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GIS-based decision support system for groundwater assessment in large irrigation project areas

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Abstract

In large canal irrigation project areas, integrated management of surface and groundwater resources can improve water use efficiencies and agricultural productivity and also control water logging. Such integrated management requires an estimation of spatial distribution of recharge and ground water flow in the underlying aquifer. Recharge occurs both as percolation losses from fields and seepage losses from the water distribution network. Percolation losses are influenced by weather, soil properties, land use, and canal water and groundwater use. Seepage losses depend on the conditions of flow in the water distribution system. In large irrigation project areas all the factors influencing the recharge of groundwater vary spatially. In this study, a geographical information systems (GIS) is used to map the spatial distribution of recharge which then serves as input to a regional groundwater flow model for simulating the behavior of the underlying aquifer. The basis is that the project area can be divided into a set of basic simulation units (BSUs) that are homogenous with respect to the conditions that influence the recharge processes. A daily field soil water balance model and a simple canal flow model are used to estimate the percolation and seepage losses, respectively. The combination of models and GIS can be used as an integrated decision support system to assess the groundwater resources and derive strategies for integrated management of canal and groundwater resources in the project area.

Keywords: GIS; Soil water balance; Seepage; Groundwater model; Irrigation

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1. Introduction

In India, large canal irrigation projects account for over 35 million hectares (m ha) of irrigated area. Of this, about 30 m ha were created after 1951, during successive Five Year

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Plans. Groundwater was the main source of irrigation in these areas prior to the introduction of canal irrigation. It continues to be so in several areas even after the introduction of canal irrigation, even though this factor was not considered explicitly in the design of canal irrigation systems. In recent years there has been considerable emphasis on integrated management of surface and groundwater resources in irrigation project areas both to augment the canal supplies and to increase agricultural productivities as well as to control ground water depletion, water logging, and soil salinity (Rosegrant and Svendsen, 1993; Water Technology Centre, 1998). Groundwater resource assessment in canal irrigation project areas is critical for the development of strategies for such integrated management.

Groundwater basin simulation models based on the physics of groundwater flow can be important tools for ground water assessment and for integrated planning and management of water resources in irrigation project areas (Sondhi et al., 1989). Recharge, pumping, boundary conditions, and aquifer parameters constitute the main input data for these models. Since, over a large area, all of these vary spatially, the models use a finite-difference or finite element scheme to represent the variations and solve the flow equation using numerical techniques. Assembling data of the model inputs and assigning parameters for each model require significant prior processing of related information. Geographic information systems (GIS) can greatly facilitate improving the assembling, display, and visualization of model inputs and parameters as well as the model outputs (Roaza et al., 1993).

In some of the earlier studies, recharge and discharge were treated as parameters of the model to be estimated by solving the inverse problem of aquifer hydrology, that is, by solving the equation of flow for known conditions of ground water heads while considering the recharge as unknown (Carrea and Neuman, 1986; Chiew and Mc Mahon, 1991; Boonstra and Bhatta, 1996). In other studies, groundwater level fluctuations were considered as indicators of the spatial distribution of recharge (Moench and Kisiel, 1970; Besbes et al., 1978; Flug et al., 1980). In irrigation project areas, seepage losses from canals and percolation losses from fields constitute the main components of recharge. These vary with the weather, soils, crops, and water use. Sondhi et al. (1989) and Rao and Sarma (1993) developed finite difference and finite element models respectively for simulating groundwater flow in large canal irrigation project areas in India. In these models, seepage losses from the water distribution system and percolation losses from fields were estimated as components of recharge using empirical norms for seepage and percolation losses developed by the Central Ground Water Board (1984). An annual lumped value of recharge for the region as whole was first estimated which was then distributed spatially over the project area by deriving recharge distribution coefficients based on the differences between observed and simulated water levels at different nodes.

Rao (1995) improved the physical basis of the estimation of recharge by using a distributed soil water balance model to calculate percolation losses and a vertical groundwater flow model for seepage losses from canals. But the models were used only for a limited arbitrarily chosen locations and their results were extrapolated for the area. The use of GIS can help to identify all possible combinations of soil type, weather, land and water use, and so forth, and facilitate improving the physical basis of recharge estimation in a much more structured and systematic fashion (Fayer et al., 1996). This is important if the models are to be used as effective decision support tools in management of water resources in irrigation project areas.

A detailed review of use of GIS in water resources applications is given by Tsihrintzis et al. (1996). Currently no GIS has the data representation flexibility for space and time, together with the algorithmic capability to be able to build process-based models internally (Corwin and Wagenet, 1996). Consequently simulation models and GIS must be coupled. Coupling can range from loose to tight coupling. In a tight coupling, the data management is integrated into the system. Characteristically, a tight coupling provides a common user interface for both the GIS and model, and the information sharing between the respective components is transparent. A loose coupling involves a data transfer from one system to another. The GIS is used to preprocess data or to make maps of input data or model results. A majority of the applications found in the literature adopt this approach because it allows use of the existing physical models with little modifications to the software (Joao and Walsh, 1992; Roaza et al., 1993).

The overriding goal of this study is to take advantage of the features of GIS and simulation models in irrigation management (Sondhi et al., 1989; Hajilal et al., 1997, 1998) to provide quantitative decision aids for groundwater resource assessment in large irrigation project areas. The GIS and simulation models of agrohydrological processes will be used to represent the biophysical processes and their variations over the large area. Specifically, the study develops a scheme for integrating GIS with recharge and groundwater flow models for groundwater assessment in large canal irrigation project areas. A case study approach is adopted since problem formulation in such studies cannot be separated from real world examples. The basis is that a GIS can be used to divide the case study area into a set of basic simulation units (BSUs) that are homogeneous with respect to the conditions that influence the groundwater recharge. The study adopts a loose coupling approach wherein the GIS is integrated with recharge models (adopted from earlier studies (Hajilal et al., 1997, 1998)) and a groundwater model developed for this study. The Godavari Delta Central Canal Irrigation Project in India (Fig. 1) is used as the case study area for applying the above scheme.

2. System design

2.1. Models and GIS

The overall scheme of the model development is presented in Fig. 2. It proceeds in two stages:

(i) Estimating recharge rates and their distribution using GIS and models for recharge components, and
(ii) Predicting groundwater flow using the distributed recharge rates mapped on to a GIS as inputs to a groundwater flow model for the aquifer underlying the project area.

Recharge is from two components, seepage losses from the water distribution system and percolation losses from cultivated and uncultivated fields. Two models namely, a canal flow model for seepage losses and a soil water balance model for percolation losses are therefore used to estimate recharge in the present study. The models have been adopted from previous studies on water management in irrigation project areas in India (Hajilal et al., 1997, 1998).

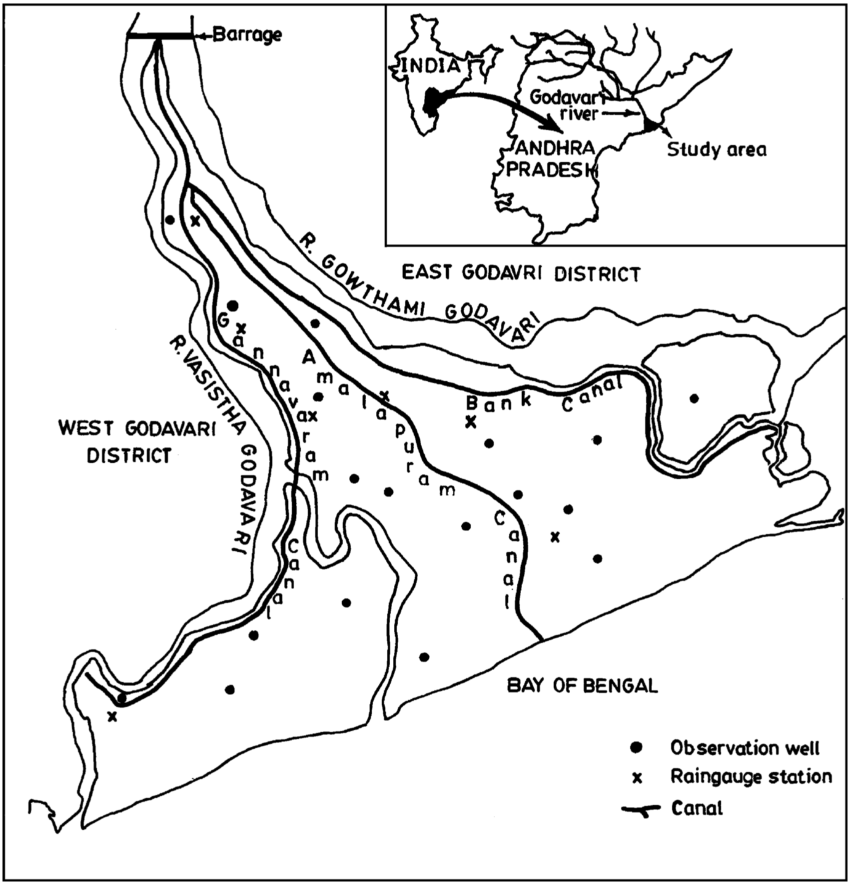

Fig. 1. Location map of Godavari Delta Central Canal Irrigation Project, Andhra Pradesh.

Additional routines were added to the adopted recharge model for estimation of percolation losses from flooded rice fields and uncultivated lands (Chowdary, 1998). A GIS is used to derive simulation units homogenous with respect to soil water balance model inputs by overlaying relevant layers. The soil water balance model is run for each simulation unit to obtain the distributed percolation losses. The percolation and seepage losses are combined with GIS to develop a recharge map of the area. The map is then used to provide data of distributed recharge for a two-dimensional finite element groundwater flow model.

2.1.1. Recharge by seepage losses from canals

Seepage losses in canals depend on the seepage rate and wetted area in the canals. These vary with flow conditions. The seepage rate depends on the bed and side slope material of the canals, and the subsurface conditions like depth to water table, permeability of the soil and aquifer medium, drainage conditions, and so forth (Rao, 1990). Hydraulic models can simulate the changes in the water surface profiles in canals with respect to time and

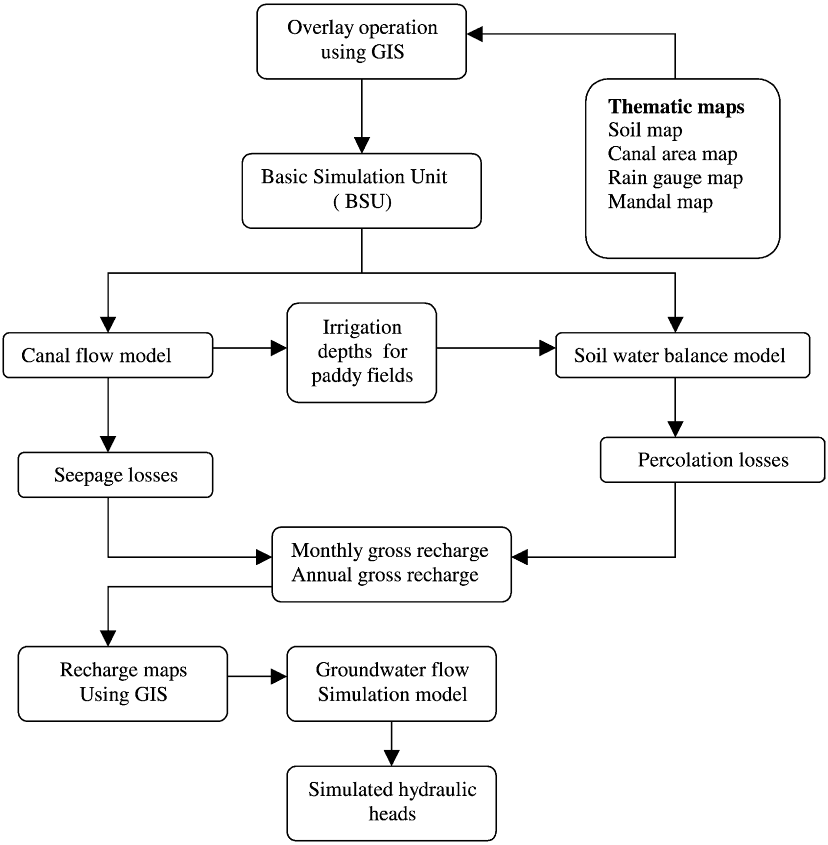

Fig. 2. Scheme of integrated framework for the assessment of groundwater in irrigation project areas.

space. The seepage losses can be assessed for specified surface and subsurface conditions using such models if the seepage rate is known. Many complicated simulation models of the hydraulics of flow in irrigation canals are available. They are highly data intensive and cannot adequately account for some actual flow conditions, like frequent canal filling and dewatering (as required for rotational irrigation practised in many schemes in India) which involve rapid flow changes. Several attempts at using such models in India have not proved to be successful. Mandavia and Acharya (1995), after a review of applications of above models under Indian conditions, recommended that simple models that use available data to be used. So, in the present study, a simple canal flow model based on uniform flow in an irrigation distributary developed by Hajilal et al. (1997, 1998) is adopted.

The model is based on the assumptions of uniform flow in a canal reach of trapezoidal cross-section and data of discharges at either ends of the reach (Fig. 3). The depth of flow at either ends of the reach is obtained by using the Manning's equation for uniform flow:

$$Q = \left(\frac{A}{n}\right) R^{2/3} \times S^{1/2} \tag{1}$$

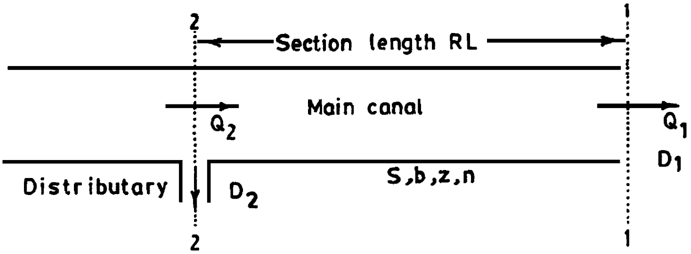

Fig. 3. Schematic representation of canal section for seepage estimation.

where n is the Manning's roughness coefficient; S denotes the slope of channel bed; A is the area of cross-section of flow (m^2), $A = BD + ZD^2$; D denotes the depth of flow (m); B is the bed width of the channel section (m); Z represents the side slope of channel; R is the hydraulic radius (m), $R = (A/P)$; P represents the wetted perimeter of the section (m), $P = B + 2D \times \mathrm{SQRT}(1 + Z^2)$.

For a particular reach B, Z, S, and n are known constants. Q is known discharge at the head of the reach. The depth of flow is estimated by solving Eq. (1) by the Newton–Raphson procedure after substituting the values of A and R from above. The calculations are repeated for all reaches of each canal for the available data of daily discharges. The same procedure can be extended to calculate seepage losses from distributaries (tertiary canals), if the daily discharges at their headworks and design parameters for each reach are also available. Such data are usually available at various sections of the main canals in many irrigation projects in India. There may be difficulties in obtaining the required data for different reaches of the distributaries. In the absence of this data, empirical norms can be adopted to calculate seepage losses from distributaries. The Central Ground Water Board (1984) recommends that about 7% of the supplies left after accounting for seepage losses in the main canals can be taken to be seepage losses in distributaries.

A rating curve is derived for each canal of the study area by regression analysis between seepage losses and discharge at the canal head works to directly estimate the seepage losses for any given discharge at the canal headworks. The canal supplies remaining after accounting for seepage losses in main canals and distributaries are available to the crops in the fields and contribute to the percolation losses.

2.1.2. Soil water balance model for percolation losses

The soil water balance is essentially the principle of conservation of mass applied to the soil reservoir. The time step of the water balance is 1 day. The depth of the soil reservoir (RD) is limited by the maximum depth (RDM) to which the roots can grow. A generalized soil water balance model was developed to estimate percolation losses from

(i) rice fields which require flooding conditions,
(ii) other cropped areas, and
(iii) uncultivated lands.

for a given set of soil, weather, and water supply conditions.

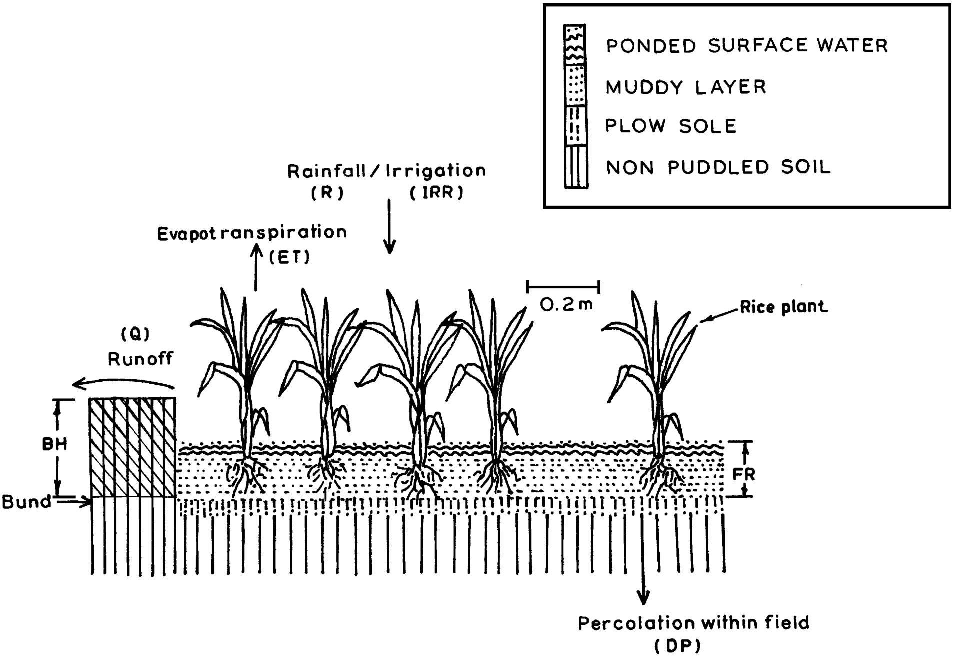

Fig. 4. Water balance components of rice field.

For a rice field (Fig. 4) the water balance equation is given by Chowdary (1998):

$$\mathrm{DFR} = R + \mathrm{IRR} - \mathrm{ET} - Q - P \tag{2}$$

where DFR is the change in free water depth in the rice field, R is daily rainfall, IRR is the field irrigation supply, ET is evapotranspiration estimated from reference ET and crop factors (Doorenbos and Pruitt, 1977), Q is the runoff estimated as rainfall in excess of that stored within the bunds of the field, and P is the deep percolation calculated using Darcy's Law. In the present study, reference ET is estimated using Modified Penman method. All quantities in the above equation are in millimeter.

For other crops the daily field water balance (Fig. 5) is given by

$$\mathrm{DS} = R + \mathrm{IRR} - \mathrm{ET} - P - Q \tag{3}$$

where DS is the change in soil moisture storage. Runoff Q is estimated by the USDA SCS curve number method with corrections for soil moisture content (Sharpley and Williams, 1990), ET is obtained from crop PET (Doorenbos and Pruitt, 1977) and percolation P is obtained by applying the piston flow concept to the infiltrated water from rainfall and irrigation. The soil reservoir is divided into two layers: (i) an active layer of depth RD in which roots are present at any given time and from which both moisture extraction and drainage would occur and (ii) a passive layer of depth (RDM − RD) from which only drainage would occur. But once the maximum root depth is attained, the entire root zone becomes only one layer of depth RDM.

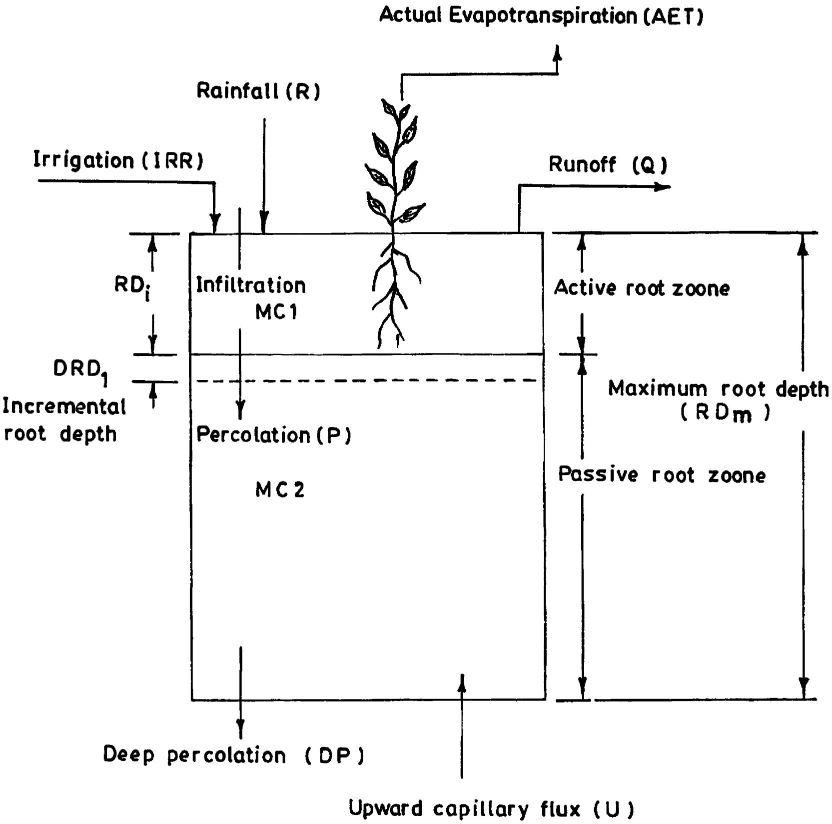

Fig. 5. Components of soil water balance model.

The detailed equations of all the processes can be found in Hajilal et al. (1997, 1998). The same have been adopted for this study. The water balance model has been tested previously at several locations in India and applied in field scale irrigation scheduling models (Purohit and Gosain, 1990; Rao, 1987; Rao et al., 1988, 1990).

For the uncultivated areas, ET in the above equation is replaced by soil evaporation E, which is estimated by a two-stage evaporation model (Ritchie, 1972).

2.1.3. GIS to map recharge

Soil water properties, daily rainfall, crops, and irrigation depths are the main input data for estimating percolation losses by the soil water balance model. The soil map, raingauge Thiessen polygons, land use map, and the map delineating areas receiving water supplies form each canal (canal command area map) represent the spatial distribution of these data. The irrigation depth, IRR is the water available after accounting for seepage losses. GIS software is used to digitize each map to create independent layers of the input data required for the model. By performing overlay operations with these layers a new map of BSUs is generated. The BSUs can be considered homogenous with respect to data of rainfall, soils,

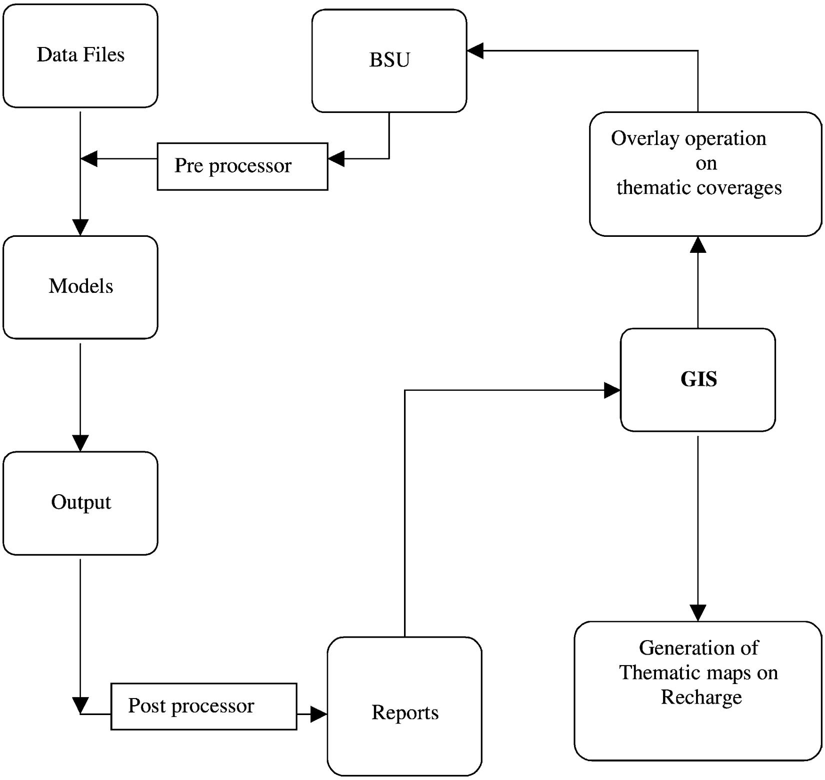

Fig. 6. GIS—model linkages for generating recharge maps.

irrigation supplies (after accounting for seepage losses above). The GIS creates a polygon attribute table (PAT) after the overlay operation which lists for each the polygon (or BSU), its identification number, and the corresponding identification numbers for the raingauges, soil types, canal systems so that appropriate data sets can be selected every time the soil water balance model is run for each BSU.

The soil water balance model is run for each BSU, so that in each model run, all the components of the daily water balance and percolation losses are output for all crops in the unit; rice, crops other than rice and uncultivated fields. The percolation losses for each cropped/uncultivated area are multiplied by their respective areas to get the percolation volumes in each BSU. The general flow of information between the GIS and the models is shown in Fig. 6. The PAT table of the BSU coverage is used to select the input files required to run the soil water balance model. A preprocessor is written to the model programmes (in FORTRAN 77) that reads this file and runs the model for each BSU. A postprocessor is written at the end of the model programmes to read the model output files and summarize the output into thematic maps of percolation losses. The percolation losses are added to seepage losses to obtain a map of recharge distribution over the area.

2.1.4. Groundwater model

In the present study, a two-dimensional triangular network finite element model for the groundwater basin of the study area is developed for simulating the ground water flow conditions in an irrigation project area. The finite element model algorithm of Swain (1978) and Hromadka et al. (1985) is adopted for the conditions of this study. The time domain in the finite element model is approximated using implicit finite difference scheme to ensure that the solution is unconditionally stable regardless of the size of the time increment (Narasimhan and Witherspoon, 1982). The groundwater flow in an unconfined aquifer is governed by the equation:

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)+N=S\frac{\partial h}{\partial t} \tag{4}$$

where $T = T(x, y)$ is the transmissivity of the aquifer, kb (m^2/s); b is the average thickness of the aquifer (m); $S = S(x, y)$ denotes the storage coefficient of the aquifer; $h = h(x, y, t)$ is the hydraulic head in the aquifer (m); $N = (x, y, t)$ represents net recharge rate per unit area ($m^3/s/m^2$); t denotes the time, and x, y are Cartesian co-ordinates in a horizontal plane.

The distributed input of recharge is derived from the recharge map generated using the GIS and recharge models. In addition to source (recharge), the solution of Eq. (4) depends on the definition of solution domain, initial conditions, aquifer parameters, and sinks (pumping) and boundary conditions. These will be specific to the area under study. Eq. (4) is solved subject to the conditions in the study area using the algorithm developed by Swain (1978).

3. Application to the study area

3.1. Case study area and data

Field data of Godavari Delta Central Canal Irrigation Project in East Godavari District of Andhra Pradesh State, India (Fig. 1) are used as a case study to develop the procedures. The Project commands an area of 84,000 ha. Rice is the dominant crop grown in this project area. The following data of relevance to estimate recharge by percolation and seepage are available:

1. Rainfall (daily for 10 years, at 7 raingauge stations in the area).
2. Evaporation (weekly averages).
3. Canal discharges (daily for 10 years, at headworks of four main canals).
4. Command area maps for all main canals.
5. Design characteristics (reach length, bed width, slopes, and full supply discharge) for various sections of four main canals.
6. Soil map of command area.
7. Map of administrative units (*mandals*).
8. Cropping pattern and groundwater wells in each *mandal*.
9. Information on aquifer parameters.
10. Ground level contours.

Rice is the dominant crop grown in two seasons (monsoon or *Kharif* season and post-monsoon or *rabi* season) covering 75% of the gross command area; 15% of the area is under coconut plantations and the remaining is under sugarcane and pulses. The canal supplies are entirely used for rice, and coconut and sugarcane are irrigated by groundwater. Pulses are grown as rainfed crops. Thus, practically all the recharge from canal supplies is from rice fields (National Institute of Hydrology, 1992).

3.2. Mapping spatially distributed recharge rates

3.2.1. Generation of basic simulation units

A raingauge Thiessen polygon map was first prepared based on the locations of the seven raingauge stations located in the study area. This and the soil map, the mandal (administrative blocks) map, and the canal command area map were digitized using GIS software ARC/INFO. The four maps were overlaid using the same GIS to obtain a map of BSUs for the study area. As this overlay operation led to a large number of spurious small polygons, that have no real meaning, have merged with the adjoining larger units (Burrough and Rachael, 1998). This process has resulted in generation of 38 BSUs for the entire study area. The polygon attribute table generated for the BSU map by the GIS identifies each of the 38 units uniquely with its corresponding soil type, raingauge station, canal system from which it receives the surface supplies, and the administrative unit to which it belongs. From the last of these and the information about the area under each crop and the groundwater draft in each BSU can be estimated.

3.2.2. Recharge maps

Recharge consists of seepage losses from the canals and distributaries and percolation losses from fields. These are obtained by running the canal flow and soil water balance models, respectively.

The seepage losses from each main canal were calculated using the data of releases and the design details of each section using the canal flow model (Eq. (1)). The losses from the distributaries (tertiary canals) were estimated as 7% of the flows available after accounting for seepage losses in the main canals. The calculations were done for all the 10 years for which data of discharges are available. A rating curve (Eq. (5)) was developed for each canal relating the seepage losses with the discharges at the canal headworks:

$$y = ax^b \tag{5}$$

where x is the discharge into the canal (cumec) and y is the seepage loss (cumec).

The rating curves were developed for each of the four canals. The values were as follows

Gannavaram canal	$a = 1.01$, $b = 0.14$ ($r^2 = 0.98$)
Amalapuram canal	$a = 1.00$, $b = 0.11$ ($r^2 = 0.98$)
Bank canal	$a = 1.02$, $b = 0.149$ ($r^2 = 0.98$)
Main canal	$a = 0.97$, $b = -0.0359$ ($r^2 = 0.98$)

The seepage losses in the canals and distributaries varied from 5 to 25% of the discharge at the canal headworks. These were assumed to be distributed uniformly over the BSUs lying within the command areas of the respective canals.

The percolation losses were calculated using the soil water balance model (Eqs. (2) and (3)). This daily soil water balance model was run for each BSU for the three land use conditions (rice, crops other than rice, and uncultivated). Eq. (3) is used for crops other than rice with uniform irrigation depths of 75 mm whenever an irrigation requirement is predicted by the model. For pulses, irrigation depths were zero, as the crops are entirely rainfed. In case of paddy, remaining daily flows after deducting for seepage in main canals and distributaries are available to the crops in the fields and these represent the daily values of irrigation depths in Eq. (2). The monthly, seasonal, and annual percolation losses for each BSU were calculated for all the years.

Table 1
Monthly recharge rates (m^3/s) for all the basic simulation units (BSUs) in the study area during the year 1994–1995

BSUs	June	July	August	September	October	November	December	January	February	March	April	May	M[a]	NM[b]	A[c]
1	1.2	2.7	2.2	1.7	1.7	1.7	2.0	2.1	1.2	0.9	0.0	1.0	1.9	1.2	1.5
2	0.2	1.0	0.7	0.5	0.5	0.6	0.5	0.7	0.2	0.1	0.0	0.5	0.6	0.3	0.5
4	0.2	0.6	0.4	0.3	0.3	0.4	0.5	0.5	0.2	0.1	0.0	0.3	0.4	0.3	0.3
3	0.1	0.7	0.5	0.3	0.3	0.4	0.3	0.4	0.1	0.0	0.0	0.4	0.4	0.2	0.3
7	0.3	1.3	1.0	1.0	0.9	1.1	1.1	1.0	0.4	0.1	0.0	0.7	0.9	0.6	0.7
6	0.3	1.7	1.3	1.3	1.2	1.4	0.7	1.1	0.3	0.1	0.0	0.9	1.2	0.5	0.9
5	0.2	1.2	0.9	1.0	0.8	0.9	0.6	0.8	0.2	0.1	0.0	0.6	0.8	0.4	0.6
10	0.1	0.7	0.5	0.5	0.5	0.6	0.6	0.5	0.2	0.0	0.0	0.4	0.5	0.3	0.4
14	0.3	1.6	1.2	1.3	1.5	1.3	1.2	1.2	0.6	0.1	0.0	0.8	1.2	0.7	0.9
9	0.3	1.8	1.4	1.4	1.3	1.5	0.8	1.2	0.3	0.0	0.0	1.0	1.3	0.6	0.9
13	0.2	1.6	1.2	1.3	1.5	1.3	0.6	1.0	0.2	0.0	0.0	0.8	1.2	0.4	0.8
17	0.4	1.7	1.3	1.4	1.6	1.3	1.0	0.9	0.6	0.1	0.0	0.8	1.3	0.6	0.9
8	0.1	0.8	0.6	0.6	0.5	0.6	0.4	0.5	0.1	0.0	0.0	0.4	0.5	0.2	0.4
22	0.9	3.8	3.0	2.5	3.0	3.3	2.5	2.4	1.2	0.3	0.0	2.4	2.8	1.5	2.1
23	0.5	2.1	1.7	1.4	1.7	1.4	0.4	0.4	0.7	0.2	0.0	1.3	1.5	0.5	1.0
24	1.0	4.7	3.5	3.1	2.3	1.9	0.8	0.8	1.5	0.3	0.0	1.8	2.8	0.9	1.8
16	0.2	1.2	0.9	1.0	1.2	1.1	0.5	0.8	0.2	0.0	0.0	0.6	0.9	0.4	0.6
12	0.3	1.5	1.1	0.9	1.1	1.4	0.7	1.1	0.3	0.1	0.0	1.0	1.0	0.5	0.8
11	0.4	2.1	1.6	1.3	1.5	1.9	1.1	1.5	0.4	0.1	0.0	1.3	1.5	0.7	1.1
19	0.1	0.7	0.6	0.6	0.7	0.6	0.2	0.3	0.1	0.0	0.0	0.4	0.6	0.2	0.4
15	0.3	1.5	1.1	0.8	1.1	1.4	0.7	1.1	0.3	0.1	0.0	1.0	1.0	0.5	0.8
29	1.1	5.2	3.9	3.4	2.6	2.9	2.8	2.7	1.6	0.3	0.0	2.0	3.2	1.6	2.4
21	0.1	0.6	0.5	0.4	0.5	0.6	0.2	0.3	0.1	0.0	0.0	0.4	0.5	0.2	0.3
20	0.4	2.3	1.7	1.5	1.1	0.9	0.9	1.5	0.4	0.1	0.0	0.9	1.3	0.6	1.0
28	0.6	3.0	2.2	2.0	1.5	2.0	2.4	2.3	0.9	0.2	0.0	1.1	1.9	1.1	1.5
18	0.3	1.7	1.3	1.0	1.3	1.6	0.8	1.2	0.4	0.1	0.0	1.1	1.2	0.6	0.9
27	0.4	2.6	2.1	2.4	2.3	2.0	1.5	1.6	0.7	0.1	0.0	1.6	2.0	0.9	1.4
25	0.2	1.4	1.1	1.2	1.2	1.1	0.9	0.9	0.4	0.1	0.0	0.9	1.0	0.5	0.8
30	0.2	0.9	0.7	0.8	0.8	0.8	0.7	0.7	0.3	0.1	0.0	0.6	0.7	0.4	0.6
31	0.1	0.7	0.5	0.4	0.5	0.6	0.4	0.5	0.1	0.0	0.0	0.4	0.5	0.2	0.4
38	0.2	1.1	0.9	1.0	1.0	0.9	0.8	0.8	0.3	0.0	0.0	0.7	0.9	0.4	0.6
26	0.4	3.1	2.4	2.7	2.7	2.5	2.2	2.1	0.8	0.1	0.0	2.0	2.3	1.2	1.7
32	0.5	2.4	1.9	2.1	2.2	2.1	1.8	1.9	0.8	0.2	0.0	1.7	1.9	1.1	1.5
33	0.5	3.1	2.4	2.6	2.8	2.8	2.3	2.5	0.9	0.2	0.0	2.2	2.4	1.4	1.9
34	0.3	1.5	1.3	1.5	1.5	1.4	1.1	1.2	0.4	0.1	0.0	1.3	1.3	0.7	1.0
35	0.6	2.7	2.4	2.7	2.8	2.6	1.9	2.0	0.8	0.3	0.0	2.5	2.3	1.3	1.8
36	0.8	4.6	4.0	4.6	4.7	4.3	3.3	3.5	1.3	0.3	0.0	4.1	3.8	2.1	3.0
37	0.0	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.0	0.0	0.2	0.2	0.1	0.2

[a] Average recharge rate for monsoon season.

[b] Average recharge rate for non-monsoon season.

[c] Average annual recharge rate.

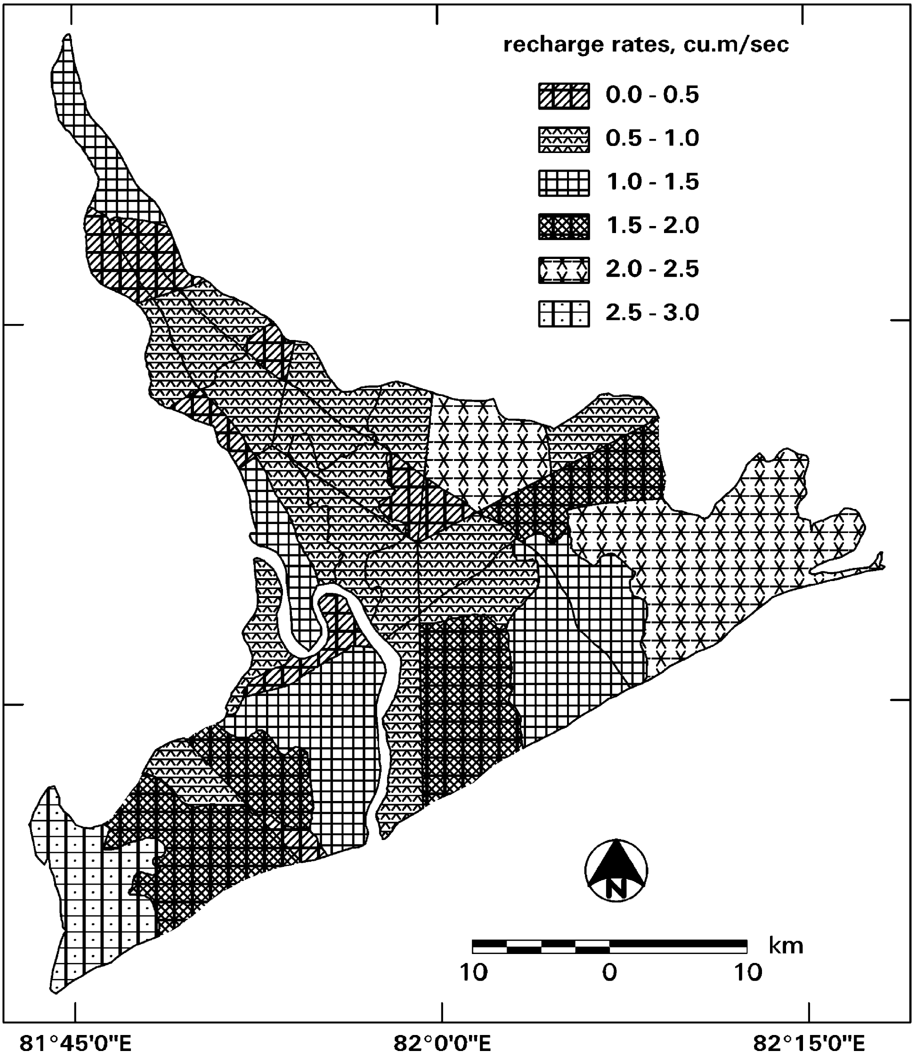

Fig. 7. Spatial distribution of annual recharge rates for the study area, 1994–1995 (m^3/s).

The seepage losses for each BSU obtained from the rating curves of the respective canals were added to the percolation losses to obtain the total recharge for 10 successive years. The monthly recharge rates for the year 1994–1995 are given in Table 1. Thematic maps of the spatial distribution of the monthly recharges and annual recharge for each year were generated by transferring the results of recharge model to GIS. The distribution of the annual recharge potential of the irrigation project area for the year 1994–1995 is displayed on GIS (Fig. 7). The recharge rates for this period varied from 0.1 to 5.2 m^3/s over the area. These variations reflect variations in weather, soils, water supplies, and land use over the command area of the irrigation project.

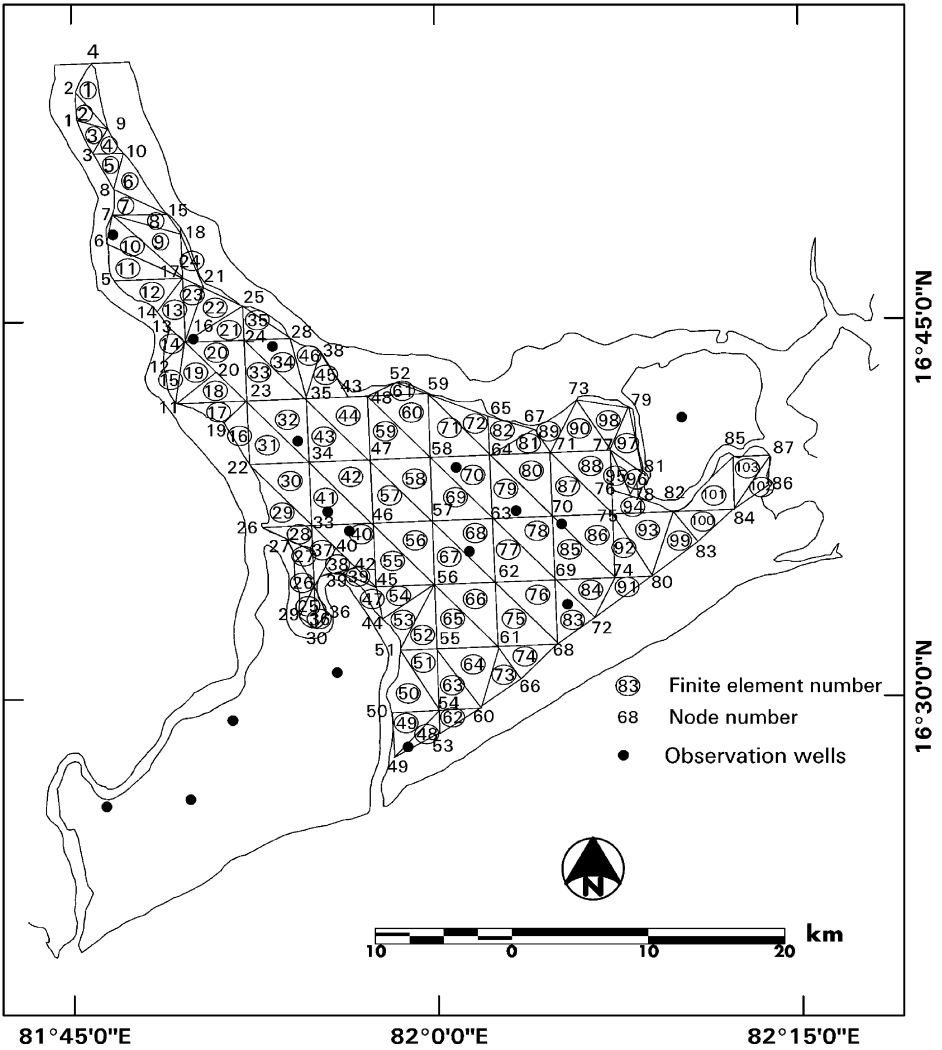

Fig. 8. Finite element grid of the study area.

3.3. Simulation of groundwater flow

3.3.1. Solution domain

The part of the command area selected for groundwater flow simulation is shown in Fig. 1. This area is of about 84,000 ha and is divided into 107 triangular elements with 87 nodal points (Fig. 8). The size of the triangle is adjusted to conform to the shape of the boundary. The size of the triangular elements is also reduced near boundaries to enable better approximation. Nodes are numbered in north–south direction, since this is the shortest distance, so as to produce minimum half-band width. The nodes are identified by their *X* and *Y* coordinates. The elements are numbered as shown in Fig. 8. Association of nodes to elements is specified by the element incidences in counter clock wise direction around the elements as shown in the figure.

3.3.2. Aquifer parameters

Aquifer parameters required by model as input are hydraulic conductivity '*K*' and specific yield '*S*'. Most of the study area is under deltaic alluvial formations and groundwater in these formations occurs generally in water table conditions. There is no major variation in geological properties and the study area can be considered to be a relatively homogeneous region with respect to these parameters. Accordingly, aquifer of the study area is considered to be a weathered zone with a thickness of 40 m, with an average transmissivity

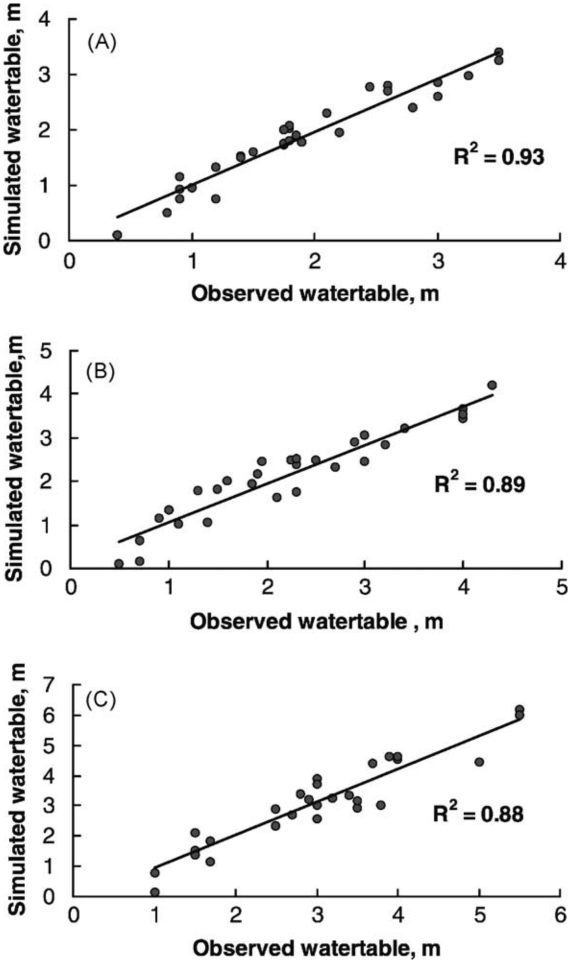

Fig. 9. Observed and simulated groundwater levels (m) in the study area for different years. (A) 1992–1993; (B) 1993–1994; and (C) 1994–1995.

value of 4000 m^2/day, and average specific yield of 0.18 (Central Ground Water Board, 1993; National Institute of Hydrology, 1992). Hence, hydraulic conductivity of 100 m/day (sand) and specific yield of 0.18 were assigned to each of the 107 elements in the area.

3.3.3. Initial conditions

The time period considered in this study is from 1992–1993 to 1995–1996 and the month is from June to May as the groundwater heads are routinely recorded in premonsoon (mid to end of May) and postmonsoon (mid to end October). As the first step, the model is used to simulate the groundwater levels in the year 1992–1993. Hence, the time period considered in the model is 1 year divided into 12 time steps, each consisting of 30 days a month. The observed water table contours in the month of May, 1992 were considered to describe the initial conditions. To obtain the initial heads, the finite element grid with 107 triangular elements and 87 nodes was superposed over a water table contour map for May 1992. Each of the 87 nodes in the flow domain was assigned an initial hydraulic head obtained by interpolation from the contour map. To estimate the saturated aquifer thickness, which would be used by the model for further computations, the depth to the base of the aquifer at each node is required. The average aquifer thickness of 40 m was subtracted from the reduced level of ground surface at each node to obtain the depth to the

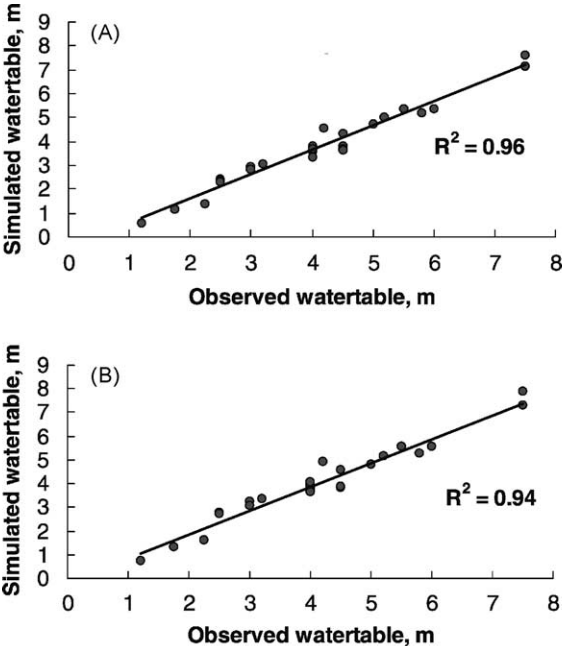

Fig. 10. Observed and simulated groundwater levels (m) in the study area for November 1995. (A) Pumping factor = 1.0; (B) pumping factor = 0.75.

bottom of the aquifer. Further the reduced level of the ground surface is given as input the model.

3.3.4. Boundary conditions

Hydrological boundaries of the study area are: the river Gowthami Godavari in the east, river Vasistha Godavari and its branch Vainateya in the west and Bay of Bengal in the south. The general nature and extent of the aquifer boundaries are shown in Fig. 1. There are 57 nodes along the boundary (Fig. 8). Since the present study area is surrounded by natural hydrologic boundaries on all sides, constant head boundary conditions were specified. The constant head boundary condition was incorporated in the model by specifying hydraulic heads at those nodes.

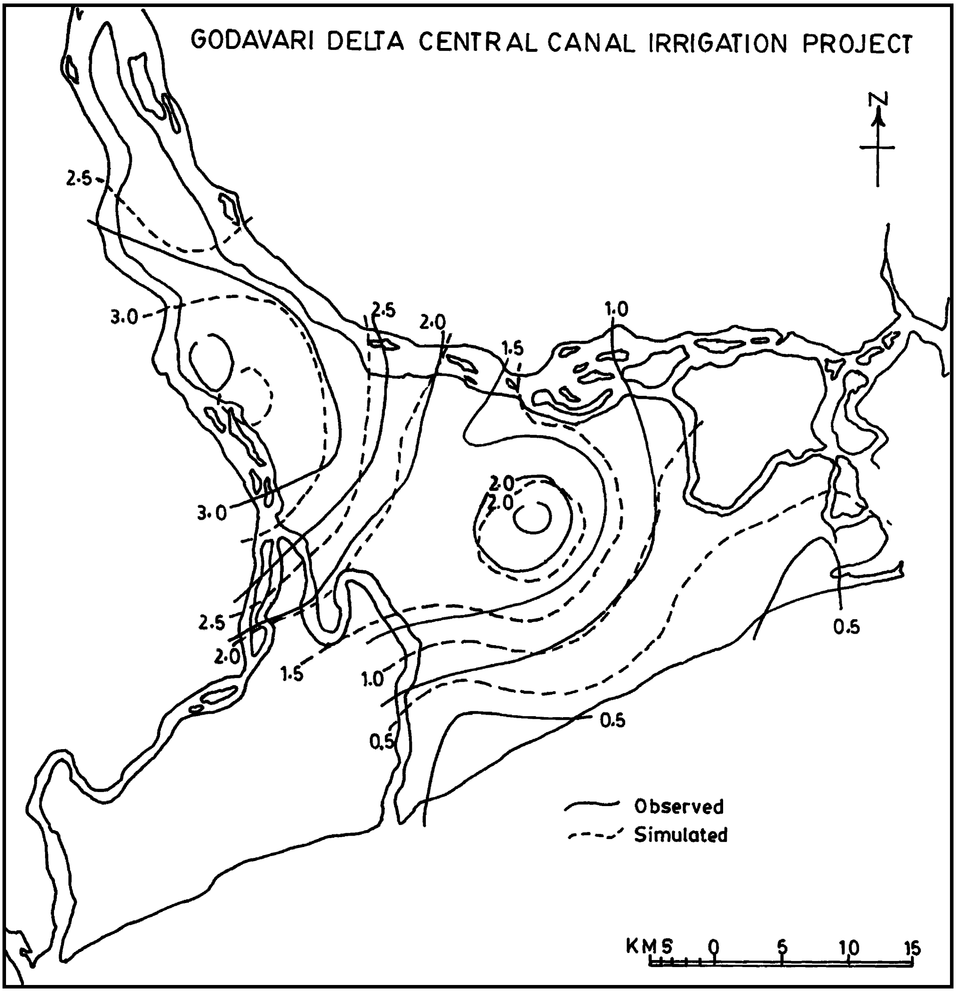

Fig. 11. Observed and simulated groundwater levels (May 1993) (m).

3.3.5. Sources and sinks

3.3.5.1. Pumping rates. Tube wells and filter point wells are the main source of groundwater in the study area. The total number of wells and filter points in the area is known with some degree of certainty. Their spatial distribution at different nodes of the finite element grid is not known. The exact time distribution of the pumpage (total draft) is also not known. So, for the initial model runs, the total draft for the entire area was to be uniformly distributed over all the internal nodes within the command area. The annual draft was also assumed to be distributed uniformly throughout the water year, that is, from June to next May. The uniform (averaged over 24 h) pumping rate at each internal node was estimated as 0.2112 m^3/s based on the number of wells and estimates of pumping from different types of wells (Chowdary, 1998). Subsequently pumping distribution coefficients were developed based on the deviation between the observed and model calculated groundwater heads at

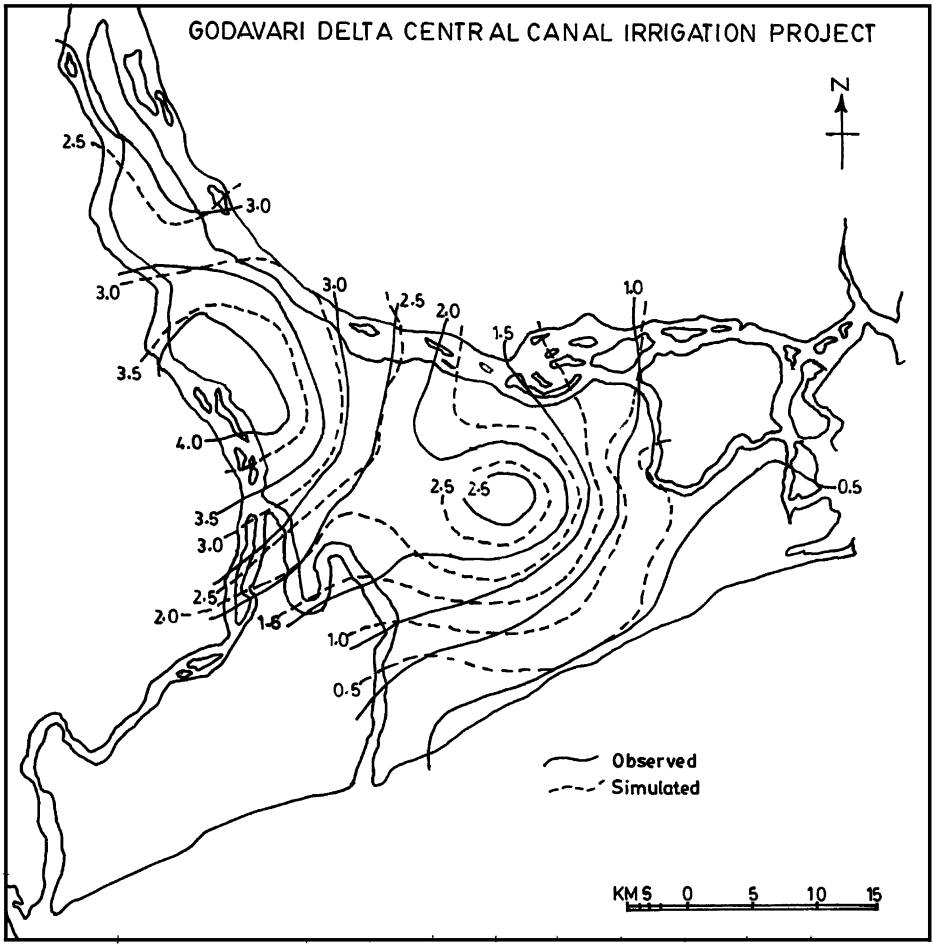

Fig. 12. Observed and simulated groundwater levels (May 1994) (m).

the end of the first year (1992–1993). A pumping factor (PF) was derived for each node based on the deviation of the model predicted heads and the observed heads at the end of year 1992–1993 (May 1993). In doing so, it was ensured that the total draft for the area remains the same as derived from the total number of wells in the study area. Thus, if the predicted heads are within ±0.5 m of the observed heads, $PF = 1$, if the difference between observed and predicted heads is >0.5, $PF = 1.5$, and if it is <-0.5, $PF = 0.5$. The distribution of pumping rates derived as above for 1992–1993 was used for the years 1993–1994, 1994–1995, and 1995–1996. Further, since pumping is an extraction from the ground water basin, a negative sign was assigned to the pumping rates at each node.

3.3.5.2. Recharge rates. The recharge rates at each node are derived from recharge in the corresponding BSU (Fig. 7). Nodes occurring within each BSU were identified by overlaying the finite element grid on the monthly recharge maps derived for each year.

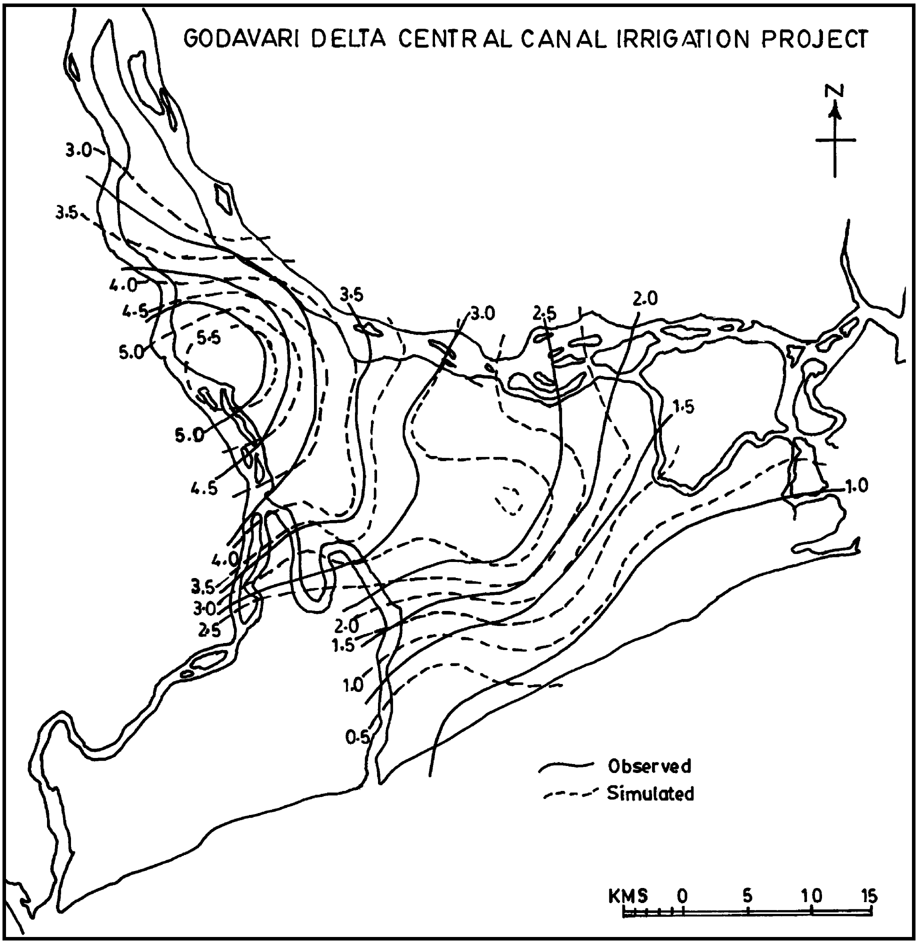

Fig. 13. Observed and simulated groundwater levels (May 1995) (m).

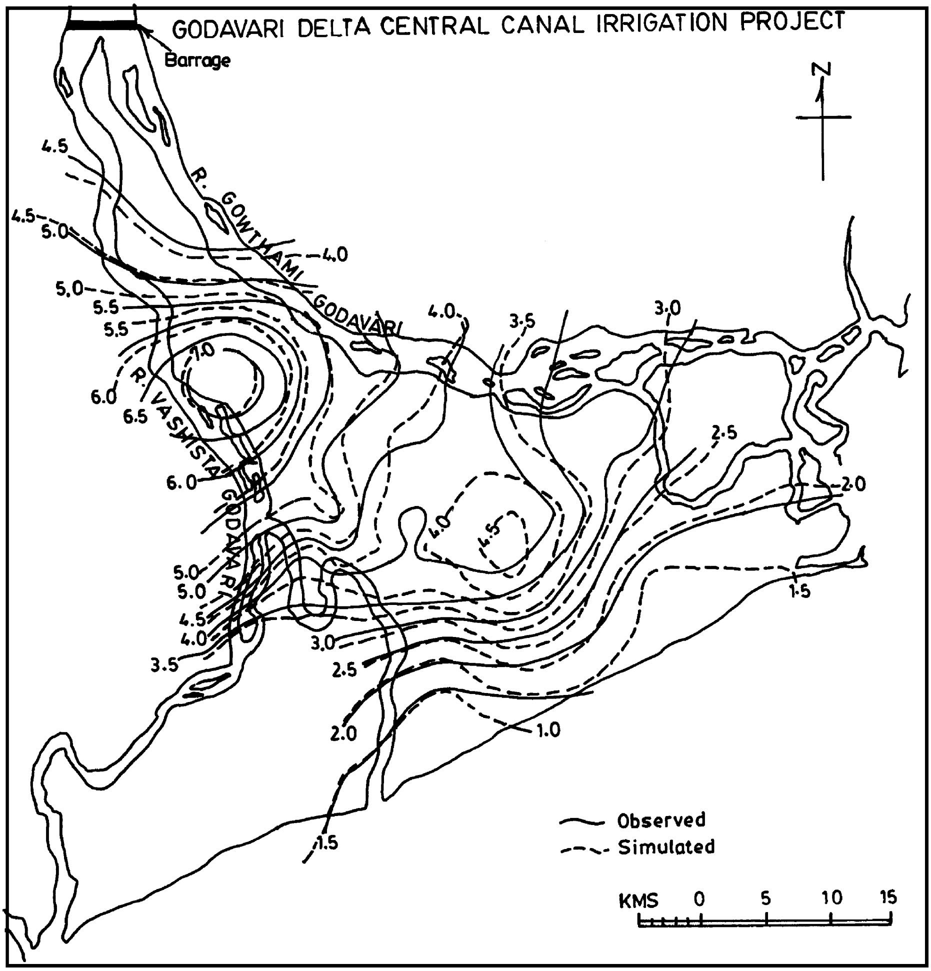

Fig. 14. Observed and simulated groundwater levels (November 1995) (m).

3.3.6. Simulation of groundwater levels

The groundwater model was run with the specified boundary conditions, initial conditions, recharge rates at each node, and the specified uniform pumping rates at all internal nodes for all the years. The computed water levels and the corresponding observed values for the period 1992–1993 to 1995–1996 are compared in Figs. 9A–C and 10A and B and the contours of observed and simulated water levels for all the internal nodes during the simulation period 1992–1996 are plotted in Figs. 11–14. The average difference between the observed and simulated water levels for most of the internal nodes varies between 0 and 0.5 m. For deviations within these limits ground water model performance can be considered satisfactory (Kisel et al., 1972; Karanjac et al., 1977; Boonstra and De Ridder, 1981). The correlation coefficient (R^2) obtained for various model simulations during the period

1992–1995 vary between 0.88 and 0.94. Thus, the recharge rates obtained using soil water balance model and canal flow model and pumping rates are representative for the study area.

For 1995 November, the model underestimated water table levels compared to earlier years (Fig. 10A). This is because, that rainfall at all raingauge stations during the year 1995 was higher compared to the other two years of study. This would have led to a lowering of pumping rates by farmers in this year. But variations in pumping rates between years were not considered in the inputs to the model. A rerun of the model with reduction of total pumping by 25% while maintaining the spatial distribution as before improved the model prediction (Fig. 10B).

3.3.7. Sensitivity to aquifer parameters

The ground water model for the irrigation project is evaluated for its sensitivity to the aquifer parameters. The parameters of the model considered are hydraulic conductivity and storage coefficient. Separate simulations were carried out with the 1992–1993 input data using the finite element model by varying the hydraulic conductivity and specific yield. Hydraulic conductivity was varied by ±50% and the storage coefficient also by ±50%. Thus, the assumed homogenity in values of ‘K’ and ‘S’ is not likely to introduce major errors. Similar observations were made by Rushton (1975), Gates and Kisiel (1974), and Boonstra and De Ridder (1981) in their studies. Thus, it can be confirmed overall that the identification of aquifer parameters and derived distributions for recharge and pumping are sufficiently accurate for applying the model in groundwater assessment and conjunctive use studies.

4. Summary and conclusions

A generalized integrated framework has been developed for assessment of groundwater resources in large canal irrigation project areas with varying soil, weather, crop, and water use conditions. The integrated framework consists of BSUs derived for the project area by overlaying rainfall, soil, water use, and administrative unit maps using GIS, simulation models; canal flow model, soil water balance model and groundwater flow model. A loose interface links the models and GIS. The basis is that using a GIS, the command area can be divided into a set of basic simulation units that are homogeneous with respect to the conditions that influence the recharge processes. The canal flow model estimates seepage losses in water distribution system and determines the water supplies available to crops for irrigation. The percolation losses from irrigation supplies are estimated by the soil water balance model. The sum of the seepage and percolation losses constitute the recharge. By running the models for the BSUs, the spatial distribution of recharge can be mapped by transferring the model output to GIS. The recharge map provides the input data to the groundwater model to predict the groundwater levels in the area. The loose link between models and GIS enables model and GIS development to proceed independently and easy adaptation of existing models. This is both time- and cost-effective. The spatial distribution of recharge derived from the GIS and of pumping based on a heuristic approach was validated by using a finite element groundwater flow model. The model predicted observed groundwater levels adequately for the study area. The soil water balance model, used to assess the percolation losses from fields, incorporates several features to facilitate estimation of percolation losses from multiple cropped areas including rice and from uncropped areas. This ensures that the model can be applied to different cropping systems that are practiced round the year in any area. Thus, the framework can be utilized for quantification of recharge and its spatial distribution which is a necessary component for assessing the potential for conjunctive use. This can be useful for simulation of the groundwater basin underlying the command area to analyze the impacts of present irrigation and additional groundwater development on the water levels in the aquifer. The framework can be used as a decision support tool for identification of a conjunctive use strategy that is most suitable for the given hydrologic and agroeconomic conditions. Optimal cropping patterns can also be derived to arrest the water table rise and maintain it at a safe depth in the command area of irrigation project. A decision support framework based on GIS and knowledge of agrohydrological processes is therefore available for groundwater assessment and management in large canal irrigation project areas.

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