CONJUNCTIVE USE OF SURFACE WATER AND GROUNDWATER RESOURCES-II

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Training Course on
HYDROLOGICAL INVESTIGATION TECHNIQUES FOR WATER RESOURCES DEVELOPMENT & MANAGEMENT
(26-28 August 2012)

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A GIS BASED CONJUNCTIVE USE SIMULATION MODEL

To help in the scientific and rational conjunctive management of irrigation water, a spatially distributed simulation model has been developed 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 (Goel 2003). Objective of the developed geo-simulation (GIS based 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. The model has been nick-named as *SINCHAI* which stands for*Simulation of Integrated Network of CHAnnels for Irrigation*(Goel and Jain, 2003). The model is briefly described below.

PURPOSE OF DEVELOPMENT

Large amount of information about various processes is involved in irrigation management of a command area. The variables, parameters and processes involved in task of irrigation management, such as cropping pattern, soil properties, rainfall, topography, groundwater depth, canal system characteristics, water use efficiencies etc. vary spatially as well as temporally. The decision-making process for irrigation management in developing countries has been handicapped with the non-availability of geographic information on real-time basis and the inability to process and analyze vast quantity of geographic data. With the advent of satellite remote sensing, it has now become possible to gather and update information of large areas at regular intervals. Using a Geographic Information System (GIS), the spatial information can be efficiently stored, analyzed and retrieved. There was a need to develop a geo-simulation model that can integrate the real-time information coming from remote sensing observations and the spatial details provided by the GIS to help the irrigation managers in analyzing the system operation under prevailing conditions of water demands and availability.

MODELING STRATEGY OF *SINCHAI*

*SINCHAI*uses the spatially distributed data of various features of the command, attribute data related to crops and soils in the command and the dynamic data related to rainfall, evapo-transpiration and canal network operation in the command. The study area is divided into square grids of uniform size. The spatial data includes crop map, soil map, Thiessen polygon map of rainfall stations, digital elevation map, flow direction map, canal layout map, canal irrigable area map, and groundwater depth map in the command. The flow chart of *SINCHAI* is presented in Figure-1.

After developing the database for the command, the model run is started for a specified week. If it is the starting week of model execution, then suitable initial soil moisture conditions in the command are assumed. Otherwise, the moisture content in the crop root zone in various grids at the end of previous week becomes the initial water content for the present week. Next, the probable rainfall and evapo-transpiration estimates in the command at various stations are obtained (either from forecast information or statistical analysis) and the soil water balance model (SWBM) is run to find the grid-wise irrigation demands.

After calculating the demands, canal network operation is simulated to find the best configuration of canal water delivery depending on the canal water availability during the week and the prevailing groundwater conditions in the command. At the end of week, knowing the actual meteorological conditions and the actual canal network operation, SWBM is run again to estimate the spatial distribution of final water content and groundwater recharge in the command and the extent of groundwater pumping requirement. Spatial estimates of pumping and recharge are then linked with a groundwater behavior model to find the groundwater table for the subsequent week. The *SINCHAI* model can be used to examine the consequences of a canal operation policy. If, as a result of the particular policy, the developed groundwater conditionsare unacceptable, the canal operation policy can be revised and model runs can be taken again. The model is run for each week of crop season to manage the available surface water and groundwater conjunctively in real-time.

*SINCHAI*operates at weekly time step and consists of two major distributed models [Soil Water Balance Model (SWBM) and Canal Network Simulation Model (CNSM)] and a number of sub-models for database generation and linkage of various models. The purpose of SWBM is to simulate the moisture variation in root zone of crops for finding spatially distributed irrigation demands, groundwater recharge, water stress conditions in crops, and soil moisture content at the end of each week. CNSM is used to analyze various scenarios of canal network operation on the basis of water demands, supply, and system characteristics. For generating revised groundwater conditions corresponding to different canal operation scenarios, an existing groundwater simulation model (Visual MODFLOW) has been linked with the scheme. Various aspects of the modeling approach and brief description of the SWBM and CNSM modules of *SINCHAI* are presented in the following:

Use of Remote Sensing Observations

Remote sensing implies sensing from a distance. These systems are used to observe the earth's surface and analyze the information about the resources. Vastness of the agricultural areas, time and manpower constraints in data collection and yearly changes in the information require fast inventory of situations. In all these circumstances, remote sensing can be looked upon as an aid in planning and decision-making. Remote sensing can be used to map the actual cropping pattern in a command area and such information can be used to find the actual crop water demand for irrigation management. With the availability of high-resolution sensors, it is now possible to delineate the exact layout of the canal system from remote sensing observations. This information, in combination with field records, can provide the spatial extent of the area that can be irrigated with different segments of the canal system. Cropping pattern derived from remote sensing data is used in the demand module (SWBM) for calculating irrigation requirements.

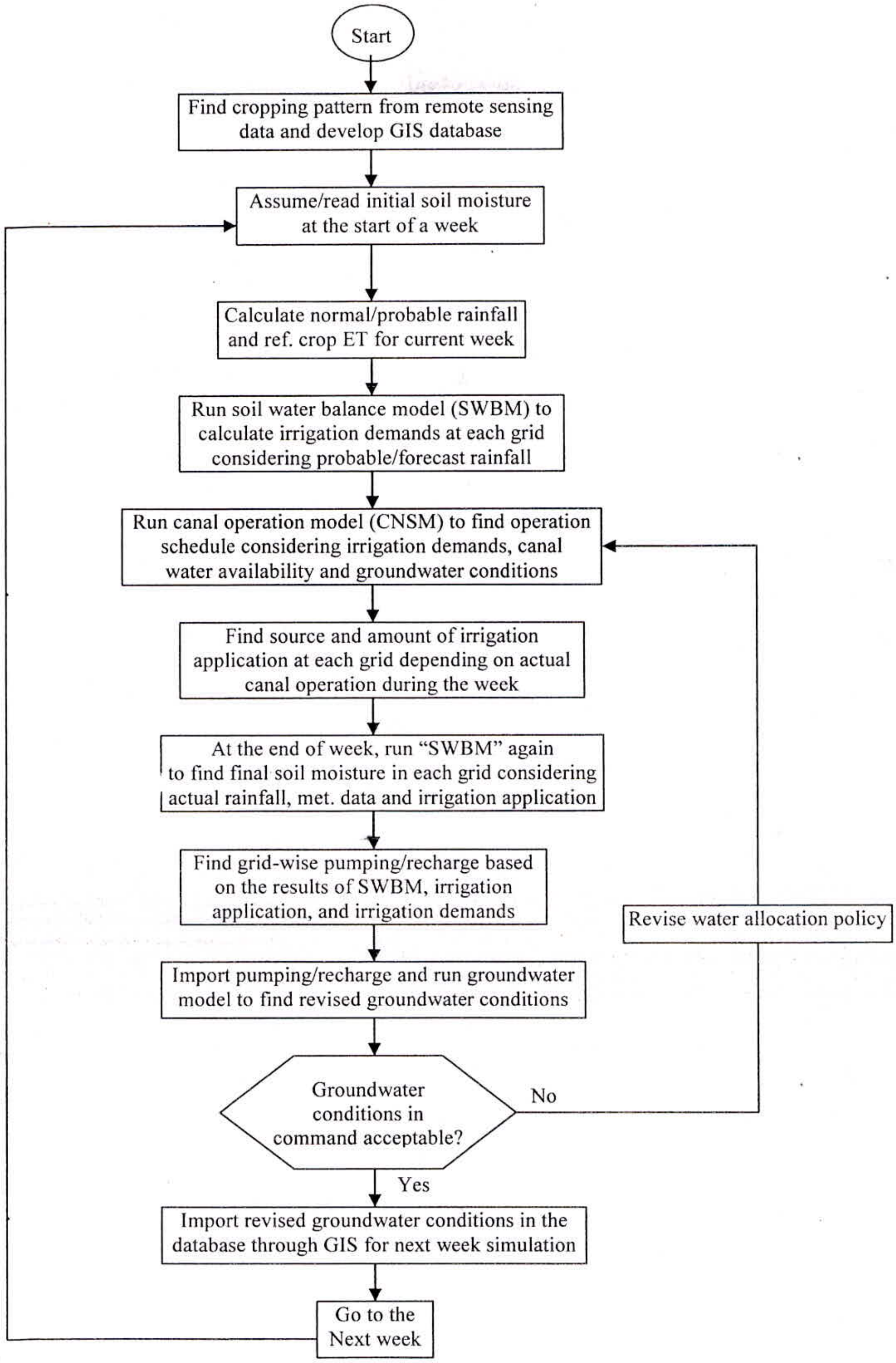

Figure1. Flow chart of *SINCHAI*

Linkage of SINCHAI with GIS Database

Irrigation management requires huge volume of data pertaining to hydrological, hydro-geological, hydro-meteorological, soil, agronomic, and cropping pattern parameters in command areas. These data need to be efficiently stored, analyzed, and retrieved in a userfriendly environment, such as a GIS. Various spatial data layers (crop map, soil map, Thiessen polygon map of rainfall stations, digital elevation map, flow direction map, canal layout map, canal irrigable area map, and groundwater depth map) are developed in GIS. Data layers are imported in *SINCHAI* and used for formulating water distribution plans in a specified week.

Rainfall Forecasting

Daily/weekly rainfall forecast is required for the subsequent week for evaluating the irrigation water demands in the command area from the irrigation system. A few options are available: i) forecasts available from IMD for the region, ii) evaluation of rainfall corresponding to some specified dependability (say 75%) using historical data, iii) use of statistical techniques such as transition probability matrix to find probable rainfall based on rainfall in the recent past.

Determination of Potential Evapo-transpiration

In this step, potential evapo-transpiration in the command based on the weather conditions (temperature, humidity, sunshine, and wind speed) is determined. This information is used to find crop water demands in the command based on the crop type, crop growth, and moisture availability in the root zone.

Soil Water Balance Model (SWBM)

Soil water balance of cropped area is a dynamic process influenced by crop and soil properties, climatological variables and topography. Knowledge of water content in soil is crucial for several agricultural applications, such as prediction of irrigation demands, crop water stress, irrigation schedules, crop yields and groundwater recharge. In *SINCHAI*, moisture variation in the root zone is simulated to find the irrigation demands in the command. Once the irrigation demands are worked out, it remains a management decision to finalize the source of water and to see how it is arranged.

The developed SWBM incorporates spatial variability of crop, soil, rainfall, and topography in the dynamics of soil- water-plant interaction for irrigation management. The module makes grid-wise computations using the raster as well as attribute data of different variables and calculates the final water content at the end of a week. Raster information includes crop type, soil type, Thiessen polygon of rainfall stations, surface elevation, flow direction, groundwater depth, and actual irrigation application. Attribute information includes properties of crops (such as maximum root depth, time to reach the maximum root depth, starting week of the crop, total time period, weekly crop coefficients etc.) and properties of soils (such as specific gravity, porosity, field capacity, permanent wilting point, and saturated hydraulic conductivity). In addition, dynamic information needs to be provided every day/week such as rainfall at different gauging stations, reference crop evapo-transpiration demand of weather, and irrigation application in command.

Two time steps are possible in the program: daily or weekly. In weekly time step, the various inputs and outputs of the system are assumed to be lumped over the whole week. In the daily time step, the water balance computation is performed for each day of the week considering daily rainfall and daily reference crop evapo-transpiration. The calculations are performed for all the days of the week and the soil moisture status at the end of the last day of the week is given as output (final water content at the end of the week).

Four output files are generated by SWBM: a) final water depth at the end of the week, b) irrigation water demand, c) stress condition, and d) deep percolation. The result files can be converted into maps or pictures and can be displayed in a GIS system. The projection of the results in the map form makes the interpretation and decision making much easier as compared to the conventional record form or tabular form. In the operation strategy of *SINCHAI*, SWBM is utilized in two steps per week. First, it is used to forecast the supplementary water demands for the forthcoming week, given the normal/probable rainfall and evapo-transpiration for the forthcoming week. Based on the forecast demands, the operation of the canal system is simulated. After the week has passed and the actual rainfall, evapo-transpiration, and actual canal operation during the week become known, the soil water balance model is run again to find the final water content at the end of the week based on the actual input to the system. This information is used to forecast the irrigation demands for subsequent week.

Canal Network Simulation Model(CNSM)

The objective of this module is to simulate the weekly operation of the canal system for satisfying crop water demands by optimizing the use of canal water and groundwater. Using the simulation model, one can analyze different operation scenarios and evaluate system performance. The proposed operation in CNSM is governed by the crop water requirements, availability of surface water in the canal system and the prevailing groundwater situation in the command area during a week.

For optimizing the use of surface and groundwater, the approach utilizes the surface water to the extent possible provided that groundwater conditions permit. This results in least power requirement for extracting groundwater and simultaneous recharging of the underground aquifer. However, if the surface water availability is less than the demand during a week, then the approach utilizes the groundwater in the region of least depth of pumping. Thus, this approach tries to equalize the groundwater regime in the command area in head and tail reaches at each time step [extraction in the area of shallow groundwater table and recharge (in the form of canal water seepage) in the area of higher groundwater depth]. Further, pumping from the shallow water table region in the command results in less consumption of power for pumping groundwater.

Another objective of developing CNSM is to account for the spatial variation of characteristics of the canal system and other important variables. Spatially distributed information used by CNSM include: crop type, layout of different canal segments, layout of local command areas of different canal segments, irrigation demands, and the depth of groundwater table from the land surface. Attribute information used by CNSM relates to the characteristics of different canal segments (discharge capacity, section details, irrigable area, conveyance efficiency, application efficiency in the local command, field channel efficiency, canal seepage rate, priority of segment demand etc. Model also requires the information about those canal segments, which are running at the end of the previous week for calculating fill-time of different segments.

The irrigation demands (obtained from the SWBM) at all grids that lie within the irrigable command of each canal segment (from canal irrigable area map) are accumulated after accounting for the water application efficiency and the field channel efficiency and the total irrigation demands in different canal segments of the entire canal network are worked out. Next, calculations are started from the tail end of the system in the upstream direction. Knowing the discharge capacity of canal segments, the required run-time and seepage loss in each segment is worked out. Canal seepage is then added to the water demands of a segment and the final run-time is computed iteratively. The water requirements are accumulated in the upstream direction after giving due consideration to canal capacity. If the canal capacity at a segment is not sufficient, then the amount of groundwater required (because of capacity constraint) in the segment is found out. The groundwater demands of intermediate segments are settled first by curtailing irrigation demands of some downstream canal segments (based on the groundwater conditions). Calculations are carried up to the head of the canal system by satisfying the capacity constraint of all intermediate segments and the total water requirement at the head is estimated. This is the canal water requirement in the command (including seepage losses) that can be satisfied from the existing canal system. Now, this requirement 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 earlier for different segment. However, if the availability is less than the demands, then, some allocation criteria needs to be evolved to find the segments of canal water supply and groundwater supply.

Five different distribution/allocation policies have been included in the model and the operator can select any one policy for the operation of the canal system. The results of different policies can be analyzed before the implementation of any particular approach. For finding the water allocation to different canal segments, calculations proceed from the head of canal system towards the tail end. Different allocation policies that have been included in the simulation model are briefly described below:

Policy 1:Head-reach priority

Under this policy, the segments in the head reach are given priority and their demands are met in full. The remaining water left at a system node is sent to the downstream segments. This policy is mainly applicable to a system with no control on the canal flow 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, curtailing the irrigation demands of some downstream canal segments compensates the deficit at the head of the canal system. The demands of such affected canal segments are met through groundwater withdrawal. The groundwater depth under each canal segment governs the identification of affected segments. The segment of least depth of groundwater is selected iteratively and the calculations are repeated for finding revised water requirement at head under changed demand scenario till the water demands match with the water availability.

Policy 3: Proportionate supply

Under this policy, water available at a system node is distributed proportionately among different segments (bifurcating from a node) in proportion to their total demands. Thus, this policy tries to equitably distribute the deficit among different canal segments.

Policy 4: Tail-reach priority

Under this policy, the allocation is started from the tail end of the system and it advances in the upstream direction as the demands of the tail-end canals are satisfied. Using this policy, the operator can visualize the total extent of the downstream canal system that can be satisfied for the available water. Since the groundwater depth in the tail-end is generally high as compared to the head reaches and canal water is given priority in tail-end, this policy also tries to equalize the groundwater regime in the command area.

Policy 5 : Conjunctive use with minimum energy demand

Under this policy, the canal-run configuration corresponding to the least energy requirement in the irrigation system for pumping groundwater is identified. After finding the canal-run configuration corresponding to Policy-2, the canal-run segments are moved in the upstream direction one-by-one and the corresponding energy requirement in the system for pumping groundwater is calculated. The configuration that results in least energy requirement is recommended.

Option is included in the model to select any one of the available allocation policies and simulate the operation of the canal system. The output of simulation analysis indicates the discharge, run-time, and seepage loss of various canal segments for the week under consideration. Output results of the simulation model are presented in the form of maps and table. Different results are presented as attributes of canal segments and can be instantly visualized in a GIS. Various maps that can be generated include: whether a canal segment is supplied water or not, cause of not running the canal segment, required discharge, run-time, seepage loss, groundwater usage etc. Detailed results of the model are presented in tabular form also.

Case Study of LakhaotiCanal Command Using *SINCHAI*

A case study of Lakhaoti command area under the Madhya Ganga Canal System in U.P. State, India is briefly presented here for illustration of *SINCHAI*. Lakhaoti branch takes off from the left of Madhya Ganga Canal (MGC) System at 82.4 km with a design discharge of about 64 cumec. MGC project was framed with the objective of diverting surplus monsoon water of Ganga River in the dry pockets of the Upper Ganga canal command. The command area of Lakhaoti branch lies between latitude 27° 45′ N to 28° 45′ N and longitude 77° 45′ E to 78°35′ E and covers an area of 205.6 thousand ha in the districts of Ghaziabad (3.8%), Bulandshahr (71.4%) and Aligarh (24.8%) in the U.P. State, India. Command area is bounded by the two main drainage of the area, Kali River in the west and Nim River in the east. The boundary of the Lakhaoti command is depicted in Figure 4. Lakhaoti branch supplies water to the area during monsoon period (June – October) for irrigation of Kharif crops. In the absence of surface water supplies in the area till 1987, irrigation demands were being met by pumpage from groundwater reservoir. Excessive pumping of groundwater in the area led to gradual depletion of water table. Introduction of canal irrigation in the year 1988 led to greater recharge to the ground water reservoir with gradual build-up of water table.

The analysis with *SINCHAI* is presented for the year 1998-99. The cropping pattern in the command in this year was obtained from the analysis of multi-temporal remote sensing data of LISS-III sensor of IRS-1C/1D satellites. The Kharif crop map of the command is shown in Figure 3. The soil map in the area was obtained from National Bureau of Soil

Survey and land Use Planning (NBSSLUP), New Delhi and is shown in Figure 4. Rainfall data of five rainfall stations (Siyana, Bulandshahr, Anupshahr, Khurja, and Atrauli) were used. Thiessen polygon of the rainfall stations is shown in Figure 5. The layout of canal network in the command was obtained from the PAN sensor data of IRS-1C satellite and the same is shown in Figure 6. By using the field information about the proposed profitable area of different minors and distributaries, the canal irrigable area of the command was obtained by trial and error and the same is shown in Figure 7. Using the topographic information from the toposheets of Survey of India, digital elevation map (DEM) of the area was generated in GIS using interpolation techniques. DEM of the area is shown in Figure 8. Using the levels of groundwater in different observation wells, groundwater surface was generated in GIS using point interpolation techniques. Subtraction of the groundwater surface from the DEM provided the groundwater depth map in the command, which is shown in Figure 9. Aquifer characteristics (conductivity and specific yield) of the command were obtained from a groundwater modeling study carried out for the area. Using the DEM of the command and the layout of canal network, the flow direction map was also obtained. Spatial information from all these thematic maps were converted to ASCII file and imported in *SINCHAI*.

Attribute information about various crops in the command, such as root depth, time to reach maximum root depth, sowing time of crop, total time of crop in the field, crop coefficients etc. were obtained from the field departments and literature. Attribute data about various soil types, such as field capacity, permanent wilting point, specific gravity, hydraulic conductivity etc. were obtained from the laboratory testing of nine different types of soils observed as per the NBSSLUP map. Canal system characteristics were obtained from the Irrigation Department and various project reports. Dynamic information, such as rainfall data at various observation stations, meteorological data for computation of reference crop evapo-transpiration, and water availability in the canal system in different weeks were also obtained from relevant field departments.

Using various types of spatial, attribute, and dynamic data, model run was taken for each week of the Kharif season of year 1998 starting from June 18. The analysis for different weeks of the Kharif season was carried out in accordance with the flow chart shown in Figure-1. The results of the SWBM

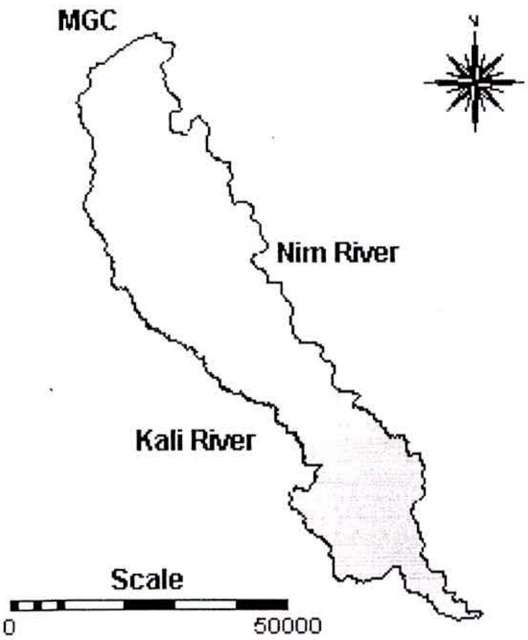

Figure2. Boundary of Lakhaoti command

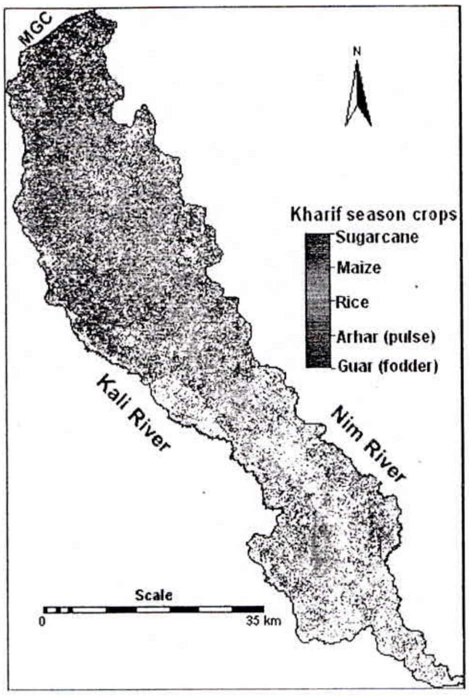

Figure3.Kharif crop map in year 1998

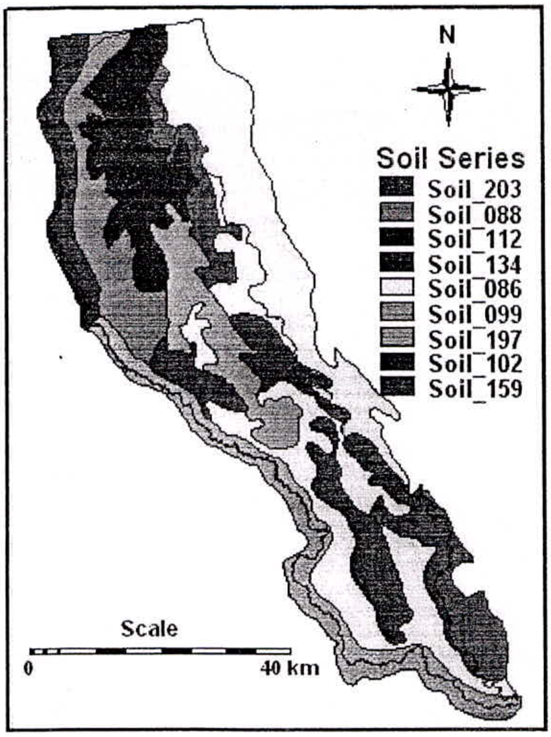

Figure4. Soil map in Lakhaoti command

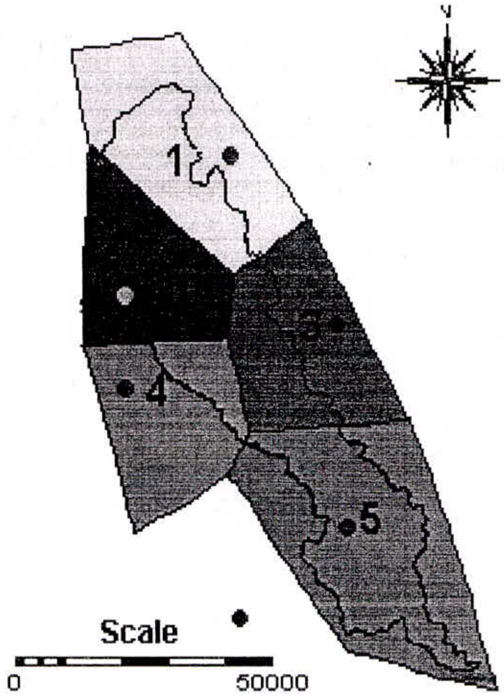

Figure5.Thiessen polygon of rainfall stations

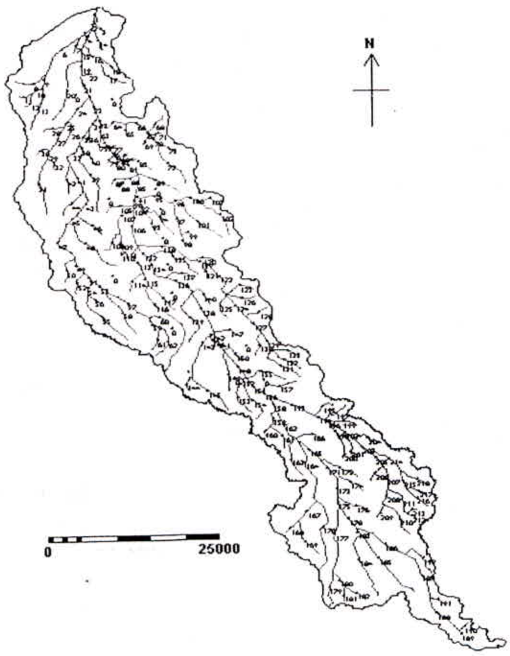

Figure6. Canal network in Lakhaoti command

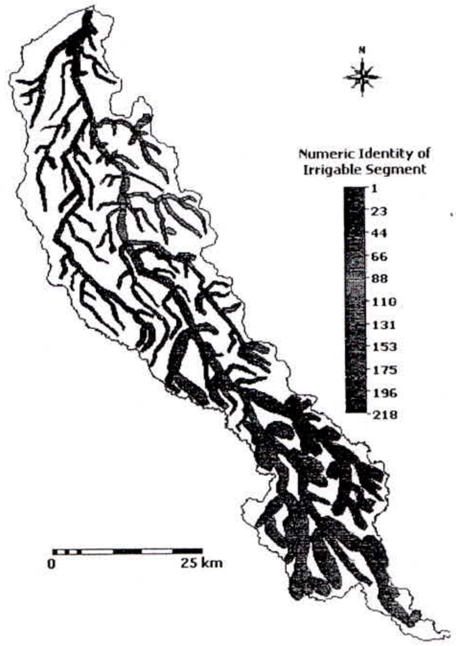

Figure7.Irrigable commands of different canals

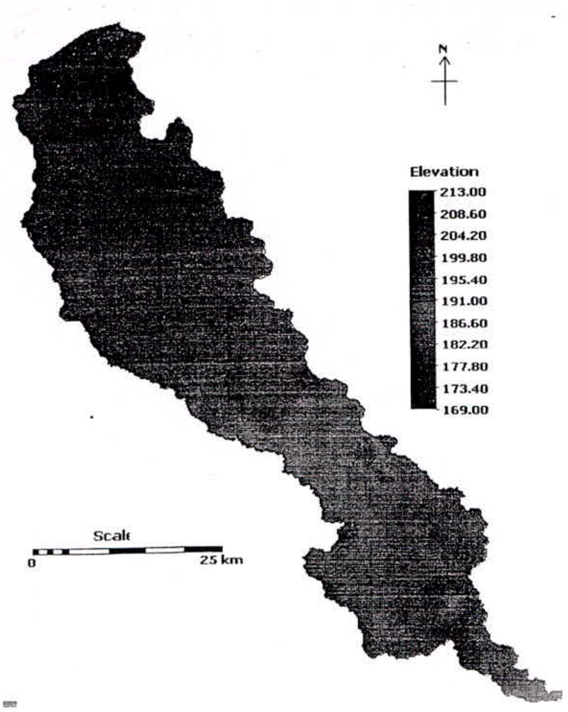

Figure8. Digital elevation map of Lakhaoti command

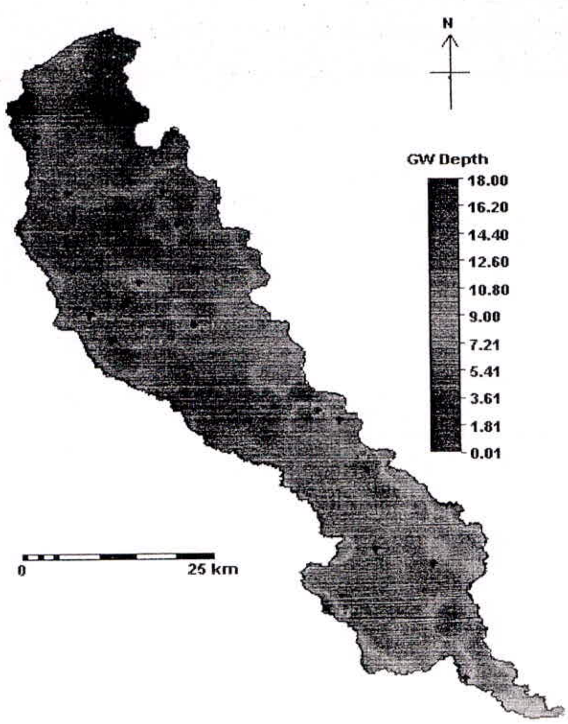

Figure9. Groundwater depth in October, 98

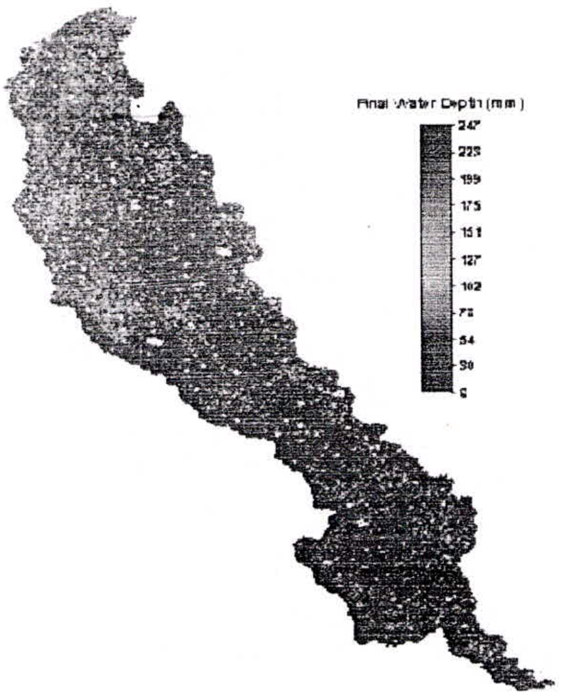

Figure10. Final water content map at the end of a week as obtained from SWBM

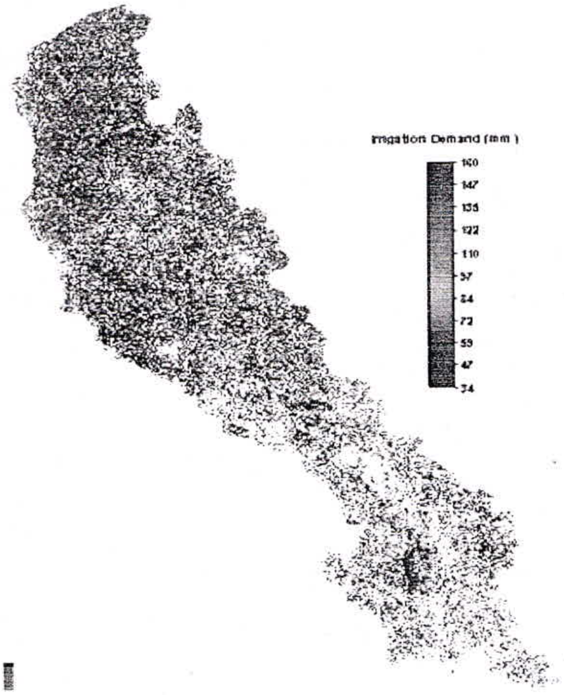

Figure11. Irrigation demands map during week as obtained from SWBM

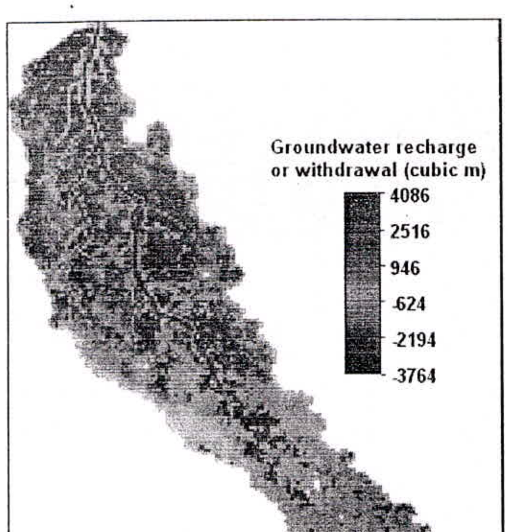

Figure.12. Groundwater recharge/withdrawal map during a week as obtained from *SWBM*

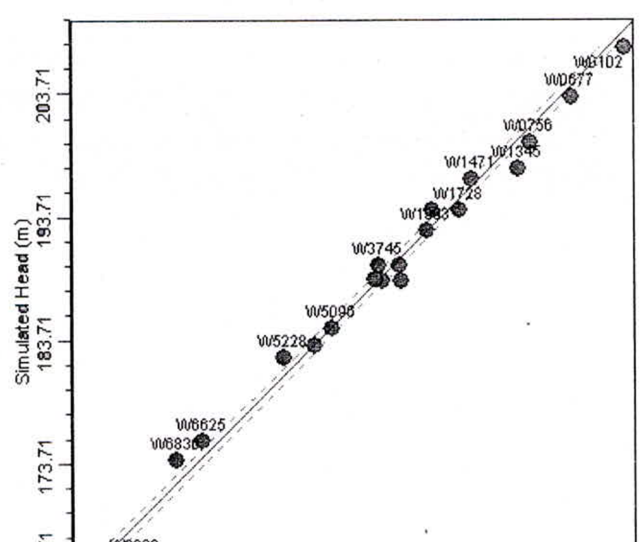

Figure13. Comparison of observed and simulated groundwater levels in October, 1998

(final water content map, irrigation demand map, and the recharge map) for one week of operation are illustrated in Figure 10 to Figure12. Groundwater observation data were available for the months of June and October 1998. Initial groundwater conditions were taken from the water table depth data at different observation wells in June and the groundwater for different months were found by convoluting the weekly pumping and recharge estimations with the groundwater behavior model (Visual MODFLOW). The match between simulated and observed groundwater levels (Figure 13) in various observation wells in October validated the model for the Lakhaoti command.

The year 1998-99 was a wet year with monsoon rainfall exceeding the normal rainfall by more than 25% in the command. To analyze the impact of different allocation policies, scarcity conditions were artificially assumed (rainfall reduced to 60% of actual rainfall and canal water availability reduced to 75% of the actual availability) and the model runs were taken separately for each of the five specified policies of surface and groundwater allocation for the full Kharif season. The results of the CNSM for one week of operation with five different policies of operation are illustrated in map form in Figure 14. The results are shown assuming that water availability at the canal head is 1000 cusec though the demands from the system 2179 cusec. From the analysis, it is found that under the assumed water deficit conditions and similar conditions of water supply to the crops, considerable amount of power (27 M Kwh) can be saved during the Kharif season in the command area under the policy of conjunctive use with minimum power demand (Policy-5) by judiciously allocating the canal water and groundwater in different weeks.

Using the concept of prioritization of a part of canal network with regard to any allocation policy, flexibility has been introduced in the model. Further, options to augment water supply at intermediate locations in canal system is also provided. The model output is linked to a GIS to visualize the operation results in form of maps. The model tries to maintain water table conditions within limits so as to avoid waterlogging and groundwater mining.

SINCHAI is still in its developmental stages. The model, at present, does not include water quality aspect. Further, it needs to be linked with a hydraulic model and an economic model for application to real field conditions. Efforts are being made to represent the field conditions as realistic as possible.

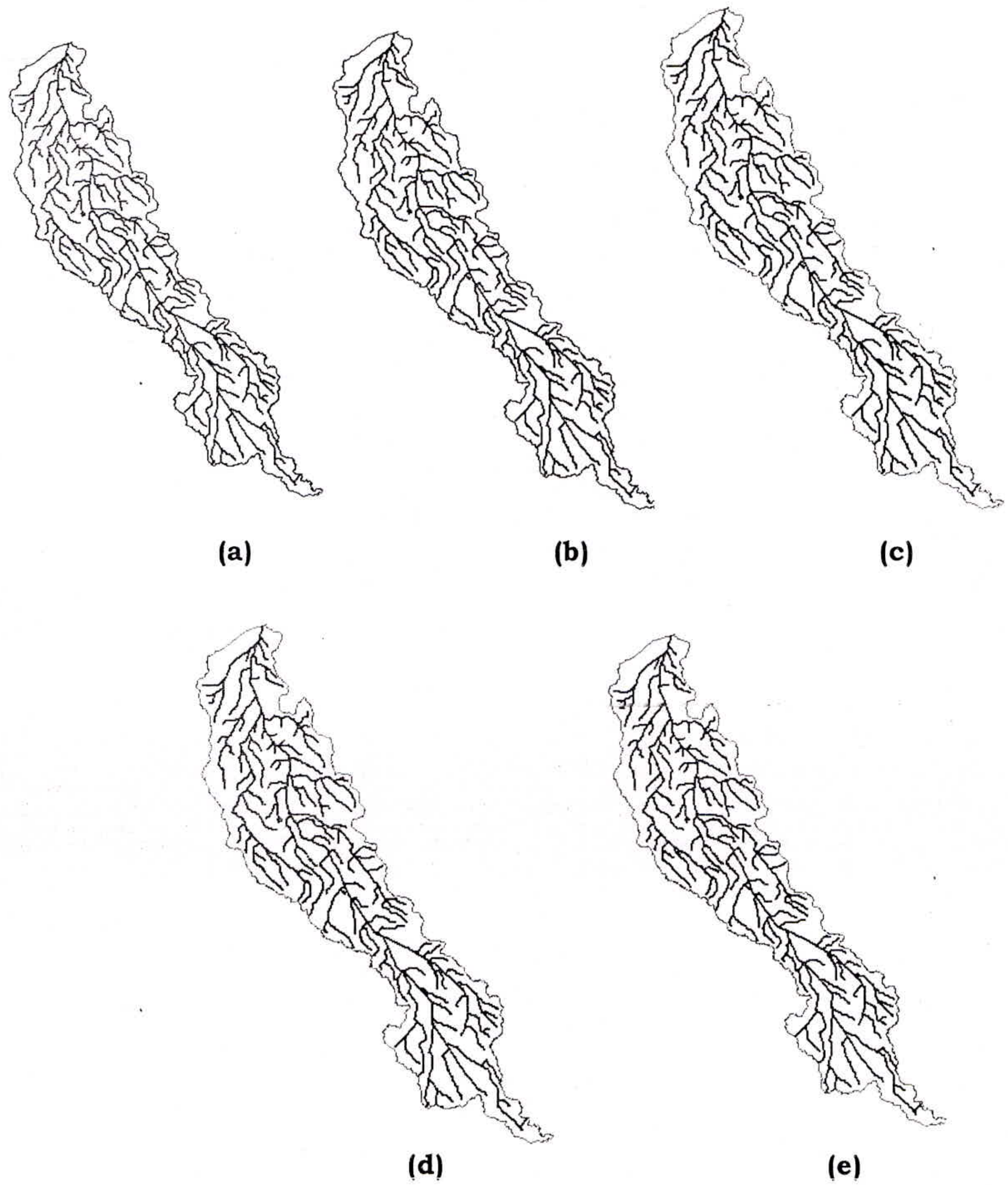

Figure14. Canal operation [Canals running (Red), Canals not running (Blue)] for a week with five different policies: (a) Policy of head-reach priority, (b) Policy of conjunctive use, (c) Policy of proportionate supply, (d) Policy of tail-reach priority, (e) Policy of conjunctive use with minimum energy demand