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A MULTILEVEL APPROACH FOR OPTIMIZING LAND AND WATER RESOURCES AND IRRIGATION DELIVERIES FOR TERTIARY UNITS IN LARGE IRRIGATION SCHEMES:

1.METHOD

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Abstract: This paper presents the area and water allocation model (AWAM), which incorporates deficit irrigation for optimizing the use of water for irrigation. This model was developed for surface irrigation schemes in semi arid regions under rotational water supply. It allocates the land area and water optimally to the different crops grown in different types of soils up to the tertiary level or allocation unit. The model has four phases. In the first phase, all the possible irrigation strategies are generated for each crop-soil-region combination. The second phase prepares the irrigation program for each strategy, taking account of the response of the crop to the water deficit. The third phase selects the optimal and efficient irrigation programs. In the fourth phase of the model irrigation programs are modified by incorporating the conveyance and the distribution efficiencies. These irrigation programs are then used for allocating the land and water resources and preparing the water release schedule for the canal network.

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**Introduction**

Large surface irrigation schemes are heterogeneous in nature i.e. with several crops, soils and a large network of canals with varying characteristics (design capacities, efficiencies, command area, length, duration of operation etc.). The schemes in semi-arid and arid regions are further associated with limited water supply and operate under rotational water distribution. 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, 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. This plan would also enable the planner not to waste water by irrigating a smaller area than optimum and not to stress the crops unnecessarily by irrigating a larger area than optimum.

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. In this case, the allocation process comprises optimally allocating the area to different crops such that maximum yields per unit area are obtained (area allocation models) (Matanga and Marino 1977; Maji and Heady 1978; Morales et al. 1987; Afshar and Marino 1989; Mayya and Prasad 1989; Paudyal and Gupta 1990; Afshar et al. 1991; Thandaveswara et al. 1992; Shyam et al.
1994 and Onta et al. 1995). The second is when the water supply is limited but the cropping pattern (or areas) is pre-decided. In this case the limited water needs to be distributed to different crops such that maximum production and benefits are obtained from the entire scheme (water allocation models) (Hiessl and Plate 1990; Paudyal and Manguerra, 1990; Rao et al. 1990; Vedula and Mujumdar 1992; Akhand et al. 1995; Kalu et al. 1995; Wardlaw and Barnes 1999 and Kipkorir et al. 2001). The third case is when the water supply is limited and the cropping pattern (or areas) can be chosen freely. Both water and area need to be allocated optimally to different crops to obtain maximum production and benefits in the scheme (land and water allocation models).

In this third category of models 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 (Kumar and Khepar 1980; Rao et al. 1986; Sritharan et al. 1988 and Martin et al. 1989), or over an individual irrigation period (Matanga and Marino 1979; Yaron and Dinar 1982 and Bernardo et al. 1988; Mannocchi and Mecarelli 1994; Mainuddin et al. 1996; Sunantara and Ramirez, 1997, Paul et al. 2000 and Sahoo et al. 2001), and incorporating those into a linear programming or dynamic programming formulation. The first approach (entire season) considers the optimum distribution of the seasonal irrigation depth over different irrigation periods of the crop season separately for each crop. Therefore, these models may not give the appropriate optimum solution in a multicrop situation. The second approach (individual irrigation period) makes use of several combinations of irrigation depth per irrigation application and the corresponding crop yield for each crop. It is therefore most appropriate in a multicrop and water-limiting situation.
All these area and water allocation models are solved at one level i.e. allocating the resources available at tertiary level to tertiary level or allocating the resources available at scheme level to scheme level (the single field type of model). But it is difficult to apply the allocation results to the operation of the scheme because these do not specify the spatial distribution of the allocated resources. The spatial distribution is important due to the different specifications and efficiency of different canals in the distribution system and the variability of soil and climate in the scheme. Therefore resources available at the scheme level need to be allocated optimally up to the tertiary level for deciding the water release schedules for the tertiary units (the multi-field type of model). Hence the problem needs to be solved differently due to variation in soil types, irrigation methods and irrigation efficiencies and characteristics of canal networks. It is essential to consider these variations while allocating the resources available at scheme level to tertiary level. The models developed by Sritharan et al. (1988); Shyam et al. (1994); Kalu et al. (1995); Onta et al. (1995); Wardlaw and Barnes (1999) and Kipkorir et al. (2001) split the irrigation scheme into several groups and each group may have different characteristics. However, Shyam et al. (1994) and Onta et al. (1995) assumed the known water allocation policy and Kalu et al. (1995); Wardlaw and Barnes (1999) and Kipkorir et al. (2001) assumed the known area allocation policy. Sritharan et al. (1988) consider optimizing the hydraulic parameters of the irrigation layout (border and furrow) along with optimizing the use of land and water resources on a seasonal basis only.

In the present paper, a resource optimization model (Area and Water Allocation Model, AWAM) is presented for rotational irrigation systems where shortages of water prevent adequate irrigation of the whole irrigable command area of the irrigation scheme. 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. In irrigation schemes with rotational water supply, the irrigation interval is assumed to be pre-determined and uniform for all crop and soil combinations. The model is executed for each set of irrigation interval over the irrigation season. The model has four phases: generation of irrigation strategies, preparation of irrigation programs, selection of irrigation programs and optimum allocation of resources. In first phase irrigation strategies based on different degrees of deficit at each irrigation are generated for each crop, soil and climate region (CSR unit) of the irrigation scheme. The irrigation strategy contains the information on the deficit that should be applied during each irrigation. In second phase for each CSR unit, irrigation programs (irrigation depth per irrigation, yield and net benefits) are prepared with the help of a simulation model for different irrigation strategies generated in first phase. The irrigation strategies generated in first phase and hence irrigation programs obtained in second phase may run into thousands. Therefore, in third phase, all these irrigation programs are screened to obtain the desired number of irrigation programs which are most optimal and efficient. The model allocates the resources up to tertiary (allocation unit) level. Hence in first stage of fourth phase, the irrigation programs for each allocation unit are obtained from the appropriate CSR units. Then the intraseasonal irrigation depths of each irrigation program are modified to consider the conveyance and distribution efficiencies associated with the particular allocation unit. The irrigation programs of different allocation units are used in second stage of fourth phase to allocate the land and water resources optimally to different crops grown on different soils in different allocation units of the scheme within different limitations and constraints and to prepare the water release schedule for each allocation unit. The formulation of the model is presented in this paper.
Area and Water Allocation Model

The Area and Water Allocation Model (AWAM) is based on a multilevel approach for allocating the land and water resources in the irrigation scheme optimally to different crops. The subsequent sections present the details of the model.

Irrigation Scheme

The AWAM model is formulated to be suitable for heterogeneous irrigation schemes under rotational water supply. In rotational water supply, the water is delivered from the source to the different fields at predetermined intervals, irrespective of the crop grown in the field, type of soil and climate. In the AWAM model also, the water deliveries are assumed to follow this pattern. Therefore AWAM is not suitable for on demand type irrigation schemes, wherein water is available to a farm at any time and thus the interval between deliveries to different fields may vary. However AWAM takes care of the detailed response of soil, plant systems to the varying depth of irrigation (from zero to maximum permissible) at every irrigation application.

Resources

The major output to be obtained from the irrigation scheme is the produce or benefits generated from the cultivation and irrigation of different crops. The inputs required to generate the output are land, water, labor, machinery, fertilizers, seeds, pesticides etc. In the present model major emphasis is given to the allocation of land and water resources to different crops. The influence of the application of different quantities of water at
different times on crop yields and net benefits, and the allocation of different quantities of water on different land areas are considered, while assuming that the other inputs do not limit the production per unit area.

**Planning and Management Unit**

The entire irrigation scheme is physically divided into a number of smaller units called “Allocation Units” (AU). The allocation unit is the part of the irrigation scheme over which land and water resources are allocated. The climate is assumed to be uniform over the AU, but the AU may include different soils and crops. The climatic conditions may be different for different AUs. The need to divide the irrigation scheme into several allocation units arises due to the heterogeneous nature and large extent of the irrigation scheme and in order to make allocation of resources and management of the irrigation scheme efficient.

The largest possible size of the AU is equivalent to the size of the irrigation scheme itself. The smallest size of the AU is the individual farm. The intermediate sizes are the command area of the secondary, tertiary and quaternary canals or their groups. The size recommended is the command area of the canals at tertiary or quaternary levels. The AWAM model has provision to allocate the resources at a lower level such as farm level from the allocation of resources at the upper level such as tertiary level.

The procedure used in optimum allocation of resources in the AWAM model uses the generation of irrigation programs for each crop grown on different soils which exist in different climatic regions of the irrigation scheme. Though the climate is assumed to be uniform over the AU, it can include several soils and crops. Therefore the generation of irrigation programs at allocation unit level would need a lot of computational time. To
overcome this problem the irrigation scheme is divided into a number of units based on climate, soil and crop, but this is not a physical division of the irrigation scheme like the AU. This division is described below.

The area of the scheme with similar climate (Region), soil (Soil group) and crop is termed as a Crop-Soil-Region (CSR) unit. The CSR units are obtained with the combination of regions, soil groups and crops. The total number of CSR units is

\[ NU = \sum_{R=1}^{NR} \sum_{S=1}^{NSR} NC_{SR} \]

where \( NU \) = number of CSR units; \( R \) = index for the region in irrigation scheme, \( S \) = index for soil group in the \( R^{th} \) region, \( C \) = index for the crop in \( S^{th} \) soil group of \( R^{th} \) region, \( NR \) = total number of regions, \( NSR \) = total number of soil groups in \( R^{th} \) region, \( NC_{SR} \) = total number of crops in \( S^{th} \) soil group of \( R^{th} \) region.

The irrigation programs are generated over the CSR unit. Each AU may have land in one or more than one CSR units, but the climate is the same over the AU. Therefore a CSR unit in AU is referred to as a Crop-Soil (CS) unit. The resources are allocated to each CS unit of each AU.

**Irrigation Season**

The irrigation season is the season for which planning is done for the irrigation and over which the scheme is operated for irrigating the crops. It may be maximum one year and minimum equivalent to one irrigation period. The irrigation season (if equivalent to one year) can be divided into the subseasons to represent the climatic variability over the year and to vary the parameters which depend on the climate (such as the number of
irrigations). Generally different crops are grown in the different (sub)seasons. Some crops may overlap different seasons.

**Irrigation Interval and Water Delivery Interval**

The irrigation interval is defined as the time between the beginnings of two successive turns of water application and for a particular irrigation it is fixed irrespective of region, soil group or crop. The irrigation interval can vary but it is generally kept the same over the subseason for ease in management.

The water delivery interval is the time between the beginnings of two successive actual applications of water. In the method used in the development of the AWAM model, some irrigations can be skipped i.e. water may not be delivered at each turn for a particular CSR unit. The water delivery interval is therefore a summation of successive irrigation intervals.

The irrigation interval (or set of irrigation intervals) is predetermined for the irrigation season but the water delivery interval is the decision variable which is the output of the AWAM model for different CSR units. The possibility of different water delivery intervals for different CSR units adds flexibility in application of water at different intervals to different crops grown on different soils and in different climatic patterns.

**Allocation Plan**

The allocation plan is the plan which contains the information on allocation of different resources (land and water), at the beginning of the irrigation season. It consists of the area
to be irrigated under different crops in different soil groups of different AUs, and the water to be delivered per irrigation to these areas.

**Different Phases of AWAM Model**

The AWAM model has the following four phases/levels and is executed for each set of irrigation intervals.

1. Generation of irrigation strategies
2. Preparation of irrigation programs
3. Selection of irrigation programs
4. Optimum allocation of resources

The linkage among all these phases is shown schematically in Fig. 1 and Fig. 2.

**Generation of the Irrigation Strategy**

The irrigation strategy is the way of scheduling irrigation for a given crop-soil-region (CSR) unit and a given set of irrigation intervals. There are several ways of scheduling irrigation for a given set of irrigation intervals by varying the amount of water to be delivered in a field at every irrigation, and therefore there are several irrigation strategies.

In land and water allocation models, the optimum irrigation strategy cannot be decided before observing all possible irrigation strategies. Therefore there is a need to generate the possible irrigation strategies, and then to select the optimum irrigation strategy or strategies among those for optimum allocation of land and water resources in the irrigation scheme.

In the model the possible irrigation strategies are generated for a set of fixed irrigation intervals. The irrigation strategy is a set containing the deficit ratios (the ratio of the amount of water applied to the root zone and the amount of water required to fill the
root zone to field capacity) for each irrigation. If there are 'Ic' number of crop irrigations (excluding presowing irrigations, if any) for a given CSR unit and \( \beta_i \) is the deficit ratio for \( i^{th} \) irrigation then a set of deficit ratio which is represented by \( \beta \) is given by

\[
\beta = \{ \beta_i, i = 1, Ic \}
\]

The deficit ratio can be varied in the range \( \beta_n \) to \( \beta_x \), where \( \beta_n \) is the lowest possible value of deficit ratio and \( \beta_x \) is the highest possible value of deficit ratio. The lowest value of \( \beta_n \) is zero, meaning no irrigation water is to be applied or the irrigation is to be skipped. \( \beta_x \) can be one, which means that the full irrigation is to be applied (however it can be more than one, where an extra amount of water is required for satisfying leaching requirements, but this aspect is not considered in the present study). The deficit ratio can be varied from \( \beta_n \) to \( \beta_x \) by a certain increment (\( \Delta \beta \)) at each irrigation.

The irrigation strategies are generated in combination of deficit ratio and irrigation by varying the deficit ratio in the given range (obtained with the given \( \beta_n, \beta_x \) and \( \Delta \beta \)) at each irrigation. This results in generating the full range of irrigation strategies (or all the possible ways of scheduling irrigation for a given set of irrigation intervals) for the given values of \( \beta_n, \beta_x \) and \( \Delta \beta \).

The number of possible irrigation strategies can be very high. For example for the crop period of 120 days and a uniform irrigation interval of 21 days, the number of irrigations is 6. If \( \Delta \beta \) is 0.2, \( \beta_n = 0 \) and \( \beta_x = 1 \), the number of irrigation strategies is 46656. The number of feasible irrigation strategies however may be much less, as described in the next section.
The model can also be used to allocate resources for prescribed irrigation strategies such as applying the full depth of irrigation or a fixed depth of irrigation at every irrigation.

**Preparation of Irrigation Programs**

This is the second phase of the AWAM model. Irrigation programs contain the information on the depth of irrigation water to be applied in field at every irrigation, the crop yield and the net benefits. These are prepared for each irrigation strategy generated in the first phase, by formulating the simulation model SWAB-CRYB which generates the information needed for allocating the resources in third and fourth phases of AWAM. The simulation model SWAB-CRYB essentially

- estimates the soil water content over the depth of the soil root zone, actual crop evapotranspiration, soil evaporation, actual transpiration and deep percolation at various instances of time during the crop growth period.
- estimates the depth of irrigation water to be applied at different irrigations during the crop growth period according to the predetermined irrigation strategy.
- estimates the crop yield and net benefits.

The results show that many possible irrigation strategies are not feasible, for example resulting in excessive soil moisture depletion and zero yield, and these are rejected.

The model SWAB-CRYB is formulated to make it applicable to major field crops grown in the command area of an irrigation scheme. It uses data which are generally available at the irrigation scheme, and general data documented by FAO (Doorenbos and
Pruitt, 1984; Doorenbos and Kassam, 1986 and Allen et al. 1998), if local data are not available. The soil water balance part of this model represents the system in more detail than used in most allocation studies. The model SWAB-CRYB involves various inflow and outflow processes and a layer based soil water balance equation. This model has some default procedures or models for simulation of many parameters but also allows the user to stipulate other procedures or models or to make direct input of certain parameters. The details are described by Gorantiwar (1995).

Field application efficiency: The irrigation depth is computed by adjusting the application depth for field application efficiency and minimum possible depth of irrigation for the crop, soil and irrigation method under consideration. The field application efficiency values published by ILRI (Bos and Nugteren, 1990) are used if not available for the location. The field application efficiency is usually estimated for the case of full irrigation, to allow for deep percolation losses from non-uniform distribution within the unit, and for runoff and management losses. All of these losses are likely to be lower with partial irrigation, so the use of published field application efficiency values may lead to high estimates of average yield reduction from deficit irrigation. Within each field, the non-uniformity of water application and infiltration into the soil will produce similar variation in yields so the model includes the possibility of specifying the field application efficiency for each crop-soil unit and irrigation.

Selection of Irrigation Programs

This is the third phase of the model. Many feasible irrigation programs (FEIP) are obtained at the end of the second phase. Incorporation of all these programs in the allocation model of the fourth phase may make the problem computationally infeasible to
solve. Moreover some of these programs are clearly not optimal and even if included in the allocation model will not appear in the solution. Therefore the number of irrigation programs for the given unit are restricted by selecting only optimal irrigation programs (OIP). If total number of OIPs exceeds the prescribed limit or a certain manageable number then the OIPs corresponding to the lowest seasonal irrigation depth and highest output and the OIPs which are efficient (OEIPs) as defined below are selected. This ensures that optimality in the final solution is not lost or is closely reached and formulation of the fourth phase becomes computationally feasible (Gorantiwar 1995 and Gorantiwar and Smout, 2003). The irrigation programs, which are finally transferred in to the fourth phase, are termed as selected irrigation programs (SIP). All the SIPs for the unit under consideration are represented by $SIP$ which is indicated by equation (3).

$$SIP = \{ SIP_p, p = 1, nsp \}$$  \hspace{1cm} (3)

where $p$ = index for irrigation program and $nsp$ is the total number of SIPs.

OIP and OEIP are defined as follows

(1) Optimal irrigation program (OIP): This is the irrigation program with a higher output than the output from other irrigation programs but with the same or lower seasonal irrigation depth as other irrigation programs. In the water limiting condition only optimal irrigation programs can appear in the final solution.

(2) Optimal efficient irrigation program (OEIP): An optimal efficient irrigation program is that optimal irrigation program which gives more water use efficiency (output per unit of water applied) (equation 4) or water use ratio (rate of increase in output to rate of decrease in output) (equation 5) than other optimal irrigation programs.
\[ W_{e_p} = \frac{O_p}{D_p} \] (4)

\[ WUR_{p} = \frac{(O_p - O_l)/(D_p - D_l)}{(O_h - O_p)/(D_h - D_p)} \] (5)

where \( W_e \) = water use efficiency in Kg/ha-mm or currency unit/ha-mm; \( W_r \) = water use ratio; \( O \) = output in Kg/ha or currency unit; \( D \) = seasonal irrigation depth (mm) and \( p, l \) and \( h \) are the indices for \( p^{th} \) OIP; OIP corresponding to the lowest seasonal irrigation depth and OIP corresponding to the highest output, respectively.

The output can be chosen as either crop yield or net benefits.

*Irrigation Programs for CSR-Units.*

The procedure described with phases-1, 2 and 3 is for generating irrigation programs for one CSR-unit. In a similar way irrigation programs are generated for all CSR-units. The irrigation programs for all CSR-units are represented by equation (6)

\[ \text{SIP}_{CSR} = C = 1, NC_{CSR}, S = 1, NS_{CSR}, R = 1, NR \] (6)

where

\[ \text{SIP}_{CSR} = \{ \text{SIP}_{pCSR}, p = 1, nsp_{CSR} \} \]

\[ \text{SIP}_{pCSR} = \{ d_{ipCSR}, i = 1, Ic_{CSR}, D_{ipCSR}, Y_{pCSR}, B_{ipCSR} \} \]

where \( Ic_{CSR} \) and \( nsp_{CSR} \) are total number of irrigations and total number of SIPs for \( C^{th} \) crop in \( S^{th} \) soil group of \( R^{th} \) region (including any presowing irrigation); and \( d_{ipCSR}, D_{ipCSR}, Y_{pCSR}, B_{ipCSR} \) are depth of irrigation for \( i^{th} \) irrigation (mm), seasonal depth
of irrigation (mm), crop yield (kg/ha) and net benefits (currency unit/ha) corresponding to
$p^{th}$ irrigation program for for $C^{th}$ crop in $S^{th}$ soil group of $R^{th}$ region, respectively.

**Irrigation Programs for Given or Known Irrigation Strategies**

The procedure described in the three different phases is for the preparation of irrigation
programs by generating irrigation strategies and then selecting appropriate irrigation
programs. But when it is necessary to prepare the irrigation programs for given or known
irrigation strategies, the phase ‘generation of irrigation strategies’ is skipped. The given or
known irrigation strategies may be in the following forms.

1. Irrigation strategy consisting of deficit ratio for each irrigation.
2. Irrigation strategy consisting of irrigation or application depth per irrigation.

Any number of irrigation strategies in both the forms can be given as input for
preparing the irrigation programs. Subsequently the irrigation programs obtained from
these forms can also be considered together with any other irrigation programs which
have been prepared from irrigation strategies generated from the irrigation strategy
generator in the third phase i.e. selection of irrigation programs. In the third phase of the
model all irrigation programs are either treated together to select the set of SIPS for the
given CSR unit, or irrigation programs prepared from given irrigation strategies are
transferred directly into the fourth phase without considering those in the process of
selection of irrigation programs, depending on the option selected.

**Optimum Allocation of Resources**
Preparation of Irrigation Programs for Each CS Unit of each AU

In the first, second and third phases, irrigation programs were generated for each CSR unit of the irrigation scheme and not for each CS unit of each AU to save the computational efforts. As a CSR unit is not a physical division of the command area of the irrigation scheme, the conveyance and distribution efficiencies could not be considered while generating irrigation programs of the CSR unit. Therefore in the fourth phase of AWAM the irrigation programs for each CS unit of each AU are obtained from the corresponding CSR unit, and then these are modified by considering the distribution and conveyance efficiencies.

Transfer of Irrigation Programs

The irrigation programs at AU level are represented as

\[ \text{IP}_{csa}, \quad c = 1, n_{csa}, \; s = 1, n_{sa}, \; a = 1, na \]  

where

\[
\begin{align*}
\text{IP}_{csa} &= \{ \text{IP}_{pessa}, p = 1, n_{pessa} \} \\
\text{IP}_{pessa} &= \{ \text{d}_{pessa}, i = 1, I_{csa}, D_{pessa}, Y_{pessa}, B_{pessa} \}
\end{align*}
\]

where \( a \) = index for AU, \( s \) = index for soil group in allocation unit, \( c \) = index for crop in soil group (\( c \) and \( s \) together represent the index for CS unit of AU), \( p \) = index for irrigation program for crop (\( c^{th} \) crop in \( s^{th} \) soil group of \( a^{th} \) allocation unit), \( i \) = index for irrigation number for an irrigation program, \( na \) = total number of allocation units, \( n_{sa} \) = total number of soil groups in \( a^{th} \) allocation unit, \( n_{csa} \) = total number of crops in \( s^{th} \) soil group of \( a^{th} \) allocation unit, \( I_{csa} \) and \( n_{pessa} \) are total number of irrigations and total number of irrigation programs for \( c^{th} \) crop in \( s^{th} \) soil group of \( a^{th} \) allocation unit (including
presowing irrigation) and $d_{iCSR}$, $D_{pCSR}$, $Y_{pCSR}$, $B_{pCSR}$ are depth of irrigation for $i^{th}$ irrigation (mm), seasonal depth of irrigation (mm), crop yield (kg/ha) and net benefits (currency unit/ha) corresponding to $p^{th}$ irrigation program for for $C^{th}$ crop in $S^{th}$ soil group of $R^{th}$ region, respectively.

These are obtained as

$$IP_{csa} = SIP_{CSR} \quad \text{if region}_a = \text{REGION}_R$$
$$\quad \text{soil}_a = \text{SOIL}_{SR}$$
$$\quad \text{crop}_{csa} = \text{CROP}_{CSR}$$

(8)

where region$_a$ = region of $a^{th}$ allocation unit, REGION$_R$ = $R^{th}$ region, soil$_a$ = $s^{th}$ soil group of $a^{th}$ allocation unit, SOIL$_{SR}$ = $S^{th}$ soil group of $R^{th}$ region, crop$_{csa}$ = $c^{th}$ crop in $s^{th}$ soil group of $a^{th}$ allocation unit and CROP$_{CSR}$ = $C^{th}$ crop in $S^{th}$ soil group of $R^{th}$ region

**Adjustments of Irrigation Depth**

In previously developed allocation models, the conveyance, distribution and application efficiencies were lumped together as a project efficiency and only one fixed value for all irrigations, crops, soils and regions was considered. Importantly however the efficiencies represent losses which may comprise the major portion of total water consumption. These are dependant on many factors (e.g. characteristics of canal network, soil, crop and timing of irrigation during the irrigation season). Therefore arbitrary consideration of these efficiencies does not result in proper allocation of the resources and also does not give a well-defined allocation plan that can be adopted for the operation of the scheme. In the AWAM model, the generation of irrigation programs in the second phase, already takes account of the application efficiency and its variation with irrigation, crop and soil. In this
stage (of fourth phase) conveyance and distribution efficiencies are considered as explained below

**Distribution efficiency:** This is the efficiency of the water distribution canal network in the AU supplying water up to the individual field and may be different for different irrigations and allocation units. This efficiency cannot be considered if the model is of the single field type as in other models described above. But this efficiency has also not been considered or embodied in the conveyance or project efficiency in other allocation models of the multifield type. In the AWAM model, provision has been made to modify the irrigation depth of each irrigation for the distribution efficiency, which itself may vary with each irrigation.

**Conveyance efficiency:** Conveyance efficiency is the efficiency of canal networks from the reservoir or river diversion to the offtakes of the allocation unit (adopted from Bos and Nugteren, 1990). The water losses which occur in conveying the water to the AU from the headworks through the canal network are substantial and depend on the conveyance efficiency of the individual canal. This in turn depends on the type of canal lining, growth of vegetation, and the carrying capacity of the canal. In many allocation studies, the conveyance efficiency is considered uniform over the irrigation season and scheme, as a part of project efficiency. In the AWAM model the conveyance efficiencies are duly considered while allocating the resources by modifying the irrigation depths in irrigation programs for conveyance losses at each irrigation and each canal. The procedure is described below.

The conveyance losses corresponding to the water to be delivered at each irrigation at each AU are computed for all CS units of AU with the conveyance losses of
canals at the level of the AU and of canals above this level (if any). The irrigation depth for each irrigation of all CS units of AU is adjusted with the corresponding conveyance losses.

The input is in the form of information on conveyance efficiency or losses for canals at each level, and the conveyance efficiencies are required to be calculated in the following forms.

1. The conveyance efficiency of the canal network from the headworks to the allocation unit for a particular allocation unit (for adjusting the irrigation depths at AU for conveyance losses in the scheme).

2. The conveyance efficiency of the canal network up to each level from the headworks for a particular allocation unit (for formulating constraints).

3. The conveyance efficiency of the canal network from the headworks to the canal for a particular canal (for formulating constraints).

From the distribution and conveyance efficiencies, it is possible to estimate the required water to be delivered from the headworks for the given irrigation depth at each irrigation for the given CS unit. The depth of water to be delivered from the headworks to the CS unit of AU for applying the required irrigation depth at the CS unit is termed the water delivery depth \((dw)\) and is computed from equation (9).

\[
dw_{ipcsa} = \frac{d_{ipcsa}}{\eta_{c,ia} \eta_{d,ia}}
\]  

(9)

where, \(\eta_{d,ia}\) = distribution efficiency for \(i^{th}\) irrigation of \(a^{th}\) allocation unit and \(\eta_{c,ia}\) = conveyance efficiency of canal network for \(i^{th}\) irrigation for \(a^{th}\) allocation unit (fraction).

The seasonal water delivery depth \((Dw)\) is computed as

\[
Dw_{ipcsa} = \sum_{i=1}^{lc,ca} dw_{ipcsa}
\]

(10)

The modified irrigation program for each CS unit of AU can be represented as
\[ \text{IP}_{\text{pca}} = \{ \text{dw}_{\text{pca}} , i = 1, I, \text{Dw}_{\text{pca}} , \text{Y}_{\text{pca}} , \text{B}_{\text{pca}} \} \]

where \( I \) = total number of irrigations during irrigation season.

**Resource Allocation (RA) Model**

This is the second stage of the fourth phase of AWAM. Phases-1, 2 and 3 and Stage-1 of Phase-4 model the physical aspects of the system, for estimating the required water delivery from the reservoir at various instances of time to irrigate various crops scientifically. The Stage-2 of Phase-4 models the system as well as allocates the resources optimally to different crops grown on different soils (CS units) in different allocation units (AUs) with the knowledge of net benefits (crop yield) for different amounts of water delivery at each irrigation turn. At this stage the model prepares the water release schedule for the canal network.

The allocation is subjected to constraints such as limitations on different resources at different levels of allocation, capacity of the system and different requirements. The linear programming optimization technique which contains the activities, objective function and the constraints, is adopted for the optimization. The details are described by Gorantiwar (1995).

**Activities**

The allocation of area to a CS unit of AU by a certain Irrigation Program is one activity. The aim is to find out the area to be allocated to each activity \( A_{\text{pca}} \) from which area and water to be allocated to each CS unit of AU can be obtained.

**Objective Function**
To generate maximum net benefits is the common objective for many irrigation schemes. This is the objective in many land allocation and land and water allocation models described earlier.

\[
\text{Max} \quad \text{OBJ} = \sum_{n=1}^{n_a} \sum_{s=1}^{n_s} \sum_{c=1}^{n_c} \sum_{p=1}^{n_p} B_{pcs} A_{pcs} + \sum_{i=1}^{i} \phi O_i
\]

where \( \text{OBJ} \) = the value of objective function (currency unit), \( A \) = Area to be allocated to each activity (non negative) (ha), \( O \) = reservoir spill or overflow during \( i^{th} \) irrigation period (non negative) (ha-m), \( \phi \) = the penalty associated with reservoir spill (negative value).

Land and water resources available in the irrigation scheme are utilized for other purposes along with irrigation. The land which is available and suitable for irrigation (irrigable command area) is used in the constraints involving any restrictions to land area. The other resource, water has also many uses. However the amount of water available for irrigation cannot be isolated like land as water for other purposes is used concurrently with water for irrigation and sometime is carried through the same canal network. The following section describes the total water use in the irrigation scheme.

**Total water use:** The AWAM model is developed to optimize the use of water which is available for irrigation, for allocating during different irrigations and to different crops grown on different soils in different allocation units. The use of water for other purposes during different periods is computed separately and is the direct input to the model. Some uses draw water directly from the reservoir, some through canal networks and some from both. Therefore these are considered in the model at appropriate places by giving proper consideration to the conveyance efficiency when users draw water from the canal network. Though the input of water required for these uses during different irrigation
periods is directly given to the model, its inclusion in the model is required for restrictions on reservoir capacity and on the capacity of the canal network.

**Physical Constraints**

These are the constraints which limit the use of resources available in the scheme according to the ability of the system to use those resources.

1. **Area constraints:** The total area to be irrigated at any instance in any soil group of an allocation unit in the irrigation scheme should not exceed the maximum irrigable area of the soil group of AU. The total area to be irrigated constitutes the area which is being irrigated under different crops, and the area which is not yet irrigated but is planned for irrigating a certain crop and is under land preparation for irrigation. This constraint is represented by

\[
\sum_{c=1}^{n_c} \sum_{p=1}^{n_p} A_{pcsa} \leq TA_{sa}
\]

for \( s=1, \ n_s \)

\( a =1, \ n_a \) and

\( i =1, \ I \)

\( A_{pcsa} = 0 \)

if \( pd_{csa} - lp_{csa} > E_i \) or

\( hd_{csa} < SI_i \)

(13)

where \( TA_{sa} = \) total area that can be irrigated in \( s^{th} \) soil group of \( a^{th} \) allocation unit (ha),

\( pd_{csa} = \) planting date of \( c^{th} \) crop grown in \( s^{th} \) soil group of \( a^{th} \) allocation unit, \( lp_{csa} = \) land preparation required for \( c^{th} \) crop grown in \( s^{th} \) soil group of \( a^{th} \) allocation unit(days), \( hd_{csa} = \) harvesting day of \( c^{th} \) crop grown in \( s^{th} \) soil group of \( a^{th} \) allocation unit, \( SI_i = \) starting day of \( i^{th} \) irrigation and \( EI_i = \) Ending day of \( i^{th} \) irrigation
The model also considers an optional area constraint. This states that the total area to be irrigated within an irrigation scheme should lie in between minimum and maximum prescribed limits of area to be irrigated.

2. Canal Capacity Constraint: In actual operation canal capacity should not restrict the specified allocation plan. Therefore the canal capacity constraints are included. These constraints state that water to be carried through the canals in the water distribution network for delivering it to different AUs should lie within the minimum and maximum limits of canal carrying capacities of the respective canals. In the AWAM model as the water is allocated at AU level (with varying depths for each CS of AU), it was thought necessary to consider the carrying capacities of all canals in the distribution network.

There are different levels in the water distribution network at which different canals offtake. At each level there may be one or more canals. In considering the limitations on canal capacities, the conveyance efficiency of the water distribution network up to each level for a particular allocation unit needs to be known. These are computed as described earlier. The possible need for canals to carry water for non-irrigation purposes is also considered.

The model allows for canal capacities to vary between different irrigation periods for example due to cleaning or to vegetation growth and/or silting of canal, respectively.

3. Outlet Capacity Constraints: If the allocation unit is served by an outlet, the consideration of this constraint restricts the delivery of the water and thus influences the allocation of area to different crops within the allocation unit according to the discharge capacity of the outlet. If several allocation units are served by one outlet, then the outlet is considered as the ‘canal’ at an appropriate level for the sake of limiting the water delivery
according to its capacity, and a constraint to its capacity can be included in the canal capacity constraints.

**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.

1. **Intraseasonal water supply constraints:** The total quantity of water to be delivered for irrigation during any intraseasonal period (irrigation period) should not exceed the total quantity of water that can be made available in that irrigation period. This varies according to the type of irrigation scheme. Therefore the intraseasonal water supply constraints are formulated differently for storage reservoir and river diversion irrigation schemes.

   1) **Storage reservoir irrigation scheme:** The total quantity that can be available for irrigation in any intraseasonal period is computed from the storage of water in the reservoir at the beginning of the period, inflows (river runoff and direct rainfall) received during the period, evaporation, seepage and other losses during the period, water transported for other purposes (both irrigation and non-irrigation and to be diverted directly from the headworks or carried through the canal network). The quantities of water lost from the reservoir due to seepage and used for other purposes during each intraseasonal period are estimated at the beginning of the irrigation season. However as the AWAM model is developed for irrigation in semi-arid regions, where evaporation losses are predominant and vary considerably during the irrigation season, these need proper estimation. Therefore, the evaporation losses during each intraseasonal period are computed within the season from the water available in the reservoir at the beginning and
the end of each intraseasonal period and from evaporation data. The intraseasonal water supply constraints are represented in the following way

\[
\sum_{a=1}^{na} \sum_{s=1}^{ns} \sum_{c=1}^{nc} \sum_{p=1}^{np} d_{\text{pca}} A_{\text{pca}} \leq ST_{i-1} - Sn + Q_i - cl_i - ol_i - sp_i - O_i
\]

for \( i = 1, I \) \hspace{1cm} (14)

Continuity

\[
ST_{i-1} = ST_{i-2} + Q_{i-1} - el_{i-1} - ol_{i-1} - sp_{i-1} - O_{i-1} - \sum_{a=1}^{na} \sum_{s=1}^{ns} \sum_{c=1}^{nc} \sum_{p=1}^{np} d_{i-1,\text{pca}} A_{\text{pca}}
\]

for \( i = 2, I \)

\[
= So \quad \text{for} \quad i = 1
\]

(15)

From equations (14) and (15), the constraints are represented by equation (16).

\[
\sum_{i=1}^{i} \sum_{a=1}^{na} \sum_{s=1}^{ns} \sum_{c=1}^{nc} \sum_{p=1}^{np} d_{i,\text{pca}} A_{\text{pca}} \leq So - Sn + \sum_{i=1}^{i} Q_{i} - \sum_{i=1}^{i} el_{i} - \sum_{i=1}^{i} ol_{i} - \sum_{i=1}^{i} sp_{i} - \sum_{i=1}^{i} O_{i}
\]

for \( i = 1, I \) \hspace{1cm} (16)

where \( So \) = initial reservoir storage (at the beginning of irrigation season) (ha-m), \( Sn \) = dead storage capacity of the reservoir or the minimum storage of water that should always be maintained in the reservoir (ha-m), \( Q_i \) = the inflow of water into the reservoir which constitutes the river runoff into the reservoir and rainfall over the reservoir (ha-m) during \( i^{th} \) irrigation period, \( el_i \) = evaporation losses from the reservoir during \( i^{th} \) irrigation period (ha-m), \( sp_i \) = seepage losses form the reservoir during \( i^{th} \) irrigation period (ha-m), \( ol_i \) = water to be diverted for other purposes (ha-m) during \( i^{th} \) irrigation period.

The inflow into the reservoir by direct rainfall is computed by knowing the maximum reservoir surface area and depth of rainfall. Evaporation losses are computed from volume vs. depth and area vs. depth relationships of the reservoir. These relationships are converted into a volume vs. area relationship of linear type to incorporate into the model.
Evaporation losses are computed at the mid point of the irrigation period, by Penman method (Penman, 1948) or pan evaporation method (Doorenbos and Pruitt, 1984) by using an appropriate factor. From equation (16) and solving further

\[
\sum_{i=1}^{N_a} \sum_{s=1}^{N_s} \sum_{c=1}^{N_c} \sum_{p=1}^{N_p} \left( d_{i,s,c,p} A_{pca} \lambda_{1, i} \right) \leq \lambda_{2, i} S_0 - S_n + \sum_{i=1}^{I} \lambda_{1, i} Q_{i, a} - \sum_{i=1}^{I} \lambda_{1, i} s_{p, i} - \sum_{i=1}^{I} \lambda_{1, i} O_{i, a} - \sum_{i=1}^{I} \lambda_{1, i} o_{i, a} + \lambda_3 \]

for \( i = 1, I \)  

where

\[
\lambda_{1, i} = 1 - 0.5\gamma_1 + e_{p, i} \quad \text{if } i = i
\]

\[
\gamma_{1, i} - \gamma_{1, i-1} e_{p, i} \quad \text{else}
\]

\[
\lambda_{2, i} = 1 - \gamma_{2} e_{p, i} \quad \text{if } i = 1
\]

\[
\lambda_{2, i} = 1 - \lambda_{2, i-1} \gamma_{1} e_{i} \quad \text{else}
\]

\[
\lambda_{3, i} = -\gamma_{2} e_{p, i} \quad \text{if } i = 1
\]

\[
\lambda_{3, i} = 1 - \gamma_{2} e_{p, i} + \lambda_{3, i} \left( -\gamma_{2} e_{p, i} \right) \quad \text{else}
\]

\[\gamma_1 \text{ and } \gamma_2 = \text{the constants of the reservoir storage volume vs. reservoir surface area relationship (slope and intercept, respectively), } e_{p, i} = \text{evaporation loss (depth) over the irrigation period (m).}\]

**II) River diversion irrigation scheme:** The formulation of intraseasonal water supply constraints in this type of scheme is straightforward as the continuity equation is not needed due to absence of a reservoir and thus carryover water storage from one period to another. The constraint is simplified to equation (18).

\[
\sum_{a=1}^{N_a} \sum_{s=1}^{N_s} \sum_{c=1}^{N_c} \sum_{p=1}^{N_p} d_{i,s,c,p} A_{pca} \leq Q_i - o_{i, a} \quad \text{for } i = 1, I
\]

**2. Reservoir Storage Constraint:** The water delivery during that irrigation period should not exceed the maximum available storage in that period and inflows received in the
irrigation period above maximum storage capacity of the reservoir and water uses/losses acts as spillage. The constraint is represented by the equation (19)

\[ ST_{i-1} + Q_i - e_{i-1} - sp_i - O_i - ol_i - \sum_{a=1}^{na} \sum_{s=1}^{ns} \sum_{c=1}^{nc} \sum_{p=1}^{np} d_{pca} A_{pca} \leq Sx - Sn \quad \text{for } i=1,I \]  

where \( Sx \) = maximum storage capacity of the reservoir (ha-m).

3. Availability and allocation of other resources: In the AWAM model, the allocation of land and water resources is considered in detail. However there are other resources (inputs) which influence the output of the irrigation scheme. These are for example fertilizers, seeds, machine hours, human laborers, pesticides, capital available etc. The AWAM model can consider the influence of availability of these resources over the entire irrigation season or individual intraseasonal periods, on allocation of land and water to different crops. But the effect of applying different quantities of resources per unit area of crop under irrigation is not considered.

Output Requirement Constraints

These constraints specify the need to generate output at a certain prescribed level and/or by a certain prescribed law.

1. Crop Constraints: These are the constraints required to put certain restrictions on the resources to be allocated (land or water) to different crops grown in the irrigation scheme according to certain predetermined criteria. The inclusion of such constraints at scheme level or AU level satisfies this requirement.

2. Food Requirements Constraints: The area and water restriction constraints for different crops described above do not specify the food production to be obtained in land and water allocation models. These constraints are therefore included separately.
Conclusion

Review of the available optimization models for allocating resources in irrigation schemes indicated the need for further development of an approach suitable for an irrigation scheme with limited water, under rotational water supply. The approach followed in this paper provides a suitable methodology for optimally allocating the land and water resources to different crops grown on different soils in the tertiary unit of the command area. This is achieved by generating the various possible irrigation strategies based on deficit irrigation, preparing the irrigation programs for these irrigation strategies with due consideration to the response of crops to deficit and then selecting optimal irrigation programs with the help of a resource optimization model. The model can then generate the optimal allocation plans for an irrigation scheme with limited water supply. The allocation of the water to tertiary level, incorporation of the different efficiencies at appropriate stages and consideration of the capacity of the canal network to carry water make the resource allocation plan adaptable in practice for the planning and operation of irrigation schemes under rotational water supply. The application of the model is considered in a second paper.
APPENDIX I REFERENCES


Captions of figures

FIG. 1 Different phases of the Area and Water Allocation Model (AWAM)

FIG. 2 Area and Water Allocation Model
Phase: 1

**Generation of Irrigation Strategies**

Generates irrigation strategies for each crop-soil-region (CSR) unit based on the different combinations of deficit ratios over all the irrigation periods.

Phase: 2

**Preparation of Irrigation Programs**

The irrigation programs consisting of information on yield/benefits and irrigation requirement (depth) per irrigation are prepared for each irrigation strategy generated in Phase:1 for each CSR unit with the following two sub-models:

- **SWAB**: simulates soil moisture in the soil root zone and estimates the actual crop evapotranspiration and the other related parameters and the irrigation requirement (depth) per irrigation.
- **CRYB**: estimates crop yield and net benefits.

Phase: 3

**Selection of irrigation programs**:

- Selection of optimal irrigation programs (OIP) from the irrigation programs prepared at Phase:2 for each CSR unit.
- Selection of efficient irrigation programs (OEIP) from all OIPs.

Phase: 4

**Optimum allocation of resources**

**Stage 1**: Transfer of irrigation programs for each crop-soil (CS) unit of allocation unit (AU) by modifying the irrigation programs (OEIPs) of Phase:3 of the corresponding CSR unit with consideration to distribution and conveyance efficiencies.

**Stage 2**: Allocation of the resources to each CS unit of AU with certain objectives and constraints with the Resource Allocation (RA) sub-model based on linear programming approach.

- Objective: Max. of net benefits/area/crop production
- Constraints: Physical/resource availability/output requirement

Preparation of water release schedule.
Input data: crop, soil, climate, command area, reservoir, etc

Set of irrigation interval over the planning period

CSR unit = 1

Generation of irrigation strategies (Phase-1)

Preparation of irrigation programs with SWAB-CRYB sub-models for all irrigation strategies obtained in Phase-1 and/or estimation of yield and net benefits for given irrigation strategies, if any (Phase-2)

Selection of OIPs and OEIPs from irrigation programs prepared at Phase-2 (Phase-3)

• Transfer of irrigation programs from CSR unit to CS unit of each AU
• Adjustment of irrigation depth of each irrigation for distribution and conveyance efficiencies (Stage-1 of Phase-4)

Preparation of area and water allocation plan and water delivery schedules for each CS of AU with the help of irrigation programs from Stage-1 of Phase-4 and RA submodel based on linear programming LP technique (Stage-2 of Phase-4).

More sets of irrigation interval?

Output: Allocation plans and water delivery schedules for each set of irrigation interval for final decision