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Water Resources Management of Hirmand River Basin for Agricultural Productions Using Stochastic Dynamic Programming

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ABSTRACT

In this study, the water content that is allocated for agricultural productions was analyzed using stochastic dynamic programming. The technical coefficients used in the study referred to the agricultural years, 2013-2014. They were obtained through the use of simple random sampling of 250 farmers in the region for crops like wheat, barley, melon, watermelon, and ruby grapes under the scenarios of drought and normal and water that is required in the most sensitive growth stages. Production function and profit function were obtained from the yield-water-product function of crops using Eviews software. Expected net profit of the system and optimal allocation of water were also calculated based on the GAMS economic analysis software. Results of the model indicates a reduction in wheat, barley, melon and watermelon production area under cultivation while at the same time an increase in ruby grapes cultivation areas under optimal conditions. The results showed that the cultivation of the ruby grape was the best product with the highest expected profit in normal and drought conditions. In general, when the expected value of net profit is positive, managers would act optimistically and they would promise the optimal level of water allocated to the farmers.

1. Introduction

Water conflicts appear when there are insufficient and less available water resources than water demands claimed by different agents (Oftadeh *et al*.,2016). From three perspectives, water plays a key role in sustainable development. First, it is consumed as a final product, second, water is an important input element in many businesses and third, it has a key role in biological organisms on Earth (Divakar, 2014). Sustainable socio-economic development in countries with low water is limited to the availability of water and its reduced quality (Ghaffour *et al*., 2013). System dynamics simulations in water resources management argue with stakeholder involvement provides an appropriate methodology to address these issues effectively (Winz *et al*., 2009). In terms of water resource management, low water would provide high risk for different sectors of development programs (Salimfard and Khodakaram, 2013). Also Dynamic water generational dematerialization indicator can be helpful with addressing regional and national water deficit problems and designing sustainable water management strategies (Ziolkowska, 2016).

The average of annual evaporation in Iran is estimated at about 70-71% of annual rainfall. In this regard, just Africa and Australia, with 70% and 80% evaporation under undesirable rainfall conditions, respectively, are lower than Iran(Mihankhah, 2012). Hirmand basin is located in the province of Sistan and Baluchistan. In all climate categories Sistan region had a hot and dry climate. Based on different calculation methods its average annual temperature is 21 C, its annual rainfall about 61.4 mm, its relative humidity close to 38% and its potential evapotranspiration is 4196 mm (Ebrahimzade and Lashkaripoor, 2012). Among the total cultivated lands of the country an area of 12 million hectares is located in Sistan and Baluchistan which 52.4% of that is located in the Sistan region (Mohamadghasemi, 2008, Tohidloo and Kashani, 1999).

Having considered finding from critically looking at past researches and the present necessity as discussed, the current study is focused on the formulation and application of two optimization scenarios named drought and normal to estimate water resources management model of the Hirmand river basin for agricultural productions using stochastic dynamic programming under the conditions of uncertainty. The formulated models were applied for aiding the optimization analyses for decisions making for crop area and water allocation.

2. Materials and methods

The yield-water-product function was used to estimate crop production function. Under each irrigation condition. Crops had their unique water-product functions estimated

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using regression methods (Tu *et al.*, 2011). This function expressed the relationship between the actual yield and the effective irrigation, so the second-degree polynomial function for estimating the crop- water function recommended by (Divakar, 2014) is as follows:

$$\mathrm{Y_a}/\mathrm{Y_m} = \mathrm{f(w)} = \mathrm{a_0} + \mathrm{a_1 w} + \mathrm{a_2 w^2} \qquad (1)$$

Where $\mathrm{Y_a}$ is the actual crop yield (tons/ha), $\mathrm{Y_m}$ is the maximum potential yield (t/ha), $\mathrm{W} = \mathrm{WA}/\mathrm{ET_m}$ is the ratio of total available water to the maximum potential seasonal evaporation in the crop, i.e. the ratio of actual evapotranspiration to the potential evapotranspiration.

Total water available for the crops was obtained through effective rainfall, irrigation and soil moisture (Mahan *et al.*, 2002), Hence:

$$\mathrm{WA_{j,cp}} = \mathrm{SM_{j,cp}} + \mathrm{EP_{j,cp}} + \mathrm{EI_{j,cp}} \qquad (2)$$

Where $\mathrm{WA_{j,cp}}$ is the total available water for plants during the growing season, $\mathrm{SM_{j,cp}}$is soil moisture in the root zone at the beginning of the growing season, $\mathrm{EI_{j,cp}}$is effective rainfall and $\mathrm{EI_{j,cp}}$is efficient water used for the crop. Depending on time and irrigation technology, actual evapotranspiration is the sum of actual soil moisture, effective precipitation, and effective watering during the growing season (Mahan *et al.*, 1997). In the studied region, the rate of effective rainfall for wheat, barley, melon, watermelon and ruby grapes was zero. Since there was no information available on soil moisture in the region, soil moisture was excluded from the calculations and it was assumed that it was hidden in the effective irrigation (Ghafarimoghadam, 2012).

Therefore, the actual evapotranspiration included effective irrigation during the growing season. Effective irrigation and potential evapotranspiration were also determined using monthly weather data for 26 years with Netwat-Cropwat Software and the Penman-Monteith method, respectively. In this method based on the types of available data, potential evapotranspiration was calculated daily and monthly. Of course, in the present study, the monthly evapotranspiration was applied. For calculating the amount of actual evapotranspiration the following formula was used (Zeng *et al.*, 2014):

$$\mathrm{ETa} = \mathrm{K_c} \times \mathrm{ETo} \qquad (3)$$

Where ETa is the actual evapotranspiration, *kc* is the plant factor varying in different crops, and ETo is the potential evapotranspiration.

Based on the water- crop yield, the total profit yield of irrigation water is expressed as follows (Dorfman , 2012):

$$\beta_{\mathrm{j}}^{\sim} = \sum \mathrm{PCP_{j,cp}} \,.\, \mathrm{Ya_{j,cp}}.\mathrm{Af_{j,cp}} - \sum \mathrm{Vc_{j,cp}}.\mathrm{Af_{j,cp}} \qquad (4)$$

Where $\mathrm{PCP_{j,cp}}$ is the crop price, $cc_{j,cp}$ is the cultivation cost, and $\mathrm{Vc_{j,cp}}$ is the variable costs of crop production. The target function can be written as:

$$\begin{aligned} &\max \beta_{\mathrm{j}}^{\sim} \\ &\mathrm{st:} \sum_{\mathrm{cp}} \mathrm{Af_{j,cp}} \leq \mathrm{A_j} \\ &\mathrm{Af^{i}_{j,cp}} \leq \mathrm{A_{j,cp}} \leq \mathrm{Af^{u}_{j,cp}} \\ &\sum_{\mathrm{cp}} \mathrm{EL_{j,cp}} \,, \mathrm{Af_{j,cp}} \leq \mathrm{Q} \end{aligned} \qquad (5)$$

Where $\mathrm{A_j}$is the total area under cultivation (ha) in the jth area, and $\mathrm{Af^{u}_{j,cp}}$ and $\mathrm{Af^{i}_{j,cp}}$ are respectively the maximum and minimum levels of cultivated areas (ha),$\mathrm{EI_{j,cp}}$ is the rate of effective irrigation required during the growing season (m^3 / ha) and *Q* is the total amount of effective irrigation available in the j^{th} region.

Following slight changes the shadow price which includes any variation in the target function, will be placed on the right side of resource limitations. It will be considered as an indicator for the ultimate value of water. In the form of an algebraic expression the shadow price is expressed as follows:(Mahan *et al.* , 2012)

$$\mathrm{MVW_j} = \Delta\pi_{\mathrm{j}}/\Delta\mathrm{Q_j} \qquad (6)$$

Where $\mathrm{MVW_j}$ is the final value of water ($/$m^3$) in the j th region $\Delta\pi_{\mathrm{j}}$, are changes in income (IRR) caused by slight variation of Q in the j^{th} region, and$\Delta\mathrm{Q_j}$ includes changes in the total amount of effective irrigation in the j^{th} region. In their research on economic allocation of water resources in Sistan region, (Shahraki and Mohamadghasemi, 2014), used the dynamic optimization models, analyzed its effect on sustainable agricultural development of the area and chose two farming patterns for okra and cucurbit studied the effects of cultivating ruby grapes on the economy of the Sistan farmers (Mohamadghasemi, 2008). Also analyzed the cost-benefit performance of agricultural crops (wheat, barley and triticale) in Sistan and Baluchistan. These crops included wheat, barley, melon, watermelon and ruby grapes which were planted under drought, wet, normal, and water requiring scenarios at the most critical growth stages. It is worth to note that, the most sensitive stage of water for horticultural and gardening crops was at the time when they enter the reproductive stage (flowering) (Ghasemi *et al.*, 2012).

Since the system manager always faces issues regarding water allocation between competing agricultural consumers (including various scenarios) and due to the fact that water supply tends be random in the future, the demand for water will also be estimated based on the needs of different scenarios and a logical period will be considered for all data (Zeng *et al.*, 2014).

In cases where the agricultural sector is informed that it has little water available, it will change its activities so that it would need less water. When there is uncertainty, the manager is supposed to create a plan in which, despite allocation of water efficiency, the system benefits increase, and in turn, the system risk reduces (Homauonifar, 2011). Hence, the random variable of water supply with P_{tk} (probability scenario *k* in time period *t*) was used to design a set of scenarios with branching structure. This model can be formulated as follows (Homauonifar, 2011)

$$
\begin{aligned}
&\max f = \sum_{i=1}^{I}\sum_{t=1}^{T} NB_{it}W_{it} - \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{r} p_{it}\ C_{it}\ D_{ik}\\
&s.t\\
&q_i \geq \sum_{i=1}^{m}(W_{it} - D_{itk}) \quad \forall i, j\\
&W_{itmax} \geq W_{it} \geq D_{it} \forall i, t, k
\end{aligned}
\tag{7}
$$

Where F is the net system profit of the planning horizon, NB_{it} is the net income of i th crop per allocated water unit, W_{it} water promised for the product i, C_{it} is the farmer's losses per unit of water promised, but not delivered in period t, D_{itk} is water scarcity for the crop *i* under scenario *k* in period *t* (in other words, some of W_{it} was not delivered at q^{th}), q^{th} is random variable of water supply in period *t*, W_{itmax} is the amount of water allocated for *i*th consumer at time *t*, P_{tk} is frequency probability of scenario *k* in period *t*, k are total number of scenarios and *t* is the most sensitive growth stage, *i* is the type of crop (i = 1 wheat, i = 2 barley, i =3 melon, i = 4 watermelon, and i = 5, ruby grape).

Model 7 expresses uncertainty in the amount of water supplied by the probability level of P_{tk}, but it considers the parameters of W_{it}, NB_{it}, C_{it} in their definite form. In the real world, however, these parameters may not be definite.

To solve this problem, the parameters of this model were considered periodically. The result of the model was as follows (Kessler & Van, 2011):

$$
\begin{aligned}
&\max f^{\pm} =\\
&\textstyle\sum_{i=1}^{m}\sum_{t=1}^{T} NB_{it}^{\pm}\, {W^{\pm}}_{it} - \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{r} P_{tk}^{\pm}\, C_{tk}^{\pm}\, D_{itk}^{\pm})\\
&s.t q_{th} \geq \textstyle\sum_{i=1}^{m}({W_{it}}^{\pm} - {D_{itk}}^{\pm}) \quad \forall i, j\\
&W_{imax}^{\pm} \geq W_{it}^{\pm} \geq D_{it}^{\pm} \forall i, t, k
\end{aligned}
\tag{8}
$$

Where $f^{\pm}$ is the net profit of the system in the planning horizon, $NB_{it}^{\pm}$ is the farmer's profit resulted from cultivation of the i th crop in period *t* per unit of water allocation, and ${W^{\pm}}_{it_0}$ is the water promised to the farmer for cultivation at time t, $C_{tk}^{\pm}h$ is the farmer's loss resulting from planting the crop per unit of water allocation promised but not delivered in period t, D_{itk} is water scarcity for the *i*th crop under the scenario *k* in period *t* (in other words, some of ${W^{\pm}}_{it}$ which was not delivered in time q^{th}), q^{th} is a random variable of water supply in period *t*, $W_{imax}^{\pm}$ is the maximum amount of water allocated for consumer *i* at time *t*, P_{tk} is the frequency probability of scenario *k* in period *t*.

Since $W_{it}^{\pm}$ is considered as a periodic parameter, equation 8 cannot be solved directly, so it needs to be oversimplified. To solve this problem y_{it} is defined as a decision variable (Lynch *et al*, 2011):

$$
\begin{aligned}
&W_{it}^{\pm} = W_{it}^{-} + \Delta W_{it} y_{it}\\
&\Delta W_{it} = W_{it}^{+} - W_{it}^{-}\\
&y_{it} \in [0,1]
\end{aligned}
\tag{9}
$$

In this equation, y_{it} is a decision variable used to define the optimal range $W_{it}^{\pm}$. , when y_{mt} reaches its highest level, $y_{it} = 1$. If the required water is delivered to the sectors, the system profit will reach its peak level. In case of losses, the reverse is true, too. When $y_{it} = 0$ and the promised rate of water is delivered, the system profit will decrease dramatically, but if the promised water is supplied, it would have the least amount of loss for the system. Substituting model 9 for model 8, the following model is obtained (Mahan *et al*, 1997):

$$
\begin{aligned}
&\max f^{\pm} = \sum_{i=1}^{m}\sum_{t=1}^{T} NB_{it}^{\pm}(W_{it}^{-} + \Delta W_{it} y_{it}) -\\
&\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{r} PC_{tk}^{-} {D_{itk}}^{-}) s.t q_{th}^{+}\\
&\geq \sum_{i=1}^{m}(W_{it}^{-} + \Delta W_{it} y_{itop} - {D_{itk}}^{-})\\
&\forall \ \ h, k = 1,2 \ldots k\ , t = 1,2, \ldots T\\
&W_{imax}^{+} \geq W_{it}^{-} + \Delta W_{it} y_{it} \geq D_{it}^{-} > 0 \qquad \forall i, t, k\\
&0 \leq y_{it} \leq 1
\end{aligned}
\tag{10}
$$

When the $W_{it}^{\pm}$ interval is defined as the optimum case, model 10 is divided into two sub-models. After solving these two sub- models, the maximum and minimum rates of total system profit can be obtained. To obtain the highest profits of the whole system (f^{+}) in model 11, the upper limit of interest (NB^{+}) and the lower limit of losses (C^{-}) of the farmer were considered. Model 11 can be formulated as follows (Mahan *et al*, 2002):

$$
\begin{aligned}
&\max f^{+} =\\
&\textstyle\sum_{i=1}^{m}\sum_{t=1}^{T} NB_{it}^{+}\,(W_{it}^{-} + \Delta W_{it}\, y_{it}) - \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{r} P\, C_{tk}^{-}\, {D_{itk}}^{-})\\
&s.t q_{th}^{-} \geq \textstyle\sum_{i=1}^{m}(W_{it}^{-} + \Delta W_{it} y_{itop} - {D_{itk}}^{-})\\
&\forall h, k = 1,2 \ldots k\ \ , t = 1,2, \ldots T\\
&W_{imax}^{\mp} \geq W_{it}^{-} + \Delta W_{it} y_{it} \geq D_{it}^{-} > 0 \forall i, t, k\\
&0 \leq y_{it} \leq 1 \qquad\qquad \forall i, t\\
&{F_{opt}}^{+}, y_{itop}\, , {D_{itk}}^{\pm}
\end{aligned}
\tag{11}
$$

In the model (11), low farmer income (NB^{-}) and low loss of water consumption are indicated. Farmer (C^{+}) was used for obtaining the lowest income limit of the system (f^{-}).

Model (12) is formulated as follows (Mahan *et al.*, 2012):

$$\max f^{+} = \sum_{i=1}^{m}\sum_{t=1}^{T} NB_{it}^{+}\,(W_{it}^{-} + \Delta W_{it}\,y_{it}) - \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{r} P\,C_{tk}^{+}\,{D_{itk}}^{+})$$

s.t

$$q_{th}^{-} \geq \sum_{i=1}^{m}(W_{it}^{-} + \Delta W_{it} y_{itop} - {D_{itk}}^{+}) \qquad (12)$$

$$\forall h, k = 1,2 \ldots k \;, t = 1,2, \ldots T$$

$$W_{imax}^{\mp} \geq W_{it}^{-} + \Delta W_{it} y_{2t} \geq D_{it}^{+} > 0 \forall i, t, k$$

$${D_{itk}}^{\pm} \geq {D_{itkOP}}^{-} , \qquad t = 1,2, \ldots T$$

The value ${F_{opt}}^{-}, {D_{itk}}^{\pm}$is obtained from the model (12). Using the solutions of the models (11 and 12), the following equations are obtained (Mihankhah, 2012):

$${F_{opt}}^{\pm} = [{F_{opt}}^{-}, {F_{opt}}^{+}] \qquad (13)$$

$${D_{itkOP}}^{\pm} = [{D_{itkOP}}^{-} , {D_{itkOP}}^{+}]$$

As a result, the optimal water allocation for the planned period is calculated as follows:

$${A_{itkOP}}^{\pm} = {w_{itkOP}}^{\pm} - {D_{itkOP}}^{\pm} \forall i, t, k \qquad (14)$$

3. Results and Discussion

The rate of targ*et al*location of water for agricultural crops was calculated by the gross irrigation requirement. Likewise, its maximum and minimum rates were also considered in terms of the highest and lowest water use efficiency in the region. The variable of maximum allocation of water to different crops was calculated based on the most unfavorable efficiency of the irrigation area. Table 2 summarizes this information.

Table 1. Allocation of water needed for crops during the most critical growth stages during the planning horizons (m^3)

Planning horizon	Required water
(3780,3520)	Wheat
(2980,2920)	Barley
(13600,13721)	Melon
(15640,15980)	watermelon
(2211,2310)	Ruby grapes

Reference: Final Report of Agriculture and Natural Resources Research Center of Sistan

Allocation of water under the drought scenario for wheat, barley, melon, and watermelon are presented in table 3.

Table 2. The results of the model under drought scenario during the most sensitive time of irrigation

Expected value	Allocated water	Target water demand	Frequency of Occurrence	Crop
(-1.86,-3.75)	2018	3780	0.47	Wheat
(-1.84,-3.60)	1938	2980	0.47	Barley
(-1.88,-3.65)	7031	13721	0.47	Melon
(-1.89,-4.41)	7555	15980	0.47	Watermelon
(-1.82,-3.53)	1182	2310	0.47	Ruby grapes

Reference: Researcher's calculation

Table 3. The solution of the model under a normal scenario during the most sensitive time of irrigation

Expected value	Allocated water	Target water demand	Frequency of Occurrence	Crop
(3514,243)	1576	3610	0.39	Wheat
(2564,324)	1007	2960	0.39	Barley
(8249,831)	6640	13690	0.39	Melon
(8117,361)	7850	15420	0.39	Watermelon
(9119,491)	1102	2298	0.39	Ruby grapes

Reference: Researcher's calculations

The solution of the target function $f^{\pm}$ represented two final expected values of net profit in the irrigation models for wheat, barley, melon, and watermelon under drought scenarios and during the planning horizon which varies between the maximum and minimum levels. If $W^{\pm} = W^{-}$, the manager will be conservative and he will promise the provision of less water to the farmers. If the promised water to the farmer is not delivered, he will choose the loss incurred from a lower harvest. Since this happens just under drought conditions, it is wise for the manager to behave moderately. Moreover, the results of the optimal allocation of water in drought conditions showed that using ruby grapes would lead to the lowest expected value. Based on the information mentioned in tables 1 and 2 the optimal allocation of water under the normal scenario for wheat, barley, melon, and watermelon are presented in table 3.

Solving the target function $f^{\pm}$is within the final expected value of net profit of the crops and in accordance with the positive normal scenario. In cases where $W^{\pm} = W^{+}$, the manager needs to behave optimistically and to promise high provision levels of the required water. The results of the optimal allocation of water under normal conditions also showed that cultivation of ruby grapes could lead to the highest expected profit.

4. Conclusions

In conclusion, due the increasing world population, coupled with the decreasing amount of available good quality water and land resources, there is a prominent need to fully optimize currently available resources to ensure that the rising food requirements are effective and efficiency met. This optimal resources use can be realized by utilizing the optimization models. In this study, economic allocation of water allocated to agricultural sector was analyzed using randomly dynamic programming for two optimization scenarios, drought, and normal. Technical factors used in the study referenced the farming years 2013-2014. It was conducted through a simple random sampling of 250 farmers in the region for crops wheat, barley, melon, watermelon, and ruby grapes.

By inserting the amounts of water scarcity and water allocation in the target function, the profit earned from economic allocation of water was obtained. The results showed that the rates of final water allocation in drought conditions for wheat, barley, melon, watermelon and ruby grapes were 2018, 1938, 7555, 7031, 1182 m^3 and in normal conditions, they were 2025, 1942, 7046, 7559, and 1189 m^3, respectively.

Moreover, the results of the model indicates a reduction in wheat, barley, melon and watermelon production area while at the same time an increase in ruby grapes cultivation areas under optimal conditions The results also showed that ruby grapes were the best crop with the highest expected profit in normal and rainy conditions.

It has been suggested to choose crop type based on the irrigated conditions. Moreover, if the farmers have enough freedom to choose and use different variables, the model can provide practical solutions in terms of establishing the amount of profit in farmers' mental calculations. Since in t0his study, the expected profit was obtained in drought and normal scenarios under the most sensitive water requirement conditions, it is wise to consider several measures so that sustainable water could be provided to the farmers to grow crops on time and earn the minimum rate of household income. It would reduce the migration of Sistani villagers to cities and neighboring provinces. It is significant to note that if the east of the country becomes haunted, it will endanger the security of the area and the whole country.

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