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Irrigation Water Management Using a Dynamic Crop Growth Model

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ABSTRACT: There has been a considerable increase in the irrigated agricultural areas all over the world in the last few decades. The major reason for such an increase can be attributed to growing demand for food by the increasing population. However, this has created a competing environment for water, which is a scarce resource but essential for agricultural production. Hence better water management practices are warranted. It follows that new scientific techniques in agriculture and in irrigation management is to be introduced. Irrigation scheduling under water deficit situation is the challenge before the scientists and engineers. It is known that the sensitivity of any crop to water deficit is not uniform throughout its growth, and therefore it is difficult to take a decision by the irrigation manager on how to distribute the deficit along the intra-seasonal periods of a crop. The practice so far has been either to uniformly distribute the deficit throughout the crop growth or to decrease the cropped area so that full irrigation can be provided. This study proposes the use of ORYZA 2000: lowland rice crop growth simulation model in conjunction with an optimization model to effectively schedule the irrigation releases from the reservoir in order to achieve minimum reduction in crop yield due to the water stress and also maximise the water use efficiency (crop per drop). The integrated ORYZA 2000: rice crop growth model with an optimization framework for operating a reservoir that irrigates multiple crops in a command area, which aim to minimize the yield reduction due to water deficit for the crop. The model is demonstrated using a case study—Chittar river basin irrigation system, Tamilnadu, India.

INTRODUCTION

Over the last 30 years irrigated areas have increased rapidly, helping to boost agricultural output and feed a growing population. Irrigation uses the largest fraction of water in almost all countries. Globally, 70 percent of freshwater that is diverted for human purposes goes to agriculture (FAO, 1996). Irrigation water demand is still increasing because the area being irrigated continues to expand. The great challenge for the coming decades will be the task of increasing food production with less water, particularly in countries with limited water and land resources. Water productivity for food production was raised as one of the major issues at the Second World Water Forum convened in March 2000 by the World Water Council in The Hague, the Netherlands, where a vision towards water security and a framework for action to achieve this was presented. One of its main targets was defined as the need to increase water productivity by 30% in 2015 for food production from rainfed and irrigated agriculture.

Water stress affects crop growth and productivity in many ways. Most of the responses have a negative effect on production but crops have different and often complex mechanism's to react to shortages of water. While agricultural water supply is increasingly limited, many irrigation schemes are routinely operated according to maximum supply conditions and lack appropriate procedures and mechanisms to adjust supply and cropping pattern to water availability. When the available water is limited the area that can be irrigated with full water supply would become limited and the food production is constraint by the area being irrigated. However, increasing the irrigated area by imposing certain stress level of water supply might help increase the irrigated area thereby increasing the food production. Nonetheless, the imposed stress levels have to be scientifically identified so that the reduction in crop yield (compared to full irrigation) is minimal. This kind of management is highly challenging since on one hand the aim is to increase agricultural production, and on the other hand the focus is to maximize the irrigated area with a specific amount of available water. Therefore accurate knowledge on the impact of reduced water supply on yield is required to define appropriate strategies to adjust crop water supply and scheme operation according to strict economic criteria that allow the optimization of net income under limited water supply. Hence, there is a clear need to provide more accurate, and in particular, dynamic tools to analyse and evaluate the crop yield responses to suboptimal water conditions.

Optimal reservoir operation for irrigation scheduling at field level has always been one of the

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most important issues in water resources management. There are number of models developed for optimal reservoir operation using different optimization techniques. To increase water productivity and produce more rice with less water, experiments were conducted with reducing ponded water depths to soil saturation or by alternate wetting/drying which reported water savings of 23% with yield reductions only 6% (Bouman and Tuong, 2001). They also reported that the water use efficiency in the case of rice crop can be increased 5 times by controlled deficit irrigation thereby saving considerable amount of water.

Optimal reservoir operation models are developed for irrigating multiple crops using genetic algorithm with the objective to maximize the sum of the relative yields from all the crops by considering fixed cropping pattern (Kumar *et al.*, 2006; Raju and Kumar, 2004). Moradi-Jalal *et al.* (2007) have used a linear programming model to optimally allocate area for various crops under full irrigation. There are limited works available in the literature for optimal area and water allocation for irrigation purpose. A bi-level linear programming model was reported for optimal area and water allocation under multi crop condition (Haouari *et al.*, 2001). Multilevel model for optimal allocation of water and land resources were developed using area and water allocation model (Gorantiwar and Smout, 2003 and Gorantiwar *et al.*, 2006). Most of these works considered crop yield reduction as a linear function of crop evapotranspiration. Yield reduction models based upon evapotranspiration (ET) ratios (e.g., Doorenbos and Kassam, 1979) cannot provide crop yield in absolute terms (i.e., mass of grain per unit cultivated area), and these models have no endogenous optimization capacity. Physiologically based crop models provide a useful tool for simulation of agricultural experiments and are applied for the task of crop water production function determination. Crop growth simulation models can be integrated with optimization algorithm to explore the improved water management options. (Ines *et al.*, 2001). Using these kind of crop water production function, crop yield response to irrigation is obtained and used to determine planning-level irrigation schedules by Brumbelow *et al.* (2007).

There are number of crop growth simulation models available and widely used for water management. One such model is 'ORYZA2000', which is used to simulate the growth, development and water balance of rice under conditions of potential production, water limitations, and nitrogen limitations (Bouman *et al.*, 2001). Lately, FAO is in the process of revising their well documented Irrigation and Drainage paper no. 33 "yield response to water", by incorporating crop growth simulation models. For the field-crops, a model named 'AquaCrop' has been developed. This model is based on biomass water productivity (or biomass water use efficiency) relationship, which is at the core of the model growth-engine (Steduto *et al.*, 2007). However, in most of the currently available crop growth simulation models, they consider almost all the parameters involved in the crop growth process viz. solar radiation, CO_2, Nutrients and water. Therefore, these models require large amount of data/ parameters to simulate the crop growth; which is not necessarily available at many places.

From the above discussions it is clear that though there have been a number of studies to develop optimal irrigation schedules for a system, most of them did not considered the dynamic growth of the crops which directly affects the net benefit in terms of production. Also, the allocation of the irrigated water can be decided in a better way by simulating the actual crop conditions in the field, which was not considered by many researchers. If one were to develop such an integrated model for irrigation water management, one need to incorporate the crop growth simulation in the optimization framework. It is evident from the above review that an approach using water productivity based crop growth simulation for optimal reservoir operation and irrigation scheduling has not received attention by many researchers.

In this research study, ORYZA 2000: lowland rice crop growth model is used to simulate the rice crop growth and yield. The primary objective of the model is to relate the amount of water applied and corresponding crop yield. An optimization model is combined with the crop growth simulation model for operating a single reservoir that irrigates multiple crops in a command area. Crop growth simulation model provide inputs to the optimization model in terms of the soil moisture and the status of crop development already achieved up to the current period. Other inputs are reservoir storage at the beginning of a period, inflow during the previous period. The solution specifies the reservoir release and optimal irrigation allocations to individual crops during an intra-seasonal period. The model optimizes a measure of crop production by simulating it during the entire crop growth period. The model is applied to a case study of Chittar basin, in Tamilnadu and the results are presented in the following sections.

ORYZA 2000: MODELING LOWLAND RICE

The ORYZA 2000 model (Bouman *et al.*, 2001) simulates the growth and development of rice crop by rate of biomass production and accumulation at different plant organs. The biomass production is calculated from the weather, crop data. The detailed information about the model theory and computer program code is given in Bouman *et al.,* 2001. Before using the model, the crop parameters should be calibrated. The important parameters calibrated specifically are development rates, partitioning factors and leaf growth rate. Using the crop, experimental, soil and weather data from the study area, important crop parameters were calibrated.

RESERVOIR OPERATION—OPTIMAL IRRIGATION SCHEDULING

In the rotational irrigation schedule, reservoir operation is in weekly time step, i.e irrigation interval is fixed as six days. The optimizer will provide the weekly irrigation schedule and crop area. Irrigation depth ranges from 0 to potential weekly water demand, including deep percolation loss which is assumed as 1cm/day. Crop area ranges from area irrigated by intensive and extensive irrigation. Overall irrigation efficiency is assumed as 60%. To check, whether the optimiser provided irrigation depth at different weeks to the given area is possible, storage continuity equation is solved for all weeks. Here inflow and climatic data is assumed to be known for the crop season. Once the irrigation schedules and cropping area satisfies the reservoir storage continuity equation, it shows that the generated irrigation schedules for the cropping area is possible. At any time if storage continuity is not satisfied, then the current irrigation schedule to the crop area is not possible. Again new irrigation schedule and crop area provided by the optimser, till it satisfies the above storage continuity for all time steps. The combined optimal irrigation scheduling and crop growth model schematic is given in Figure 1.

An irrigation schedule which satisfies the reservoir storage continuity equation is given as input to the crop growth simulation model, to simulate the crop yield for that particular irrigation schedule. Again, the crop yield is given as input to optimizer. Like this the cycle will continue many times, till it reaches the optimal or near optimal irrigation schedule and cropping area.

Testing Data

In this study, crop, experimental, soil and weather data were taken from field experiment conducted at Tamil Nadu Agricultural University, Coimbatore, India. Experiment conducted during the Kharif 2000, using the crop variety ADTRH-1 (Luikham, 2001). From the experiment crop growth phenology, Leaf Area Index (LAI), total above ground biomass and yield data were collected at regular intervals. Using these model, parameters like crop development rates, partitioning factors and leaf growth rates were estimated. Three different irrigation treatment data were used for parameter estimation. The irrigation treatments are (1) 5 cm irrigation is given at the same day when the standing water disappears, (2) 5 cm irrigation is given at one day after the disappearance of the standing water and (3) 5 cm irrigation is given at three days after the disappearance of the standing water. All other data are same as variety IR72 (Bouman *et al.*, 2001).

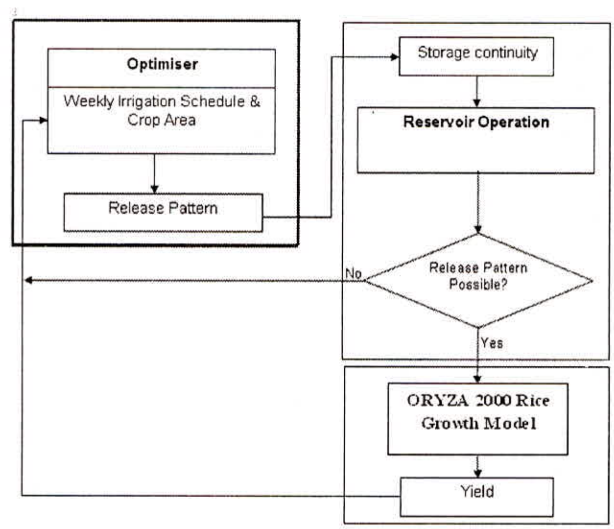

Fig. 1: Schematic representation of the combined ORYZA 2000: crop growth simulation—Optimal irrigation scheduling Model

Study Area

Karuppanadhi is one of the important tributaries of river Chittar. The reservoir details are given in the Table 1.

Table 1: Karuppanadhi Reservoir Particulars

Capacity	5.2 Mm^3
Command Area	3146 ha
Crops	Rice, Pulses
No. of Anicuts	6
No. of Irrigation Tanks	72
Command area under tanks	7963 ha (Indirect Command area)

Rice is the major crop in this sub-basin. Cropping pattern is decided based on how much area of rice crop can be irrigated with the available water. In the remaining area dry crops are grown. Coconut is grown in 17% of the command area (garden land). Generally garden lands are having their own water sources well/bore wells. So, water allocations to Coconuts are not considered. Remaining 83% of cultivable command area is available for rice crop and dry crops. Water release priority is first given to direct command area. Surplus is diverted to the irrigation tanks to irrigate indirect command area. For optimal reservoir operation—irrigation scheduling, July 1996–October 1996 reservoir inflow and rainfall data used. Chittar river basin map is shown in Figure 2.

RESULTS AND DISCUSSION

The combined simulation-optimisation model developed in this research work was applied to the Karupanathi Reservoir Project for irrigation, Tamilnadu, India. Reservoir data like daily inflow to the reservoir, reservoir storage at the beginning of the season, daily rainfall, etc are used for the period from July, 1996 to October, 1996. Water is released from the reservoir during June to October and October to February for two rice crops cultivation.

The model was solved for different amounts of water deficits viz. no deficit, to around 20% deficit. Model output is water allocation along with weekly irrigation schedules and yield for different deficit conditions and the corresponding cropping area under rice crop. The effect of controlled water stress on yield reduction and total yield from the irrigation project are given in Table 2. Here available total water is same for all water allocation scenarios.

The observed crop growth from the field experiment and ORYZA 2000 crop growth model simulated crop growth are shown in Figure 3. The model slightly under estimates the LAI and biomass and over estimates the yield.

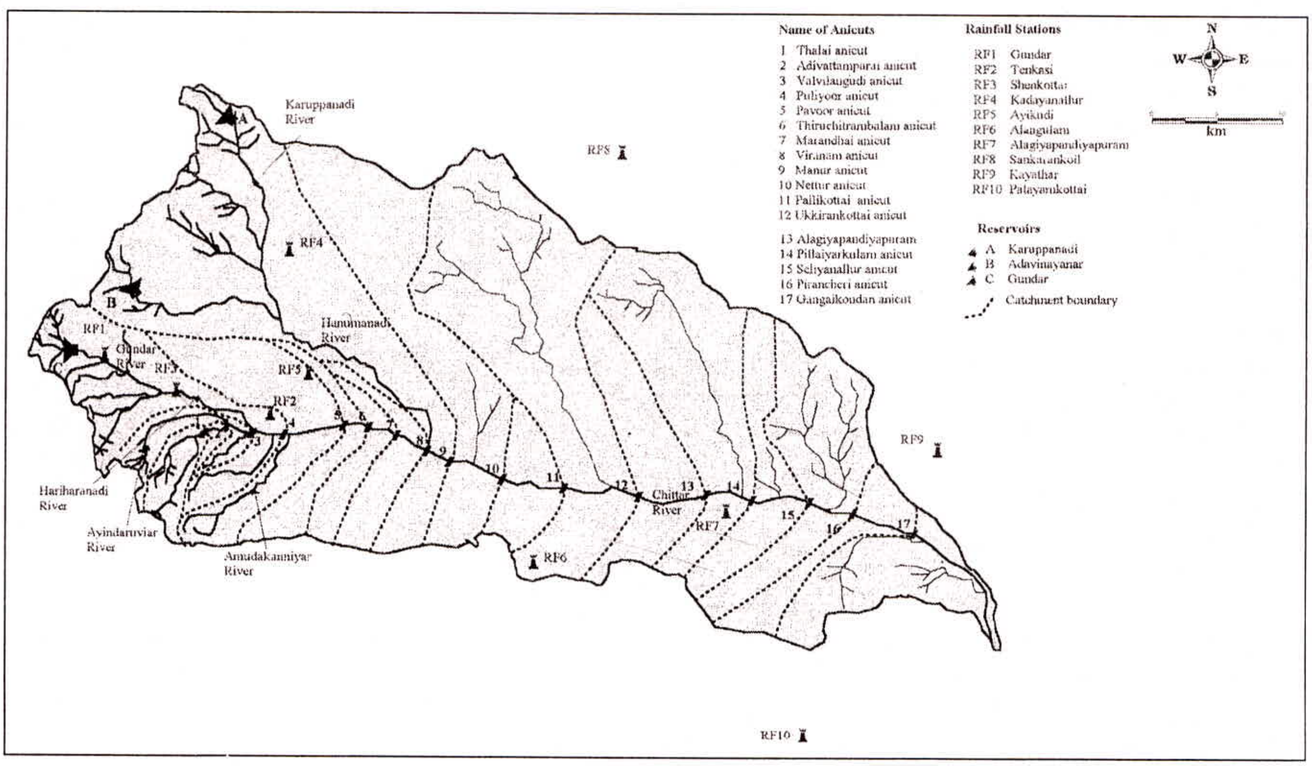

Fig. 2: Chittar river basin

Table 2: Different Levels of Water Allocation, Yield Reduction and Total Yield

Water Used, mm*	*Yield, Kg/ha*	*Area, ha*	*Total Yield, Kg*	*Water Reduction, (%)*	*Yield Reduction (%)*	*Total Yield Increase, (%)*
1090	5558	1075	5974850	0	0	0
947	5123	1220	6250060	13	7.8	4.6
862	4860	1308	6356880	21	12.5	6.3

*includes irrigation and effective rainfall.

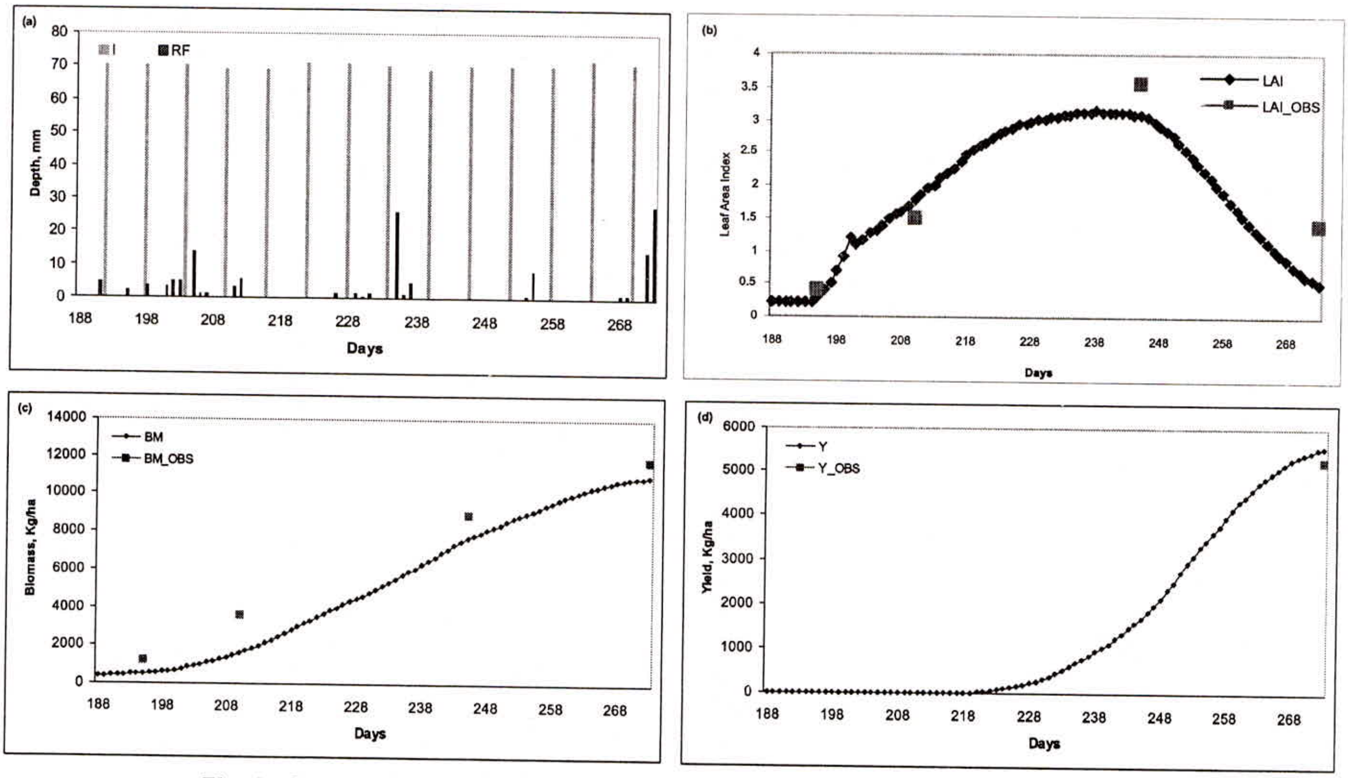

Fig. 3: Comparison of observed and simulated crop growth for potential production. (a) Irrigation and effective rainfall, (b) Leaf area index, (c) Biomass and (d) Yield

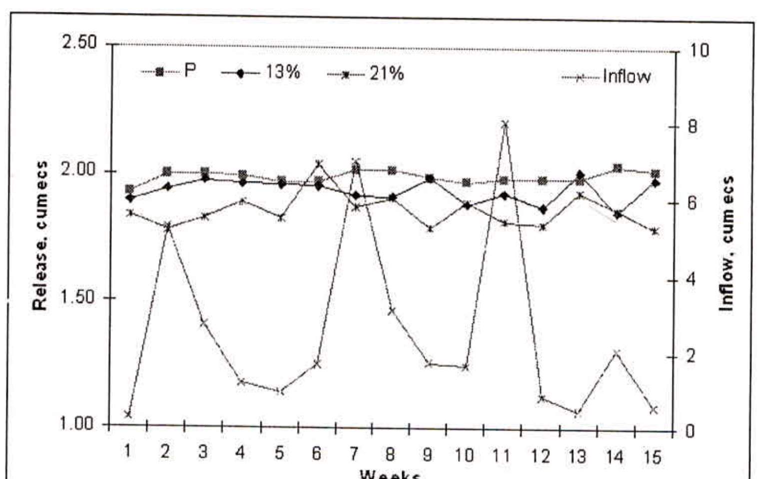

Fig. 4: Reservoir release and inflow during the crop season

Compared to reduction in water allocation, yield reduction is not significant (Table 2). As water allocation reduces, yield per hectare is reduced but cropping area is increased. This in turn increases the overall yield from the irrigation project. So, the controlled deficit water allocation will increase the water productivity (crop per drop of water).

Figure 4 shows the reservoir inflow during the crop season and reservoir releases towards irrigation for different water allocation scenarios. As per the reservoir operating policy, the release pattern is 25 cusecs continuously for the whole crop season, but all the water allocation scenarios are different from the reservoir operating policy release pattern.

CONCLUSIONS

The paper reports the formulation and application of a combined optimal reservoir operation for irrigation scheduling and crop growth model under simulation—optimisation framework. The combined model developed in this study for the seasonal or annual operation of irrigation reservoir. The model has been applied to Karupanadhi reservoir irrigation system of Chittar basin in Tamilnadu, India. The results are encouraging, and it is observed that the model identifies the sensitive growth period effectively and reduces the deficit in water availability during the critical period. In general, the results suggest that the model can be applied for irrigation planning.

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