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Incorporating economical issues and uncertainties of long-term inflow forecast for decision making on agricultural water allocation during droughts

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Abstract. Optimum water allocation for agricultural sector as the main water consumer in the beginning of operation period under drought condition is of great importance. However, one of the most important information under such a condition is the long-term inflow forecast that is associated with high uncertainty. This paper is aimed to present a methodology to incorporate this uncertainty as well as economical issues for water allocation. For this, various models, including optimization of agricultural water allocation under water scarcity, long-term flow forecast and quantification of the forecast uncertainties are developed and linked. The results show that the presented methodology is able to properly consider socio-economical issues and coordinates well with the operational requirements. The Zayandeh Rud dam and irrigation system is selected to explore the methodology of this research work.

Keywords. Agricultural water allocation – Uncertainty – Forecasting – Economical approach – Drought management – Zayandeh Rud basin.

Incorporer les questions économiques et les incertitudes quant aux prévisions d'apports à long terme dans la prise de décisions pour l'allocation de l'eau agricole lors des sécheresses

Résumé. *L'allocation optimale de l'eau au sein du secteur agricole en début de saison culturale est très importante en période de sécheresse. Une des informations les plus importantes dans de telles conditions est la prévision à long terme des apports, qui est caractérisée par une très grande incertitude. Cet article propose une méthodologie pour incorporer cette incertitude ainsi que les dimensions économiques au processus de décision d'allocation. Les résultats montrent que cette méthodologie incorpore ces dimensions de manière efficace et cohérente avec les besoins opérationnels. Le barrage du Zayandeh Rud et les systèmes d'irrigation associée ont été sélectionnés pour explorer et appliquer cette méthodologie.*

Mots-clés. *Allocation de l'eau agricole – Incertitude – Prévision hydrologique – Approches économiques – Gestion des sécheresses – Bassin du Zayandeh Rud.*

I – Introduction

Decision about optimum water allocation for agricultural sector as the main water consumer at the beginning of operation period under drought condition is of great importance. However, one of the most important information for such decisions is the long-term inflow forecast that is associated with high uncertainties. This paper is aimed to present a methodology to incorporate this uncertainty as well as economical issues for water allocation. This issue is rarely considered in the water resources references and the paper relays on some of the economical researches such as Willcocks (1994). To explore the methodology, Zayandeh Rud basin is selected as case study. The water system of the basin includes a dam with the capacity 1450 million cubic meters (MCM) and 8 irrigation networks with the total area of 205,127 hectares.

II – Methodology

The methodology of this research work can be divided to four modules. They are: (i) optimization of water allocation by incorporating constrains and factors such as physical characteristics of the dam and agricultural networks, crop type, growth stages and sensitivity to water stress; (ii) development of a fuzzy model to estimate the dam's water release for agricultural sector and optimization of midyear storage; (iii) annual inflow forecast and quantifying its uncertainty, using a fuzzy model; and (iv) decision making for water allocation with respect to economical issues and uncertainties.

1. Water allocation optimization model

This module indicates amount of water release from the dam and allocate water optimally among the irrigation networks during 22 hydrological years (1983-84 to 2004-05). It includes four optimization models. More details about it are available in Moghaddasi *et al.* (2009). Sub-model 1 determines irrigation scheduling for the dominant crops during the growing season based on a 10-day irrigation period (the usual irrigation period in the Zayandeh Rud basin). The objective function maximizes the ratio of actual yield per unit area (kg/ha) to maximum yield per unit of area (kg/ha):

$$MAX : \frac{Y_{ac}}{Y_{\max c}} = 1 - \sum_{g=1}^{n} Ky_g \left(1 - \frac{ETa_{c,g}}{ET\max_{c,g}}\right) \quad (1)$$

where $ETa_{c,g}$ and $ETmax_{c,g}$ are actual and maximum evapotranspiration for growth stage g of crop c in stage g (mm/10 days) respectively, Ky_g is water sensitivity coefficient for growth stage g and n is total number of growth stages. Maximum yield per unit of area of wheat, barley, sugar beet and alfalfa is 9000, 7000, 70,000, 50,000 and 2833 kg/ha correspondingly.

Sub-model 2 maximizes the total benefit of the crops within each irrigation unit:

$$MAX\left\{\sum_{k=1}^{K} F_k(V_k) A_k Y_{\max k} P_k\right\} \quad (2)$$

where k is total number of crops, A_k is planted area for each crop (ha), $Y_{max\,k}$ is maximum yield (kg/ha), P_k is marketing price per kilogram (unit) and $F_k(V_k)$ is functional relation between maximum relative yield and allocated irrigation water. Sub-model 3 distributes water among the networks to maximize total benefits. The objective function is:

$$MAX\left\{\sum_{n=1}^{N} P_n(V_n)\right\} \quad (3)$$

$P_n(V_n)$ is functional relation between maximum benefit and allocated water for each unit and N is total number of irrigation systems. Finally, Sub-model 4 indicates optimal water release from the dam to get maximum benefits from the total irrigation systems:

$$MAX\left\{\sum_{y=1}^{Y} P_y(Q)\right\} \quad (4)$$

where $P_y(Q)$ is functional relation between maximum benefit and allocated water for each year (y).

2. Fuzzy modelling of water allocation for agricultural sector

Due to complexity of the previous model and extrapolate the previous results for future conditions, a fuzzy model developed to simulate the dam's water release based on the outputs of the optimization model. For this, it was run for 22 years of historical data to prepare required information to setup the fuzzy model. Evaluating different inputs, the river annual inflow and reservoir storage were selected and the output is the dam annual release for the agriculture sector.

To define membership functions (MF) in the fuzzy model, the inputs and outputs data are classified by self-organizing feature map (SOFM) (Chen and Mynett, 2003, 2004). Also, to generate the fuzzy rules, fuzzy associative maps (FAM) and bootstrap fuzzy relevance test (BFRT) (Krone and Taeger, 2001) methods are applied. More details about these methods have been expressed in Hosseini Safa *et al.* (2010). The computed RMSE and R^2 are 62.4 and 0.86, respectively that shows quite acceptable performance of the fuzzy model.

3. Fuzzy modelling of inflow forecast

Similarly, a fuzzy model developed to forecast annual inflows that are one of the inputs to the previous fuzzy model. Various inputs such as seasonal south oscillation index (SOI), seasonal minimum, mean and maximum temperature were evaluated in this regard. Similar approaches are also applied to define membership functions and fuzzy rules (Hosseini Safa, 2009). The coefficient of determination between observed and forecasted flows is 0.52.

4. Decision making for water allocation with economical approach

This module is based on the methodology, which is suggested by Willcocks (1994). The method is explained by a simple example. Consider a company wants to decide about amount of materials to be stored. If the buying and selling prices of a specific item are 300 and 500 unit; and d_1 to d_3 indicate number of units of stored item, then it will be possible to indicate income and profit for each strategy as shown in Table 1 [e.g. 400 (1000-600) means 2 units are already stored (2×300) and both of them is later sold (2×500)]. Now, if possible number of sales has probabilities of 0.05, 0.60 and 0.35 respectively then for each strategy, a value can be calculated that shows its performance in comparison with other strategies. Higher values show lower risk of that decision. So, as it is shown the table, strategy 2 is associated with lower risk and gets suggested.

Table 1. Calculative profit and loss (T_i) based on various strategies

Sale values (q_i)	Store alternatives			Profit values		
	d_1	d_2	d_3	d_1	d_1	d_1
$q_1 = 0$	0	-300	-600	$0 \times 0.05 = 0$	$-300 \times 0.05 = -15$	$-600 \times 0.05 = -30$
$q_2 = 1$	0	200	-100	$0 \times 0.6 = 0$	$200 \times 0.6 = 120$	$-100 \times 0.6 = -60$
$q_3 = 2$	0	200	400	$0 \times 0.35 = 0$	$200 \times 0.35 = 70$	$400 \times 0.35 = 140$
Ti				**0**	**175**	**50**

III – Discussion and results

Here, we try to show how the aforementioned model is customized for a frequent water resources management problem, which is indicating allocable agriculture water during a drought at the beginning of a growing season.

1. Clustering of release values

The dam release is a continuous variable, which needs to be discrete. The computed releases for the historical data by the optimization (Sub-model 1) and fuzzy (Sub-model 2) methods was clustered by a SOFM map technique and then averaged as shown in Table 2. Therefore, the manager decide about one of the release levels (R1 to R5) considering the forecasts and economical factors.

Table 2. Various water release levels and the center of clusters (million cubic meters, MCM)

Center of cluster (optimization)	Center of cluster (fuzzy)	Water release levels values (fuzzy + optimization)/2	Range of clusters	Release levels
881	928	905	850-970	R1
1021	1060	1040	970-1080	R2
1113	1136	1125	1080-1165	R3
1216	1195	1205	1165-1250	R4
1297	1277	1287	1250-1350	R5

2. Estimation of loss due to incorrect prediction of water release level (R)

If R is predicted incorrectly then the system will lose some benefits, which can be due to releasing of extra water because of over forecasting or reduction of releases due to under estimation of river flow. We have assumed that the water managers will update the forecast each four months. So, Table 3 indicates ratios of water that needed to be modified. For instance, if R3 is predicted and R1 happens, it means irrigation units will face with shortage of (R3-R1). Now for adaptation, the water managers reduce the declared water allocations up to 79% and 71% during the second and third 4 months, respectively. Consequent losses are also needed to be estimated.

Table 3. Adaptation coefficient for transformation of R values

Predicted R	Occurred R				
	R1	R2	R3	R4	R5
R1	–	1.19*	1.26	1.39	1.49
	–	1.23+	1.32	1.47	1.59
R2	0.84	–	1.06	1.16	1.25
	0.76	–	1.09	1.24	1.38
R3	0.79	0.95	–	1.10	1.18
	0.71	0.92	–	1.14	1.26
R4	0.72	0.86	0.91	–	1.08
	0.62	0.81	0.87	–	1.10
R5	0.67	0.80	0.84	0.93	–
	0.58	0.74	0.80	0.91	–

Decreasing or increasing coefficient of water allocation for second (*) and third four months (+)

For this, it is necessary to calculate relative yield (Y_a/Y_{max}) for each crop (Sub-model 1) based on various scenarios of predicted and observed R. it also needs actual evapotranspiration (ETa) and maximum evapotranspiration (ET_{max}), which are estimated based on the climate condition of year 1994 as a normal meteorological year during historical data. ET_{max} is a function of climate condition for each year and is constant for all release levels (R1 to R5). To determine ETa, it is computed by optimization models based on predicted release level and get multiplied by the adaptation coefficient for transformation of R values (L1 and L2) that will be explained in the next section. Therefore, benefit due to various scenarios of prediction and occurrence of Rs are computed as follow (Table 4):

(calculated Y_a/Y_{max} for each crops) x (optimal planted area based on initial prediction (in above example planted area based on R3 releasing) x (price for each crop)

Table 5. Consequent benefit (million dollars) in various scenarios of prediction and occurrence of R

Predicted R	Occurred R				
	R1	**R2**	**R3**	**R4**	**R5**
R1	92.8	95.7	96.7	97.9	98.7
R2	83.0	105.9	106.8	107.7	108.0
R3	78.9	101.5	109.5	110.2	110.7
R4	69.7	91.2	98.9	113.1	113.6
R5	62.8	82.3	89.3	102.3	115.1

In case of the aforementioned example (prediction of R3 and occurrence of R1), the system income is $78.9 million, while it could be $92.8 million in case of correct forecast (loss = 78.81 - 92.79 or 13.97 million dollars).

3. Probabilistic inflow forecast and selection of release level (R)

The next step is inflow forecasts and their respective probability of occurrence, which is done by the Sub-model 2-3. Furthermore, the releases are indicated based on the results of the KNN model. For more clarification, an example is shown in Table 5 for hydrological year 2002-03, when the basin faced one of the recent droughts. Columns 1 to 3 are constant and what changes is only column 6 for each year. Column 4 is indicated by the allocation fuzzy model (section 2-2) and reservoir storage at the beginning of this year, which was equal to 150 MCM. Then output of forecast fuzzy model that is membership function of inflow is estimated. The inputs of this model were spring SOI (equal to -8.2), spring minimum temperature (12.43℃) and summer inflow of Zayandeh Rud river (268.7 MCM). Probability of the inflow levels (Q) based on analysis of membership function of inflow (Fig. 1) is given in column 6.

Table 5. Probability of inflow levels (Q) for the year 2002-03

Release levels (1)	Release level values (2)	Inflow levels (3)	Range of inflow levels (4)	Inflow levels values (5)	Probability (6)
R1	905	Q1	700-1100	980	0.352
R2	1040	Q2	1100-1400	1320	0.152
R3	1125	Q3	1400-1700	1550	0.183
R4	1205	Q4	1700-2000	1850	0.084
R5	1287	Q5	2000-2600	2110	0.229

Now, the best strategy for agriculture water allocation from the reservoir is determined by multiplying probability of each Q (col. 6) by losses due to its respective R value. But, another factor interferes: the view point of the water managers about facing with the following 2 situations: (i) the predicted R value is less than the occurred R and the system confronts surplus water (situation L1); and (ii) the predicted R value is greater than the occurred R and water resources management can't perform its obligations (situation L2). In this methodology water manager assigns some values for L1 and L2. If both situations have the same consequences for his system, then L1 = L2 = 1. Otherwise they can indicate different values (e.g. L1 = 1 and L2 = 3). Table 6 and 7 show the best suggestion for the releases based on the different judgments. Equal values for L1 and L2 lead to allocation of 1287 MCM (Q5 then R5). But, for L1 = 1 and L2 = 3 (i.e. water managers hesitate to face with inability of performing their commitments) it suggest Q2 and the allocation will be 1040 MCM.

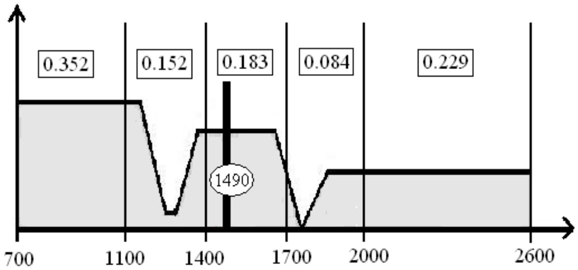

Fig. 1. Probability of the inflow levels (Q) based on analysis of membership function.

Table 6. Determination of the best option for water release (R), L1 = L2 = 1

Predicted Q	**Occurred Q**				
	Q1	**Q2**	**Q3**	**Q4**	**Q5**
Q1	92.79 × 0.352	95.70 × 0.352 × 1	96.66 × 0.352 × 1	97.86 × 0.352 × 1	98.74 × 0.352 × 1
Q2	82.98 × 0.152 × 1	105.87 × 0.152	106.83 × 0.152 × 1	107.70 × 0.152 × 1	108.04 × 0.152 × 1
Q3	78.81 × 0.183 × 1	101.46 × 0.183 × 1	109.52 × 0.183	110.22 × 0.183 × 1	110.66 × 0.183 × 1
Q4	69.67 × 0.084 × 1	91.16 × 0.084 × 1	98.92 × 0.084 × 1	113.12 × 0.084	113.61 × 0.084 × 1
Q5	62.79 × 0.229 × 1	82.31 × 0.229 × 1	89.33 × 0.229 × 1	102.29 × 0.229 × 1	115.07 × 0.229
Sum	79.93	94.85	99.07	103.91	107.32

Table 7. Determination of the best option for water release (R), L1 =1 and L2 = 3

Predicted Q	**Occurred**				
	Q1	**Q2**	**Q3**	**Q4**	**Q5**
Q1	92.79 × 0.352	95.70 × 0.352 × 1	96.66 × 0.352 × 1	97.86 × 0.352 × 1	98.74 × 0.352 × 1
Q2	82.98 × 0.152 × 3	105.87 × 0.152	106.83 × 0.152 × 1	107.70 × 0.152 × 1	108.04 × 0.152 × 1
Q3	78.81 × 0.183 × 3	101.46 × 0.183 × 3	109.52 × 0.183	110.22 × 0.183 × 1	110.66 × 0.183 × 1
Q4	69.67 × 0.084 × 3	91.16 × 0.084 × 3	98.92 × 0.084 × 3	113.12 × 0.084	113.61 × 0.084 × 1
Q5	62.79 × 0.229 × 3	82.31 × 0.229 × 3	89.33 × 0.229 × 3	102.29 × 0.229 × 3	115.07 × 0.229
Sum	174.46	185.00	156.60	150.76	107.32

IV – Conclusion

This research work aimed to present a methodology to indicate allocable water for agriculture sector during droughts. The following conclusions can be drawn from this study:

(i) The suggested methodology could properly incorporate economical components and uncertainties in the calculations, as well as judgments of the water managers. This feature of the methodology makes it very close to what has been pointed out as shared vision planning (Loucks and Gladwell, 1999).

(ii) The method is flexible to accept and embed other approaches too. For instance, substitution of other forecasting method is easily possible. Similarly, changing other adaptation strategies while facing with errors in the forecasts.

(iii) Having the two coefficients (L1 and L2) based on the view point of mangers makes it possible to incorporate social concerns in the calculations, too.

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