

GIS-based decision support system for real time water demand estimation in canal irrigation systems

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In canal irrigation systems in India, water supplies reach the fields through a network of main canals, branch canals (secondary canals) and distributaries (tertiary canals). The distributary is the basic unit of irrigation management in large canal systems, as it is the last point of control in main irrigation systems operation. This study presents a scheme for the development of a Geographic Information Systems (GIS)-based decision support system (DSS) for real time water demand estimation in distributaries. The DSS dynamically links a field irrigation demand prediction model for the area irrigated by a distributary with a GIS of the canal network. The system allows interactive selection of distributaries and on-line real time estimation of water demands in each distributary over the entire network. For real time estimates, the model is used with current season information on weather, weather forecasts and distributary level information on crops and soils. Since the distributary is the unit of operation, the DSS integrates well with the actual process of decision-making by the operators of canal irrigation systems in India. The availability of such a quantitative decision-support tool for irrigation systems operation can have a powerful impact on the overall water management strategy to be adopted in an irrigation project area, particularly in the event of a shortfall in water supplies. The development of the overall scheme and procedures is illustrated with data from a case study area in India.

THE creation of a number of large irrigation systems in India contributed significantly to gains in food production provided by the Green Revolution. It also improved food security in the region and reduced the dependence of agriculture on the vagaries of the monsoons. However, the increasing costs of creation and maintenance of these systems, and doubts about the long-term sustainability of the soil and water resources in their command areas, have led to much criticism and concern. This relates mainly to the low operational efficiencies of the large systems (ranging between 30 and 40%), and consequent water losses in

transmission and low crop yields¹⁻⁵. There is agreement that substantial benefits can be derived even from relatively small increases in operating efficiency⁶.

The operation of large canal irrigation systems is a complex task. In the major irrigation systems of India, water is delivered over a large area (10,000 to a million hectares or more in India) with spatially variable soils, crops and weather conditions. The irrigation supplies reach the fields through a hierarchical network of main canals, branch canals (secondary canals) and distributaries (tertiary canals). The distributary is usually the last point of control for main irrigation system management as downstream of this level, irrigation is either field-to-field or under the direct control of the farmers. The irrigation supplies into each distributary are decided based on the estimated water demands of the crops in the area irrigated by it, after accounting for field-application losses. The demands depend on soil, weather and crop conditions in the irrigated area. Further, the total areas irrigated by different distributaries also vary. The irrigation demand estimation for each distributary is therefore independent of other distributaries. The individual distributary-level water demands are aggregated to assess irrigation supply requirements at higher levels (branch canals and main canals) of the irrigation system after accounting for transmission losses⁷. The operational efficiencies depend on the extent to which the irrigation supplies match the demands at each hierarchical level of the network. Thus, estimating periodically, and in real time, the water demands of individual distributaries of the canal network are critical for improving the overall operational efficiencies of large irrigation systems.

Most earlier studies in real time irrigation system management to improve operational efficiencies^{8,9} have focused on water releases at the reservoir level, after aggregating the irrigation demands at different hierarchical levels to this level. The temporal variability of reservoir inflows is the primary source of uncertainty in these studies. They do not include the variability of distributed demands in real time at the field, distributary and other levels of the water distribution system. When the problem of assessing irrigation requirements for real time operation of irriga-

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tion systems at the distributary level was addressed¹⁰, the spatial variations in soil and crop were not explicitly considered. Some studies^{11,12} addressed the problem of real time operation of irrigation systems at three stages, reservoir releases, transfer to field level after accounting for channel losses and water allocation to crops. Here too, the uncertainty was limited to variations in inflows and the irrigation requirements of crops were considered to be constant in different periods. In nearly all these studies, the focus is on coping with uncertainty caused by variable water supplies.

To increase operational efficiencies, variable irrigation supplies need to be matched in real time with the variable irrigation requirements over space. Spatial data management tools like Geographic Information Systems (GIS) can effectively include spatial variability of soil, crop, water supply and environment in dealing with the complex problems of water resources management¹³. Earlier studies in large-canal irrigation systems management that involved use of GIS tools, dealt with agricultural performance evaluation by combining them with remote sensing and hydrologic models^{14,15}. These studies were essentially diagnostic in nature and aimed at evaluating the uniformity and sustainability of irrigation as reflected by the crop yields. While such studies can be useful in irrigation planning and policy, they do not address the operational problems faced by irrigation managers in real time.

A basic operational problem faced by irrigation managers is the estimation of irrigation requirements at the level of each distributary at the beginning of every irrigation cycle. The difficulty lies in obtaining quick, systematic and realistic estimates of the demand in real time for different distributaries in the canal network in the presence of spatial variations in weather, soil and crop in the areas irrigated by them. This study develops a scheme for providing a GIS-based tool for irrigation system managers to assist them in making such estimates. It is shown that the features of GIS for storing, manipulating and analysing spatial data related to soil, crop and weather can be used to (i) provide an effective information system for the project area that is interactive and representative of the hierarchy of irrigation system operation, and (ii) obtain real time, systematic and quick estimates of irrigation demands in the distributaries taking-off from different canals/branch canals.

For (ii), irrigation demand prediction models are integrated with current season information on weather, weather forecasts and local information on crop and soil in a GIS environment. Since the distributary is the basic unit of decision making in the operation of the canal system, it allows quick estimation of the spatial variations in irrigation requirements in different distributaries that form the canal network, by interactively selecting them in the GIS. The procedures are illustrated by applying them to a case-study area.

The case study area and problem

The case-study area forms a part of the Sone irrigation project in Bihar, India. The Sone project is a river diversion scheme built on the river Sone. The river is a tributary of the Ganga. The project irrigates about 400,000 ha during the monsoon (kharif season) and 175,000 ha during the rabi (winter season). The area receives about 1100 mm of rain, over 80% of which occurs over the monsoon season (June to September). Soils are alluvial and vary from light to heavy-textured clays. Rice is the main crop grown in the area in the kharif (monsoon) season. The irrigation system has been operative¹⁶ since 1871. The canal network consists of main canals and several branch canals (Patna canal, Arrah canal, Behea branch canal, Dumraon branch canal, Buxar canal, Chausa branch canal, Garachoubey branch canal). Each branch canal has a network of several distributaries (tertiary canals) and minor distributaries or minors. Data from the irrigation distributaries of the Patna canal network of the Sone irrigation system are used for the case study.

The Patna canal (Figure 1) extends over 70 km and irrigates nearly 190,000 ha through a network of 40 distributaries. The study area is bounded by the river Sone

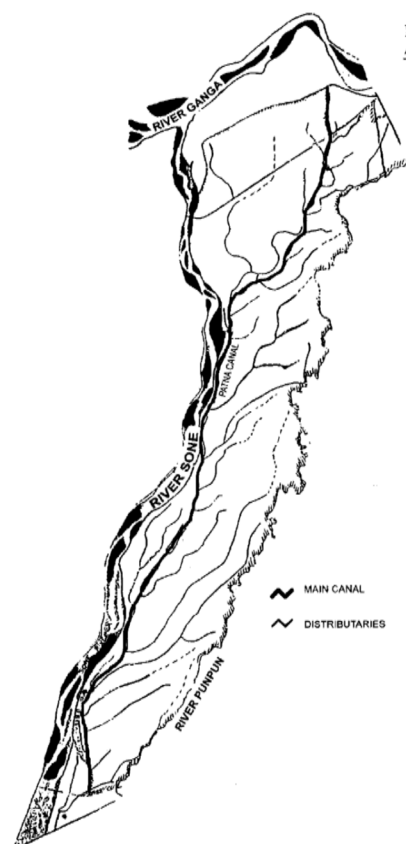


Figure 1. Command area of Patna canal system.

on the west, river Punpun on the east and the river Ganga in the north. The area irrigated by each distributary ranges from < 200 to > 25,000 ha. The distributaries operate on a two-week cycle (10 days on and 4 days off). Rice is the sole irrigated crop during the rainy season, grown under standing-water conditions. Rice requires about 150 mm depth of standing water in the field during transplanting of seedlings. The designed discharge capacities of the distributaries are not adequate to meet the irrigation requirement of all the fields for transplanting the entire area irrigated by them in one irrigation cycle. For this reason, transplanting of the rice fields under each distributary is usually 'staggered' (distributed) over 3 or 4 irrigation cycles (6–8 weeks during mid or late June to August). In effect, this would mean that within the total area irrigated by an individual distributary, the rice crops in different fields would be at different stages of development depending on the date (irrigation cycle) of transplanting. This leads to variable soil water and standing water conditions in different rice fields irrigated by a distributary during any irrigation cycle.

The irrigation managers in the area are required to prepare a 'water indent' (release requirement) for each distributary before the beginning of each irrigation cycle, based on the anticipated water requirements of the rice crop in its area to the end of the cycle, after accounting for channel losses through seepage. The indents for individual distributaries are aggregated to prepare a water indent for releases into the Patna canal of which they form the water distribution network. Precise estimation of irrigation requirements of the crops for each irrigation cycle at the distributary level is therefore critical for main system management in the project area.

The irrigation requirements for an irrigation cycle of a distributary depend on the standing water depth in the rice fields at the beginning of the cycle and the anticipated evapotranspiration and percolation losses to the end of the cycle. These would vary for different fields depending on the dates of transplanting. They would also depend on the forecast information on rainfall. A systematic procedure for assessing the crop water status and irrigation release requirements in different distributaries in real time, which includes the variations in transplanting dates and other spatial variations within its total area, can assist irrigation managers in making more realistic irrigation demand estimates. Incorporating the procedure in a GIS environment will permit interactive selection of distributaries on a computer screen to estimate their release requirements. This will provide a powerful decision support tool for the main irrigation system management in the area.

Development of decision support system

The decision support system (DSS) has two components. The first component is essentially a spatial information

system of the canal network with the distributary as the basic unit of information. The second component will enable irrigation managers to decide on the 'water indents' for each distributary, by estimating in advance the irrigation releases required at the head of the distributary for each biweekly cycle of its operation. The basis of the DSS is that if a soil water balance model is linked dynamically to the GIS of the canal system with the distributary as the basic unit, the irrigation releases for any distributary can be estimated on-line by simple interactive selection of the distributary in the GIS. The selection will automatically identify (from the attribute table in GIS) the relevant input data files for the soil water balance model (rainfall, soil and crop data files) for the selected distributary. Since rice is the only irrigated crop in the area in the rainy season, the crop transplanted on different dates is treated as an independent crop and the soil water balance model is run separately for each date of transplanting. The releases for each distributary will depend on water requirements of crops (rice transplanted on different dates) estimated by the model, their areas and conveyance efficiencies. The soil water balance model is thus run at daily time steps in two stages: (i) with current season data of daily weather up to the starting date of the irrigation cycle, and (ii) with forecast data of weather to the end of the irrigation cycle. (For model development and demonstration, historical data are used as a perfect forecast.)

This two-stage process is repeated for each irrigation cycle of the distributary. In this way, the GIS-based framework facilitates interactive selection of the distributary, and in preparing a water indent for the distributary for the next irrigation cycle.

GIS of study area

The canal network map of the Patna canal system with 40 distributaries was digitized using ARC/INFO GIS software. The distributary is treated as the basic unit of the GIS. Relevant design data (name, reach of main canal, chainage, length, design discharge, cultivable command area, nearest raingauge station, dominant soil type, etc.) of each distributary were added to the arc attribute table created in the GIS (Table 1). The corresponding data for any distributary are automatically identified, when it is selected interactively in the GIS.

The soil water balance model

A daily time-step soil water balance model for rice, developed in earlier studies^{7,17,18}, was adopted for use in the study area. The equations describing the processes in the model are sufficiently general, and the model and programmes have been tested and used over a variety of environmental conditions. The parameters of the model are

also directly derived from information of soil textural properties. The major modifications for this study are to the input and output routines of the model to accept input from the GIS and variable transplanting dates for rice in the area. The output routines provide information on the depths of standing water at the end of each day, and predict these depths over the next irrigation cycle of two weeks after including information of weather forecasts.

Traditionally, rice is transplanted and grown under continuously flooded conditions with about 5 to 10 cm or more depth of standing water throughout the season. This practice has been considered desirable not only for adequately meeting the water needs of rice, but also for an efficient supply of nutrients to the crop and effective weed control in the field. Such practices and others like

puddling of soils for reducing percolation rates, complicate the soil water balance computations. The water balance of a puddled rice field (Figure 2) is given by:

$$FR_t = FR_{t-1} + R_{t-1} + IRR_{t-1} - ET_{t-1} - DP_{t-1} - Q_{t-1}. \quad (1)$$

In eq. (1), FR_t is water depth in the field at the beginning of day t , R_{t-1} and IRR_{t-1} are rainfall and irrigation applied respectively, at the beginning of day $(t-1)$, and ET_{t-1} , DP_{t-1} and Q_{t-1} are evapotranspiration, percolation and surface runoff during day $(t-1)$. These components are expressed in depth units (mm) and the time period considered is one day. Capillary rise from groundwater is ignored on the basis that the plough layer remains under saturated conditions for a considerable length of the crop growth period and is at a higher moisture potential than the capillary fringe at deeper depths¹⁹.

Table 1. Attribute data of distributaries of the Patna canal system

Distributary identification no.	Name	Design discharge (cusecs)	Irrigable area (ha)	Raingauge* identification no.	Soil* identification no.
1	Manora	139	4695	2	1
2	Teldiha	60	2029	2	1
3	RPC1	24	817	2	1
4	Tejpura	24	800	2	1
5	Tejpura feeder	17	575	2	1
6	Chanda	191	6465	2	1
7	RPC2	18	605	2	1
8	LPC1	0	0	2	1
9	Tuturkhi	113	3838	2	1
10	Mali	387	13118	2	1
11	Ancha feeder	37	1265	2	1
12	Kochasa	588	19904	2	1
13	RPC3	15	505	2	1
14	Amra	210	7106	2	1
15	Imamganj	167	5671	2	1
16	RPC4	5	180	2	1
17	LPC2	8	273	2	1
18	RPC5	8	286	2	1
19	LPC3	8	260	2	1
20	Rampur Chauram	83	2816	2	1
21	Aiyara	144	4887	2	1
22	Murka	272	9216	2	1
23	RPC6	0	0	1	1
24	LPC4	0	0	1	1
25	Paliganj	360	12197	1	1
26	RPC7	0	0	1	1
27	Dorwa	131	4436	1	1
28	RPC8	0	0	1	1
29	Dhana Minor	10	319	1	1
30	Jwarpur	0	0	1	1
31	Maner	784	26547	1	1
32	Adampur	97	3270	1	1
33	Rewa	115	3904	1	1
34	Tangrila	31	1050	1	1
35	Khajuri	44	1485	1	1
36	Fatehpur	317	10741	1	1
37	Manjhauri	69	2337	1	1
38	Kurkuri	88	2962	1	1
39	Danapur	126	4263	1	1
40	Patna	26	876	1	1

*Data from two raingauges are used. Raingauge 1 is at the tail end of the Patna canal and Raingauge 2 is near its headworks. Data for only one soil type are used, as the soils in the case study area do not vary significantly, particularly after puddling the rice fields. However, the DSS software is sufficiently general to deal with such variations.

Rainfall in excess of bund height leaves the system as surface run-off (Q).

$$Q = R + FR - BH, \quad (2)$$

where BH is bund height in mm. Further, according to the recommended agronomic practices, the rice field is drained once during the season, at the peak tillering stage (about 45 days after transplanting for medium duration varieties of rice) of the crop and maintained in the drained condition for 3 or 4 days to prepare the field for application of fertilizers. The specific days of drainage period are 45 to 47 days after transplanting. Standing water depth at the beginning of three days and rainfall which occurs during these days, are treated as run-off.

Deep percolation is the vertical downward movement of water below the crop root zone. Percolated water is not available for use by the crop. Percolation is governed by the hydraulic conductivity of the soil profile and the depth of standing water on the field. The percolation rate of puddled rice fields is affected by a variety of factors like soil structure, texture, bulk density, mineralogy, organic matter content and concentration of salt in soil solution²⁰. The percolation rate is further influenced by water regimes in and around the field. Increased depths of ponded water increase percolation due to the larger hydraulic gradient²¹. Further, because of puddling, the soil layer below the root zone (approximately 30 cm from the soil surface) gets compacted. As a result, the saturated hydraulic conductivity of this layer is reduced when compared to that of unpuddled fields. The reduction in saturated hydraulic conductivity caused by puddling varies with the texture of the soil. The reduction is four to five times for clay loam soil, eight to ten times for sandy loam soil²²⁻²⁴ and ten to fourteen times for sandy clay loam soil^{25,26}. Accordingly, in the present study, the saturated hydraulic conductivity values are selected based on texture and reduced by a suitable factor to take

care of the puddling effect. The daily percolation rate out of the root zone (30 cm) layer is computed by Darcy's law as:

$$DP = -k_s dh/dz, \quad (3)$$

where DP is percolation out of the root zone in mm/day, k_s is saturated hydraulic conductivity in mm/day (after accounting for puddling effects) and dh/dz is head gradient. DP is calculated using eq. (3), so long as $FR > 0$. If the standing water disappears in any irrigation cycle, DP is given by the difference in water depth between the soil at saturation and field capacity. When soil moisture falls below field capacity, DP is assumed to be zero. This is a common assumption in field scale soil water balance models.

Evaporation from the soil and water surface and transpiration from the plant leaves are combined and treated together as evapotranspiration (ET). ET for rice depends mostly on climatic conditions²⁰. Maintaining ET at the potential rate, i.e. the rate which is not hindered by water shortage, is essential for high yields of rice²⁷, because yields will decline with decreasing rate of ET . In the present study, actual ET is assumed to equal potential ET , if soil moisture content is above or equal to field capacity. During the periods, when the soil moisture falls below field capacity (this can happen when the irrigation supplies are inadequate in any irrigation cycle to meet the potential ET requirements over its entire duration and when water supplies are cut off before the crop reaches maturity), actual ET is assumed to decrease linearly with soil moisture content between field capacity and permanent wilting point. Crop coefficients used in the estimation of actual ET are adopted from FAO²⁸. The following relationship was used to estimate daily mean evapotranspiration:

$$PET = K_c * ET_o, \quad (4)$$

where ET_o is crop reference evapotranspiration in mm, K_c is crop coefficient and PET is potential evapotranspiration. ET_o values were estimated using the modified Penman method²⁸.

The model runs from transplanting date up to the harvest date. An irrigation depth of 150 mm is applied at the time of transplanting to both saturate the total root depth and allow for about 10 cm of standing water on the field. The high irrigation requirement at transplanting and the limited channel capacity lead to staggering of the transplanting activities over the command area of the distributary. A staggering period of two weeks is considered to coincide with the irrigation cycles. In each cycle, 25% of the command area is transplanted. These reflect the general conditions in the study area. The irrigation requirements in subsequent cycles are estimated using the soil water balance model by scheduling irrigations of 50 mm depth on any day within the irrigation cycle, when the depth of standing water falls to 10 mm or less. Irrigation is cut-off two weeks before harvest.

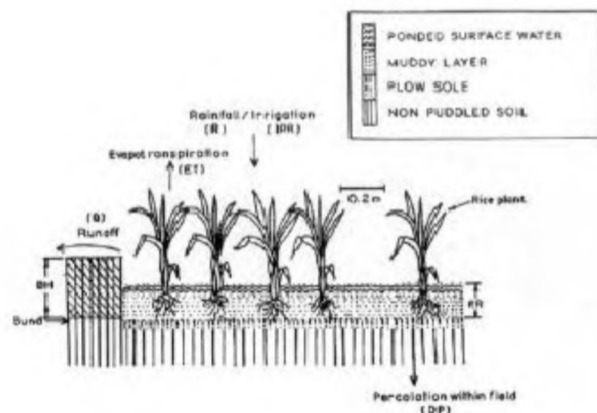


Figure 2. Water balance components of rice field.

The dates of irrigation scheduling during the growing season and the cut-off date for irrigation before harvest will vary with the transplanting date of the crop. Thus rice transplanted on different dates needs to be treated as different crops for running the soil water balance model. Since there are four transplanting dates, the soil water balance model is run four times in each cycle. The irrigation requirements for the areas of the crops transplanted on the four different dates are cumulated to arrive at the irrigation indent for the next irrigation cycle. The input data required for running the model for each distributary are summarized in Table 2.

Dynamic linkage between model and GIS

The GIS of the Patna canal system and the rice water balance model were dynamically linked for real time application in any season (Figure 3). This linkage allows:

- (i) Selection of the distributary of interest on screen to identify the corresponding weather station and soil data files.
- (ii) Running the rice field water balance model for each transplanting date in real time up to current date in any year, after entering the current date in response to screen queries.
- (iii) Preparing a report of the current water status in rice fields in the command area of the distributary transplanted on different dates.
- (iv) Preparing a water indent for the irrigation requirements at the head of the distributary for the next irrigation cycle, after accounting for weather forecasts and conveyance losses.
- (v) Proceed to next distributary.

Steps (i) to (v) are carried out sequentially and on-line within the GIS environment. The user need not at any stage come out of the GIS environment. For steps (i) to (iv), the complete sequence is run for each distributary with actual rainfall data up to the current date and with the forecast data of daily rainfall for the next 14 days of

the irrigation cycle. At the end of this cycle, which is also the beginning of the next cycle, the actual rainfall data for this period would be available. Before the irrigation indents are prepared for the next cycle, the actual rainfall data of the previous cycle are used to assess the water status at the beginning of the cycle, and the entire sequence is repeated. For this reason, the model needs to be run twice for any irrigation cycle – first with forecast rainfall for the current cycle and then with the actual rainfall in this cycle, when the irrigation cycle advances to the next.

Results and discussion

Individual distributaries can be selected by users from the GIS and reports of water status in fields and indents for water for the next irrigation cycle on any given date can be prepared quickly on-line and in real time. The results for one cycle are presented in Figure 4. Once the distributary is selected, the soil water balance model runs at daily time steps with the soil, rainfall and crops data up to the starting day of the irrigation cycle for which the water indent for the distributary is to be prepared. For the two-week period following this date, the model uses the forecast rainfall data to calculate the daily water balance to the end of the irrigation cycle. To illustrate the method, daily historical data for the period of the irrigation cycle are used as a perfect forecast. The report shown in Figure 4 is prepared for such a perfect forecast. The report also lists information on the soil water and crop conditions at the beginning of the irrigation cycle. The entire process (after the distributary is selected in GIS) is automated and made user-interactive within the GIS. The results of running the model for one distributary with historical rainfall data of one season, assuming perfect rainfall forecasts for all the irrigation cycles of 14 days beginning July 1 are presented in Figure 5.

The demands vary significantly over the different cycles, and in the initial irrigation cycles they exceed the capacity discharge of the distributary. In such periods,

Table 2. Input data for soil water balance model

Identification number of distributary (selection in GIS)
Corresponding identification numbers of raingauge stations and soil types (from GIS attribute table)
Daily rainfall for each raingauge station (mm)
Forecast rainfall
Initial soil moisture and soil moisture content at saturation for each soil type (mm/cm)
Reduction factor for hydraulic conductivity because of hard pan (for each soil type)
Transplanting date (day and month)
Number of transplanting dates
Crop duration (days)
Maximum root depth (cm)
Days to attaining maximum root depth
Bund height (mm)
Date of start of drainage period and duration
Days to cut-off date of irrigation
Daily reference evapotranspiration (mm)
Daily crop coefficients

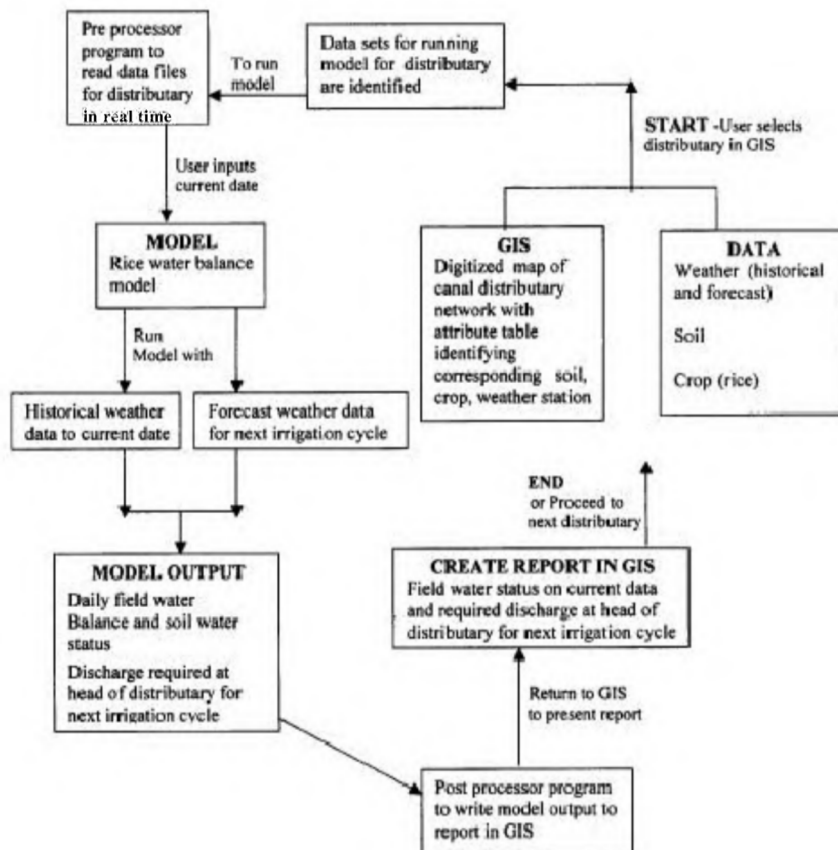


Figure 3. Dynamic user-GIS-model linkages in decision support system.

there may be a need to prioritize water allocations among the crops in the area irrigated by the distributary. Since the report produced for each irrigation cycle (Figure 4) also includes information on the soil moisture, standing water on fields and crop development conditions, irrigation managers can use this report, together with agronomic knowledge of crop responses to stress, to support decisions on prioritizing water allocations among crops. In the later periods (Figure 5), the requirements are far less than the capacity discharge, even in periods with low rainfall. This is because the crops transplanted in the early irrigation cycles reach the maturity stage in these cycles and do not need irrigation. Only the area under the late transplanted crops will need irrigation, leading to a reduction in water demand for the distributary. In the absence of a formal decision support framework to assist irrigation managers, they tend to be conservative and indent in excess of the requirement even in the later irrigation cycles. If the DSS is used to prepare the water release indents, water can be conserved in the reservoir in the later irrigation cycles and used for the winter season crop, which is planted after harvest of rice.

The results presented in this study were based on historical data, and perfect forecasts of rainfall at the begin-

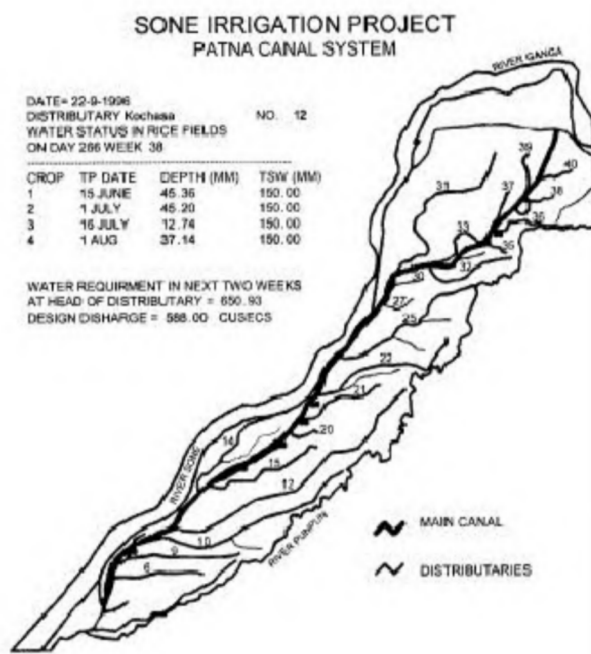


Figure 4. GIS-model output for selected distributary.

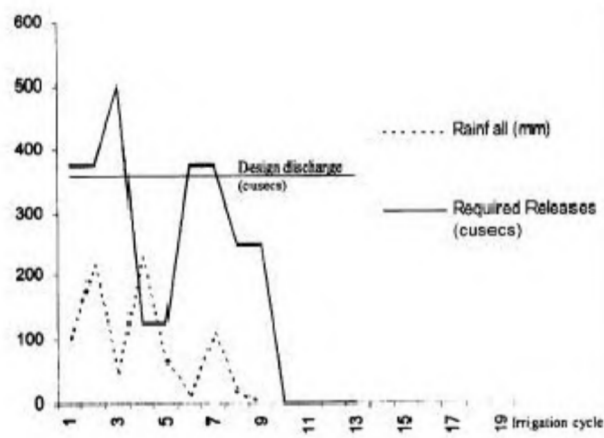


Figure 5. Irrigation indents (required releases) for Paliganj distributary in different irrigation cycles.

ning of each irrigation cycle were used to demonstrate the feasibility of developing a GIS-based framework for real time water demand estimation in irrigation projects. However, field applications in real time would need to use actual medium range weather forecasts (5–7 days ahead), which are now being made available by the IMD on request for any location in the country. The use of these forecasts would not alter the model development and application presented above in any way. The only change is to the input data for the irrigation cycle, which would change to the forecast data for the cycle instead of the historical data for the period which was used for the perfect forecast case. The framework presented here is ideally suited for the effective use of medium range weather forecasts, as the system status is clearly defined (Figure 5) at the beginning of each irrigation/forecast cycle.

However, it is interesting to note²⁹ that in situations where the available water storage capacity of the soil is high, irrigation depths are fixed and irrigation decisions are based on continuous monitoring of soil and crop conditions (as with the soil water balance model); the decisions themselves are not likely to be significantly influenced by errors in medium range weather forecasts. What is relevant and important is the monitoring of the soil water balance with respect to the current season weather data up to the time when the forecast is used. Since the situation described here meets the above conditions (and there is provision for an additional storage of water up to the bund height), errors in forecast may not significantly influence the irrigation indents for each cycle.

Conclusion

The study developed a GIS-based decision support system for water demand estimation in canal irrigation systems. The Patna canal network of the Sone Irrigation Project in India was used as a case study. The main problem faced

by water managers is estimating demand at the head of the distributaries of the canal network in advance for each irrigation cycle. This is mainly because of spatial variations in weather and rice crop transplanting dates. It was shown that real time water demands for any distributary can be estimated by linking dynamically the GIS of the canal system with a soil water balance model and current season data of weather, weather forecasts, and crop and soil conditions. The system managers can obtain the required information by simply selecting the distributary in the GIS. The DSS also allows quick estimation of the variations in irrigation requirement in different distributaries that form the canal network and comparisons with the available channel capacities and actual supplies. Such visualizations, when combined with strong agronomic knowledge and judgment, can have a powerful impact on the overall water management strategy to be adopted in the command area of the irrigation project. Though the various procedures have been developed for the case study area selected, they are sufficiently general to be adopted to other canal irrigation networks.

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