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Optimal Planning for Water Resources Allocation (Case study: Hableh Roud Basin, Iran)

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Abstract

The world is facing severe challenges in meeting the rapidly growing demand for water resources. In addition, irrigation water which is the largest use of water in most developing countries and arid and semi arid regions, will likely have to be diverted increasingly to meet the needs of the households in urban areas and industry sectors whilst remaining a prime engine of agricultural growth. A Linear Programming (LP) model has been developed to allocate the land and water resources to different crop activities for maximizing the net return. Application of the model for the irrigation water management revealed that in winter, 89.4% of available channel water was utilized, out of which 55.9% and 18.5% were allocated for wheat and barley, respectively .The remaining 25.6% channel water was allocated for cotton and watermelon. Since there were enough channel water supplies in this season, only 10.6% of available groundwater was utilized. In the absence of constraint on conjunctive use, there would have been no groundwater exploitation, and 100% of the channel water, which is much cheaper than groundwater, could have been utilized, if required. During summer season, the entire quantities of water available in channel as well as groundwater resources were utilized. In this season, as there was limited channel water supply, considerable part of the irrigation requirement was met from available groundwater. Based on the LP analysis, out of total available channel water, 43.2% was allocated to cotton cropping, which was most profitable as compared to all other crop activities, followed by 38.3%, 9.5% and 9% to crop activities including watermelon, barely and wheat, respectively. Out of total available groundwater, 65.8% was allocated to cotton whose irrigation water need was high and the remaining 34.2% was shared by wheat, barley and watermelon cropping activities. The model predicts that in the case of changes in irrigation water supply, it will be economic to change the cropping pattern.

Keywords: Optimization; Hableh Roud basin; Surface water; Allocation; Iran

1. Introduction

Water scarcity has emerged as one of the most serious concerns in the 21st century. It is estimated that 2.7 billion people will face water scarcity by 2025 (UN, 1994). Against a growing alarm of ‘water wars’, several global agencies, national governments and NGOs have been concerned with emerging water ‘crises’ and potential water conflicts . For example, projections of water supply and population growth rates predict a dark scenario of the future; while the average per capita supply of water will decrease by one-third by 2025; water use will increase by about 50% during the same period. For instance, Iran is facing severe water shortage due to geographical

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and demographic arguments. In many areas, water is available to users at no cost or at a heavily subsidized price. Thus neither water managers nor water users have incentives to conserve water, so water is overused and wasted instead of being treated as a scarce resource (Wagner 1995). The subject of efficient water use has attracted much attention and new strategies for water development and management are urgently required to change severe national, regional, and/or local water scarcities that can depress agricultural production, because rationing of water to the household and industrial sectors, damage the environment, and escalate water-related health problems. A large share of water to meet new demands must come from water conservation from existing uses through an optimum allocation of water. The subject of water allocation and use has gained increasing prominence, partly because of recognizing that some regions and communities have ran out of water permanently, or temporarily, at least for some uses. Permanent deficits have become evident in the Middle East region as a whole; temporary shortages were occurred during droughts in the prone regions and extreme drought related problems were occurred during the 1990s in southern Africa, as well as in California and even in humid north-west Europe during particularly dry years such as the 1995 summer. Seasonal shortages are commonplace in semi-arid countries during dry summers (Rosegrant et al., 1994).

Optimal management must be then the primary approach to achieving sustainable water resources, both in national and international scales. It is at the basin scale that water allocation decisions have wider economic implications. As a result, policy instruments designed to make more rational and economic use of water resources are likely to be applied at this spatial scale.

Generally, river basins have long been acknowledged as the appropriate unit of analysis for water resources management and have also been nominated by the United Nations Conference on Environment and Development as the unit of analysis for integrated water resources management in Agenda 21, chapter 18. The activities suggested in chapter 18 include the development of interactive databases, forecasting models, economic planning models and methods for water management and planning, and the optimization of water resources allocation under physical and socio- economic constraints (Labadie et al. 1994).

Clearly, the allocation of water resources in river basins is a critical issue. The sustainability of future economic growth and environmental health depends on it. However, river basins are inherently complex systems with many interdependent components. Efficient and comprehensive analytical tools are needed to make the rational water allocation decisions necessary to achieve sustainable water use strategies for many river basins. Water managers try to allocate water to meet demands as well as to maximize the benefits that it provides to the communities (Loucks et al., 2005, Hewitt et al., 2005).

Many researchers have implemented a number of optimization methods to derive planning and operating strategies for land and water systems. For example, Helweg and Labadie (1987) developed a water allocation mechanism for the Bonsall sub-basin of the San Luis Rey River basin, with emphasis's on cost-effective salinity management strategy. The basic idea for this mechanism is to accelerate the downstream transport of salts by encouraging the utilizing application of pumped water in downstream. The authors developed a management algorithm, combining an optimization model and a detailed quantity-quality simulation model to implement this technique. The optimization model generates least-cost alternatives for distributing water over the sub-basin. Peralta et al. (1990); and Lefkoff and Gorelick (1990) applied simulation-optimization models to determine an optimal irrigation strategy that maximizes crop yield while preventing groundwater contamination. Wong et al. (1997) presented a methodology to determine multi- period optimal conjunctive use of surface water and groundwater with water quality constraints.

In agriculture sector, where various crops are competing for a limited quantity of land and water resources, linear programming is one of the best tools for optimal allocation of land and water resources (for example Khepar and Chaturvedi, 2006; Kaushal et al., 1985; Panda et al., 1995; Paul et al., 2000). Most of the studies of optimization on irrigation water management adopt simplified or linear objective functions to maximize the net benefits while selecting an optimum cropping pattern.

The objective of this paper is to assess the potential of optimization models to address critical issues related to increasing water demand and the resulting competition over water in the context of past modeling experience in both the economic and hydrologic disciplines. It is only by considering all interactive components that benefit from or damage the resource that optimal use from a social standpoint can be established. Thus, with the growing scarcity of water and increasing competition for water across sectors, economic considerations in water allocation are going to be more important in river basin management. The river basin has been acknowledged to be the appropriate unit of analysis to address these challenges facing water resources management; and modeling at this scale can provide essential information for policy makers in their decisions on allocation of resources (Knapp, 1996).

2. Materials and methods

2.1. Study area

The Hableh Roud Basin is located in the north-central Iran; and lies between 51°39' to 53° 08' east longitudes and 34°26' to 35° 57’ north latitudes (Figure 1). It has an area of 12,667 km^2 while the Garmsar region which is a suitable alluvial fan for agricultural activities and settlements is about 730 km^2. It is bound by the Alborz Mountains in the North and by the Central Desert of Iran in the South. The basin is very cold in the mountains and has an arid climate in the outlet. The average temperature in the basin ranges from 40°C in the summer to -15 °C during winters. The basin altitude ranges from 818 m a.s.l. in the lowlands to about 4075 m a.s.l. in the highlands. Annual precipitation is variable and ranges from 358 mm to 88 mm and averages about 150 mm in the agricultural area. Evaporation especially in the lower parts is high throughout the year and estimated as 1284 mm/year. Since precipitation of the lower parts does not meet the crop water demand, the farming activities are largely dependent on irrigation. In many areas, groundwater table is increasingly dropping. Overexploitation of the aquifers combined with misuse of land resources has led to salinization of the water and soils and a sinking water table. The groundwater table sinks at a very considerable rate.

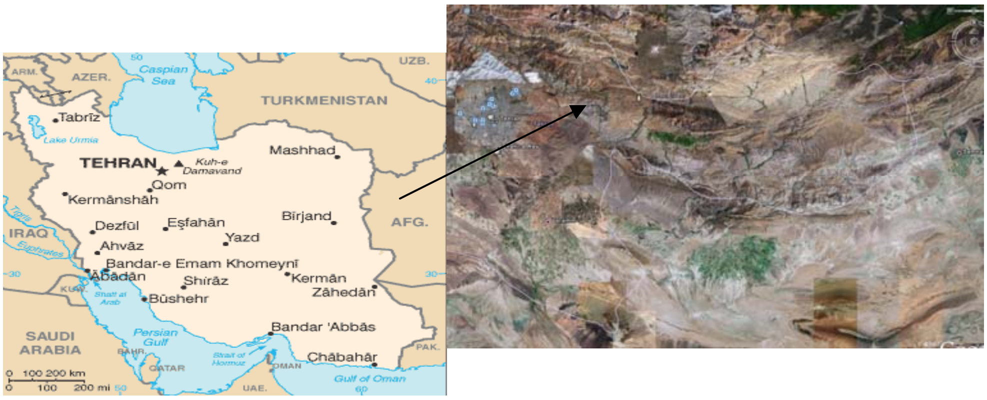

Fig. 1 .The location map of the study region

2.2. Methods

For water resources planning and management purposes a usual approach considered to be optimization modeling. The solutions of optimization models are based on objective functions of unknown decision-variables that are to be maximized or minimized. The constraints of an optimization model contain decision-variables that are unknown and also parameters whose values are assumed to be known. Constraints are expressed as equations and inequalities.

The solution of an optimization model, if one exists, contains the values of all of the unknown decision-variables. It is mathematically optimal in a way that the values of the decision-variables satisfy all the constraints and maximize or minimize an objective function. This ‘optimal’ solution is of course based on the assumptions regarding to the model parameters, the chosen objective function and the structure of the model itself (Sethi, 2002; Tsur et al., 1991).

The approach (or algorithm) most appropriate for solving any particular optimization model depends in part on the particular mathematical structure of the model. There is no single universal solution procedure that will efficiently solve all optimization models. Hence, model builders tend to model water resources systems by using mathematical expressions that are of a form compatible with one or more known solution approaches. Approximations of reality, made to permit model solution by a chosen optimization solution procedure, may justify a more detailed simulation to check and improve on any solution attained from that optimization.

To date, no single model type or solution procedure has been judged best for all the different types of issues and problems encountered in water resources planning and management. Each method has its advantages and limitations. One will experience these advantages and limitations as one practices the art of model development and application (Young, 1996).

The linear programming technique has been widely used to formulate the conjunctive use to arrive at an optimal allocation of surface and groundwater, to maximize the benefits within the framework of given constraints and proposed cropping pattern (Khepar and Chaturvedi, 2006). In the present study, the “LINDO 10” package was used to solve the model. The objective function has been formulated for maximizing the net benefit resulting from the cropping activities in the study area. The objective function is formulated considering benefit and costs of proved water, which can be expressed as equation 1:

$$Z = \sum PjAjYj - \sum VCjCC - \sum VGj\, CG - \sum Bj\, Aj \qquad (1)$$

where Z : net income from all the crop activities in Rials; *j* is the number of crops in the study area (*j*=1, 2, . . ., *nz*); Pj is the gross income from crop activity j, (Rials/ha); *Aj* the area under crop *j* (ha); *Yj* the yield of crop *j* (t/ha); VCj , VGj : volume of channel water and groundwater, respectively used for crop activity j, (MCM); CC : cost of channel water, (Rials/ha) ; CG : cost of pumping for groundwater, (Rials/ha); Bj : fixed costs of cultivation of crop activity j, (Rials/ha)

The objective function is to be maximized subject to a variety of constraints including:

1. Water requirement constraints:

The total irrigation required for all the crops shall be met by surface and groundwater allocations. In this study irrigation requirement has been considered at the place of channel outlet. Therefore, constraints for water need for the crops can be written as:

$$\sum IRjAj \leq (VCjVGj) \qquad (2)$$

Where IRj is net irrigation required for crop activity j during the activity (mm)

2. Area availability constraints:

The total land allocated for different crop activities cannot exceed the total available land.

$$\sum A_j \leq A_t \qquad (3)$$

Where A_t is available area of land for cropping activities (ha)

3. Surface water availability constraints

Channel water used for different crop activities in any season can not exceed the available supply

$$\sum VC_j \leq C_w \qquad (4)$$

Where Cw is available channel water supply (Mm^3)

4. Groundwater availability constraints.

In the study area, limited amount of groundwater is available to supplement the channel water. Groundwater used for different crop activities cannot exceed the available groundwater.

$$\sum VGj \leq G_W \qquad (5)$$

Where Gw is available ground water supply (Mm^3)

5. Non-negativity constraints:

$$Aj \geq 0 \qquad (6)$$

$$VC\,j \geq 0 \qquad (7)$$

$$VGj \geq 0 \qquad (8)$$

3. Results

The developed linear programming model is solved and the results are presented here. The principal crops that are grown in the region are wheat, barely, cotton and watermelon. The monthly water needs of the plants in the region were calculated (Table 1). As shown in Table 2 the economic indices for each crop were calculated based on the prices and available information/data resources in a long term period.

Table 1. Water requirements of crops in the region (m^3/ha)

Month/ Crop	Wheat	Barley	Cotton	Watermelon
Jan.	0	0	0	0
Feb.	0	30	0	0
Mar.	340	360	0	0
Apr.	1250	1320	70	0
May	1860	1790	850	870
Jun.	1410	740	1670	1430
Jul.	0	0	2620	2220
Aug.	0	0	2340	1810
Sep.	0	0	1500	260
Oct.	0	0	340	0
Nov.	670	670	0	0
Dec.	0	0	0	0
Total	5530	4910	9390	6590

Table 2. Economic indices for each crop in the Hableh Roud basin

Index /Crop	Wheat	Barley	Cotton	Watermelon
Yield(kg/ha)	4957.63	3869.19	1398.15	20830.52
Production cost(Rials/ha)	369840	425470	561830	1236670
Net Return(Rials/ha)	756770	777430	5582360	4066840
Current area(ha)	7490	6402	6876	4522

The entire area available for the agriculture is found to be 25,290 ha, out of the total 30 000 ha, excluding 4710 ha area under, shrubs and or barren land including salt pans.

The available water from channel network is provided by Hableh Roud and the long term yield of the river is calculated based on the river gauged data (Table 3). Meanwhile, there are several shallow and deep wells in the study region which are exploited by the farmers for irrigation. Table 3 provides the monthly average exploitation rate of groundwater in the region.

Table 3. The long term average volume of surface and ground water yield (MCM)

Month	Surface water	Ground water
Jan.	14.09	0.53
Feb.	12.61	0.93
Mar.	12.47	1.27
Apr.	18.34	2.24
May	25.34	1.91
Jun.	20.45	1.26
Jul.	13.77	1.34
Aug.	12.72	0.73
Sep.	11.11	0.62
Oct.	6.56	0.94
Nov.	14.94	0.78
Dec.	15.35	0.65

The area allocated for different cropping activities under current and optimal plan of water resources allocation is presented in Table 4. Application of the model for the irrigation water management revealed that in winter, 89.4% of available channel water was utilized, out of which 55.9% and 18.5% was allocated for wheat and barley, respectively .The remaining 25.6% channel water was allocated for cotton and watermelon. Since there were enough channel water supplies in this season, only 10.6% of groundwater available was utilized. In the absence of constraint on conjunctive use, there would have been no groundwater exploitation, and 100% of channel water, which was much cheaper than groundwater, could have been utilized, if required. During summer season, the entire quantities of available channel as well as groundwater were utilized. In this season, as there was limited channel water supply, considerable part of the water need was met from available groundwater. Out of total available channel water, 43.2% was allocated for cotton, which was most profitable as compared to all other crop activities followed by 38.3%, 9.5% and 9% to crop activities including watermelon, barely and wheat respectively. Out of total available groundwater, 65.8% was allocated to cotton whose water need was high, and the remaining 34.2% was shared by wheat, cotton, barley and watermelon cropping activities. The model predicts that in the case of changes in irrigation water supply, it will be economic to change the cropping pattern (Figure 2).

Table 4. Comparison of current and optimum status of water allocation plan

Crop	Current area (%)	Optimum area (%)
Wheat	42.7	39.7
Barley	28.3	23.7
Cotton	21.8	25.3
Watermelon	7.2	11.3
Total	100	100

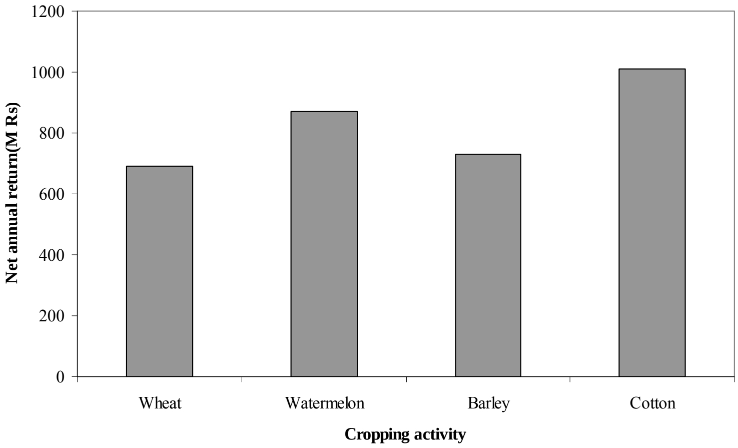

Fig. 2. Net annual return for different cropping activities in an allocation plan with conjunctive use (Surface water and groundwater)

4. Discussion and Conclusion

As shown in Table 4 the results of linear optimization process indicate that in the study region the optimum areas of the land for wheat and barely is less than the current cultivated land for these crops. In other words, the current condition for these crops is not economic while in the cases of cotton and watermelon, the optimum areas of land allocated is larger than the current condition. The results suggest that changes in cultivation pattern may bring more profitability to the area which will consequently reduce poverty, migration and other unfavorable consequences. This finally may lead to sustainable status of the region.

This work presents the benefits of conjunctive use of the surface water and groundwater resources. The decrease of channel water supply coupled with the irregular delivery schedule does not provide enough opportunity to the farmers for deciding about its allocation and distribution at the farm level (Babu, 1996). The farmers' decision in respect of channel water utilization was neither strictly planned nor governed by any standard set of practice. The inadequacy of channel water supply created the need for groundwater development, which offered greater opportunity for decision-making. The pattern of groundwater utilization by the farmers indicates that they are aware of the economics of groundwater pumping and so long as the profit from the groundwater utilization exceeded the cost of groundwater exploitation, an increase in price of water does not necessarily lead to higher water use efficiency. The quality of groundwater creates significant variations in the productivity of farms. However, the cultivation of salt- tolerant and high yielding varieties of crops, crop diversification, and fresh and brackish water aquaculture offer opportunities to improve both water productivity as well as income of the farming community in this region.

Given that water scarcity in arid areas arises due to the complex interactions of precipitation, soil, vegetation, human activities and socio-political processes, holistic and long term measures are required to solve the problems of scarcity (Rosegrant, 1994). The major concern is the future of water resources which is probably the limiting factor in the region and the subsequent livelihood for the people in the basin. Hence an optimal approach is required through involvement of key stakeholders to articulate key issues in order to establish strategies and the way forward (Booker et al., 2005).

Freshwater is already scarce and the condition is getting worse day-by-day due to unfavorable climatic conditions. So the best way to increase the water productivity is to utilize the available resources in the most efficient way by using the scientific water management techniques. The farmers in this region need some well prepared lands (precised land leveling/grading and restoration of the stream) as far as the knowledge related with flood irrigation is concerned. Improving efficiency beyond the prevailing level is only possible through the introduction of pressurized irrigation methods, which at present level of water pricing is not found economically viable. The adoptability of any cropping pattern depends on its profitability. The economic analysis indicates that irrigation, constitutes about 53% of the costs of cultivation. Salt tolerant varieties of the important crops have been developed for various ranges of salinity and alkalinity with high yield potential. The cultivation of these tolerant varieties in the saline/sodic groundwater regions would be an effective method for increasing the productivity of salty groundwater. The use of groundwater with marginal quality groundwater for crop production coupled with fish pissiculture (fish farming) offer great opportunity to improve the water productivity. The groundwater coming out through the fish pond for irrigation would provide extra income to the farmers.

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