Chapter Five. Integrating Surface and Subsurface Flow Simulation Models

5.1. INTRODUCTION

It is clear that the simulation of surface water flow of an area is not completed until the effects of the aquifers underneath the area are taken into consideration and the same can be said for the simulation of groundwater flow. The interactions between surface and subsurface water flow appear in the forms of spring flow, seepage flow, and groundwater recharge. This section describes how these interactions can be simulated using the map-based models developed in Chapter Three and Chapter Four.

In the map-based surface water flow simulation model, the two types of objects used are the subwatershed object (polygon) and river object (arc). In the groundwater flow simulation model, two basic objects are the cell object (polygon) and the cell boundary line object (arc). Physically, the interaction between surface water flow and subsurface water flow occurs on these line and polygon objects. Therefore, if additional attributes (states) describing the existence (and the types) of subsurface modeling objects can be added to the these existing objects, the interaction between surface and subsurface water flows can be simulated. The following section describes how the existing surface and subsurface objects are modified so that they can be used to simulate the interactions between surface and subsurface water flows.

5.2. CONSTRUCTION OF SURFACE AND SUBSURFACE SIMULATION OBJECTS

To design an integrated surface and subsurface water flow simulation model, the spatial relationships between surface and subsurface simulation model objects need to be defined. The relationships between surface subwatershed and subsurface cell objects can be (1) one-to-one, (2) one-to-many, (3) many-to-one, and (4) many-to-many. Naturally, relationships between surface and subsurface objects tend to be one-to-many or many-to-many because surface and subsurface objects are defined using different criteria. To simulate the interaction when surface and subsurface objects have relations (2), (3), or (4), the simulation program needs to add internal loops to distribute water among related objects.

To illustrate, let us assume that the integrated model is constructed with one surface subwatershed object to many groundwater cell objects. In this case, the spatial relationships must first be established, e.g. through the IDs of surface and subsurface objects. After the recharge contribution of a surface subwatershed is estimated, an internal loop is needed to distribute the recharge water to all the groundwater cells related to the subwatershed. For the same reason, after simulating the groundwater flow, another internal loop is again needed to distribute aquifer discharge to their related surface objects. Although programming techniques exist to speed up the internal loop computations, the speed is usually accomplished at the expense of computer memory because additional memory variables are usually needed. Therefore, an integrated model created with surface and subsurface model having one-to-many relationships requires either more computation time or needs more memory allocation, and either way, the model program becomes larger and more complicated.

To avoid this complication, the integrated surface and subsurface water flow simulation model is designed in such a way that a one-to-one relation is maintained among all the simulation model objects of different classes. The task of maintaining one-to-one relationship between the objects from different classes is accomplished in this research by adopting the subwatershed objects used in surface water flow simulation model as the cells for the groundwater simulation model.

By keeping the one-to-one relationship between surface and subsurface objects, the integrated surface and subsurface simulation model has three essential classes of objects, which include (1) a polygon class used as both subwatershed objects for the surface and cell objects for the subsurface water flow simulations; (2) a river line class for surface flow simulation, and (3) a cell boundary line class used for the subsurface water flow simulation model. The states (attributes) of these three objects are listed in Tables 5.1, 5.2 and 5.3.

By comparing Table 5.1 with Tables 3.1 and 4.1, it can be seen that Table 5.1 is the combination of Tables 3.1 and 4.1 because in this integrated surface and subsurface water flow simulation model, subwatershed polygons are used in both models. Since the river line objects are not essential objects in the groundwater simulation model, the river line objects remain unchanged. Because the cell boundary line objects used in the subsurface water flow simulation model are not used in the surface water flow simulation mode, they also remain unchanged.

Because the fundamental structures of the objects used in map-based surface and subsurface water flow simulation model remain unchanged in the integrated model, the same programs used in the surface and subsurface models can be used in the integrated model with some small modifications. Due to this reason, the goal of integrating the surface and subsurface flow simulation models can be accomplished by constructing a control program that activates the map-based surface and subsurface water simulation models constructed in Chapter Three and Chapter Four in a proper sequence.

Keeping the states of essential objects unchanged simplifies the data exchange procedure between the surface and subsurface objects. Because water exchange between the surface and subsurface model occurs through surface subwatershed, river line and subsurface cell objects. If these objects have one-to-one relationship to one another, the results of one object can be directly mapped into another, which greatly reduces the size of the model program and the model's computer memory requirement.

It should be understood, however, that although keeping the one-to-one relations between the surface and subsurface objects is a way to make program and data exchange scheme simple and efficient, it is not an essential requirement in the design of the integrated model. The same methodology will still work when the one-to-one relationship does not exist because program procedures can be added to establish the spatial relationships and data exchange between the surface and subsurface objects.

Table 5.1. The Attributes of a Subwatershed/Cell Polygon Object

	StateName	**Function** (What the attribute represents)
1	Shape	Pointer pointing to the map location of the object
2	Area	Area of watershed polygon (m^2)
3	Perimeter	Perimeter of watershed polygon (m)
4	Cover_	Polygon ID, based on which pointers to the time-series vectors (PFlowVt,sprVt, rchVt, headVt, dhVt, dvolVt, etc.) associated with the polygon are constructed.
5	Cover_id	User assigned polygon ID
6	Grid_Code	Key code linking subwatershed polygon with the river line object it contains
7	Pisdone	0 indicates the polygon has NOT been simulated, 1, otherwise, and the value indicates the number of river sections between this polygon and the basin outlet
8	PFlow	Local flow contribution (m^3/s)
9	FlowTime	Average time it takes for water to flow from an grid-cell element on the subwatershed to the outlet point (s)
10	DiffNum	Diffusion number of PFlow measuring the extent of PFlow spread out
11	VFact	Overland flow velocity (m/s)
12	ThmRslt	Created for thematic plotting of a selected attribute at a given time step
13	Hasgrd	1 indicates there is a groundwater object underneath, 0, otherwise
14	ToGrd	The percentage of PFLOW that recharges to the groundwater system, (m^3/s)
15	MFL	Mean flow length of a subwatershed (m)
16	Msurp	Soil moisture surplus of the subwatershed (mm/s)
17	ToRes	The fraction of the subwatershed water surplus that goes to subsurface reservoir
18	ResK	Mean residence time of water in a subsurface reservoir [T]
19	KV	Hydraulic conductivity (m/s)
20	Head0	Initial piezometric head in the polygon cell
21	Rch0	Initial recharge to the polygon cell (mm/s)
22	Spr0	Initial spring flow of the polygon cell (m^3/s)
23	Pmp0	Initial pumpage from the polygon cell (m^3/s)
24	ghb0	0 indicates the cell is not a constant head cell, non-zero, otherwise. The non-zero value equals the constant water level of the cell (m)
25	evt0	Initial evaporation in the polygon cell (mm/s)
26	Btm	Bottom elevation of the polygon cell (m)
27	Top	Top elevation of the polygon cell (m)
28	Cnfd	0 indicates that the polygon is not confined, 1, otherwise
29	SV1000	Storativity
30	headn	Water level of a polygon cell at step N, (final time step of the simulation) (m)
31	dvol	Mass inflow of a polygon at step N (final time step of the simulation) (m^3/s)
32	sprele	Spring elevation (m)
33	sprK	Coefficient connecting the spring flow rate to the water level of the cell (m^2/s)

Table 5.2. The Attributes of a River Line Object

	StateName	Function (What the attribute represents)
1	Shape	Pointer pointing to the map location of the object
2	Fnode_	Node ID number of the starting point of a river line section
3	Tnode_	Node ID number of the ending point of a river line section
4	Lpoly_	Left polygon machine-assigned-ID (ID of the polygon to the left of the line)
5	Rpoly_	Right polygon machine-assigned-ID (ID of the polygon to the right of the line)
6	Length	The length of the river line section (m)
7	Cover_	Machine assigned river line id
8	Cover_id	User assigned river line id
9	Grid_code	Key code linking subwatershed polygon with the river line section it contains
10	LIsDone	Flag 0=the river line has NOT been simulated, otherwise, simulated, and the value indicates the number of reaches between this river line and basin outlet
11	IsHead	IsHead=1, indicates a head section (the section with no upstream river lines)
12	IsOutlet	IsOutlet=1, indicates a outlet section (the last river line on a river network)
13	FFLOW	The flow rate at FNode of a river line (m^3/s)
14	TFLOW	The flow rate at TNode of a river line (m^3/s)
15	Dflow	The water withdrawal on the river line (diversion flow rate) (m^3/s)
16	Velocity	Flow velocity on a river line (m/s)
17	LossC	Loss coefficient related to a river line (1/m)
18	Timelag	Flow time between the Tnode of a river line and its longest upstream flow path [T]
19	MELE	Mean elevation of a river line (m)
20	HasDam	0 indicates no dam, non-zero indicates there is dam(s) and the non-zero value is the dam-id of the first dam on the river line
21	Hasresp	0 indicates no response function, non-zero, otherwise, and the non-zero value equals the number of elements in the response function
22	Hasgrd	0 indicates no groundwater flow model exists, 1, otherwise
23	togrd	The percentage of river flow that goes to groundwater recharge

Table 5.3. The Attributes of a Cell Boundary Line Object

	StateName	Functions&Values
1	Fnode_	From-node of a line
2	Tnode_	To-node of a line
3	Lpoly_	Machine-assigned ID of the polygon to the left of the line
4	Rpoly_	Machine-assigned ID of the polygon to the right of the line
5	Length	Length of the line
6	Cover_	Machine-assigned ID of the line
7	Cover_id	User-assigned ID of the line
8	ldx	dx of a line, dx=xn-x0. dx is the x component of a boundary-line-vector
9	ldy	dy of a line, dy=yn-y0. dy is the y component of a boundary-line-vector
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 the line
13	CCY	y coordinate of the center point of the line
14	Slength	Distance between the center points of the two polygons sharing the line
15	isbnd	0=the line is not an external boundary, 1=a boundary line with internal polygon to the right of the line, -1=a boundary line with internal polygon to its left
16	bndtp	0 indicates a non-flow boundary and 1 indicates a constant head boundary
17	Bhead	The value gives the value of constant piezometric head if bndtp=1
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)

Now that the objects are constructed, the following section explains how an integrated surface and subsurface simulation model can be constructed from these objects under a GIS environment.

5.3. CONNECTIONS BETWEEN SURFACE AND GROUNDWATER MODELS

To integrate surface and groundwater simulation models, it is necessary for the objects in the surface and groundwater simulation models to connect to each other so that the outputs of one model can be used as inputs of the other. In this simulation model, the linkage between the surface and subsurface simulation modules is established through two state variables and a group of spatially-referenced time-series tables. One state variable is created to store the information regarding the spatial relationships of the objects and is used to keep the connectivity between surface and subsurface modeling objects. The connectivity is usually established through the unique object identification number such as Cover_ (machine-assigned-ID), or Grid_Code. The Grid_Code of an object is assigned by the watershed delineation procedure discussed in Chapter Three. Figure 5.1 shows the IDs used to connect the simulation model objects. The other state variable is used to identify the data type as well as the quantity of exchange. In this integrated model, spatially-referenced time-series tables connected to model maps are constructed based on the concepts developed in Chapter Three and are accessible by the model programs.

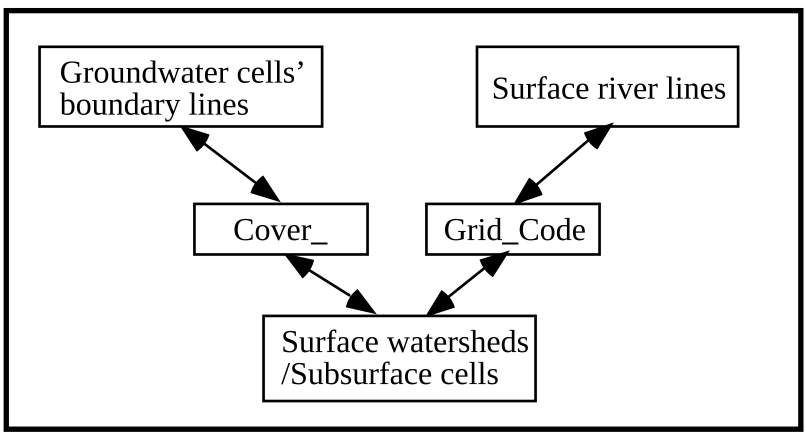

Figure 5.1. Connections between surface and subsurface objects

In this integrated map-based flow simulation model, the connection between a river line object and a subwatershed polygon object is established through Grid_Code assigned to these objects by the watershed delineation procedure. The connection between a subwatershed polygon and a groundwater model cell polygon is established through the state Cover_ or Cover-id, and the connection between a river line object and a groundwater cell polygon is established through Grid_Code (river) to Grid_Code (Subwatershed) to Cover_ (Groundwater Cell) (Figure 5.1).

For a river line object in the surface simulation model, two states, HasGrd and ToGrd, and two spatially-referenced time-series tables SprVt.dbf, RchVt.dbf, are used to store the volumes of water exchange between the objects in surface and groundwater models for each simulation time step. The values of HasGrd and ToGrd indicate if a groundwater unit exists underneath and if so, the recharge rate. SprVt.dbf and RchVt.dbf are accessible by both groundwater and surface water flow simulation models. The table, SprVt.dbf is used to store the spring flow time-series and RchVt.dbf is used to hold the recharge time-series. In general, the spring flow outputs of the groundwater simulation model are held in SprVt.dbf to be used as inputs to the surface water flow model. The recharge outputs of the surface water flow simulation model are held in RchVt.dbf to be used as inputs to the groundwater model.

Because in the integrated surface and groundwater model, subwatersheds used in surface water flow simulation and cells used in the groundwater model are merged, the information can be exchanged directly through the record number of the feature attribute table (FTAB). The states, HasGrd and ToGrd, and three spatially-referenced time-series tables, SprVt.dbf, RchVt.dbf and PmpVt.dbf are used to control the water exchange between the objects in surface and subsurface water flows.

5.4. SIMULATING THROUGH THE SPACE AND TIME

Before a simulation model for a hydrologic process that occurs in the domains of both space and time can be constructed, one has to decide the simulation sequence over space and time (Figure 5.1). To complete the simulation process, the model needs to loop through each spatial feature at each time step. Depending on the nature of the process, a program can be designed in such a way that the simulation model visits all spatial feature objects for a given time step before it moves on to next time step (TIME-FIRST-THEN-SPACE), or once the simulation model has visited one spatial feature, it simulates the process on that feature for all the time steps before it moves on to next feature object on the spatial domain (SPACE-FIRST-THEN-TIME).

For the map-based surface water flow simulation model, SPACE-FIRST-THEN-TIME simulating sequence is used because (1) the flow process through all steps in an object can be simulated using the information associated with that object alone, and (2) the effects of an object on the river network can be replaced by a set of flow time-series data. For the subsurface water flow simulation model, however, TIME-FIRST-THEN-SPACE scheme is used because, a simulated variable, e.g. water level, of all spatial feature objects at a given time step must be calculated simultaneously before the simulation model can move on to the next time step.

Because the surface and subsurface models designed in this study use different simulation sequences over the space features and over time domain, the integration of surface model and subsurface model is achieved via the data exchanges through the time-series tables. The scheme proposed to integrate surface and subsurface simulation models is discussed in Section 5.5.

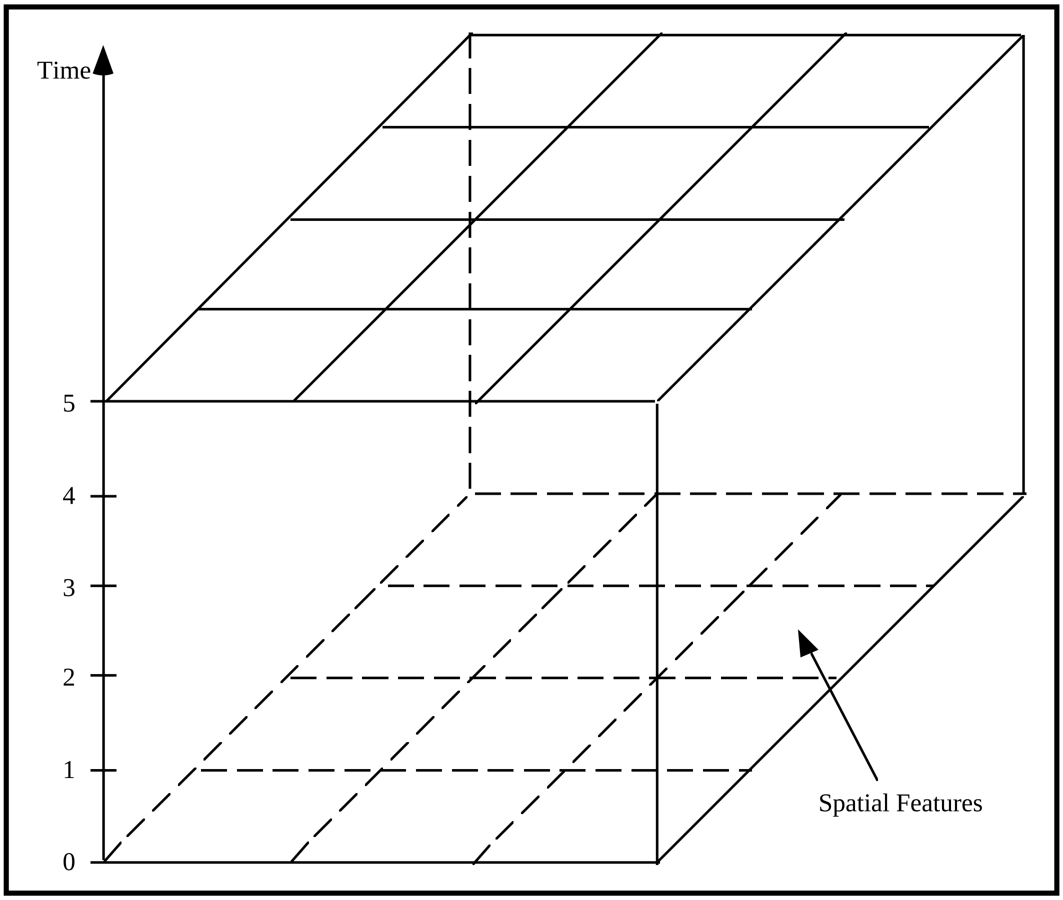

Figure 5.2. The spatial and time domains of a simulation model

5.5. Integration of Surface & Subsurface Water Flow Simulation Models

As discussed in Section 5.4, the integration of the surface and groundwater simulation model is to be accomplished through the spring flow and recharge time-series tables created to hold the volumes of water exchanges between these two models. During a simulation, the spring flow time-series produced by the groundwater model is used as input by the surface flow simulation model and the recharge time-series produced by the surface flow simulation model is used as input by the groundwater simulation model. Because the same simulation sequences used in map-based surface water flow simulation model and subsurface water flow simulation are used in the integrated model, the integration scheme proposed above can be accomplished by using a short main program to call alternately the map-based surface and subsurface simulation models.

To illustrate the general simulating procedure for an integrated model, let us assume that the model starts with surface water flow module. It is clear that spring flow time-series is needed to simulate the surface water flow. Because spring flow comes from the groundwater simulation model that has not yet run, an initial estimates of spring flow are needed. Once the spring flow time-series are estimated, the surface water flow simulation can proceed. As a result of surface water flow simulation, recharge flow time-series are produced. The recharge flow time-series are then used as inputs by the groundwater flow simulation model to complete the groundwater simulation. As a result of this groundwater simulation, a set of spring flow time-series are produced. The spring flow time-series are compared with the estimated spring flow time-series to check for discrepancies. If the discrepancies are small, the simulation results will be deemed as converged and the simulation procedure will be stopped. Otherwise, the newly simulated spring flow time-series will be used for the surface water flow simulation model for the next iteration. The procedure is repeated until the spring flow time-series converges or the maximum number of iterations specified by a user is reached. The procedure described above is illustrated in Figure 5.3.

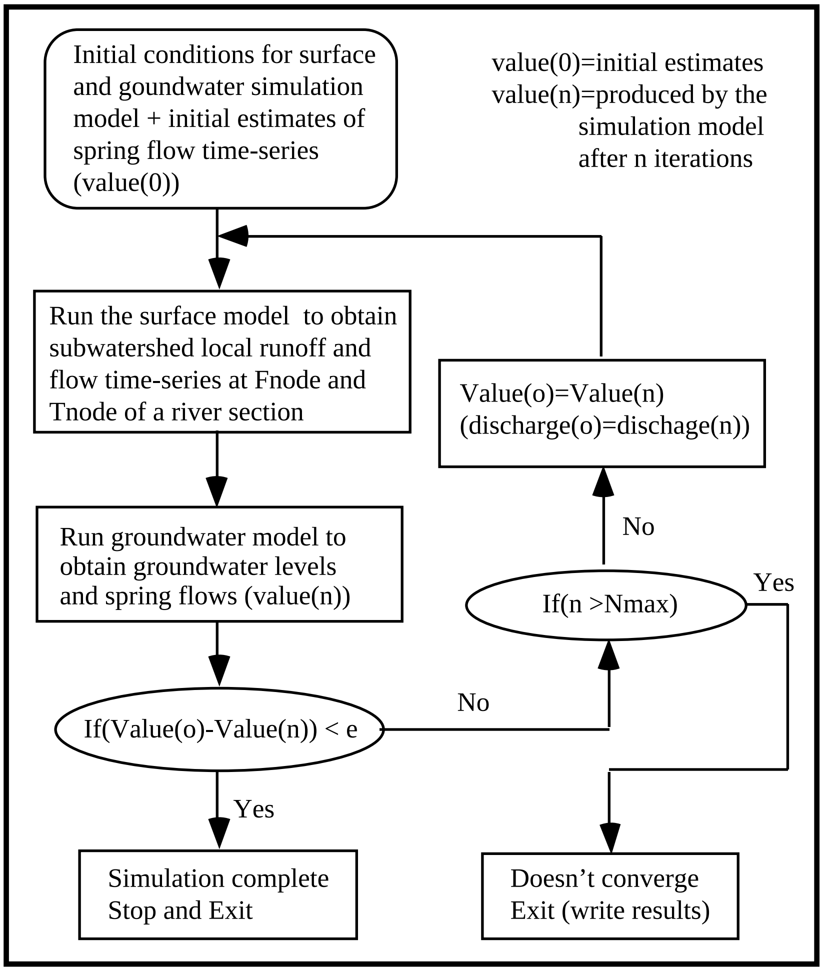

Figure 5.3. Simulating procedure of an integrated model

5.6. An Application Example of the Integrated Model

Using the procedure described above, the integrated model is applied to the Iullemeden region of the Niger River Basin to simulate the surface and subsurface water flow interaction. The groundwater simulation module of the integrated model is constructed from the map-based surface simulation model using the subwatershed polygons of the surface water flow model as its model cells. The study region and the physical parameters of the map-based Iullemeden model (Map-Based model) are extracted from a Modflow groundwater model (Modflow model) constructed for the same region by the Food and Agriculture Organization (FAO), (Guerre, 1995). The study region of the Modflow model is discretized into a 60r x 42c cells with the origin at the upper-left corner of the region. The sizes of the cells from row 1 to 35 are dx*dy=20*20 (km) and those of the cells from row 36 to 60 are: dx*dy=20*10 (km). Based on the Modflow model conditions, a map-based Iullemeden groundwater model of 60 polygons is constructed. The procedure used to construct the map-based Iullemeden model is given below:

(1) Using the INTERSECT function of ARC/INFO, the polygon maps (NGBASIN) used in the surface water flow simulation model is intersected with the groundwater model mesh (IUPOLYPJ) to create intersected converge INTIUPLY. The purpose of this map operation is to create spatial relationships between the subwatershed polygons and Modflow model mesh (Figure 5.4).

(2) Selecting all the subwatersheds that intersect with the mesh of Modflow model and assigning their HASGRD state value to one (HASGRD=1) indicating that there is a groundwater aquifer below. With HASGRD=1, when the surface water flow simulation model runs through these polygons, recharges will be evaluated (Figures 5.4 and 5.5).

(3) Running the program (GFlnsfld.pre) to select all boundary lines of the subwatersheds that will be used as groundwater cells, setting HASGRD state of these boundary lines to one (HASGRD=1), and defining the external boundary line of the groundwater model (Figures 5.4 and 5.5).

(4) Using the intersect coverage, the converting program (CONVERT.UTL) is applied to extract model parameters, initial and boundary conditions from the Modflow model and put into the Map based model. These parameters include: hydraulic conductivity, the aquifer's bottom and top elevations, initial water level, pumpage, evaporation, and a recharge time-series.

The Modflow model also produced a spring flow time-series at cell (48r,13c) (Figure 5.7). Cell (48r,13c) is contained in subwatershed GC116 in the map based model. The purpose of applying the Map based model is to see if the map-based model can reproduce the spring flow time-series at the designated location under a similar modeling conditions as those used by the Modflow model. The Modflow groundwater simulation model is used to evaluate the model result of this map-based flow simulation model because the Modflow model is most widely used and tested among all groundwater simulation models (Anderson and Woessner, 1992).

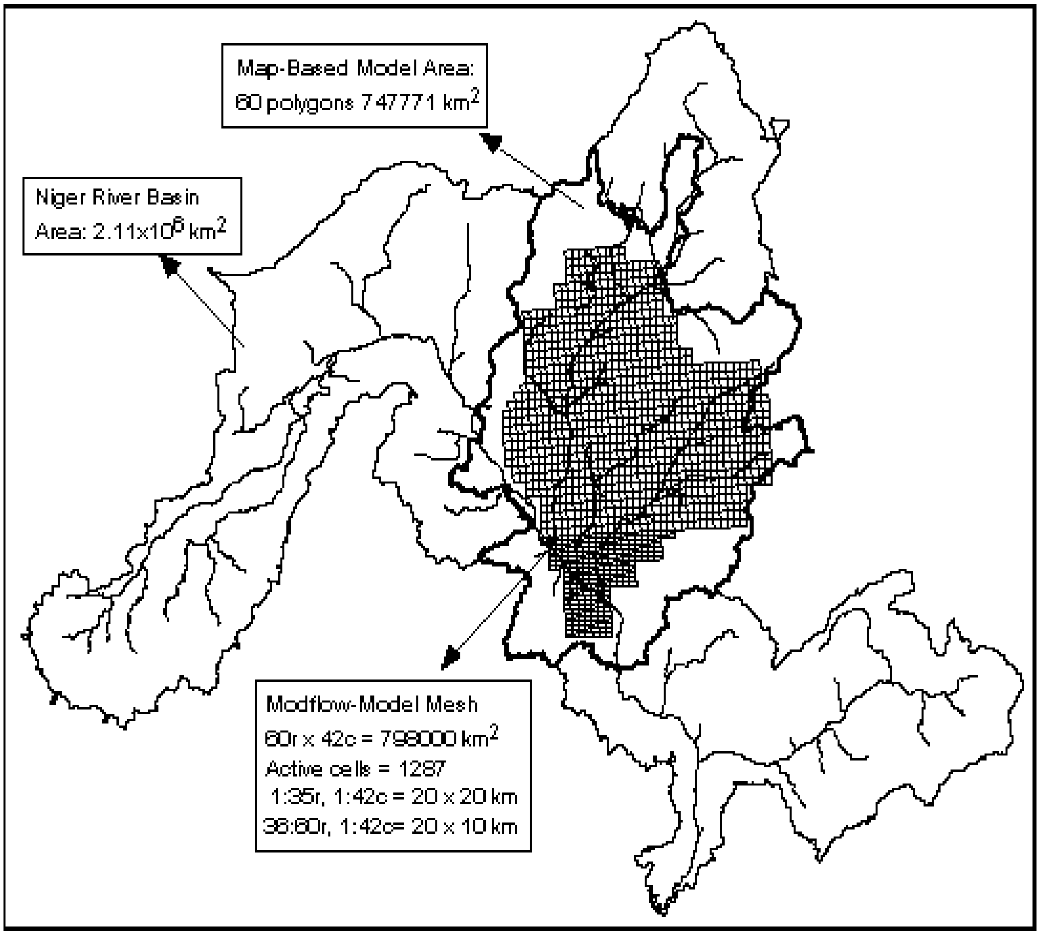

Figure 5.4. The study area of the map-based and Modflow Iullemeden groundwater models

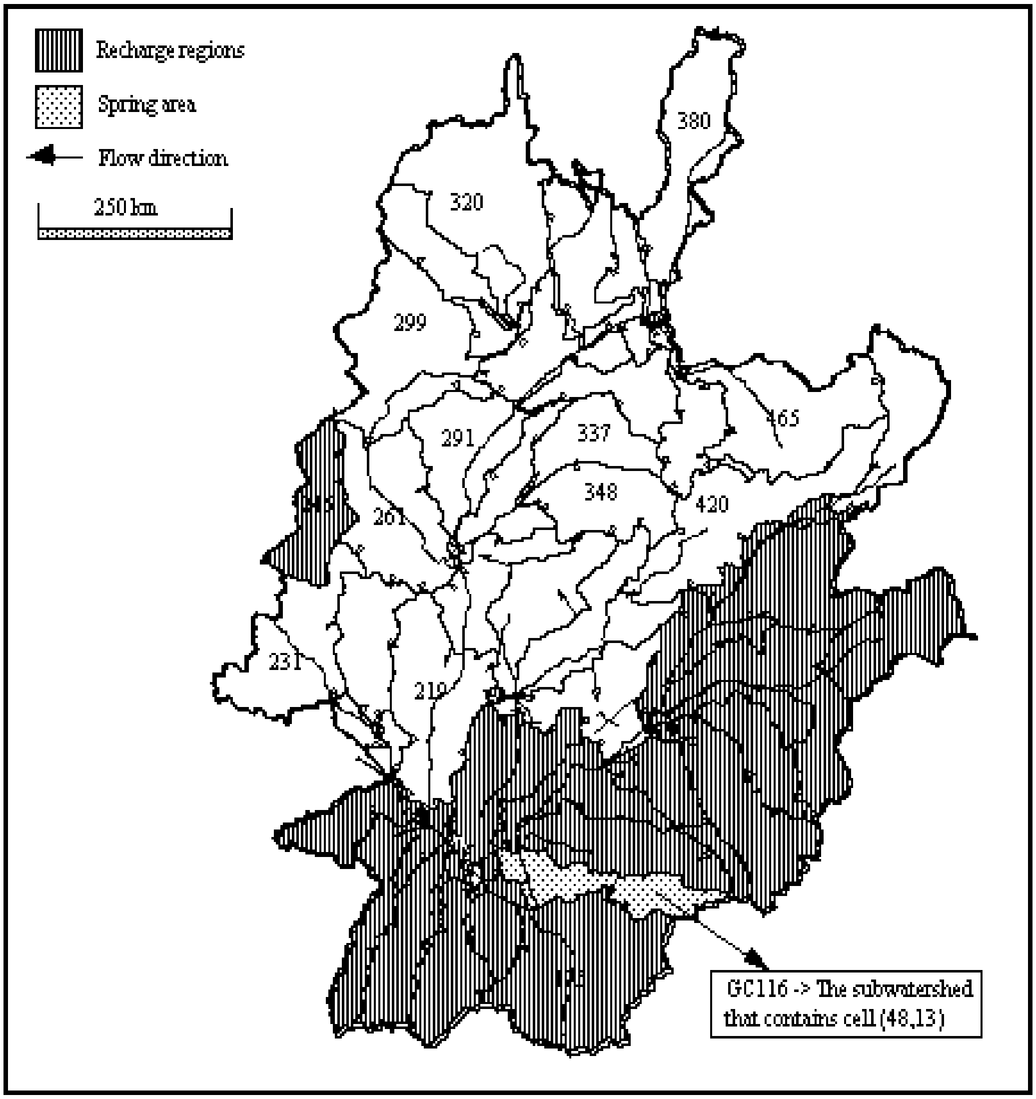

Figure 5.5. The polygons of the map-based groundwater simulation model

As discussed above in Table 5.1, the parameters that control the spring flow time-series of the map based model are SPRELE and SPRK. The parameter, SPRELE gives the elevation of a spring orifice and SPRK is a coefficient that relates the head difference between the aquifer water level and the elevation of the spring orifice to the spring flow rate. In the map based model, SPRK is also used as an logical variable to indicates if a subwatershed polygon has a spring (SPRK≠0) or not (SPRK=0).

Using the data sets extracted from the Modflow model and under the surface water flow simulating conditions (Chapter Three) for the 90 month period between July, 1983 and Dec, 1990, the map-based model are tested with different sets of SPRK. The spring flow time-series produced by (SPRK=7.46 m^2/s) is given in Figure 5.6. The monthly average spring flows produced by the map based model over the seven and half year period are listed in Table 5.4 and compared with those produced by the Modflow model. The last column in Table 5.4 is computed using a formula similar to Equation 4.10 to show the relative difference between the spring flow rate produced by the map based model and those produced by the Modflow model.

Table 5.4. The Monthly-Average Spring Flows at GC116 Produced by the Map Based Model and at Cell (48,13) by the Modflow Model

Month	Modflow (m3/s)	Map-Based (m3/s)	error%
(1)	(2)	(3)	|(2)-(3)|/(3)
January	1.000	0.971	2.900
February	2.200	2.158	1.909
March	6.100	6.025	1.230
April	8.600	8.507	1.081
May	9.700	9.604	0.990
June	10.800	10.701	0.917
July	9.500	9.414	0.905
August	3.100	3.047	1.710
September	1.900	1.851	2.579
October	1.300	1.252	3.692
November	2.600	2.547	2.038
December	1.400	1.348	3.714

The results listed in Table 5.4 show that the differences between the monthly average spring flows produced by the Map based model and those produced by the Modflow model are within 4%. The spring flows produced by the Map based model and Modflow model are plotted in Figure 5.7.

Although in running the map-based integrated model, the recharge data extracted from the Modflow model are used directly and not produced by the map-based surface water flow simulation model, the surface water flow simulation model has the ability to reproduce the same set of recharge data by adjusting the TOGRD attribute of each subwatershed polygon and river line object.

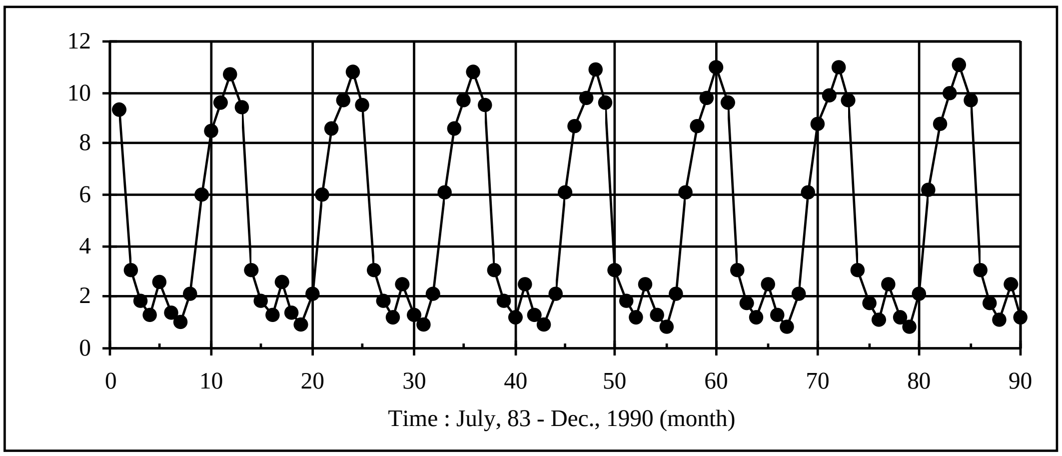

Figure 5.6. The spring flow time-series at GC116 produced by the Map based model

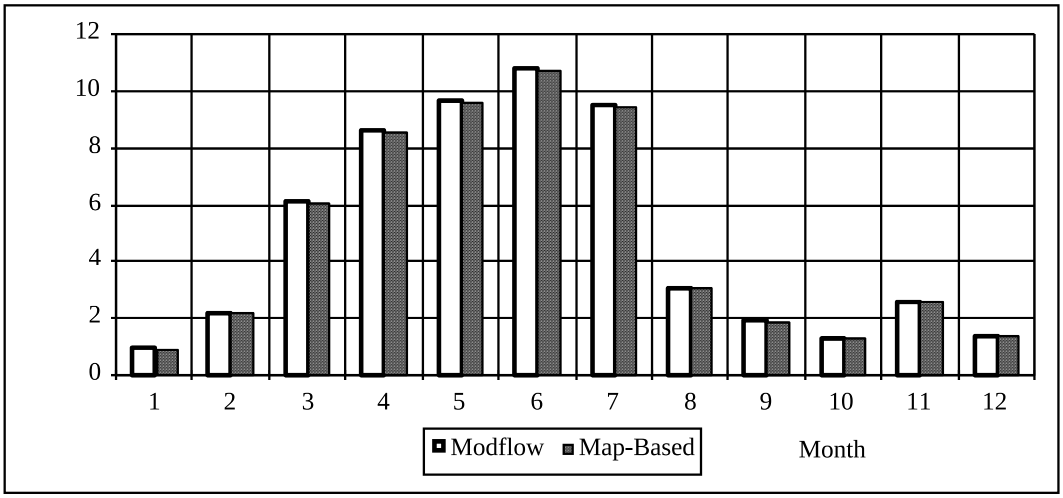

Figure 5.7. The monthly-average spring flows at GC116 produced by the Map based model and at cell (48,13) by the Modflow model

5.7. Model Integration - Confined vs. Phreatic Aquifers

In general, a phreatic aquifer close to the surface will work interactively with surface water. Therefore, in simulating the interaction between the surface water and a phreatic aquifer, the subwatersheds used as model units for surface water flow simulation should also be used as groundwater simulation units to simplify the water exchange procedure. On a phreatic aquifer, the locations and discharge rates of groundwater contribution to surface water flow can usually be jointly determined by the aquifer water levels and surface water levels. Because these values are simulation model results, they are unknown until the simulation model is run. In other words, the recharge/discharge locations and quantities are "computed" by the simulation.

For a deep aquifers, however, the surface and groundwater water exchange is usually determined by both geological formations and piezometric heads in the aquifer. Because the geological formation has to be given, the possible locations of recharge and discharge (spring flow) need to be given prior to the simulation. The simulation model is then used only to determine the quantities of the water exchange. Therefore, for a deep aquifer, it may not be appropriate to use subwatershed polygons as the groundwater model cells. Because surface water flow in most cases is of single direction, recharge to the groundwater can be determined by the surface water flow simulation, which makes it possible to run the groundwater model separately from the surface model and using the time-series data tables (SprVt.dbf and RchVt.dbf) pass the water exchange after each run. In this way, the surface and groundwater water models are coupled only through the data exchange and in most cases.

The program section that simulates the water exchanges between surface and subsurface water would remain largely unchanged for both phreatic aquifer and confined aquifers. The differences in simulating water exchanges lies mainly in data preparation. To simulate water exchange between a phreatic aquifer and surface water flow, one can simply provide the initial water levels of aquifer and let the simulation model determine the location and quantities of water exchange. To simulate water exchange with a confined aquifer, one needs to provide additional information regarding the locations and characteristics of the springs and recharge points before the simulation model can be constructed.

5.8. Chapter Summary

This chapter explores the possibilities of integrating the surface and subsurface water flow simulation models using the concept of object-oriented programming and GIS techniques. The results of this research can be summarized below:

1. In constructing the map-based flow simulation models in this research, the surface water flow is described by a river network analysis algorithm while the groundwater flow is described by a two dimensional potential flow equation. Because of this difference, the simulation programs for these two problems are self-contained and use different simulation procedures through space and time. Therefore, it is difficult and inefficient to integrate the two simulation models into a single program entity.
2. Because of these differences in surface and subsurface water flow simulation models, the integration of these two models needs to be accomplished through the modeling data sets. Two databases, recharge and spring flow time-series tables, that these two simulation models both share, can be used for data exchange purposes.
3. The connectivity of the surface and subsurface modeling objects can be established through some properly constructed states of these objects (Tables 5.2 and 5.3).
4. When the subwatersheds of surface water flow simulation model and cells of subsurface water flow simulation model do not have the same shapes and sizes, the spatial relationships between surface and subsurface modeling entities may be established through some GIS map operating procedures such as INTERSECT and UNION. Using these relationships, the results of one model can be converted and used as the inputs for another model..
5. When using the proposed method (i.e. model integration through data exchange) to integrate surface and subsurface simulation models, because surface water flow simulation needs aquifer discharge as its input and groundwater flow simulation requires recharge as its input,

one of these time-series needs to be estimated or known to start the simulation. If estimated values are used, the simulation procedure needs to be iterated until the modeled time-series converged.

6. Although by adjusting the values of SPRK, the map-based groundwater model can generate correct spring flow time-series for the map-based surface water model, the water levels produced by the map-based groundwater model are not as accurate when compared to those calculated by a Modflow model, because in an integrated model, the areas of the groundwater computation units (polygon cells) are too large.