We compared these results with those obtained by the direct current resistivity method. The depth of investigation of TEM data is determined by the time at which the signal decays to noise level, source strength, loop size and resistivity of the earth[8]. In the present investigation, we have used 20 × 20 sq. m transmitter loop powered by a 12 V battery and a 5 × 5 sq. m receiver loop placed in the centre of the transmitter. Data collected from the field are processed and interpreted to generate resistivity–depth images from the decay curve. The smooth interpreted section along the two profiles is shown in Figure 4 *a* and *b*. The resistivity section obtained from TEM data at shallow depth broadly agrees with the corresponding section obtained by imaging and VES data.

Aquifer geometry and groundwater flow direction in a complex geological environment of the Himalayan foothills region are defined on the basis of integrated VES, EIP and TEM geoelectrical techniques. The study indicates high resistivity of unsaturated, unconsolidated and porous coarse material of the Bhabhar Formation. Finer subsurface material in saturated condition towards the southern part is indicated by low resistivity. Two aquifers separated by a clay formation are inferred in the middle part of the area. The clay layer is discontinuous in some areas, indicating interconnection between the two aquifers.

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Development of GIS interface Con2grid for groundwater model

M. S. Mane[1,*], D. K. Singh[2], A. K. Singh[2] and A. K. Bhattacharya[2]

[1]Division of Agricultural Engineering, and
[2]Water Technology Centre, Indian Agricultural Research Institute, New Delhi 110 067, India

Simulation of groundwater behaviour is required to predict water-table fluctuation in response to varying groundwater pumping and recharge conditions. Groundwater models are widely used for simulation of groundwater behaviour. Numerical simulations often involve handling of large-scale spatial and non-spatial input and output datasets. Geographic Information System (GIS) provides an integrated platform to manage, analyse and display these datasets and facilitates modelling efforts in data compilation, calibration, prediction and display of results. Groundwater models, such as MODFLOW, needs datasets of various parameters such as surface elevation, bottom elevation, percolation, seepage, etc. in ASCII format. Preparation of input files of these parameters is a difficult task and time-consuming, which can be made simple with the use of GIS. However, an interface program is necessary to couple the GIS with the groundwater model. An attempt was made to develop an interface for preparing the data file required for MODFLOW. ArcInfo interface Con2grid for groundwater flow model PMWIN was built as an extension for facilitating the simulation of groundwater behaviour. The extension includes pre-processing of spatially distributed (point, line and polygon) data for model input and post-processing of model output. With the help of ArcInfo interface, any coverage of spatially distributed data can be converted into ASCII files of user-defined grid dimensions. The pre- and post-processing capabilities of Con2grid were demonstrated for simulation of groundwater behaviour in western Indo-Gangetic Plains, Uttar Pradesh, India.

Keywords: Con2grid, groundwater models, interface, simulation.

SIMULATION models play an important role in the estimation of groundwater potential and prediction of aquifer response to groundwater pumping and recharge. Extensive reviews of groundwater models are available in the literature[1–3]. According to Johnson *et al.*[4], numerical models such as MODFLOW[5] provide an efficient tool to assist in the water resource decision process. A simplified representation of the system may in some cases, be obtained by the development of response function from numerical models. It was also reported that MODFLOW could produce pre-

*For correspondence. (e-mail: mahanandmane@rediffmail.com)

dictive simulations of cause and effect when properly calibrated and applied to an area. Application of modern tools like Geographic Information System (GIS) can enhance the capability and efficiency of groundwater models in cases where spatial and temporal variability in rainfall, irrigation, soil, crop and weather need to be considered in simulating groundwater behaviour. GIS has the capability of handling the large-scale spatial and non-spatial databases. Its ability to perform complex spatial analysis like map overlay, creation and integration of various types of databases and integration with simulation models makes it an efficient tool for analysis and interpretation of spatial and non-spatial datasets. Normally, the integration of a model with GIS is done through a computer program referred as an interface.

Tsou and Whittemore[6] developed an ArcView interface for the groundwater flow and transport models MODFLOW and MT3D. The extension included pre-processing of spatially distributed data for model input and post-processing of model output. Models could be automatically calibrated through the ArcView interface by external linking to programs such as PEST. The efficient pre- and post-processing capabilities and calibration link were demonstrated for groundwater modelling in southwest Kansas.

GIS has been coupled to simple functional models of recharge to map a regional assessment of relative potential recharge[7,8]. Maidment[9] presented a review of GIS applications in hydrologic modelling. Harries *et al.*[10] and Wilson *et al.*[11] reported integration of the ArcInfo GIS with groundwater flow and contaminant transport models. The interfaces reviewed need to be modified if used under Indian conditions, where advanced methods of data collection are not used in many areas. This becomes difficult because the source codes of these programs are not made available. In the present study an attempt was made to develop a user-friendly interface program, Con2grid to integrate the groundwater model with ArcInfo GIS, which can be used to prepare the input file of the model from the data collected under Indian conditions for simulating groundwater behaviour.

The interface program was developed in Arc Macro Language of ArcInfo GIS. The program converts the point, line or polygon coverage in grid format of user defined size and saves them as ASCII files. These files can directly be used as input files by MODFLOW after changing the header file information. The output files generated by MODFLOW can be imported in ArcInfo GIS. Subsequently, the programs prepares the Digital Elevation Model (DEM) of predicted water tables. A simplified system architecture of Con2grid integration with MODFLOW is presented in Figure 1.

A typical menu of the Con2grid model is given in Figure 2. The various attributes were attached to the points, lines and polygons in the respective coverages. These coverages were the inputs to Con2grid.

Functions of Con2grid include pre-processing of spatially distributed (point, line and polygon) data to prepare the input files for the model, post-processing of model output to display the spatially distributed result and preparation of the DEM. Capability of Con2grid was demonstrated for groundwater simulation in western Indo-Gangetic Plains, Uttar Pradesh (UP).

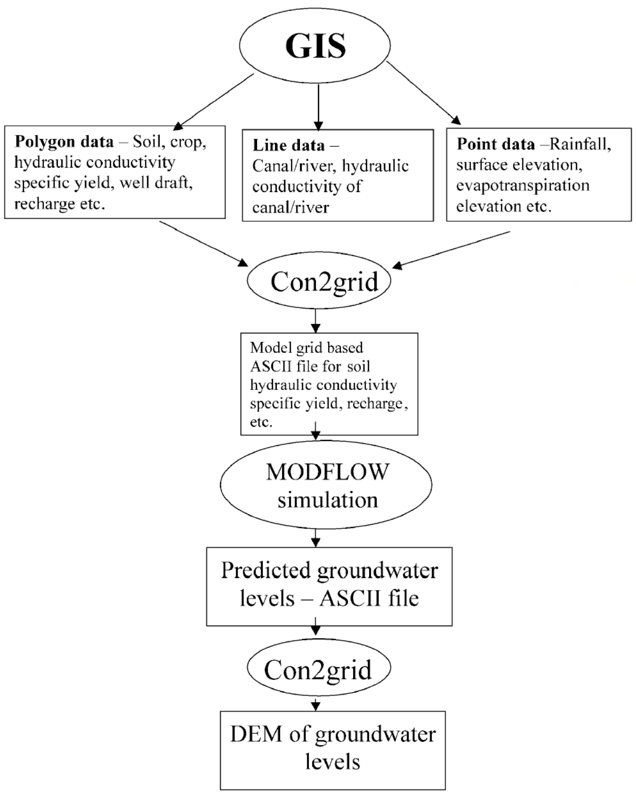

Figure 1. System architecture of Con2grid and MODFLOW integration.

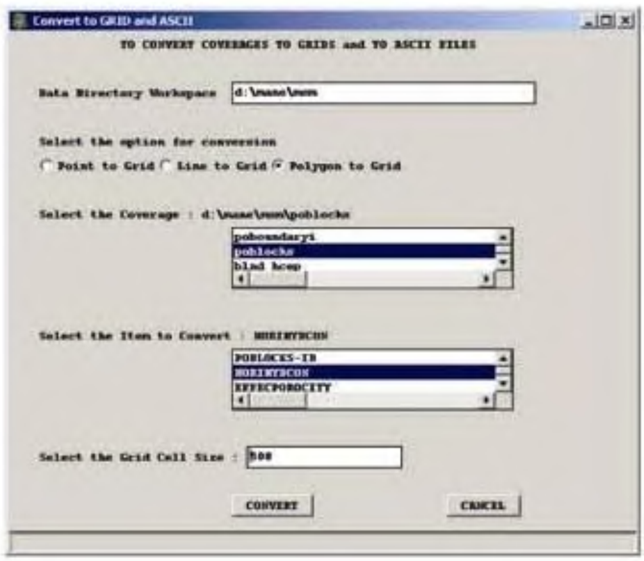

Figure 2. A typical menu of Con2grid.

MODFLOW is a modular three-dimensional finite difference groundwater model developed by the US Geological Survey[5]. The model can simulate the effects of wells, rivers, drains, head-dependent boundaries, recharge and evapotranspiration. MODFLOW simulates the steady state and non-steady flow in the irregularly shaped flow system in which the aquifer layers can be confined, unconfined or a combination of both. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through riverbeds can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic, and the storage coefficient may be heterogeneous.

The general groundwater flow equation is solved using the finite-difference approximation. The flow region is subdivided into blocks in which the medium properties are assumed to be uniform. The values of input parameters are defined for each block. The vertical direction zones of varying thickness are transformed into a set of parallel 'layers'. Several solvers are provided for solving the associated matrix problem; the user can choose the best solver for the particular problem. Mass balances are computed for each time-step and as a cumulative volume from each source and type of discharge.

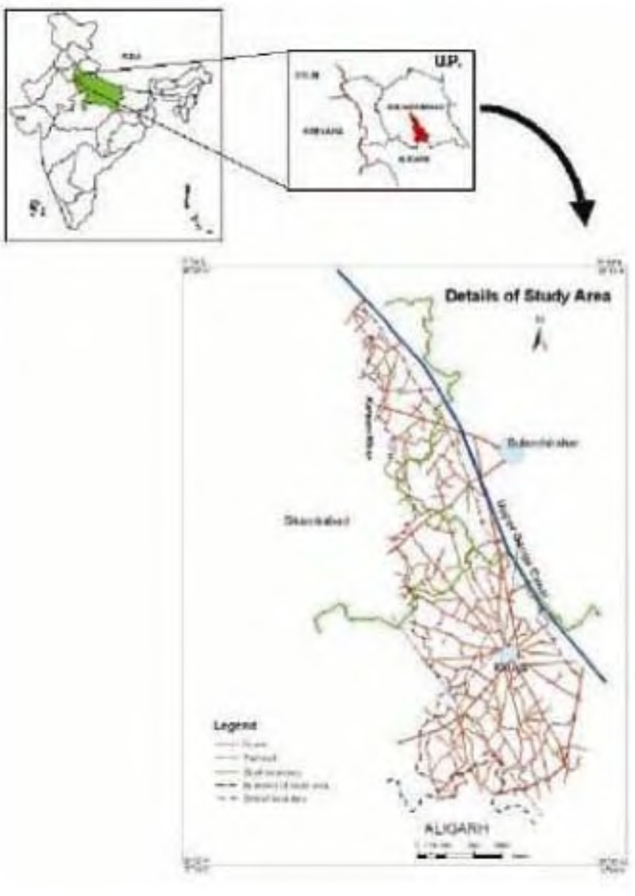

Figure 3. Location map of the study area.

Con2grid was applied to integrate MODFLOW with ArcInfo 8.0.2 GIS for predicting the water-table fluctuation in the command area of Dadupur distributary, Bulandshahar district under the Upper Ganga Canal system falling in the western Indo-Gangetic Plains (Figure 3). The model was calibrated and validated with the observed water-table data and used to predict the water table trend at various levels of groundwater pumping and canal seepage.

The study area is bounded by the Upper Ganga Canal in the east, River Karwan in the west and the Southern administrative boundary of Khurja block in the south. It has an area of 293 sq. km, lying between 28°0′–28°25′N lat. and 77°25′–78°0′E long. It covers part of three revenue blocks, namely Bulandshahar, Sikandarabad and Khurja.

As required by MODFLOW, the study area was discretized into rectangular grids. The resolution of the grids was decided upon the variability of the input parameters. There was not much variability in soil properties and rainfall. Based on this, a grid size of 1 km × 1 km was adopted. The grid so obtained is also referred as a cell. The discretized map of the study area is shown in Figure 4. Con2grid was used for preparation of various input files for each polygon representing land units pertaining to recharge, pumping, canal lengths, etc. in ASCII format.

Simulation of the water-table fluctuations was carried out for the pre-monsoon and post-monsoon periods. In the present study, observed pre-monsoon (1994) water levels were taken as initial condition. The required input files were generated using the GIS. Aquifer parameters were taken from the Central Ground Water Board (CGWB) report and are given in Tables 1 and 2.

Seepage from the canal and stream was estimated from their length, cross-section and respective hydraulic conductivity values. The average recharge rates for different grids during monsoon and non-monsoon periods were estimated as 0.007 m/day and 0.0056 m/day respectively, during 1994–95. Other simulation parameters were taken according to the requirement of MODFLOW.

The DEM of surface and bottom elevation, and water-table depths during different seasons were prepared using iterative finite-difference interpolation technique. Various thematic maps like soil map, irrigation map, etc. were prepared using ArcInfo GIS. Projected maps of various themes were used to derive information on area, canal length, land elevations, land use, soil type, etc.

The output of MODFLOW, which gives the grid-wise water-table depths, was displayed using GIS capabilities. This made the interpretation of simulation results easier.

Table 1. Hydraulic conductivity of the study area

Block	Hydraulic conductivity (m/day)	Specific yield (fraction)
Bulandshahar	0.69	0.1035
Sikandarabad	0.78	0.121
Khurja	1.66	0.1425

Table 2. Well draft per unit grid

	Well draft, pre-monsoon 1994 to post-monsoon 1994 (m^3/d)		Well draft, post-monsoon 1994 to pre-monsoon 1995 (m^3/d)	
Block	Command area	Groundwater irrigated area	Command area	Groundwater irrigated area
Bulandshahar	307	132	918	393
Sikandarabad	265	113	795	341
Khurja	498	213	1497	642

Figure 4. Grid coverage of the study area.

The different pre- and post-processing functions performed by Con2grid with respect to different input and output data of MODFLOW are summarized in Table 3.

Con2grid was used to interface the groundwater model MODFLOW for simulating the groundwater behaviour. Input files for model were prepared using it. A typical output of Con2grid is shown in Figure 5.

The model was calibrated for transient simulation. Simulated and measured values of water levels were compared and aquifer parameters were adjusted to improve model predictability. Calibration was done for pre- to post-monsoon water levels of 1994. The model was validated for post-monsoon (1994) to pre-monsoon (1995) water levels. Non-availability of continuous water-table data was a constraint in the calibration of the model for longer periods. Comparison of observed and predicted values of water levels for each grid is shown in Figure 6 *a* and *b*. The scatter plot and best fit curve (R^2 = 0.967) showed close agreement between observed and predicted water table depths. Results of the model validation are presented in Table 4. Attainment of successful calibration and validation suggests that Con2grid accurately carried out the pre-processing of different input data.

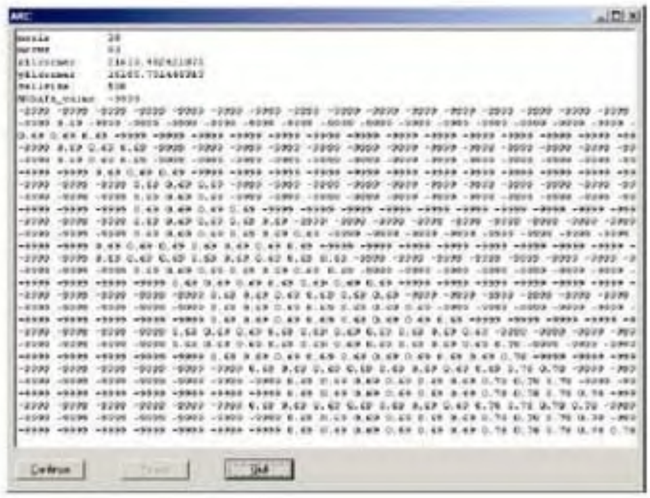

Figure 5. Output of Con2grid.

DEM of predicted water-table depths generated using Con2grid is shown in Figure 7. This demonstrates the post-processing capability of Con2grid. The calibrated model was used to predict the effect of increase in groundwater pumping on water table (Figure 8). In this case, it was assumed that groundwater pumping continues at the rate of increment (ha-m/yr), as experienced between 1984 and 1991, at the existing level of canal water use, as in 1994–95. Simulation was done for the period 1994–2004. In Figure 8, the X-axis represents the years starting from 1994 to 2004, i.e. 1 for 1994 up to 10 for 2004. Figure 8 reveals that groundwater level will go down if pumping continues at this rate and, decline in water table is more in groundwater-irrigated areas compared to canal-irrigated areas.

Table 3. Pre- and post-processing done by Con2grid

Model input	Data source	Available format	Pre-processing method	Remarks
Pre-processing				
ET surface elevation	Survey of India toposheets	Map	Con2grid	Conversion of point-based values to model-based grid values
Head in the river/stream	CGWB report	Map	Con2grid	Conversion of line-based values to model-based grid values
Hydraulic conductance of river	CGWB report	Map	Con2grid	Conversion of line-based values to model-based grid values
Hydraulic conductivity	CGWB report	Tabular	Con2grid	Conversion of polygon-based values to model-based grid values
Specific yield	CGWB report	Tabular	Con2grid	Conversion of polygon-based values to model-based grid values
Well draft	CGWB report	Tabular	Con2grid	Conversion of polygon based-values to model-based grid values
Recharge from rainfall, return flow from irrigation and tank seepage (used soil, crop data as primary data)	NBSSLUP maps, toposheets, irrigation maps	Calculated using standard procedure	Con2grid	Conversion of polygon-based values to model-based grid values
Max ET rate	CGWB report	Calculated by using procedure given in FAO-56	Con2grid	Conversion of polygon-based values to model-based grid values
Post-processing				
Groundwater level	MODFLOW simulation result	ASCII file	Con2grid	ASCII file converted to DEM

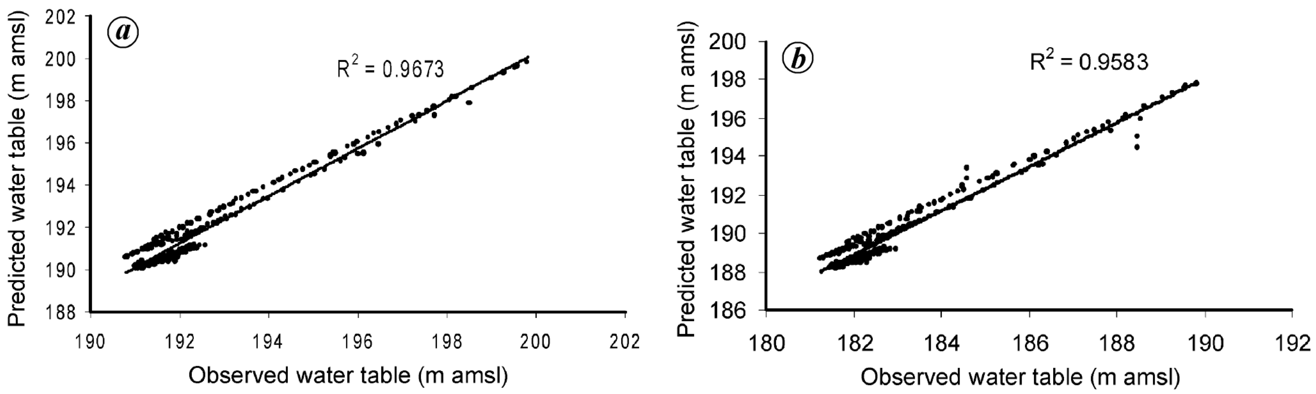

Figure 6. ***a***, ***b***, Results of model calibration.

Table 4. Observed and predicted water-table depths in the observation wells

Location of observation well	Observed water-table depth (m amsl)		
	Days after initial levels	Observed	Predicted
North	180	198.468	198.677
Southeast side	180	191.850	191.073
West	180	191.670	191.376

Con2grid and MODFLOW were also used for planning of conjunctive water use in an irrigation command. However, discussion pertaining to this aspect is beyond the scope of the present communication.

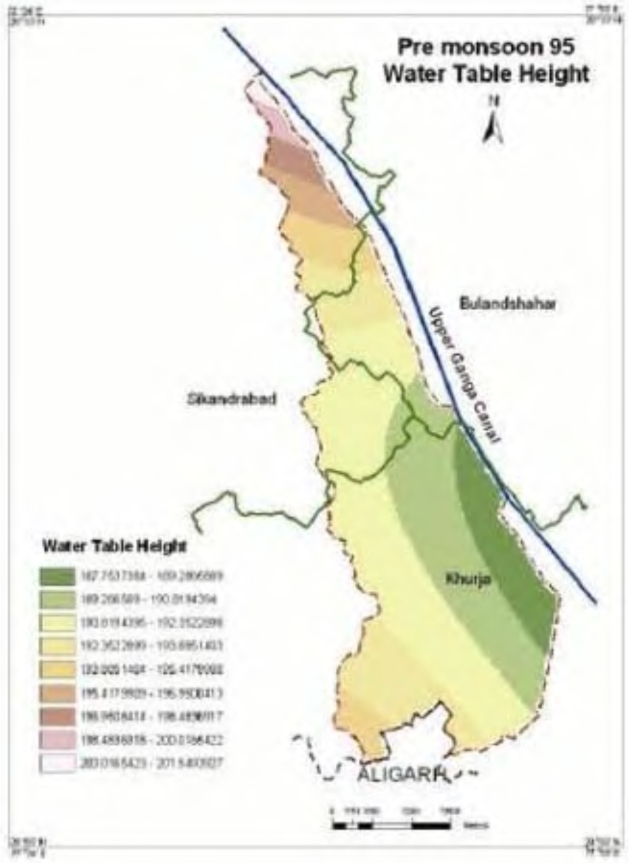

Figure 7. DEM of predicted pre-monsoon water-table depth for 1995 generated using Con2grid.

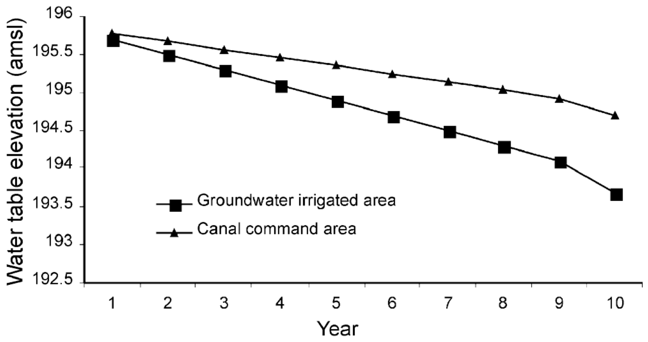

Figure 8. Predicted mean water-table depth for canal and groundwater irrigated areas for Bulandshahar during the period 1994–2004.

GIS was interfaced with MODFLOW to prepare input files and process the output of the model. A user-friendly interface program Con2grid written in Arc Macro Language, prepared input files and performed various operations like conversion of polygon to grid, assigning values of various model input parameters to each grid, linking the model with GIS and displaying the model output. Con2grid was applied to perform these operations for predicting water table using MODFLOW in the command of Dadupur distribuary under Upper Ganga Canal System, western UP. The results revealed that the pre- and post-processing capability of Con2grid saves the time required for preparing input files and displaying of the results.

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