OPTIMIZING THE INTERBASIN WATER TRANSFER
FOR IRRIGATION DEVELOPMENT

By

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ABSTRACT

In case the intrabasin water resources are not adequate for the basin development, interbasin transfer is often considered as one of the solutions. Interbasin water transfer, which is usually associated with a long distance transfer, results in increased cost of water.

This paper describes a mathematical optimization model which computes the optimal quantities of water to be transferred from other basins for irrigation purposes in conjuction with the optimal land use allocation, under a set of conditions and constraints.

The problem is formulated as a goal programming model. Two algorithms are considered. One is the standard linear programming algorithm and the other is a special algorithm which combines characteristics of L_1 norm approximation with linear programming properties. A case study is analysed to demonstrate the applicability of the proposed formulation.

Introduction

With the increasing demand for food, regional growth may depend on the development of marginal resources for increasing agricultural output. A major concern (φροντίδα - δουλειά) of irrigation and development planners is how to find the optimal size of the areas allocated to the various crops. In the past it was customary to select these areas according to their suitability to the specific local conditions only (e.g. weather, soil, past experience etc). Nowdays in many areas, especially those in arid (ξηρός) and semi-arid regions, the availability of water is an important constraint on the feasibility of reclaiming (= reclaim = αναμορφώνω - αποξηραίνω) marginal lands for crop production. In such cases it is imperative to use the available water resources as efficiently as possible.

Research has revealed that a common characteristic of most regions is a space and time imbalance of water demand and natural supplies. Man in his social practice has removed this time imbalance by impounding excess water supplied during times of high availability and releasing it during times of demand, as well as pumping ground water whenever feasible. Due to the large number of parameters usually involved in land use allocation, mathematical models have been proposed to derive practical solutions to these problems [Roger and Smith (1970), Lakshminarayana and Rajagopolan (1977), Matanga and Marino (1979), McCuen et al (1978)].

In case that there is no storage facility available, the land use allocation obtained will be associated with large quantities of unused water during the periods of low demand. Hence, the planner persisting in the assumption that the water requirements of the crops during their "critical period" are

fully satisfied, and attempting to increase the areas under irrigation, will be faced with two alternatives: He must either use an auxiliary source of water for the period of high demand (e.g. interbasin water transfer) or let the soil moisture shortages develop in the root zone of the crops. In the first case the cost of supplying each additional unit volume of water is drastically increased in order to keep the crop yield at the potential level, whereas in the latter case a reduction in the crop yield is anticipated due to unfavourable soil moisture conditions developed. The model described in this paper deals with the first case.

Planning for interbasin water transfer projects requires adequate and reliable information on many factors concerning the basin under development as well as the supply basin.

It is recognized that a decision upon an interbasin transfer should be based on economic, social, environmental and political considerations. Hopefully this will be discussed in detail by other contributors. In this study, however, the attention is focused on the economic aspects of the problem. Therefore the amount of water to be transferred is optimized in conjunction with the land use allocation of the basin under development.

According to the proposed formulation it is examined whether it is better in economic terms to use the available water resources of the basin and include a small area in the irrigation development zone or to increase the irrigated area and transfer water from another basin. In the latter case the optimal amount of interbasin transfer should be also found.

The Goal Programming Model.

This section describes the formulation of the land and water optimization problem as a standard goal programming model. There are two basic principles behind the construction of this model: first, that it should reasonably represent reality; and second that it should be well-based on a powerful and easy to use algorithm.

The standard form of a goal programming model has been presented by Charnes and Cooper (1977) and may be mathematically described as follows :

διατύπωση Charnes and Cooper.

Find vectors $\underline{d}^+$ and $\underline{d}^-$ such that

$$\text{minimize} \quad (\underline{w}^+\underline{d}^+ + \underline{w}^-\underline{d}^-) \tag{1a}$$

subject to

$$A\underline{x} + I\underline{d}^+ - I\underline{d}^- = \underline{g} \tag{1b}$$

$$(\underline{d}^+ \cdot \underline{d}^- = 0) \tag{1c}$$

$$\underline{d}^+ \geq 0, \ \underline{d}^- \geq 0 \tag{1d}$$

when $d^+ = \{ V - \Sigma \ldots$ 0, otherwise

In this formulation $\underline{w}^+$ and $\underline{w}^-$ are row vectors with non-negative constant elements representing the relative weights to be assigned to positive ($\underline{d}^+$) and negative ($\underline{d}^-$) column vectors of over-achievement and underachievement of goals, respectively. A is a matrix of coefficients, $\underline{x}$ is a column vector of the decision variables, I is the identity matrix and $\underline{g}$ is a column vector of desired "goals" to be met "as closely as possible".

It can be shown that the nonlinear conditions (Eq. 1c) between $\underline{d}^+$ and $\underline{d}^-$ need not be maintained throughout a series of iterations, because these vectors are complimentary [Charnes and Cooper (1977)]. Hence the above minimization problem is a straightforward linear programming problem.

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To determine the optimal allocation of land use a measure of optimality must be selected. For the case described here the expected total economic loss due to the imbalance between water supply from the main source and demand, was selected as means of comparing alternatives in land use allocation. Let the penalty cost, c_i, represent the relative weight to be assigned to positive and negative deviations of the water requirements from the water availability levels (V_i-goal) of the intrabasin resources. The optimization model has the general form:

from the goal.

Find $A_j \mid j = 1(1)k$ such that

$$\text{minimize} \sum_{i=1}^{n} c_i \left| V_i - \sum_{j=1}^{k} w_j^i A_j \right| \tag{2}$$

where

- k is the number of crops grown,
- n is the number of months covered by the model,
- A_j is the land parcel allocated to the j-th crop,
- w_j^i is the water requirement of the j-th crop during the i-th month, and
- V_i is the available volume of water from the main source during the i-th month.

By defining

$$\delta_i^+ = \begin{cases} \left| V_i - \sum_{j=1}^{k} w_j^i A_j \right|, & \text{when } V_i - \sum_{j=1}^{k} w_j^i A_j > 0 \\ 0 & , \text{ otherwise,} \end{cases} \tag{3a}$$

$$\delta_i^- = \begin{cases} \left| V_i - \sum_{j=1}^{k} w_j^i A_j \right|, & \text{when } V_i - \sum_{j=1}^{k} w_j A_j < 0 \\ 0 & , \text{ otherwise} \end{cases} \tag{3b}$$

and taking into account that, the penalty cost c_i^- of inter-basin transfer (overachieving the goal V_i) is different from the penalty cost c_i^+ of using the intrabasin resources only (underachieving the goal V_i), one can replace the aforementioned minimization problem (2) with the following :

Find A_j, δ_i^+, δ_i^- for $j=1(1)k$ and $i=1(1)n$

such that

$$\text{minimize} \sum_{i=1}^{n} (c_i^+\delta_i^+ + c_i^-\delta_i^-) \tag{4a}$$

subject to

$$\sum_{j=1}^{k} w_j^i A_j + \delta_i^+ - \delta_i^- = V_i \tag{4b}$$

$$A_j \geq 0, \ \delta_i^+ \geq 0, \ \delta_i^- \geq 0 \tag{4c}$$

for $j = 1(1)k$ and $i = 1(1)n$

This formulation is a standard goal programming model equivalent to (1), where the relative weights are replaced by the penalty cost c_i^+ and c_i^-.

Constraints

The following additional constraints limit the policy space for the attainment of the stated objective.

(i) Land Availability Constraints

The sum of the parcels of land allocated to various crops should be equal to the total available area for irrigation, namely

$$\sum_{j=1}^{k} A_j = A_0 \tag{5}$$

in which A_0 is the total area available for irrigation.

(ii) Economic Constraints

The net benefit from each unit volume of water used from the second source should exceed the cost of supplying it. Since the water is distributed to the land parcels A_j which correspond to various crops, the net benefit may be obtained from the weighted sum of the unit area net benefit of each crop multiplied by the corresponding percentage area. Thus the general economic constraints are

κόστος

$$\sum_{j=1}^{k} r_j^i \frac{A_j}{A_0} \geq c_i^- \ , \quad i = 1(1)n \tag{6}$$

where

r_j^i stands for the net benefit from the unit volume of water used to irrigate the j-th crop during the i-th month, and

c_i^- is the cost of the unit volume of water from the second source during the i-th month. Q1.

(iii) Land Allocation Constraints

Management considerations set a maximum and a minimum value for irrigated acreages under each crop:

$$\lambda_j A_0 \leq A_j \leq \mu_j A_0 \qquad j = 1(1)k \tag{7}$$

in which λ_j and μ_j are fractions of irrigated area allocated to j-th crop.

Obviously many other constraints may be added if one wishes to take into account other physical and technical limitations associated with labour availability, soil suitability, rotational cropping pattern etc. However, for simplistic purposes these constraints are not included in the work reported here.

Computational Aspects

Goal programming is a special extension of linear programming. In particular, optimization problem (2) can be interpreted as a disguised form of best approximation in the L_1 norm for which solution procedure using linear programming has been proposed by Spyropoulos et.al (1973). Furthermore the minimization problem (4) is a particular weighted approximation problem in which $c_i^+ \neq c_i^-$, with c_i^+ and c_i^- being constants. This choice of weights gives a measure of approximation which is not a norm. Hence problem (4) is a best approximation problem in an asymmetrically weighted L_1 measure [Young and Kiountouzis (1979)]. This could be solved using either a standard linear programming algorithm or the particulary fast algorithm LONESKY [Spyropoulos et al (1973)] which combines characteristic properties of the L_1 approximation with experience gained from experiments in linear programming. An adaptation of LONESKY could also be used to handle the additional constraints (5), (6) and (7). Finally, we note that by using the transformation

$$A_j = \alpha_j + \lambda_j A_0, \quad j = 1(1)k \tag{8}$$

the constraints (7) are replaced by

$$\alpha_j \leq (\mu_j - \lambda_j) A_0 \tag{9}$$

thus reducing the total number of constraints by k.

Numerical Application - Case Study

To illustrate the proposed methodology we have considered data from Thessaly Plain (Greece). Three of the main crops in the area were selected, namely cotton, sugar beet and corn. The average monthly water requirements of these crops are presented in Table 1.

It is assumed that the limiting factor is the water, whereas there is no practical limitation as far as the area under each crop is concerned, except that, for our case, the total available area for irrigation (A_0) is 300×10^3 stremmas. Supplementary water is planned to be conveyed from another basin. (e.g. Acheloos River - interbasin transfer). Considering a subarea in Thessaly Plain with monthly volume of water available from its main source as in Table 2, the following problem arises:

Which is the additional quantity of water drawn from the second source and how the land should be allocated to the various crops?

For this case we have considered that the total cost of water per m^3 is 0.5 drs ($c_i^+ = 0.5$ drs) for the main source and 2.5 drs from the second source ($c_i^- = 2.5$ drs). The net benefit r_j, from the unit volume of water used to irrigate the crops, was taken constant for the months considered and was calculated, in drs/m^3, as $r_1 = 6.5$ (Cotton), $r_2 = 3.7$ (Sugar Beet) $r_3 = 7$ (Corn).

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Solving the problem as it is formulated in Eqs 4a, 4b and 4c, with the additional constraints (5) and (6) the following optimal solution was calculated:

Area allocated to Cotton,	$A_1 = 0$ stremmas
Area allocated to Sugar Beets	$A_2 = 0$ stremmas
Area allocated to Corn	$A_3 = 300 \times 10^3$ stremmas
Volume of excess water in June	$\delta_1^+ = 7380 \times 10^3$ m^3
Volume of water used from auxiliary source in July	$\delta_2^- = 4159 \times 10^3$ m^3
Volume of water from auxiliary source in August	$\delta_3^- = 5256 \times 10^3$ m^3

The total cost of water used for irrigation during these three months, is 27227.5×10^3 drs.

Λόγω που το corn έχει περισσότερη απόδοση από το cotton

Concluding Remarks

In this paper it was show that goal programming can be em ployed to provide estimates of optimal allocation of irr: gated land to different crops and if necessary optimal i terbasin water transfer so that the total economic loss d to the imbalance between water supply from the main sour and demand is kept to minimum. Depending on the project o jectives additional constraints may be introduced to refle factors as land availability, economic labour limitations etc.D to the special structure of the model two algorithms cou be used to solve it: either a standard linear programmi algorithm or a particularly fast algorithm proposed for t L_1 norm discrete approximation. Since both algorithms a based on linear programming post,optimal analysis, that i cludes sensitivity analysis,could be carried out, to provi valuable information about the stability of the optimal s lution. The model was applied to a case study in Greece a the optimal solutions have been reported.

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Table 1

Monthly water requirements of the crops (mm/month)

Crops	Months		
	June	July	August
Cotton	66	108	111
Sugar Beet	132	133	108
Corn	105	121	78

285
373.
304

Table 2

Monthly volume of water available from the main source (m^3/month)

Month	June	July	August
Volume	38880×10^3	32141×10^3	18144×10^3

SUBJECT 5

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