# An integrated optimisation model of reservoir and irrigation system applying uniform deficit irrigation


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**Abstract:** An optimisation model was derived for deficit irrigation to study four scenarios of water price-irrigation system combinations. The nonlinear objective function was optimised within a three-dimensional decision domain including: deficit irrigation ratios of wheat and tomato; and cropping area ratio of wheat to tomato. Four scenarios were employed regarding two pricing configurations including subsidised and non-subsided water prices and two irrigation systems as well. The results of the integrated optimisation model showed that the optimised deficit irrigation ratios are not changed by altering water price in each irrigation system. However, deficit irrigation of wheat crop increases net-benefit of farmers in subsidised price while, the net-benefit of farmers is not increased under the deficit irrigation of wheat crop with non-subsided water price and tomato crop in both price configurations. Sensitivity analysis of the model showed that annual tomato cropping costs and price are the most sensitive parameters in the optimisation.

**Keywords:** deficit irrigation; off-stream reservoir; nonlinear optimisation model; non-subsidised price; irrigation system.

**Reference** to this paper should be made as follows: Banihabib, M.E., Zahraei, A. and Eslamian, S. (2015) 'An integrated optimisation model of reservoir and irrigation system applying uniform deficit irrigation', *Int. J. Hydrology Science and Technology*, Vol. 5, No. 4, pp.372–385.

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## 1 Introduction

Research on performance and optimisation of irrigation systems are focused by many researches (Eslamian et al., 2012, 2013; Morankar, 2013). Cropping area can be increased by saving water from the application of deficit irrigation method for a constant available water resources. The study of economic efficiency of deficit irrigation using subsided and non-subsided water (considering reservoir operation costs and irrigation network) can be used for assessment of water demand management in countries located in arid and semi-arid climates like Iran.

Although deficit irrigation techniques and its special case (dry farming) have been widely employed by the farmers in Iran and other countries with arid climates for a long time, the first research was published in 1920 and many studies have been reported since 1980 (Fardad and Golkar, 2002; Kheirabi et al., 1997; Shaabani et al., 2008). English and Nuss (1982) showed that applying deficit irrigation and using sprinkler irrigation system, cropping area was increased and farmers' net-benefit enhanced by 42%. Here, net-benefit is the income minus the cost of project. Ghahraman and Sepaskhah (1997) indicated using deficit irrigation of potato, cotton and tamarisk in case study of Esfarayen, cropping areas were increased by 25%, 10% and 25%, respectively (Tavakoli, 1996). Various equations are available for determination of crop yield reduction by using deficit irrigation method (Doorenbos and Kassam, 1979; Zhang et al., 2002). Jensen (1968) presented a model for determining crop yield reduction by water stress in different growing stages. Stewart and Hagan (1973) proposed an equation for deficit irrigation and then it was improved by Doorenbos and Kassam (1979) for different growing stages (uniform deficit irrigation). This equation was applied for defining crop yield reduction using deficit irrigation technique in Cropwat software by Food and Agriculture Organization (FAO) in 2000 (Smith et al., 2002). Gorantiwar and Smout (2003) showed that under deficit irrigation condition, cropping area increased by 30%–45% and gross production grew by 20%–40%. Sahoo et al. (2001) used linear programming and analytical hierarchy process in a study and the results revealed that net-benefit increased by 40% applying optimised deficit irrigation.

Most of the investigations on deficit irrigation are based on field study of the deficit irrigation of single crop and a few researches are focused on optimisation of deficit irrigation of several crops in a cropping pattern for different irrigation systems (Arabzadeh and Tavakoli, 2006; Fardad and Golkar, 2002). A study on deficit irrigation of dominant cropping pattern is reported using FAO crop yield function without optimisation of cultivated area ratio and the effect of reservoir management in optimisation (Shaabani et al., 2008).

In addition, reviewing the above-mentioned papers shows that in some cases deficit irrigation ratio was optimised without considering reservoir management. Instead of considering reservoir optimisation for determination of water allocation, usually the water allocation is assumed to be constant in the researches. Furthermore, non-subsided water price should also be determined by taking construction and operation costs of reservoir and irrigation system into account to examine the effect of price change on optimised deficit irrigation and the net-benefit of farmers as well. In comparing the economic effects of deficit irrigation between surface and pressurised irrigation (sprinkle and drop irrigation) systems it would be crucially needed considering irrigation network and the reservoir as an integrated system. Thus, the main aim of this paper is to develop an integrated optimisation model of irrigation and reservoir system to find out optimal cropping pattern and deficit irrigation ratios under the four scenarios of water price-irrigation system combinations.

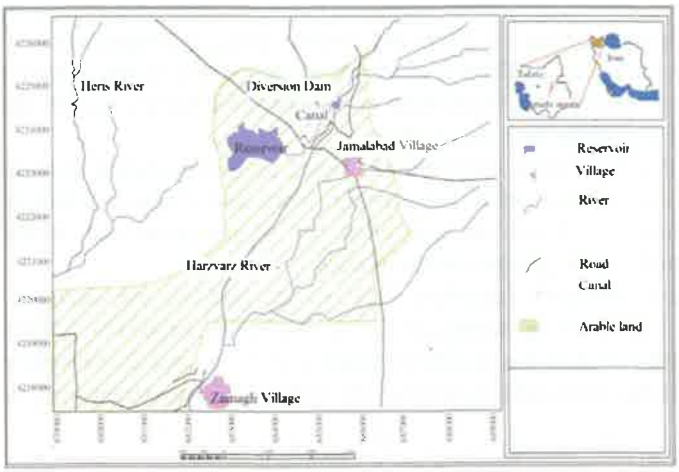
## 2 Materials and methods

### 2.1 Case study data

Case study of this research is located in Heris Township, Eastern Azerbaijan province, northwest of Iran. Harzvarz off-stream reservoir and its irrigation system are the case study of this research. Figure 1 shows the location of the case study. Harzvarz off-stream reservoir is designed on Harzvar River, which is one of Talkherood headspring in Lake Urmia Basin. Average annual temperature is 7.1°C and average annual rainfall is 400 mm in the study area. The climate of the study area is semi-arid and the main water resources of the reservoir is provided by construction of diversion dam on Harzvar River and transferring water by transmission canal to the reservoir. The average annual withdrawal volume was 4.52 million cubic metres (MCM) which is 21% of Harzvar River water resources in April, May and June. Averagely, 2.46 MCM of run off from upstream basin of the dam is another water resource for the reservoir. There are 3,000 hectares of arable land in the downstream of the reservoir. Although the existing cropping pattern of the region includes wheat, potato, tomato and fruit trees, the main crops are wheat and tomato. In addition, crop yield reduction coefficients are only provided for wheat and tomato by the field studies to use in the optimisation model (Farahmand et al., 2006;

Fardad and Golkar, 2002). While winter wheat is resistant to deficit irrigation, tomato is sensitive to deficit irrigation. Winter wheat growth season is from November to the middle of July whereas tomato growth season duration is from the middle of May to the middle of September in the region. Yield response factors of winter wheat and tomato are needed for formulation of the optimisation model. Yield response factor of winter wheat is determined using collected field data by the local office of ministry of agriculture (Fardad and Golkar, 2002). Yield response factor of tomato is determined by field study in similar climate and soil condition in Karaj (Farahmand et al., 2006).Yield response factors of winter wheat and tomato are 1.34 and 1.43 respectively. Since winter wheat and tomato are dominant cropping of the region and there is no data on other products' yield response factors, only wheat and tomato are considered in the optimisation model.

**Figure 1** Location of the case study (see online version for colours)




## 2.2 *Optimisation model*

Objective function of the optimisation model was derived based on maximising net-benefit of reservoir and farming project as follows.

$$MAX: NB = y_w p_w \omega A_T + y_t p_t (1-\omega) A_T - m\left[(C_{aw} + C_{sw} + C_{Nw}) + (C_{at} + C_{st} + C_{Nt})\right] - C_R \quad (1)$$

where

$$\omega = A_W / A_T \quad (2)$$

$$y_w = y_{\max w}\left\lfloor 1 - K_{yw}\left(1 - \left(ET_w / ET_{\max w}\right)\right)\right\rfloor \quad (3)$$

$$y_t = y_{\max t}\left\lfloor 1 - K_{yt}\left(1 - \left(ET_t / ET_{\max t}\right)\right)\right\rfloor \quad (4)$$

$$ET_t = \left[\left((1-\alpha_t) d_{nt} + P_e\right) / f_t\right] \quad (5)$$

$$ET_w = \left[\left((1-\alpha_w)d_{nw} + P_e\right)/f_w\right] \tag{6}$$

The factors of above equations are as follows: NB is net-benefit; $y_w$ and $y_t$, are wheat and tomato actual crop yield respectively; $K_{yw}$ and $K_{yt}$ are wheat and tomato crop response coefficient to deficit irrigation respectively ; $p_w$ and $p_t$, are wheat and tomato unit price respectively; $A_T$ is total cultivated area; $A_w$ is wheat cultivated area; $\omega$ is wheat cultivated area ratio; $C_{aw}$ and $C_{at}$, are annual costs of wheat and tomato cropping respectively; $C_{sw}$ and $C_{st}$, are annual costs of pressurised irrigation system of wheat and tomato cropping respectively; $C_{Nw}$ and $C_{Nt}$, are annual costs of surface irrigation system of wheat and tomato cropping respectively; $C_R$ is construction and operation costs of the reservoir; $ET_w$ and $ET_t$, are actual evapotranspiration due to the deficit irrigation of wheat and tomato respectively; $ET_{\max w}$ and $ET_{\max t}$, are the potential evapotranspiration of wheat and tomato respectively; $d_{nw}$ and $d_{nt}$, are net crop water requirement of wheat and tomato respectively; $\alpha_w$ and $\alpha_t$, are deficit irrigation ratios of wheat and tomato respectively; $f_w$ and $f_t$, are irrigation cycles of wheat and tomato cropping, respectively; $P_e$ is effective rainfall; $m$ is conversion coefficient of annual average value to the present value of costs depending upon interest rate. Depending on the type of irrigation system, parameters $C_{Nw}$, $C_{Nt}$ or $C_{sw}$ and $C_{st}$ can be zero or non-zero.

Wheat and tomato price estimation is based on governmental guaranteed purchase price and average market price, respectively. Dam and irrigation network construction costs are determined based on unit price list of irrigation and drainage works of management and planning organisation of Iran.

In objective function, [equation (1)], $\omega$, $\alpha_w$ and $\alpha_t$ are decision variables of optimisation. By replacing equations (2) to (8) in the objective function, it will be clarified that the function is a nonlinear function of $\omega$, $\alpha_w$ and $\alpha_t$. Therefore, it cannot be optimised by linear optimisation models. The optimisation constraints are as:

$$\sum_{i=1}^{12} O_i \geq R_d \left[\frac{(1-\alpha_w)d_{mw}\cdot\omega\cdot A_T}{R_{aw}} + \frac{(1-\alpha_t)d_{nt}(1-\omega)A_T}{R_{at}}\right] \tag{7}$$

or

$$A_T \leq \left(\left[\left(\sum_{i=1}^{12} O_i\right)\cdot R_{aw}\cdot R_{at}\right] \Big/ \left[\left((1-\alpha_w)d_{nw}\cdot\omega\cdot R_{at} + (1-\alpha_t)d_{nt}(1-\omega)\cdot R_{aw}\right)\times R_d\right]\right) \tag{8}$$

and;

$$\frac{S_{i+1}-S_i}{\Delta t} = I_i - O_i - O_{si} - E_i \tag{9}$$

$$S_i \geq S_{\min} \tag{10}$$

$$S_i \leq S_{\max} \tag{11}$$

$$\frac{S_{i+1}-S_i}{\Delta t} \leq SR_{\max} \tag{12}$$

$$A_T \leq A_{\max} \tag{13}$$

$$\alpha_w \leq \alpha_{w\max}, \alpha_t \leq \alpha_{t\max} \quad (14)$$

$$O_{si}, I_i, O_i, \alpha_w, \alpha_t, \omega \quad E_i \geq 0 \quad (15)$$

In the above equations: $R_d$ is water supply ratio; $R_{\alpha w}$ and $R_{\alpha t}$, are irrigation efficiency of wheat and tomato products respectively; $O_i$ is monthly volume of water release from reservoir; $I_i$ is monthly volume of water inflow into reservoir; $O_{si}$ is monthly volume of reservoir spillway outflow; $E_i$ is monthly volume of evaporation from reservoir surface; $S_i$ is monthly volume of reservoir storage; $S_{\min}$ is minimum volume of reservoir storage; $S_{\max}$ is maximum volume of reservoir storage; $SR_{\max}$ is the maximum monthly reservoir release to avoid rapid drawdown phenomenon; $A_{\max}$ is the maximum arable area; $\alpha_{w\max}$ is the maximum deficit irrigation ratio of wheat; $\alpha_{t\max}$ is the maximum deficit irrigation ratio of tomato.

Since the objective function was a nonlinear function of decision variables of wheat cropping area ratio ($\omega$), wheat deficit irrigation ratio ($\alpha_w$) and tomato deficit irrigation ratio ($\alpha_t$), discrete points were defined in three-dimensional decision space and the maximum of the objective function was determined by investigating in the discrete points of decision. Discrete points of decision space were determined as follows:

Wheat cropping area ratio ($\omega$) was evaluated for 0%, 20%, 40%, 50%, 60%, 80% and 100%. At least 60% of the cropping area in the region was dedicated to the strategic products (wheat) based on the current agriculture policy, however farming can be non-profitable in the case of removing water subside. Therefore, imposing the type of cropping to the farmer was not considered in optimisation and zero value is tested for wheat cropping area. Since wheat crop is less sensitive to deficit irrigation than tomato crop, wheat deficit irrigation ratio ($\alpha_w$) was examined from 0% to 80% with 10% steps and tomato deficit irrigation ratio ($\alpha_t$) was examined from 0% to 50% with 10% steps. Thus, considering the above mentioned steps, a three-dimensional grid system is provided where each point is indicated by three decision variables including $\alpha_w$, $\alpha_t$ and $\omega$. There were 378 discrete decision points. AGWAT was used to calculate the actual evapotranspiration of wheat and tomato. AGWAT Software is a similar software to Cropwat and is an Iranian software to calculate the actual evapotranspiration of crops. Crop response coefficients were applied based on field data (Farshi et al., 1997). Then equation (8) was satisfied as constraint of optimisation and $A_T$ is determined. The obtained $A_T$ was used in maximising the objective function. In the optimisation model, the following assumptions were used:

- First, deficit irrigation ratios were uniform during wheat and tomato growth.
- Second, there was no limitation in terms of investment and human resources and only total cropping area of the products were restricted to maximum of 3,000 hectares.
- Third, in total cropping area, merely single type of irrigation system was used in each scenario.
- Fourth, the costs are estimated based on 2007 prices. Wheat price was guaranteed by government and tomato price was considered as average price of the market.

### 2.3 Optimisation scenario

Objective function is examined using 378 discrete decision points for the following 4 scenarios and optimised points are determined by maximising the objective function.

- First scenario: surface irrigation system with subsidised water supply;
- Second scenario: surface irrigation system with non-subsided price water supply;
- Third scenario: pressurised irrigation system with subsidised water supply;
- Fourth scenario: pressurised irrigation system with non-subsided price water supply.

Subsidised price is water delivery price according to the prices in 2007 and non-subsided water price is obtained based on the annual average cost of dam and irrigation network construction and operation.

## 3 Discussion and results

Optimised values of decisions variables were determined for the scenarios of this study applying the developed optimisation model. Comparisons of results of the scenarios are discussed and presented in the following sections.

### 3.1 Evaluation of the effects of applying non-subsided water price

Table 1 shows the results of optimised wheat and tomato deficit irrigation ratios for different cropping pattern using surface irrigation system. Also, optimisation results for subsidised price and non-subsided water price are illustrated in Table 1. Table 2 represents the similar results for the pressurised irrigation system. Tables 1 and 2 indicate while optimised deficit irrigation ratio of tomato is zero, wheat optimised deficit irrigation percentage is 80% for all cropping patterns and both irrigation systems. It is due to high sensitivity of tomato crop efficiency and relative resistance of wheat crop to deficit irrigation. Optimised cropping pattern is 20% wheat cropping and 80% tomato cropping intensity for surface irrigation systems ($\omega$ = 0.2) and 100% tomato cropping pattern for surface irrigation systems ($\omega$ = 1). It means that the changing of surface irrigation system to pressurised one (by increasing irrigation efficiency) impacts on optimised cropping pattern and increased tomato cropping area. The net-benefit ratios in the case of using subsidised water to the case of non-subsided water price are shown in Tables 1 and 2. It shows that removing subside decreased net-benefit for all cropping patterns. Thus, the net-benefit of farmers at least becomes double in case of applying subsidised water price to non-subsided water price in surface irrigation system. This ratio is 1.14 for pressurised irrigation system. Thus, eliminating subsidies in surface and pressurised irrigation system decrease farmers' net-benefit to 85% and 14%, respectively.

**Table 1** The maximum net-benefit for different cropping pattern and surface irrigation system (comparison of scenarios 1 and 3)

| *Cropping pattern* | *Subsided water supply* | | | *Non-subsided water supply* | | | *Net-benefit ratio* | *Controlled water by the dam (MCM)* |
|---|---|---|---|---|---|---|---|---|
| | *Deficit irrigation of wheat (%)* | *Deficit irrigation of tomato (%)* | *Net benefit (million Rials)* | *Deficit irrigation of wheat (%)* | *Deficit irrigation of tomato (%)* | *Net-benefit (million Rials)* | | |
| Wheat 100% | 0 | - | 37,935 | 80 | - | –11,975 | -3.17 | 4.43 |
| Wheat 80%<br>Tomato 20% | 80 | 0 | 51,335 | 80 | 0 | 7,752 | 6.62 | 4.28 |
| Wheat 60%<br>Tomato 40% | 80 | 0 | 56,700 | 80 | 0 | 20,670 | 2.74 | 4.24 |
| Wheat 50%<br>Tomato 50% | 80 | 0 | 56,688 | 80 | 0 | 23,311 | 2.43 | 4.11 |
| Wheat 40%<br>Tomato 60% | 80 | 0 | 57,735 | 80 | 0 | 26,082 | 2.21 | 4.09 |
| *Wheat 20%*<br>*Tomato 80%* | *80* | *0* | *58,180* | *80* | *0* | *29,136* | *2* | *3.99* |
| Tomato 100% | - | 0 | 55,577 | - | 0 | 28,599 | 1.94 | 3.70 |

**Table 2** The maximum net-benefit for different cropping pattern and pressurised irrigation system (comparison of scenarios 2 and 4)

| *Cropping pattern* | *Subsided water supply* | | | *Non-subsided water supply* | | | | *Controlled water by the dam (MCM)* |
|---|---|---|---|---|---|---|---|---|
| | *Deficit irrigation of wheat (%)* | *Deficit irrigation of tomato (%)* | *Net benefit (million Rials)* | *Deficit irrigation of wheat (%)* | *Deficit irrigation of tomato (%)* | *Net-benefit (million Rials)* | *Net-benefit ratio* | |
| Wheat 100% | 0 | - | 13,201 | 0 | - | –6,787 | –1.9 | 4.29 |
| Wheat 80%<br>Tomato 20% | 80 | 0 | 37,642 | 80 | 0 | 18,086 | 2.08 | 4.23 |
| Wheat 60%<br>Tomato 40% | 80 | 0 | 96,599 | 80 | 0 | 77,245 | 1.25 | 4.20 |
| Wheat 50%<br>Tomato 50% | 80 | 0 | 114,299 | 80 | 0 | 94,999 | 1.20 | 4.14 |
| Wheat 40%<br>Tomato 60% | 80 | 0 | 126,293 | 80 | 0 | 107,021 | 1.18 | 4.04 |
| *Wheat 20%*<br>*Tomato 80%* | *80* | *0* | *144,186* | *80* | *0* | *124,963* | *1.15* | *3.93* |
| Tomato 100% | - | 0 | 152,382 | - | 0 | 133,164 | 1.14 | 3.75 |

Figure 2 shows net-benefit of wheat cropping for different deficit irrigation ratios and non-subsided water supply price. Regarding to Figure 2, removing subsidies on water caused farmers loss net-benefit and using deficit irrigation made the condition worse. Farmers' loss in non-subsidised water price condition was for both surface and pressurised irrigation system. In case of pressurised irrigation system, net-benefit loss rate due to the cost of the system was more severe than surface irrigation system case.

**Figure 2** Net-benefit of wheat cropping for different deficit irrigation ratios and non-subsided water supplying price (comparison of scenarios 2 and 4)

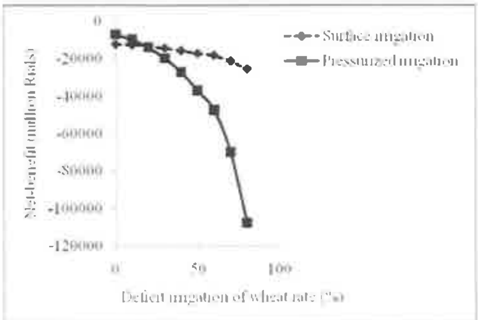



Figure 3 shows the ratio of wheat net-benefit in the case of applying deficit irrigation to the net-benefit with employing full irrigation for different deficit irrigation ratios and subsided water-supplying price. In case of using pressurised irrigation system, applying deficit irrigation decreased farmers' net-benefit. Nonetheless, in case of using surface irrigation system, applying deficit irrigation improved farmers' net-benefit. As in optimised deficit irrigation ratio (80%), net-benefit of wheat cropping for subsidised water price was increased by 2.27 times of full irrigation due increasing cropping area. Comparing the Figures 2 and 3 reveals that in both subsidised and non-subsidised water, applying deficit irrigation in case of pressurised irrigation system made considerable net-benefit reduction for wheat cropping. However, applying deficit irrigation in surface irrigation system increased net-benefit in the case of using subsidised water and it caused net-benefit reduction of wheat cropping in non-subsidised water scenario.

**Figure 3** Ratio of deficit irrigation net-benefit to full irrigation of wheat cropping by using subsided water (comparison of scenarios 1 and 3) (see online version for colours)

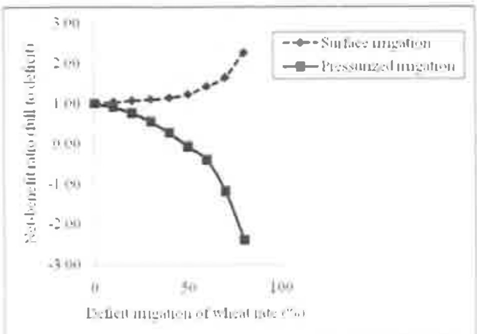
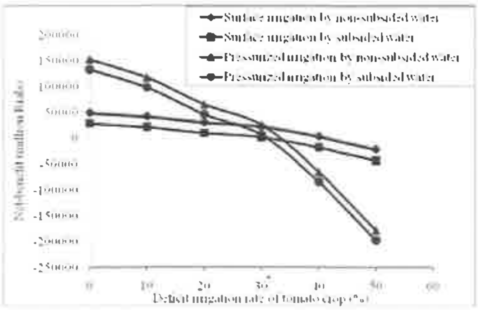


Figure 4 shows the variation of net-benefit by deficit irrigation ratio for the scenarios. It indicated that applying deficit irrigation to tomato cropping decreased farmers' net-benefit for the entire scenarios. Reduction of net-benefit had higher rate for pressurised irrigation system due to the smaller increase of cropping area by using saved water in this system. This is also due to the fact that water consumption in pressurised irrigation system was low and limited application of deficit irrigation is possible.

**Figure 4** Net-benefit of tomato cropping for the four scenarios



## *3.2 Evaluation of the effect of irrigation system modification*

Net-benefit of optimised cropping pattern of wheat and tomato and optimised deficit irrigation ratio for both of applying subsidised and non-subsidised water status are respectively presented in Tables 3 and 4. Table 3 shows that optimised cropping pattern was consisted of 20% wheat and 80% tomato and optimised deficit irrigation ratios of the products was 80% and 0%, respectively in the application of subsidised water by surface irrigation system scenario. However, in the application of subsidised water by pressurised irrigation system scenario, optimised cropping pattern was consisted of 100% tomato with full irrigation. Under the conditions that surface irrigation system is replaced by pressurised irrigation system for the application of subsidised water, optimised cropping pattern was changed to 100% tomato cropping and farmers with full irrigation. In this condition, net-benefit became 4.6 times more than of farmers' net-benefit in surface irrigation system. The reason for increase of net-benefit is the extension of cropping area due to using extra water released by application of deficit irrigation and improving irrigation system. Comparison of Tables 3 and 4 shows that optimised deficit irrigation ratios and cropping pattern do not change in the case of non-subsidised water. However, net-benefit was increased by upgrading surface irrigation system to pressurised irrigation system. The reason for increasing the net-benefit is reduction of water supply cost and increasing cropping area of tomato due to using saved water by using pressurised irrigation system.

**Table 3** Net-benefit for surface and pressurised irrigation system in case of using subsided water (comparison of scenarios 1 and 3)

| | *Surface irrigation system* | | | *Pressurized irrigation system* | | | | |
|---|---|---|---|---|---|---|---|---|
| *Cropping pattern* | *Deficit irrigation of wheat (%)* | *Deficit irrigation of tomato (%)* | *Net-benefit (million Rials)* | *Cropping pattern* | *Deficit irrigation of wheat (%)* | *Deficit irrigation of tomato (%)* | *Net-benefit (million Rials)* | *Net-benefit ratio* |
| Tomato 80% Wheat 20% | 80 | 0 | 58,180 | Tomato 80% | 80 | 0 | 152,382 | 2.6 |

**Table 4** Net-benefit for surface and pressurised irrigation system in case of using non-subsided water (comparison of scenarios 2 and 4)

| | *Surface irrigation system* | | | *Pressurized irrigation system* | | | | |
|---|---|---|---|---|---|---|---|---|
| *Cropping pattern* | *Deficit irrigation of wheat (%)* | *Deficit irrigation of tomato (%)* | *Net-benefit (million Rials)* | *Cropping pattern* | *Deficit irrigation of wheat (%)* | *Deficit irrigation of tomato (%)* | *Net-benefit (million Rials)* | *Net-benefit ratio* |
| Tomato 80% Wheat 20% | 80 | 0 | 29,136 | Tomato 80% | 80 | 0 | 133,164 | 4.6 |

## *3.3 Sensitivity analysis of the optimisation model*

Sensitivity analysis of objective function was carried out to deal with existing uncertainties of the effective influential factors in the optimisation. Wheat crop response coefficients, products price, construction and operation costs of dam, irrigation, and farming were the parameters that was used in sensitivity analysis. Tables 5 and 6 show the effect of the variation of parameters on net-benefit. Tables 5 and 6 indicated that annual costs of Tomato cropping cost and tomato cost were the most sensitive parameters on net-benefit and optimisation results changed by the variation of these two parameters more than the other parameters.

**Table 5** Sensitivity analysis of the optimisation parameters on net-benefit using surface irrigation system

| *Parameter* | *Tomato price* | *Wheat price* | *Wheat response coefficient* | *Construction and operation cost of dam* | *Wheat cropping cost* | *Tomato cropping cost* | *Construction cost of irrigation* | *Operation cost of irrigation* |
|---|---|---|---|---|---|---|---|---|
| Variation of net-benefit (%)/variation of parameter (%) | 4.39 | 0.14 | –0.08 | –0.69 | –0.08 | –2.42 | –0.28 | –0.06 |

**Table 6** Sensitivity analysis of the optimisation parameters on net-benefit using pressurised irrigation system

| *Parameter* | *Tomato price* | *Wheat price* | *Wheat response coefficient* | *Construction and operation cost of dam* | *Wheat cropping cost* | *Tomato cropping cost* | *Construction cost of irrigation* | *Operation cost of irrigation* |
|---|---|---|---|---|---|---|---|---|
| Variation of net-benefit (%)/variation of parameter (%) | 3.92 | 0.13 | –0.07 | –0.16 | –0.07 | –2.33 | –0.39 | –0.09 |

## 4 Conclusions

In this research, an integrated optimisation model of uniform deficit irrigation and reservoir management is presented to evaluate water price and irrigation system changes. Non-subsided water price was determined by considering construction and operation cost of dam and irrigation network. Changing the farmers' net-benefit by alteration of surface irrigation system to pressurised one was examined by the optimisation model. The model was applied for Harzvarz off-stream reservoir located in the north east of Tabriz City in Eastern Azerbaijan Province, Iran. The optimisation model combined two plants; a crop resistant to deficit irrigation (wheat) and a crop sensitive to deficit irrigation (tomato) were used in optimisation of cropping pattern. Different cropping area ratios were examined for different cropping pattern of the products. Considering the nonlinearity of objective function, optimised values of cropping area ratios and deficit irrigation ratios of the products are investigated in discrete point of decision domain. Following results are obtained using the suggested model:

- Since applying deficit irrigation for wheat crop decreases farmers' net-benefit for both surface and pressurised irrigation system, in the case of removing agricultural water subsidises, cropping of only wheat is not economically justifiable.
- Deficit irrigation of wheat cropping enhanced farmers' net-benefit in configuration of surface irrigation and subsidised water supply. Applying optimised deficit irrigation on wheat crop as 80%, net-benefit was 2.27 times of full irrigation by surface irrigation system. However, deficit irrigation of wheat crop by subsidised water diminished farmers' net-benefit in both surface and pressurised irrigation systems.
- Sensitivity analysis of the optimisation parameters showed that the optimisation results were sensitive to the price of tomato and annual costs of its cropping more than other parameters.
- By upgrading surface irrigation system to pressurised one, farmers' net-benefit increased 4.6 times by applying subsidised water and 2.6 times by applying non-subsidised water for optimised cropping pattern and deficit irrigation. This was due to increasing tomato cropping area by using saved water of irrigation system improvement.

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