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AWAM-A Model for Optimal Land and Water Resources Allocation

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Abstract

The planning for irrigation water management in an irrigation scheme consists of the preparation of an allocation plan for distribution of land and water resources to different crops up to tertiary or farm level, and water delivery schedules in terms of timing and amount of water delivery for this allocation plan according to the set objectives/targets. It is necessary to consider the heterogeneity in soils and climate, and complexity of the water distribution network, while developing the allocation plans. Further, there is a need to allocate water both efficiently and equitably. Preparation of the allocation plan becomes a complex process when the water availability is less than the demand for water for adequate irrigation of the culturable command area of the irrigation scheme. In the past, several methodologies have been developed to prepare allocation plans but these models do not consider the above-mentioned requirements together. This paper presents the developed model, AWAM (Area and Water Allocation Model) that addresses the heterogeneity in an irrigation scheme and includes the performance measures of productivity and equity while developing the allocation plans. The AWAM model has four phases to be executed separately for each set of irrigation interval over the irrigation season. The paper briefly discusses the applicability of the AWAM model by producing land and water allocation plans and water delivery schedules for case study of Nazare medium irrigation scheme in southern India.

Keywords: *optimization, irrigation, land & water allocation, productivity, equity*

1.0 Introduction

The irrigation schemes in semi-arid and arid regions operate under rotational water distribution. These schemes are usually large and heterogeneous in nature i.e. with several crops, soils and a large network of canals with varying characteristics. The practice of spreading water over a large area has been a strategy of irrigation in these irrigation schemes, mainly to provide protective irrigation and alleviate famine. As a result of this, water is relatively short in supply compared to land and most cultivable command areas do not get enough water (adequate irrigation depth). Hence the irrigation management in such cases is a complex process. It requires decisions on how much water and area should be allocated to different crops when grown on different soils and in different parts or regions of the scheme (the allocation plan), based on water availability, maximization of benefits, equitable water supply, different needs and physical constraints of the scheme. Similarly releasing the appropriate quantity of water at the appropriate time to the different crops in different fields from the reservoir

headwork through the canal system (the water release schedule) is also important for the maximum benefits. Hence it is important to identify the optimum allocation plan and corresponding water release schedule for the canal network.

As compiled by Gorantiwar (1995) and Smout and Gorantiwar (2005), there are three possible modeling approaches depending on the water availability in the schemes, based on which decisions can be made regarding the allocation of land and water to different crops and the schedule of operation of the canal system. The first is when the water supply in the scheme is adequate; the second is when the water supply is limited but the cropping pattern (or areas) is pre-decided and the third case is when the water supply is limited and the cropping pattern (or areas) can be chosen freely. The approach adopted in the third category of models is most appropriate as the area and water resources are allocated optimally to different crops without assuming the allocation policy for any of the resources as known. This is done by considering several alternative levels of crop water requirement and the corresponding yield over the entire season or over an individual irrigation period.

In the present paper, a resource optimization model (Area and Water Allocation Model, AWAM), based on the third category approach, is presented for rotational irrigation systems where shortages of water prevent adequate irrigation of the whole irrigable command area of the irrigation scheme. This model optimally allocates the area and water to different crops grown in different regions of the irrigation scheme while considering the equity in distribution of resources such as water or irrigated area or output such as crop production or net benefits.

2.0 AWAM Model

The AWAM model (Gorantiwar, 1995 and Smout and Gorantiwar, 2005) (figure 1) allocates the land area and available surface water to different crops cultivated in different parts of the irrigation scheme to maximize the net benefits from the irrigation and is developed for irrigation schemes which operate under rotational water supply. The model is designed for allocating the resources available at scheme level to the tertiary level and for deciding the water release schedule at tertiary level. The irrigation interval is assumed to be pre-determined and uniform for all crop and soil combinations. The AWAM model has four phases and is executed for each irrigation interval or a set of irrigation intervals over the irrigation season or year. These are: generation of irrigation strategies (Phase-1), preparation of irrigation programs (Phase-2), selection of irrigation programs (Phase-3), and optimum allocation of resources (Phase-4).

2.1 Phases of AWAM model

2.1.1 Generation of irrigation strategies

The area of an irrigation scheme with similar climate (Region), soil (Soil group) and crop is termed as Crop-Soil-Region (CSR) unit (but this is not a physical division of the irrigation scheme). Water scarcity in these schemes may make deficit irrigation an effective means to meet the objectives of the irrigation scheme. There are several ways to provide deficit irrigation for each specified CSR unit. There is a need to select the optimal way which has to be arrived by considering all CSR units, water availability

and characteristics of the command area of irrigation scheme together (Keller et al 1992 and Gorantiwar and Smout 2005). Hence to allocate water optimally requires estimates of the outputs obtained from several possible strategies that are based on different combinations of deficit (percentage moisture stress in the soil root zone on the day of irrigation) over all the irrigation periods (Gorantiwar and Smout 2005). In Phase-1 irrigation strategies are generated for each CSR unit for a specified set of irrigation intervals. This results in several irrigation strategies for each CSR unit, each with variable deficit for each irrigation.

2.1.2 Preparation of irrigation program

In Phase-2 an irrigation program that consists of information on yield/benefits and irrigation requirement (depth) per irrigation is prepared for each irrigation strategy of each CSR unit for a specified set of irrigation intervals. The irrigation program is prepared from the following two sub-models. The details of these submodels are described by Gorantiwar(1995) and Smout and Gorantiwar (2005).

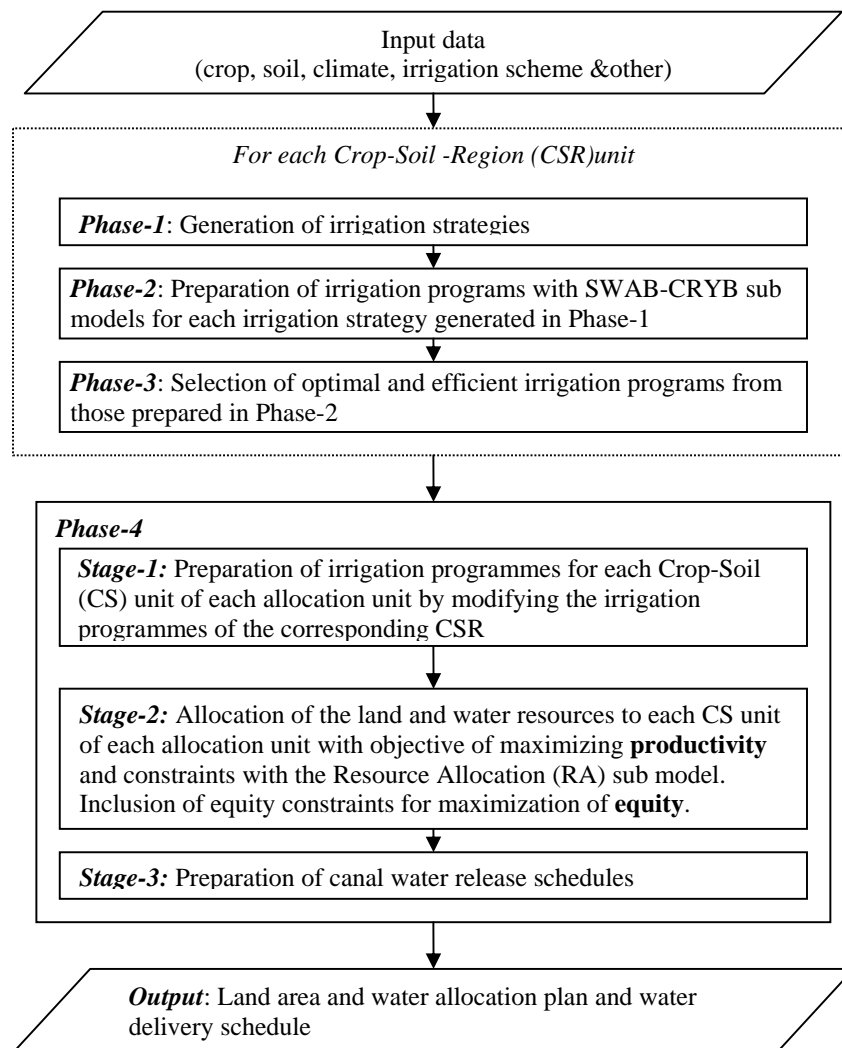


Figure 1. Area and Water Allocation (AWAM) model

SWAB: In response to deficit for each irrigation (specified in the irrigation strategy), this sub-model simulates daily soil moisture in the soil root zone, estimates daily actual crop evapotranspiration, the irrigation requirement (depth) per irrigation and the other related parameters.

CRYB: This sub-model estimates crop yield from the actual evapotranspiration estimated in SWAB sub-model and computes net benefits.

2.1.3 Selection of irrigation programs

Phase-2 may generate many irrigation programs of which several may not be important. For example the irrigation programs generated with irrigation strategies having full deficit for successive irrigations may simulate zero yield or the irrigation programs generated with irrigation strategies having no deficit for successive irrigations may simulate maximum yield but with excessive irrigation water requirement. Moreover some of these programs may not be optimal and even if included in the optimization model of the fourth phase will not appear in the solution. Incorporation of all these programs in the optimization model may also make the problem computationally infeasible to solve. Therefore in Phase-3 the number of irrigation programs for the given unit is restricted by selecting only optimal irrigation programs. The model selects for each CSR unit a specified number of irrigation programs, which are both optimal and efficient according to specified criteria.

2.1.4 Optimum allocation of resources

Phase-4 of the model allocates land and water resources optimally to different crops cultivated on different soils in different allocation units. It utilizes the selected irrigation programs generated in Phase-3.

The entire irrigation scheme is physically divided into a number of smaller units called "Allocation Units" (AU) over which land and water resources are allocated. These units may include different soils and crops however the climate is assumed to be uniform over a particular AU. The need to divide the irrigation scheme into several AUs arises from the heterogeneous nature and large extent of the irrigation scheme. By dividing the scheme in this way it is possible to make allocation of resources, water delivery schedules and management of the irrigation scheme efficient. The largest possible size of an AU is the size of the irrigation scheme itself and the smallest size of an AU is an individual farm or field served by one outlet. The intermediate sizes are the command areas of the secondary, tertiary and quaternary canals or groups of these canals.

Phase 4 of the model allocates land and water resources optimally to Crop-Soil (CS) units of each AU. A CS unit is a unit with similar crop and soil properties within an AU. This phase performs the allocation in three stages.

Stage-1: The phase-3 selects the specified number of irrigation programs for each CSR unit. In this stage of Phase-4, each CS unit of an AU is assigned with the irrigation programs of the CSR unit having the same crop, soil and climate. As stated earlier a CSR unit is not a physical division of the irrigation scheme and hence the distribution and conveyance efficiencies can not be considered while working out the irrigation requirements for each irrigation. An AU however is a physical division of the irrigation scheme and hence these efficiencies are included at this stage by modifying the

irrigation requirements of each irrigation of the selected irrigation programs appropriately.

Stage-2: In this stage, the resources are allocated to each CS unit of each AU with chosen objective (maximization of net benefits) and constraints (resource availability, physical and output requirement) with the Resource Allocation (RA) sub model (described later). The RA sub model is solved by linear programming. The decision variables are the area to be irrigated under different crops on each soil type (CS) of the AU and following different irrigation scheduling underlined in irrigation programs prepared for the corresponding CS of AU. Note that these irrigation programs are prepared in Phase-2; screened in Phase-3 and modified in Stage-1 of Phase-4. The output of the model is thus area to be irrigated under different crops cultivated on each soil type of the AU and the corresponding irrigation program. Thus this stage gives the optimum allocation plan.

Stage-3: In this stage, the water release schedule for the canal system for the optimum allocation plan is prepared by determining the irrigation scheduling of the selected irrigation program for each CS unit of AU (obtained in Stage 2 of Phase 4).

2.2 Resource Allocation (RA) sub model

The objective of the RA sub model is to maximize the net benefits and thus in turn maximize the productivity while maximizing the equity subjected to several constraints related to availability and requirement of different resources. The objective function and constraints are briefly described below, and the detailed mathematical formulation of RA sub model is presented by Gorantiwar (1995), Smout and Gorantiwar (2005) and Gorantiwar et al (2006).

2.2.1 Objective function

The objective function is proposed for the maximization of the net benefits. The alternative objective function is the maximization of the irrigated area.

2.2.2 Constraints

2.3.2.1 Physical constraints: These are the constraints that limit the use of resources available in the scheme according to the ability of the system to use these resources:

Area constraints, Canal capacity constraints and Outlet capacity constraints.

2.3.2.2 Resource availability constraints: These constraints set the limits on availability of different resources in the scheme, depending on which land area is allocated to different activities:

Intraseasonal water supply constraints and Reservoir storage constraint.

2.3.2.3 Output requirement constraints: These constraints specify the need to generate output at a certain prescribed level and/or by a certain prescribed law:

Crop constraints and Food requirements constraints.

2.3.2.4 Equity constraints: the following four means of achieving equity are incorporated in the model through the equity related constraints:

Equity in crop area, Equity in water, Equity in crop production and Equity in net benefits.

3.0 Application

3.1 Case study irrigation scheme

The applicability of AWAM model to obtain the land area and water allocation plans is demonstrated with the help of case study on the “Nazare Medium Irrigation Scheme” in a semi-arid region of Maharashtra State of India. This irrigation scheme is representative of storage reservoir irrigation schemes that operate under rotational water supply in south Asia.

The irrigation season of this scheme starts from the 15th October and ends on 14th October of the next year. There are three distinct crop seasons within the irrigation season. These are winter (*Rabi*) (15th October to 14th February), summer (15th February to 14th June) and rainy (*Kharif*) (16th June to 14th October). In this study, the irrigation season was considered to spread over *Rabi* and summer crop seasons only. Normally the irrigation interval in *Rabi* season is 21 days and in summer season is 14 days.

The irrigation scheme is supplied from a reservoir by a main canal and one distributory canal. The cultural command area (CCA) of the irrigation scheme is 3539 ha. There are 28 direct outlets (4 on the main canal and 24 on the distributory canal) and four minors (all on distributory canal) with 9 outlets. The CCA of all 28 outlets and 4 minors were considered as allocation units, resulting in 32 AUs. The data related to allocation units in terms of different efficiencies (application, distribution and conveyance); soil types etc were obtained from different sources.

The climatological data was collected from local daily records and the climate over the reservoir and the entire command area was assumed as uniform and thus there was only one 'Region'. The command area is characterized with four different types of soils (clay, loam, sandy loam and silty clay). In the present study as two crop seasons formed the irrigation season, gram, sorghum, onion, wheat (*Rabi* crops), groundnut and sunflower (summer crops) were considered in the analysis. Based on the previous trend in the irrigation scheme, a fixed cropping distribution was assumed of gram-25%, sorghum-20%, onion-10% and wheat-15 % in *Rabi* and Sunflower –10 % and groundnut-20% in summer season. This fixed cropping distribution was considered for investigating the issues under consideration in this paper, though the AWAM model can also consider the free cropping distribution in which the model is free to select any crops depending on which crops produce maximum total net benefits from the irrigation scheme (refer to Gorantiwar 1995 and Smout and Gorantiwar 2005).

3.2 Results

The allocation plans and water delivery schedules were obtained for seven sets of irrigation interval. These were: 14 days (I-14); 21 days (I-21); 28 Days (I-28); 35 days (I-35) {both *Rabi* and summer seasons}; 21 in *Rabi* and 14 in summer (I-21-14); 28 in *Rabi* and 21 in summer (I-28-21); and 35 in *Rabi* and 21 in summer (I-35-21). These were obtained for two scenarios; one did not include equity (no equity) and other included equity in water distribution (with equity). The productivity and equity values

associated with the allocation plans and water delivery schedules, for the two scenarios and seven sets of irrigation interval are presented in figure 2.

Productivity is quantified as the ratio of the output (measured as net benefits in monetary units) to the maximum output attainable from the resources available (land and water). The maximum net benefit B_{max} , was obtained for the irrigation interval of 14 days under the “no equity” scenario. Hence the productivity values for different scenarios and irrigation intervals were computed with reference to B_{max} by considering this value as the maximum attainable. Equity is related to the distribution of water to different allocation units based on cultivable command area (CCA) and can be quantified by allocation ratios of different AUs as proposed by Gorantiwar (1995) and Gorantiwar and Smout (2005). The allocation ratio for a specified AU is the ratio of the actual allocation proportion as a result of allocation of water to the desired allocation proportion for this AU. The interquartile allocation ratio (IQAR) is used as the measure of equity. IQAR is defined as “the average allocation ratio of the poorest quarter divided by the average allocation ratio of the best quarter” (Gorantiwar 1995 and Gorantiwar and Smout 2005).

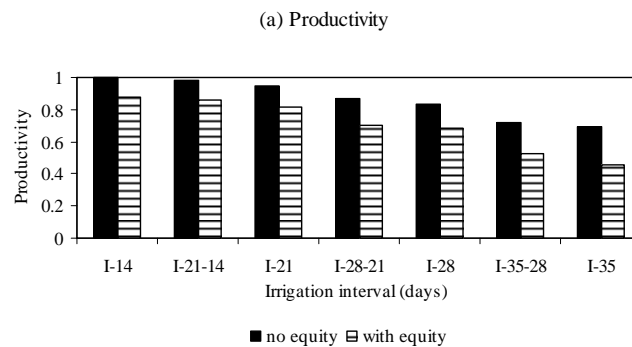


Figure 1. Productivity for ‘no equity’ and ‘with equity’ scenarios for different irrigation intervals for Nazare Medium Irrigation Scheme, India.

Figure 1 shows that the productivity values decrease with the irrigation interval for both scenarios. The results for equity show the equity is 1.0 for the scenario of ‘with equity’ for all irrigation intervals and zero for the ‘no equity’ scenario, for all irrigation intervals. For Nazare Irrigation Scheme under study, where in the objective is to achieve maximum equity with the productivity, the allocation plan for the scenario of maximum equity would be useful. The details of this allocation plan are presented in Table 1, which shows for each AU, the area allocated for irrigation and the volume of water allocated in the plan for this scenario.

It is necessary to prepare the water delivery schedules according to the allocation plans. Currently the schedules are prepared for the allocation plans that are based on the adequate irrigation. However for deficit irrigation, the delivery schedules need to be prepared differently as the water allocated is different for different allocation units and during different irrigation periods. An extension of the AWAM model is a procedure to prepare water delivery schedules for the allocation plans that are based on deficit irrigation by using integer programming and genetic algorithm. However for lack of space, the details are not discussed in this paper.

Table 1. Land area and water allocation plan by proposed methodology

AU	CCA of AU (ha)	Area (ha)	Water (ha-m)	AU	CCA of AU (ha)	Area (ha)	Water (ha-m)
1	39	18.55	8.04	17	145	61.36	29.87
2	36	15.59	7.42	18	147	62.20	30.29
3	8	3.47	1.65	19	118	51.25	24.31
4	27	11.73	5.56	20	661	223.76	136.19
5	395	146.38	81.38	21	65	28.14	13.39
6	33	14.29	6.80	22	156	67.54	32.14
7	59	25.62	12.16	23	30	12.69	6.18
8	22	9.55	4.53	24	37	15.66	7.62
9	211	73.31	43.47	25	89	37.66	18.34
10	68	29.53	14.01	26	93	39.35	19.16
11	62	26.93	12.77	27	115	48.66	23.69
12	142	49.24	29.26	28	30	12.69	6.18
13	127	55.15	26.17	29	32	13.54	6.59
14	81	35.18	16.69	30	87	36.81	17.92
15	217	94.24	44.71	31	35	14.81	7.21
16	82	37.99	16.89	32	90	38.08	18.54

4.0 Conclusions

This paper highlighted the importance of considering both productivity and equity while developing the allocation plans and water delivery schedules for an irrigation scheme with limited water supply and presented the approach to develop the allocation plans and the water delivery schedules for optimization of productivity and equity. This enables the irrigation authorities to select the appropriate allocation plans depending on the local situation. The results of the model obtained with one case study on an irrigation scheme in central India indicated that the productivity and equity conflict with each other, if the water resources are allocated optimally.

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