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Integrated non-linear model for optimal cropping pattern and irrigation scheduling under deficit irrigation

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ABSTRACT

A non-linear optimization model for deficit irrigation is proposed in the present study to maximize the net financial return within the available resource constraints. The deficit levels of irrigation are kept as variables in the model with a flexibility to keep the crops either at full irrigation or deficit irrigation in order to maximize the net financial return. The model optimizes the deficit levels, cropping pattern and decade (10 days) optimal water withdrawals for the existing land and water resources. The proposed model is applied to Khairpur East canal command of the Lower Indus Basin. The overall optimal net financial return was increased by 92.5% and the total optimal cropped area was enhanced by 109.7% under deficit irrigation as compared to the existing cropping pattern although the net financial return per hectare of land was reduced under deficit irrigation. The optimal net financial return can further be increased by 17.5% if the existing tube well capacity is augmented by 75% in the command area. The surface water availability was also reduced to work out its impact on the optimal cropped area. Although the net financial returns reduced with a reduction in the surface water availability but the optimal irrigated cropped area remained almost the same under deficit irrigation. However the cropping pattern and optimal deficit levels of different crops changed as the surface water availability is reduced. Further, a balanced optimal production of crops would require imposing upper and lower constraints on the quantity of the production of crops in place of crop areas under deficit irrigation.

1. Introduction

Agriculture is a main user of the world's water resources. World population is growing day by day and consequently the water demand is also mounting up particularly in the agricultural sector to feed the rising population. The contribution of irrigated agriculture to food production is important. Therefore, sustainability of irrigated agriculture would demand the efficient management of the available finite water resources under the existing constraints. It is particularly important in the Indian subcontinent in view of the alarming water scarcity (Garg and Hassan, 2007).

Traditionally, agricultural research is focused primarily on maximizing the yield per unit area by allocating water to different crops according to their water requirements (Afshar and Marino, 1989; Mayya and Prasad, 1989; Paudyal and Gupta, 1990; Thandaveswara et al., 1992; Shyam et al., 1994; Onta et al., 1995; Garg and Ali, 1998). In the recent years, focus is also shifting to increase productivity within the constraints of available limited water resources. Therefore, deficit irrigation is also becoming a possible option i.e. intentionally under irrigating crops to reduce water requirement while minimizing the adverse affect of extreme water stress on crop yield. The reduction in the yield may be small as compared to the benefits gained through diverting the saved water to cover more cropped area under irrigation. English (1990), Reca et al. (2001), Singh et al. (2001) and Pereira et al. (2002) demonstrated that deficit irrigation may be useful in increasing the crop production, irrigated area and the net economic returns from the command area. Gorantiwar and Smout (2003) proposed a three-stage simulation optimization model based on deficit irrigation approach for optimal allocation of water from a reservoir. Vedula et al. (2005) proposed a linear programming model for optimal use of ground and surface water to maximize the annual relative yields of the crops. Gorantiwar and Smout (2005) developed a resource allocation, area and water allocation model with limited water supply through a variable depth irrigation approach. Gorantiwar and Smout (2006) further formulated the simulation optimization model based on full or deficit irrigations for irrigation schemes of central and south India. Khare et al. (2007) proposed

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an economic optimization model to discover the potential of conjunctive use of surface water and groundwater by using linear programming model (LPM) with various climatological uncertainties. Wang et al. (2008) developed a dynamic model for equitable distribution of water in water scared areas and maximized the total economic returns of the command area. Montazar et al. (2010) proposed a non-linear optimization model and the soil water balance algorithm to optimize the water allocation planning in a deficit agricultural water resources systems. Gupta et al. (2012) studied the persistent and mobility of pesticides under deficit irrigation. Raul et al. (2012) developed an Irrigation scheduling model (ISM) and a LPM for optimal allocation of surface water and groundwater under uncertainty of hydrologic events like rainfall and canal water availability.

The literature review indicated that most of the optimization models used an economic criterion to find out the optimal cropping pattern to maximize the benefits for the optimal allocation of land and water resources of a command. Irrigation scheduling models (ISM) are mostly not integrated in the optimization models under deficit irrigation. The actual yield is obtained by the ISM under fixed deficit levels and is then used in the optimization models to find out the optimal cropping pattern and resource allocation. Therefore these optimization models may optimize for a particular deficit level and may not give an overall optimal solution under deficit irrigation.

The present study aims to develop a optimization model to maximize the net financial returns by taking the deficit levels also as a variable in the model. The irrigation scheduling is also integrated in the model and optimal deficit levels are worked out for different crops to give the optimal cropping pattern and optimal allocation of the water resources.

2. Methodology

2.1. Model development

A NLP model is developed to obtain the optimal deficit levels for different crops to maximize the net financial returns and to work out the corresponding optimal cropping pattern and the optimal allocation of surface and ground water resources. The canal water, being essentially a gravity flow system, is less costlier as compared to the ground water in the Indian subcontinent. In the study area of the Lower Indus Basin, the ground water was around nine times costlier than the canal water for an average lift. Hence there was no necessity to couple the ground water hydraulics with surface water as the ground water would only be utilized if the crop water requirements could not be met with surface water. However the interaction between surface and ground water is considered by imposing a ground water balance constraint such that the annual ground water withdrawals cannot be more than the annual ground water recharge. A ground water management model can be separately worked out to keep the ground water levels within desirable limits as shown by Garg and Ali (2000).

The objective function includes the net financial returns from the crops and the costs of canal and ground water. The net financial return from the crop is calculated by subtracting the crop production cost from the market value of the crop. The crop production costs are inclusive of non-water related costs like seeds, fertilizers, etc. and no change in the existing farm practices is assumed. The model is applied on decade (10 days) basis and the variables in the model include: Decade water withdrawals from the canal and tube well for irrigation, areas under different crops and deficit levels for different crops. The objective function for maximizing the net financial return from the crops can be expressed as:

$$\text{Maximize}\, Z = \sum_{c=1}^{\text{NCR}} \left[A_c \times y_{m_c} \times \left(\frac{y_a}{y_m}\right)_c \times \text{ECR}_c\right] - \sum_{t=1}^{\text{NDY}} (\text{OM}_{\text{sw}} \times \text{sw}_t + \text{OM}_{\text{gw}} \times \text{gw}_t) \quad (1)$$

where Z is net financial return; c and t are the indices for the crop and decade (10 days) irrigation interval respectively; NCR is the total number of crops; A_c is irrigated area of cth crop (ha); y_{m_c} is maximum crop yield per hectare of cth crop (100 kg per ha); ECR_c is net financial return per 100 kg of cth crop (Rs per 100 kg); $(y_a/y_m)_c$ is relative yield of cth crop; OM_{cw}, OM_{gw} are operation and maintenance costs of surface water and ground water respectively (Rs/ha-m); sw_t is surface water allocated in tth decade (ha-m); gw_t is ground water allocated in tth decade (ha-m) and NDY is number of decade (10 days) irrigation interval in a year. Relative yield of the cth crop in Eq. (1) can be expressed by using the multiplicative approach (Doorenbos and Kassam, 1979; Smith, 1992) as follows:

$$\left(\frac{y_a}{y_m}\right)_c = \prod_{\text{gs}=1}^{\text{Ngs}c} \left[1 - k_{y_{\text{cgs}}} \left\{1 - \left(\frac{\text{ET}_a}{\text{PET}}\right)_c\right\}\right] \quad (2)$$

where Ngs$c$ is total number of crop growth stages for the cth crop; $k_{y_{\text{cgs}}}$ is crop yield reduction factor for cth crop under gsth crop growth stage; PET is potential evapotranspiration for cth crop and ET_a is actual evapotranspiration. ET_a can be written as:

$$\text{ET}_a = k_s \times \text{PET} \quad (3)$$

where k_s is soil water stress coefficient and can be written as (Allen et al., 1998):

$$k_s = \frac{\text{TAW}-D_r}{\text{TAW}-\text{RAW}} = \frac{\text{TAW}-D_r}{(1-p_m)\text{TAW}} \quad (4)$$

where TAW is total available soil water in the root zone (mm); RAW is readily available soil water in the root zone (mm); D_r is root zone depletion (mm) and p_m is the maximum allowable deficit level (fraction of TAW) within which no water stress condition exists. D_r will be greater than RAW at the water stress condition and can be written as:

$$D_r = p_s \times \text{TAW} \quad (5)$$

where p_s is the allowable deficit level (fraction) of TAW at water stress condition. Therefore using Eqs. (3)–(5), Eq. (2) can be written as:

$$\left(\frac{y_a}{y_m}\right)_c = \prod_{\text{gs}=1}^{\text{Ngsc}} \left[1 - k_{y_{\text{cgs}}} \left\{1 - \frac{(1-p_{s_c})}{1-p_{m_c}}\right\}\right] \quad (6)$$

where p_{s_c} and p_{m_c} are the deficit levels under stressed and no stressed conditions for the cth crop respectively.

The objective function is considered to be bounded by the following constraints:

(i) Surface water diversion in each decade must not exceed either the decade canal capacity or water available at the river in a decade.

$$\text{sw}_t \le \min(\text{CW}_t, \text{RW}_t) \quad (t = 1, 2 \ldots \text{NDY}) \quad (7)$$

where CW_t and RW_t are canal capacity and water availability in river at tth decade respectively (ha-m).

(ii) Total ground water withdrawal through tube well in any of the decade must not exceed the decade available capacity of the tube wells.

$$\text{gw}_t \le \text{TWC}_t \quad (t = 1, 2, \ldots \text{NDY}) \quad (8)$$

where TWC_t is existing tube well capacity for tth decade.