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Optimization of Energy Requirement for Operation of an Irrigation System

Manmohan K. Goel
National Institute of Hydrology, Western Himalayan Regional Centre
Satwari, Opposite Military Hospital, Jammu Cantt. - 180 003 (J&K), INDIA
E-mail: goel_m_k@yahoo.com

Sharad K. Jain
National Institute of Hydrology
Roorkee, Uttaranchal - 247 667, INDIA

Umesh C. Chaube
Department of Water Resources Development and Management,
Indian Institute of Technology Roorkee, Roorkee, Uttaranchal - 247 667, INDIA

ABSTRACT: Agriculture sector in India accounts for nearly 80% of fresh water and 30% of energy consumption. In other developing countries also, available water and energy resources are already under considerable stress and there is general realization that traditionally low efficiency of systems can no longer be accepted and needs to be improved. Poor management of irrigation water use is one of the principal reasons for low water and energy use efficiency. Further, a range of environmental problems, such as waterlogging, leaching of agro-chemicals, soil salinization etc. are also linked to inefficient water use. Generally, there are multiple objectives of irrigation water management: maximize net return, minimize irrigation costs, maximize yield, optimally distribute a limited water supply, minimize groundwater pollution etc. After a cropping pattern is adopted in an irrigation command, irrigation requirements depend on the crop and soil characteristics, meteorological conditions, and rainfall. To best allocate the water resources with the available surface water resources (through irrigation canals) and groundwater development in the region, an irrigation manager is required to take decisions in real-time to meet the water demands in a command area. Thus, for a given cropping pattern, canal network and groundwater development, one of the objectives of irrigation water management could be optimization of energy requirement for pumping groundwater. A conceptual spatially distributed model has been developed for the optimization of energy requirement for the operation of an irrigation system. The model computes crop water demands in the command area in real-time and calculates the water demands at the canal system head after accounting for the system characteristics and seepage losses. Based on the availability of water at canal head, the model computes optimum configuration of the canal network operation during each week. This model can be used by the irrigation manager for real-time operation of a canal system. The model results have been tested for a crop season with the data of Lakhaoti branch canal command in UP State, India. The results demonstrate that considerable energy can be saved by rationally operating a canal system in real-time.

INTRODUCTION

Availability of irrigation water continues to be the first and foremost requirement for promoting technologically superior agriculture. It is rightly said, "Agriculture sustains life whereas irrigation sustains agriculture". From just 8 million hectares (M ha) in the year 1800, irrigated area across the world increased five-fold to 40 M ha in 1900, to 100 M ha in 1950 and to just over 255 M ha by the year 1995. With almost one-fifth of world irrigated area (50.1 M ha net irrigated area), India has the largest irrigated land in the world (Postel, 1999). Seckler *et al*. (1998) have estimated that around 70% of water used world-wide each year produces 30 to 40% of the world's food crops on 17% of arable land. As per Tardieu (2000), half of the increase in food production has come from the irrigated area during the last 25 years. Further, the author predicts that projected population growth during the coming years will require an increase in food production of 3 to 4% per year, the largest share of which is expected to come from irrigated agriculture.

Irrigation is the largest consumer of fresh water. However, it has now been established that inappropriate irrigation management practices around the globe have converted around 100 M ha of arable land into unusable land because of waterlogging and salinity

(Tardieu, 2000). Poor management of irrigation water delivery system is one of the principal reasons for low water use efficiency in irrigation. Inadequate and often unreliable water deliveries in the main system result in reduced yields, reduced incomes, and reduced utilisation of created potential. In addition, a range of environmental problems, such as waterlogging, leaching of agro-chemicals and consequent pollution of surface and groundwater, soil salinization etc. are linked to inefficient water use. The challenge of increasing food production requires improvements in the management of irrigation water.

In developing countries, demand for water and energy resources is rapidly increasing in all sectors. Padmanabhan (2005) has given Indian scenario of energy requirement for different sectors: 40% for industries, 27% for agriculture, 22% for domestic, and 11% for others. Now with limited and diminishing non-renewable energy resources and increasing water and energy demands, there is an urgent need for improvements in efficiency of water and energy use. National Water Policy (2002), vide para 9.1, has also advocated for adoption of appropriate techniques for optimizing efficiency. A large number of models developed for improved irrigation water management (Lenselink and Jurriens, 1992). Wurbs (1994) has presented a comprehensive review of computer models for water resources planning and management. Mujumdar (2002) has summarized mathematical tools for irrigation water management. More than 100 irrigation and hydrology software have been cited at IRRISOFT (http://www.wiz.uni-kassel.de/kww/irrisoft / irrisoft_i.html) which contains a database of software and their links.

Agriculture sector being most demanding in terms of fresh water (~80%) and energy (~30%), there is an urgent need to improve the water and energy use efficiency as an improvement of even a small percentage in the usage of these resources can significantly influence the overall scenario. Huygen *et al.* (1995) have stated several objectives of irrigation management as "Maximize net return, minimize irrigation costs, maximize yield, optimally distribute a limited water supply, minimize groundwater pollution...". However, with the present need of energy conservation and its best utilisation, optimum management of irrigation water for minimizing the energy requirement for withdrawing groundwater in an irrigation command could be one of the objectives.

During the last three decades, application of operation research techniques to water resources has produced a number of models to help irrigation manager in operation of a canal system (such as SIMIS, CAMSIS, INCA, OMIS, IMSOP etc.). ICID-CIID (2000) has brought out a catalogue of various canal operation simulation models developed in the past. A spatially distributed simulation model has been developed [Goel (2003) & Goel *et al.* (2005)] that can integrate various processes of irrigation management from micro-scale (field level) to macro-scale (overall command) and provide a comprehensive analysis of the total system. Objective of the developed geo-simulation model is to integrate the spatial information on different variables related to irrigation water demand and supply for real-time conjunctive operation of a canal network. The model uses the remote sensing observations for ascertaining the prevailing cropping pattern in the command and is linked to GIS database for utilizing the spatially distributed data of different variables. GIS is also used to depict the model results in map form for easy comprehension and visualization. This paper presents the simulation approach adopted for optimizing the operation of the canal system for minimizing the energy requirement for pumping groundwater. Model application is demonstrated for Lakhaoti canal command under the Madhya Ganga Canal System in U.P. State, India.

BRIEF DESCRIPTION OF MODEL

Irrigation managers have to take decisions in real-time on how best to allocate the available water to meet spatially distributed demands in a command area. Large amount of spatial, temporal and attribute information (cropping pattern, crop and soil properties, rainfall, topography, groundwater conditions and development, canal system characteristics etc.) are involved in irrigation water management in a command area. However, all available information may not be utilized in decision making for a variety of reasons—database management is unscientific or mathematical tools are not used to utilize and integrate the multi-disciplinary information for arriving at some meaningful conclusion. The aim of this model is to help in the rational conjunctive management of irrigation water.

MODELING STRATEGY

The model uses spatially distributed data of various features of the command area (crop map, soil map, Thiessen polygon map of rainfall stations, digital elevation map, canal layout map, canal irrigable area map, groundwater depth map), attribute data related to crops and soils and the dynamic data related to rainfall, evapotranspiration and canal network operation. The model operates at weekly time step and consists of three major sub-models: a) Demand model [also called Soil Water Balance Model (SWBM)], b) Allocation model [also called Canal Network Simulation Model (CNSM)], and c) Groundwater behaviour model.

Soil water balance of cropped area is a dynamic process influenced by crop and soil properties, climatological variables and topography. The purpose of SWBM is to simulate the moisture variation in root zone of crops for finding spatially distributed irrigation demands, groundwater recharge, crop water stress, and residual moisture content at the end of each week. Input data to SWBM include the raster maps (as specified earlier), crop and soil properties, and the dynamic data of rainfall and evapo-transpiration. Two time steps are possible in this sub-model: daily or weekly. In weekly time step, the various inputs (rainfall and evapo-transpiration) and outputs of the system are assumed to be lumped over the whole week while in daily time step, daily rainfall and daily reference crop evapo-transpiration are considered for water balance computation as per the following equation,

$$WD_t = WD_{t-1} + RF_t + IRR_t + OLFI_t - AET_t - DPER_t - OLFO_t \quad \ldots(1)$$

where WD_t is the equivalent soil water depth in root zone at the end of t^{th} day (mm), WD_{t-1} is the equivalent soil water depth in root zone at the end of $(t-1)^{th}$ day (mm), RF_t is the rainfall occurring over the grid on t^{th} day (mm), IRR_t is the depth of irrigation water applied on the t^{th} day (mm), $OLFI_t$ is the overland inflow to the grid from adjacent higher elevation grid on t^{th} day (mm), AET_t is the actual crop evapo-transpiration on t^{th} day (mm), $DPER_t$ is the deep percolation loss going out of root zone on t^{th} day (mm), and $OLFO_t$ is the overland flow going out of the current grid on t^{th} day (mm). Depending on the crop properties at a grid, root zone during the simulation week (effective soil depth) is determined. Using soil properties, various water holding characteristics are determined in terms of equivalent water depths. In equation (1), RF_t and IRR_t are the dynamic data provided to the model. AET_t is a function of the reference crop-evapotranspiration and the stress condition at the grid and is computed recursively. $DPER_t$ and $OLFO_t$ are functions of water available at the grid, hydraulic conductivity of the soil and the groundwater depth. $OLFI_t$ is dependant on the $OLFO_t$ and the flow direction. Equation (1) is applied to all the grids of the command and the supplementary water demands are computed.

Four spatial maps are generated by the SWBM: a) residual moisture at the end of a week, b) irrigation water demand, c) crop water stress, and d) groundwater recharge. The maps can be displayed in a GIS system for easier interpretation and decision making. A view of the irrigation demand map generated by the SWBM is shown in Figure 1. In the overall modelling scheme, SWBM is utilized in two steps for each week. First, it is used to forecast the irrigation demands for the forthcoming week corresponding to the normal/probable rainfall and reference evapo-transpiration. Based on these demands, the operation of the irrigation system is simulated. At the end of week, SWBM is run again using actual rainfall, evapo-transpiration, and canal operation to find the residual moisture content. This information is used to forecast demands for the next week.

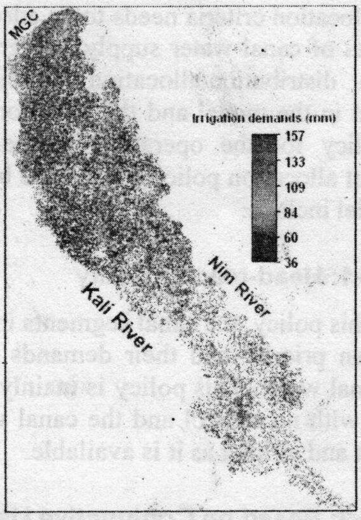

Fig. 1: Irrigation demand map as obtained from *SWBM*

After calculating the irrigation demands, allocation model (CNSM) is used to simulate the canal network operation and find the best configuration of canal water delivery depending on the canal water availability at the system head and the prevailing groundwater conditions in the command. CNSM can be used to examine the consequences of different canal water allocation policies. If, as a result of a particular allocation policy, the developed groundwater conditions are unacceptable, the canal operation policy can be revised and CNSM runs can be taken again. CNSM is run for each week of crop season to manage the available surface water and groundwater conjunctively in real-time. The approach in CNSM utilizes canal water to the extent possible provided that groundwater conditions permit.

CNSM uses the raster information (canal network layout, layout of irrigable areas of different canal segments, irrigation demand map, and groundwater depth map), attribute information related to canal system characteristics, and dynamic information about the canal system operation in the previous week. Spatial irrigation demands are transferred to the respective canal segments after accounting for the water application efficiency and field channel efficiency. Next, demands are accumulated starting from the tail end towards the system head after accounting for the discharge capacity of canal segments, required run time and seepage losses and the total demand at the canal head is worked out. This demand is compared with the available water at the system head. If the water availability is more than or equal to the required demand, then the system is operated according to the discharge requirement as calculated for different segments. However, if the canal water availability is less than the demand, then some allocation criteria needs to be adopted to find the segments of canal water supply and groundwater use. Various distribution/allocation policies have been included in the model and the operator can select any one policy for the operation of the canal system. Different allocation policies that have been included in the model include:

Policy–1: Head-reach Priority

Under this policy, the canal segments in the head reach are given priority and their demands are met in full with canal water. This policy is mainly applicable to a system with no control and the canal water is utilized as far as and as long as it is available.

Policy–2: Based on Conjunctive Use of Water

Under this policy, canal water demands of some canals are curtailed (depending on the depth of groundwater pumping) to compensate for the deficit at the canal system head. The canal segments with least groundwater depth are selected iteratively and the calculations are repeated till the canal water demands at system head match with the availability.

Policy–3: Proportionate Supply

Under this policy, water available at a junction node (where two or more canal segments meet) is distributed proportionately among the segments in proportion to their total demands. This policy tries to equitably distribute the deficit among different canal segments.

Policy–4: Tail-reach Priority

Under this policy, allocation is started from the tail-end of the system and it advances in the upstream direction. With this policy, the operator can visualize the extent of downstream canal system that can be satisfied with the available canal water.

Given the raster, attribute, and dynamic data, canal water availability at the system head, and with any one of the four policies, the CNSM computes the discharge, run-time, and seepage loss in various canal segments for the week under consideration. Output of CNSM can be presented as maps in GIS and tables. A view of the canal operation map corresponding to the policy of head-reach priority (Policy–1) is shown in Figure 2.

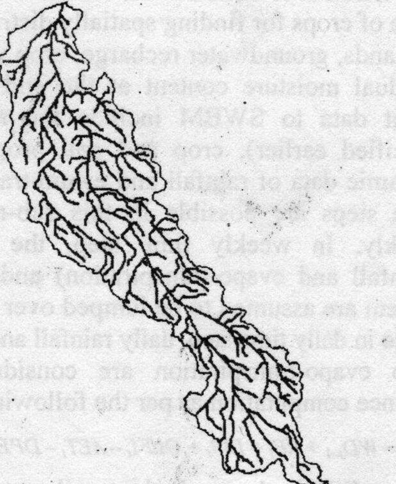

Fig. 2: Canal operation [Running (red), Not running (blue)] with Policy–1

For generating revised groundwater conditions corresponding to different canal operation scenarios, a groundwater model (Visual MODFLOW) has been linked with the modeling scheme. The model is also linked to the ILWIS GIS system for preparation of spatial input maps and for presentation of outputs in map form. The flow chart of the overall modeling approach is presented in Figure 3.

ENERGY OPTIMIZATION THROUGH RECURSIVE SIMULATION

Under the allocation policy of conjunctive use (Policy–2), the deficit of canal water at the system head is compensated by using groundwater in those canal segments that have relatively shallow groundwater depth. However, it is generally observed that groundwater occurs at shallow depth in the head-reaches and at greater depth towards the tail ends of the command areas because of: a) larger use of canal water in the head reaches resulting in higher percolation through the fields and the conveyance system, b) larger seepage from the canal system in the head reaches because of higher discharge and run-time, c) lesser usage of groundwater in the head-reaches because of availability of canal water. Therefore, the policy of conjunctive use allocates more canal water to the tail-end canal segments (having deeper groundwater table) as compared to the head-reach canals. A view of the canal operation map corresponding to the policy of conjunctive use is shown in Figure 4.

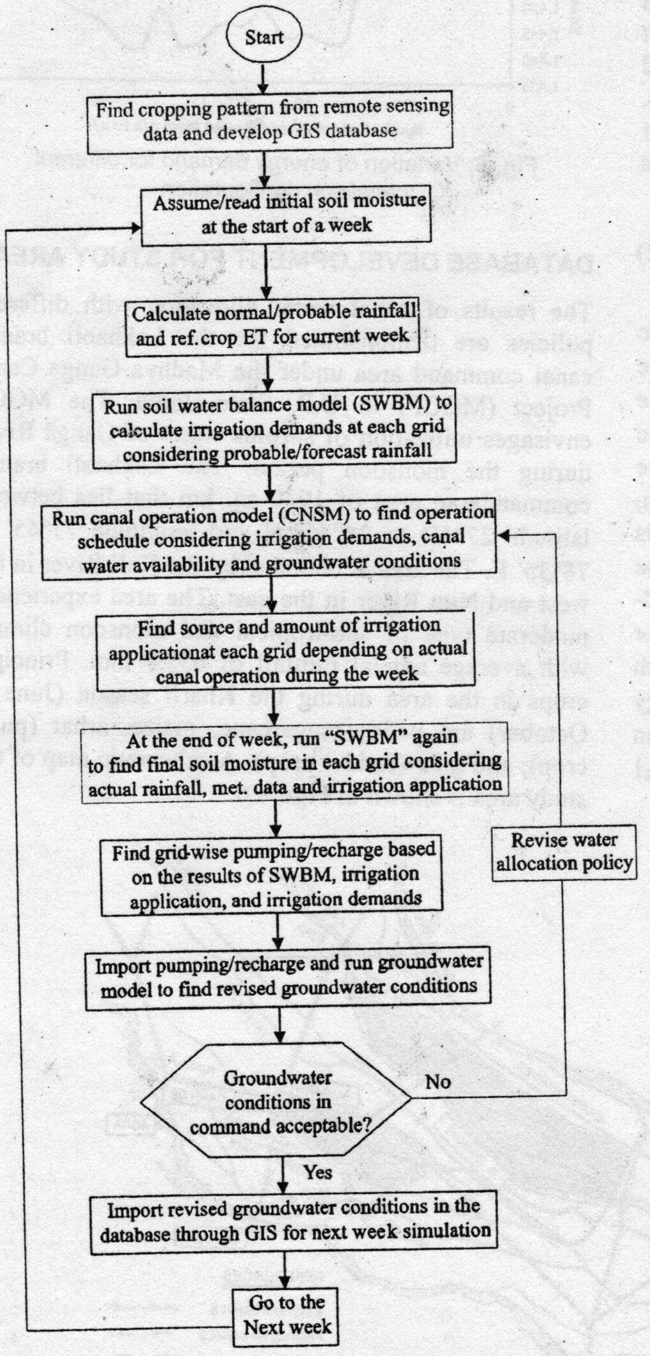

Fig. 3: Flow chart of modeling scheme

While framing the conjunctive use policy, it has been envisaged that the policy would result in reduced energy demand for pumping groundwater because of canal water supply in deeper water table areas and groundwater use in shallow water table areas. However, the results for a hypothetical deficit condition for the Lakhaoti command showed that the energy requirement using conjunctive use policy is more than the policy of head-reach priority. The reason for this anomaly lies in the higher seepage losses through the conveyance system and the reduced effective utilisation of the canal water for meeting irrigation demands. Since large distance is traversed in taking the canal water to the deeper water table areas in Policy–2, the effective utilisation of water for meeting irrigation demands decreases and more groundwater is pumped for meeting the overall irrigation demands which increases the total energy requirement. The results of adopting different policies are presented in Table 1.

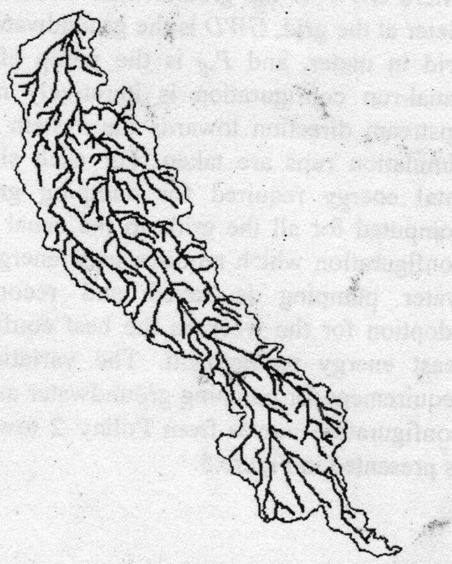

Fig. 4: Canal operation with policy of conjunctive use

In view of the results of policy of head-reach priority (more effective utilisation for meeting irrigation demands due to lesser seepage, but canal water use in shallow water table areas and groundwater pumping in deeper water table areas) and the policy of conjunctive use (reduced effective utilisation for meeting irrigation demands due to larger seepage loss, but canal water use in deeper water table areas and groundwater pumping in shallow water table areas), it was envisaged that there may exist a canal configuration (somewhere in-between the configurations of the conjunctive use policy and the head-reach policy) which if operated, must result in higher effective utilisation, decreased seepage and minimum energy requirement for pumping groundwater. So, recursive simulation runs of the CNSM have been taken assuming different configurations of canal water supply. Simulation analysis is started from the canal-run configuration of Policy–2 (shown in Figure 4). Next, the most distant canal segment from the system head which is being supplied canal water in the previous simulation run is selected for curtailment of canal water supply (its demands now being met with groundwater) and the saved canal water is used to meet the demands of some upstream segments (selected iteratively on the basis of minimum depth of pumping). Energy requirement (ENER in kilowatt-hour) for pumping groundwater in each grid is calculated by the following equation,

$$ENER = \frac{9.817 * GWW * GWD}{36 * P_{eff}} \quad \ldots (2)$$

where GWW is the groundwater withdrawal in cubic meter at the grid, GWD is the groundwater depth at the grid in meter, and P_{eff} is the pump efficiency. The canal-run configuration is iteratively moved in the upstream direction towards the system head and the simulation runs are taken. For each simulation run, total energy required for pumping groundwater is computed for all the grids in the canal network. The configuration which requires least energy for groundwater pumping is saved and recommended for adoption for the week as the best configuration with least energy requirement. The variation of energy requirement for pumping groundwater as the canal-run configuration moves from Policy–2 towards Policy–1 is presented in Figure 5.

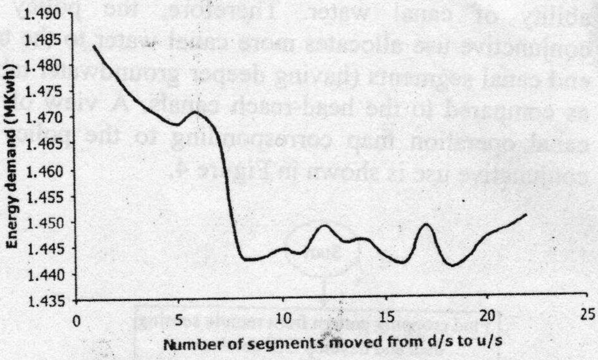

Fig. 5: Variation of energy demand for different canal-run configuration

DATABASE DEVELOPMENT FOR STUDY AREA

The results of canal water allocation with different policies are demonstrated for the Lakhaoti branch canal command area under the Madhya Ganga Canal Project (MGCP) in U.P. State, India. The MGCP envisages utilization of surplus water of Ganga River during the monsoon period. The Lakhaoti branch commands an area of 1930 sq. km that lies between latitude 27°45′ to 28°45′ N and longitude 77°45′ to 78°35′ E. The area is bounded by the Kali River in the west and Nim River in the east. The area experiences moderate type of sub-tropical and monsoon climate with average annual rainfall of 653.7 mm. Principal crops in the area during the Kharif season (June to October) are paddy, sugarcane, maize, arhar (pulse crop), and guar (fodder crop). A schematic map of the study area is shown in Figure 6.

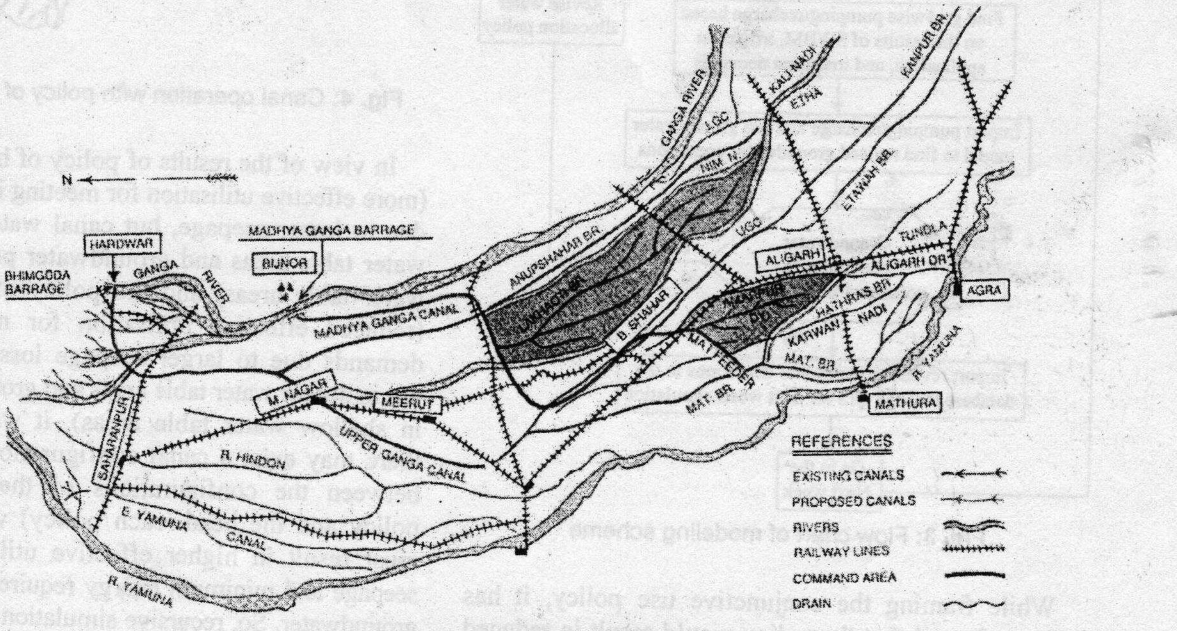

Fig. 6: Schematic map of MGC system

The model has been run with the data of Lakhaoti command area at weekly time step covering the full Kharif season (June to October) of the year 1998. Various raster maps that have been prepared for the model application include: a) crop map of the command [using multi-temporal remote sensing analysis of IRS-1C LISS-III sensor data], b) soil map [from digitization of NBSSLUP soil map], c) Thiessen polygon map of rainfall stations, d) digital elevation map [using GIS analysis of contours and spot levels from SOI toposheets, e) flow direction map [from DEM], f) groundwater depth map [from water level data in observation wells], g) canal network layout map, h) map of irrigable command areas of different canal systems, i) specific yield map of the aquifer, and j) transmissivity map of the aquifer. The crop map of the area is shown in Figure 7 while the canal network map is shown in Figure 8. Details of database generation are given in (Goel, 2003). ILWIS—a GIS software from ITC, The Netherlands, in the public domain has been used. The database has been prepared using a grid size of 24 m.

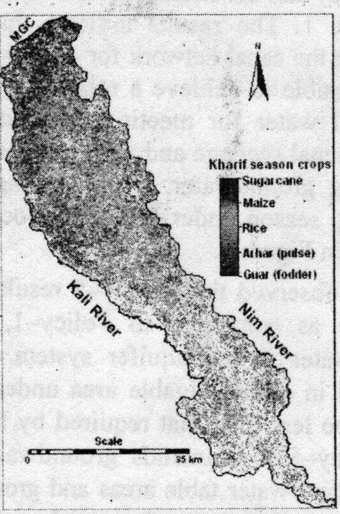

Fig. 7: Crop map (1998) in Lakhaoti command

Attribute data relates to the properties of different crops and soils, and canal system characteristics. Root depth characteristics and the fraction of available water for different crops have been obtained from FAO (1977). Crop factors and other characteristics of different crops have been taken from the Irrigation/Agriculture Department. Soil samples have been collected from many locations in Lakhaoti command and moisture holding characteristics of different soil types have been determined by laboratory analysis. Various characteristics of canal segments that are used by CNSM include: discharge capacity, length, bed width, water depth, side slope (V:H::1:z), irrigable area, conveyance efficiency, application efficiency in irrigable command, field channel efficiency in the irrigable command, seepage rate per unit wetted area, number of tube wells operating in the irrigable command, average power of pumping plants, number of hours for which power supply is generally available in the irrigable command, and linkage of various canals. Some of these details (e.g. discharge capacity, length, bed width, water depth, side slope etc.) have been obtained from the Irrigation Department while some other details have been suitably assumed. Dynamic information (daily rainfall data at five raingauge stations, daily evapo-transpiration, and fortnightly canal water supply) in the Lakhaoti command during the year 1998 has been obtained from the concerned departments. Aquifer characteristics in the command area (specific yield and transmissivity) have been obtained from an earlier groundwater modeling study carried out for the same area (Nayak *et al*., 1990).

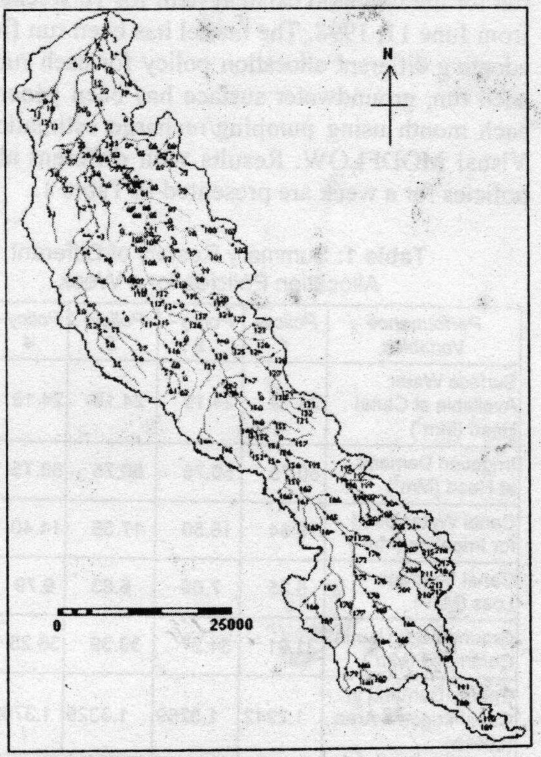

Fig. 8: Canal network in Lakhaoti command

DISCUSSION OF RESULTS

The *SWBM* and *CNSM* sub-models have been run at weekly time step from June 11, 1998 to October 15, 1998 while the groundwater model (Visual MODFLOW) has been run at monthly time step to determine revised groundwater surface in different months. The *SWBM* has been run considering actual rainfall and evapo-transpiration data as input and grid-wise irrigation demands, recharge, and final water content during each week have been worked out. Using the irrigation demands and actual supply of canal water at the system head, the *CNSM* has been run to find the grid-wise canal water application and groundwater withdrawal. The year 1998 was a wet year with monsoon rainfall exceeding the normal rainfall by about 20% resulting in reduced irrigation demands in most part of the Kharif season. In CNSM, different allocation policies are invoked only when there is water deficit condition in the command and the total demand at canal head exceeds the water availability. For this reason, hypothetical water deficit condition has been assumed so that different allocation policies could be analyzed. For this purpose, weekly rainfall in the year 1998 has been taken to be 60% of the actual rainfall and the water availability at canal head is reduced to 75% of the planned supply in the canal system. The model has been run for the Lakhaoti canal system for 18 weeks starting from June 11, 1998. The model has been run five times adopting different allocation policy for each run. Under each run, groundwater surface has been generated for each month using pumping/recharge estimations with Visual MODFLOW. Results with different allocation policies for a week are presented in Table 1.

Table 1: Summary Results of Different Allocation Policies for a Week

Performance Variables	*Policy–1*	*Policy–2*	*Policy–3*	*Policy–4*	*Policy–5*
Surface Water Available at Canal Head (Mm^3)	24.19	24.19	24.19	24.19	24.19
Irrigation Demand at Head (Mm^3)	50.75	50.75	50.75	50.75	50.75
Canal Water Used for Irrigation (Mm^3)	18.84	16.50	17.36	14.40	18.57
Canal Seepage Loss (Mm^3)	5.35	7.69	6.83	9.79	5.62
Groundwater Use in Command (Mm^3)	31.91	34.37	33.39	36.25	32.18
Energy Demand in Canal-irrigable Area (MKwh)	1.2942	1.3269	1.3329	1.3706	1.286

Of the available water at canal system head, maximum water has been used to meet irrigation demands under the policy of head-reach priority (Policy–1) as seepage losses are minimum. However, this policy does not take the groundwater conditions into consideration (except that canal water is not supplied to the water-logged area) and supplies canal water in the area of relatively shallow groundwater table (head-reaches). This results in higher energy requirement for pumping groundwater in other areas of command which have relatively deeper water table. Similarly, Policy–3 (proportionate supply) and Policy–4 (tail-end priority) also do not take the groundwater conditions into account and adoption of these policies result in higher canal seepage loss and higher energy demand. The policy of conjunctive use (Policy–2) takes groundwater conditions into account while allocating canal water and groundwater. However, since deeper water table generally occurs in the tail-reaches of command, this policy allocates canal water in the tail reaches of command with the result that canal seepage losses increase and effective water use for irrigation application decreases. This results in increased withdrawal of groundwater, though from a shallower water table area. The overall energy requirement for groundwater pumping under Policy–2 may be less or more than that under Policy–1 depending on the extent and location of groundwater pumping.

The results of policy of optimum energy requirement (Policy–5) that is obtained after recursive simulation between the canal-run configurations of conjunctive use policy and the head-reach policy are also presented in Table 1. The results indicate that by judiciously selecting the canal network for operation during a week, it is possible to achieve a relatively higher utilization of canal water for meeting irrigation demands with higher canal seepage and with least energy demand for pumping groundwater. Canal seepage losses for the full crop season under different allocation policies are plotted in Figure 9.

It is observed that Policy–5 results in higher canal seepage as compared to Policy–1, thus recharging more water in the aquifer system. Yet, the energy demand in canal-irrigable area under Policy–5 comes out to be less than that required by Policy–1. Further, as Policy–5 recommends groundwater withdrawal in the shallow water table areas and groundwater recharge (in terms of seepage loss and recharge from field application of canal water) in deeper water table areas, it tries to maintain balanced groundwater conditions in the overall command, thus reducing the ill-effects of water logging and groundwater mining. Canal-run configuration corresponding to minimum energy requirement is presented in Figure 10. In comparison to the results with four conventional policies, results with policy of minimum energy demand (Policy–5) indicate that by judiciously selecting the canal network for operation during a week, it is possible to achieve a relatively higher utilization of canal water for meeting irrigation demands with higher canal seepage and with least energy demand for pumping groundwater.

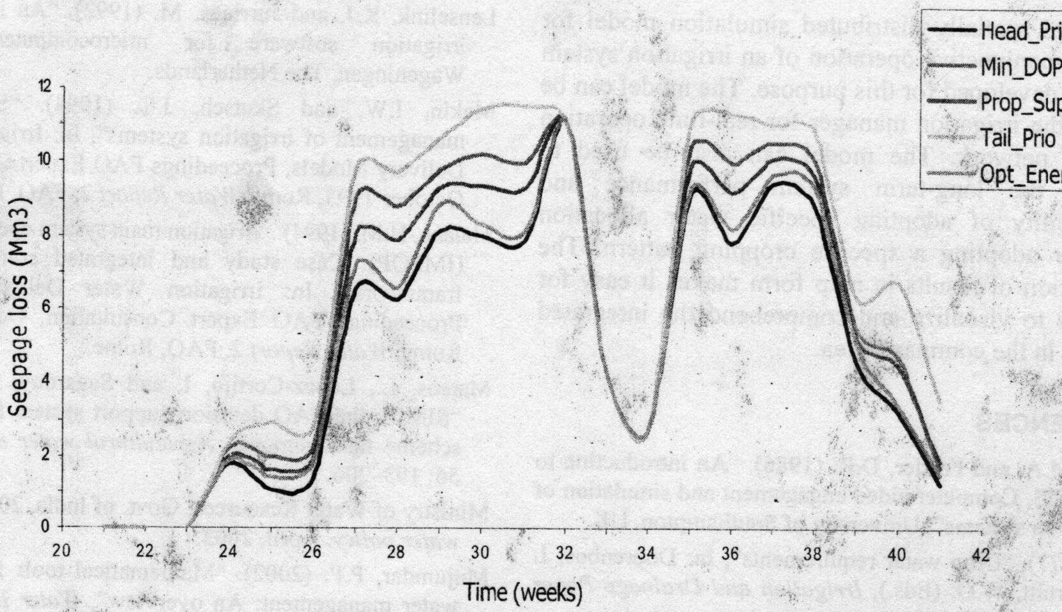

Fig. 9: Canal seepage losses under different allocation policies

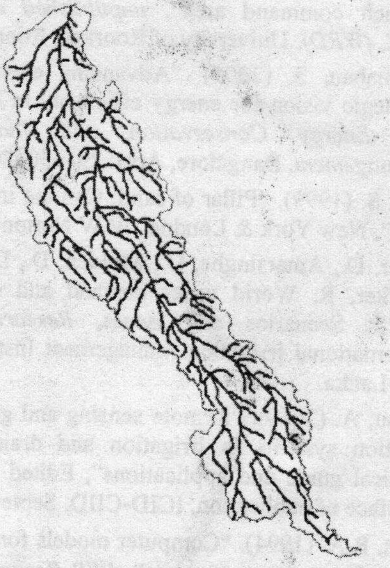

Fig. 10: Canal operation with policy of minimum energy demand

If the energy requirement in the total command area for all the 18 weeks of operation is compared, the energy requirement (in MKwh) under different allocation policies for meeting full irrigation demands comes out to be: Policy–1 (2596.10), Policy–2 (2593.07), Policy–3 (2607.02), Policy–4 (2659.67), and Policy–5 (2568.82). Thus, policy of minimum energy demand results in saving of 27.28 MKwh of energy as compared to policy of head-reach priority. The reason for this large saving in energy in the total command area could be recharge through the canal seepage in areas of deeper water table such that water table builds up and the areas adjacent to canal-irrigable areas withdraw water from a comparatively shallow depth resulting in further saving of energy. It needs to be mentioned here that the amount of energy saving under Policy–5 is case specific and depends on a number of factors such as irrigation demands, water deficit at head, cropping pattern, aquifer characteristics etc.

CONCLUSION

With the increasing water and energy demands and their limited resources, it is imperative to use the available water and energy resources as efficiently as possible. Irrigation is a one of the major consumers of water and energy. Integrated and judicious use of surface water and groundwater resources could play an important role in solving some of the major water-related problems in irrigation commands. A recursive simulation approach is presented here for optimizing the energy requirement for pumping groundwater. The approach also results in balancing the groundwater conditions in a command area so as to reduce water logging and groundwater mining. It is seen that comprehensive analysis of an irrigation system in real-time in terms of demands and availability of resources and the system characteristics and constraints can result in judicious management of the resources such that system efficiency can be increased and the system can be made more sustainable in the long run. A conceptual spatially distributed simulation model for real-time conjunctive operation of an irrigation system has been developed for this purpose. The model can be used by the irrigation manager for real-time operation of canal network. The model can also be used to evaluate the long-term system performance and sustainability of adopting specific water allocation policy or adopting a specific cropping pattern. The presentation of results in map form makes it easy for the users to visualize and comprehend the integrated situation in the command area.

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