This process continues until the new reservoir volume ($S'_{t+1}$) is obtained which is almost equal to $S_{t+1}$.

**Case (3):** $S_{Minimum} > S_{t+1}$, in this condition the tunnel discharge is equal to zero ($Q_{Tunnel} = 0$), so $LE_t$ and $Q_{Tunnel}$ are calculated at $S_t$ and $S_{t+1} = S_{Minimum}$.
These three cases ran for 480 months (40 years) and the results are used for optimization and simulation of the YPGZWT project.

**Dynamic programming**

DP is a recursive optimization procedure popularized by Belman (1957) which breaks down an optimization problem in N decision variables into a series of N independent single variable optimization. It is based upon what is known as the principle of optimality. The optimal set of decisions in a sequential decision process has the property that whatever the initial budget level, decision point, and decision are up to that point, the remaining decision constitutes an optimal sequence of decisions for the remaining problem. The principle of optimality is best explained through use of the example used previously.

DP can be solved in two ways: beginning at the right and moving from the right to the left, called the backward-moving (but forward-looking) algorithm. Alternatively, this can be beginning at the left and moving from the left to the right, called the forward-looking (but backward-looking) algorithm. Both methods will find the best path through the problems.
DP (forward-looking) model, which is used in this research, is capable of simultaneous modeling of the water balance equation and hydraulic analysis of water transfer tunnels for three reservoir systems of water resources. This model has the capability of performing hydraulic calculations and it can link to EPANET software for the hydraulic calculations.

Four dams and three tunnels for transfer of water to the Zayanderud reservoir are available in the YPGZWT project. Changing the diameter of the tunnel and the dam height affects the entire system. To solve the equations of the whole system by DP, the problem is divided into a number of stages. In this case, the water level in Yalan, Pashandegan, Gokan and Zayanderud reservoirs and the diameter of tunnels were considered as the state variable and the decision variable, respectively. As the water level in Zayanderud reservoir is specified, so the general display DP model for YPGZWT project is shown in Figure 7. Because of the uncertainty of the time series inflow to Zayanderud reservoir, use of the DP backward method for solving the problem is not possible. Therefore, the DP forward method is used.

According to Figure 7, the state variable (water levels or dam height) is separated into 3 m intervals. The normal level of Yalan dam is separated from 2,115 to 2,142, Pashandegan dam from 2,095 to 2,122, and Gokan dam from 2,077 to 2,104.

As already mentioned, water transfer efficiency is considered equal to 95%. Therefore, the decision variables (tunnels diameter) must be determined for 95% of water transfer efficiency from the upstream dam to the downstream dam.

To determine the tunnel diameter, balance equations need to be solved monthly for a 40-year period according to the flowchart shown in Figure 8.

As shown in the flowchart, to find the decision variable, the balance equation should be solved for the entire period and for the different tunnel diameters. This shows that the tunnel can achieve 95% transfer of the flow.

In the next step, after determining the tunnel diameter, the link cost is calculated for each link. The cost of each link includes the cost of construction of the tunnel and its upstream dam. Finally, after defining all the links cost according to the above method, the DP model is used for determining the lowest cost case.
On the other hand, two parameters are crucial in any optimization problem: (1) objective function; and (2) constraints; these parameters need to be specified.

Objective function and constraints

The purpose of this research is also to minimize the economic costs of the YPGZWT project, while all administrative and technical constraints are considered. The cost of the project includes the construction of Yalan, Pashandegan and Gokan dams and tunnels to convey water to the reservoir in downstream dams.

In this study, tunnel construction costs were calculated for different diameters by economic analysis, which are shown in Figure 9. Figure 10 also shows the cost breakdown of the dam which was calculated for the different heights.

There is a direct relation between the dam height and the regulatory volume of the dam reservoir (Figure 3), i.e. an increase in the dam height increases the volume of the dam reservoir. On the other hand the efficiency of water transfer in the tunnel is increased due to the increase of hydraulic balance in several months.

As can be seen in Figure 9, to optimize the cost of the system the lower tunnel diameter results in lower costs. However, the maximum water velocity of the tunnel should not be more than 3 m/s. In addition, due to the implementation problems, the tunnel diameter should not be less than 2.5 m.

Another limitation of the project is the water transfer efficiency, which is considered as 95%. This efficiency should be determined after numerous simulations of the system for a specific diameter of tunnel with different water heights in the reservoir. Based on the above-mentioned facts, the objective function and constraints could be written as follows:

Objective function:

\[
\text{Min}\left( \sum (L \times ULC(d_k) + Cost_{Dam}(d_k)) \right)
\]

(2)

Constraints:

\[
d_k > 2.5
\]

(3)

\[
\left( \frac{\sum_{j=1}^{40} \sum_{i=12}^{1} Q_{ij} - \sum_{j=1}^{40} \sum_{i=12}^{1} Sp_{ij}}{\sum_{j=1}^{40} \sum_{i=12}^{1} Q_{ij}} \right) \times 100 = 90
\]

(4)

\[
\left( \frac{\sum_{j=1}^{40} \sum_{i=12}^{1} R_{Agr}_{ij}}{\sum_{j=1}^{40} \sum_{i=12}^{1} D_{Agr}_{ij}} \right) \times 100 = 95
\]

(5)

\[
\left( \frac{\sum_{j=1}^{40} \sum_{i=12}^{12} R_{Envi}_{ij}}{\sum_{j=1}^{40} \sum_{i=12}^{12} D_{Envi}_{ij}} \right) \times 100 = 100
\]

(6)

\[
0 < V_i(d_k) < 3
\]

(7)

where \(i\) is the index of the number of months of simulation during a year, \(j\) is the index of the number of months of simulation, \(Q\) is the inflow discharge into the reservoir during the simulation in cubic million meter (MCM). \(Sp\) is the overflow discharge from the reservoir during simulation (MCM), \(d_k\) is the various diameters of tunnel, \(ULC(d_k)\) is the unit cost of the tunnel length with diameter of \(d_k\), \(Cost_{Dam}(d_k)\) is the dam’s cost in proportion to the tunnel's diameter, \(R_{Agr}\) is the mount of released water from the upstream dam for irrigation needs (MCM), \(D_{Agr}\) is the amount of required water.
in the downstream (MCM), $R_{\text{Envi}}$ is the amount of released water for environmental needs (MCM), $D_{\text{Envi}}$ is the least amount of river's environmental needs from the upstream dam (MCM), $V_i(d_k)$ is the velocity of water through the tunnel at the normal level of $i$ and in the tunnel with a diameter of $k$.

In this investigation, at first DP (forward-moving) and a DE algorithm were used for simulation and later the best diameter and dam height for optimization of water transfer system was determined. To solve the DP (forward-moving) and DE, an integrated simulation of hydraulics and water resources for the various combinations of the water elevation and the tunnel diameter was required.

**Simulation of overall system**

To determine the tunnel diameter (decision variable) between reservoirs at the specific normal level (state variable), a simulation technique was used. For this purpose, one of the links in Figure 7 was selected and the diameter determined by simulation. Therefore, the link between Yalan and Pashandegan dams with normal levels of 2,115 and 2,095 m respectively is selected.

Firstly, the dead level (lowest water level) of Yalan dam needs to be determined. Since the tunnel is designed with two slopes, the dead level is equal to the highest point as compared to the base of YP tunnel. The location of the
point where the slope of the tunnel is changed to 14,466 m away from Pashandegan dam. On the other hand, the tunnel slope is equal to 0.0001, and the YP tunnel base level at the maximum point is equal to the Yalan dead level. So, it can be written that:

Yalan dead level = YP tunnel base level at the highest point = Pashandegan normal level + (slope tunnel × distance between the point where the slope of the tunnel is changed and Pashandegan dam)

After computing, the Yalan dead level is 2,096.44 m, hence simulation was conducted based on information in this example and the results are shown in Figure 11. The Yalan dam inflow is known according to Figure 11(a).

By simultaneous solving of the hydraulic and water balance equations, all unknown parameters in Equation (1) are determined. Also the water transfer efficiency is calculated as follows:

\[
\text{Eff} = \left(1 - \frac{\sum_{i=1}^{516} S_{i}}{\sum_{i=1}^{516} Q_{i}}\right) \times 100
\]  \hspace{1cm} (14)

where \(Q\) is the inflow discharge into the reservoir during the simulation in cubic million meter (MCM). \(S_{i}\) is the overflow discharge from the reservoir during simulation (MCM).

If this system is run for different diameters then the water transfer efficiency is calculated for each diameter and the results are shown in Figure 12. Form this figure, the YP tunnel diameter that transfers 95% of the water from Yalan to Pashandegan can be obtained.

**RESULTS AND DISCUSSION**

Based on the methodologies described above, the diameters of tunnels are decision variables that are calculated by using the balance equation and integrated hydraulic tunnel model (see the flowchart in Figure 8) for 40 years. Table 1 shows the YP tunnel diameter with 95% water transfer rate and its total cost (tunnel cost and Yalan dam cost), according to the different water levels in Yalan and Pashandegan dams which are specified in Figure 7.

Figure 11 | Schematic view of long-term water transfer simulating between Yalan and Pashandegan dam.
As shown in Table 1, there are 94 links from Yalan to Pashandegan dam. Belman (1957) found that in the DP (forward-looking) model, from all links that reach to the next node in the next stage, there is only one link that is the optimal solution. Hence, in Table 1, the optimal solution is marked between the water levels (Yalan and Pashandegan normal water elevation).

### Table 1  |  Tunnel diameter and total cost in 95% water transfer efficiency from Yalan dam to Pashandegan dam

<table>
<thead>
<tr>
<th>Normal water elevation in Pashandegan dam (m)</th>
<th>2,095</th>
<th>2,098</th>
<th>2,101</th>
<th>2,104</th>
<th>2,107</th>
<th>2,110</th>
<th>2,113</th>
<th>2,116</th>
<th>2,119</th>
<th>2,122</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal water elevation in Yalan dam (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,115 Diameter (m)</td>
<td>2.812</td>
<td>2.986</td>
<td>3.234</td>
<td>3.544</td>
<td>3.928</td>
<td>4.459</td>
<td>5.503</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Cost ($ \times 10^6$)</td>
<td>86.95</td>
<td>90.45</td>
<td>95.72</td>
<td>102.67</td>
<td>111.75</td>
<td>124.80</td>
<td>150.46</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,118 Diameter (m)</td>
<td>2.677</td>
<td>2.803</td>
<td>2.986</td>
<td>3.234</td>
<td>3.544</td>
<td>3.928</td>
<td>4.459</td>
<td>5.503</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Cost ($ \times 10^6$)</td>
<td>87.06</td>
<td>89.37</td>
<td>93.04</td>
<td>98.33</td>
<td>105.28</td>
<td>114.36</td>
<td>127.41</td>
<td>153.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,121 Diameter (m)</td>
<td>2.564</td>
<td>2.668</td>
<td>2.791</td>
<td>2.97</td>
<td>3.21</td>
<td>3.519</td>
<td>3.899</td>
<td>4.431</td>
<td>5.487</td>
<td>None</td>
</tr>
<tr>
<td>Cost ($ \times 10^6$)</td>
<td>87.71</td>
<td>89.70</td>
<td>91.99</td>
<td>95.58</td>
<td>100.59</td>
<td>107.59</td>
<td>116.58</td>
<td>129.47</td>
<td>155.52</td>
<td></td>
</tr>
<tr>
<td>2,124 Diameter (m)</td>
<td>2.459</td>
<td>2.540</td>
<td>2.638</td>
<td>2.765</td>
<td>2.926</td>
<td>3.150</td>
<td>3.453</td>
<td>3.836</td>
<td>4.385</td>
<td>5.487</td>
</tr>
<tr>
<td>Cost ($ \times 10^6$)</td>
<td>89.16</td>
<td>90.60</td>
<td>92.38</td>
<td>94.81</td>
<td>98.06</td>
<td>102.67</td>
<td>109.32</td>
<td>118.21</td>
<td>131.55</td>
<td>158.81</td>
</tr>
<tr>
<td>2,127 Diameter (m)</td>
<td>2.372</td>
<td>2.443</td>
<td>2.515</td>
<td>2.608</td>
<td>2.734</td>
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<td>3.097</td>
<td>3.396</td>
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<td>93.49</td>
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<td>112.23</td>
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<td>2,130 Diameter (m)</td>
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<td>95.09</td>
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<td>2.414</td>
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<td>2.693</td>
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<td>2.407</td>
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<td>2.846</td>
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<td>98.68</td>
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<td>2.284</td>
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<td>2.402</td>
<td>2.483</td>
<td>2.576</td>
<td>2.689</td>
<td>2.846</td>
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<td>101.89</td>
<td>102.63</td>
<td>103.60</td>
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<td>2.391</td>
<td>2.473</td>
<td>2.564</td>
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<td>108.05</td>
<td>109.61</td>
<td>111.19</td>
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**Figure 12** | Diameter tunnel versus water transfer efficiency for Yalan and Pashandegan normal.
As can be seen in Table 1, for a constant level in Yalan dam, by increasing the normal level in Pashandegan dam, the tunnel diameter between them increases. Since the normal level of Pashandegan dam is increasing, the hydraulic level between the two sides of the tunnel in different months is decreasing and causes the flow velocity in the tunnel to decrease.

For example, according to Table 1, for 95% transfer water efficiency, when the normal level in Yalan and Pashandegan dams is 2,115 and 2,104 m, respectively, the tunnel diameter should be 3.544 m. If the Pashandegan normal level is 2,107 m, the tunnel diameter should be 3.928 m, as seen in Table 1. The ability to water transfer from the 2,115 m Yalan normal level to the Pashandegan dam with 2,116, 2,119 and 2,122 m normal levels are impossible and in Table 1 is shown as ‘None’.

The results revealed that when the normal water level in Yalan and Pashandegan dams are 2,115 and 2,095 m, respectively, the project has the minimum cost. This issue is highlighted in Table 1.

After determining the optimal links from the Yalan to Pashandegan dams, inflows to the Pashandegan dam should be determined (by using the flowchart in Figure 6). So, in this case there will be 10 times series of inflow to Pashandegan dam with the equal inflow volume but different time distributions.

When the inflows were revealed, the next step of the DP model was started. In this step the PG tunnel diameter with a 95% water transfer rate and Pashandegan dam are optimized. So, as in the previous step the Pashandegan–Gokan tunnel diameter is a decision variable. Hence the PG tunnel diameter with 95% water transfer rate and its associated total cost (tunnel cost and Pashandegan dam cost) are shown in Table 2.

According to Table 2, 90 links exist between different normal water levels that are able to transfer 95% of water flow. Among these links, there are 10 optimal links which

### Table 2 | Tunnel diameter in 95% water transfer efficiency from Pashandegan dam to Gokan dam and total cost

<table>
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<tr>
<th>Water normal elevation in Pashandegan dam (m)</th>
<th>2,095</th>
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<th>2,103</th>
<th>2,107</th>
<th>2,110</th>
<th>2,113</th>
<th>2,116</th>
<th>2,119</th>
<th>2,122</th>
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<td>Water normal elevation in Gokan dam (m)</td>
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<td>2,104</td>
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<td>131.28</td>
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<td>146.81</td>
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<td>None</td>
<td>None</td>
<td>None</td>
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<td>3.158</td>
<td>3.292</td>
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<td>3.750</td>
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<td>None</td>
<td>None</td>
<td>None</td>
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<td>3.745</td>
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<td>145.70</td>
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<td>141.01</td>
<td>145.25</td>
<td>146.47</td>
<td>151.64</td>
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<td>148.58</td>
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<td>Diameter (m)</td>
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<td>2.866</td>
<td>2.939</td>
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<td>152.28</td>
<td>152.81</td>
<td>153.44</td>
<td>154.12</td>
<td>154.90</td>
<td>155.76</td>
<td>156.89</td>
<td>158.08</td>
<td>159.47</td>
</tr>
</tbody>
</table>
are marked. Then, inflows to Gokan dam for these optimal links are calculated.

The next step is to optimize the GZ tunnel diameter with 95% water transfer rate and the Gokan dam cost. In this case, because the Zayanderud normal water level is kept constant, therefore all links which are located between Gokan and Zayandrud dam are equal to 10 while only one of them is optimal (Table 3). Also from Table 3, the total costs related to any of the links from Yalan dam to Zayanderud dam can be seen. Considering Table 3, the optimized case can be found among all the available cases in Figure 7.

Figure 13 shows the optimum link among the existing links for YPGZWT project. In the optimum link, the total cost is US$350.7 million and consists of tunnels and the dam costs. The dams’ elevation and tunnels diameter for the optimum case is shown in Figure 13 and Table 4.

As can be seen, by reducing the level varied between the hydraulic reservoirs, the tunnel diameter is increased and by increasing the level varied between the hydraulic reservoirs, the tunnel diameter is reduced.

When the normal level of downstream dam is constant in a 95% water transfer efficiency, by increasing the normal level of upstream dam the diameter of the tunnel reduces and vice versa, see Tables 1–3.

CONCLUSIONS

This paper has focused on the application of the DP model for optimal design of the YPGZWT project. In the water transfer system, exploiting reservoirs with hydraulic and water resources occurs at the same time, when both hydraulic and hydrologic modeling flow conditions are considered together. Due to scale of these projects and the associated costs, optimization in these projects is important. The integrated solution of water resource balance and hydraulic equations were used to optimize water transfer in this project. Four dams and three water transfer tunnels were used for transferring water from Yalan dam to Zayanderud dam in the YPGZWT Project in Iran. As the available software in the market are not capable of integrating the modeling of hydraulic and water resources, hence, DP the model integrated solution of water resource balance and hydraulic model which was developed in this work is used to optimize the YPGZWT Project for 95% of transfer efficiency of water. Changing the diameter of the tunnel and the upstream and downstream dam heights affects the entire system.

In this work, the water level in Yalan, Pashandegan, Gokan and Zayanderud reservoirs and the diameter of tunnels were considered as the state variables and decision variables, respectively. State variable (water levels or dams height) is separated in 3 m intervals. The normal level of Yalan dam is discreted from 2,115 to 2,142 m, Pashandegan dam from 2,095 to 2,122 m, and Gokan dam from 2,077 to 2,104 m. On the other hand, water transfer efficiency is considered equal to 95%. So the decision variables (tunnels diameter) must be determined for 95% of water transfer efficiency from the upstream dam to the downstream dam. In this investigation, to determine the diameter tunnels, a balance equation must be solved monthly for a 40-year period. Since the water flow through the tunnel is under

<table>
<thead>
<tr>
<th>95% water transfer efficiency</th>
<th>Water normal elevation in Zayanderud dam (m)</th>
<th>Diameter (m)</th>
<th>Cost ($ × 10^6)</th>
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<tr>
<td></td>
<td></td>
<td>2,104</td>
<td>Diameter (m)</td>
</tr>
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</table>
pressure, increasing the dam height will cause the tunnel diameter to decrease for constant water conveyance efficiency.

The results showed that Yalan, Pashandegan and Gokan dams with a height of 135, 44 and 106 m, respectively, and Yalan–Pashandegan, Pashandegan–Gokan and Gokan–Zayanderud tunnel diameters of 2.812, 3.294 and 5.432 m, respectively, were the most economically optimal combination for water transferring in the YPGZWT Project where the cost of this project is 350.70 million US dollars. All results would provide 95% of agricultural consumption and environmental needs and it concedes all constraints of the target function. Furthermore, by increasing the roughness of the tunnel, the reservoir volume and tunnel diameter is increased.

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