Chapter Four. A Map-Based Groundwater Simulation Model

In this chapter, a map-based groundwater simulation model is constructed to demonstrate how the concepts of object-oriented programming and geographic information system (GIS) can be applied to simulate groundwater flow. As stated above in Chapter One and Chapter Three, the purpose for applying the concept of object-oriented programming and the technique of GIS is to enable the integration of the three components (programs, data, and maps) that jointly define a simulation model.

4.1. INTRODUCTION

A map-based groundwater simulation model has all the same benefits brought by the integration of the three components of a simulation model as a map-based surface water flow simulation model has. In addition, it has the following two advantages over models constructed without GIS.

A map-based groundwater simulation model and surface water flow simulation model can be integrated through the maps they share in common.

Because global coordinates can easily be used as the reference system for a GIS map, the results of a map-based groundwater simulation model can also be presented in a global reference coordinate system, which makes it easier for the model results to be interpreted and used than when the groundwater model is constructed in a model coordinate system whose exact geographic location has not been precisely defined.

As described in Chapter two, this map-based groundwater simulation model is constructed on a polygon coverage and an arc coverage (Figure 4.1). To fully utilize the data structure provided by the GIS, the continuity equation in form of Equation 2.23 is applied to the polygon objects, while the momentum equation in the form of Darcy's law (Equation 2.24) is applied to the boundary line objects. With this type of design, the groundwater simulation procedure is greatly simplified.

Just like in map-based surface water flow simulation model, the map-based groundwater simulation model also has three modules, pre-processor, processor, and post-processor. The task of the pre-processor is to construct the groundwater modeling objects from ordinary GIS maps. Using the base maps constructed by the pre-processor, the processor simulates groundwater flow on the line objects based on the momentum equation and computes water levels on the polygon objects based on the continuity equation (Figure 4.1). After each simulation, the post-processor is used to analyze and display modeling results. The post-processor is also used for model modification and data management purposes.

4.2. THE CONSTRUCTION OF MODEL BASE MAPS

The polygon map of a map-based simulation model originates from ARC/INFO's polygon coverage and the line map of the model results from applying the BUILD line procedure to the polygon coverage.

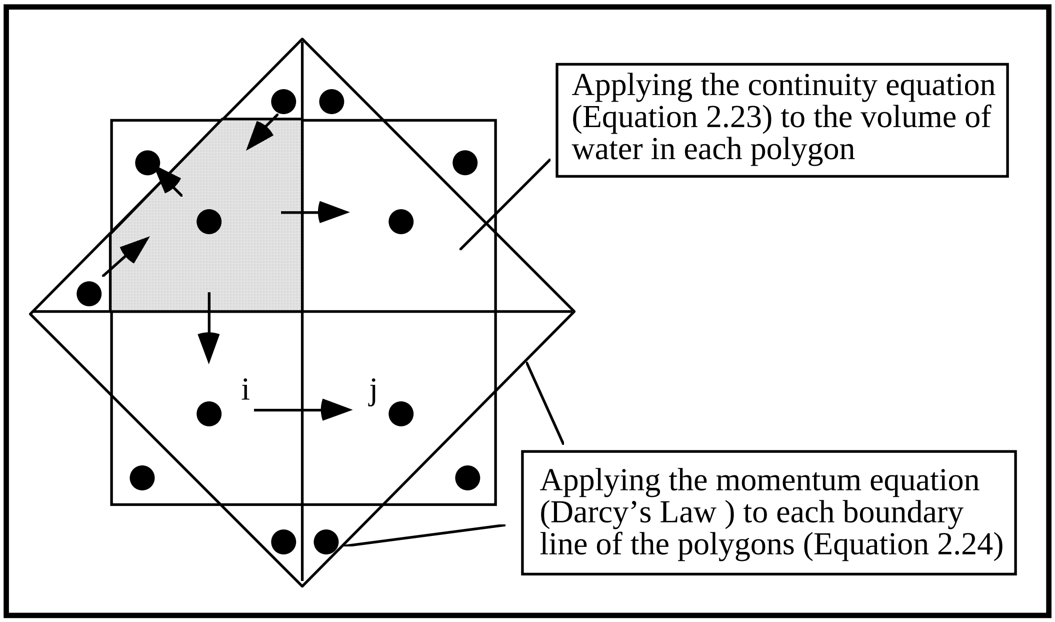


Figure 4.1. The conceptual design of a map-based groundwater model

These two ARC/INFO coverages are then processed by three pre-processor programs. The pre-processing procedures turn the features in the polygon and arc coverages into the cell polygon objects and cell boundary line objects. This map-feature to object transformation is carried out in three steps:

(1) Appending new attributes to arc and polygon map features carried out by a table modification program [GFmdfld.pre].

(2) Filling in the newly created attributes of polygons with appropriate values to convert them into polygon objects. These include the attributes such as hydraulic conductivity, aquifer type (confined or phreatic), top and bottom elevation, and storativity etc. A list of polygon attributes to be processed is given in Table 4.1. This task can either be carried out by a program [GFplyfld.pre], or manually.

(3) Filling in the newly created attributes of lines with appropriate values to convert them into line objects. A list of the line attributes is given in Table 4.2. This task is carried out by a spatial feature analysis program [GFlnsfld.pre].

After the maps are processed, the cell and its boundary line objects have the states listed in Tables 4.1 and 4.2.

Table 4.1. The Attributes of a Polygon Cell Object

	State	**Function (What the attribute represents)**
1	Area	Area of a polygon (m^2)
2	Perimeter	Perimeter of a polygon (m)
3	Cover_	Machine-assigned polygon ID, based on which the pointers to the time-series tables (sprVt, rchVt, headVt, dhVt, dvolVt, etc.) are constructed.
4	Cover_id	User assigned ID of a polygon
5	KV1000	Hydraulic conductivity (m/s)
6	Head0	Initial water level in a polygon cell (m)
7	Rch0	Initial recharge in a polygon cell (mm/s)
8	Spr0	Initial spring flow in a polygon cell (m^3/s)
9	Pmp0	Initial pumpage in a polygon cell (m^3/s)
10	ghb0	0 indicates the polygon is not a constant head cell, otherwise, a constant head cell and the value of ghb0, is the constant water level of the cell (m)
11	evt0	Initial evaporation in a polygon cell (mm/s)
12	Btm	Bottom elevation of a polygon cell (m)
13	Top	Top elevation of a polygon cell (m)
14	Cnfd	0 indicates the polygon is not confined, otherwise, the polygon is confined
15	SV	Storativity
16	headn	Water level of a polygon cell at step N, (the last simulation time step) (m)
17	dvol	Mass inflow to a polygon at step N (the last simulation time step) (m^3/s)
18	sprele	Spring elevation (m)
19	sprK	Spring flow ~ cell water level ratio-constant (m^2/s)

Table 4.2. The Attributes of a Boundary Line Object

	State	**Functions & Values**
1	Fnode_	From-node of a line
2	Tnode_	To-node of a line
3	Lpoly_	Machine-assigned id of left polygon
4	Rpoly_	Machine-assigned id of right polygon
5	Length	Length of the line (m)
6	Cover_	Machine-assigned id of a line
7	Cover_id	User-assigned id of a line
8	ldx	dx of a line, dx=xn-x0. dx is the x component of a boundary-line-vector (m)
9	ldy	dy of a line, dy=yn-y0 dy is the y component of a boundary-line-vector (m)
10	fcosx	cosine of the angle between the normal vector to the left of the line and x-axis
11	fcosy	cosine of the angle between the normal vector to the left of the line and y-axis
12	CCX	x coordinate of the center point of a line
13	CCY	y coordinate of the center point of a line
14	Slength	Distance between the center points of the two polygons sharing the line (m)
15	isbnd	0 indicates the line is not an external boundary, 1=a boundary line with internal polygon on the right, -1=a boundary line with internal polygon on the left
16	bndtp	0 indicates a non-flow boundary, 1 indicates a constant head boundary
17	Bhead	The value of constant head level if bndtp gives a non-zero value (m)
18	xflux	x component of water flow rate across a line (m^3/s)
19	yflux	y component of water flow rate across a line (m^3/s)

4.3. THE SIMULATION MODEL FORMULATION

The main program of the groundwater model consists of three loops, which are a time-loop, a polygon-loop and a line-loop. The time-loop marches through the time dimension and simulates groundwater flow situation for each time step. The time-loop becomes an iteration-loop under steady state. For each time step on the time-loop, the line-loop is first carried out to compute water flow across each line object based on the piezometric heads computed at the last time step using the Darcy’s law. Following the line-loop, the polygon-loop is carried out to calculate the water level changes in each cell polygon object based on the continuity equation. The functions of these three loops and their relations to each other are shown in a program flow-chart (Figure 4.2) and in a quasi-Avenue code

(Figure 4.3). The equations and methodologies used by the line-loop and polygon-loop are explained in sections 4.3.1, and 4.3.2.

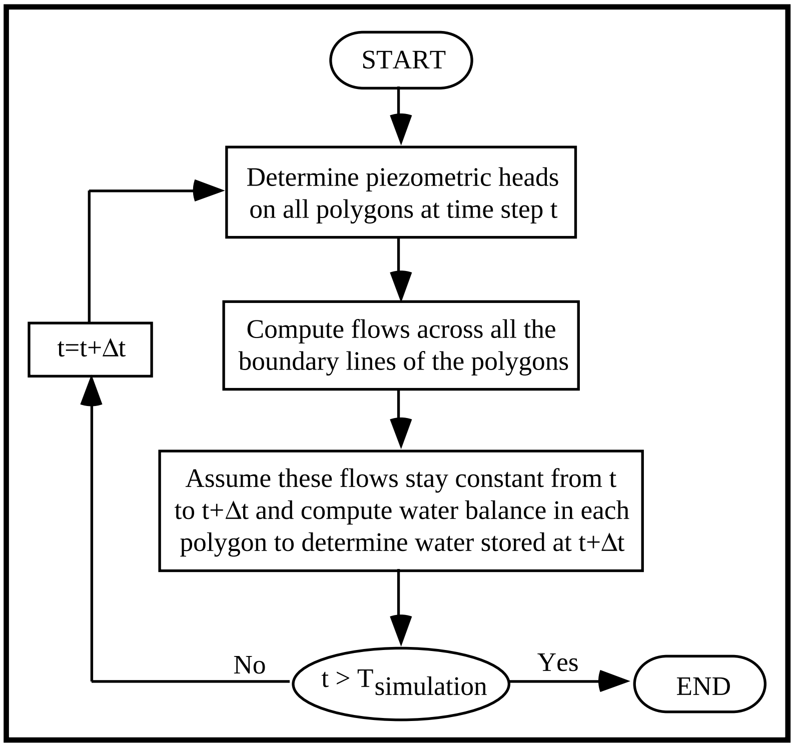


Figure 4.2. Program flow chart of the groundwater simulation model

```
For each timestep in 1..NumberOfTimeSteps
    For each line in TheArcCoverage
        {Compute the mass flow Across the line using Darcy’s Law}
    End
    For each cell in ThePolygonCoverage
        {Compute the new water level of the cell using the continuity equation}
    End
End
```

Figure 4.3. Three loops in the groundwater simulation algorithm

The input data sets of the model are stored either in the feature attribute tables (FTAB) of the basic model maps or in the spatially-referenced time-series tables associated with the basic model maps.

4.3.1. The Construction of the Line-Loop

The line-loop is constructed to simulate mass flow across each line object to obtain the mass exchanges between two adjacent cells (Figure 4.4). For each boundary line section, the mass flux across the boundary line from the Left-Polygon (Lpoly) to Right-Polygon (Rpoly) is computed using the momentum equation in the form of Darcy's Law (Equation 4.1).

$$\vec{q}_{rl}^{\,t} = -\vec{q}_{lr}^{\,t} = -K_{lr} \cdot \left(\frac{dh}{ds}\right)_{lr}^{t} \cdot \vec{s}_{lr} \approx -K_{lr} \cdot \frac{(h_l^{t-1} - h_r^{t-1})}{SL_{lr}} \cdot \vec{s}_{lr} \qquad (4.1)$$

where,

$\vec{q}_{lr}^{\,t}$ = mass flux from Lpoly to Rpoly across the boundary line, [L/T]

$\vec{s}_{lr}$ = a unit direction vector pointing from Lpoly to Rpoly in parallel with the line connecting the centers of Lpoly and Rpoly,

$\left(\frac{dh}{ds}\right)_{lr}^{t}$ = derivative of h in the direction of $\vec{s}_{lr}$,

K_{lr} = hydraulic conductivity between Lploy and Rpoly in the direction of $\vec{s}_{lr}$ [L/T], $K_{lr} = \frac{K_{lr}^{Lpoly} + K_{lr}^{Rpoly}}{2}$,

K_{lr}^{Lpoly}, K_{lr}^{Rpoly} = hydraulic conductivities of cells Lpoly and Rpoly,

SL_{lr} = distance between the centered points of cells Lpoly and Rpoly, given by Slength of a line object [L],

h_l^{t-1}, h_r^{t-1} = water levels of cells Lpoly, and Rpoly respectively, at time step t-1.

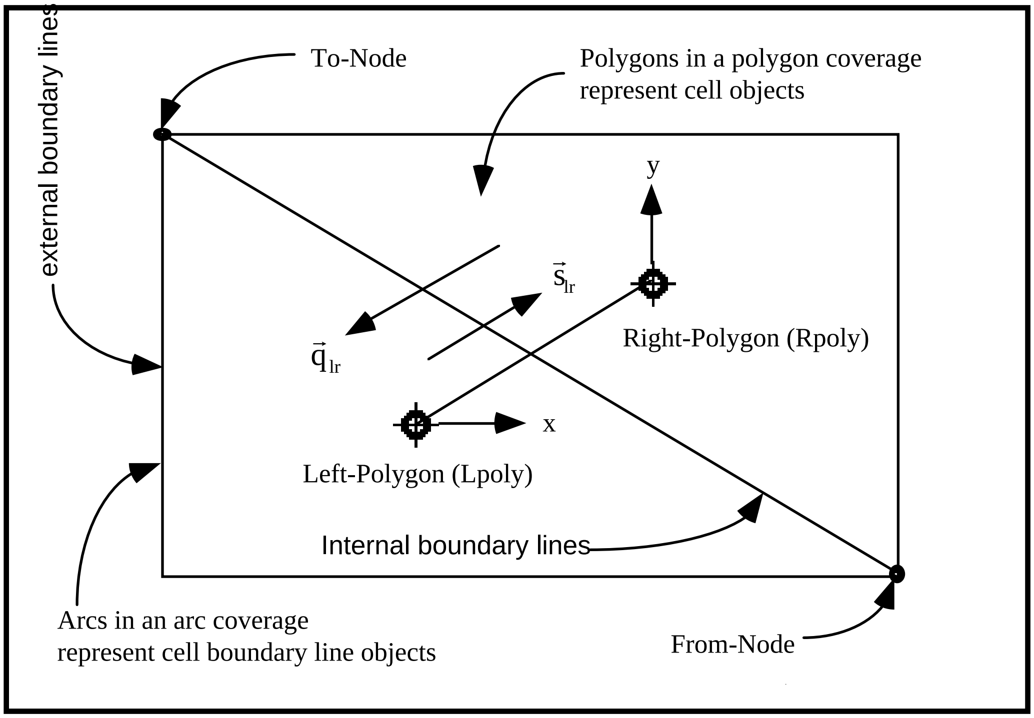


Figure 4.4. The arc and polygon coverages used by the simulation model

It is assumed that the value K_{lr} can be estimated from the hydraulic conductivity of the cells Lpoly and Rpoly. It is also assumed that the flux lines across a boundary line are uniformly distributed and parallel to each other. With these assumptions, the mass flow rate across a line object can be computed by applying the cross product to the flux vector and boundary line vector (Equation 4.2). A boundary line vector is defined as the straight line connecting the From-Node (FNode) to the To-Node (TNode) of the line. The direction of boundary line vector is the same as FNode to TNode direction.

$$\vec{Q}_s = h_s \cdot (\vec{q} \times \vec{l}) = h_s \cdot \begin{pmatrix} \vec{i} & \vec{j} & \vec{k} \\ q_x & q_y & 0 \\ l_x & l_y & 0 \end{pmatrix} = h_s \left(q_x l_y - q_y l_x \right) \vec{k} \qquad (4.2)$$

where, $\vec{Q}_s$ = mass flow rate across line section s [L^3/T], A positive value indicates water flow goes from Lploly to Rpoly.

$\vec{q} = q_x \vec{i} + q_y \vec{j}$ = flux across line section s, computed using Equation 4.1 [L/T],

$\vec{l} = l_x \vec{i} + l_y \vec{j}$ = boundary line vector of section s, [L], l_x and l_y are given by ldx, and ldy attributes of a boundary line object (Table 4.1).

h_s = the average depth of the aquifer at on line section s [L], Based on the aquifer type of the adjacent cell objects, h_s is computed using one of the following equations:

(1) If both aquifers under Lpoly and Rpoly are phreatic aquifers, then

$$h_s = avg\left\{(h_l - b_l), (h_r - b_r)\right\} \qquad (4.3a)$$

(2) If both aquifers under Lpoly and Rpoly are confined aquifers, then

$$h_s = \min\left\{(t_l - b_l), (t_r - b_r)\right\} \qquad (4.3b)$$

(3) If the aquifer under Lpoly is phreatic while the aquifer under Rpoly is confined, then

$$h_s = \min\left\{(h_l - b_l), (t_r - b_r)\right\} \qquad (4.3c)$$

(4) If the aquifer under Lpoly is confined while the one under Rpoly is phreatic, then

$$h_s = \min\left\{(t_l - b_l), (h_r - b_r)\right\} \qquad (4.3d)$$

t_l, t_r = the top elevations of a confined aquifer under Lpoly and Rpoly, respectively [L],

h_l, h_r = the phreatic surface elevations of a phreatic aquifer under Lpoly and Rpoly, respectively [L],

b_l, b_r = the aquifer bottom elevations of an aquifer Lpoly and Rpoly [L].

The exchange of water volume between two polygons sharing a boundary line section s in a given time step can be computed using:

$$\vec{V}_s = \vec{Q}_s \cdot \Delta t \qquad (4.4)$$

A positive value of $\vec{V}$ indicates $|V_s|$ is taken from Lpoly and put into Rpoly and negative, from Rpoly to Lpoly. The volume of water exchange $|V_s|$ is used by the polygon-loop to calculate the water levels of cell objects at the end of the current time step.

4.3.2. The Construction of the Polygon-Loop

The continuity equation used in the model to compute mass balance for a cell object at a given time step t is given below (reproduced from Equation 2.23):

$$\Delta t^t \cdot \left[A_i \cdot \left(R_i^t - P_i^t - Q_i^t\right)\right] + \sum_j V_{ij}^t = A_i \cdot S_i \cdot (h_i^t - h_i^{t-1}) \qquad (4.5)$$

where,

Δt^t = time interval at time step t,

A_i = area of cell i [L^2],

R_i^t, P_i^t, and Q_i^t = recharge, pumpage and discharge of the aquifer under cell i at time step t, respectively,[L^1T^{-1}],

V_{ij}^{t} = volume of water that enters cell i through boundary j at time step t [L^3],

S_i = the storativity (for a confined aquifer) or the specific storage (for a phreatic aquifer, of cell i,

h_i^t = water level of cell i at the end of time step t [L],

h_i^{t-1} = water level of cell i at the end of time step t-1 [L]. The water levels of the cell objects are used by the line-loop to compute the volume of water crossing a boundary line object for next time step.

4.3.3. Treatment of Time-Series Data Sets

The map-based groundwater simulation model uses the time-series database tables described in Section 3.3 to store and manage all the model related time-series data. Using this method, seven database tables are created to store the spatially-referenced time-series data sets for the groundwater simulation model. Table 4.3. summarizes the functions of each data table.

Table 4.3. Tables for Spatially-Referenced Time-Series Data Sets

Table Name	**Time Series Data [UNIT] {FieldWidth.DecimalPoints}**
dhtb.dbf	Water level changes dh(t) of a cell object [L] {8.3}
gfvtb.dbf	Storage changes DV(t) of a cell object [L^3/T] {14.11}
headtb.dbf	Water level H(t) of a cell object [L] {8.2}
pmptb.dbf	Pumpage P(t) applied to a cell object [L/T] {8.2}
rchtb.dbf	Recharge R(t) applied to a cell object [L/T] {8.2}
sprtb.dbf	Spring flow SPR(t) of a cell object [L/T] {8.2}
xfluxtb.dbf	x component of flow across a cell boundary line object [L^3/T] {14.11}
yfluxtb.dbf	y component of flow across a cell boundary line object [L^3/T] {14.11}

All the database tables listed in Table 4.3 use the same data structure in which, the records (rows) correspond to time dimension and fields (columns) correspond to the spatial features with which the time vectors are associated. During the modeling process, the spatially-referenced time-series data are stored and retrieved according to the time step given by the time-loop and spatial location given by either the line-loop or polygon-loop.

4.4. TREATMENT OF MODELING CONDITIONS

As the groundwater simulation model depends heavily on the initial and boundary conditions, this section is devoted to discuss how the initial and boundary conditions are processed in the map-based groundwater simulation model.

4.4.1. Treatment of Boundary and Initial Conditions

The boundary related information is stored in the Isbnd and Bndtp attributes of a line object (Table 4.2). The Isbnd values of a line object indicate if the line object is a external boundary line. A line object with Isbnd=0 is not an external boundary line. A line object with its Isbnd=-1 is an external boundary line with the exterior to its right and a line with its Isbnd=1 is an external boundary line with the exterior to its left. Bndtp assumes a zero value for all the internal boundary lines and no-flow external boundary lines. For constant head boundary lines, Bndtp=1, and when Bndtp=1, the value of the Bhead attribute of the line object gives the constant water level.

The initial conditions such as initial water level, recharge, pumpage and spring flow, are stored with a cell polygon object. As shown in Table 4.1, initial water level, spring flow rate, recharge rate and pumpage rate of a cell object are stored in the attributes head0, spr0, rch0 and pmp0 of the object.

4.4.2. Treatment of Internal Boundary Conditions

The internal boundary conditions are used to simulate rivers and springs.

1. Treatment of Constant or Prescribed Water Level Cells

The situation of a constant or prescribed water level cell is identified by a non-zero value of ghb0 (general head boundary) attribute associated with a cell object. The value of ghb0 indicates the constant water level value that is maintained through the process of simulation. Constant head cell objects can be used to simulate rivers and springs. For a time-varying general head boundary condition, the value of ghb0 gives the water level at the initial time step and the time-series table (gbhtb.dbf) holds the prescribed water levels at the general head boundary (GHB) cells for each of the following time steps.

2. Treatment of Springs

Spring flow is identified and simulated in the model by two attributes of a cell object, SprK and SprEle. SprEle gives the elevation of the spring orifice, and SprK gives the relation between the spring flow rate and the cell water level. SPRK=0 indicates that no spring exist in the cell object. The spring flow can be computed using Equation 4.6 which is formulated in a way similar to the method used by ModFlow, (McDonald and Harbaugh, 1988).

$$Spr_i^t = SprK_i \cdot (h_i^t - SprEle_i) \tag{4.6}$$

where,

Spr_i^t = spring flow rate on cell object i at time step t (m^3/s),

$SprK_i$ = a coefficient linking the spring flow rate to the water level of the cell, $SprK_i$ can be used as a calibration factor. To ensure dimensional consistency, $SprK_i$ needs to have a dimension of $[L^2/T]$, (m^2/s).

h_i^t = water level on the cell object i at time step t (m),

$SprEle_i$ = spring elevation level (m).

3. Treatment of Rivers

Rivers and surface drains can be treated using a method similar to that used to treat springs. The equation used to simulate flow exchange between a river section and an aquifer can be written as:

$$Riv_i^t = RivK_i \cdot (h_i^t - RivEle_i) \qquad (4.7)$$

where,

Riv_i^t = flow contribution of the aquifer cell to river section i (m^3/s),

$RivK^i$ = a coefficient linking the aquifer flow contribution to the head difference between the water level in the river and water level in the cell $[L^2/T]$, (m^2/s).

h_i^t = water level on cell object i at time step t (m),

$RivEle_i$ = average bed elevation of river section i (m).

In Equations 4.5 and 4.6, the parameters RivEle, SprEle, etc. are related to surface topology and can be computed using some spatial analysis procedures in GIS. Other parameters, such as RivK, SprK, etc., need to be provided by the user or be calibrated using an optimizing procedure similar to those developed in Section 3.6.

4.5. THE MAP-BASED POST-PROCESSORS AND UTILITIES

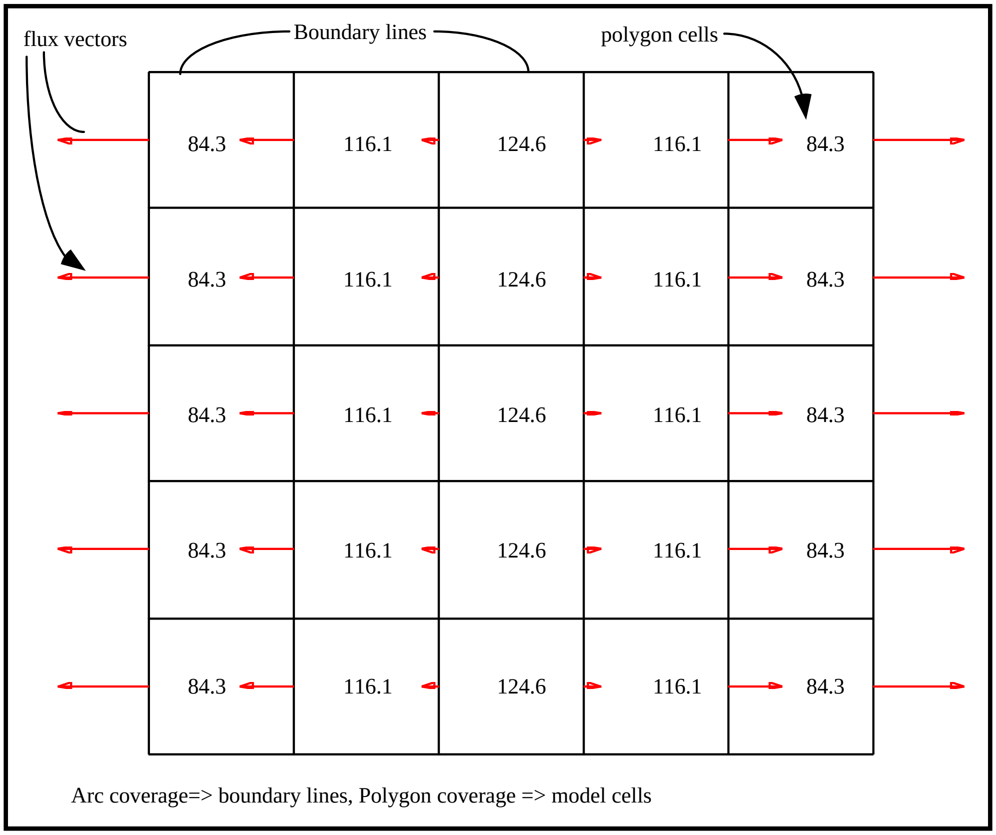
Using the program's capability of having access to both model maps and database tables, utility modules are developed so that the model related tasks such as modifying model conditions and displaying and analyzing model results can be performed directly from the model maps.

4.5.1. Plotting the Water Levels and Flow Distributions

This module is designed to plot water levels of groundwater cells and water flux on the boundary lines at a user specified time step. The module is activated by the event of either clicking on the model base map, or making the selection from the map menu. Once activated, the module can provide instructions to guide the user through the plotting process. Figure 4.5 shows an example of the plotting result. In combination with the groundwater simulation module, this water level and flow distribution plotting program is also used to plot the water level and flow distributions for each time step on the model base maps during the simulation process so that the model progress can be monitored on the model base maps.

4.5.2. Plotting Time Series Data at a Specified Location

To understand the behavior of an aquifer and its simulation model, it is sometimes necessary to plot and analyze the time-series data such as the time variation of water level, storage, inflow and outflow at a given location. The module of plotting spatially-referenced time-series data is designed for this purpose. When the module is activated from the map, the location related information (e.g., p(x,y)) is passed to the plotting program and based on that information, the program first identifies the map feature that covers the user selected point. The identification number of the selected map feature is then used to identify the time-series vector stored in the time-series data tables. The time-series data of a location that can be plotted for data display and analysis include: water head level, water level changes, pumpage, recharge, and spring flows.



84.3	116.1	124.6	116.1	84.3
84.3	116.1	124.6	116.1	84.3
84.3	116.1	124.6	116.1	84.3
84.3	116.1	124.6	116.1	84.3
84.3	116.1	124.6	116.1	84.3

Figure 4.5. The water level and flow distribution plot

4.5.3. Modification of Model Conditions

Because the maps and databases are integrated, the model conditions of a map-based model can be easily modified. This section describes how some of the most commonly adjusted conditions can be changed.

1. Modification of Boundary Conditions

The boundary conditions of the model are controlled by the line object states Isbnd, bndtp, and Bhead, where the state isbnd indicates (1) the object is not an boundary (isbnd=0), (2) the object is a boundary line with the external region on its left-hand-side (isbnd=1), or (3) the object is a boundary line with the external region on its right-hand-side (isbnd=-1). When $isbnd \neq 0$, the state bndtp is used to indicate the type of the boundary conditions, with bndtp=0 indicating a no-flow boundary condition and bndtp=1 indicating a constant head boundary condition (flow condition). The state Bhead is used only when $isbnd \neq 0$ and bndtp=1. Under these conditions, the value of Bhead indicates the water level at the boundary line. When simulating unsteady state groundwater flow, the value Bhead can be allowed to vary from one time step to another with the creation of a time-series database table. Because the model boundary conditions are controlled by these three states of the line objects and the states of an object can be retrieved and modified directly from a model map, the boundary conditions can be modified directly from the model maps. The methods used to connect the maps and the databases are logically similar to those used in the post-processors described in Chapter Three and Sections 4.5.1 and 4.5.2 of this chapter.

2. Modification of Pumping Situations

The model's pumping condition is jointly prescribed by state pmp0 of a polygon object and a time-series table (pmptb.dbf) associated with the polygon objects. When modeling under steady state, the value of pmp0 indicates the pumping rate for an object (with pmp0=0 indicating no-pumping). Under unsteady state, the value of pmp0 gives the pumping rate at the initial stage. Whenever pmp0 (for steady state) and pumping time-series (unsteady state) associated with an object are changed, the model's pumping condition is modified. As the state and time-series table containing the pumping information are connected to the polygon map, the method used to pass information between maps and time-series tables described above in Section 4.5.2 is used for data modification.

3. Modification of Recharge Conditions

The model's recharging situation is jointly described by state rch0 of a polygon object and a time-series table (rchtb.dbf) associated with the polygon objects. The recharge conditions of a map-based model can be modified in the same way the pumping conditions are modified.

4. Other Modeling Conditions

Other model conditions such as drainage and general head boundary conditions can be treated and modified in the same way as the model's pumping and recharging conditions are treated.

4.6. MODEL VERIFICATION

To verify the concept and ensure the program's correctness, the map-based model is applied to solve the problem of groundwater flow in a phreatic aquifer with accretion (dual-river-problem) (Bear, 1979) to see if model results match a theoretical solution. The problem assumes two parallel rivers of 50 km apart and cut into a phreatic aquifer. These two rivers can act as line sources/sinks of the aquifer. The river levels and aquifer water level are initially at elevation of 50 m. The aquifer has impermeable boundaries on north and south sides. An impermeable bed is present at elevation 0 m. A uniformly distributed recharge of 1mm/day is applied on the surface. Other parameters of the example problem are listed in Figure 4.6.

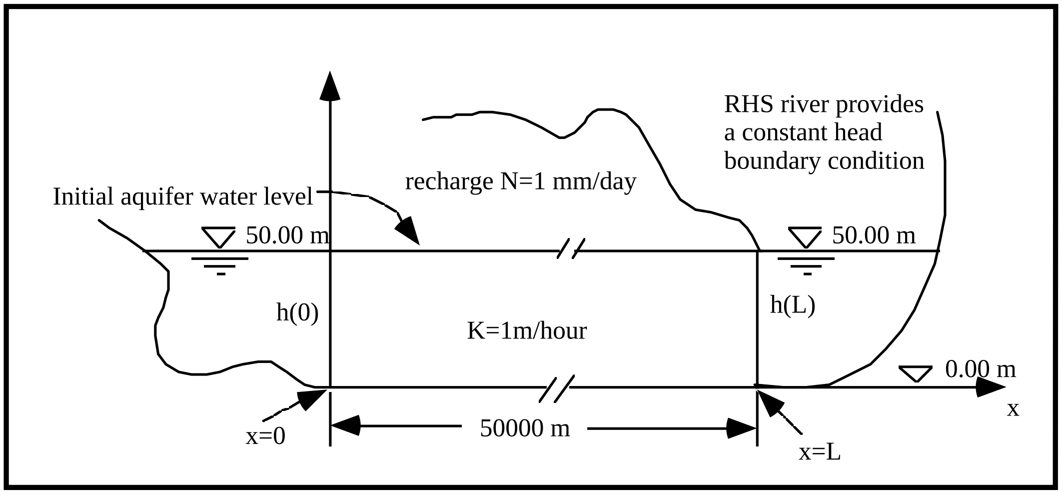


Figure 4.6. A cross-section of the example problem

The continuity equation of the groundwater flow under these conditions can be written as (Bear, 1979):

$$K\frac{d}{dx}\left(h\frac{dh}{dx}\right) + N = 0 \tag{4.8}$$

where,

K = hydraulic conductivity of the aquifer [L/T],

h = *h(x)* = water level of the aquifer at x meters from the left-hand-side river,

N = recharge rate [LT^{-1}].

When deriving Equation 4.8, it is assumed that (1) at the boundaries where river intersect the aquifer (x=0 and x=L) the aquifer has vertical equipotentials (h=h(0) and h=h(L)) and (2) every where the flow is essentially horizontal.

By integrating Equation (4.8) and considering the boundary conditions: x=0, $h = h(x_0)$ and x=L, $h = h(x_l)$, the shape of the water table h=h(x) can be obtained (Equation 4.9):

$$\begin{aligned} &K\left([h(x)]^2 - [h(x_0)]^2\right) - Nx(L-x) \\ &-K\frac{x}{L}\left([h(x_1)]^2 - [h(x_0)]^2\right) = 0 \end{aligned} \tag{4.9}$$

where, $h(x_0)$ = Water level at x=0,

$h(x_l)$ = Water level at x=L, (L=50000 meters),

N = recharge rate [L/T].

A map-based model with 5x5=25 cells is constructed to simulate the problem (Figure 4.5) and run under the transient-state with the time-step Δt=1day to approach the theoretical solution asymptotically. Table 4.4 shows the water levels produced by the map-based simulated model and theoretical solution (Equation 4.9). The discrepancy (error% in Table 4.4) of the water levels produced by the theoretical solution and the simulation model is measured by:

$$\Delta\% = \frac{|dh_t - dh_s|}{|dh_t|} \tag{4.10}$$

where,

$\Delta\%$ = relative error between the theoretical and simulated solutions,

$dh_t = h_t - h_b$ = difference between the water level at a point x and the water level at the boundary produced by the theoretical solution,

$dh_s = h_s - h_b$ = difference between the water level at a point x and the water level at the boundary produced by the simulation model.

As shown in Table 4.4 that the maximum relative error produced by the simulation model is 3.7%. Therefore, it can be concluded that when properly constructed, the map-based groundwater flow simulation model (GFlowSim) can produce simulation results with reasonable accuracy (e.g., less than 5%). Figure 4.7 shows the phreatic surface profile produced by the model results and theoretical solution. Figures 4.8 and 4.9 display the temporal variation of water levels and net in-flow through cell boundaries. As can be seen from Figure 4.9, when the steady state is reached, the total outflow through a cell's boundaries at a given time step equals the total recharges that enters the cell in the same time step.

Table 4.4. The Water Levels in the Aquifer (Simulated vs. Theoretical)

Distance	Solution	Simulated	Solution (dh)	Simulated (dh)	Error%
(1)	(2)	(3)	(4)=(2)-50.00	(5)=(3)-50.00	(6)=(|(5)-(4)|/(4))*100
0	50.00	50.00	0.00	0.00	0.000
5000	84.70	83.41	34.70	33.41	3.717
15000	115.90	116.50	65.90	66.50	0.910
25000	124.58	124.41	74.58	74.41	0.227
35000	115.90	116.50	65.90	66.50	0.910
45000	84.70	83.41	34.70	33.41	3.717
50000	50.00	50.00	0.00	0.00	0.000

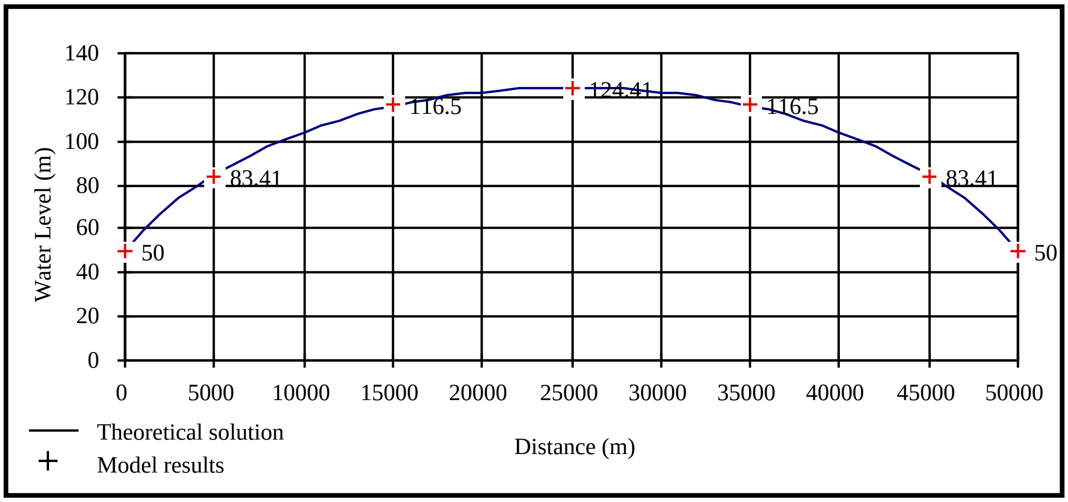


Figure 4.7. The phreatic surface, theoretical vs. simulated, of the dual-river problem

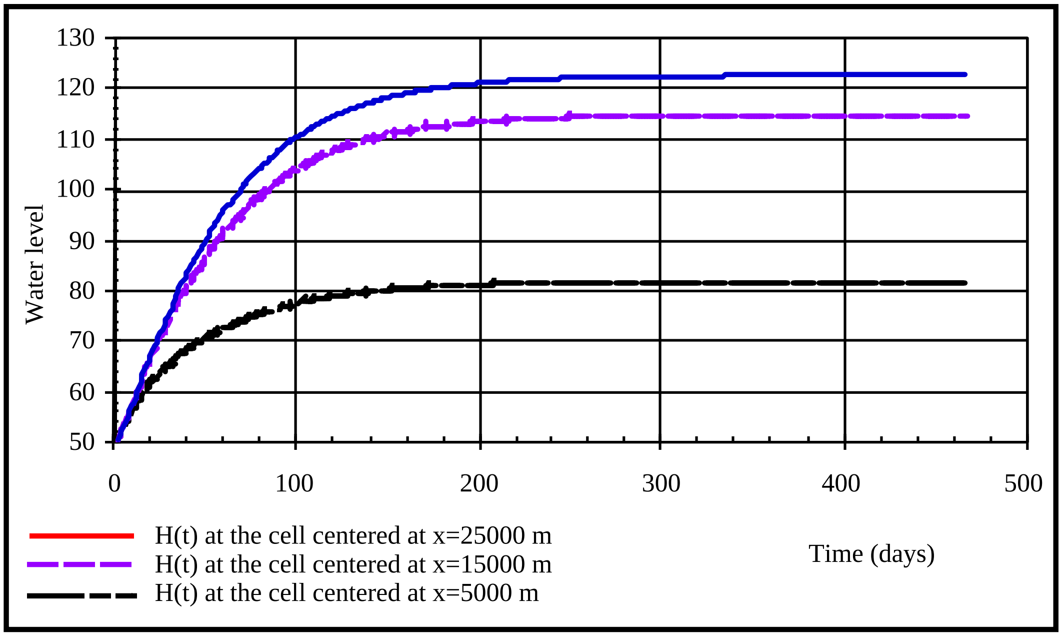


Figure 4.8. The water levels vs. time

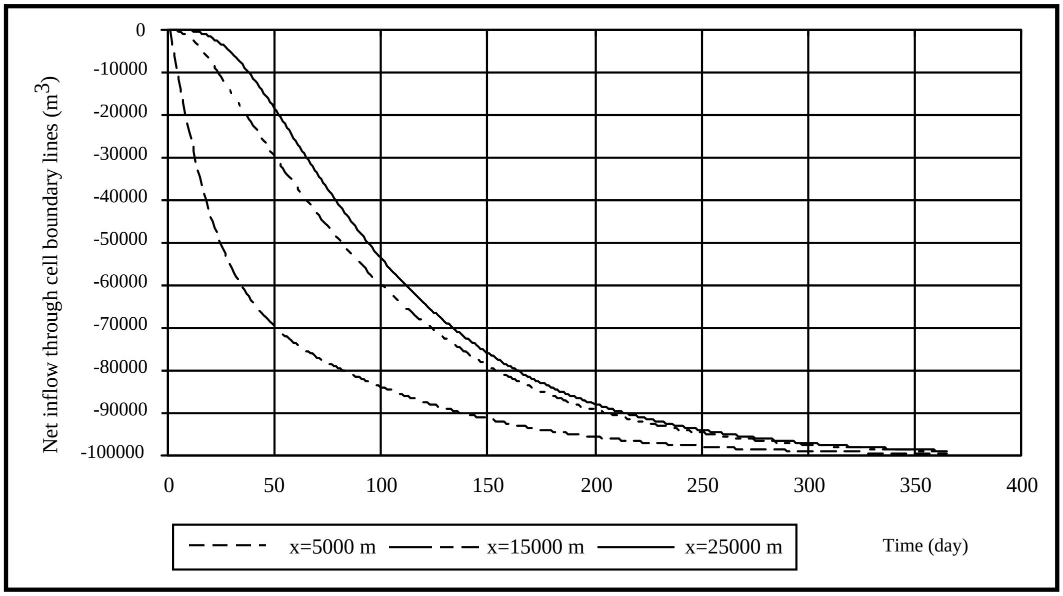


Figure 4.9. The net in-flow through the boundaries of a cell

4.7. CHAPTER SUMMARY

The map-based groundwater simulation model is constructed using the relations between the cells (polygons) and their boundaries (arcs) kept in ARC/INFO polygon and arc coverages. To work within the spatial databases of polygon and line coverages, for each time step (each iteration in case of steady state), the model first applies the Darcy's law to each boundary line object to calculate the volume of water flow crossing the line. Using the volumes of the water flow defined on the boundary line objects, together with recharge, pumping, and spring flow time-series defined on the polygons, the continuity equation is then applied to the polygons to calculate the water levels at the end of the time step. The new water levels are then used to start the simulation for the next time step. This procedure is repeated until the final time step is reached.

In general, the following can be said about the model:

(1) A map-based groundwater simulation model can be constructed on any ARC/INFO polygon coverages using a set of pre-processing programs.

(2) The modeling process can be activated and its progress monitored on the base maps so that run time errors can be detected as they occur.

(3) Model results can be displayed on the map for interpretation.

(4) Model conditions can be modified directly from the model maps.

(5) Because in the model, the continuity equation and momentum equations are applied separately, the model mesh can be of irregular shape. For this reason, subwatersheds used in the surface water flow simulation can be used by the groundwater model as its basic mesh.

(6) Because the way time-series data sets are created, the model is not very efficient when working with a large number (about 500) of polygons.