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Development and application of a GIS based groundwater modeling system

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Abstract

To carry out systematic groundwater assessment, exploration and management and to use these for protection of optimal groundwater yield, a data analysis and management system is required. Thus, the object of this research was to develop and apply software that integrates GIS and groundwater modeling: GISGAM (GIS for groundwater analysis and management system). The GIS program ArcView and the groundwater-modeling program MODFLOW were used for the GISGAM. The program components consist of a pre-processor, a processor, and a post-processor for groundwater modeling. In addition, GIS functions such as input, manipulation, analysis and output of data were embedded into the program. In applying the program to pilot area, topography, geology, soil, land use and well databases, and a groundwater flow model were constructed for the study area. This case study revealed the advantage and convenience of groundwater modeling using GIS capabilities. By integrating GIS and the groundwater model, the impact of changing values of hydrogeological constants on model results could be more easily evaluated.

Keywords: GIS, Groundwater modeling, MODFLOW, ArcView,

1. Introduction

Since 1960, unrestrained and sporadic development of aquifers and uncontrolled use of groundwater resources has degraded and depleted the groundwater and caused subsidence of land. This situation needs assessment of groundwater exploration, database development and

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management, which should then be used for protection of groundwater. To achieve this, a groundwater flow analysis and management system must be introduced. The aim of this study is to develop such an analysis and management system: GISGAM (GIS for Groundwater Analysis and Management). The system analyzes the groundwater flow with the use of GIS and allows scientific and systematic management of groundwater.

The groundwater-modeling program is inconvenient for management of spatial data and modifying the input data is difficult. The GIS has no default functions for analysis of groundwater flow, but has many functions for database construction, display, printing, management and analysis. Therefore, it was necessary to develop a system integrated between GIS and a numerical groundwater flow model to lessen the restrictions of each application. The benefits of integrating GIS and a groundwater-modeling program are efficiency and ease of management, input, display and analysis of spatial data for groundwater modeling. Consequently, the groundwater-modeling program was integrated with a GIS program to produce the one-stop solution, GISGAM.

There are some other studies of integration of GIS and groundwater-modeling programs. The groundwater modeling procedure was integrated within the GIS (El-Kadi et al. 1994). The package ModelGIS was developed by integrating MODFLOW with ARCINFO using FORTRAN 77 and Arc Macro Language (AML) (Brown et al. 1996). ArcView was used for preparation and visualization of input data for MODFLOW program (Inbau and Rindahl 1997) and a graphical user interface for MODFLOW was developed in the Argus environment (Allen et al. 1997). A regional groundwater flow model was constructed by integrating GIS and MODFLOW (Brodie 1999) and the interface for groundwater modeling was designed and implemented using MODFLOW and ArcView (Rindahl and Bennett 1996). The main difference of GISGAM to other studies is GISGAM is a complete single package with many kinds of GIS functions in the ArcView environment. There are some commercial programs that have spatial-processing capabilities such as GMS (Groundwater Modeling System) and Visual MODFLOW. These programs do not use the GIS engine, so they can have some inconvenience or limitation to use GIS data and spatial function.

Integration of GIS and physical process models can be classified in three levels (Fig. 1). The first level is ad hoc integration. In this level, a GIS database and a model are developed separately. The data is extracted from the GIS database and the model is then executed with these files. The second level is partial integration. The GIS provides data, which are used for processing in a common user interface. The third level is complete

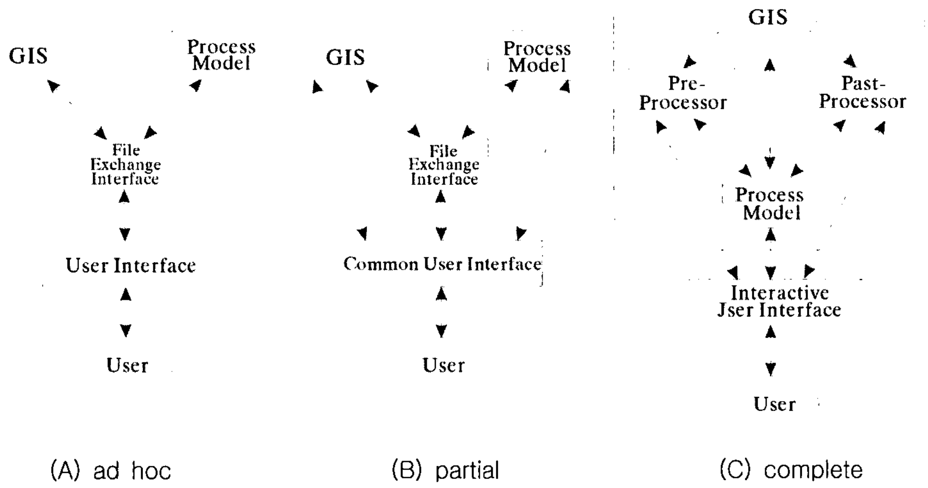


Figure 1. The level of GIS and model integration.

integration. The complete model is within the GIS. The system developed in this study is at the second level of partial integration.

A systematic evaluation tool for groundwater flow, a GIS and groundwater flow modeling program were integrated and applied. ArcView 3.2 was used as the GIS tool and MODFLOW96 was used as the groundwater flow modeling tool. The graphical user interface (GUI) between the GIS and the groundwater model was developed using Avenue (the macro language of ArcView) and the C programming language. To test the application of GISGAM, groundwater flow modeling was performed on the Youngkwang area (Fig. 2), Korea. The development and operating environment was Windows 95/98/2000/NT. GISGAM was developed in Windows NT 4.0 on a Pentium IV PC. Because the development tools were Avenue and C language in ArcView 3.2 with Spatial Analyst, ArcView 3.2 with Spatial Analyst is needed to run GISGAM. ArcView is a widely used desktop GIS program and Avenue is a programming language and development environment that is fully integrated with ArcView. A numerical groundwater flow model is a tool that simulates a real groundwater flow environment using simplified formulas. MODFLOW (Harbaugh and Mcdonald 1996) is comprised of block-centered finite difference code that can simulate the behavior of various aquifer types. It imports various types of data corresponding to the names of its eight packages: BAS (basic), BCF (block-centered flow), Well, Recharge, River, Drain, General head boundary, and Evapotranspiration.

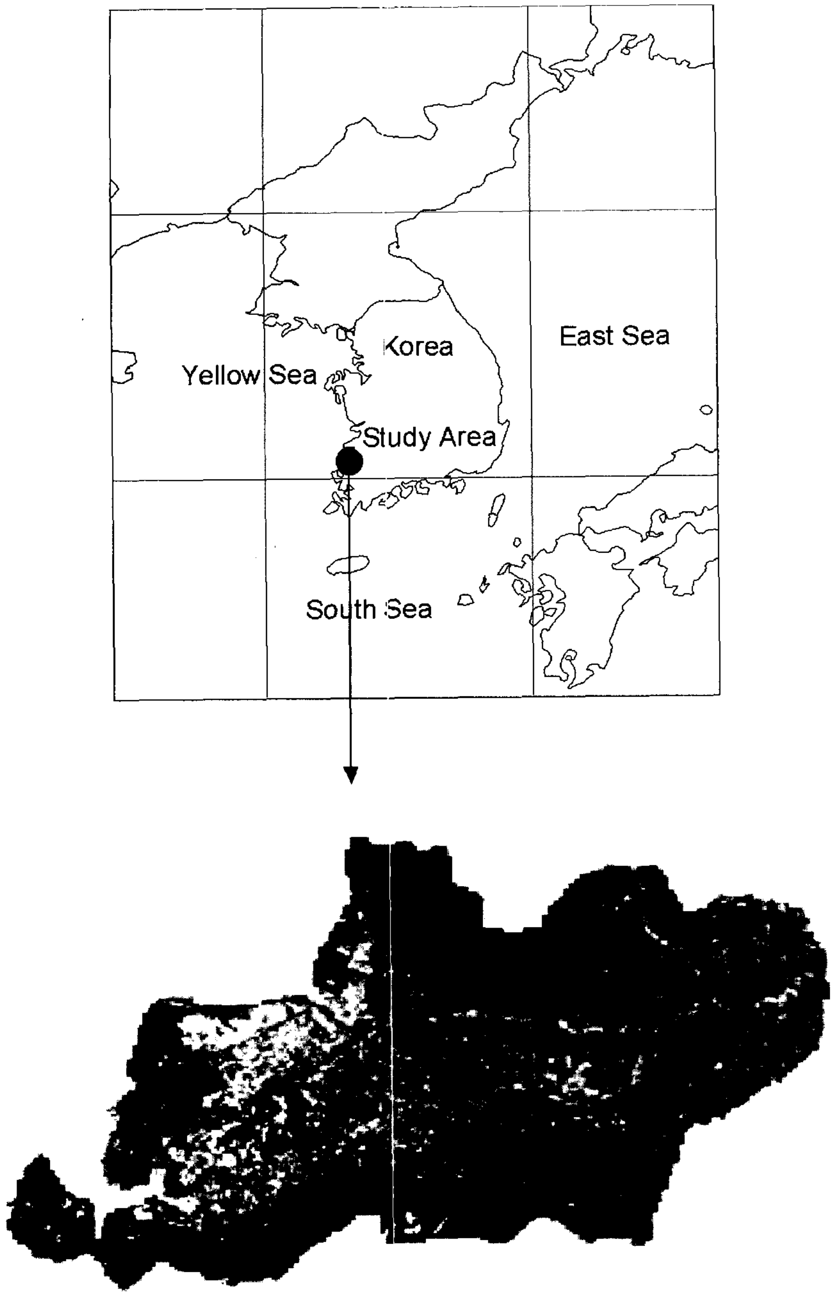


Figure 2. Study area.

2. Architecture and Functions of GISGAM

2.1 Architecture of GISGAM

Three steps are needed to integrate GIS and groundwater flow modeling. The pre-processor step is for constructing the hydrogeologic database and converting it into input data files for the numerical groundwater flow model. The processor stage is for performing groundwater modeling and calibration. The post-processor stage is for converting the results of the modeling and calibration data into a spatial database. The system architecture is shown in Fig. 3. The first step is to convert the database into ARC/INFO GRID format (raster format) and finally into an ASCII format for input to MODFLOW. The second step is to simulate the groundwater head per grid cell and model layer using the converted database. The last step is to convert the simulated groundwater head from an ASCII format into ESRI GRID and shapefile formats for use in other applications.

The pre-processor generates the MODFLOW input files from a GIS database and values that are entered by the user. Once the MODFLOW input files have been made, they are processed by MODFLOW. There are two types of input data to MODFLOW. One type is a text or numerical value; e.g., case selection, name, or time. A dialog box appears and asks for the selection text or a numeric value. The other type is spatial data that must be entered as an array in MODFLOW, e.g., elevation, recharge, or well package. The array can be entered as a constant value, shapefile, GRID file, or an ASCII file. In the case of the constant value, a single value is entered for all rows and columns. If the array is provided as a shapefile or a GRID file, then it is input as an ArcView Shapefile or ARC/INFO GRID file. Lastly, if the array is entered as an ASCII file, then it is entered as an ASCII file. Most of the MODFLOW packages have one or two arrays containing information about the

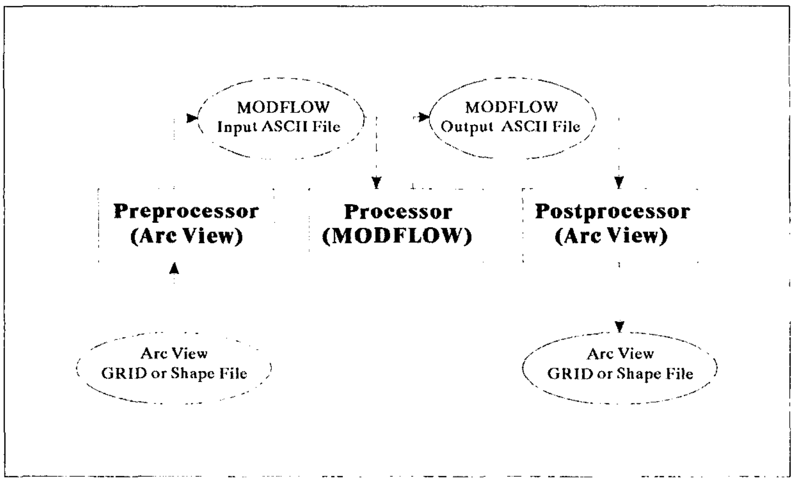


Figure 3. GISGAM architecture.

groundwater-modeling domain. MODFLOW can use ASCII formatted files with a free format array. These ASCII formatted arrays can be derived from GRID files directly or through shapefiles and converted into GRID files.

The processor runs MODFLOW to calculate the groundwater head distribution of each grid cell using the input data from the pre-processor. In the processor, numerical calculation methods such as SIP (Strongly Implicit Procedure), SSOR (Slice Successive Overrelaxation) can be selected. Next, the values that need to be processed are specified and names of the files that contain the input data are selected and the ASCII output file name is assigned.

The post-processor converts the MODFLOW output file into a GIS database compatible file. Firstly the post-processor selects the groundwater head, draw down or water budget and then the selected one converted to GRID file. GISGAM can then visualize, query, and analyze the output file and the converted output can be used for another application that needs groundwater head information.

2.2 Function of GISGAM

GISGAM is composed of the default View, Table, Chart and Layout components of ArcView. Most of the additional groundwater modeling functionality is accessible through the View component. The GISGAM system is composed of 11 pull down menus and 34 tool buttons. The GISGAM menus and tool buttons are shown in Fig. 4. The program uses pull-down menus, dialog boxes, and icons. The main menu consists of 'Data Management', 'Groundwater Flow Analysis', 'Topographic Analysis', 'Data Analysis', 'Edit', 'View', 'Theme', 'Graphics', 'Windows' and 'Help'.

The 'Data Management' menu controls the system with functions such as close, save, print, and exit. The 'Analysis Groundwater Flow' menu is for analyzing the groundwater flow, including making the input file, model running, viewing output files. The 'Topographic Analysis' menu is for analyzing the topographic surface. The 'Data Analysis' menu is for analyzing the GRID data. The 'Edit' menu has functions related to editing. The 'View' menu provides function related to screen viewing such as setting the view properties and legend style, adding or deleting themes, and zooming in or out. The 'Theme' menu has functions related to the data layers such as setting properties, start edit, saving edit, editing of legend, making or deleting labels, invoking

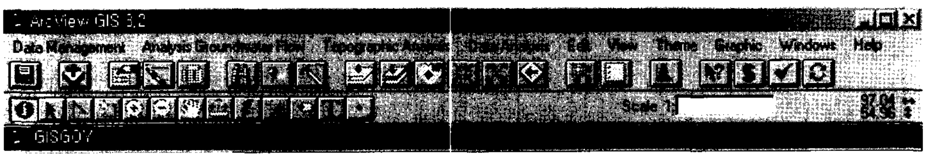


Figure 4. The GISGAM graphical user interface.

the Table environment and query. The 'Graphics' menu has functions related to graphical editing such as setting properties, aligning, grouping and ungrouping. The 'Windows' menu has functions related to arranging windows. The 'Help' menu provides the help to GISGAM.

Tool buttons are provided for the following functions: save project, add theme, change properties, change legend, open the table, find, query, zoom in or out, select or deselect, help. Also these tool buttons are used to identify, point to, reshape a feature, select features, zoom in or out, pan, measure distances, hot link, set the area of interest, place labels on features, place text, and to add graphics. The details of the pull down menus and tool buttons are listed in Table 1.

Table 1. Menu structure and its function.

Data Management	Close	Closes the active view, table, chart, layout, or script
	Close All	Closes all views, tables, charts, layouts, and scripts
	Set Working Directory	Sets the working directory
	Save Project	Saves the project file to current name
	Save Project As	Saves the project file to new name
	Print	Print the view contents
	Print Setup	Setup printer
	Export	Exports the view or layout you are working on to a file
	Manage Sources	Allows you to delete, copy, and rename data sources
	Import Grids	Converts ASCII, IEEE floating-point, USGS DEM, and US DMA DTED files to grid data
	Export Grids	Converts grid data sets to either an ASCII or IEEE floating-point file format
	Exit	Ends GISGAM
Groundwater Flow Analysis	Open Name File	Opens the MODFLOW name file
	Make Name File	Make the MODFLOW name file
	Basic Data Input	Make input file for MODFLOW BAS and BCF packages
	Recharge	Make input file for MODFLOW recharge package
	River	Make input file for MODFLOW river package
	Drain	Make input file for MODFLOW drain package
	Evapotranspiration	Make input file for MODFLOW evapotranspiration package
	General Head Boundary	Make input file for MODFLOW general head boundary package
	Well	Make input file for MODFLOW well package
	Output Control	Make input file for MODFLOW output control
	Run	Make MODFLOW SIP or SOR file and run the MODFLOW
	Convert Output File	Convert the MODFLOW output file to grid file
	View Draw down	Display draw down grid
	View Water Level	Display water level grid
	View Water Budget	Display water budget text file
Topographic Analysis	Interpolation	Interpolates a value for a cell, using the surrounding points in a point theme
	Contour	Produces an output line theme from an input grid or TIN theme
	Slope	Identifies the slope, or maximum rate of change
	Aspect	Identifies the steepest down-slope direction
	Hillshade	Compute hillshade that is used to determine the hypothetical illumination of a surface

Table 1. Menu structure and its function.

Data Analysis	Properties Find Distance Proximity Density Cell Statistics	Set the output spatial extent and resolution for analysis operations Finds the distance to the closest feature in the active theme Assigns areas of proximity to features found in the active theme Calculates a continuous density surface from points Calculate a statistic based on the values for the locations between the input grid themes.
Data Analysis	Summarize Zones	Computes a summary statistic for each zone in a grid or feature based on the cell values in another grid theme that fall within each zone
	Histogram By Zone	Creates a chart with a separate histogram distribution of a grid theme for each area of the same attribute in another theme
	Tabulate Areas	Performs a cross tabulation of the zones between two input themes
	Map Query	Creates a grid theme as output. You can change the expression and re-evaluate the grid theme without creating a new grid theme
	Map Calculator	Performs analysis on grid themes using math expressions. Arithmetic, trigonometric, Boolean, and relational operations are available
	Neighborhood Statistics	Calculates a statistic for the values found in a specified neighborhood using a point or grid theme
	Reclassify	Allows you to change the values in a grid theme by specifying new ones
	Buffering	Opens the Create Buffers wizard, which steps you through the process of placing buffers around features
	GeoProcessing	Offers six geoprocessing options such as dissolve, merge, clip, intersect, union, and assign data by location
Edit	Cut Themes Copy Themes Delete Themes Undo Edit Cut Graphic Copy Graphic Delete Graphic	Deletes the active theme(s) from the Table of Content to clipboard Copies the active theme(s) in your view to the clipboard Deletes the active theme(s) from the Table of Content Performs an Undo Cuts the selected graphics or features to the clipboard Copies the selected graphics or features onto the clipboard Deletes currently selected graphics or features without placing them on the clipboard
	Paste Select All	Pastes data that has been copied or cut onto the clipboard Selects all the graphics that have been drawn on a view
View	Properties	Lets you review and change the properties of the view you are working on
	Add Theme	Lets you add one or more themes to the current view from existing data sources
	New Theme	Creates a new, empty theme in your view
	Make Grid	Make grid with row and column
	Themes On	Make all themes in a view visible or make all themes in a view invisible
	Themes Off	Make all themes in a view visible or make all themes in a view invisible
	Layout	Puts the view you are working on into a layout
	Legend Style	Change the current and default style for the table of contents display in all your current views
	Full Extent	Zooms to the full extent of all the themes in a view
	Zoom In	Zooms in on the center of a view or a layout by a factor of 2.0
	Zoom Out	Zooms out from the center of a view or a layout by a factor of 2.0
	Zoom To Themes	Zooms to the spatial extent of the geographic features in the active theme(s)
	Zoom To Selected	Zooms to the spatial extent of the currently selected features in the active theme(s)
	Find	Finds a feature in a view, table, or chart that has the attribute value you type in

Table 1. Menu structure and its function.

Theme	Properties	Lets you review and change the properties of the active theme
	Starting Edit	Use this option to make the active theme editable or finish editing it if it is already editable
	Save Edits	Allows you to save all edits made to the theme during the current edit session
	Save Edits As	Allows you to save your edits out to a new shape file rather than changing the original shape file
	Convert to Shape File	Converts the active theme into an ArcView shape file and lets you add the shape file as a theme
	Cover to Grid	Converts the selected features of each active theme to a grid theme
	Edit Legend	Lets you change how the active theme is displayed
	Legend Show/Hide	Lets you hide the legend of the active theme(s) in your view's Table of Contents
	Auto Levels	Opens the Auto Label window where you can set rules for labeling the features of the active theme
	Remove Labels	Use this to remove the labels from the active theme(s)
	Table	Use this to open the attribute table for the active theme(s) in the view you are working on
	Query	Lets you query data according to tabular attributes by building a query expression
	Clear Selected	This control deselects any selected features in the active theme(s)
Graphic	Properties	Lets you review and change the properties of the active graphic
	Text Properties	This dialog is where you change how new text and label objects will appear
	Size and Position	Let you change the size and position of graphics of the selected graphics
	Align	Aligns the selected graphics in the view or layout you are working on relative to each other
	Send Front	Brings a selected graphic to the front of other graphics
	Send Back	Puts a selected graphic behind other graphics
	Group	Groups selected graphics into a single graphic so you can manipulate them as one object
	Ungroup	Ungroup the selected, previously grouped graphic into individual graphics
	Attach	Use this control to attach all or selected graphics to the active theme in a view
	Detach	Use this control to detach graphics from the active theme(s) in a view
Windows	Tile	Arranges the windows in your ArcView session side by side
	Cascade	Arranges the windows in your ArcView session in an overlapping pattern
	Arrange Icons	Arranges all the icons representing minimized windows in a line at the lower left corner
	Show Symbol	Opens ArcView' s Symbol Window that contain palettes
Help	ArcView Help	Displays the Help Topics dialog so you can access ArcView's help system
	GISGAM Help	Displays GISGAM help contents
	About GISGAM	Displays the version number of ArcView, the licensed user name, organization etc.

3. Application of GISGAM

GISGAM procedure consists of three steps: pre-process, process and post-process. In the pre-process step, databases for features such as topography, geology, soil, land use, and wells are designed and constructed, and an interface converts them to an appropriate input format for the groundwater model. In the process step, the model uses the input data made during the pre-process step to derive a hydraulic head of each finite difference cell and model layer, the water budget of the region. In the post-process step, a spatial database from the results of the process step is constructed for use in any other application that needs groundwater head data.

3.1 Study area and GIS database construction

The study area, a part of Youngkwang County in Korea, covers an area of about 91.95km^2 from latitude 35°14'00"N to 35°18'30"N and from longitude 126°17'30"E to 126°27'30"E. The geology of the study area consists of Pre-Cambrian gneiss, metasedimentary rock of an unknown age, Jurassic granite, Cretaceous volcanic rock, dikes and Quaternary alluvium. Efficient development and management of groundwater is needed in the study area because of the increasing demand for groundwater and the existence of various potential sources of groundwater pollution, including agricultural activities, industrialization, and seawater intrusion.

The data layers for the study area were collected from various sources and formed into a spatial database prior to using GISGAM. The spatial databases were administrative districts, facilities, topographic contours, drainages, roads, rail roads, Digital Elevation Models (DEM), hillshaded images, slope, aspect, geology, faults, wells, soil, JERS (Japanese Earth Resource Satellite) image, LANDSAT TM (Thematic Mapper) Image, and land use (Lee et al. 1998). Information about the layers of the constructed GIS, including source, source data scale, and data type are shown in Table 2. The ARC/INFO GIS software was used to construct the database of the study area.

Table 2. Constructed GIS layers in study area

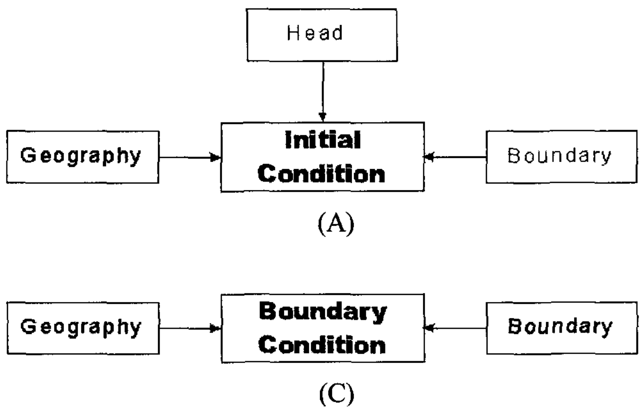
Layer	Data Source	Scale or Resolution	Data type
Administrative Districts	Topographic Map	1:5,000	Coverage
Facilities	Topographic Map	1:5,000	Coverage
Elevation contours	Topographic Map	1:5,000	Coverage
Drainage	Topographic Map	1:50,000	Coverage
Roads	Topographic Map	1:50,000	Coverage
Rail Roads	Topographic Map	1:50,000	Coverage
Digital Elevation Models	Contour	1:50,000	GRID
Hillshaded Image	DEM	1:50,000	Image
Slope	DEM	1:50,000	GRID
Aspect	DEM	1:50,000	GRID
Geology	Geological Map	1:50,000	Coverage
Faults	Geological Map	1:50,000	Coverage
Wells	Well Inventory	1:50,000	Coverage
Soil	Soil Map	1:50,000	Coverage
JERS OPS Image	JERS OPS Image	18 m × 18 m	Image
LADNSAT TM Image	Landsat TM Image	30 m × 30 m	Image
Land Use	Landsat TM Image	30 m × 30 m	GRID

3.2 Creation of groundwater modeling input files from database

The MODFLOW input files were created from the constructed hydrogeologic database. The input files for each package were made by converting ARC/INFO GRID to ASCII files. The data for BAS, BCF, River, Recharge, and Well packages for MODFLOW were made in this way. The method used for creating input as ARC/INFO GRIDs are as follows.

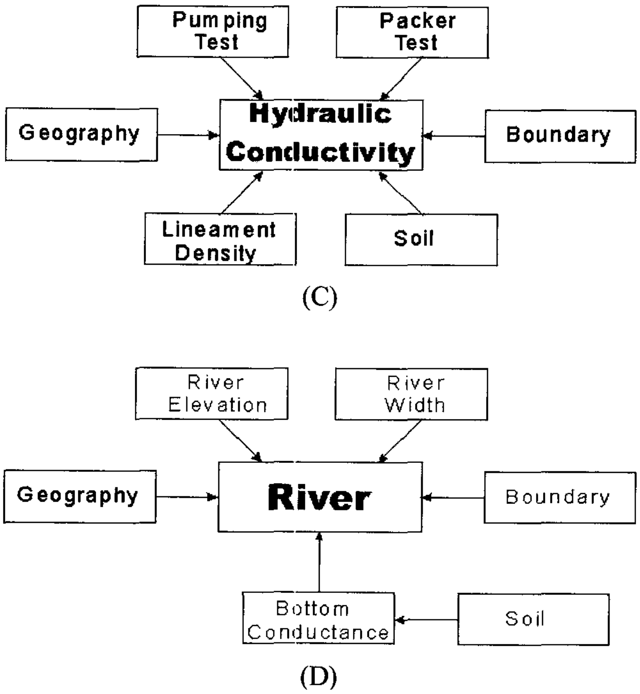
The BAS package includes the fundamental elements of the finite-difference numerical groundwater flow model; i.e., information about the grid constructed for the model region: time data, and initial and boundary conditions. The grid should cover the whole model region and have uniformly sized cells. The most important thing to consider in constructing the grid is the width of the river in the model region, because the cell size of the ARC/INFO GRID will represent the width of river. To achieve this, a thematic map with information about the geography of the study area was used. In constructing boundary conditions for the study area, the active cells of the model grid were established as the cells on the inner side of the catchment boundary-the physical boundary of the groundwater flow being the basin system. A large water body or sea is classified as a constant head boundary condition. In constructing the initial conditions for the study area, the groundwater head data measured from each observation well were used. Using these point data, initial head values for all cells in the study area grid were interpolated using IDW (Inverse Distance Weighted) method (Fig. 5 (a)). The physical boundary condition of the aquifer was calculated from grid coverage and a geographical coverage (Fig. 5 (b)).

The BCF package requires information about the characteristics of the aquifer, e.g., which aquifer, heterogeneity, hydraulic



(A) initial condition (B) boundary condition

Figure 5. Data integration to create MODFLOW input data.

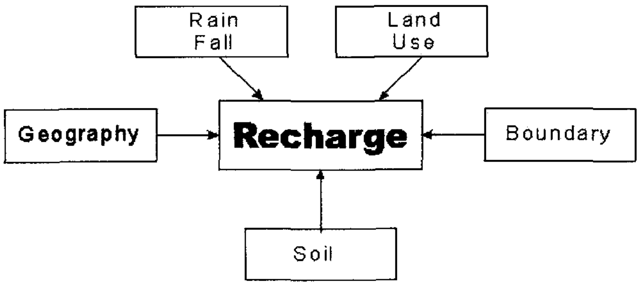


(C) hydraulic conductivity (D) river

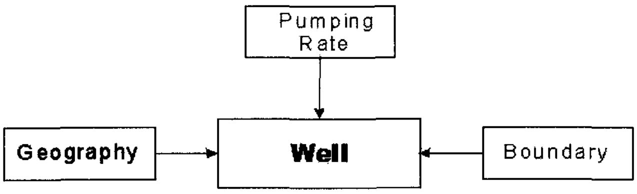
Figure 5. Data integration to create MODFLOW input data.

conductivity or transmissivity, storage, and thickness of each layer. Two things were assumed: the first was that the shallow located is mainly influenced by the soil, because soil drainage capacity can play an important role in groundwater flow; and the other assumption was that a deep aquifer is influenced by density of the lineaments of the study area, because lineaments such as faults and joints can play an important role in groundwater flow. The hydraulic conductivity was determined from a soil map and lineament density map as well as pumping and packer tests. Soil drainage was used to calculate the surface layer hydraulic conductivity and lineament density was used to calculate the deep layer conductivity, because of insufficient hydraulic conductivity data (Fig. 5 (c)). Vertical leakage was calculated using vertical hydraulic conductivity.

The RIV (River) package relates to rivers; it requires information about the location, the river stage, the river bottom elevation, and the conductance of the riverbed, in each river reach. River package data were determined from the grid and river coverage, which includes river elevation, width and bottom conductance (Fig. 5(d)). River data are



(E)



(F)

(E) recharge (F) well

Figure 5. Data integration to create MODFLOW input data.

composed of four ARC/INFO GRID data sets. The first set includes the river location information, the second set includes river elevation information, the third set includes vertical hydraulic conductivity information, and the last data set includes river bottom elevation information.

The RCH (Recharge) package relates to recharge, and it requires information about the precipitation on each cell in the study area. Recharge of groundwater by rainfall was calculated by the SCS (Soil Conservation Service) method, which uses the rainfall, soil and land use coverage (Fig. 5(e)).

The WEL (Well) package related to requires information about the well locations, screen depth, and injection or pumping quantity of each well. Discharge of groundwater by wells was determined from the well coverage, which has groundwater pumping rate information (Fig. 5(f)).

3.3 Run and output of groundwater modeling

MODFLOW was run using the input files created from the hydrogeologic databases. After running MODFLOW, the steady state non-pumping head distribution results from the model from top to bottom: layer 1, layer 2, and layer 3, respectively, are shown in Fig. 6. The groundwater recharge and discharge amount was found to be 9131.5

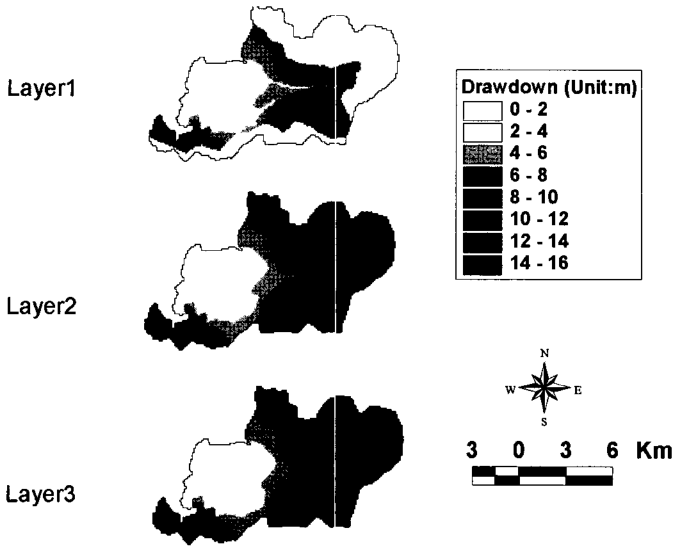


Figure 6. ARC/INFO GRID data converted from MODFLOW output of steady-state non-pumping modeling results.

m3/day. The river' s influence on layer 1 is stronger than on layer 2 and layer 3. In layer 1, most of the groundwater flows to the river, but in layers 2 and 3, relatively large amounts of the groundwater flow out to the sea. The output file derive from running MODFLOW is the groundwater head in the form of an ASCII matrix and a water budget of each layer. The groundwater head matrix was converted to ARC/INFO GRID format for each layer.

4. Discussion and Conclusions

The object of this study was to develop and apply the technique of integrating GIS and a groundwater modeling program. Thus, the design and development of GISGAM through integrating a GIS and a groundwater-modeling program was performed. The GIS program, ArcView, and the groundwater flow model, MODFLOW, were used because of function, cost and reliability considerations. The GISGAM modules are pre-processor, processor, and post-processor for increased independence of the system. Topographic, geological, soil, land use, precipitation, well, and lineament spatial databases were used by GISGAM in a case study. The constructed databases were prepared as input data for GISGAM. The GISGAM software package was effectively applied to the study area, using the constructed databases.

The result of the application was that

effective modeling of the study area was possible. It was possible to assign various values to hydrogeologic constants easily and quickly so that modeling of various conditions could be done easily and quickly. Moreover, a groundwater modeling technique is a more accurate and reliable method for calculating groundwater levels than is interpolation of well data. Using the technique and system developed here, simulation of the distribution of the groundwater head can be achieved much more easily, but only if there is sufficient and appropriate data in the GIS database for groundwater flow modeling. Especially for zoning of hydrogeologic parameters, it becomes much easier to change the zone and its value. As a result of this, it is possible to simulate the groundwater system under various conditions. The results from the groundwater flow model can be used in other applications easily and directly in a GIS environment.

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