Water Resources Management (2005) 19: 539–554
DOI: 10.1007/s11269-005-2071-4

Integrating Remote Sensing and GIS Techniques with Groundwater Flow Modeling for Assessment of Waterlogged Areas

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(Received: 11 July 2003; in final form: 5 February 2005)

Abstract. False Colour Composites (FCC's) of IRS-1A LISS-II sensor pertaining to the dates 9th April 1989 and 7th December 1989 are used to delineate the pre-monsoon and post-monsoon surface waterlogged areas in a region around Habibpur sub-distributary bounded by Vaishali branch canal and Gandak river in North Bihar, India for the year 1989 using visual interpretation technique. Also, digital data of IRS-1C LISS-III sensor pertaining to the dates 7th December 1998 and 6th April 1999 are analyzed in a digital image processing software – ERDAS Imagine 8.3.1, to delineate the pre-monsoon and post-monsoon surface waterlogged areas for the year 1998–1999. Further, for the study area, the waterlogging conditions are delineated for the year 1991–1992 using the groundwater flow modeling software package, MODFLOW. The results obtained using satellite remote sensing data and groundwater flow modeling are integrated in a GIS environment in ERDAS Imagine for assessment of the waterlogging areas.

Key words: digital analysis, ERDAS Imagine, GIS, groundwater flow modeling, MODFLOW, NDWI, remote sensing, visual interpretation, waterlogging

1. Introduction

The term waterlogging usually refers to a condition of high subsurface water table affecting the growth and yield of crops. On the other hand, accumulation of surface runoff and thereby stagnation of water over depressed lands due to the restriction of natural passages of water which may arise because of inadequate surface drainage or due to the higher water level elevation at the outfalls also cause waterlogging which is termed as surface waterlogging. Waterlogging and drainage problems of such nature pose a serious threat to the world's productive agricultural land. In India, the total area suffering from waterlogging is estimated to be about 33 000 km^2 (Bhattacharya, 1992). Out of this, the state of Bihar constitutes an area of nearly 9000 km^2 and the problem is stated to be serious in the Gandak command lying in the lower reaches of the Gandak basin (Second Bihar State Irrigation Commission, 1994). The major causes of waterlogging in the Gandak command include superfluous irrigation supplies, seepage losses from canals, impeded subsurface drainage and lack of proper land development. Further, the accumulation of rain and flood waters in a number of 'Chaurs' i.e. bottom lands created by seismic disturbance in the earthquake of 1934 and depressions known as 'Mauns' created due to shifting of river courses because of deposition of heavy sediment load coupled with lack of natural drainage facility and unfavorable outfall conditions have aggravated the situation. A proper assessment of these waterlogged areas is a prerequisite for finding a solution to the problem.

Several groundwater flow modeling studies have focused on assessing the waterlogged areas and to control problems of waterlogging and salinization. These studies include Konikow and Bredehoeft (1974), Ramana *et al.* (1995), Gates *et al.* (2002), Dawoud and Allam (2004) etc. Further, several studies have demonstrated the usefulness of remote sensing and geographical information system (GIS) techniques in detecting and monitoring waterlogged and saline/alkaline soils (Choubey, 1996; Lohani *et al.*, 1999; Dwivedi *et al.*, 2001 etc.). In this study, an attempt has been made to integrate remote sensing and GIS techniques with groundwater flow modeling for assessment of waterlogged areas. Surface waterlogging conditions in an area around Habibpur sub-distributary bounded by Vaishali branch canal and Gandak river in North Bihar, India are delineated using satellite remote sensing data. For this area, surface and subsurface waterlogging conditions are also delineated using the groundwater flow modeling package, MODFLOW (McDonald and Harbough, 1988). The results obtained using satellite remote sensing data and groundwater flow modeling are integrated in a GIS environment to assess the waterlogged areas.

2. Study Area

A region around Habibpur sub-distributary bounded by Vaishali branch canal (VBC) and Gandak river in North Bihar, India forms the study area (Figure 1). The study area lies between latitudes 25°56′N and 26°05′N; and longitudes 84°57′E and 85°08′E and has an areal extent of 181.6 km^2. Paddy is the main crop in the area. Maize and wheat are other important cereal crops. Besides this, pulses, oil seeds and some cash crops such as sugarcane and tobacco are also grown in the area. The average annual precipitation in the area is 1168 mm out of which 10% occurs during summer season (March to June), 85% occurs during kharif season (July to October) and the rest i.e. only 5% occurs during rabi season (November to February). Flow in Gandak river is the main source of water supply for irrigation in the region. Irrigation is provided through 18 numbers of outlets in Habibpur sub-distributory which is an off take from VBC. As these canal networks are fed through diversion of river flows, they carry water mainly during kharif season and have insufficient water for irrigation during other two cropping seasons. To

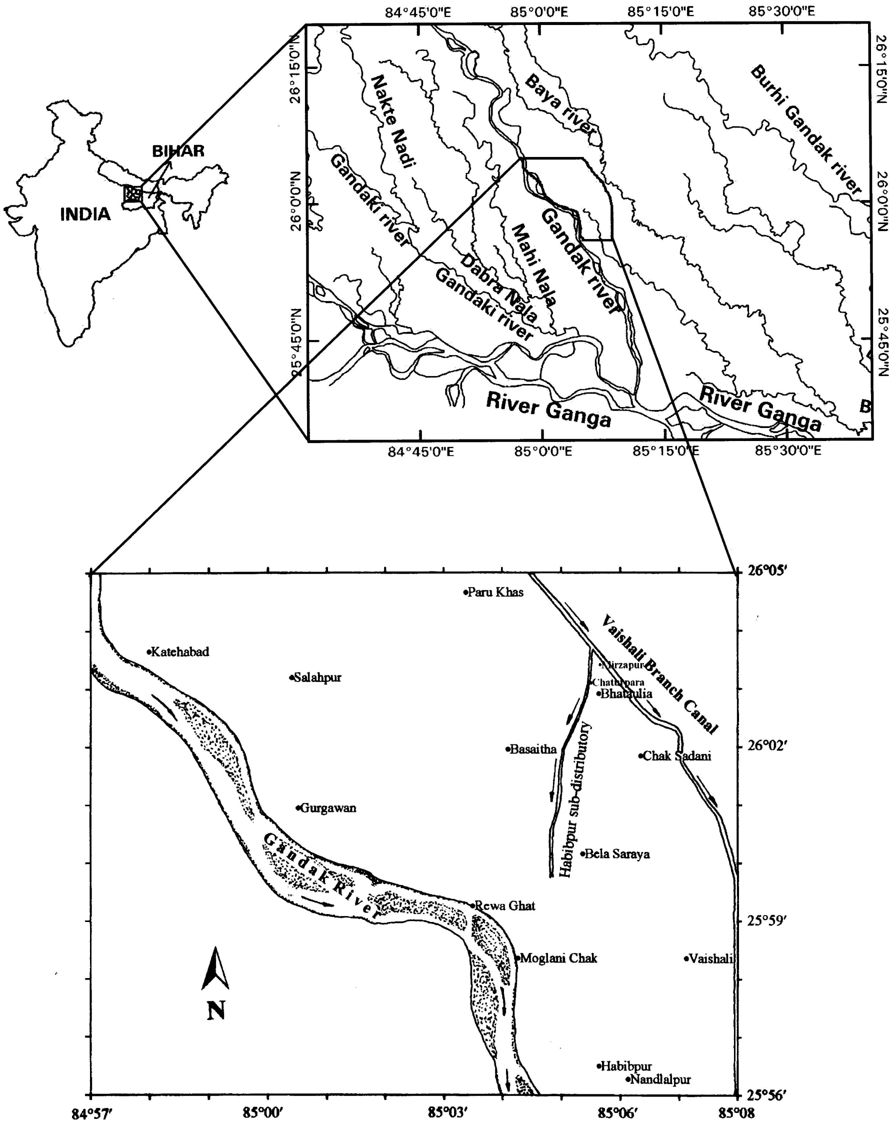

Figure 1. Index map of study area around Habibpur sub-distributary bounded by Vaishali branch canal and Gandak river in Bihar (India).

supplement the uncertainties in surface water supplies farmers use groundwater in a limited way to meet irrigation requirements during these two seasons although groundwater is available at shallow depths. Also, there are quite a few shallow depressions in the study area termed as "Chaurs" and "Mauns" having no drainage outlet to river. During high floods these depressions form a sprawling sheet of water rendering kharif cultivation impossible. Occasionally, these conditions continue

Table I. Details of remote sensing data used for the year 1989

Type of data	Date	Scene	Path/Row
IRS-1A LISS-II FCC	09.04.89	B2	22/49
IRS-1A LISS-II FCC	07.12.89	B2	22/49

Table II. Details of remote sensing data used for the year 1998–1999

Type of data	Date	Scene	Path/Row
IRS-1C LISS-III digital data	07.12.98	Full	104/53
IRS-1C LISS-III digital data	06.04.99	Full	104/53

till the month of December or January, rendering agricultural land unfit for rabi cultivation.

3. Data Used

3.1. REMOTE SENSING DATA

For delineation of pre-monsoon and post-monsoon surface waterlogged areas in the study area for the year 1989, False Colour Composite (FCC) paper prints of IRS-1A LISS-II sensor are used (Table I). The FCC's of IRS-1A LISS-II sensor correspond to the bands 4, 3 and 2 having wavelength ranges 0.77–0.86 μ (Near Infra Red (NIR)), 0.62–0.68 μ (Red) and 0.52–0.59 μ (Green), respectively, and are geo-coded at 1:2,50,000 scale. The spatial resolution of IRS-1A LISS-II camera is 36.25 m.

For delineation of pre-monsoon and post-monsoon surface waterlogged areas in the study area for the year 1998–1999, digital data of IRS-1C LISS-III sensor are used (Table II). Each scene has information of four spectral bands which correspond to Green (0.52–0.59 μ), Red (0.62–0.68 μ), NIR (0.77–0.86 μ) and Middle Infra Red (MIR) (1.55–1.70 μ). The spatial resolution for the Green, Red and NIR bands is 23.5 m, while the spatial resolution of MIR band is 70.9 m.

The ancillary data used includes information and maps of the basin such as contour map, land use information, soil map and geological information. Survey of India (SOI) toposheet numbers 72C and 72G of the scale 1:2,50,000; and 72C5, 72C6, 72C9, 72C10, 72C13, 72C14, 72G1, 72G2, 72G5, 72G6, 72G9, 72G10, 72G13 and 72G14 of the scale 1:50,000 are also used for preparation of the base maps and for remote sensing data interpretation.

3.2. GROUNDWATER DATA

To assess the waterlogging conditions in the study area, for the year 1991–1992, one year observed daily water table data (10-05-91 to 12-05-92) for four locations at Mirzapur, Chaturpara, Bhataulia and Chak Sadani in the study area are used.

4. Analysis of Remote Sensing Data

4.1. VISUAL INTERPRETATION TECHNIQUE

FCC's of IRS-1A LISS-II sensor for the year 1989 are visually interpreted for delineation of the surface waterlogged areas. Initially, a base map of the study area and its surroundings consisting mainly of drainage network, roads, railways, canals and bridges is prepared from the SOI toposheets. The satellite data for the year 1989 are registered with the base map after matching some of the identifiable features like crossing of roads, railways, canals, bridges etc. on both the base map as well as on the satellite data. The waterlogged areas from IRS-1A, LISS II FCC's are transferred on to the base map by optical processing of the two scenes of different dates i.e. before and after the monsoon. The waterlogged areas are delineated based upon the sharp contrast between water spread and the adjacent areas on the satellite data. The standing water areas appear as dark blue to black depending upon the depth of water, while the wet areas appear as dark grey to light grey in colour/tone on the imagery.

4.2. DIGITAL ANALYSIS

The digital data of IRS-1C LISS-III sensor for the year 1998–1999 are processed and analyzed using the ERDAS Imagine 8.3.1 software (ERDAS Inc., 1997). Initially, the digital data of both scenes are geo-referenced. The imagery of 7th December 1998 is considered as the base (master) since it is very sharp and clear. This image is first registered by taking various control points from the SOI toposheets. The projection type used is 'Polyconic' with the spheroid and datum as 'Modified Everest'. Subsequently, image-to-image registration is performed in order to register the second image of 6th April 1999.

The most important output from the analysis of remote sensing data is the delineation of water spread area which represents the surface waterlogged area. McFeeters (1996) developed the "Normalized Difference Water Index" (NDWI) for delineation of open water features and enhance their presence in remotely sensed digital imagery. This index is calculated as follows:

$$\mathrm{NDWI} = \left(\frac{\mathrm{Green} - \mathrm{NIR}}{\mathrm{Green} + \mathrm{NIR}}\right) \tag{1}$$

While using Equation (1) for processing a multi-spectral satellite image, water features have positive values while soil and terrestrial and vegetation features have zero or negative values which can be easily eliminated (McFeeters, 1996).

In this study, modeling technique, which is the most advanced and accurate method that tests multiple conditions to determine whether a pixel represents water or not, is used to identify the water pixels using data of different bands. After, analyzing the spectral reflectance of water pixels in both the images (pre- and post-monsoon digital data pertaining to the year 1998–1999), an algorithm is developed and used to identify water pixels using data of different bands. The algorithm matches the signatures of a pixel with that of water and then identifies whether a pixel represents water or not. In addition, it also checks for the NDWI which is created as a separate image. In all the images, it is found that the NDWI for water is either equal to or greater than 0.32. The algorithm checks for the following condition for each pixel. If the condition is satisfied, then the pixel is recorded as water, otherwise not.

> "If the digital number (DN) value of NIR band of a pixel is less than the DN value of the Red band and the Green band, and the NDWI is $\geq$0.32, then it is classified as water, otherwise not".

The above condition is applied in the form of a model in the ERDAS Imagine software and the model runs are taken for both the images.

5. Groundwater Flow Modeling

The MODFLOW software package is used to simulate the groundwater fluctuation of each cropping season of the year and study the waterlogging scenario of the area. MODFLOW is a MODular 3-dimensional finite difference groundwater FLOW model (McDonald and Harbough, 1988). Several authors have demonstrated the application of MODFLOW in groundwater flow modeling studies (Kirshen, 2002; Chen and Chen, 2003; Eusuff and Lansey, 2004; Naveh and Shamir, 2004 etc.). The modular structure of MODFLOW software consists of a main program and a large number of independent subroutines called 'modules'. The modules, in turn, are grouped into 'packages' which deal with a single aspect of simulation. In this study, 'well', 'river', 'evapotranspiration', 'general head' and 'recharge' packages are used. In the process of model development, groundwater fluctuation for each cropping season is modeled using the package. The simulation is carried out for unsteady flow for an irregularly shaped flow system and combination of unconfined leaky confined aquifer system. The external stresses such as pumpage from wells, areal recharge, evapotranspiration and interaction between river/canal aquifer systems are considered during simulation.

5.1. INPUT DATA PREPARATION

5.1.1. *Discretization of the Study Area*

The study area of 20 $\times$ 16 km is divided into 100 $\times$ 80 equal sizes gridal network i.e 8000 cells having a cell dimension of 200 $\times$ 200 m. The number of active cells in the model domain is 4540 having an area of 181.6 km^2. The lithological information of seven boreholes in the study area indicates a complex sub-surface geological formation with changing lithological units. The sub-surface formation consists of sand of various grades, silt, clay, gravel and their admixtures. From the litholog, a general trend of different sub-surface formations is established. Similar lithological units are combined and formations are grouped into three categories namely fine sand, clay mixed with fine sand and sand for all the seven boreholes. These reclassifications are done to provide the number and thickness of layers required as an input to the model. The average thickness of the three layers are 15, 15 and 50 m consisting of fine sand, clay mixed with sand and sand, respectively.

5.1.2. *Hydraulic Properties*

The transmissivity values are in the range of 400–700 m^2/day with specific yield (S_y) and coefficient of storage (S) as 12–20% and 0.15 respectively (Central Ground Water Board, 1993). The input value of hydraulic conductivity (K) for first (fine sand), second (clay mixed with fine sand) and third (sand) layer vertically downwards are 10.0, 1.0 and 25.0 m/day, respectively (Kruseman and de Ridder, 1991; Boonstra, 1989). Specific storage values are 0.01, 0.002 and 0.0001 for the three layers. The vertical hydraulic conductivity is 1/20 times its horizontal value.

5.1.3. *Initial and Boundary Conditions*

The initial condition was taken in summer season. As described earlier, one year observed daily water table data (10-05-91 to 12-05-92) for four locations are available. In the study area, west and east side is bounded by Gandak river and Vaishali Branch Canal (VBC) flowing from north to south. The VBC and Habibpur sub-distributary are considered as streams. Flow between the stream and the groundwater system is estimated using the following formula:

$$\mathrm{QRIV} = \mathrm{CRIV}(\mathrm{HRIV} - h_{i,j,k}) \quad (2)$$

$$\mathrm{CRIV} = \frac{K.L.W}{M} \quad (3)$$

where QRIV is the flow between the stream and the aquifer $[L^3T^{-1}]$, CRIV is the hydraulic conductance of the stream-aquifer interaction $[L^2T^{-1}]$, HRIV is the head in the river $[L]$, $h_{i,j,k}$ is the head at the node in the cell underlying the stream reach $[L]$ in which the subscripts i, j, and k describe the location of a cell in terms of rows, columns and layers, respectively, K is the hydraulic conductance of river bed $[LT^{-1}]$, L is the length of the reach contained in the river cell $[L]$, W is the width of the river $[L]$ and M is the thickness of the river bed material $[L]$.

Hydraulic conductance of stream-bed material is 0.04 m/day. Thickness of the bed material is 2.0 m for river and 0.25 m for canals. The average width of Gandak river in the model domain, VBC and Habibpur sub-distributary are 750, 10 and 4 m, respectively. The cell length is 200 m. Three stress periods with a duration of 4 months each coinciding with three cropping seasons of the year namely summer (March to June), kharif (July to October) and rabi (November to February) are considered in the model. The details of different data types used as input to the 'river package' are given in Table III. North and south side of the study area does not have any conventional hydrological boundaries. These two sides are considered as General Head Boundaries (GHB).

Table III. Details of river parameters used as input in the 'River package'

Stress period	Entry (North) Stage (m)	Entry (North) River bed elevation (m)	Exit (South) Stage (m)	Exit (South) River bed elevation (m)	CRIV (m^2/day)
Gandak river					
Summer	151.50		150.00		CRIV value for: Gandak = 3,000 m^2/day, VBC = 320 m^2/day and HSD = 117m^2/day.
Kharif	153.50	148.00	152.00	146.50	
Rabi	152.50		151.00		
Vaishali branch canal (VBC)					
Summer	155.31		152.20		
Kharif	156.65	155.31	153.54	152.20	
Rabi	155.72		152.61		
Habibpur sub-distributary (HSD)					
Summer	155.24		154.42		Gradient of: Gandak = 1:15,000 VBC = 1:8,000 and HSD = 1:4,500.
Kharif	156.33	155.24	155.41	154.42 (Last point)	
Rabi	155.40		154.63		

5.1.4. *Estimation of Stresses*

Stresses in a groundwater system are usually due to outflow from the aquifer or inflow into the aquifer. In the present model domain, the components of outflow consist of pumpage from aquifer, evapotranspiration, rivers and boundaries. The inflow components consist of recharge through rainfall, irrigation return flow and due to boundaries etc. The outflow from the aquifer is defined as discharge and inflow is termed as recharge.

Withdrawal from aquifer and the evapotranspiration are considered as discharge components. A total of 800 tube wells pumping from first and third layer with discharge of 25 m^3/day for each well are considered as input during summer and rabi seasons (Central Ground Water Board, 1993). Evapotranspiration values for the cropped area (16, 60 and 60% of the total area during summer, kharif and rabi seasons, respectively) in the model domain are calculated as 5.31, 3.66 and 3.02 mm/day, respectively (Doorenbos and Kassam, 1979; Hargreaves *et al.*, 1985). Areal recharge through rainfall and irrigation return flow due to spreading of water on the field through 18 numbers of outlets of the Habibpur sub-distributary are considered as external recharge.

5.2. CALIBRATION OF THE MODEL

The model is simulated with the initial and boundary conditions, input values of aquifer parameters and external stresses to/from the model domain. The output i.e. the computed water table elevations are compared with the observed water table elevations in the study area for the three stress periods. Initially during model simulation, the difference between the observed and computed water table elevation for the three stress periods are noticeable and thus, the aquifer parameters and/or stresses are modified considering the prevailing conditions in the study area to achieve an acceptable match between the computed and observed water table elevations. The computed water table elevations obtained with the calibrated parameters show a close agreement with the observed water table elevations as shown in Figure 2. The calibrated values of hydraulic conductivity for first, second and third layers are 5.0, 1.0 and 20.0 m/day, respectively, while the calibrated values of evapotranspiration are 6.37, 4.39 and 4.14 mm/day for summer, kharif and rabi seasons, respectively. Further, in order to evaluate the performance of the calibrated results, the computed water table elevations obtained after calibration are compared with observed water table elevations using i) model efficiency (EFF) (Nash and Sutcliffe, 1970) and ii) root mean square error (RMSE). It is observed that the values of EFF for summer, kharif and rabi seasons are 90, 93 and 94%, respectively, while the values of RMSE

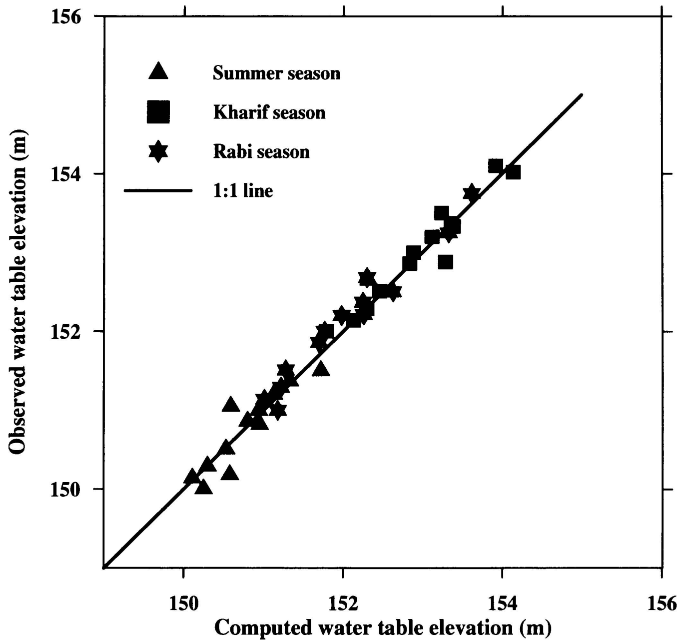

Figure 2. Computed versus observed water table elevations obtained after calibration of MODFLOW for summer, kharif and rabi seasons.

are 0.21, 0.16 and 0.18 m, respectively. Thus, there is a very close agreement between the computed and observed water table elevations, and hence, the calibration process was terminated at this stage.

6. Results and Discussion

6.1. DELINEATION OF SURFACE WATERLOGGING CONDITIONS USING REMOTE SENSING TECHNIQUE

Using visual interpretation technique, the pre-monsoon and post-monsoon surface waterlogged areas in the study area for the year 1989 are delineated from the LISS-II FCC's of 9th April 1989 and 7th December 1989, respectively (Figure 3(a)). Some of the delineated surface waterlogged areas are verified using the ground truth information obtained from State Hydrology Cell and Water and Land Management Institute (WALMI), Patna, India. From Figure 3(a), it is observed that the area under pre-monsoon waterlogging is 0.35 km^2 which forms 0.2% of the study area; while the area under post-monsoon waterlogging is 5.02 km^2 which forms 2.8% of the study area.

Using modeling technique, the pre-monsoon and post-monsoon surface waterlogged areas in the study area for the year 1998–1999 are delineated from the geo-referenced LISS-III images of 6th April 1999, and 7th December 1998, respectively (Figure 3(b)). Some of the delineated surface waterlogged areas are verified on the basis of ground truth information obtained from field visits to various places in the study area during the period of satellite pass. From Figure 3(b), it is observed that the area under pre-monsoon waterlogging is 1.80 km^2 which forms 1% of the study area; while the area under post-monsoon waterlogging is 11.37 km^2 which forms 6.3% of the study area.

6.2. DELINEATION OF WATERLOGGING CONDITIONS USING GROUNDWATER FLOW MODELING

The waterlogging conditions in the study area for the year 1991–1992 are delineated using the calibrated groundwater flow model MODFLOW.

The computed depth to water table contours at the end of summer season i.e. June 1991 (Figure 4(a)) demarcate the waterlogged ($<$2.0 m below ground level (bgl)) and non-waterlogged ($>$2.0 m bgl) areas. The total extent of waterlogged area is 104.8 km^2 and the areas for which depth to water table is $<$1.0 m bgl is 15.8 km^2. This shows that considerable area in the model domain has shallow water table.

The initial condition of kharif season is the groundwater table elevation at the end of summer season. The computed depth to water table contours at the end of kharif season i.e. October 1991 (Figure 4(b)) shows that the extent of waterlogged area ($<$2.0 m bgl) is 128.2 km^2. The area for which the depth to water table is $<$1.0 m bgl is 83.8 km^2 with surface waterlogging ($<$0.0 m) in 45.6 km^2 area. This shows that considerable area in the model domain remains under surface waterlogging

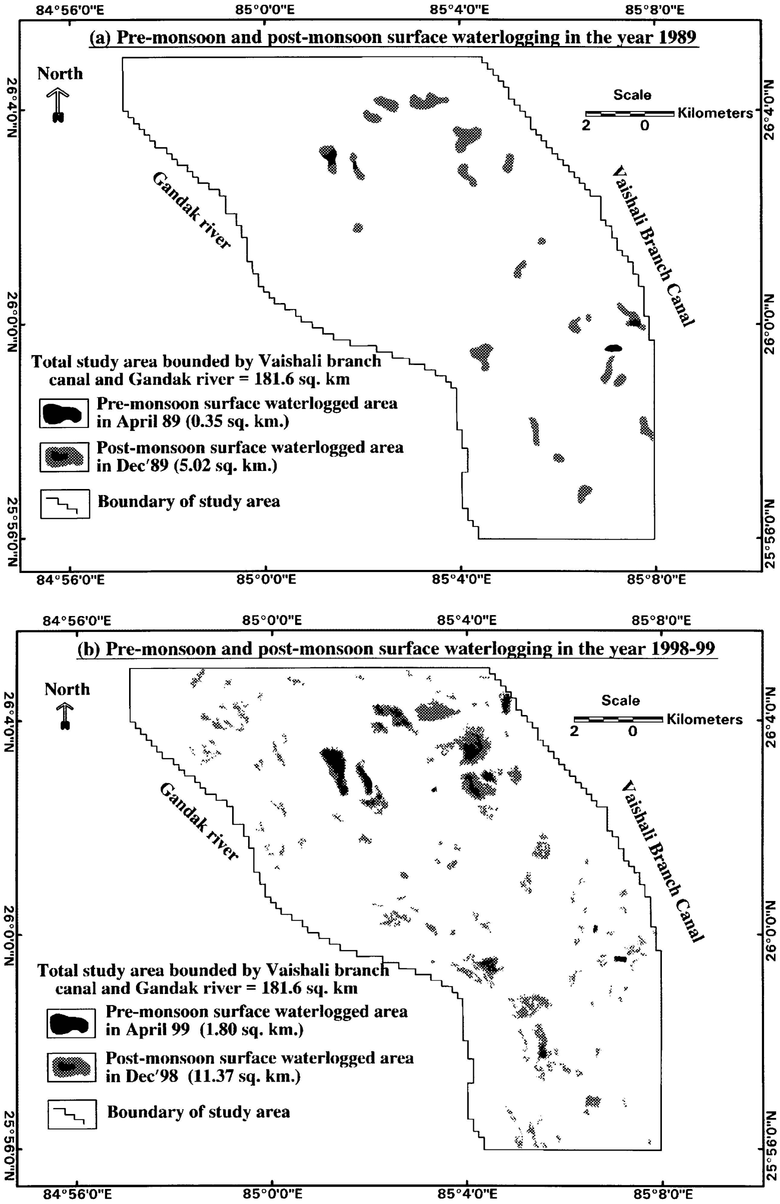

Figure 3. Surface waterlogging conditions in the study area delineated from (a) IRS-1A LISS II FCC for the year 1989, and (b) IRS-1C LISS-III digital data for the year 1998–1999.

condition. The depth to water table contours also show waterlogged areas near VBC and Habibpur sub-distributary during kharif season since the canal operates for all 120 days in the kharif season. Field visit to these areas at the end of kharif season showed that the agricultural fields in these areas remain submerged due to canal release and its seepage to the adjoining areas.

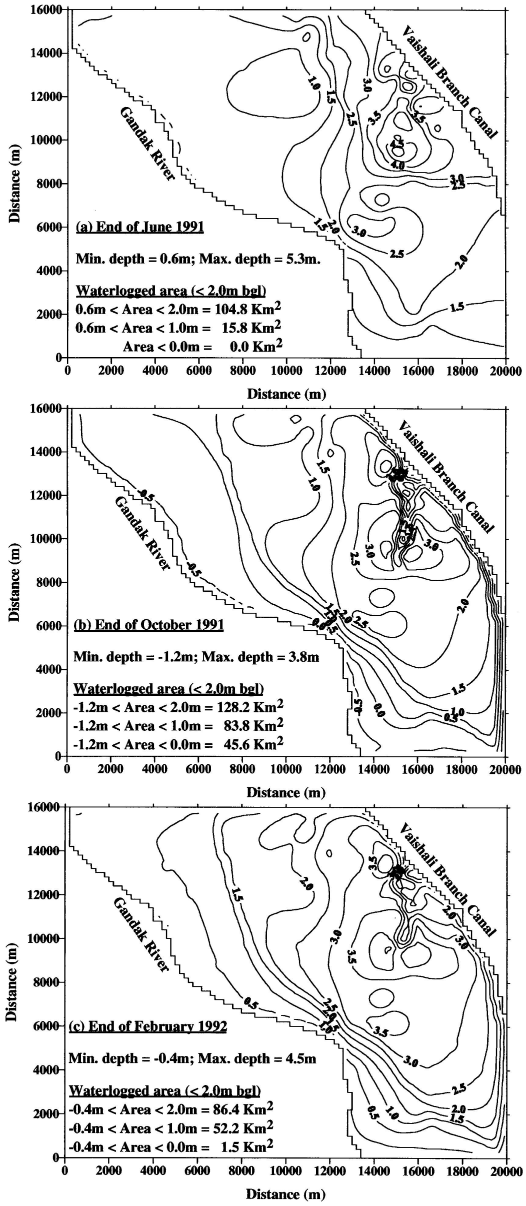

Figure 4. Depth to water table contours (m) in the study area obtained from MODFLOW (a) at the end of June 1991, (b) at the end of October 1991, and (c) at the end of February 1992.

The computed depth to water table contours at the end of rabi season i.e. February 1992 (Figure 4(c)) shows that the extent of waterlogged area (<2.0 m bgl) is 86.4 km^2 and the areas for which the depth to water table is <1.0 m bgl is 52.2 km^2 with surface waterlogging (<0.0 m) in 1.5 km^2 only.

6.3. INTEGRATION OF RESULTS IN A GIS ENVIRONMENT FOR ASSESSING THE WATERLOGGED AREAS

6.3.1. *Pre-Monsoon Waterlogging Conditions*

The pre-monsoon surface waterlogged areas in April 1989 and April 1999 obtained from remote sensing data and the depth to water table contours at the end of June 1991 obtained from MODFLOW are integrated in a GIS environment in ERDAS Imagine to assess the pre-monsoon waterlogging conditions in the study area (Figure 5(a)). It is observed from Figure 5(a) that there is an increase in the pre-monsoon surface waterlogged area from 0.35 to 1.80 km^2 i.e. 1.45 km^2 (0.8% of the study area) as obtained through remote sensing data over a period of ten years from 1989 to 1999. It is also observed that the problems of pre-monsoon surface waterlogging which existed in some of the regions in the study area in the year 1989 have become more severe by the year 1999. Also, some of the areas which were not affected by surface waterlogging earlier in the year 1989 are surface waterlogged in the year 1999. A comparison of the surface waterlogged areas obtained through remote sensing data with the depth to water table contours obtained from MODFLOW reveals that in regions where surface waterlogging conditions exist (as obtained through remote sensing data), the depth to water table is only 1.0 m in some regions, whereas it is as high as 2.5 to 3.0 m in some other regions. This is because of the presence of a large number of "Chaurs" and "Mauns" in the study area which get filled up during the monsoon season.

6.3.2. *Post-Monsoon Waterlogging Conditions*

The post-monsoon surface waterlogged area in December 1989 and December 1998 obtained from remote sensing data and the depth to water table contours at the end of October 1991 obtained from MODFLOW are integrated in a GIS environment in ERDAS Imagine to assess the post-monsoon waterlogging conditions in the study area (Figure 5(b)). It is observed from Figure 5(b) that there is an increase in the post-monsoon surface waterlogged area from 5.02 to 11.37 km^2 i.e. 6.35 km^2 (3.5% of the study area) as obtained through remote sensing data over a period of ten years from 1989 to 1998. A comparison of the surface waterlogged areas obtained from remote sensing data with the depth to water table contours obtained from MODFLOW reveals that in the regions adjoining the river Gandak where surface waterlogging conditions exist (as obtained through remote sensing data), the depth to water table contours vary from 0 to −0.5 m, thus indicating a direct relationship between the surface waterlogging conditions (as obtained through remote sensing data) and depth to water table contours. However, in some other regions where surface waterlogging conditions exist (as obtained through remote sensing data), the depth to water table vary from 0.5 m to 1.0 m in some regions, whereas it is as high as 2.0 to 2.5 m in some other regions. As stated earlier, this is because of the presence of a large number of "Chaurs" and "Mauns" in the study area which get filled up during the monsoon season.

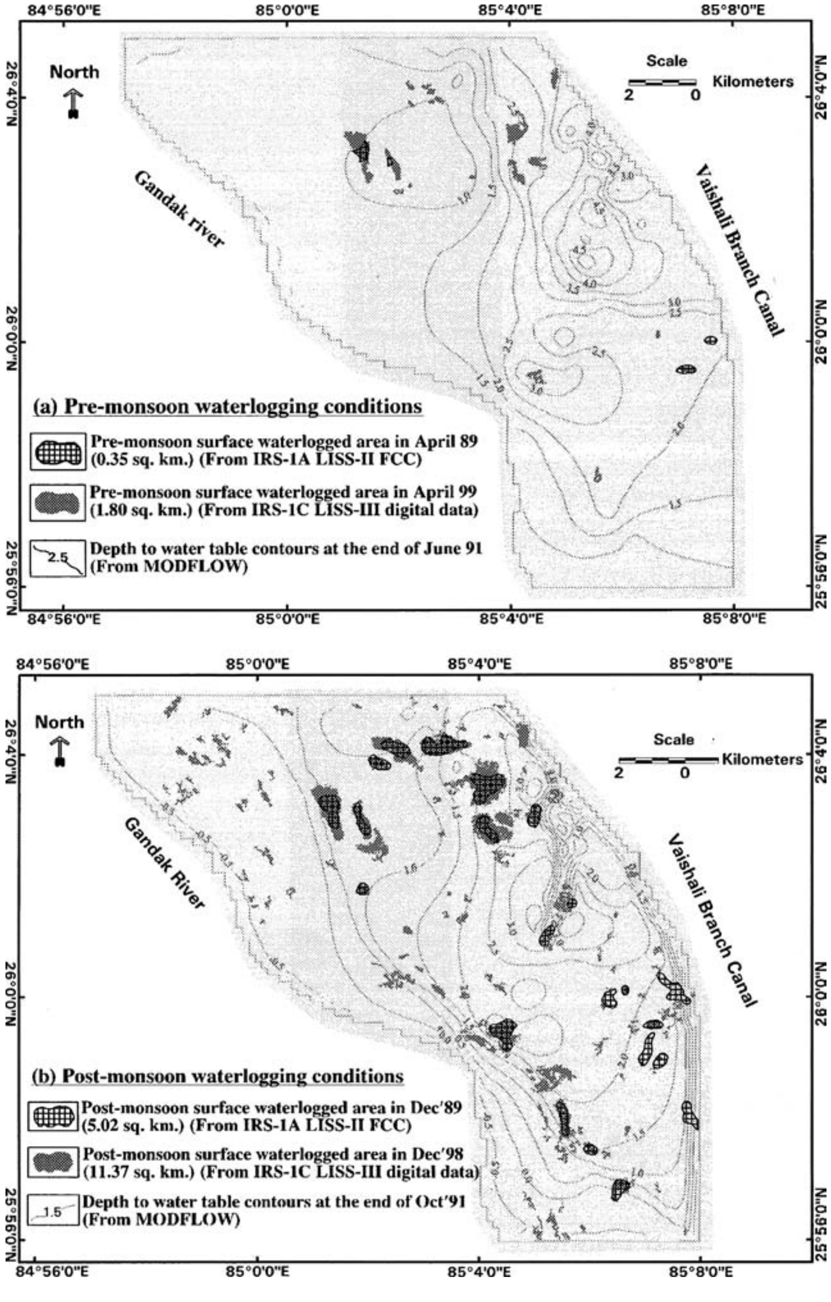

Figure 5. (a) Pre-monsoon, and (b) Post-monsoon waterlogging conditions in the study area obtained using integration of remote sensing technique and groundwater flow modeling in a GIS.

7. Conclusions

For a region around Habibpur sub-distributary bounded by Vaishali branch canal and Gandak river in North Bihar, India, the pre-monsoon and post-monsoon surface waterlogged areas for the year 1989 delineated from the IRS-1A LISS-II FCC's are 0.35 and 5.02 km^2, respectively. While, the pre-monsoon and post-monsoon surface waterlogged areas for the year 1998–1999 delineated from the digital data of IRS-1C LISS-III are 1.80 and 11.37 km^2, respectively. Further, the surface and subsurface waterlogging conditions in the study area for the year 1991–1992 are delineated using groundwater flow modeling software MODFLOW which reveal that the pre-monsoon (i.e. at the end of June 1991) waterlogged areas are 104.8 km^2 while the post-monsoon (i.e. at the end of October 1991) waterlogged areas are 128.2 km^2. The results obtained from remote sensing data and groundwater flow modeling are integrated in a GIS environment in ERDAS Imagine to assess the waterlogged areas for the study area. The study demonstrates utility of integration of remote sensing and GIS techniques with ground water flow modeling for assessment of waterlogged areas particularly in regions where waterlogging conditions occur both due to excessive irrigation and accumulation of rain and flood waters.

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