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Map-based surface and subsurface flow simulation models: An object-oriented and GIS approach

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ABSTRACT

MAP-BASED SURFACE AND SUBSURFACE FLOW SIMULATION MODELS: AN OBJECT-ORIENTED AND GIS APPROACH

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A hydrology simulation model is composed of three elements, which are (1) equations that govern the hydrologic processes, (2) maps that define the study area and (3) database tables that numerically describe the study area and model parameters. When a model is constructed with its three elements separated, its portability and user-friendliness are usually limited because any modification of one component will not be reflected in the others. The purpose of this research is to develop a map-based flow simulation model with all three model-components integrated. The model is constructed under a geographic information system (GIS) and based on the concepts of object-oriented programming. As its name suggests, a map-based model is map-centric and it allows all the regular model procedures such as construction, simulations, modifications, and result-processing to be activated directly from the model maps. Based on this 'map-centric' and object-oriented concept, a map-based surface/subsurface water flow simulation model is developed and successfully applied to simulate surface and subsurface flow on the Niger River Basin in West Africa. In the process of constructing this map-based model, techniques are also developed to address and solve some GIS

related problems such as treatment of spatially-referenced time-series data, feature-oriented map operations, dynamic segmentation of an arc, and integration of flows along a line.

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Chapter One. Introduction

A hydrologic simulation model is, in general, composed of three basic elements, which are (1) equations that govern the hydrologic processes, (2) maps that define the study area and (3) database tables that numerically describe the study area and model parameters. When a model is constructed using a procedural programming language, such as FORTRAN, these three elements are usually processed separately and then assembled at runtime to form a model. Because of this separation, the modification on a model map will not automatically update its related databases and programs. Therefore, each time the model study area is changed or additional data are obtained, the procedure and efforts of the data collection and preparation used to construct the original model are repeated to construct a new model. The situation can be improved if all three elements of a simulation model can be integrated and if standard map bases can be built for extensive regions.

On the other hand, when looking back into the history of the numerical modeling in the area of water resources, it can be seen that the general trend of the modeling approach is moving from the periods of (1) 'function-centric' where numerical models were self-contained and supported by their own data sets, through (2) 'data-centric', where models were supported by some general database management systems, and towards (3) 'map-centric' where models would be supported by or written in GIS.

The purpose of this research is to develop a map-based flow simulation model with all of its three components integrated. In doing so, this research attempts to move towards the goal of constructing a 'map-centric' modeling approach. The map-based model is based on the concepts of object-oriented programming (OOP) and is built using a geographic information system (GIS).

The maps and databases are integrated using GIS data management tools while the data sets and programs are integrated by applying the concepts of OOP. To demonstrate how these three elements are integrated and how an integrated model can be applied to simulate hydrologic/hydraulic processes, two map-based flow simulation models, one for surface flow and one for groundwater flow are constructed using ArcView GIS as the host environment. These two models are then connected through data tables to simulate the interactions between surface and subsurface water flows. ArcView is selected as the host environment for the models because it provides both spatial database management and object-oriented programming capabilities. The remainder of this section is used to provide a brief review on the history of GIS applications in hydrologic modeling and a discussion of the GIS-related problems to be solved in this research.

A geographic information system (GIS) is designed to visualize, store and analyze the information about the locations, topology, and attributes of spatial features. In most GIS programs, data are stored and managed in a relational database embedded in the system. A GIS program can perform regular database management tasks in addition to its spatial analysis capabilities. For this reason, GIS can be considered as a relational database management system with a map interface for data presentation. In GIS, locational data and their map representations are dynamically linked so that any changes made in the databases are reflected immediately on its map presentation. The linkage between the map and databases makes GIS an ideal and strong tool for spatial data visualization and analysis.

On the other hand, hydrologic or hydraulic models are designed to simulate the processes of surface or subsurface water flow. Because the flow processes are spatially distributed, a great amount of spatially related physical data needs to be prepared and analyzed in order to construct a simulation model.

As model data processing is a tedious procedure, it is desirable to use GIS to accelerate the data preparation process. For this reason, ever since the beginning of GIS development about 16 years ago, many attempts have been made to introduce GIS into the hydrologic and hydraulic modeling process. As a result of these efforts, ARC/INFO has been linked to some hydrologic/hydraulic models such as the Hydrologic Engineering Center's HEC1 (Warwick, 1994) and HEC2 (Djokic, 1994) models, to river basin models (Grayman, 1991), to groundwater models such as MODFLOW (Watkins, 1996, McKinney, 1996), and other subsurface flow and transport models (Leipnik, 1993). More examples of this type of GIS applications can found in various publications (Kuo, 1993), but generally, this type of model-coupling has not been easy to accomplish, even though the model-coupling can be done.

Although it is generally agreed that when used properly, GIS makes a good pre-processor and post-processor for hydrologic/hydraulic simulation models, there are still problems to be solved and techniques to be improved in order to have a better integration of GIS with the hydrologic and hydraulic modeling. Listed below are the areas that will be discussed in this dissertation.

• Developing a Simulation Model with Its Three Elements Integrated

Although using GIS as a hydrologic/hydraulic model's pre-processor and post-processor has the benefits of reducing the amount of data preparation work, enhancing spatial data display and revealing some hidden spatial relations, the effort and cost of developing a GIS interface can also be significant and sometimes, outweigh the benefits of using it (DeVantier, 1993). One of the reasons for this high development cost is that both GIS databases and simulation models are usually self-contained and have different data structures. As a result of this difference, a great number of programs and procedures need to be constructed simply for data conversion purposes.

This problem can be mitigated if a simulation model is constructed with all three of its elements integrated, because in such a model, the programs and maps would share the same databases and the problems of data inconsistency would be eliminated.

High set-up and operating cost can also be improved if a GIS interface developed for one model can be shared by other models. This study also attempts to develop a GIS-based system that provides a digital description of the environment to which models can be attached (Maidment, 1993). This system is used for the following three purposes: (1) as a spatial data storage and management system, (2) as a driver to feed different models with different types of data, and (3) to run these models. This type of system enables the data sharing so that a database developed for one model can be used for another. For example, data sets constructed for a rainfall-runoff model can be shared by a groundwater simulation model, a data set prepared for a for long term soil-water balance computations can be used for short term storm-flood simulation model, and so on.

• Constructing a Groundwater Simulation Model under GIS

Because most groundwater simulation models are self-contained and require a specific input data format, it is not easy to integrate an external groundwater model with a GIS. However, because GIS has the ability to manage and display spatially-referenced data, it is desirable to use GIS to support groundwater simulation models. To achieve this goal, a map-based groundwater model is constructed within the GIS environment using the concepts of spatial database management and OOP. The user interface and data processing capability of this map-based model are enhanced by the spatial data display and analysis capabilities of the GIS.

- **Connecting the Spatially-Referenced Time-Series Data with GIS**

Because most hydrologic processes are time dependent, spatially-referenced time-series data are frequently encountered in simulating hydrologic events. Therefore, it is important to have an efficient data structure and data management system to handle spatially-referenced time-series data. Data structures designed during this research can be either embedded in or connected to a GIS map to manage the spatially-referenced time-series data efficiently and effectively.

- **Enhancing the Ability of GIS to Perform Feature-Oriented Map Operations**

Another focus of this research is the feature-oriented map operations. Feature-oriented operations refer to the spatial operations applied to a given map feature that may also involve the features of other maps (coverages). A collection of programs were designed that allow feature-oriented map operations to be performed on multiple GIS maps. A feature can be a line in an arc coverage, a point in a point coverage, or a polygon in a polygon coverage.

In GIS, spatial objects are grouped according to their feature types into thematic layers. Objects grouped into the same layer form an individual entity called a coverage. As a result of this grouping, inter-layer object operations cannot be performed efficiently in GIS. However, in order to design a hydrologic model within GIS or to make GIS work efficiently with an external hydrologic model, one has to be able to select objects of one layer based on the attributes of the objects in other layers. Methods are designed in this study to allow more efficient feature-oriented map operations for this purpose.

In the following chapters, the problems listed above are addressed and studied. The major goal of this study is to construct map-based simulation models (with all three of their components integrated) using the concepts of object-oriented programming, relational database management, and GIS.

Chapter Two (1) provides a brief review of the development of object-oriented programming, (2) introduces the concept of a map-based simulation model and the theories from which this concept originates, (3) reviews the governing equations of some hydrologic/hydraulic processes related to the model construction, and (4) describes the relationships between the programs, map-features and databases.

In Chapter Three, the concepts discussed in Chapter Two are used to develop a map-based surface water flow simulation model.   In the process of model construction, problems relating to the treatment of spatially-referenced time-series data, feature-oriented map operation, and dynamic segmentation are analyzed and solved. Other commonly encountered problems such as model calibration, model post-processing, and model modification are also addressed in Chapter Three.

In Chapter Four, the concept of map-based modeling is used to develop a map-based groundwater simulation model. To design such a model, the concepts of object-oriented programming and relational databases are applied so that the model procedures are consistent with the structure of spatial databases and model maps. The map-based model simulates the groundwater flow by alternately applying the continuity equation to the polygon features and momentum equation (Darcy’s Law) to the boundary lines of the polygon features.

In Chapter Five, the map-based surface and subsurface flow simulation models are merged to simulate the interaction of surface and subsurface water flows. Notable issues be discussed regarding the integration of these two models are (1) the construction of modeling objects for surface and subsurface flows, (2) the treatment of deep and shallow aquifers, (3) the methods used for data exchange, and (4) modeling procedures over time and spatial domains.

In Chapter Six, the summary and conclusions of this research are provided, in which the technique developed and knowledge acquired from this research are described and evaluated together with some comments regarding possible future research in the area.

Chapter Two. Simulating Surface and Subsurface Water Flows

2.1. Concept of Object-Oriented Programming

As this study relies heavily on the concept of object-oriented programming, this section briefly reviews the history of object-oriented programming and the definition of object-oriented programming terms that will be used. After this review, the concepts of object-oriented programming will be compared with those of procedural programming languages to identify their differences.

The definitions of the terms given in this section come from the book Object-Oriented Programming (Gunther, 1994), with some modifications based on other references in the field.

Object-oriented programming (OOP) originated with the programming language Simula (Dahl 1966). This language was designed as a tool for simulating physical processes, such as water flow on a river system, that take place in the real world. The notion of objects was probably first introduced in Simula in the 1960s, but it was not formally defined until the early 1980s when the language Smalltalk was developed at the Xerox Research Center in Palo Alto (Goldberg, 1983).

One of reasons why OOP is growing rapidly is that it is simple in concept and resembles physical reality. The principal strength of the object-oriented programming language lies in its ability to handle complexity in a transparent and close-to-nature manner (Razavi, 1995). The major concepts of OOP are object, class, and inheritance. By definition, objects with the same attributes (states) and behavior are grouped into a single class. Subclasses can be generated from an existing class and these subclasses inherit all the states and behaviors of their parent class. It is the concept of inheritance that gives OOP the ability to handle complex problems and the ability to combine the efforts of multiple programmers and researchers (Wegner 1990). For example, a class created by programmer A can be taken and used by programmer B to generate a new subclass by adding new attributes and methods (element functions) to it. Because the new subclass automatically inherits all the attributes of its super-class created by A, programmer B does not need to know how these attributes are constructed but may concentrate on the construction of the new attributes and methods. This concept of class-inheritance is also a plus for program debugging because if anything ever goes wrong with the new subclass, programmer B needs only to concentrate on the new attributes and methods he or she added to the new subclass (assuming its super-class is properly designed and A is a good programmer). The research efforts of programmers A and programmer B can easily be used by programmer C to construct his subclasses, which will inherit all the attributes and methods developed by programmers B and A. In this way, the research efforts and results of different programmers and researchers can be accumulated to form a complex system. To better understand OOP, some common terms are described below:

Objects: Objects are structures with state and behavior. Objects can cooperate to perform complex tasks and can communicate with each other by means of messages. Objects also have precise interfaces specifying which messages they accept. The closest counterpart of an object in procedural programming is a record or a structure in C or FORTRAN.

Class: Classes describe the properties of objects. Classes in OOP can be viewed as (1) a means of identifying objects with the same properties, which can be used to distinguish objects with different structure and behavior; (2) a structuring mechanism, similar to a procedure, which improves the readability and maintainability of programs, and (3) a means of creating new members (objects) of the class. The relationship between objects and their classes is many-to-one. Each object belongs to exactly one class while one class can have many objects. For example, a subwatershed can be a polygon object and the collection of all subwatersheds in a river basin form a subwatershed polygon class.

Inheritance: Inheritance refers to the propagation of properties from super classes to subclasses. This property allows OOP to derive new classes from the existing classes. This concept does not exist in procedural programming languages.

Types: Type is a property of variables and expressions, .e.g., integer type, real type, character type, etc. There is no difference between types in procedural and OOP language.

Object References: Object references can be viewed as pointers to objects. They are variables pointing to the memory area where an object is stored. Therefore, they are very similar to a pointer used in a procedural programming language.

Variable: Variables contain object references. A variable can be viewed like a pointer in programming language C. Variables within classes are class variables and variables within objects are instance variables. A class variable is similar to a global variable in a procedural programming language, while an instance variable is similar to the field variable or record component, e.g. type auto in C.

Messages: Messages are the way objects communicate with one another. The invocation of message is called a message send while the object that is to process the request is called the receiver of the message. Messages are similar to procedural calls in a procedural programming language.

Methods: Methods are the algorithms attached to each object to perform the requests sent by other objects via messages. Methods correspond to procedural declarations in procedural programming languages.

Subclass and Superclass: If class B is derived from class A, then class B is subclass of A, while A is the superclass of B. An object from a subclass inherits all the attributes and behavior from its superclass. For example, two classes: feature attribute table class (FTAB) and value attribute table class (VTAB) exist in the ArcView. A FTAB table is a database table connected to a GIS map and a VTAB table is just a regular database table without direct map connection. Feature attribute table (FTAB) is a subclass of value attribute table (VTAB). Therefore, an FTAB table inherits all the attributes (field types) from VTAB class. What makes FTAB a new class is that an FTAB table has a new SHAPE field, which does not exist in its superclass VTAB.

Dynamic Binding (Late Binding): Dynamic binding is the mechanism that enables an object to decide what action to take and how to act at run time. In contrast to dynamic binding is static binding or early binding, in which all the actions of an object are decided at the time when the program is constructed. For example, a function can be defined as Z=x*y to compute the multiplication of two variables x and y. Dynamic binding make it possible that the type of return value Z depends on the types of x and y. That is, when x and y are of integer type, the return value is also of integer type and when x and y are of float type, the return value is also of float type.

Before ending this section, two additional OOP facts that are important to this study should be pointed out: (1) the logical parallel between classical procedural programming and OOP and (2) the mutual independence of behavior and state of an object.

The differences between procedural programming and OOP lie mainly in how the programs are organized, the modules are called, and the variables are stored and retrieved. As to procedure itself and program construction, the logic applied to classical procedural programming is very similar that used in OOP. Therefore, the programming logic used in procedural programming can be easily applied to OOP.

Although in an object-oriented programming language, state, behavior, and interface are used jointly to define an object, they can each be defined independently from one another. This fact can be used to support the design of a generic GIS database management system. In the context of hydrologic analysis, the state of an object can be described by the attributes of a stream section or a river basin while the behavior can be viewed as the hydrologic processes occurring on a river section or a river basin. Since state and behavior are independent, they can be treated separately with state variables being stored and managed in a GIS database and behaviors being described by various models.

2.2. Conceptual Design of an Integrated Hydrologic Model

This section describe how the concepts of object-oriented programming will be used to design a map-based surface flow simulation model.

The classes of polygon and line objects are of essential importance to this study because river basins can be represented by polygon objects and rivers can be represented as line objects. The equation, object=state+behavior will be used to define these two classes of objects.

- **River Basin and Polygon Classes**

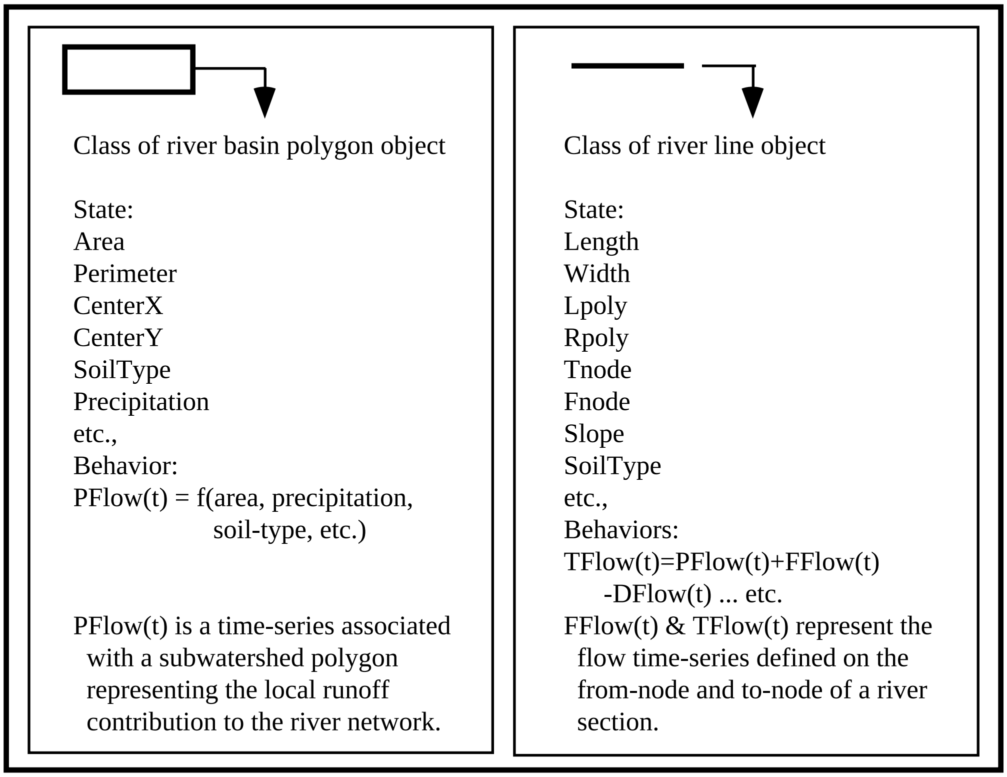
For a given object in the polygon object class, its state can be described by area, perimeter, shape, etc. Its behaviors are drawing-itself, coloring-itself, getting-dimension, returning-center etc. Getting-dimension, returning-center, and drawing-itself are the names of element functions (methods) of the objects that perform the tasks of getting the dimension sizes, returning the center point of the polygon object, and drawing and coloring the object. Element functions are the functions that are defined by a class to be associated with an object of the class.

River basin polygons can be viewed as a subclass derived from the polygon object class. Therefore, for a given river basin object, its state can be described by the properties it inherits from the polygon object class plus its own unique state properties, such as soil type, rainfall depth, slope, streams it contains, adjacent basins, hydraulic conductivities K_x and K_y, etc. For the same reason, the behavior of a river basin object can also be described by the behavior properties that it inherits from polygon object classes plus the behaviors of all kinds of hydrologic and hydraulic processes, which can be described by different hydrologic and hydraulic models.

- **River Section and Line Classes**

For a given object in the line object class, its state can be described by its length, To-Node (Tnode), From-Node (Fnode), Left-Polygon (Lpoly), Right-Polygon (Rpoly), shape, etc. In an ARC/INFO arc coverage, Fnode and Tnode are used to denote starting point and ending point IDs while Lpoly and Rpoly are used to denote the IDs of polygons to the left and to the right of a line. An object's behaviors may be drawing itself, coloring itself, getting-dimension, returning-center, getting-end-point, getting-start-point, etc. Again, getting-dimension, returning-center, etc., are the names of the element functions of an object that perform the tasks of getting the dimension sizes, returning the center point of the line, drawing and coloring the line object.

A river object belongs to the line object class. Therefore, for a given river object, its state can be described jointly by the properties that it inherits from the line object class plus the behaviors of all kinds of hydrologic or hydraulic processes which are described by different hydrologic and hydraulic models. Figures 2.1 and 2.2 show the examples of classes and objects. Figure 2.2 shows the map of the Guadalupe River Basin created by applying a watershed delineation procedure (Maidment, 1994) to a 3 arc-second digital elevation model (DEM) of the area.



Class of river basin polygon object

State:
Area
Perimeter
CenterX
CenterY
SoilType
Precipitation
etc.,
Behavior:
PFlow(t) = f(area, precipitation, soil-type, etc.)

PFlow(t) is a time-series associated with a subwatershed polygon representing the local runoff contribution to the river network.

Class of river line object

State:
Length
Width
Lpoly
Rpoly
Tnode
Fnode
Slope
SoilType
etc.,
Behaviors:
TFlow(t)=PFlow(t)+FFlow(t) -DFlow(t) ... etc.
FFlow(t) & TFlow(t) represent the flow time-series defined on the from-node and to-node of a river section.

Figure 2.1. State and behavior defined on an object

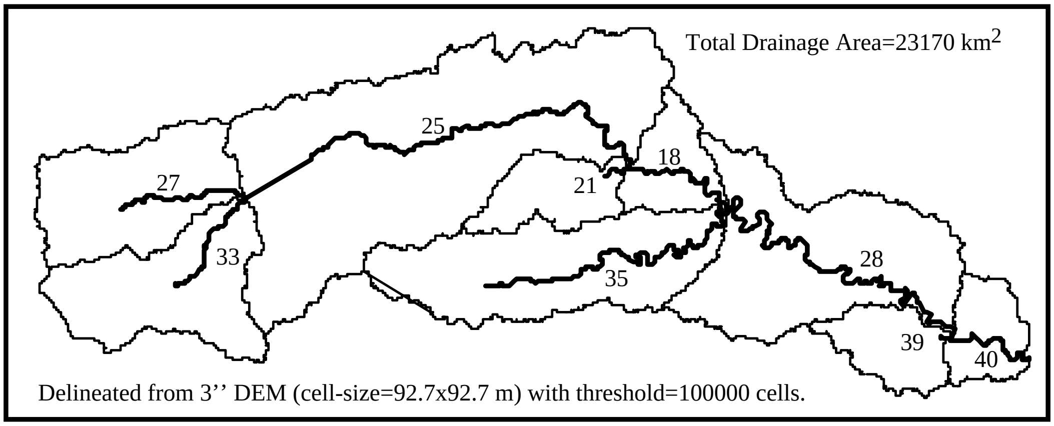
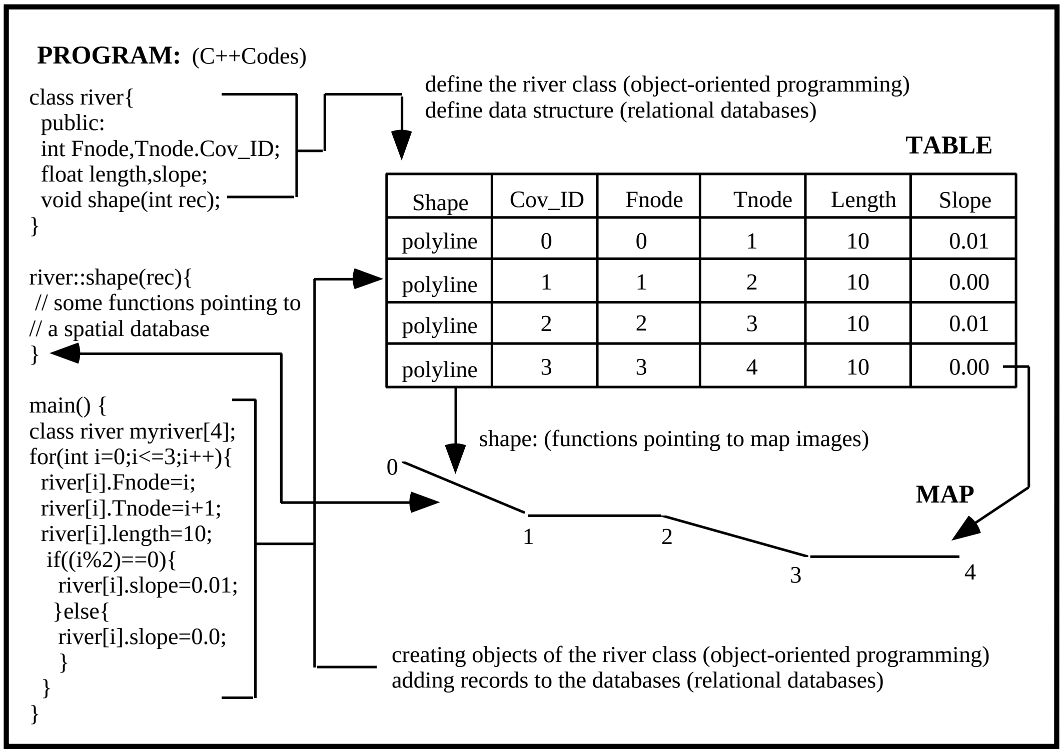

Total Drainage Area=23170 km^2
25
18
21
27
33
35
28
39
40
Delineated from 3’’ DEM (cell-size=92.7x92.7 m) with threshold=100000 cells.

Figure 2.2. Guadalupe River Basin in Central Texas - an example of river line and watershed polygon objects

2.3. Relationships between Maps, Databases and Programs

In order to construct a map-based simulation model, it is important to understand the relations between the maps, relational databases and programs. Figure 2.3 shows how an object is defined and referenced in an object-oriented programming language, in a relational database, and on a map. C++ is used here to illustrate how an object is defined in an object-oriented programming language.

As stated above, an object is defined by the equation: object = state + behavior. The behavior of an object is governed by some equations. Equations are usually translated into element functions. In the same way, states of an object are defined as variables of a class. The program section in Figure 2.3 illustrates how a class is defined and objects generated in C++. In this example program, objects are created in two steps. First, a class is defined and functions declared, and then the instances (objects) of the class are generated. These two steps are analogous to the actions of creating a database structure (template) and adding records to the database. When a GIS map is constructed, a relational database is also created to store the spatially-referenced data sets. Such databases appear as feature attribute tables (FTAB) in the ArcView program. In the database of a GIS map, one field is used to hold the pointers to the geographical features on the map. In a class, states (variables) and behaviors (element functions) can be defined as either private or public. A private variable/function is accessible only by other elements of the same object while a public variable/functions can be called by other objects. The distinction of private and public types of functions and variables provides a mechanism for programs to control the messages (requests) exchanged between objects.


PROGRAM: (C++Codes)
define the river class (object-oriented programming)
define data structure (relational databases)
TABLE
shape: (functions pointing to map images)
MAP
0
1
2
3
4
creating objects of the river class (object-oriented programming)
adding records to the databases (relational databases)

```
class river{
  public:
  int Fnode,Tnode.Cov_ID;
  float length,slope;
  void shape(int rec);
}

river::shape(rec){
 // some functions pointing to
// a spatial database
}

main() {
class river myriver[4];
for(int i=0;i<=3;i++){
  river[i].Fnode=i;
  river[i].Tnode=i+1;
  river[i].length=10;
   if((i%2)==0){
     river[i].slope=0.01;
    }else{
     river[i].slope=0.0;
     }
  }
}
```

Shape	Cov_ID	Fnode	Tnode	Length	Slope
polyline	0	0	1	10	0.01
polyline	1	1	2	10	0.00
polyline	2	2	3	10	0.01
polyline	3	3	4	10	0.00

Figure 2.3. Presentation of objects in a program, database and map

2.4. Governing Equations for Surface and Subsurface Water Flows

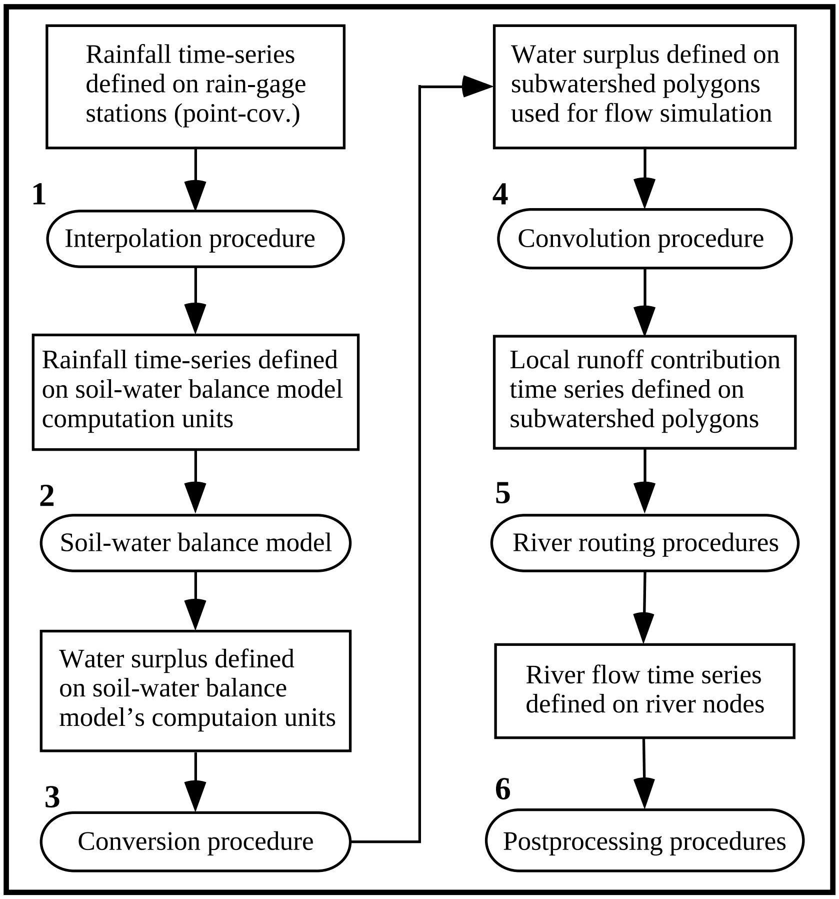
Given a numerical simulation model, there are always two components, which are mathematical equations governing the process and attribute data (extracted from maps and other sources) supporting the equations. In the context of OOP, a mathematical equation describes the behavior while a set of attribute data describes the state of an object.

The following sections review the equations governing the surface and subsurface water movements that will be used for the map-based simulation model design in this study.

2.4.1. Equations Related to the Surface Water Flow Simulation

Two types of models are considered for surface water flow simulation: one for stream flow and one for overland flow. Figure 2.4 shows the data flow path on the map-based surface water flow simulation model.

As it can be seen from Figure 2.4, six procedures are used to process and convert the rainfall data sets and produce flow time-series the river section nodes.



Rainfall time-series defined on rain-gage stations (point-cov.)
1
Interpolation procedure
Rainfall time-series defined on soil-water balance model computation units
2
Soil-water balance model
Water surplus defined on soil-water balance model's computaion units
3
Conversion procedure
Water surplus defined on subwatershed polygons used for flow simulation
4
Convolution procedure
Local runoff contribution time series defined on subwatershed polygons
5
River routing procedures
River flow time series defined on river nodes
6
Postprocessing procedures

Figure 2.4. Data flow path in the map-based surface water flow simulation model

The input data for this map-based surface water flow simulation model are a set of rainfall time-series defined on the rain-gauge stations on the study area.

These rainfall time-series are interpolated to each of the computation units of a soil-water balance model (procedure 1). The interpolated rainfall time-series are used by the soil-water balance model (procedure 2) to produce soil-water surplus time-series defined on the computational units of the soil-water balance model. If subwatershed polygons are used as the computational units of the soil-water balance model, the water-surplus time-series can be used directly by a convolution procedure (procedure 4) to produce the local runoff contributions. Otherwise, a conversion procedure (procedure 3) has to be applied to convert the water-surplus from a set of time-series defined on the soil-water balance units to another set of time-series defined on the subwatershed polygons before the convolution procedure can be applied. The convolution procedure produces a flow time-series representing the runoff contribution of each subwatershed. The river routing procedures (procedure 5) together with the river network analysis procedure (to be discussed in Chapter Three) are then applied to generate flow time-series defined at the starting and ending points of each river line section in the river network.

In the following sections, the equations governing the soil-water balance computation, water surplus to runoff conversion, river flow routing, and the methods for converting time-series data between different spatial features are discussed.

2.4.1.1. The Soil -Water Balance Model

A soil-water balance model estimates the soil-water surplus given a precipitation time-series, soil-water holding capacity information, and potential evaporation information. The surplus is defined as water which does not evaporate or remain in soil storage and is available to generate surface and subsurface runoff. Surplus can be estimated using a simple bucket model

(Thornthwaite, 1948, Willmott *et al*., 1985, Mintz and Serafini, 1993). In the simple bucket model, the basic equations for calculating surplus are:

$$\frac{w(t)}{\Delta t} = \frac{w(t-1)}{\Delta t} + P(t) - E(t) \qquad (2.1a)$$

$$\begin{aligned} S(t) &= \frac{(w(t) - w^*)}{\Delta t};\ w(t) = w^* \quad \text{if } w(t) > w^* \\ S(t) &= 0;\ w(t) = w(t) \quad\quad\quad \text{if } w(t) \le w^* \end{aligned} \qquad (2.1b)$$

where,

$S(t)$ = surplus $[LT^{-1}]$,

$P(t)$ = precipitation $[LT^{-1}]$,

$E(t)$ = evaporation $[LT^{-1}]$,

$w(t)$ = soil moisture storage of the computation unit at time step t [L],

w^* = soil-water holding capacity [L],

Δt = computation time step [T].

• Constructing a Precipitation Surface From Rainfall Data

The precipitation data are usually available in the form of time-series data associated with the locations of rain-gauge stations. These rainfall time-series need to be spatially interpolated to the cells on which equation 2.1 will be applied. There are many algorithms available to perform spatial interpolation, such as the methods of triangulated irregular network (TIN), Kriging, Thiessen polygons, two-dimensional spline, and inverse-distance weighting. Procedures for applying these interpolation methods can be found in numerous publications, e.g. the series of ARC/INFO User's Guide, (ESRI, 1992). When the method of TIN is used for the interpolation, a TIN is first constructed from the point coverage of rain-gauge stations. The ARC/INFO function TINLATTICE can then be used to interpolate the rainfall values to the centers of soil-water balance computation units.

- **Computing the Evaporation**

Three types of equations are available for potential evaporation estimations (Applied Hydrology, pp82-86) and they are listed below.

(1) Energy method:

$$E_r = \frac{R_n}{l_v \cdot \rho_w} \qquad (2.2a)$$

where,

E_r = the estimated evaporation rate[LT^{-1}],

R_n = net radiation flux {200 W/M^2}={200 J/SM^2},

l_v = latent heat of water vaporization{2441 KJ/Kg},

ρ_w = water density{997 Kg/M^3}.

The numbers listed in {} are used to provide a sense of the parameter's normal value range.

(2) Aerodynamic method:

$$E_a = B(e_{as} - e) \qquad (2.2b)$$

where,

E_a = the estimated evaporation rate[mm],

e_{as} = vapor pressure at water surface {3167 Pa at 25^{o}C},

e = vapor pressure of the air,

$$B = \frac{0.622k^2\rho_a u_2}{p\rho_w[2\ln(z_2/z_o)]}$$

k = Von Karman’s constant, k = 0.4,

ρ_a = air density, { $\rho_a = 1.19\ kg/m^3$ at 25^{o}C},

p = ambient air pressure, {p = 101.3 kPa at25^{o}C},

u_2 = air velocity at elevation Z_2,

Z_0 = reference height of boundary.

(3) Combined aerodynamic and energy method:

$$E = \frac{\Delta}{\Delta+\gamma}E_r + \frac{\gamma}{\Delta+\gamma}E_a \tag{2.3}$$

where,

$\Delta = \frac{de_s}{dT} = \frac{4098 e_s}{(237.3+T)^2}$ = vapor pressure gradient with temperature,

γ = psychometric constant.

In this research, the energy method (Equation 2.2a) is used to estimate the potential evaporation in the simple bucket model.

- **Setting the Model’s Initial Conditions**

As can be seen from Equation 2.1, computation of soil-moisture surplus is an iterative procedure, and the initial soil moisture storage w(t=0) is needed before the computation can start. Since the initial soil moisture storage is typically unknown, the following water balancing procedure is applied to force the net change in soil moisture from the beginning to the end of a specified balancing period to zero, i.e., $w(0) - w(n+1) < \xi$, where n is the number of time steps of the computation period, and ξ is a user specified tolerance (ξ = 0.1 mm is used in the research). Starting with the initial soil moisture being set to the water-holding capacity, budget calculations are made to until t=n+1. w(0) is then set to w(n+1) to start another budget calculation circle until the condition $w(0) - w(n+1) < \xi$ is satisfied.

2.4.1.2. Converting Time-Series between Different Spatial Features

The soil-water balance model produces a time-series of water surplus defined on the model's computation units. Because the units used for the soil-water balance usually are not the subwatershed polygons used for surface water flow simulation, the time-series of water surplus values needs to be converted so that the values are defined on the subwatersheds. This section describes the procedure for the conversion of a data set defined on one type of spatial features to those defined on another set of spatial features.

To illustrate the procedure, assume P is a set of data defined on In-Coverage and is to be converted so that it is defined on Out-Coverage. The first step of the data converting procedure is to use the INTERSECT function provided by the ARC/INFO to establish the spatial relationships between In-Coverage and Out-Coverage. The INTERSECT operation produces a new Intersect-Coverage. As shown in Figure 2.5, nine components of P on the In-Coverage will become four components defined on Out-Coverage after the conversion. Assume the area on each feature on the In-Coverage to be A_1, A_2, ..A_9, and the areas of map units on the Intersect-Coverage to be I_{ij}, with i representing the In-Coverage ID and j representing the Out-Coverage ID. Let OP and IP represent the components of P defined on the Out-Coverage and defined on the In-Coverage, respectively. The equations used for OP_1 can then be written as:

$$OP_1 = \frac{IP_1 \cdot I_{11} + IP_2 \cdot I_{21} + IP_4 \cdot I_{41} + IP_5 \cdot I_{51}}{I_{11} + I_{21} + I_{41} + I_{51}} \qquad (2.4a)$$

if P is an intensive property, and

$$OP_1 = IP_1 \cdot \frac{I_{11}}{A_1} + IP_2 \cdot \frac{I_{21}}{A_2} + IP_4 \cdot \frac{I_{42}}{A_4} + IP_5 \frac{I_{51}}{A_5} \qquad (2.4b)$$

if P is an extensive property.

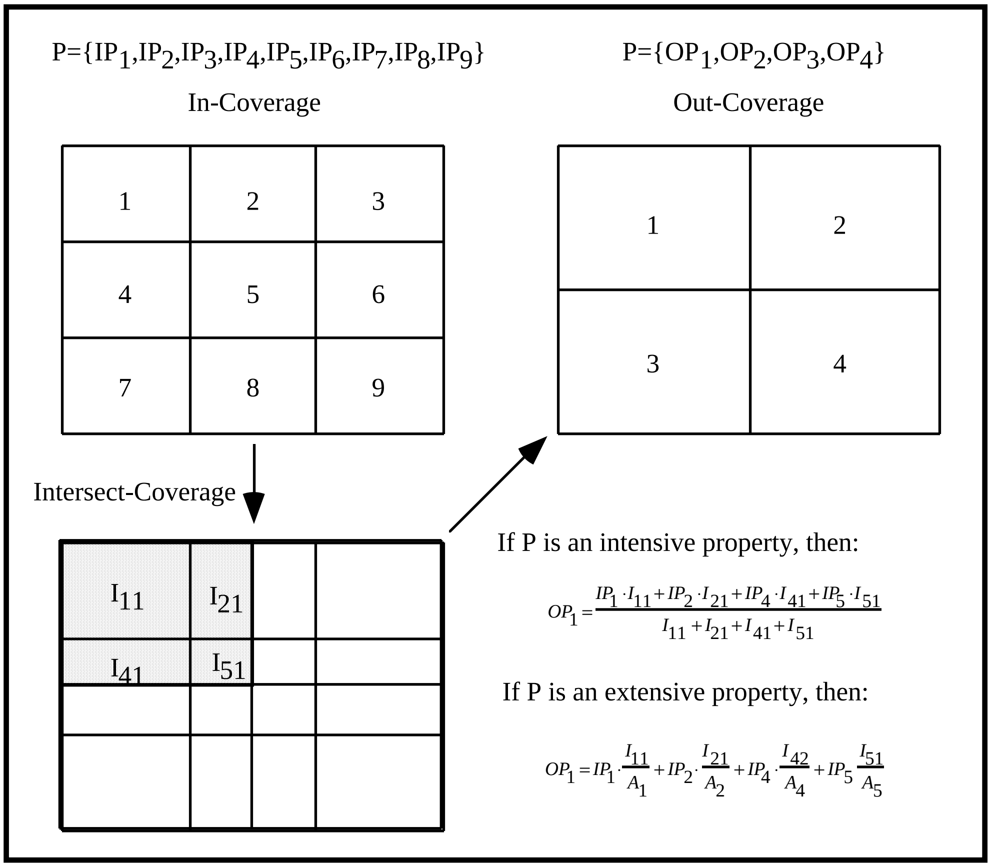

P={IP$_1$,IP$_2$,IP$_3$,IP$_4$,IP$_5$,IP$_6$,IP$_7$,IP$_8$,IP$_9$}
In-Coverage
P={OP$_1$,OP$_2$,OP$_3$,OP$_4$}
Out-Coverage
1
2
3
4
5
6
7
8
9
1
2
3
4
Intersect-Coverage
I$_{11}$
I$_{21}$
I$_{41}$
I$_{51}$
If P is an intensive property, then:
$OP_1 = \frac{IP_1 \cdot I_{11} + IP_2 \cdot I_{21} + IP_4 \cdot I_{41} + IP_5 \cdot I_{51}}{I_{11} + I_{21} + I_{41} + I_{51}}$
If P is an extensive property, then:
$OP_1 = IP_1 \cdot \frac{I_{11}}{A_1} + IP_2 \cdot \frac{I_{21}}{A_2} + IP_4 \cdot \frac{I_{42}}{A_4} + IP_5 \frac{I_{51}}{A_5}$

Figure 2.5. Converting data sets between different spatial features

In general, the conversion equations can be written as:

$$OP_j = \sum_i IP_i \cdot I_{ij} \tag{2.5a}$$

if P is an intensive property, and

$$OP_j = \sum_i IP_i \cdot \frac{I_{ij}}{A_i} \tag{2.5b}$$

if P is an extensive property, where,

OP_j = property P defined on unit j at the Out-Coverage,

IP_i = property P defined on unit i at the In-Coverage,

I_{ij} = the area of unit i on the In-Coverage that intersects with unit j on the Out-Coverage,

A_i = the area of unit i on the In-Coverage. To convert time-series data, equation 2.5 needs to be applied to the data at each time step.

2.4.1.3. Convolution Procedure Used To Compute Local Runoff

The time-series representing the local runoff of a subwatershed to the river network (PFlow(t)) can be calculated from the time-series of water-surplus (SurpF(t)) defined on the subwatershed. In the following text, when referring to a time-series in general, for example, PFLOW, the notation PFlow(t) will be used and when referring the same time-series related to a specific spatial feature, the notation $PFlow_i^t$ will be used; a subscript (i) indicates the spatial feature index and a superscript (t) indicates the time index. Because the water surplus can reach a river section through either overland flow or through subsurface flow, the portion of surplus flow that reaches a river section through overland flow will be referred to as SFlow(t) and the portion that goes into the subsurface before it reaches the river section will be termed as OFlow(t) (Figure 2.6). Based on this assumption, we have:

$$PFlow(t) = SFlow(t) + OFlow(t) \tag{2.6}$$

The overland flow portion (SFlow(t)) can be computed from SurpF(t) using equation (Olivera and Maidment, 1996):

$$SFlow_i^t = \sum_{k=0}^{\min(t,N)} SurpF_i^{t-k} (1-\alpha_i) \cdot U_i^k \qquad (2.7)$$

where,

$SFlow_i^t$ = local surface water flow contribution (m^3/s), of subwatershed i at time step t,

$SurpF_i^{t-k}$ = soil moisture surplus (m^3/s) of subwatershed i at time step t-k,

U_i^k = k-th component of the response function of $PFlow_i^t$ on $SurpF_i^t$,

α_i = the fraction of surplus that goes to subsurface, $(0 \le \alpha_i \le 1)$,

N = total number of components in the response function U_i^k. The response function of $PFlow_i^t$ on $SurpF_i^t$ used in this study is given below:

$$U_i^k = \frac{1}{2k\sqrt{\pi D_i \frac{kv_i}{T_i}}} \exp\left(- \frac{(1-\frac{kv_i}{T_i})^2}{4D_i \frac{kv_i}{T_i}} \right) \quad k=1,2,3....N \qquad (2.8)$$

where,

k =1,2,3...N, the index of components in the response function,

D_i = dispersion coefficient for subwatershed i, Dispersion coefficient is used to measure the degree of the spreading of overland water flow over time.

v_i = average overland flow velocity for subwatershed i (m/s),

T_i = average overland flow time for subwatershed i (s).

Figure 2.6 is constructed to illustrate how the parameters of Equation 2.8 can be estimated. In Figure 2.6, subwatershed i is composed of a number of cells (elements) and for a given element e, its flow length l_e can be calculated using the GRID module in ARC/INFO. The flow time of water from element e to the outlet of the subwatershed can be estimated by dividing the flow length l_e by the average flow velocity v_e, which could estimated from the topology and land cover information of the subwatershed. The average overland flow time for subwatershed P_i is then computed using:

$$T_i = \sum_{e=1}^{N_e} t_e \cdot \frac{A_e}{A_i} \qquad (2.9)$$

where, A_e and A_i are the areas of element e and subwatershed i, respectively.

When all the elements forming the subwatershed have the same size, which is the case when the GRID module is used, Equation 2.9 becomes:

$$T_i = \frac{1}{N_e} \sum_{e=1}^{N_e} t_e \qquad (2.9a)$$

where, N_e = the number of elements in the subwatershed.

Using the Zonalstats function provided by the GRID module in ARC/INFO, the average overland flow length l_i and standard deviation σ_i of the flow length for subwatershed P_i can also be calculated. With these two parameters, the dispersion coefficient for the subwatershed P_i can be computed using:

$$D_i = \frac{\sigma_i^{\,2}}{2(l_i^{\,2})} \qquad (2.10)$$

where,

σ_i = the standard deviation of the flow length for subwatershed P_i,

l_i = the average overland flow length for subwatershed P_i.

The subsurface water flow component of PFlow(t) is considered to be going through an imaginary under-ground-reservoir whose flow can be simulated using a linear-reservoir-model (Equations 2.11 and 2.12):

$$OFlow_i^t = S_i^{t-1} / K_i \qquad (\mathrm{t} = 1, 2, 3, ...) \qquad (2.11)$$

$$S_i^t = S_i^{t-1} + (SurpF_i^t \cdot \alpha_i - OFlow_i^t) \cdot \Delta t \qquad (2.12)$$

where,

$OFlow_i^t$ = PFlow's subsurface component at time step t, on polygon i [L^3T^{-1}],

S_i^t = storage of the underground reservoir at time step t, on polygon i [L^3],

K_i = the linear reservoir constant [T].

After the components simulating surface and subsurface water flows are computed, the local flow contribution of subwatershed i at time step t is computed using Equation 2.6.

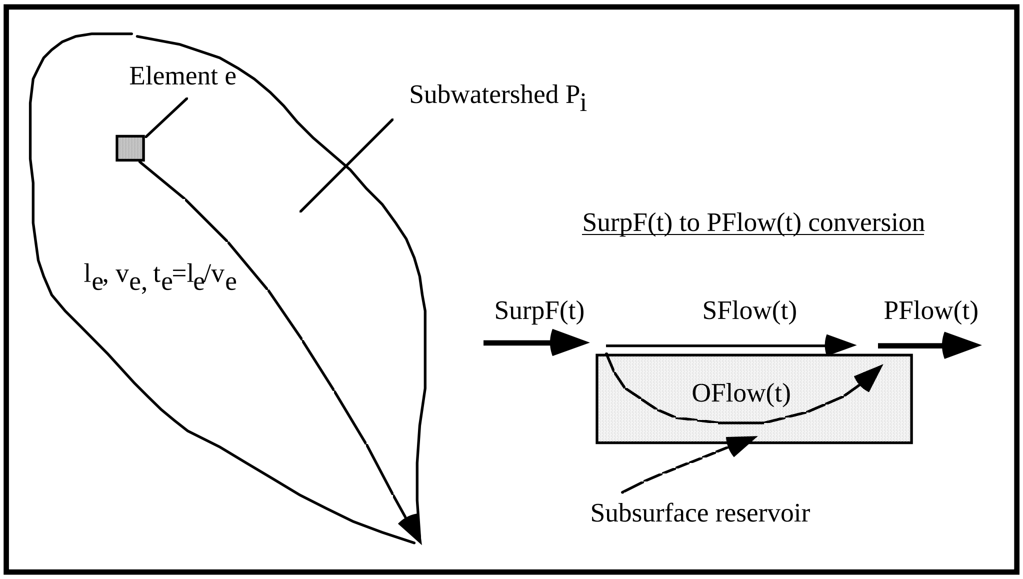


Figure 2.6. Converting SurpF(t) to PFlow(t)

2.4.1.4. Flow Routing on a River Section

The flow in a river section shown in Figure 2.7 can be simulated using the Muskingum or Muskingum-Cunge method (McCarthy, 1938, Cunge,1969, Chow *et al.*, 1987). The Muskingum method is based on the principle of continuity and a relationship between discharge and the temporary storage of excess volumes of water in a river section during the simulation period. The principle can be expressed as:

$$\frac{dS}{dt} = I(t) - Q(t) \tag{2.13}$$

where,

S = the volume of water in storage in a river section, *I(t)* = water inflow time-series (hydrograph) of the river section [L^3T^{-1}],

Q(t) = water outflow time-series of the river section [L^3T^{-1}].

In deriving the flow routing formula for the Muskingum method, it is assumed that the storage volume in a river section (Figure 2.7) is composed of two portions: a wedge storage and a prism storage. It is further assumed that the cross-sectional area of the water flow is directly proportional to discharge into the section, the volume of prism storage is K•TFlow(t) and the volume of wedge storage is K•X•(FFlow(t)-TFlow(t)), where K is a proportionality coefficient and X is a weighting factor showing the relative importance of FFlow(t) and TFlow(t). With these assumptions, the total storage of the section can be written as:

$$S(t) = K \cdot TFlow(t) + K \cdot X \cdot (FFlow(t) - TFlow(t)) \qquad (2.14)$$

The formula of Muskingum routing method is derived by expressing the storage change of the section between time step t and t-1 in terms of FFlow(t) and TFlow(t) using Equation 2.14. Muskingum-Cunge method is derived based on the Muskingum method taking into consideration the lateral flow (PFlow(t)). Detailed descriptions of Muskingum-Cunge flow routing method can be found in Applied Hydrology (Chow *et al.*, 1987), Hydrology for Engineers (Linsley *et al*, 1982), and Handbook of Hydrology (Maidment, 1993).

The Muskingum-Cunge flow routing method is described by the following equation:

$$\begin{aligned} \mathrm{TFlow(t)} = \mathrm{C_1} \cdot \mathrm{FFlow(t)} + \mathrm{C_2} \cdot \mathrm{FFlow(t-1)} \\ + \mathrm{C_3} \cdot \mathrm{TFlow(t-1)} + \mathrm{C_4} \end{aligned} \qquad (2.15)$$

where,

TFlow(t) = flow time-series at the To-Node of a river line,

FFlow(t) = flow time-series at the From-Node of a river line,

C1, C2, C3, C4 = coefficients related to river and flow characteristics. These coefficients are computed using equations given below:

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X)+\Delta t} \tag{2.16a}$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X)+\Delta t} \tag{2.16b}$$

$$C_3 = \frac{2K(1-X)-\Delta t}{2K(1-X)+\Delta t} \tag{2.16c}$$

$$C_4 = \frac{PFlow_i^t - DFlow_i^t - Loss_i^t}{2K(1-X)+\Delta t} \tag{2.16d}$$

$K = \frac{\Delta x}{\bar{c}}$, K is a storage constant [T], (2.16e)

$$X = \frac{1}{2} - \frac{Avg(TFlow, FFlow)}{2\bar{c}\overline{B}\,S_e\Delta X} \tag{2.16f}$$

X = a weighting factor showing the relative importance that FFlow and TFlow have on the river section’s storage,

Δx = the length of the river section, [L]

$\bar{c}$ = kinematic wave velocity [LT^{-1}],

$\overline{B}$ = cross-sectional top width associated with average of TFlow and FFlow,

S_e = the energy slope, andΔX = length of a river section.

To ensure the stability of the flow routing, C_3 needs to be non-negative. From equation 2.16c, it can be seen that in order for $C_3 \geq 0$, we need to have:

$\Delta t \leq 2K(1-X)$. The method used to ensure that the time step Δt satisfies the non-equality relationship will be discussed in section 3.4.2.

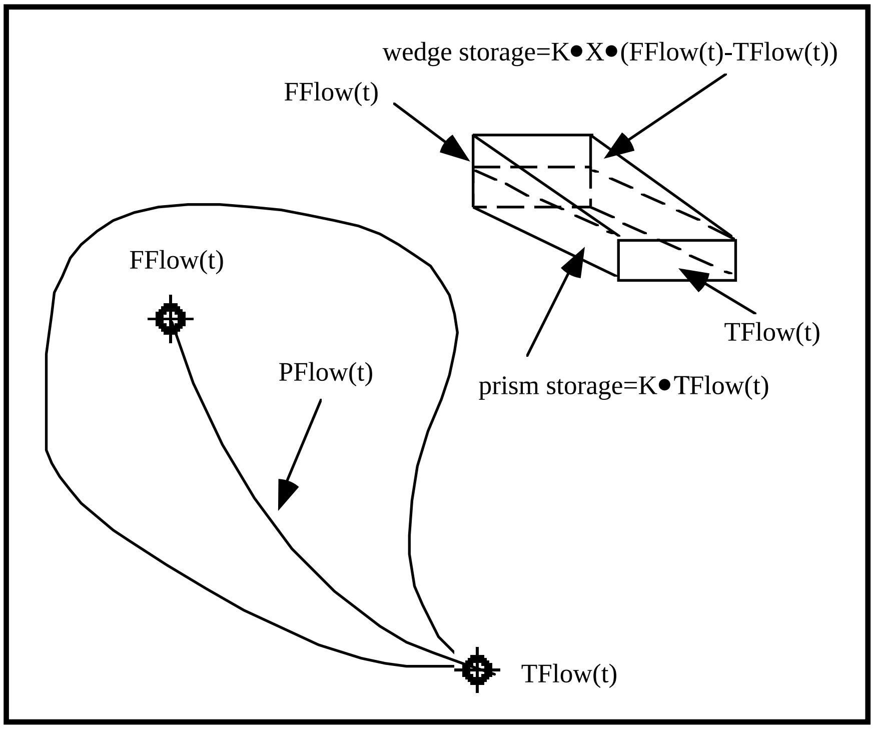


Figure 2.7. Flow routing on a river section

2.4.2. Equations Used for Groundwater Flow Simulation

The continuity equation for groundwater flow in three dimensions can be written as (Bear, 1979):

$$-\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right)+N(x,y,z,t)=S\frac{\partial h}{\partial t} \qquad (2.17)$$

where,

h = piezometric head of the aquifer [L],

N(x,y,z,t) = a point source (or point sink when N is negative) [T^{-1}], at point (x,y,z),

$S = \bar{\rho} g(\alpha + \beta)$ = specific storage [L^{-1}],

$\alpha = \frac{1}{1-n}\frac{dn}{dp}$ = the matrix compressibility [$M^{-1}LT^{2}$],

$\beta = \frac{1}{\rho}\frac{dp}{dp}$ = the water compressibility [$M^{-1}LT^{2}$],

n = the porosity of the aquifer,

q_x, q_y, q_z = the components of the specific discharge vector $\vec{q}$ [LT^{-1}] in x, y, z directions. $\vec{q}$ can be computed using Darcy's law:

$$\vec{q} = -K\, grad\, h = -K\nabla h \tag{2.18}$$

where,

K = the hydraulic conductivity of the aquifer [LT^{-1}],

$\nabla = (\frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial z}\vec{k})$ is gradient operator.

The continuity equation for groundwater flow in a phreatic aquifer in two dimensions (Figure 2.8) can be written as:

$$-(\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y}) + R - P = S\frac{\partial h}{\partial t} \tag{2.19a}$$

or

$$\frac{\partial}{\partial x}(K_x h\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y h\frac{\partial h}{\partial y}) + R - P = S\frac{\partial h}{\partial t} \tag{2.19b}$$

where,

K_x and K_y are the hydraulic conductivity in x and y directions,

$Q_x = -K_x h \frac{\partial h}{\partial x}$ = the discharge per unit width of the aquifer in x direction [L^2T^{-1}],

$Q_y = -K_y h \frac{\partial h}{\partial y}$ = the discharge per unit width of the aquifer in x direction [L^2T^{-1}],

R = R(x,y,t) = recharge to the aquifer [LT^{-1}],

P = P(x,y,t) = pumpage from the aquifer [LT^{-1}]

S = specific storage.

Equations 2.19a and 2.19b can be derived by integrating Equation 2.17 over the Z dimension while taking into consideration (1) the Dupuit horizontal flow assumption, (2) Leibnitz rule and (3) the boundary condition at the phreatic surface. Detailed derivation procedure can be found in the book Hydraulics of Groundwater (Bear, 1979). A brief description of Leibnitz rule and the boundary condition at the phreatic surface is given here.

For an aquifer of thickness $B = Z_2(x,y,t) - Z_1(x,y,t)$ and given a scalar $h(x,y,z,t)$ defined on the aquifer, according to Leibnitz rule, we have:

$$\frac{\partial}{\partial t}\int_{Z_1(x,y,t)}^{Z_2(x,y,t)} h dz = \frac{\partial}{\partial t}(B\bar{h}) = \int_{Z_1}^{Z_2} \frac{\partial h}{\partial t} dz + h\Big|_{Z_2} \frac{\partial Z_2}{\partial t} - h\Big|_{Z_1} \frac{\partial Z_1}{\partial t} \qquad (2.20)$$

where, $\bar{h} = \frac{1}{B}\int_{Z_1}^{Z_2} h dz$.

Assuming a phreatic surface with accretion (Figure 2.8) is moving at a velocity of V_s, the continuity requirement yields the following equation:

$$(\vec{q} - \vec{N}) \cdot \vec{n} = n_e V_s \cdot \vec{n} \qquad (2.21)$$

where,

n_e = effective porosity,

$\vec{n}$ = the normal direction of the phreatic surface,

N = the rate of accretion [LT^{-1}].

Equation 2.21 states that the phreatic surface should move at a velocity such that the rate of water storage variation under the surface equals the rate of water exchange across the surface.

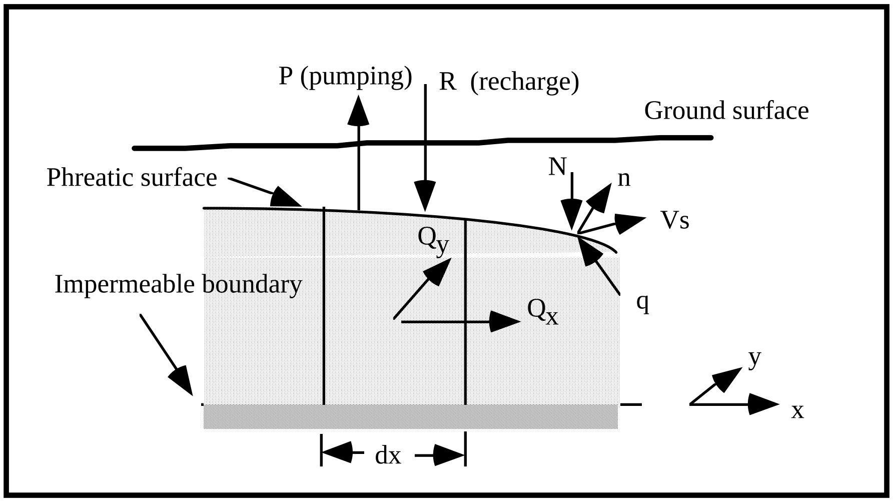


Figure 2.8. Water flow in a phreatic aquifer

The continuity equation for water flow in a confined, inhomogeneous anisotropic aquifer in two dimensions can be written as:

$$\frac{\partial}{\partial x}(T_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_y \frac{\partial h}{\partial y}) + R - P = S_S \frac{\partial h}{\partial t} \tag{2.22}$$

where,

h = h(x,y,t) = piezometric head of the aquifer at point x,y [L],

$T_x = T_x$ (x,y) = aquifer transimisivity in x direction [L^2T^{-1}],

$T_y =$ T_y (x,y) = aquifer transimisivity in y direction [L^2T^{-1}],

S_S = aquifer storativity. If the aquifer is inhomogeneous and isotropic, we have $T_x =$ T_y = T(x,y). If the aquifer is homogeneous and isotropic, we have T_x = T_y = T.

Equation 2.22 can also be derived by integrating equation 2.17 over the aquifer thickness while taking into consideration of Leibnitz rule and aquifer's top and bottom boundary conditions.

To solve Equation 2.19 (or Equation 2.22) numerically, the first step is to discretize the region of interest, i.e. to replace the continuous region for which a solution is desired by an array of points. These points are usually the center points of grid cells or corner points of a grid. Then either a finite element or a finite difference method is applied to these points to convert the differential equation into a set of linear equations. This set of linear equations are then solved by some appropriate solver. Detailed discussions on the subject of solving the equations using finite element and finite difference methods can be found in the textbooks by Becker *et al*. (1981), Remson *et al*. (1971), Desai (1979), Wang and Anderson (1982), Huyakorn and Pinder (1983), and numerous articles, e.g., Pinder and Gray (1977).

Because solving the groundwater flow equation in form of the equation 2.19 or 2.22 is complicated and computational intensive, models based on this type of equations such as Modflow (McDonald and Harbaugh, 1988) and GWSim4 (TDWR, 1974) are usually self-contained. Therefore, it is difficult to fully integrate this type of groundwater model with a geographic information system (GIS).

To avoid this difficulty, a map-based groundwater simulation model will be constructed. The map-based model is constructed on a polygon and the polygon's boundary line coverages. This model simulates groundwater flow by alternatively applying the continuity equation to the polygon objects and the momentum equation to the polygon boundary line objects. This section describes the concept of the map-based groundwater simulation model. A detailed model constructing and programming procedure are discussed in Chapter Four.

Figure 2.9 illustrates the concept of the map-based groundwater simulation model. The continuity equation (discretized in time) derived from Equation 2.19 or Equation 2.22 for a polygon object in Figure 2.9 can be written as:

$$\Delta t^t \cdot \left[A_i \cdot \left(R_i^t - P_i^t - Q_i^t\right)\right] + \sum_j V_{ij}^t = A_i \cdot S_i \cdot (h_i^t - h_i^{t-1}) \qquad (2.23)$$

where,

Δt^t = time interval at time step t,

A_i = area of cell i,

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, [LT^{-1}],

V_{ij}^t = volume of water that enters cell i through boundary j at time step t [L^3], The computation of V_{ij}^t is based on the momentum equation

(Darcy's Law) and a line integration technique to be discussed in Chapter Four.

S_i = the storativity (for a confined aquifer) or the specific storage (for a phreatic aquifer, of cell i [L^0T^0],

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].

Also in Figure 2.9, the momentum equation in the form of Darcy's law can be applied to each boundary line of the polygon objects and for a given boundary line object, the momentum equation can be written as:

$$\vec{q}_{ij}^{\,t} = -k_{ij}\frac{dh}{ds}\vec{s} \approx -k_{ij}\frac{h_j^{t-1} - h_i^{t-1}}{\Delta s_{ij}}\vec{s} \qquad (2.24)$$

where,

k_{ij} = hydraulic conductivity between polygons i and j [LT^{-1}],

$\vec{q}_{ij}^{\,t}$ = flux of water [LT^{-1}] across the boundary line between polygons i & j at time step t,

$\vec{s}$ = a unit vector pointing from the center of polygon i to that of polygon j,

Δs_{ij} = distance between the centers of polygons i and j [L],

h_j^{t-1}, h_i^{t-1} = water levels of polygons j and i at time step t-1 [L].

The logic of the map-based model is simple. Given the initial head levels of the polygons, Equation 2.24 is applied to each boundary line object to compute groundwater flow across each boundary line object. As a result of this computation, the water volumes (V_{ij}^t) transported in and out of each polygon object in the first time step are obtained. With V_{ij}^{t} known, the continuity equation (Equation 2.23) is then applied to each polygon object to calculate the water level at the end of first time step. This procedure of alternatively applying the momentum equation to line objects and the continuity equation to polygon objects will be repeated until the end of the simulation period.

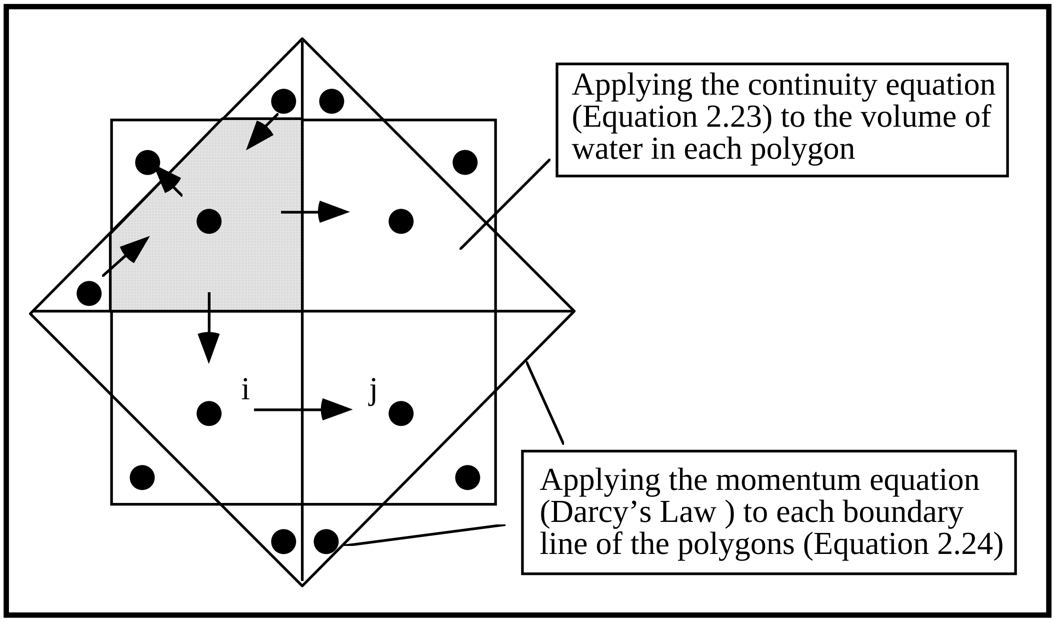

Applying the continuity equation (Equation 2.23) to the volume of water in each polygon
i
j
Applying the momentum equation (Darcy's Law) to each boundary line of the polygons (Equation 2.24)

Figure 2.9. The conceptual design of a map-based groundwater model

2.5. Chapter Summary

As it can be seen from this section, the surface water flow processes (overland flow, river flow etc.) can be simulated one region at a time when the water exchange between subwatersheds can be represented by a set of time-series data. For this reason, surface water flow processes for a subwatershed can be simulated by making a sequence of functional calls in a certain order.

Also, it can be seen from the equations presented above that the data supporting these equations can be categorized into two types, static and dynamic. Static data do not change throughout the whole simulation period, while dynamic data vary from one time step to another. The dynamic data type itself can be further divided into two types, predetermined and run-time determined. Predetermined dynamic data, such as rainfall time-series, are known before running the model. Run-time determined dynamic data, such as the groundwater flow velocity field used to compute Courant number ($Co = \frac{V \cdot \Delta t}{\Delta x}$) for a given time step, are not known until the simulation of previous time steps is completed. The reason for making this data classification is that different types of data may require different data structures for efficient data storage and retrieval. Detailed discussions about the treatments of different data types are presented in Chapter Three.

The map-based groundwater simulation model is constructed by applying the finite difference form of the continuity equation (Equation 2.23) to the water volumes of polygon objects and the finite difference form of the momentum equation (Equation 2.24) to the polygon boundary line objects. Because the spatial features are grouped into line and polygon coverages in ARC/INFO, separately applying these two equations to these two types of objects greatly simplifies the solution procedures.

Chapter Three. A Map-Based Surface Water Flow Simulation Model

3.1. Introduction

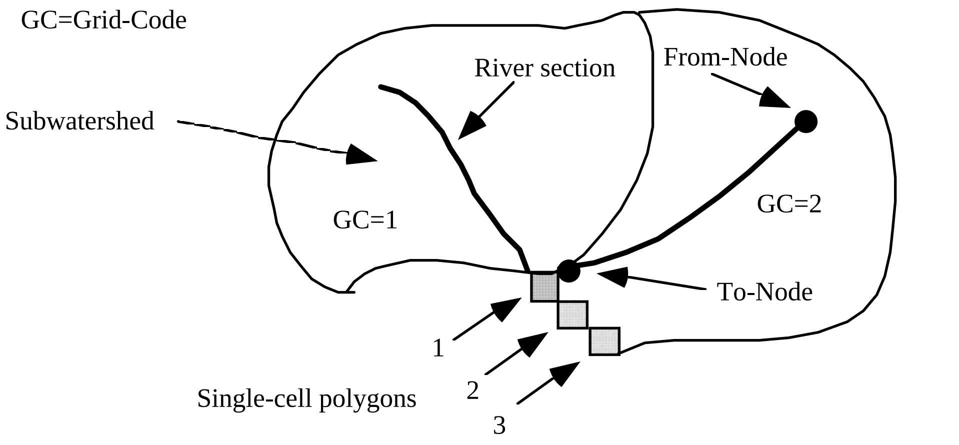
Through the construction of a map-based surface water flow simulation model (SFlowSim) for the Niger River Basin in West Africa, this chapter demonstrates how the three elements (maps, data sets, and programs) of a simulation model are integrated.

The map-based surface water flow simulation model can be used for the water resources assessment and management of a river basin. The model can be applied to any area where a digital elevation model (DEM) is available or to a region whose river basin polygons and river lines are available. Listed below are the tasks that this model can accomplish:

- Simulate river flow time-series based on precipitation defined on watershed polygons or water surplus defined on soil units. After applying the simulation model to a river basin, the flow rates are available at the From-Node and To-Node (termed FFlow and TFlow, respectively, in the model) of each river line. The From-Node and To-Node represent the starting and ending points of a river section line (Figure 3.1). The Post-processor of the simulation model can also interpolate flow rates to any user defined points along the river section.
- Estimate the flow contribution of each subwatershed (termed PFlow in the model).
- Allow reservoir objects to be added to a river section and simulate their effects.

- Allow diversion points to be set on a river section and simulate their effects on downstream river flows.
- Plot a longitudinal flow profiles along a user specified river section.
- Plot the flow time-series (FFlow(t) and TFlow(t)) of a river section or the flow contribution time-series of a subwatershed.
- Allow a user to clip out part of a river basin to create a sub-model so that a more detailed study of the selected subregion can be performed.
- Optimize model parameters to facilitate the calibration of the simulation model.
- Allow a user to modify the modeling conditions directly from the model base maps.
- Integrate with the map-based groundwater simulation model to simulate the flow interaction between surface and subsurface water flows.

Three classes of objects are essential for this map-based surface water flow simulation model. They are (1) a line class created to represent river sections, (2) a polygon class created to represent the subwatersheds associated with the river sections, and (3) a point class created to represent reservoirs or diversion points within any river section. Each river section is an instance (object) of the line class, with its states being stored in a line value attribute table and its behavior described by some flow routing equations. As each record is added to the line attribute table, a new river section object is created. The same thing can be said for the river basin polygon and reservoir point classes.



(1) Assuming single-cell polygons 1, 2, 3, all have a Grid-Code (GC) value of 1
(2) Running ARC/INFO DISSOLVE function will dissolve cell 1 with subwatershed GC=1, but not single-cell polygon 2, and 3, because they don't share any common boundary lines with subwatershed GC=1.
(3) After running the AVENUE program SFdslv.pre, single-cell polygons 2, and 3 will have their Grid-Code reassigned to 2.
(4) Running ARC.INFO DISSOLVE function again will dissolve cell 2, and 3 with the subwatershed GC=2, because they now share at least one common boundary line.

Figure 3.1. Solving the problem of one-line-to-many-polygons

3.2. MODEL CONSTRUCTION PROCEDURE

Based on their functions, the programs in the map-based surface water flow simulation model can be grouped to form three modules: pre-processor, processor and post-processor. The pre-processor is used to create the model objects, construct model base maps, create time-series data tables and process time-series data. The processor is used simulate water flow on the rivers and subwatersheds. The post-processor is used to analyze and display model results. The post-processor also contains utility programs that can be used to modify model maps and modeling conditions and to perform map operation and database management tasks. Figure 3.2 shows the components of the map-based surface water flow simulation model (SFlowSim) and its construction procedure. The following section discusses the functions of the pre-processor and the construction of model maps.

3.2.1. Preparing Maps for a Map-Based Simulation Model

The maps (river and basin coverages) of a map-based simulation model are constructed by applying the river basin delineation procedure (Maidment, 1994) to a digital elevation model (DEM). As a result of running this delineation procedure, two map coverages are produced. One is a line coverage representing the rivers and the other one is a polygon coverage representing the drainage areas of the rivers. Figure 2.2 shows the rivers and subwatersheds of the Guadalupe River Basin created by delineating a 3" (with a grid cell size of 92.7x92.7 meters) DEM of the region. These river line and subwatershed polygon coverages are imported into an ArcView project and processed by a set of AVENUE programs (pre-processor). The processed river sections form a river network whose members have a one-to-one relation with the subwatershed polygons associated with the river network. The pre-processor programs and simulation model's basic assumptions are discussed below.

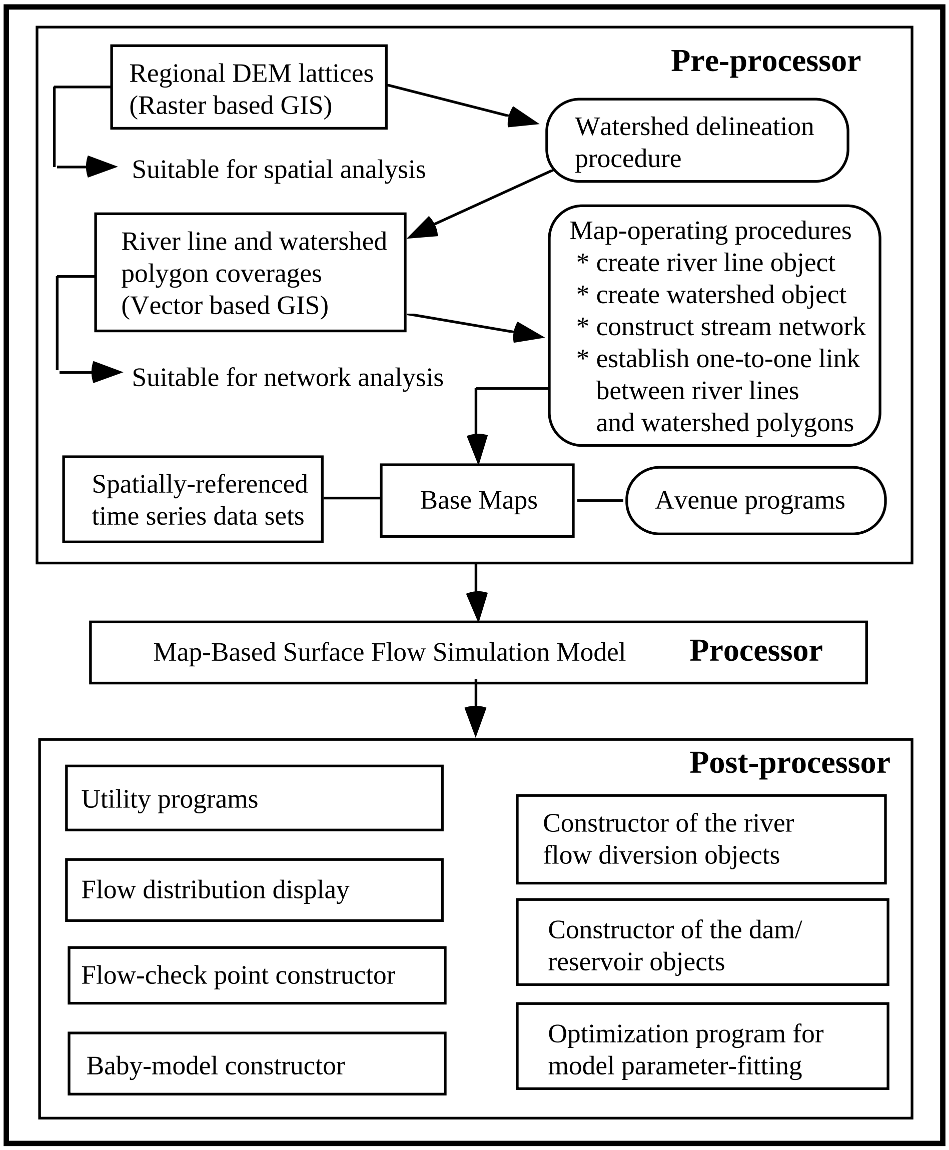


Figure 3.2. Components of the map-based model SFlowSim

3.2.2. Basic Assumptions for a Map-Based Simulation Model

A map-based surface water flow simulation model is constructed based on the following assumptions about the river network and subwatersheds:

(1) Each subwatershed contains one and only one river section,

(2) The simulated quantities such as water flow, chemical mass etc., cannot be transported between subwatershed polygons unless through the river sections that connect them. When the surface water simulation model is integrated with groundwater simulation model in Chapter Five, this condition will be modified to allow water in an integrated model to flow from one subwatershed to another subwatershed through the aquifer underneath them.

(3) For a given river section, the From-Node is always at the upstream end and the To-Node, at the downstream end.

(4) The vertices of a given line[1] are indexed in such a way that a zero index vertex is associate with the From-Node, and for a line of n+1 vertices, the vertex with index n is associated with the To-Node.

Condition (1) is imposed to ensure the one-to-one relationship between the descriptive features of polygon and line coverages. This condition is reasonable because one river subwatershed can contain one and only one river section. Condition (2) is imposed so that network routing is possible. Because river basin boundary lines are formed by the points where elevation potential reaches local maximum, condition (2) is consistent with the definition of a river basin. Condition (2) is therefore reasonable when imposed on water and substances carried by water in a river basin. Condition (3) is imposed to create a river network. Condition (4) is imposed to enable the dynamic segmentation of a line so that any given point on the line can be identified by a fraction representing the ratio between the distance of that point to the From-Node and the total length of the line.

[1] . In ARC/INFO, a line (arc) is represented as a connected set vertices.

3.2.3. Construction of Basic Maps

The vector GIS coverages created by the grid-based watershed delineation procedure (Maidment, 1994) may not meet the assumptions listed above because the raster-to-vector conversion procedure does not always ensure a one-to-one relationship between river lines and subwatershed polygons. The problems to be corrected are usually one-line-to-many-polygons and one-polygon-to-many-lines. The problem of one-line-to-many-polygons is usually caused by the existence of single-grid-cell (single-cell) polygons.

Figure 3.1 shows an example of the problem created by the single-cell polygons. To correct the problem, these single-cell polygons need to be eliminated by dissolving them into the appropriate subwatershed polygons. ARC/INFO provides a DISSOLVE function that will dissolve polygons that (1) have the same value of a given field (e.g. Grid-Code) and (2) share a boundary line. For the single-cell polygons that have the same value of Grid-Code with a subwatershed polygon but do not share any boundary lines with the subwatershed, an AVENUE program is written to reassign to each of these single-cell polygons the Grid-Code of a subwatershed that shares the same boundary line with it. The AVENUE program will first identify and put all single-cell polygons into a list. Then for each member of the list, the program uses LPoly_ and RPoly_ attributes of the polygon's boundary lines to identify one of its adjacent subwatershed polygons, whose Grid-Code value is then assigned to that of the single-cell polygon. The fields LPoly_ and RPoly_ of a line (arc) attribute table hold the machine-assigned IDs of left polygon and right polygon, respectively. After all the single-cell polygons have their Grid-Code reassigned, the DISSOLVE function of the ARC/INFO program is reapplied with Grid-Code as the dissolving value to eliminate the single-cell polygons. This procedure solves the problem of one-line-to-many-polygons.

The problem of one-polygon-to-many-lines can occur in the situations of (1) split river line segments in a single subwatershed, (2) multiple river line segments within one subwatershed, and (3) incorrect node indexing on the river line coverage. Figures 3.4 and 3.5 illustrate the examples of these situations. One of the tasks of the pre-processor is to eliminate the problem of one-polygon-to-many-lines by running a series of map-processing programs to modify the ARC/INFO coverages created by the watershed delineation procedure. After modification, these two coverages (river line and subwatershed polygon) will meet the four conditions listed in section 3.2.2. and be ready for use by the map-based flow simulation model. The functions of each program in the pre-processor are described below:

1. Creating River Line and Subwatershed Polygon Objects [SFmdfld.pre]

This program adds attributes to the standard ARC/INFO arc attribute table (AAT) and polygon attribute table (PAT) to create river line and watershed polygon objects. The attributes of a watershed polygon object and a river line object are listed in Table 3.1. and Table 3.2. Detailed explanations of these attributes will be given when they are used.

The states of an object are used in this simulation model to describe the physical features of the object and/or to control the processes in the simulation programs. These states can be used in a program as either a regular variable or logical variable or both. When a state of an object is used to describe a physical parameter of the object, it is treated by the simulation program as a regular variable and the program is interested only in the return values of that state (variable).

Table 3.1. The Attributes of a Subwatershed Polygon Object

	State	**Function (What the attribute represents)**
1	Shape	Pointer pointing to the map location of a polygon object
2	Area	Area of a watershed polygon (m^2)
3	Perimeter	Perimeter of a watershed polygon (m)
4	Cover_	Polygon ID, based on which pointers to 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 field linking a subwatershed polygon with the river line section it contains
7	Pisdone	0 indicates the polygon has NOT been simulated, non-zero, otherwise, and the value equals the number of polygons between this polygon and the outlet
8	PFlow	Local flow contribution, for unsteady state, it gives the average flow rate over the models simulation period (m^3/s).
9	FlowTime	Average time it takes for flow starting from an element (a grid cell) on a subwatershed to reach the outlet point of the subwatershed (s)
10	DiffNum	Diffusion number of PFlow indicating the extend of the PFlow spread-out
11	V	Overland flow velocity (m/s)
12	ThmRslt	For thematic plotting of a selected attribute at a given time step
13	Hasgrd	0 indicates no groundwater flow model exists underneath, 1, otherwise
14	ToGrd	The percentage of flow recharging to the groundwater system
15	MFL	Mean flow length of a subwatershed (m)
16	Msurp	Soil moisture surplus (m^3/s) (subwatershed river flow contribution)
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]

Table 3.2. The Attributes of a River Line Object

	State	Function (What the attribute represents)
1	Shape	Pointer pointing to the map location of an object
2	FNode_	Node ID of the starting point of a river line section
3	TNode_	Node ID 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 a 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	0 indicates a river line has NOT been simulated, non-zero value indicates otherwise, and the value equals the number of joints between this river line and the basin outlet
11	IsHead	1 indicates a river line is a head section (section with no upstream river lines)
12	IsOutlet	1 indicates a river line is a outlet section (last section on a stream network)
13	FFLOW	The flow rate at the FNode of a river line (m^3/s)
14	TFLOW	The flow rate at the TNode of a river line (m^3/s)
15	DFlow	The water withdraw on a 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 to the TNode of a river line along its longest upstream flow path (s)
19	MELE	Mean elevation (definition to be decided) of a river line (m)
20	HasDam	0 indicates there is no dam in the river line, non-zero indicates otherwise, and the value is the dam-id of the first dam on the river line
21	Hasresp	0 indicates no response function is available, non-zero value indicates otherwise, and the value equals the number of the elements in the response function
22	Hasgrd	0 indicates no groundwater flow model exists underneath, 1 indicates otherwise
23	togrd	The percentage of river flow that goes to groundwater recharge

When a state of an object is used by a program for procedure-control purpose, the state is treated by a program as both a logical variable and a regular variable. In this case, the program is interested in both the return values of the state (variable) and the ranges which these values fall into. When a state is used by a program for the purpose of procedure control, a zero-value usually indicates FALSE/NO, a non-zero value usually indicates TRUE/YES. In addition, the non-zero value is also used as a pointer to either a new function, another object, or values of the physical characteristic of the object. For example, when the state, HasDam of a river line object returns a value zero, it indicates that there is no dam on the river line. When HasDam returns a non-zero value, it indicates there is at least one dam located on the river line and the value is also the identification number (ID) of the first dam on that river line.

Formulating such a design minimizes the number of states of an object so that the number of fields of the database table can be minimize to save the computer memory space and improve program efficiency.

2. Sorting Nodes and Vertices of River Lines [SFsortr.pre]

This program sorts the nodes of river line sections so that the From-Node (FNode) of a river line section is always on the upstream end and To-Node (TNode) is always on the downstream end. The program also sorts the vertices of a river line so that the vertex with zero-index is located at the FNode of the line.

This program first identifies all the river outlet segments and puts the IDs of these river segments into a list. Then, for each member (outlet river line segment) of the list, the program performs the following procedure. Starting with a member on the list, the program traces first in the upstream and then in the downstream direction on the river network with the member as its outlet segment. When moving in the upstream direction, the program travels from arc to arc according to the connectivity established by the FNode and TNode of the arcs (river line sections), corrects the incorrectly indexed nodes, and identifies the river junction sections until a head river section is reached. A head river section is defined as the first river section in a river network, i.e., the river section with no upstream river sections. A junction section is defined as a river section with more than one immediate river sections. The program then starts to move downstream and stops at each junction section to see if all its upstream river section nodes have been sorted. If not, the program stops moving downstream and starts to move upstream again along another branch of the network that has not yet been checked by the program. The program repeats these upstream and downstream movements until the outlet section is reached.

Figure 3.3 illustrates the program logic and Figure 3.4. shows an example result of applying the SFsortr.pre program to a stream reach network.

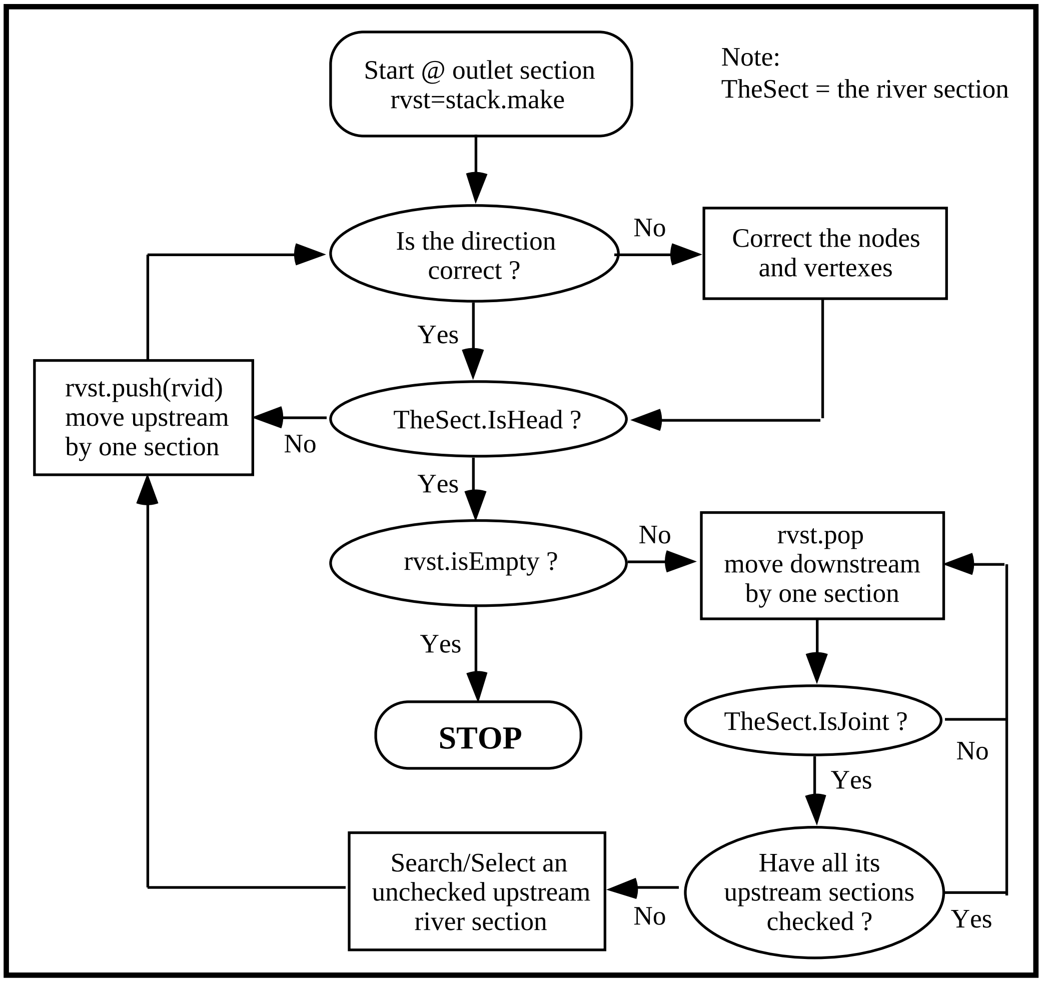

Start @ outlet section
rvst=stack.make
Note:
TheSect = the river section
Is the direction correct ?
No
Correct the nodes and vertexes
Yes
rvst.push(rvid) move upstream by one section
TheSect.IsHead ?
No
Yes
rvst.isEmpty ?
No
rvst.pop move downstream by one section
Yes
STOP
TheSect.IsJoint ?
No
Yes
Search/Select an unchecked upstream river section
No
Have all its upstream sections checked ?
Yes

Figure 3.3. Program flow chart for Pre-processor Sfsortr.pre

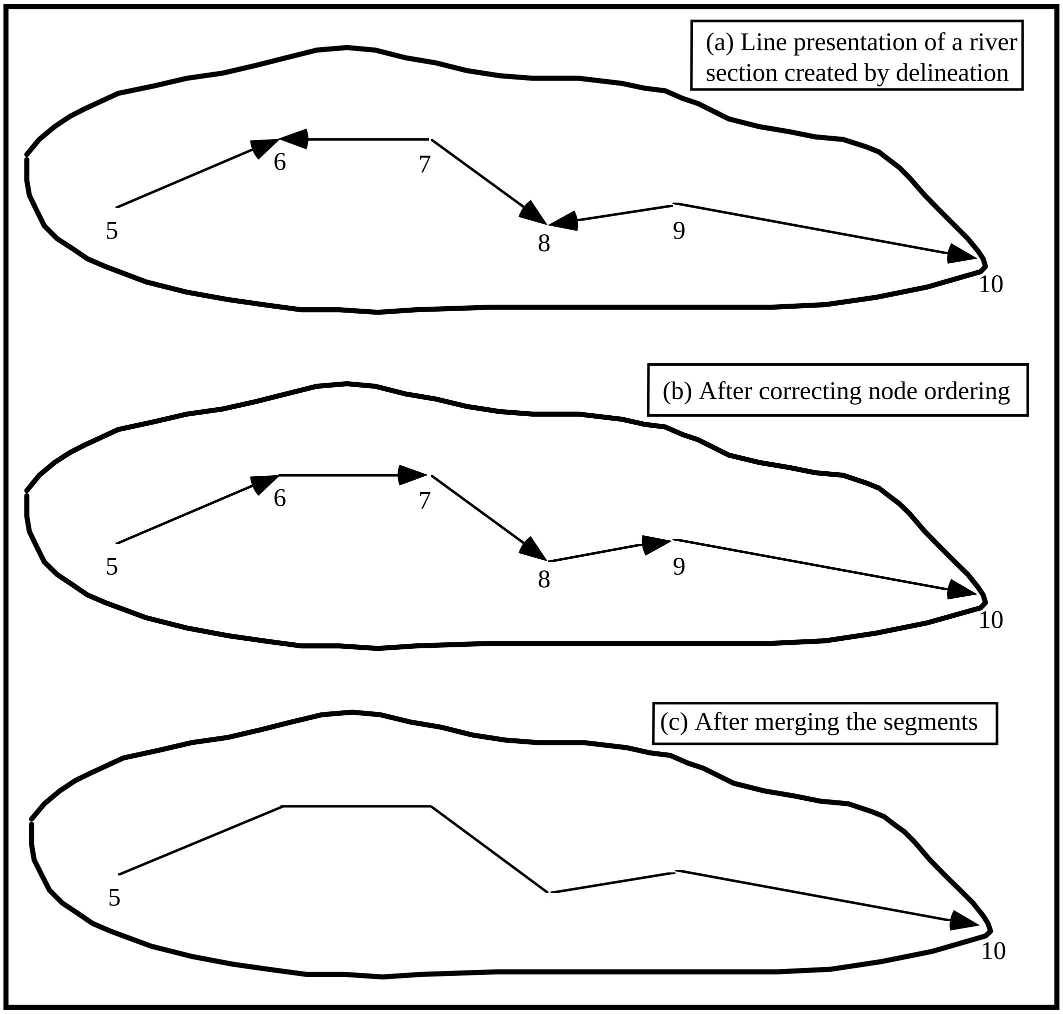

(a) Line presentation of a river section created by delineation
5
6
7
8
9
10
(b) After correcting node ordering
5
6
7
8
9
10
(c) After merging the segments
5
10

Figure 3.4. Merging multiple river segments into one river section

3. Cleaning the River Line Splits [SFsplit.pre]

The purpose of the river split cleaning program is to remove any river splits that are contained in one subwatershed polygon so that each subwatershed polygon contains only the river segments that can form one single line. A split is defined as three river segments forming an "Y" shape that are contained by a single subwatershed (Figure 3.5). Without correction, the polygon that contains split river lines will have a one-to-many relation with the river lines. The splits are caused by the conversion procedure used transform a grid coverage to a vector line coverage. When using the GRIDLINE or STREAMLINE functions to convert a delineated grid lattice to a line coverage, the cells (referred to as joint-cells) at the locations where three subwatersheds joint can assume any ID of these three subwatersheds. If the ID-values assigned to the river line segments at the joint cell are inconsistent with those assigned to the subwatersheds, the problem of line split will occur. Although the lengths of these split lines are typically small (1 to 1.414 times the grid cell size), each one of them still forms a record in the spatial database file. Because of their small sizes, it is difficult to detect and correct them manually.

The split-cleaning program works in the following way. For each polygon in the river basin coverage, the program searches through features on the river line coverage to select all the line segments that are contained within the polygon and sends the selected lines to a list. If the number of line segments selected is greater than one, then for each line segment in the list, the program saves its FNode number. This FNode number is then used to select all the line segments in the list that have that FNode as their TNode. If the number of selected lines is greater than one, then an upstream split is found. To correct the problem, for each one of the split segments, its FNode number is used to trace upstream to find its upstream segment. Once an upstream segment is found, its stream ID is used to reset the stream ID of the split river segment. Figure 3.5 illustrates the correction of a split.

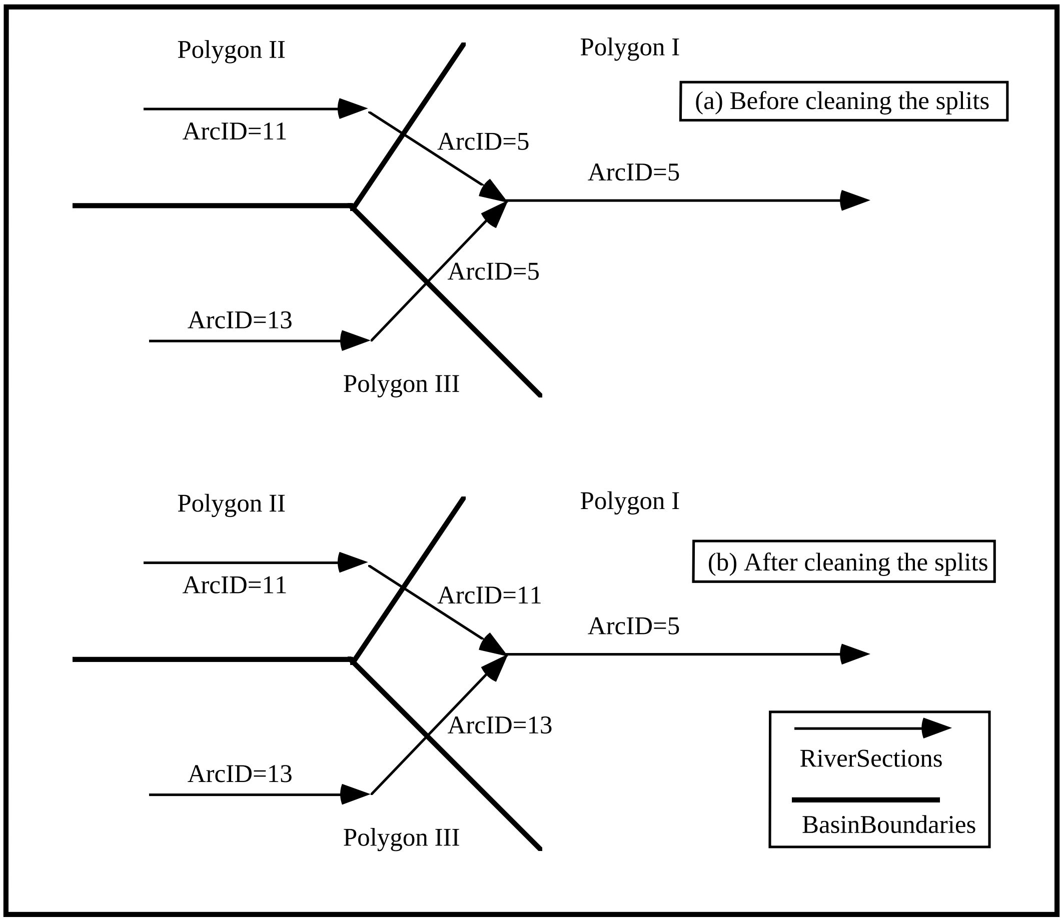


Figure 3.5. Rearranging river sections

3. Merging Multiple River Segments into one River Section [SFmg1ln.pre]

The purpose of the segment merging program is to merge any multiple line segments contained by a single subwatershed polygon into one single line object so that each subwatershed contains only one line section. To do this, the program first creates a new line coverage (NewCov) from the old river line coverage (OldCov). This NewCov is used to hold the river line objects that will be merged. Then, for each polygon in the subwatershed coverage, the program searches through the river line coverage (OldCov) to select the line segments that are contained by the polygon. If the number of selected records equals one, the program simply copies the river line object to the NewCov database. If the number of lines selected is greater than one, the program will first check through these lines to make sure they are connected to each other in a correct order from upstream to downstream. If they are not, the program will correct the problem based on the TNode and FNode indexes of each line segment. These line segments are then merged and copied to NewCov. To merge these line segments, the nodes and vertices of each line segment are extracted and put into a list based on the order of the line segment. The merged line is then created from this point list.

Upon the completion of the program, SFmg1ln.pre, the NewCov line coverage, and the subwatershed polygon coverage have the following properties: (1) each subwatershed polygon in the basin polygon coverage contains one and only one river line section, (2) each river line section is contained by one and only one subwatershed polygon, (3) the line sections are all connected in the order with FNode on the upstream end and TNode on the downstream end, and (4) all the vertices of a line are correctly indexed with the zero indexed node at the FNode. Figure 3.4 shows an example result of applying SFsortr.pre and SFmg1ln.pre to a river line coverage.

3.3. Database Design for Spatially-Referenced Time-Series Data

Because the simulation model is constructed to simulate surface water flow over both space and time, a database with a data structure that allows efficient storage and retrieval of spatially-referenced time-series data needs to be developed before the simulation model construction can start. This section discusses the design of such a database and how spatially-referenced time-series data are managed in this map-based surface water flow simulation model.

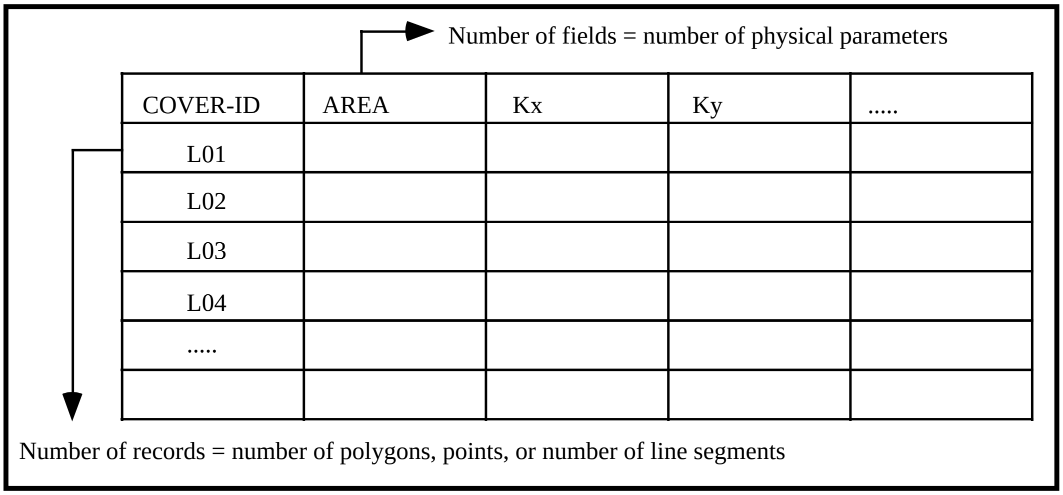
3.3.1. Two Types of Spatially-Referenced Data

Based on the number of values a physical parameter can have for one location, spatially referenced physical data for a surface and ground water simulation model can be divided into two categories, one value per location (or one-to-one), and many values per location (or one-to-many). The examples of one-to-one data type are: the area of a polygon, the latitude and longitude of a point, or the length of a river section. Time-series data are of the one-to-many data type. Examples include: precipitation records, runoff records, and water level records.

During a modeling process, in order to store and retrieve these two types of data efficiently, different data structures and retrieval methods need to be used. In designing these data structures and data management systems, it is assumed that a location feature, whether it is a polygon region, a line river, or a point runoff station, can be uniquely identified by a location ID (COVER-ID).

3.3.2. Data Structure for Data of One-to-One Type

Data of the one-to-one type can be stored as location attributes attached to a conventional GIS coverage. In this type of database, location ID is used as a key field for data storage and it is also the only information needed to retrieve a data value of a given physical parameter. The data structure of a one-to-one data type is illustrated below in Figure 3.6.


Number of fields = number of physical parameters
Number of records = number of polygons, points, or number of line segments

COVER-ID	AREA	Kx	Ky	.....
L01				
L02				
L03				
L04				
.....				

Figure 3.6. Database structure for the one-to-one data type

3.3.3. Data Structure for Data of the One-to-Many Type

Data of the one-to-many type can be stored in separate databases with one database file for each parameter at each location. The file structure of the one-to-many data type is illustrated in Figure 3.7. In this type of databases, a file name should reflect the location ID and the name of the physical parameter that it stores. The number of files for a given parameter will be equal to the number of spatial features where the time-series data are available. However, because the number of spatial features is usually large causing large number of files to be created, this type of data structure is inefficient for data storage and retrieval.

To avoid creating and managing a large number of files, another type data structure is designed and used in this study to manage the spatially-referenced time-series data. According the this design, a single data file is created for each spatially-referenced, time-varying attribute. In the file, the time-series data defined on a map is stored in a rectangular table data structure (i.e. the data structure of a relational-database), in which, the columns (fields) corresponds to the spatial features on a map and rows (records) corresponds to the time steps. Figure 3.8 illustrates this type of data structure. The data structure is designed in such a way that a one-to-one relationship exists between the fields of a time-series database and the spatial features of the map on which the time-series data are defined. The header (field name) is constructed by concatenating some letters related to the name of the location with a unique location ID. The letters can be the abbreviation of either the name of the attribute or the field name of the location ID in the spatial database table.

The key field for this type of database is TIME for time-series data, and STAGE-ID for multiple-stage data. To retrieve a data value for a given physical parameter, one can first get the Location-ID from an appropriate map coverage, then use the parameter name together with the location ID to open the appropriate file and select the field associated with the location, and finally, use the STAGE-ID or TIME value to locate the correct record for data retrieval.

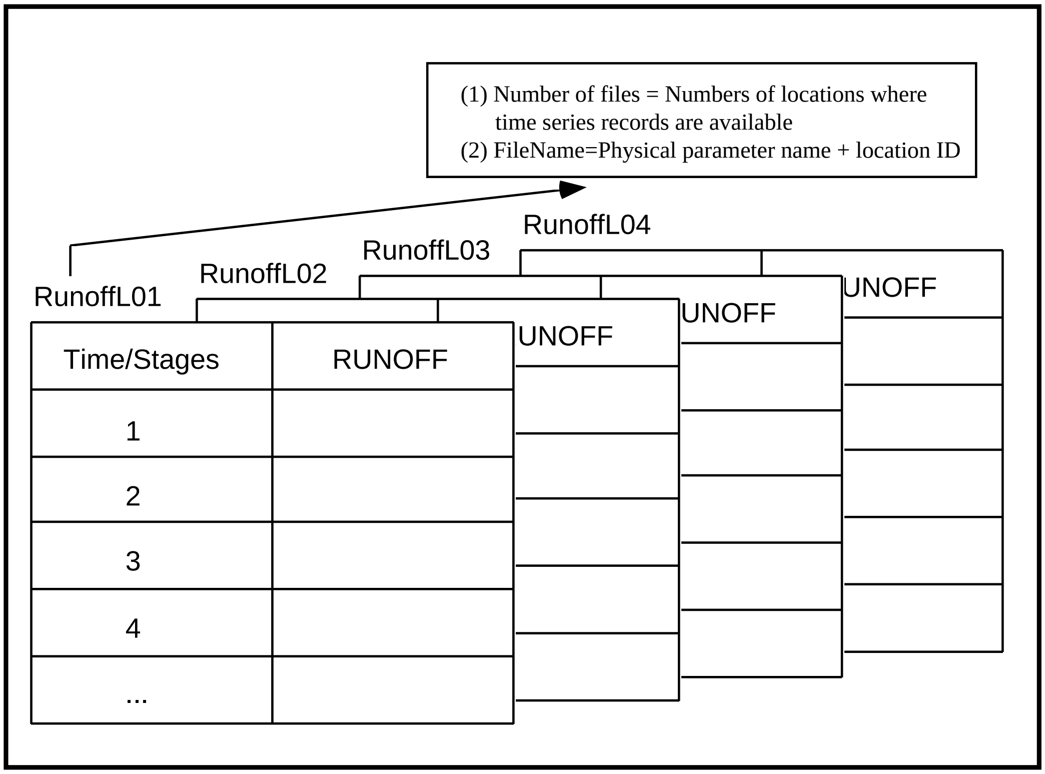

(1) Number of files = Numbers of locations where
time series records are available
(2) FileName=Physical parameter name + location ID
RunoffL04
RunoffL03
RunoffL02
RunoffL01
UNOFF
UNOFF
UNOFF
Time/Stages
RUNOFF
1
2
3
4
...

Figure 3.7. The database files for the one-to-many data type

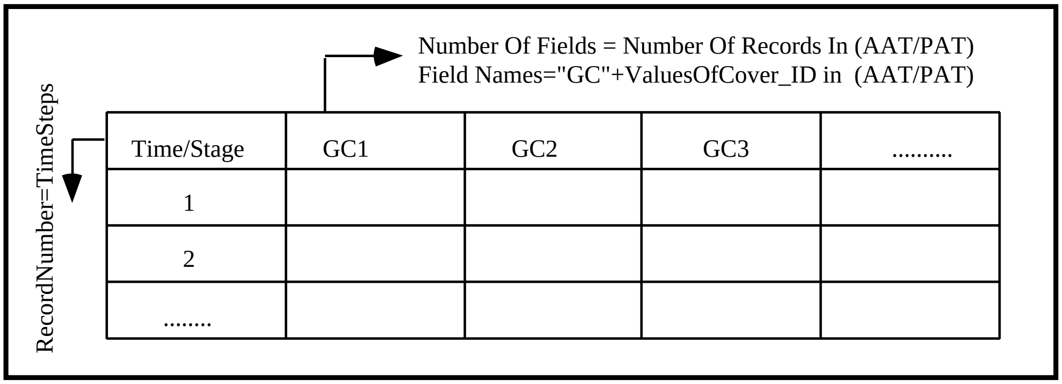

Number Of Fields = Number Of Records In (AAT/PAT)
Field Names="GC"+ValuesOfCover_ID in (AAT/PAT)
RecordNumber=TimeSteps
Time/Stage
GC1
GC2
GC3
....
1
2
....

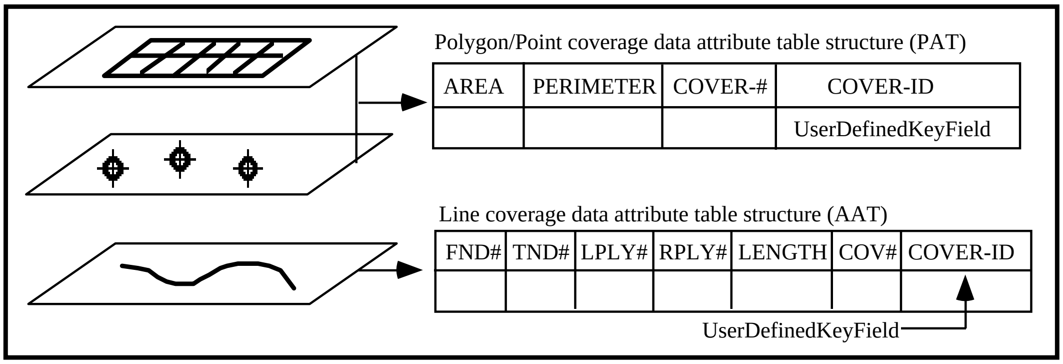
Figure 3.8. The database structure for one-to-many data type

3.3.4. Connections between Databases and the GIS Feature Attribute Tables

In ARC/INFO, feature attribute tables (FTAB) are INFO files associated with each feature type. For a given coverage, a FTAB is created from a template of standard items based on the feature types of the coverage. Figure 3.9 shows the data structures for FTABs associated with each type of coverage.

As stated above, a single database with the template shown in Figure 3.6 can be created to store all the physical data of one-to-one type. The table is then joined through a linking field (usually the COVER-ID) to the FTAB. Once this table merge procedure is completed, the value of a given parameter at any location can be retrieved using the value of the key field (COVER-ID). Because the data items are merged with the value attribute table of a GIS coverage, data retrieval and modification procedures are straightforward.

For the data of one-to-many type, a separate database table with the template shown in Figure 3.8 is created. As this type of database is not physically joined with the FTAB of a map, its data retrieval and modification at a given location need are done through the linkage created by AVENUE programs. To retrieve a time-series record, information about the parameter name, location ID, and the TIME or STAGE-ID are needed. The parameter name and location ID jointly tell the program which database file to open and which field to select, and TIME allows the program to select the correct record number for data retrieval. Figure 3.10 illustrates the data flow path for spatially-referenced time-series data.



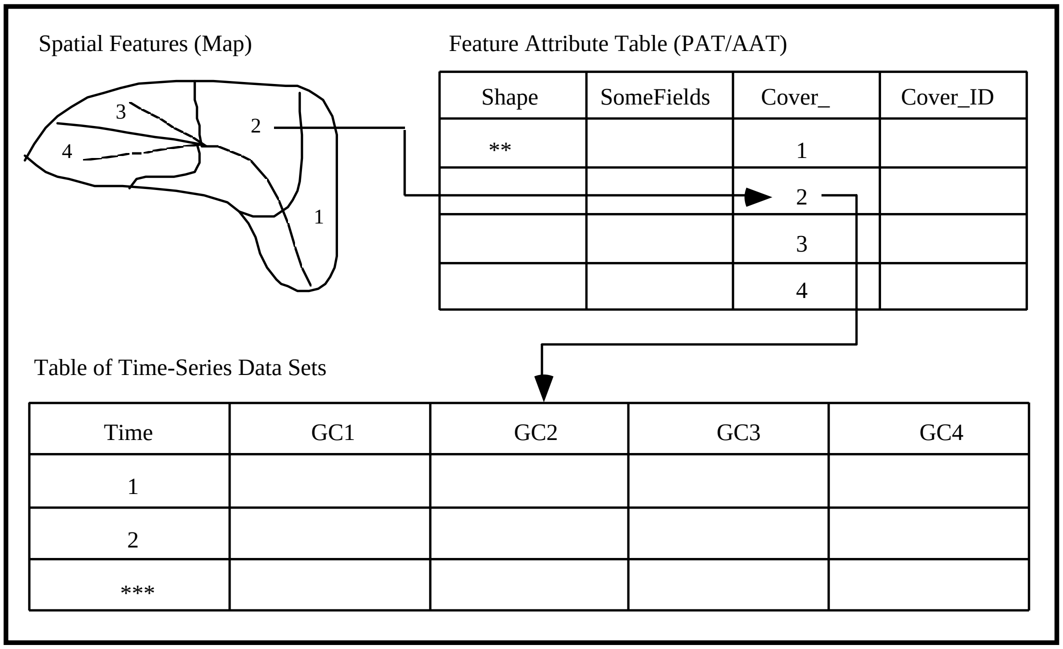
Polygon/Point coverage data attribute table structure (PAT)

AREA	PERIMETER	COVER-#	COVER-ID
			UserDefinedKeyField

Line coverage data attribute table structure (AAT)

FND#	TND#	LPLY#	RPLY#	LENGTH	COV#	COVER-ID

Figure 3.9. Feature attribute tables in ARC/INFO



Feature Attribute Table (PAT/AAT)

Shape	SomeFields	Cover_	Cover_ID
**		1	
		2	
		3	
		4	

Table of Time-Series Data Sets

Time	GC1	GC2	GC3	GC4
1				
2				
***				

Figure 3.10. Connection between maps and spatially-referenced time-series data

3.4. Construction of the Surface Flow Simulation Program

The map-based surface water flow simulation model simulates flow on the river network based on the flow-routing equations introduced in Chapter Two and the equations to be introduced in the following sections. In the model, water movement in a river network is simulated at three levels: (a) watershed-to-river water movement defined on a subwatershed polygon, which transfers either the precipitation or the soil-moisture surplus into the local stream flow contribution, PFlow(t), (b) water movement on a river section contained in a subwatershed polygon, and (c) water movement between river sections on the river network (inter-section water movements). The algorithm that simulates the water movements between river sections also performs network analysis on the river network to determine an appropriate sequence for simulating each subwatershed. The algorithms that simulate water movements (a) and (b) are problem dependent and are flexible. For this reason, this map-based surface water flow simulation model can easily be modified to simulate other water flow related phenomena, such as non-point source pollution analysis so long as the simulation module for PFlow(t) is properly modified. The following sections show how water movement is simulated in this map-based surface water flow simulation model.

3.4.1. Simulating Water Movement between River Sections

The following facts and concepts are used to construct the object-oriented algorithm that simulates water movement on the river networks.

(1) A line coverage has been constructed using the method described in Section 3.2.3. to represent the river network.

(2) A polygon coverage has been constructed using the method described in Section 3.2.3. to represent subwatershed polygons.

(3) The features in the river line and subwatershed polygon coverages have a one-to-one relationship so that the features of these two coverages are connected through a common key field.

(4) Corresponding to each feature on the line and polygon coverages there is a record in the river line attribute table (RFTAB) and polygon feature attribute table (PFTAB) associated with their respective coverages. Routing through the river network and subwatersheds corresponds to processing though the records in the RFTAB, and PFTAB.

(5) The water movement on the stream network is based on the principle of continuity (e.g. Equations 3.1a and 3.1b) and the connectivity of the network maintained by the From-Node and To-Node of each river line object.

As shown in Tables 3.1 and 3.2 and in Figure 3.11, the PFlow (PFlow(t) for unsteady state) associated with a subwatershed polygon object is used to represent the object's local flow contribution. FFlow and TFlow (FFlow(t) and TFlow(t) for unsteady state) associated with a river line section are used to represent the river flow rate at FNode and TNode of the river line object. Besides applying the continuity equations (Equations 3.1 and 3.2) to the river network to simulate the water movement between the river sections, this module also determines a the order in which subwatersheds will be simulated.

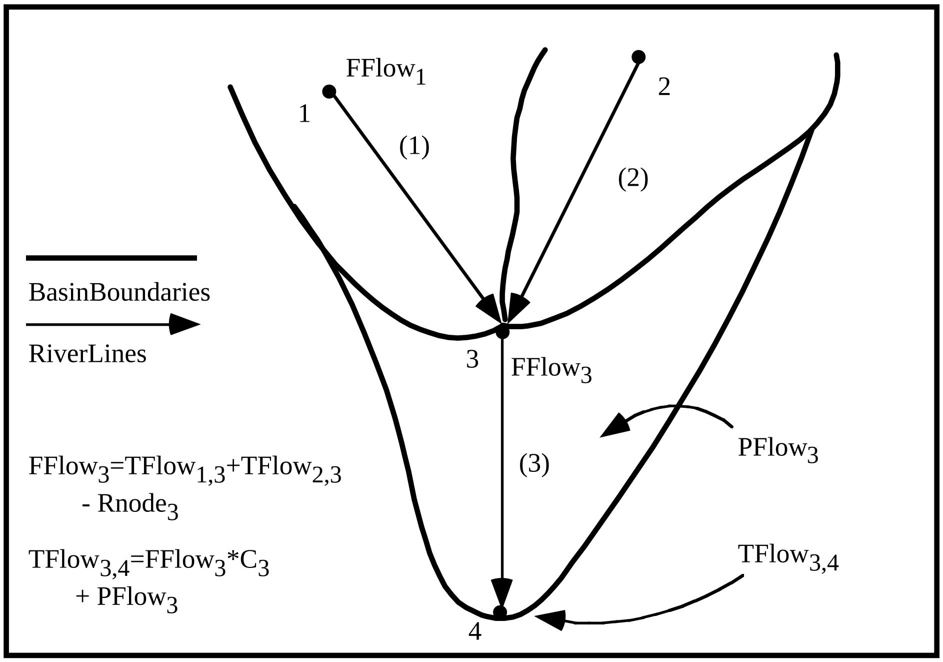


Figure 3.11. River basin flow routing system

The sequential order is constructed using a stack-based algorithm. A stack is an array (collection) that allows the Last-In-First-Out (LIFO) access to its elements. The algorithm is described below (See Figures 3.12a and 3.12b).

When simulating the water movement between the river sections, each stream line and each subwatershed are treated as entities. The effect that a stream section and its subwatershed have on the stream network can be replaced by a value, TFlow of the river section for steady state, or by a vector TFlow(t) for unsteady state. In other words, as soon as TFlow, (or TFlow(t) for unsteady state) of a subwatershed is acquired, the river section as well as the streams upstream of the section can be cut-off from the remainder of the network.

As the algorithms used to simulate the physical processes in terms of PFlow, FFlow, and TFlow depend on the modeling conditions and methodology used, they can be different from one model to another. The flow simulation algorithms used in this research are presented in sections 3.4.2, and 3.4.3. To illustrate how water movements between river sections are simulated, it is assumed that (1) the PFlow of a subwatershed polygon object is retrievable by sending a request to the polygon object, and (2) FFlow and TFlow can be computed based on the PFlow defined on the subwatershed polygons and the connectivity of the river network. Under steady state, the relationships (Equations 3.1 and 3.2) between FFlow, PFlow, and TFlow can be derived from the principle of mass conservation and the connectivity of the river network (Figure 3.11).

Given a river section *i*, we have:

$$FFlow_i = \sum_k TFlow_{k,i} + R_i \tag{3.1a}$$

if this river is not a head section, or

$$\mathrm{FFlow_i} = \mathrm{PFlow_i} \bullet \frac{\mathrm{Thrd_i}}{\mathrm{Area_i}} \tag{3.1b}$$

if this river is a head section, where,

i = a river section’s ID (=FNode#),

j = a river section’s TNode#,

k = the ID of river sections that have node i as their To-Nodes,

$FFlow_i$ = flow rate at From-Node of river section *i* (m^3/s),

$TFlow_{k,i}$ = flow rate at To-Node (i) of river section *k* (m^3/s),

R_i = source term (pumping or recharging) at node *i* (m^3/s),

$\mathrm{Thrd_i}$= threshold defining a river starting point used in basin delineation,

Area_i= area of the subwatershed that contains river section *i* (m^2).

The flow rate at the To-Node is given by:

$$TFlow_{i,j} = FFlow_i * C_i + PFlow_i - DFlow_i \qquad (3.2a)$$

if this river line is not a head section, and

$$\text{TFlow}_{i,j} = \text{PFlow}_i - \text{DFlow}_i \qquad (3.2b)$$

if this river line is a head section, where,

i = river section ID,

C_i = river sectional flow gain/loss coefficient of river section *i* (1/m),

$PFlow_i$ = runoff contribution of river basin polygon *i*, that contains river section *i* (m^3/s),

$DFlow_i$ = flow diversion on river section i (m^3/s).

Figures 3.12a and 3.12b show the program flow chart of the module that simulates the water movement between river sections. The center-piece of the algorithm is a stack used to keep track of the stream lines that the model has traveled, so the algorithm can be called a stack-based stream network analysis algorithm. The logic of the algorithm is explained below.

It can be seen from the program flow chart (Figures 3.12a and 3.12b) that, for a given river section, the program starts with searching upstream to find the stream sections flowing into it. There are three possible outcomes of the search.

(1) If no upstream section is found, and the section is not the head section, then a mistake must have occurred either in the programming procedure or in the

stream network formulation. The program will exit and print an error message for program debugging.

(2) If one or more upstream sections are found, at least one of them is not yet simulated, the current river object (identified by its ID) is pushed into the stack and the program moves upstream to one of the river objects not yet simulated. This procedure is repeated until a head section is found. Once a head section is identified, the program searches through the subwatershed polygon attribute table (PFTAB) to identify the subwatershed containing the head section. If none is found, the program exits and prints an error message. Otherwise, the program issues a request to the flow simulation module defined on the subwatershed polygon to get PFlow. Equations 3.1b, and 3.2 are used to compute the FFlow and TFlow of the river object. Once this is done, the algorithm moves to the next downstream river section by issuing a pop request to the stack. At this downstream section, the algorithm again searches upstream and checks the if all the upstream sections have been simulated. Based on the outcome of this search and test, the program decides if it can simulate water movement on the current river object or whether it must push this stream object into the stack and move upstream.

(3) If one, or more than one upstream sections are found, and all have their flow simulations completed (indicated by state value, isdone=1), the river flow is simulated at the current section. The program searches for the subwatershed containing the current river section. One and only one basin should be found. If not, the program prints out an error message and exits. Otherwise, the program issues a request to the subwatershed polygon to get the PFlow and uses Equations 3.1a and 3.2 to compute FFlow and TFlow.

The procedure is repeated until the outlet section is reached and its flow is simulated. This procedure is illustrated in the flowchart shown in Figures 3.12a and 3.12b.

The program is designed in such a way that it allows the model to be applied on any user defined portion of a river basin. The program can also be used to simulate water flow in a region having more than one river network.

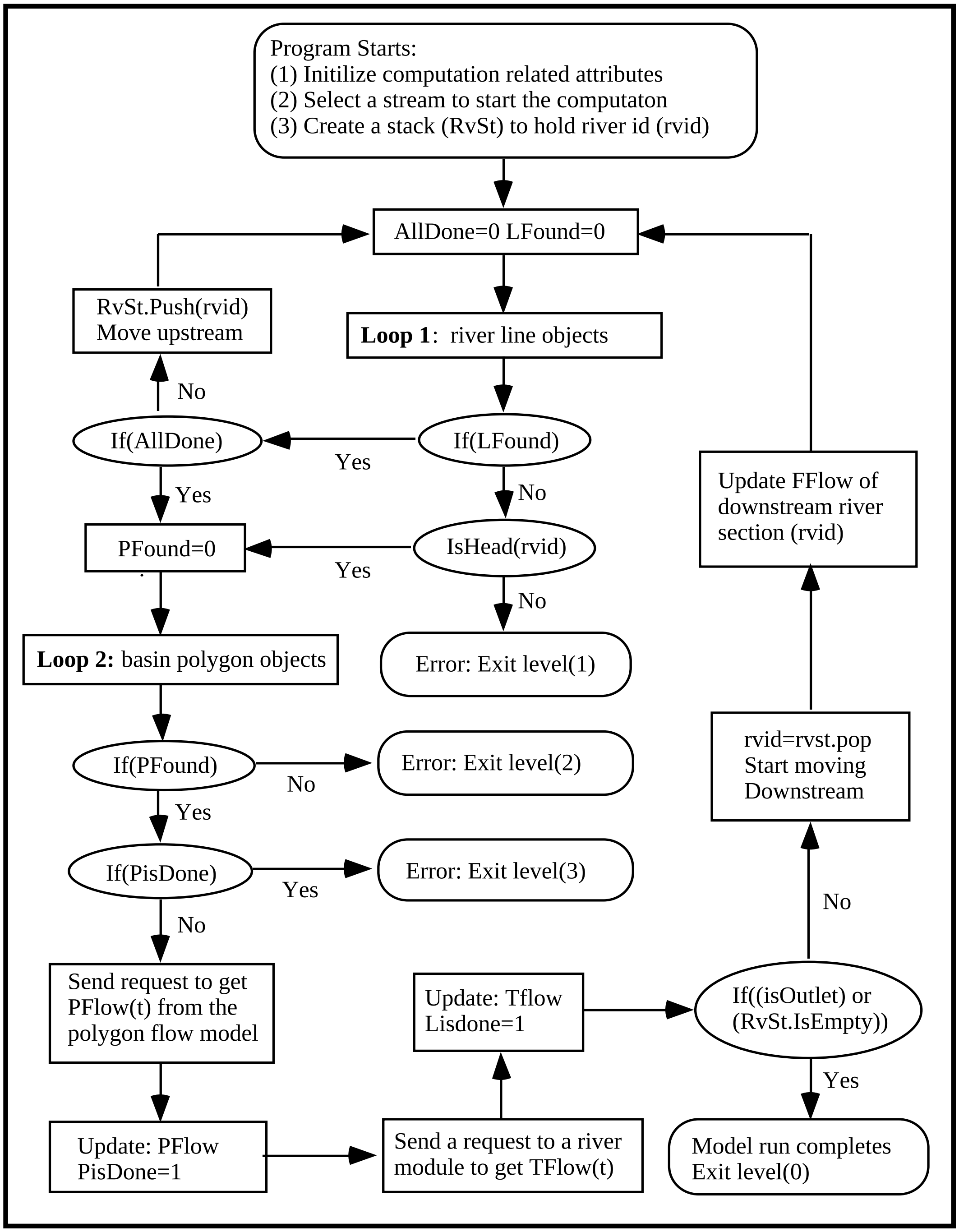


Figure 3.12a. The main loop of algorithm simulating water movement within and between subwatersheds

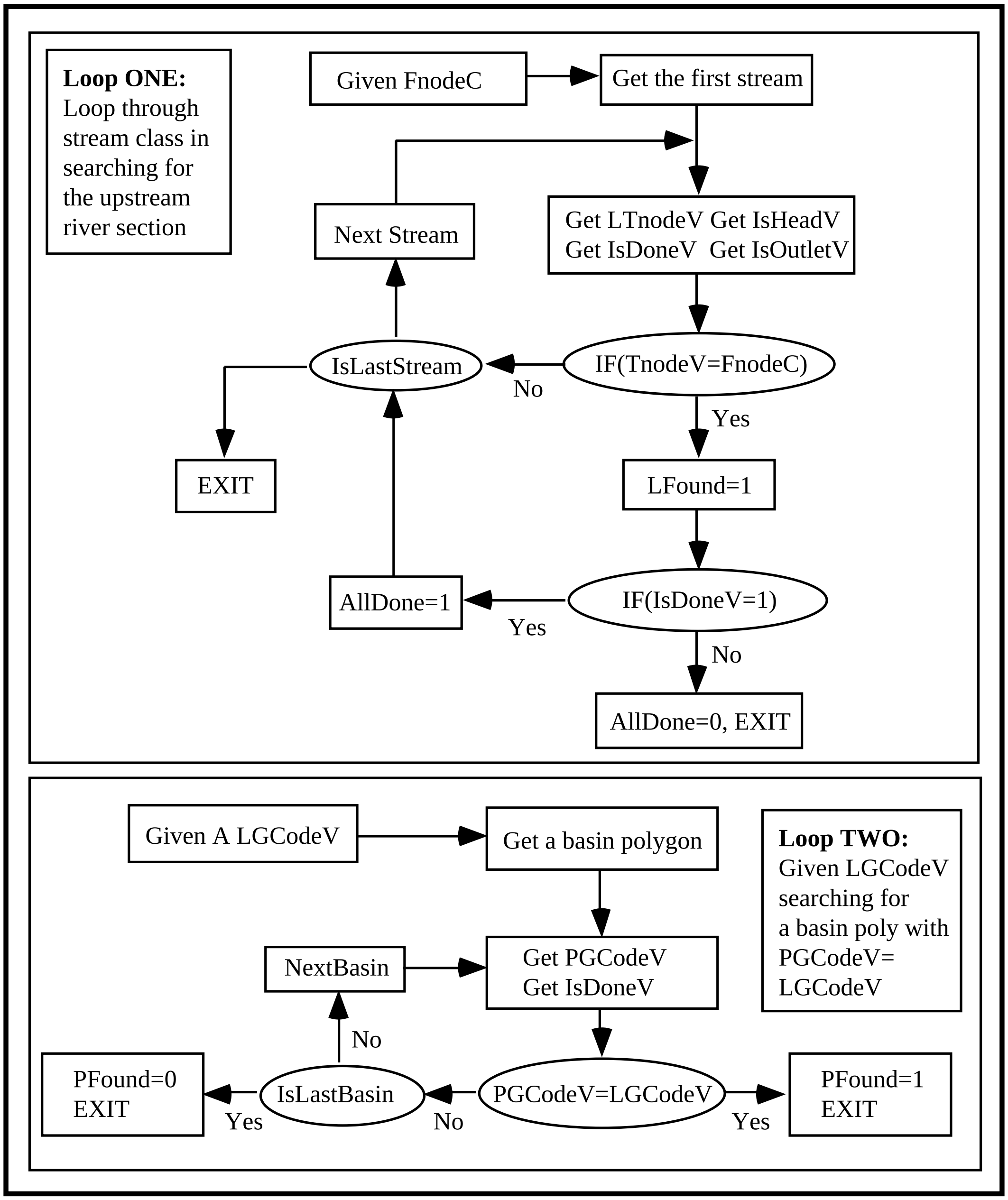


Figure 3.12b. Subloops of the algorithm simulating water-movement within and between subwatersheds

As an example to show how inter-subwatershed water movement is simulated on a river network, line section 25 (be referred to as S25 here after) in Figure 3.13 is selected to start a simulation run. The sequence by which the simulation model is applied to each river section on the stream network is described below.

From S25, realizing its upstream section S27 has not been computed yet, the program pushes S25 into the stack and moves upstream to S27. Because S27 is a head section, the program gets PFlow from the subwatershed containing S27, computes FFlow and TFlow for S27, then issues a pop request to the stack to get S25 and moves downstream to S25. On S25, it finds that S33, another upstream section of S25, has not been simulated. The program again pushes S25 into the stack and moves upstream to S33, gets the PFlow from the polygon containing S33, and moves downstream to S25. This time, the program finds that all its upstream sections (S27, S23) have been simulated and it is time to simulate water movement from the From-Node to To-Node of S25. The model will then activate a module that simulates water movement between the From-Node and To-Node of a river section to simulate the water movement on section S25. After this, the program sends a pop request to the stack to get S18 and moves downstream to S18. This procedure is repeated until the outlet section is reached and simulated. Figure 3.14 gives the sequence by which the program visits and simulates river sections on the river network shown in Figure 3.13.

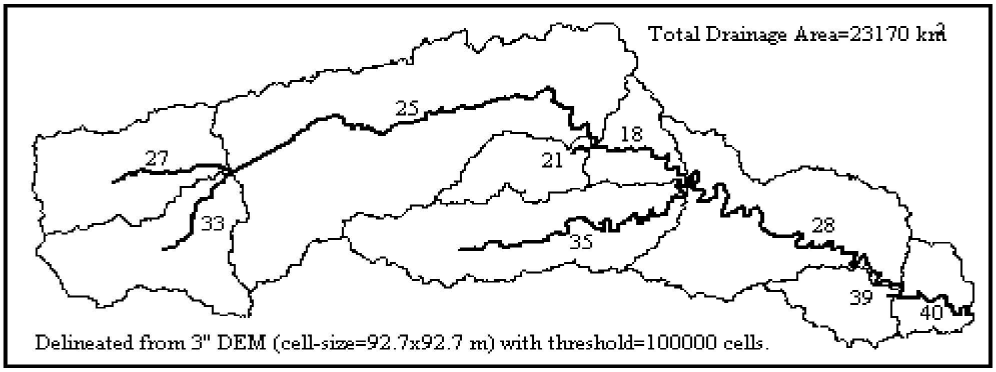

Total Drainage Area=23170 km^2
25
27
33
21
18
35
28
39
40
Delineated from 3" DEM (cell-size=92.7x92.7 m) with threshold=100000 cells.

Figure 3.13. The Guadalupe River Basin

* → S25 → S27 → S25 → S33 → S25 → S18 → S21 → S18 →
S28 → S35 → S28 → S40 → S39 → S40 OutletReached (Loop 14 times)

Figure 3.14. Program travel path given by the stack-based algorithm

3.4.2. Simulating Water Movement within a River Section

This section describes how water movement from the From-Node to the To-Node on a river section is simulated. As discussed at the beginning of this section, this simulation model is designed in such a way that by changing the modules used to compute PFlow, FFlow, and TFlow (element functions), the model can be used to simulate different hydrologic processes without changing the stack-based stream network analysis procedure.

In this map-based surface water flow simulation model, four flow routing modules are available to simulate water movement between the From-Node and the To-Node. These four modules use (1) a response function method, (2) a two-step function method, (3) dam/reservoir model combined with the two-step function method, and (4) a Muskingum-Cunge method. All of these four modules are constructed based on the principle of continuity. Figure 3.15 shows the logic of the program used for river routing. IMax in Figure 3.15 stands for the maximum time step interval allowed before the Muskingum method becomes unstable. HasDam, HasResp, and Muskingum are the states of a river line object given in Table 3.2. As can be seen from this figure, the decision of selecting one specific simulation module (out of four) is made based on the river features at run-time. The theory and programming methodology used to construct each of these four modules are discussed below:

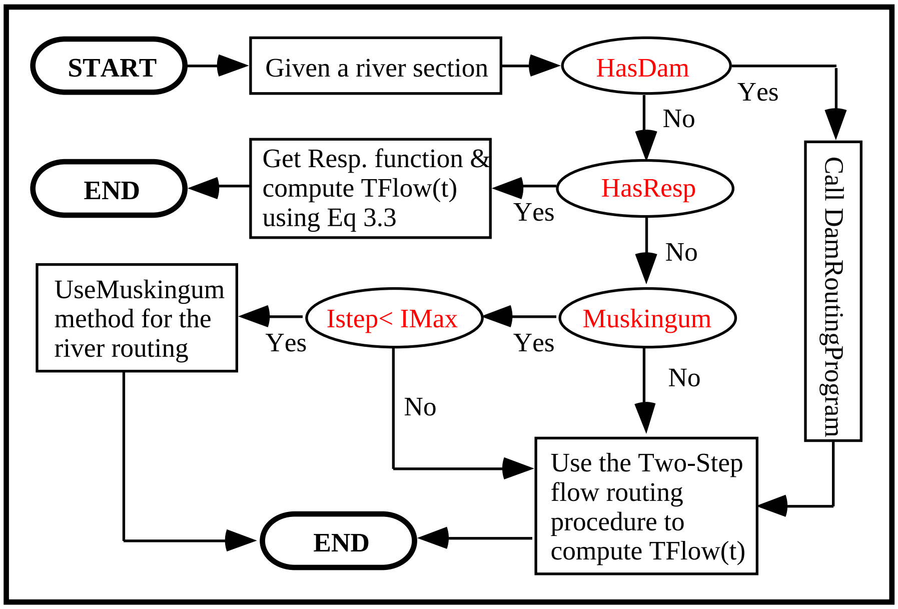


Figure 3.15. Program flow chart of river section flow routing module

(1) The Response Function-Based Flow Routing Module

The state, HasResp, of a river line object, indicates if a user-supplied response function (Maidment, 1993) is available for the river section. HasResp=0 indicates no response function is available and HasResp=k (k≠0) indicates a user-supplied response function is available and the response function has k components. When a river section has a response function that takes the water flow time-series at the From-Node as an input and produces the flow time-series at the To-Node as an outputs, this response function is used to simulate water movement between the From-Node and To-Node of the river section. The response-function-based flow routing module is constructed using the following equation:

$$TFlow_{i,j}^{t} = \sum_{k=0}^{min(t,N)} FFlow_{i}^{t-k} \cdot U_{i}^{k} + PFlow_{i}^{t} - DFlow_{i}^{t} - Loss_{i}^{t} \qquad (3.3)$$

where,

$TFlow_{i,j}^{t}$ = TFlow of river section i (with j as its To-Node), at time step t (m^3/s),

$FFlow_{i}^{t-k}$ = FFlow of river section i at time step t-k (m^3/s),

U_{i}^{k} = the response function of N elements for river section i,

$PFlow_{i}^{t}$ = PFlow of subwatershed i at time step t (m^3/s),

$DFlow_{i}^{t}$ = flow diversion of river section i at time step t (m^3/s),

$Loss_{i}^{t}$ = stream water loss of river section i at time step t (m^3/s).

The water loss in a river section is computed using the following equation:

$$Loss_{i}^{t} = FFlow_{i}^{t} \cdot Length_{i} \cdot LossC_{i} \qquad (3.4)$$

where, $Length_{i}$ = the length of river section i, (m),

LossC$_i$ = loss coefficient of river section i, (1/m), a river line attribute that can be used as a model calibration parameter.

(2) The Two-Step Flow Routing Module

This flow routing model is a special case of the response function flow routing model. This module is used when a user-supplied response function is not available and when the use of Muskingum method is not computationally efficient, i.e., when the size of simulation model time step is much greater than the average travel time through the reach, $\Delta t >> \frac{L_i}{v_i}$. Given below is the equation used for the two-step flow routing module:

$$\begin{aligned} TFlow_{i,j}^{t} &= FFlow_i^{t-1} \cdot Llag_i + FFlow_i^{t} \cdot (1 - Llag_i) \\ &\quad + PFlow_i^{t} - DFlow_i^{t} - Loss_i^{t} \end{aligned} \tag{3.5}$$

where, $Llag_i$ = The normalized time lag between From-Node and To-Node of river section i,

$$Llag_i = \frac{L_i / V_i}{\Delta t}, \tag{3.6}$$

L_i = the length of river section i (m),

V_i = the average flow velocity on river section i (m/s),

Δt = the size of simulation time step.

As it can be seen from Equation 3.5, the two-step flow routing module is based on the principle of continuity of water flow and guarantees that the water mass will be preserved.

(3) Dam and the Two-Step Flow Routing Module

The state, HasDam, of a river line object, indicates if dams (or reservoirs) exist on the river section. HasDam=0 indicates there is no dam on the river section. HasDam=k, (k≠0) indicates there is at least one dam located on the river section, and the value k is also the ID number of the first dam on the section. When one or more dams exist on a river section, the reservoir routing procedure (DAMRT.ave) is called to simulated the effects of reservoirs on the river flow. Whenever reservoirs exist on a river section, the two-step flow routing module is used to simulate the water movement on the river segments between the dams and From-Node and To-Node of the river section. The dam simulation module is discussed in Section 3.5.1.

(4) Muskingum-Cunge Flow Routing Module

The state, Muskingum, of a river line object, indicates if the Muskingum-Cunge river routing method will be used for the river section. Muskingum=0 indicates the Muskingum method will not be used to simulate water movement on the river section and Muskingum=n (n≠0) indicates that the Muskingum flow routing method will be used if the number of internal loops is less than n. The internal loops are constructed to ensure the computational stability of the Muskingum river flow routing procedure. The internal loop is discussed further below. The Muskingum-Cunge method is introduced in Chapter Two and the flow routing equations derived for the method are reproduced here as Equations 3.7 and 3.8.

$$TFlow_{i,j}^{t} = C_1 \cdot FFlow_i^{t} + C_2 \cdot FFlow_i^{t-1} + C_3 \cdot TFlow_{i,j}^{t-1} + C_4 \qquad (3.7)$$

where,

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X) + \Delta t} \qquad (3.8a)$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X) + \Delta t} \qquad (3.8b)$$

$$C_3 = \frac{2K(1-X) - \Delta t}{2K(1-X) + \Delta t} \qquad (3.8c)$$

$$C_4 = \frac{PFlow_i^t - DFlow_i^t - Loss_i^t}{2K(1-X) + \Delta t}\ , \qquad (3.8d)$$

$K = \dfrac{\Delta x}{\bar{c}}$, K is a storage constant [T], (3.8e)

$$X = \frac{1}{2} - \frac{Avg(TFlow, FFlow)}{2\bar{c}\bar{B}S_e\Delta X} \qquad (3.8f)$$

X = a weighting factor showing the relative importance that FFlow and TFlow have on a river section’s storage, $(0 \le X \le 0.5)$, where 0 indicates pure storage and 0.5, indicates pure translation,

$\bar{c}$ = kinematic wave velocity (m/s),

$\bar{B}$ = cross-sectional top width associated with average of TFlow and FFlow,

S_e = the energy slope,

Δx = the length of a river section.

To ensure the stability of the flow routing, C_3 needs to be greater than zero. From equation 3.7c, it can be seen that in order for $C_3 \ge 0$, we need to have $\Delta t \le 2K(1-X)$. When the simulation time step Δt does not satisfy this relationship, the time step needs to be subdivided into smaller steps. In the simulation model, $C_3 \ge 0$ is achieved by subdividing a simulation model time step into multiple n internal time steps so that $\Delta t_i = \frac{\Delta t}{n} \le 2K(1-X)$. When n is too large, the round-off errors accumulated by the internal loop may outweigh the benefits brought by using the Muskingum-Cunge method. In this event, the simulation model switches to use the two-step function flow routing module (Figure 3.15).

3.4.3. Simulating Water Movement within a Subwatershed

In this map-based surface water flow simulation model, PFlow(t) represents local runoff generated in a subwatershed. Several methods are available to calculate PFlow(t) from precipitation observations, e.g. by spatially interpolating the precipitation to the center point of each subwatershed and then converting the precipitation to PFlow(t). In the Niger River Basin simulation model, PFlow(t) is constructed from the soil-moisture surplus time-series produced using a simple bucket model. As the input data sets for the soil-moisture balance model, monthly time-series tables of precipitation and potential evaporation for the period July 1983 to December 1990 were estimated at each point on a regular mesh of 0.5 degree cells covering the study area. This computational mesh was selected because long term mean monthly estimates of rainfall and temperature at these points were available from C.J. Willmott at the University of Delaware. As discussed in Chapter Two, a convolution procedure (Olivera and Maidment, 1996) is used to convert soil-moisture surplus to local runoff (SurpF(t)-> PFlow(t)).

Using this method, PFlow(t) is simulated with two flow components. One is SFlow(t) used to simulate the overland flow and the other one is OFlow(t) used to simulate the subsurface water flow. The overland flow is estimated by applying the concept of unit hydrograph to the soil surplus, SurpF(t). The equations that the subwatershed to river water movement simulation module uses are given below:

$$SFlow_i^t = \sum_{k=0}^{\min(t,N)} SurpF_i^{t-k}(1-\alpha_i)\cdot U_i^k \qquad (3.9)$$

where,

$\mathrm{SFlow}_\mathrm{i}^\mathrm{t}$ = local flow contribution (through surface) of subwatershed i at time step *t* (m^3/s),

$SurpF_i^{t-k}$ = soil moisture surplus of subwatershed i at time step t-k (m^3/s),

U_i^k = k-th component of the response function of $PFlow_i^t$ on $SurpF_i^t$,

α_i = the fraction of surplus that goes to subsurface, $(0 \le \alpha_i \le 1)$,

N = total number of components in the response function U_i^k.

The response function of used in this study is given below:

$$U_i^k = \frac{1}{2k\sqrt{\pi D_i \frac{kv_i}{T_i}}}\exp\left(-\frac{\left(1-\frac{kv_i}{T_i}\right)^2}{4D_i\frac{kv_i}{T_i}}\right) \quad k{=}1{,}2{,}3....N \qquad (3.10)$$

where,

k =1,2,3...N, the index of components in the response function,

D_i= dispersion coefficient for subwatershed i, Dispersion coefficient is used to measure the degree of the overland water spreading through time.

V_i = average overland flow velocity for subwatershed i, (m/s),

T_i = average overland flow time for subwatershed i (s).

The values of these parameters for a subwatershed can be estimated either through hydrologic analysis of the subwatershed or through the optimization module to be discussed later in this chapter.

The subsurface water flow component of PFlow(t) is considered to be going through an imaginary underground reservoir. The flow through the reservoir can be simulated using a linear reservoir model. Equations used to perform flow routing through a linear reservoir are given below:

$$OFlow_i^t = S_i^{t-1} / K_i \qquad (\mathrm{t} = 1,2,3,....) \tag{3.11}$$

$$S_i^t = S_i^{t-1} + (SurpF_i^t \cdot \alpha_i - OFlow_i^t) \cdot \Delta t \tag{3.12}$$

where,

$\mathrm{OFlow}_\mathrm{i}^\mathrm{t}$ = the subsurface flow component at time step *t*, on polygon i (m^3/s)

$\mathrm{S}_\mathrm{i}^\mathrm{t}$ = storage of the under-ground-reservoir at time step *t*, on polygon *i* (m^3),

K_i = the linear reservoir constant representing the average residence time of water in the reservoir (s).

After these two components are computed, the local flow contribution of subwatershed *i* at time step *t* is computed using Equation 3.13.

$$PFlow_i^t = SFlow_i^t + OFlow_i^t \tag{3.13}$$

3.5. Other Simulation Model Objects

This section describes three other classes of objects used in the simulation model, dam/reservoir object, flow-check object, and flow-diversion object. All these objects appear as a points on a point coverage and are located on a river line object. The point location on the river line is dynamically calculated from a user specified cursor location. The algorithm that performs the dynamic line segmentation is described in Section 3.6.4.

3.5.1. The Dam Objects

The dam/reservoir objects are designed to simulate the effects of dams and reservoirs on river flows. The states of a dam/reservoir object are given in Table 3.3. A utility program is available to construct dam/reservoir object directly and interactively from a river map. For each dam object created, a new record is added to the dam feature attribute table (FTAB) and a time-series table is created to hold time-series data sets for reservoir routing. The states of a dam object are listed in Table 3.3a and the fields in the dam routing time-series table are given in Table 3.3b. The graphic point on the dam coverage is connected to the dam's FTAB through the shape field in the FTAB. The connection to its associated time-series table is established through the DamId and the name of the time-series table.

During a flow simulation, the presence of a dam/reservoir object is detected by the simulation model through the return value of the HasDam state of a river section.

HasDam=0 indicates that no dam is located on the river section. The return of a non-zero value of HasDam indicates that there is at least one dam on the river section and the non-zero value is the Dam-ID of the first dam located on the river section.

Table 3.3a. The Attributes of a Dam/Reservoir Object

State	**Function (What the attribute represents)**
Shape	Pointer pointing to the map location of the object
Damid	The ID of a dam/reservoir object, Damid is also a pointer pointing to the time-series table associated with the reservoir
DamName	The name of a dam/reservoir
Capacity	Capacity of a reservoir (m^3)
Area	The water surface area of the reservoir when storage=capacity (m^2)
Upst	The active storage of the dam/reservoir (m^3)
DeadSt	The dead storage of the dam/reservoir(m^3)
Evt	The evaporation rate of the reservoir (mm/day)
Pdam	Damid of the upstream dam located on the same section, 0=No upstream dam
Ndam	Damid of the dam downstream of the dam on the same stream section, 0=No dam located downstream
Storage0	Initial storage of the reservoir (m^3)
Area0	Initial water surface area of the reservoir (m^2)

Table 3.3b. The Fields of a Dam-Routing Time-Series Table

FieldName	**Function (What the attribute represents)**
Time	Simulation time steps
Inflow	Inflow time-series of the reservoir (m^3/s)
DmdFact	Demand factor of each simulation time step
WithDraw	Water withdraw of each time step
NetEvp	Net evaporation of each time step (mm/day)
Sarea	Surface area of each simulation time step (m^2/s)
Spill	Discharge (including water used for power generation) of each time step (m^3/s)
Storage	Storage at the end of each simulation time step (m^3/s)

In the process of a river flow routing, if a reservoir is detected on a river section, the river routing program will call the dam simulation module DAMRT and pass the Dam-ID and FFlow(t) to DAMRT. The DAMRT module will then simulate the behavior of the reservoir. The simulation is based on the information passed to it from the river-routing program, the states of the dam object, and the reservoir operating rules. The results of the simulation are stored in a time-series database table associated with the dam, of which, discharge time-series (spill-vector) is passed back to the river routing program to be used as FFlow(t). If more than one dam exist on a river section, the output of the first dam becomes the input of next dam. This loop will continue until the last dam of the river section is reached and simulated. The output of the last dam is then returned to the river routing program to be used as FFlow(t).

The module DAMRT, that simulates a reservoir water balance is constructed based on equation 3.14 (Chow *et al.*, 1987):

$$S^t = S^{t-1} + (I^t - Yd^t - A^t e^t - Q^t)\Delta t \qquad (3.14)$$

where,

I^t = inflow in time step t (m^3/s),

S^t = reservoir storage at time step t (m^3),

Yd^t = withdrawal at time step t, given by the reservoir operation rule (m^3/s),

$A^t e^t$ = evaporation loss at time step t (m^3/s),

e^t = evaporation loss rate at time step t (m/s),

A^t = reservoir water surface area (m^2).

The reservoir water surface area, A^t, is estimated using the equation (Woelke, 1985):

$$A^t = (S^{t-1})^{0.72} \qquad (3.14a)$$

where, Q^t = reservoir water release to downstream at time step t (m^3/s).

Reservoir release is given by the reservoir's operating rule subject to the following constraints:

$$Q^t \geq \frac{S^{t-1}}{\Delta t} + (I^t - Yd^t - A^t e^t) - \frac{S_c}{\Delta t} \qquad (3.15a)$$

$$Q^t \leq \frac{S^{t-1}}{\Delta t} + (I^t - Yd^t - A^t e^t) - \frac{S_d}{\Delta t} \qquad (3.15b)$$

where, S_c = the reservoir storage capacity (m^3),

S_d = the reservoir dead storage (m^3).

Relation 3.15a ensures that at any time step, the reservoir storage will not be greater than the reservoir capacity, and relation 3.15b ensures none of the water in the dead storage goes into release.

Inflow to a reservoir is computed differently based on the location of the reservoir. When a reservoir is located at a non-head river section and is the first on the river section, Equation 3.16a is used to compute the inflow.

$$I^t = FFlow^t(1 - Llag) + FFlow^{t-1} \cdot Llag + PFlow^t \cdot \frac{\Delta A}{A} \qquad (3.16a)$$

where,

$Llag = \dfrac{(XL/v)}{\Delta t}$ = fractional time it takes for water to travel from the From-Node to the location of the dam,

XL = the distance between the From-Node and dam location (m), v = river flow velocity (m/s),

Δt = the size of time step of the simulation (s),

ΔA= regional area between FNode and the reservoir location (m^2). WhenΔA is not given, it can be estimated using Equation 3.16b:

$$\Delta A = \frac{XL}{TL} \cdot A \tag{3.16b}$$

A = the total area of the subwatershed where the reservoir is located,

TL = total length of the river section.

When a reservoir is located at a head section and is the first on the river section, Equation 3.16c is used to compute the inflow.

$$\begin{aligned} I^t = & \left[PFlow^t \cdot (1 - Llag) + PFlow^{t-1} \cdot Llag \right] \cdot (\frac{\Delta A_{thrd}}{A}) \\ & + PFlow^t \cdot \frac{\Delta A}{A} \end{aligned} \tag{3.16c}$$

where, ΔA_{thrd} = threshold area that initializes a river used in watershed delineation procedure.

Comparing Equation 3.16c with 3.16a, it can be seen that in the head river section, $FFlow^t = PFlow^t \cdot (\frac{\Delta A_{thrd}}{A})$. When a reservoir is not the first reservoir on a river section, its inflow is computed using equation 3.16d.

$$I_i^t = \left[Q_{i-1}^t \cdot (1 - Llag) + Q_{i-1}^{t-1} \cdot Llag\right] + PFlow^t \cdot \frac{\Delta A}{A} \qquad (3.16d)$$

where,

i = sequential numerical index of the dams in a river section with i=1 for the first dam on the river section. i=2,3,4..,

$Llag = \dfrac{(XL/v)}{\Delta t}$ the fractional time it takes for water to travel from dam i-1 to i,

XL = travel distance along the river line from dam i-1 to i,

Q_{i-1}^t = water release of reservoir i-1 at time step t. (m^3/s).

It can be seen from the equations above that dam simulation module uses Equations 3.14 and 3.15 to perform the reservoir water balance computation and uses the two-step flow routing module to simulate the flow in the river segments between the dams. More complex reservoir operating rules such as the ones introduced in the works of Loucks (Loucks, 1981) could also be included in this dam/reservoir simulation model.

3.5.2. The Flow-Check Point Objects

The flow-check objects are created at the locations where stream flow estimations are desired because the simulation model produces the flow estimates only at the From-Node and To-Node of each river section. A utility program is written to allow the interactive construction of these objects on a river network. Table 3.4 lists the attributes of a flow-check point object. The algorithm used to interpolate flow rate to a flow-check point is discussed in Section 3.6.4.

Table 3.4. Attributes of a Flow-Check Point Object

State	**Function (What the attribute represents)**
Shape	Pointer pointing to the map location of the object
Pointid	Identification number of a flow-check point
FFlow	FFlow of the river line object on which a flow-check point is located
TFlow	TFlow of the river line object that a flow-check point is located
IFlow	Flow interpolated at a flow-check point
Oline	A flag specifying if a flow-check point is located on a river (Oline=0 indicates the flowchk point is on the river line, Oline=1 indicates the point is not on the river line but within the simulated area, and Oline=-1 indicates the point is out of the area)
Pcntage	between the distance of a Flow-Check point to From-Node and the length of the river section.
Length	The length of the river section where a flow-check point is located

3.5.3. The Flow-Diversion Point Objects

When a flow diversion point has a constant flow rate, it is incorporated into the river object associated with the point. The diversion rate is put into the attribute DFlow of a river object. When a flow diversion point has a time-varying flow rate, it can be simulated using the reservoir object with constant storage and no evaporation loss. These objects are detected and simulated by the river flow routing module.

3.6. UTILITY PROGRAMS AND POST-PROCESSORS

The utility programs of this map-based simulation model are constructed to allow interactive model modification and make easy result presentations possible. This section describes the designs of these interactive model modification and result presentation programs.

3.6.1. Construction of a Sub-Model

When simulating surface water flow process on a large river basin, it is sometimes necessary to isolate a portion of the river basin for more detailed study. For this purpose, it is desirable to clip a portion of the river basin from the main model to form a sub-model. When a simulation model is constructed in the traditional means, constructing such a sub-model requires an effort comparable to that used to construct the original basin model. In this map-based simulation model, however, a sub-model can be constructed interactively from the existing basin model in a 'real-time' operating style, i.e. when a portion of the map is selected and copied, a new model of the selected region is created. The procedure to create a sub-model is listed below:

(1) select the maps necessary to create the model by making their corresponding themes active in an ArcView's view window,

(2) select the features (polygons, lines, or points) from each map that fall into the study region of the sub-model,

(3) run the sub-model construction utility program (CLIPMDL.utl) to create the sub-model.

Because the model is constructed based on the concept of object-oriented programming, the newly created sub-model inherits all the features of the original model. Therefore, once constructed, all the programs applied to the original model can be applied to the sub-model. Figure 3.17 in Section 3.6.2 shows an example of a sub-model. The logic of the program that enables interactive sub-model creation is explained below.

It is known that for each feature object on a geographic map there is a record in the relational database table containing the states of the object and the model programs have the ability to access both the map feature and its associated record. In procedure (1), at the same time when each map is selected, its related database table is also selected, and in procedure (2), when features on these maps are selected, their corresponding records in the database tables are also selected.

The functions of the sub-model construction program [CLIPMDL.utl] are (1) to make one copy of map-templates (class) for each user-selected map, (2) to loop through each selected database table and copy the selected records to its newly created map-template, and (3) to create an alias for the newly-created maps so that they are the same as those for the maps in the original models. The reason that newly created maps keep the same alias as those of its original maps is that the maps are referenced in the model programs by their alias. Programs identify maps by their alias rather than their real file name, and if the maps of the sub-model have the same alias as those of original maps, all the programs used in the original model can be applied to the sub-model without any modifications.

The sub-model construction utility program also identifies the sources of the river network so that inputs related to those streams can either be inherited from the original model simulation results or supplied by the user. A source stream is defined as a river section whose inflow streams in the original model are cut off by the clipping procedure.

3.6.2. Optimization Algorithms

This section describes the optimization algorithms developed for the purpose of simulation model calibration. Two optimization algorithms, multi-directional and interactive, are developed in this research for the purpose of model calibration. Both algorithms require a user to provide, on a space defined by the optimization variables, a value range for each variable to be calibrated. The interactive model usually requires multiple runs to get an optimal solution and for each optimization process, a new solution space based on previous runs needs to be defined. The second method, multiple directional optimization requires a user to define only the solution space at the beginning of a calibration process. After the solution space is defined, the optimization model applies a bisection algorithm on each dimension to search for an optimal solution set. The concepts of both optimization modules are discussed below in Sections 3.6.2.1. and 3.6.2.2.

3.6.2.1. The Interactive Optimization Algorithm

The purpose of this interactive optimization algorithm (IOA) is to calibrate the model parameters for this map-based simulation model. The optimized parameters are defined as a set of parameters that produce a best-fit between a simulated and observed river flow time-series at a given location. Two standards (match standard) used by the algorithm to evaluate the extent of fit are: sum of mass discrepancies (SMD) and sum of root mean square errors (RMSE). A best-fit time-series can be defined as the time-series that minimizes RMSE and produces zero SMD. SMD function is used to ensure that the average flow rate produced by the simulation model equals that of the observed in the same period of time. RMSE function is used to pursue the best match between the simulated flow time-series and observed flow time-series. Since the model is designed in such a way that the optimization algorithm is independent of the match standards used, a user of the model can add other standards to achieve better matches on the low flow and peak flow period. Mathematically, the sum of mass discrepancies can expressed as:

$$SMD = \frac{\sum_{t=1}^{n}(O^t - F^t)}{\sum_{t=1}^{n} O^t} \qquad (3.17)$$

The sum of root mean square error can be expressed as:

$$RMSE = \frac{\sqrt{\sum_{t=1}^{n}(O^t - F^t)^2}}{\sum_{t=1}^{n} O^t} \qquad (3.18)$$

where, O^t = observed flow rate at time step t at a flow gage station,

F^t = simulated flow rate at time step t at the same flow gage station. The function F^t can be written as:

$$F^t = F(x_1, x_2, x_3, \ldots x_n) \qquad (3.19)$$

where, $x_1, x_2, x_3, \ldots x_n$ = model parameters. The parameter optimization problem becomes the problem of finding a parameter set $\vec{P} = \{x_1, x_2, x_3, \ldots x_n\}$ that satisfies:

$$SMD = \frac{\sum_{t=1}^{n}(O^t - F^t)}{\sum_{t=1}^{n} O^t} = SMD(x_1, x_2, x_3, \ldots x_n) = 0 \qquad (3.17a)$$

and minimizes:

$$RMSE = \frac{\sqrt{\sum_{t=1}^{n}(O^t - F^t)^2}}{\sum_{t=1}^{n} O^t} = \mathrm{RMSE}(x_1, x_2, x_3, \ldots x_n) \qquad (3.18a)$$

As an example to show how the interactive optimization algorithm works, the procedure of optimizing two variables, X_1 and X_2, for a simulation model based on the standards imposed in Equations 3.17 and 3.18 is described below.

The algorithm assumes that the lower and upper limits of X_1 and X_2 are known or could be reasonably estimated. Let the lower and upper limit for X_1 and X_2 be designated as x_{1min}, x_{1max}, x_{2min}, and x_{2max}, respectively. The optimization problem is equivalent to finding the X_1, X_2 combination from the parameter space $\{X_1,X_2\}$ that gives a minimum SMD and RMSE (Figure 3.16). The algorithm first discretizes each variable (represented as one dimension in the parameter space) into a user specified range. In this example, 6 steps are specified for parameter X_1 and 5 for X_2. As a result, 30 X_1~X_2 parameter combinations are formed. The interactive optimization algorithm then uses these parameter sets to run the simulation model 30 times, and computes the RMSE and SMD based on each simulation result. The parameter set that returns the minimum RMSE or SMD is manually selected as the first estimate. A finer step size can now be used to form another grid around the first estimate to form another parameter set in search for a better fit. The procedure can be repeated several times until an optimal is found.

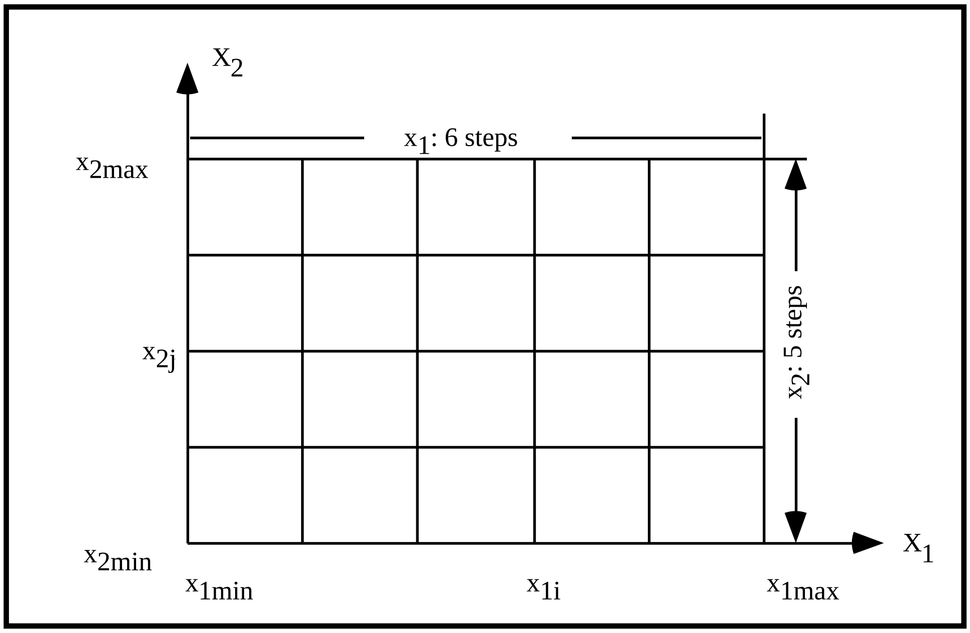


Figure 3.16. Problem solution space X_1~X_2

The procedures of applying this interactive optimization model to the region above the Koulikoro flow-gauging station in the Niger River Basin is described below to show the technical details of the optimization model application. Figure 3.17. shows the region whose parameters are to be optimized.

The region above the Koulikoro flow-gauging station consists of 10 subwatersheds with a total drainage area of 120,000 km^2. The flow-gauging station is located at a distance 0.814 percent (measured from the From-Node of the arc) of the total length on the outlet river section. Monthly runoff records of 90 months from July 1983 to December 1990 at the Koulikoro flow-gauging station are processed and used. The input data sets for the map-based simulation model are the time-series of soil-moisture surplus defined on each subwatershed polygon. The time-series of soil-moisture surplus are produced using the soil-water balance model described in Chapter Two.

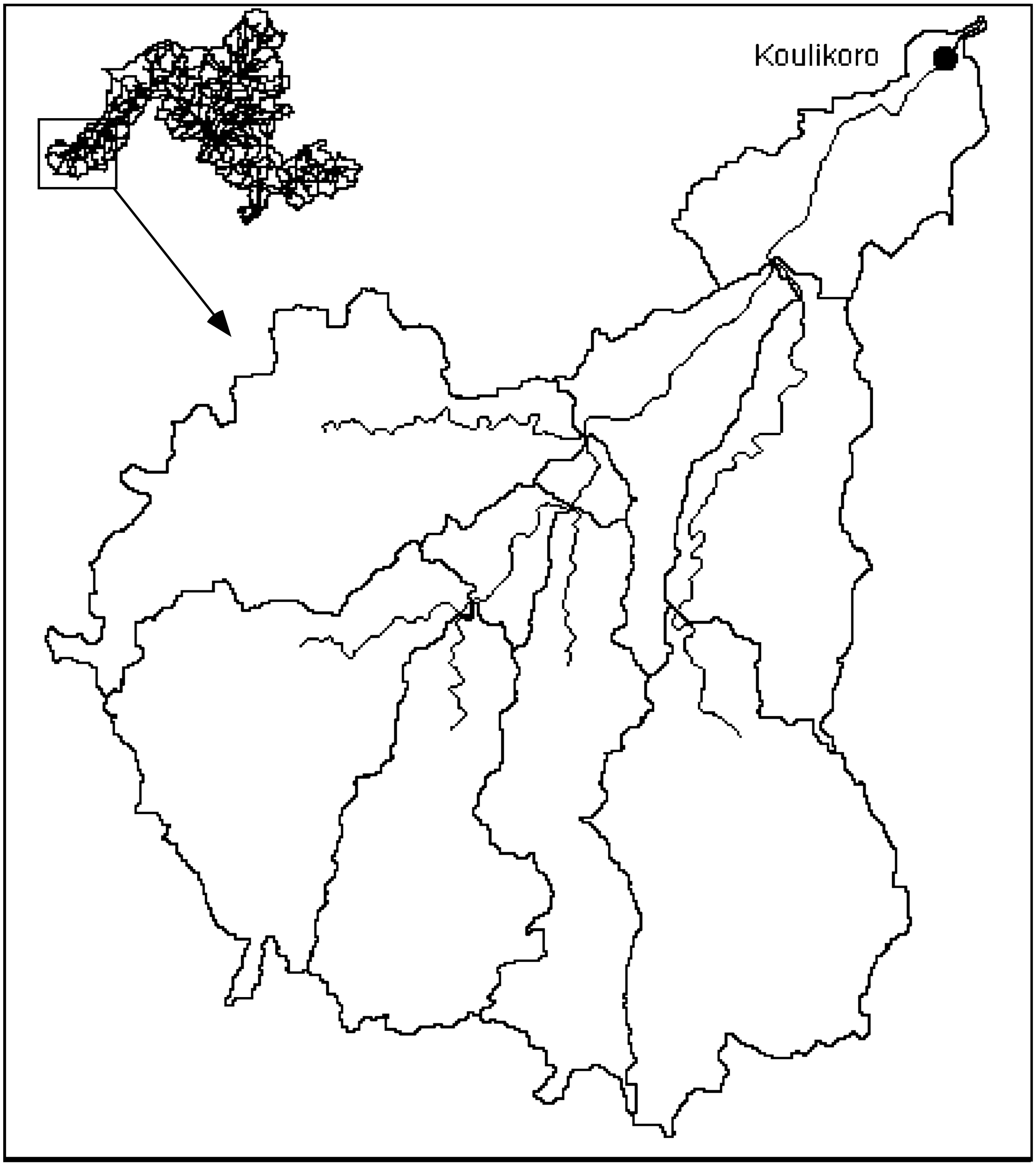


Figure 3.17. The area above the Koulikoro flow-gauging stations

The purpose of applying the optimization model to the region is to find a set of values for the loss-coefficient and flow velocity of each river section so that the river flow time-series produced by the simulation model at Koulikoro matches that of observed at the location. The match is defined by Equations 3.17 and 3.18.

As an estimate, ranges of the loss-coefficient[1] and average flow velocity on the river are estimated as below:

$$0.00001 \leq \text{lossC} \leq 0.0007 \text{ (1/km)}$$
$$0.2 \leq V \leq 0.55 \text{ (m/s)} \tag{3.19}$$

The range of each variable is divided into 4 intervals with 5 steps, which creates a testing space of 5x5=25 data sets. After applying the interactive optimization model under such conditions, four charts are generated by the model to show the parameter values that produce the best fit. These four charts are (1) RMSE vs. parameter set (Figure 18a), (2) SMD vs. parameter set (Figure 18b), (3) flow time-series plot of observed vs. simulated when RMSE is the minimum, and flow time-series plot of observed vs. simulated when |SMD| is the minimum. The last two charts are not shown here because similar charts will be produced later in Section 3.6.2.2.

Figures 3.18a and 3.18b show the plots of SMD and RMSE for each parameter sets. It can be seen from the plots that the minimum RMSE can be achieved by adjusting the river velocity while the minimum SMD can be achieved by adjusting the loss-coefficient of the river. In most situations, to have zero mass discrepancy between the simulated time-series and the observed time-series is very important. Figure 3.18b shows that the SMD curve crosses zero under all 5 velocity values used indicating the zero mass discrepancy can be achieved by varying the loss-coefficient alone. Therefore, by selecting a flow velocity that produces a minimum RMSE followed by adjusting the loss-coefficient of river sections to get a zero mass discrepancy, it is possible to find a set of velocities and loss-coefficient that produce zero SMD while minimizing RMSE.

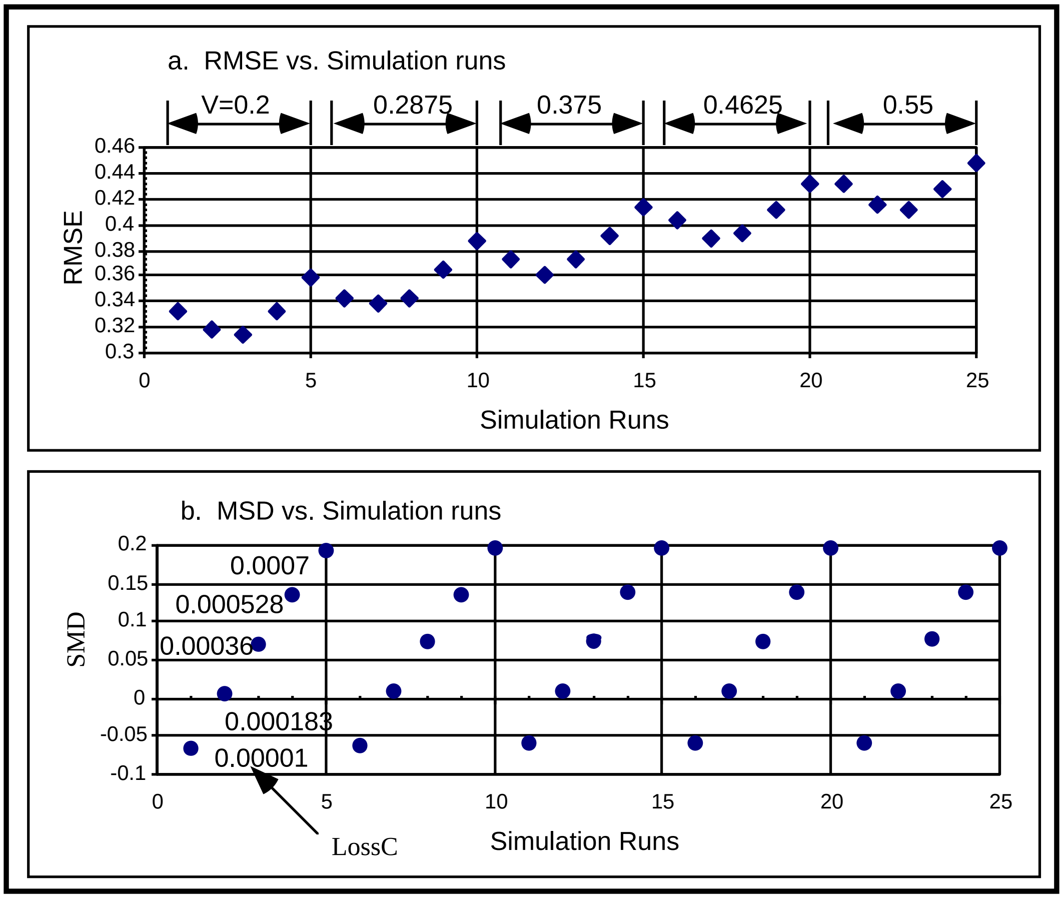


Figure 3.18. Model calibration (SMD and RMSE vs. simulation runs)

Because this optimization run only produced the minimum RMSE and |SMD| out of the predetermined parameter sets, further optimization runs are still needed in order to find the river velocity and loss coefficient combination that produces the minimum RMSE and |SMD| values. As can be seen from Figure

[1] . Loss in a river section is computed by: Loss=RiverLength*LossC*FlowRate while flow loss on

3.18a, the value of RMSE may still go down if river velocity is further reduced. Because for each run, this optimization model requires a user to specify a new range for each model calibration parameter based on the previous run, using this interactive optimization for the simulation model calibration can be a lengthy process.

Another problem one may face when using this interactive optimization model is to decide the ranges of parameters for a new run after an optimization run is done because when the number of calibration parameters is greater than two, the plots like Figure 3.18 will not be available, and without these plots, the patterns of RMSE and SMD variations cannot be easily detected. Because of these problems, this interactive optimization model is never used to calibrate the simulation model in this study. Instead, the optimization model based on a direction set method described in the following section is responsible for all the model parameter calibrations.

The reasons why this interactive optimization model is discussed in this section are (1) this model provides an alternative means of simplifying model calibration procedure when the number of parameters to be calibrated is low and (2) this model produces charts showing the effects that each model parameter has on the changes of RMSE and SMD (Figure 3.18) when the number of parameters is two.

3.6.2.2. Optimization Module Based on a Direction Set Method

Using directional method, the optimization problem presented in Equations 3.17a and 3.18a can be stated as:

a subwatershed is computed by: Loss=MeanFlowLength*LossC*PFlow

Given as inputs the vectors $\vec{P}$ and $\vec{n}$, and functions, $RMSE(\vec{P})$, from Equation 3.18a, and $SMD(\vec{P})$, from Equation 3.17a, find a scalar setλ_n that minimizes $RMSE(\vec{P}+\lambda_n\vec{n})$ and satisfies $SMD(\vec{P}+\lambda_n\vec{n})=0$, where $\vec{P}$ is a vector pointing to a point *P* in a *N*-dimensional space and $\vec{n}$ is the unit vector in nth dimension of the *N*-dimensional space. Once the scalar set is found, the new vector $\vec{Q}=\vec{P}+\lambda_n\vec{n}$ is pointing to the point in the n-dimensional space whose coordinates gives the optimal values of the parameter set.

In searching for the optimal vector $\vec{Q}$, this optimization model uses the bisection method (Press *et al.*, 1992) in each dimension to perform successive line minimization. The bisection method is used for its simplicity and reliability, i.e. when a root is contained in a range, the root will not be lost during the iterative root-finding procedure if bisection method is used.

Before the bisection method can be used to search for a root of a function *G(x)=0* (Figure 3.19(A)), an interval [x_a,x_b] containing the root needs to be provided. For a continuous function, whether the interval contains a root can be easily checked by testing the function values at the end points of the interval. If the function values have different signs at the end points, then at least one root is contained in the interval. The concept of the bisection algorithm is simple. Once an interval containing at least one root is given, the algorithm will evaluate the function at both endpoints and the midpoint. The endpoint giving the function value the same sign as that of the function value at the midpoint is then replaced by the midpoint. The procedure is repeated until the function value at the midpoint is sufficiently close to zero. The criteria for convergence is problem dependent and can usually be given by a user. For our problem of solving equation $SMD(x) = 0$, the convergence criteria are:

$$\left| SMD(x_{mid}) \right| < 10^{-5} \qquad (3.20a)$$

or

$$\frac{\left(|x_1| + |x_2| \right)}{2} < \varepsilon \approx \sqrt{k} \qquad (3.20b)$$

where, $x1,x2,x_{mid}$ = the endpoints and midpoint of last iteration, respectively,

ε = the convergence criterion given by a user, and

κ = a computer's floating point precision, 10^{-8} for float (single precision) and 10^{-15} for double precision. Similar convergence criteria is used for the procedure that minimizes the RMSE.

Detailed discussion regarding how the convergence criteria should be set can be found in books on numerical methods (e.g., Press *et al.*, 1992).

Using the bisection algorithm to search for the minimum point of a function follows a similar logic to the method used to find a function root. Starting with a given interval $[x_a,x_b]$ and $x_b>x_a$ (Figure 3.19(B)), the program first evaluates the values at the endpoints and the midpoint of the interval. If the function value at the middle point is greater than those at the endpoints, the program will continue on to evaluate the function points at the locations of $x_a+0.25(x_b-x_a)$, $x_a+0.75(x_b-x_a)$, and so on, until a point whose function value is less than at least one endpoint is found, and the point would be used as x_{mid}. To decide the next move, the program evaluates the function value at $x_{tmp}=x_{mid}+dx$, where dx is a small number comparable to ε in Equation 3.20b. If $F(x_{mid})$ <

$F(x_{tmp})$, then x_{mid} is used to replace x_b to start the next iteration, otherwise, x_a will be replaced. The procedure is repeated until the function F(x) converges to its minimum point or until the user specified maximum number of iterations is reached.

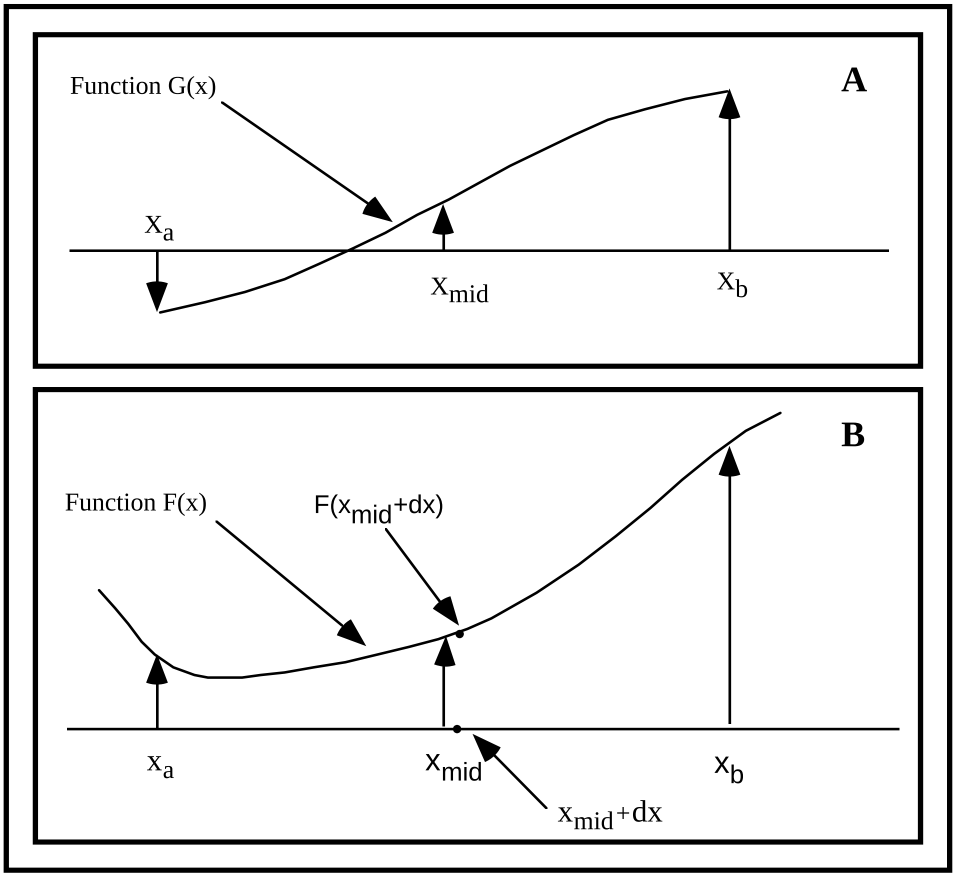


Figure 3.19. Using bisection method to find root and minimum points of a function

3.6.3. Simulation Model Calibration

The optimization models developed in the last section are used in this section to optimize model parameters for the purpose of simulation model calibration.

Figure 3.20. shows the map of the Niger River Basin and the locations of the flow-gauging stations where reasonably reliable observed monthly flow time-series data are available for the time period between July of 1993 and December of 1990. For model calibration purposes, five sub-models, each associated with a flow-gauging station, are created. The optimization model based on the direction set method is applied to each sub-model to optimize the model parameters within its region. Based on river basin characteristic and the simulation model structure, it was decided that six parameters affect the simulated river flow time-series. These six parameters are listed in Table 3.3.

Table 3.5. Simulation Model Parameters To Be Calibrated

	State	**Function (What the attribute represents)**
1	ToRes	The fraction of a subwatershed water surplus that goes to the subsurface reservoir
2	ResK	Mean residence time of water in a subsurface reservoir [T]
3	VFact	Overland flow velocity (m/s)
4	PlossC	Subwatershed loss coefficient (1/m)
5	Velocity	Flow velocity on a river line (m/s)
6	LossC	Loss coefficient related to a river line (1/m)

After applying the optimization module to the Koulikoro sub-model (Figure 3.17) with all six parameters selected it was found that the parameters ToRes and ResK have little impact on the simulation results, although the combination of ToRes=0.1 and ResK=7 produces slightly better results than other combinations of these parameters. Therefore, ToRes=0.1 and ResK=7 are used throughout the whole model calibration process.

Because both river velocity and overland flow velocity (Vfact) affect flow distributions over the time domain, only one of them is needed for the optimization. For model calibration, the overland flow velocity (Vfact) is set to 0.013 m/s(=46.8 m/hr) while the river velocity was used in the optimization model to minimize the RMSE.

Because overland flow occurs mostly in the form of small streams, and because subwatershed water loss is estimated using the formula WaterLoss = PFlow*MeanFlowLength*PLossC, which resembles the water loss formula used in river loss estimation, it was decided that the polygon flow loss coefficient PlossC should be set equal to the river flow loss coefficient, LossC.

After these considerations, the river water loss (LossC) and river velocity (Velocity) are selected as the optimization parameters for the simulation model.

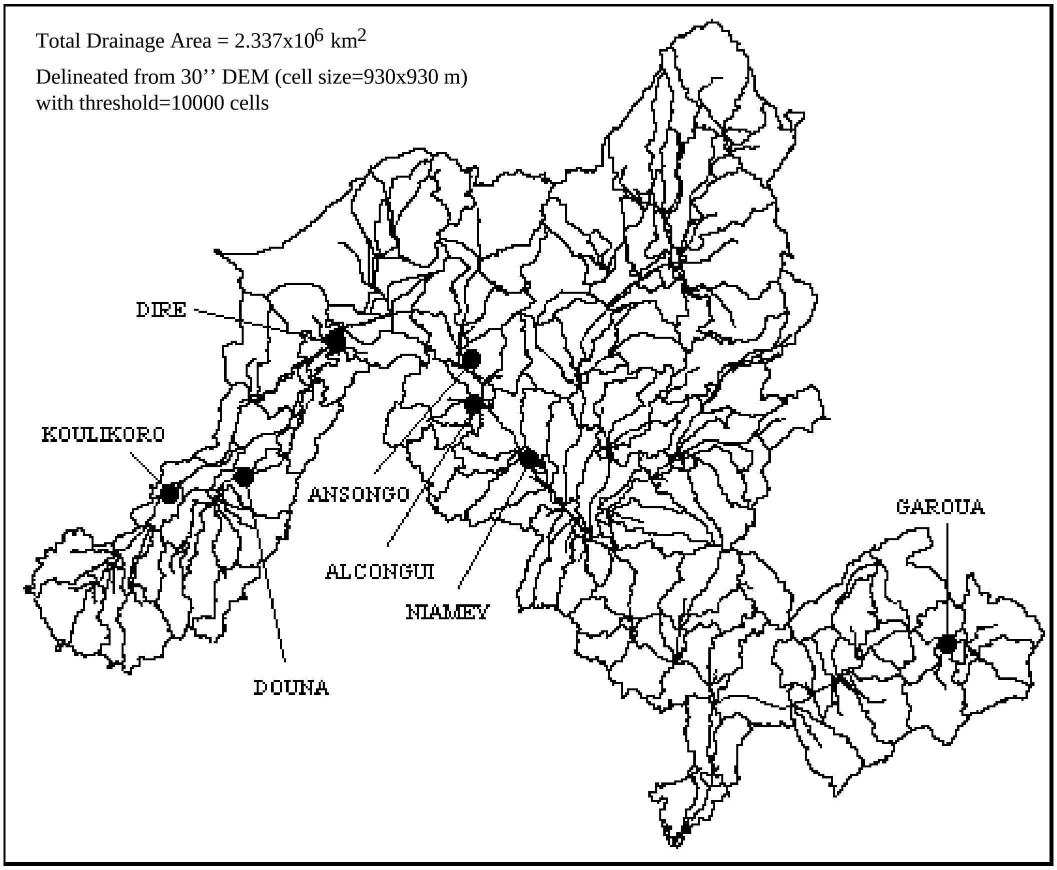

Total Drainage Area = 2.337x10^6 km^2
Delineated from 30’’ DEM (cell size=930x930 m)
with threshold=10000 cells
DIRE
KOULIKORO
ANSONGO
ALCONGUI
NIAMEY
DOUNA
GAROUA

Figure 3.20. The locations of flow-gauging stations in the Niger River Basin

Figure 3.21 shows the converging path of RMSE and SMD of the simulated river flow time-series at Koulikoro when applying the bisection-optimization scheme. Figures 3.22 and 3.23 show the plot of the observed vs. simulated flow time-series when the parameter sets obtained from the optimization model are used. From Table 3.6, it can be seen that when the river velocity is 0.192 m/s (row 11), and Loss-Coefficient for the river and subwatershed is 0.000985 /km, the best fit has RMSE=0.32 and SMD=0.0000116 (row 22). These two values indicate that in a 90 month period, the simulated flow time-series produced the same amount of mass while about 16%(=32%*0.5) of the mass is incorrectly placed in the time domain when compared with the observed flow time-series.

Figure 3.22a also shows that when using the calibrated parameters, the model underestimates both the high and low flows. The possible explanations of the underestimation may be the following reasons:

(1) in the simulation model, the same LossC value is applied to all the river sections and subwatersheds in the sub-model simulated area,

(2) LossC is kept constant throughout the whole simulation period,

(3) the surplus produced by the soil-water balance model may not be adequate to generate the observed stream flow.

The underestimation caused by reasons (1) and (2) can be corrected to some extent by assigning spatial and temporal variations to LossC but using non-constant LossC will make the optimization model become more complicated. The underestimation caused by reason (3) can be corrected by either using a better soil-water balance model with improved data sets or adopting other means to produce soil-moisture surplus (SurpF(t)) and subwatershed runoff contribution (PFlow(t)). The estimation can probably also be improved by reducing the sizes of subwatershed polygons and the number of subwatersheds selected for each sub-model.

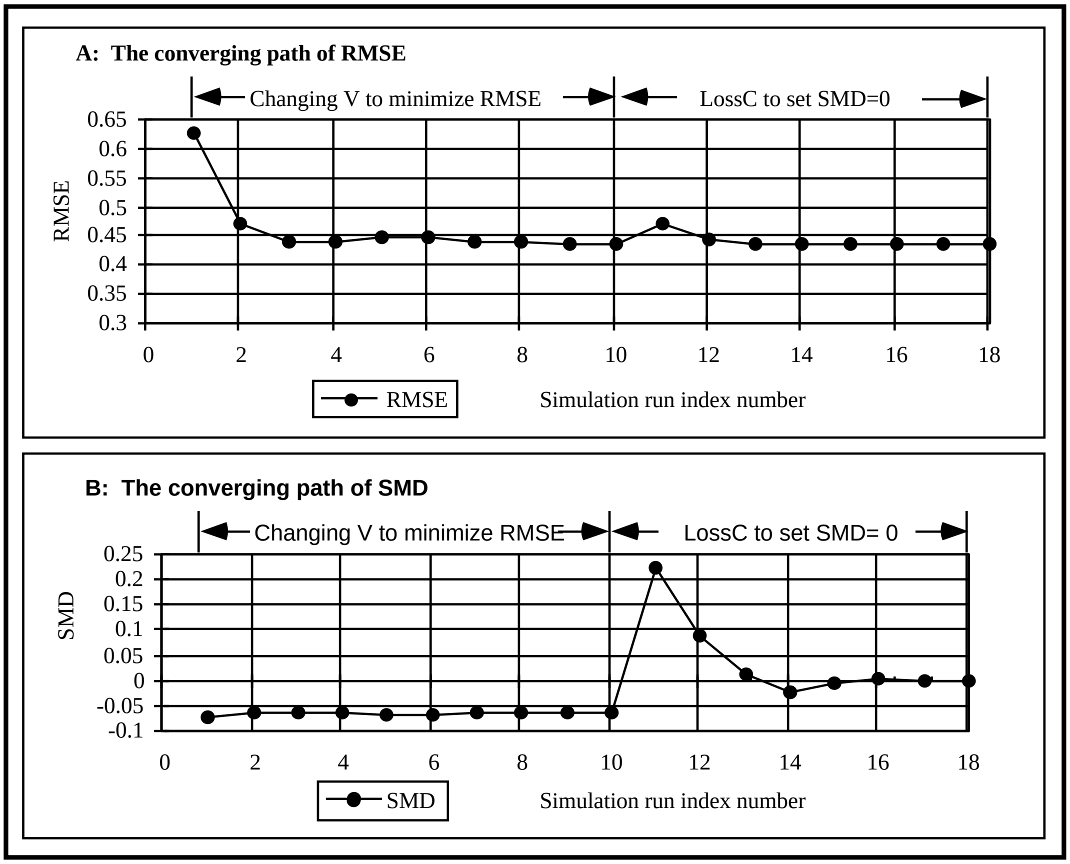


Figure 3.21. Using bisection method to fit two simulation model parameters (LossC and Velocity)

Table 3.6. Optimization of River Flow Velocity and Loss Coefficient

Index	RMSE	SMD	P-value	Parameter-optimized
1	1.1312006	-0.1048283	0.0500000	Ngriver.shp,Velocity,0.05,0.4,1
2	0.4353920	-0.1303611	0.4000000	Ngriver.shpRatio ,Velocity,0.05,0.4,1
3	0.3635078	-0.1295793	0.2250000	Ngriver.shp,Velocity,0.05,0.4,1
4	0.3637302	-0.1295891	0.2260000	Ngriver.shp,Velocity,0.05,0.4,1
5	0.3926416	-0.1277653	0.1375000	Ngriver.shp,Velocity,0.05,0.4,1
6	0.3913918	-0.1278081	0.1385000	Ngriver.shp,Velocity,0.05,0.4,1
7	0.3634192	-0.1289932	0.1812500	Ngriver.shp,Velocity,0.05,0.4,1
8	0.3631668	-0.1290096	0.1822500	Ngriver.shp,Velocity,0.05,0.4,1
9	0.3612605	-0.1293339	0.2031250	Ngriver.shp,Velocity,0.05,0.4,1
10	0.3612916	-0.1293474	0.2041250	Ngriver.shp,Velocity,0.05,0.4,1
11	0.3610867	-0.1291775	0.1921875	Ngriver.shp,Velocity,0.05,0.4,1
12	0.3921203	-0.2030196	0.0007000	Ngriver.shp,LossC,0.0007,0.0013,0
13	0.3200113	0.1924934	0.0013000	Ngriver.shp,LossC,0.0007,0.0013,0
14	0.3198814	0.0100611	0.0010000	Ngriver.shp,LossC,0.0007,0.0013,0
15	0.3484921	-0.0924330	0.0008500	Ngriver.shp,LossC,0.0007,0.0013,0
16	0.3314523	-0.0402009	0.0009250	Ngriver.shp,LossC,0.0007,0.0013,0
17	0.3251588	-0.0148247	0.0009625	Ngriver.shp,LossC,0.0007,0.0013,0
18	0.3224380	-0.0023209	0.0009813	Ngriver.shp,LossC,0.0007,0.0013,0
19	0.3211422	0.0038874	0.0009906	Ngriver.shp,LossC,0.0007,0.0013,0
20	0.3217759	0.0007864	0.0009859	Ngriver.shp,LossC,0.0007,0.0013,0
21	0.3221004	-0.0007651	0.0009836	Ngriver.shp,LossC,0.0007,0.0013,0
22	0.3219352	0.0000116	0.0009848	Ngriver.shp,LossC,0.0007,0.0013,0

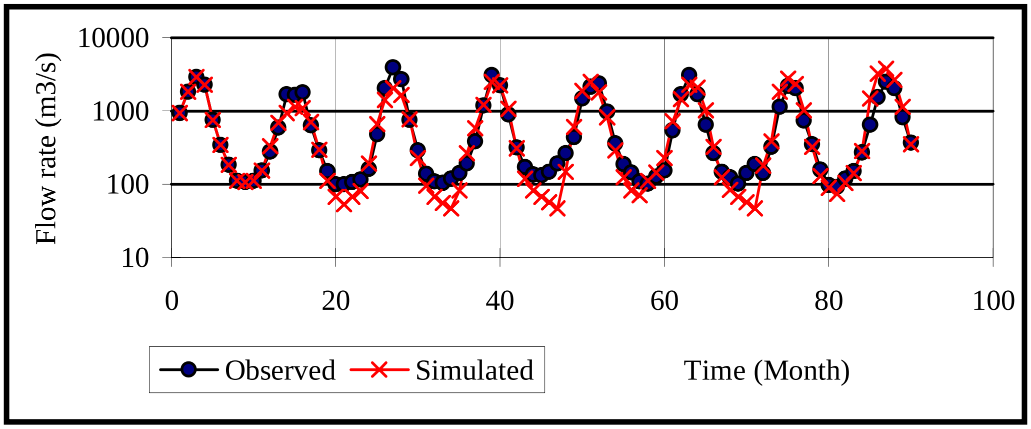


Figure 3.22a. Observed vs. simulated flow time-series at the Koulikoro flow-gauging station (flow rate on base 10 logarithm scale)

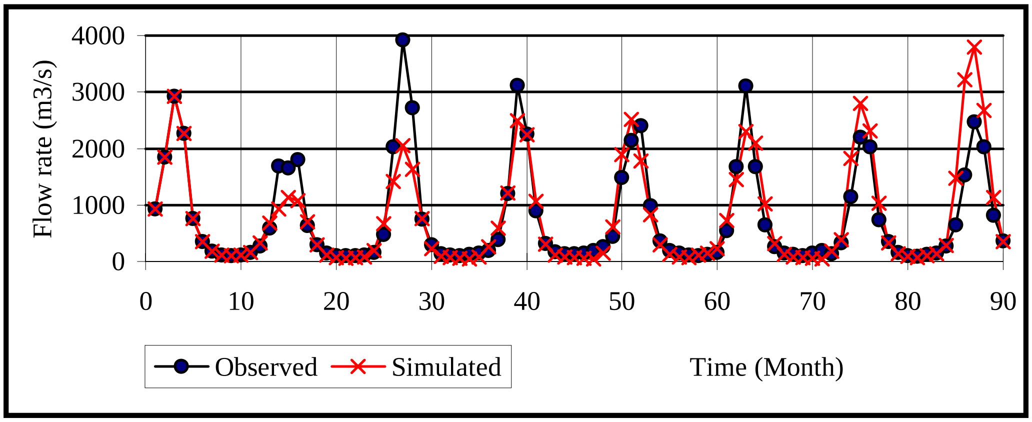


Figure 3.22b. Observed vs. simulated flows at the Koulikoro flow-gauging station

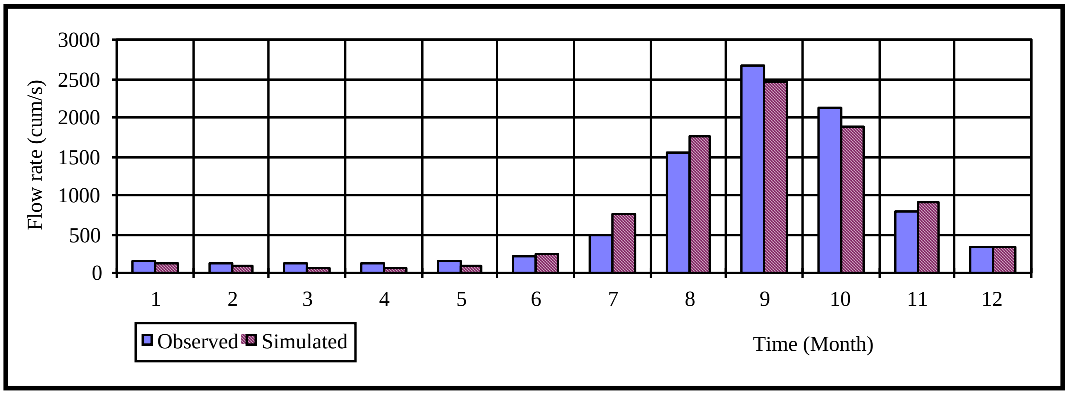


Figure 3.23. Observed vs. simulated mean-monthly flow at the Koulikoro flow-gauging station

Using the same procedure, sub-models were created for the regions associated with four other flow-gauging stations. On each sub-model, the optimization model is used to calibrate two simulation model parameters against the long-term (1961-1990) monthly average flow and flow time-series in a seven and a half year representative period (90 months from July, 1983, to December, 1990). The results of these calibrations are summarized in Table 3.7.

Table 3.7. Calibration Parameter Values for the Sub-Models

Station Name	Time-series	LossC (1/km)	Velocity (m/s)	RMSE	SMD
Koulikoro	90 months	0.00098	0.192	0.3219	0.0000116
	LongTerm	0.001	0.1656	0.1429	-0.0026
Douna	90 months	0.002826	0.0656	0.3736	-0.00394
	LongTerm	0.000964	0.1029	0.1997	-0.0004
Dire	90 months	0.000609	0.184	0.278	-0.00134
	LongTerm	0.00253	0.08	0.3735	0.000167
Ansongo	90 months	0.00027	0.289	0.1986	0.00095
	LongTerm	0.0002935	0.2113	0.093	-0.00287
Niamey	90 months	0.000433	0.4859	0.399	0.00013
	LongTerm	0.00692	0.29	0.262	-0.0008

3.6.4. Flow Interpolation Module

This module is created to interpolate the river flow rates to a flow-check point object. Due to its ability to dynamically segment an arc, the module is also used in the optimization models and dam/reservoir object construction modules to define the location of a point object.

The flow interpolation problem can be described as: given the flow rates at From-Node (FFlow) and To-Node (TFlow) of an arc, find the flow rate at a given point A located on the arc (Figure 3.24). The equation used for the flow rate interpolation at point A can be written as:

$$IFlow_A = FFlow + (TFlow - FFlow) \cdot \frac{SL}{TL} \qquad (3.21)$$

where,

$IFlow_A$ = Interpolated flow rate at point A,

SL = river distance between From-Node and point A,

TL = river distance between From-Node and To-Node, (point a and point g in Figure 3.24).

As shown in Figure 3.24, a river line section consists of a set of straight line segments. Before SL can be computed, it is necessary to identify which segment contains point A. In Figure 3.24, α and β are two angles formed by the line segment and the lines connecting point A to the end nodes of the line segment. It follows that if the line segment contains point A, the condition $((0^o \leq \alpha < 90^o)$ and $(0^o \leq \beta < 90^o))$ holds. This condition is referred to as "condition-A" in this section. Otherwise, one of the angles is less than 90^o, while the other angle will be greater than 90^o. It is also true that if the angle formed by two non-zero vectors $\vec{A}$ and $\vec{B}$ is less than 90^o, we have the dot product:

$$\vec{A} \cdot \vec{B} = x_a x_b + y_a y_b > 0 \tag{3.22}$$

Because in an ARC/INFO coverage, the x,y coordinates of a point are readily available, the dot product and the angle formed by any to vectors can be evaluated using Equation 3.22. Therefore, to compute SL in equation 3.21, the flow interpolation program needs first to find out which river segment contains point A. Using the river section given in Figure 3.24 as an example, the method for computing SL is described below.

Starting from segment ab, the program evaluates the angles ∠Aab, and ∠Aba. Since angle ∠Aba is greater than 90^o, condition-A does not hold indicating that segment ab does not contain point A. Therefore, length ab is added to SL. Applying the same procedure to segment bc reveals that condition-A does not hold for segment bc either so the length of segment bc is also added to SL. On segment cd, the program finds that condition-A holds indicating that the segment contains point A. After adding the remaining segment cs of cd to SL, the program uses Equation 3.21 to linearly interpolate the river flow rate to point A.

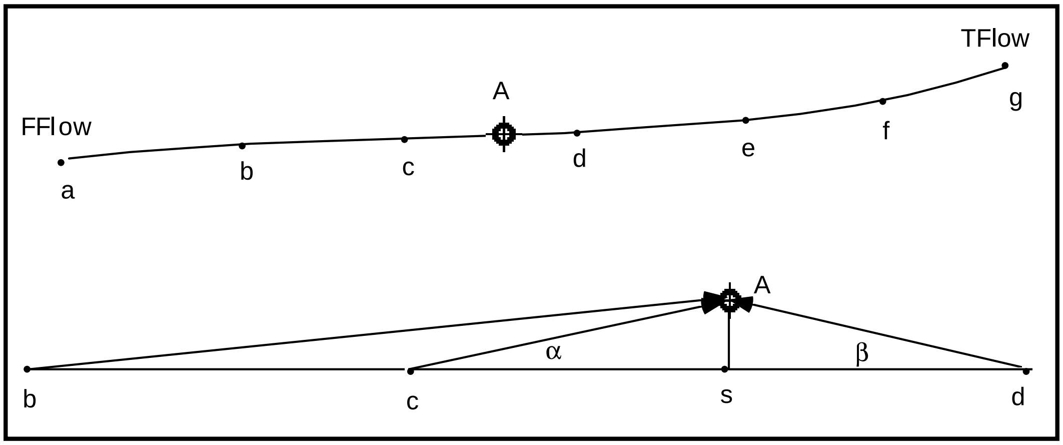


Figure 3.24. Interpolating river flow rate at a given point

The remaining segment cs can be computed using Equation 3.23 (in reference to Figure 3.24):

$$\begin{aligned} |cs| &= |cA| \cdot \cos(\alpha) \\ &= \frac{(x_A - x_c)(x_d - x_c) + (y_A - y_c)(y_d - y_c)}{\sqrt{(x_d - x_c)^2 + (y_d - y_c)}} \end{aligned} \qquad (3.23)$$

3.6.5. Plotting a Longitudinal Flow Profile

The map-based model allows a user to activate tasks directly from a map, greatly simplifying some map-oriented operating procedures. In this and the next section, two map-oriented post-processing modules are introduced to illustrate the strength brought by the integration of programs, maps, and databases.

To perform the hydrologic analysis of a river system, it is often necessary to plot the longitudinal flow profile on a river. If maps and databases are not integrated, the river sections of interest first have to be selected, then the flow data for the selected river sections have to be extracted from the database.

Finally, these data have to be sorted before they can be sent out to plot. The procedures are repeated each time a different river section is picked or flow conditions changed. In addition to the inefficiency brought by this tedious data extraction and data processing procedure, the curve plotted is usually not shown together with the map, which further hinders the interpretation of the plot.

In this map-based simulation model, because a program has access to both the maps and database tables, the longitudinal profile of any selected river sections can be plotted with a simple click on a river section. The logic of the plotting module is described below.

When a river section is selected, its location information is passed on to the plotting program (SFtrplt.pst). Based on the location information and river network connectivity kept by the From-Node and To-Node of each river line, the program traces downstream until the outlet section of the river network is reached. As each river section is found, the flow information related to that river section is collected from the flow table. Because the flow data is collected at the same time river sections are traced, the collected data set is already in the correct order to make the plotting procedure an easy next step. As the plotting program moves from section to section downstream, the section it reaches is highlighted on the map, so that visually, the user can be ensured that no mistake is made in the tracing procedure. The river sections remain highlighted when their longitudinal flow profile plot is on display which helps with profile interpretation (Figure 3.25). When plotting of another river section is desired, the user can simply mark the new selection by clicking at the desired location and let plotting program perform the tasks of river section tracking, data extracting, and curve plotting.

3.6.6. Plotting Time-Series Data at a Selected Location

This program (SFtmplt.pst) is designed to plot the temporal distribution of a physical parameter at a given location. Like the program designed to plot the longitudinal flow profile, this program is also activated directly by a click of mouse on the model maps. When the location information is passed on to the plotting program, the program uses the location information (location ID) to select the time-series (vector) associated with the location and make a plot like that shown in Figure 3.25. The program is designed to work with the spatially-referenced time-series data stored in a database table with the data structure described in Section 3.3.

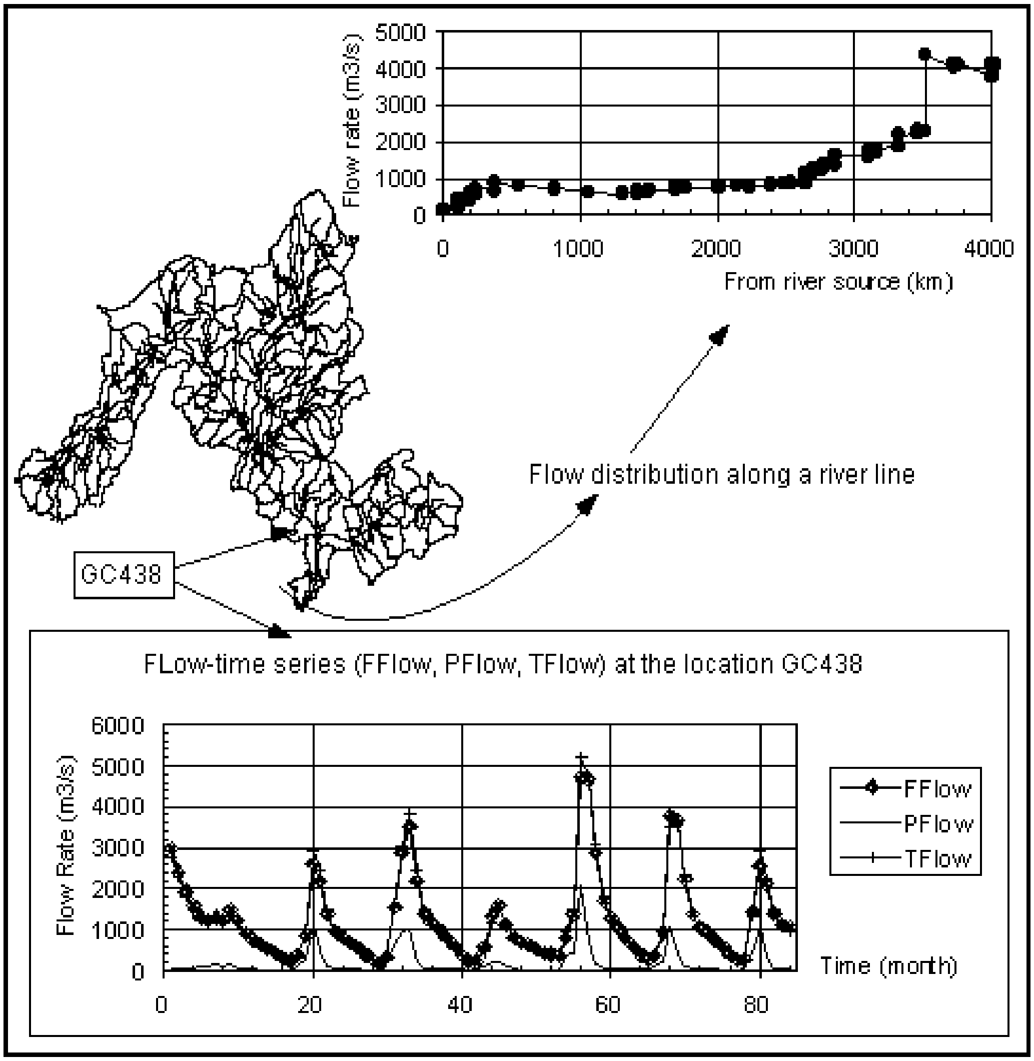


Figure 3.25. Plotting flow distributions with the map-based surface water flow simulation model

3.7. Chapter Summary

The map-based surface water flow simulation model is constructed based on the concepts of object-oriented programming and GIS. The model is designed in such a way that all three components of a model, programs, maps, and databases, are integrated.

The basic maps of the map-based model are an arc coverage containing the river lines and a polygon coverage containing the subwatershed polygons. Both maps can be constructed by applying a watershed delineation procedure to a digital elevation model (DEM) of the study region. A sequence of map operations and data structure modifications are performed on these two coverages by a set of pre-processor programs to create river objects, subwatershed objects, and finally, a river network. The connectivity of the river network is maintained by the From-Node and To-Node of each river section on the network. The river sections and subwatershed polygons have a one-to-one relationship.

To simulate river flow, the attributes FFlow and TFlow (FFlow(t) and TFlow(t) for unsteady state) are created for each river object to hold the flow rates at the From-Node and the To-Node of the stream line object. For each subwatershed, PFlow (PFlow(t) for unsteady state) is created to represent the subwatershed's local runoff contribution. The basic relationships between these three quantities are established based on the principle of continuity and are given by Equations 3.1a, 3.1b and 3.2.

The sequential order by which each subwatershed in the stream network is simulated is constructed by a stack-based stream network analysis algorithm developed for this simulation model. The design of this stack-based stream network analysis algorithm is based on the connectivity established by the From-

Node and To-Node of each arc in the network. After the sequential order is decided, Equations 3.3 through 3.12 given in Section 3.4.2. are used to establish the relations between PFlow(t), FFlow(t), and TFlow(t) and simulate water movement on the river network.

Since the stack-based stream network analysis algorithm can be applied to any stream network that fits the assumptions given at the beginning of this chapter, it can be used to simulate other environmental processes as well. For example, if PFlow(t) represents some pollutant sources defined on a polygon object and the pollutant transport mechanism can be established on the rivers, the pollutant mass loading time-series FFlow(t) and TFlow(t) associated with the From-Node and To-Node can be simulated the same way that water flow is simulated. In fact, the process that this model simulates may vary with the type of model used to compute PFlow(t) on each subwatershed.

The integration of programs, maps, and databases allows easy creation of sub-models, making it possible to divide a big study region into several sub-regions for studies with different levels of detail.

To calibrate the simulation model, two optimization models having direct access to the maps, databases, and simulation models are constructed. Of these two models, the interactive optimization model can be used to calibrate no more than 3 parameters at a time because the model needs multiple runs to complete the calibration process, and for each new run the model requires a user who relies largely on the two-dimension plots (Figure 3.18) to define the problem solution space.

The optimization model based on a direction set method is used for all the simulation calibrations in this study. The optimization program is designed in such a way that it does not put a limit on the number of parameters that can be calibrated at one time. But when the number of parameters to be calibrated is more than four, it may take a long time to complete the optimization procedure. The model also requires a user to provide ranges for all the calibrating parameters at the beginning of a calibration procedure.

Although SMD and RMSE (Equations 3.17 and 3.18) are used in the optimization model to evaluate how well the observed and simulated time-series water, the optimization program is designed in such a way that other standards such as lag-one correlation can be easily added.

The validation procedure of the map-based simulation model is not carried out in this study for the following two reasons:

(1) Because the main purpose of this study is to integrate the three components of a model, the major effort has been devoted to the design and testing of the model programs and the communications between the programs to ensure a smooth integration. A large amount of work is also used to create a smooth pre-processing procedure.

(2) In the Niger River Basin area, it is difficult to find a second set of the required data time-series, such as rainfall distribution and river runoff observations that covers the same length of time without substantial amount of missing records.

The main program (SFlowSim.prc) is designed in such a way that its operation is independent of the modules used to simulate PFlow(t), FFlow(t) and TFlow(t). The model currently provides four modules for simulating water flow on river sections. Because all these four modules are hydrological (lumped) flow routing algorithms, this map-based surface water flow simulation model can be categorized as a hydrological (lumped) flow routing model, comparable to other hydrological (lumped) flow simulation models. If hydraulic (distributed or semi-distributed) flow routing modules such as the methods based on the differential equations of motion and continuity in an open channel (Saint-Venant equations) were used, this map-based model would become a hydraulic based (distributed) simulation model. At one point of this study, a hydraulic routing module based on the kinematic wave routing method was designed and tested successfully to run with the main program. The module was later disconnected from the main program because not enough field data were available for the Niger River Basin area to support the hydraulic routing module.

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.

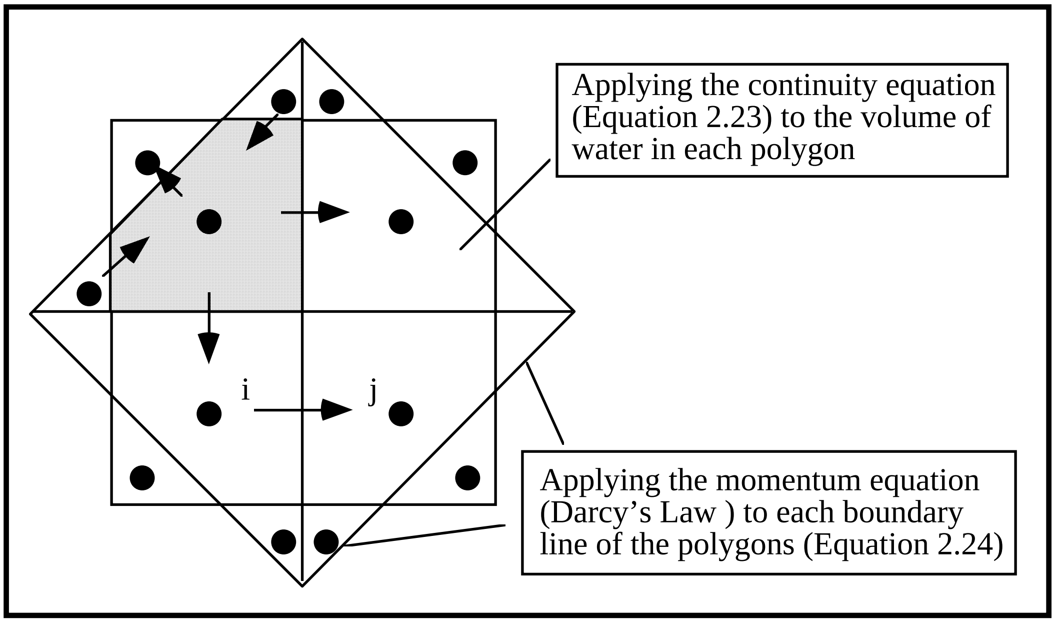

Applying the continuity equation (Equation 2.23) to the volume of water in each polygon
i
j
Applying the momentum equation (Darcy’s Law) to each boundary line of the polygons (Equation 2.24)

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.

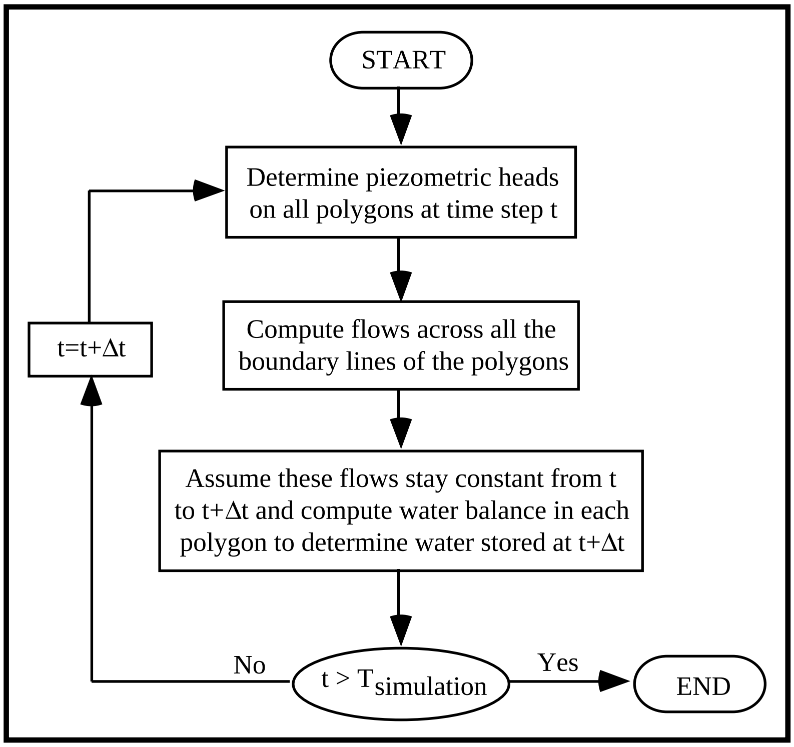

START
Determine piezometric heads on all polygons at time step t
Compute flows across all the boundary lines of the polygons
Assume these flows stay constant from t to t+Δt and compute water balance in each polygon to determine water stored at t+Δt
t > T simulation
No
Yes
END
t=t+Δt

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.

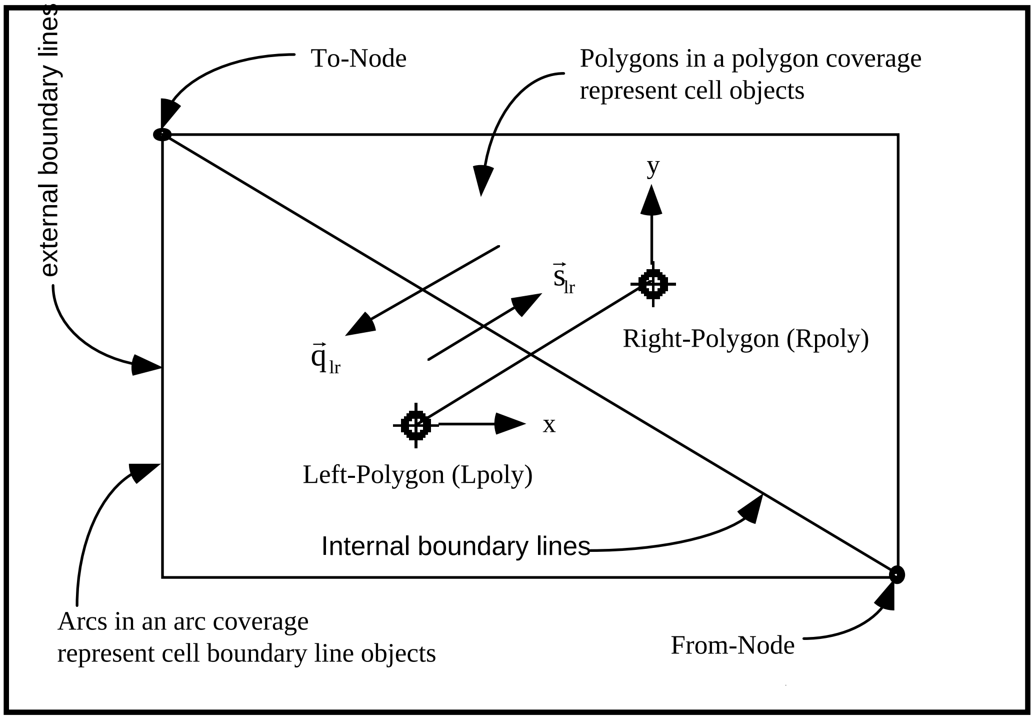


Figure 4.4. The arc and polygon coverages used by the simulation model

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.

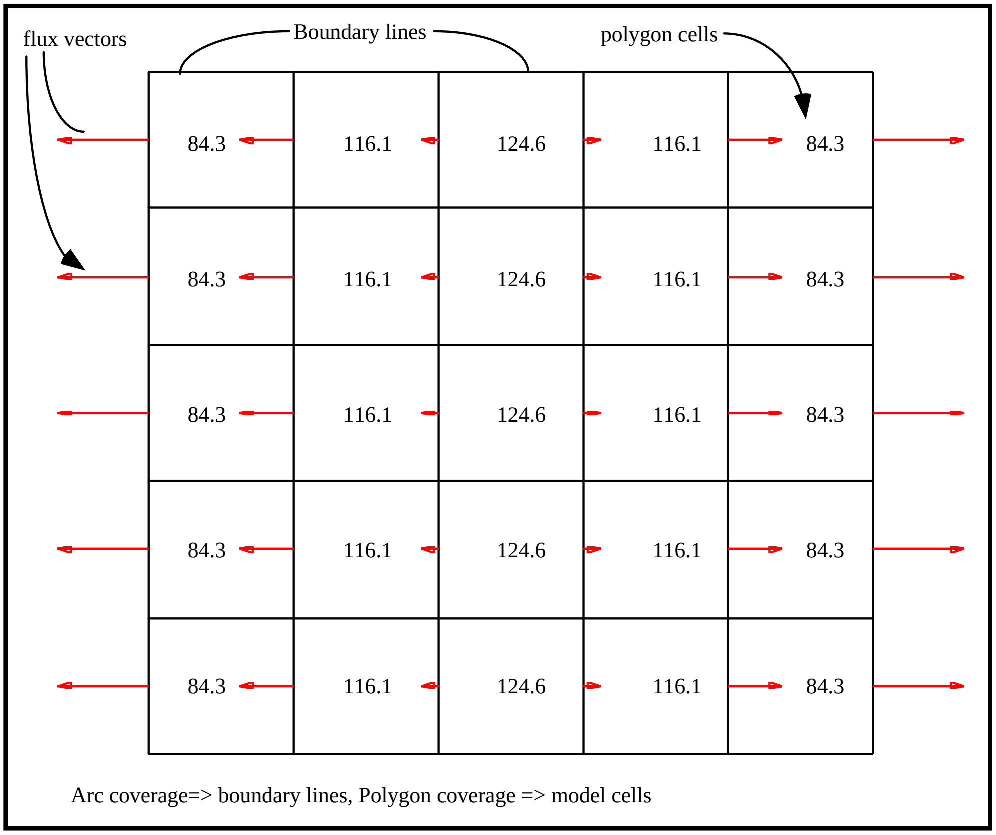

flux vectors
Boundary lines
polygon cells
84.3
116.1
124.6
116.1
84.3
Arc coverage=> boundary lines, Polygon coverage => model cells

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.

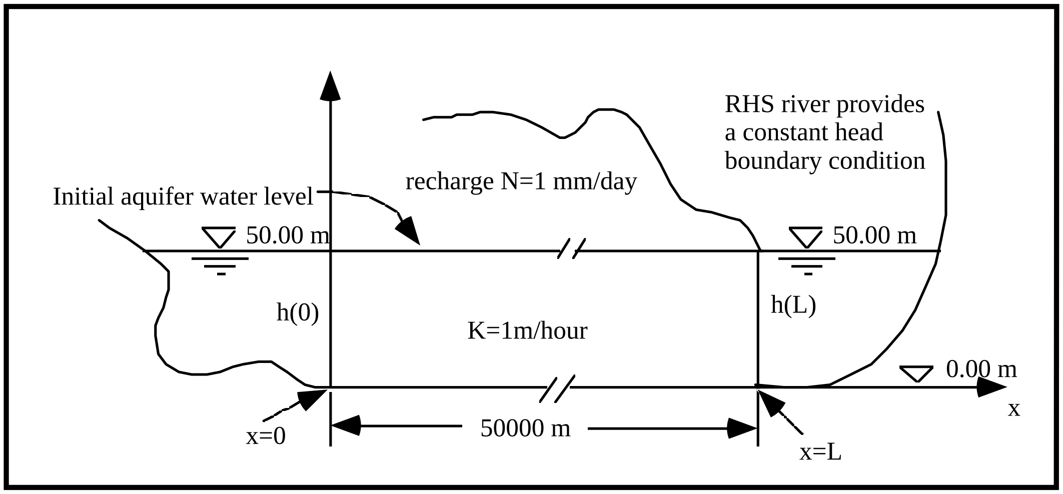


Figure 4.6. A cross-section of the example problem

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

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

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):

$$\begin{aligned} &\mathrm{K}\left([\mathrm{h}(\mathrm{x})]^2 - [\mathrm{h}(\mathrm{x}_0)]^2\right) - \mathrm{Nx}(\mathrm{L}-\mathrm{x}) \\ &- \mathrm{K}\frac{\mathrm{x}}{\mathrm{L}}\left([\mathrm{h}(\mathrm{x}_1)]^2 - [\mathrm{h}(\mathrm{x}_0)]^2\right) = 0 \end{aligned} \qquad (4.9)$$

where, $\mathrm{h}(\mathrm{x}_0)$ = 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:

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

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

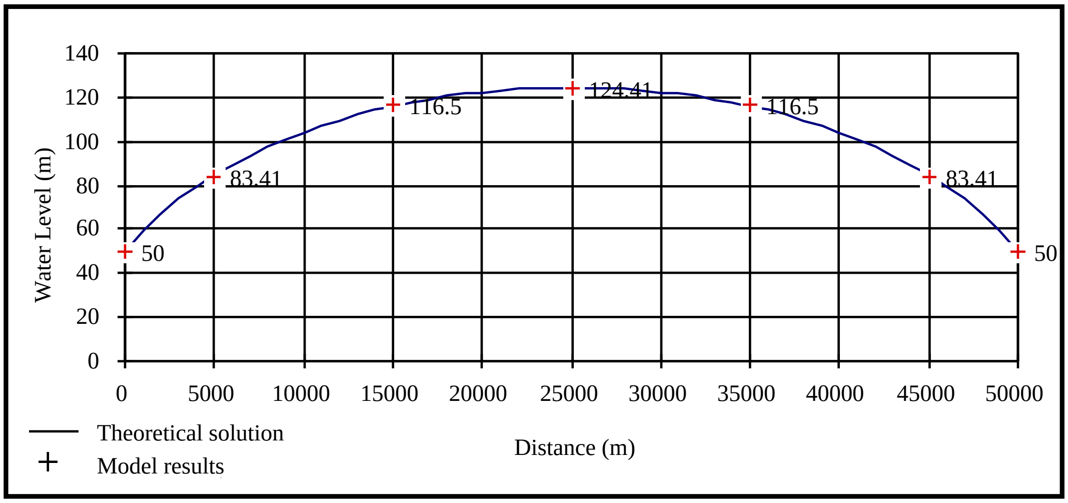


Figure 4.7. The phreatic surface, theoretical vs. simulated, of the dual-river problem

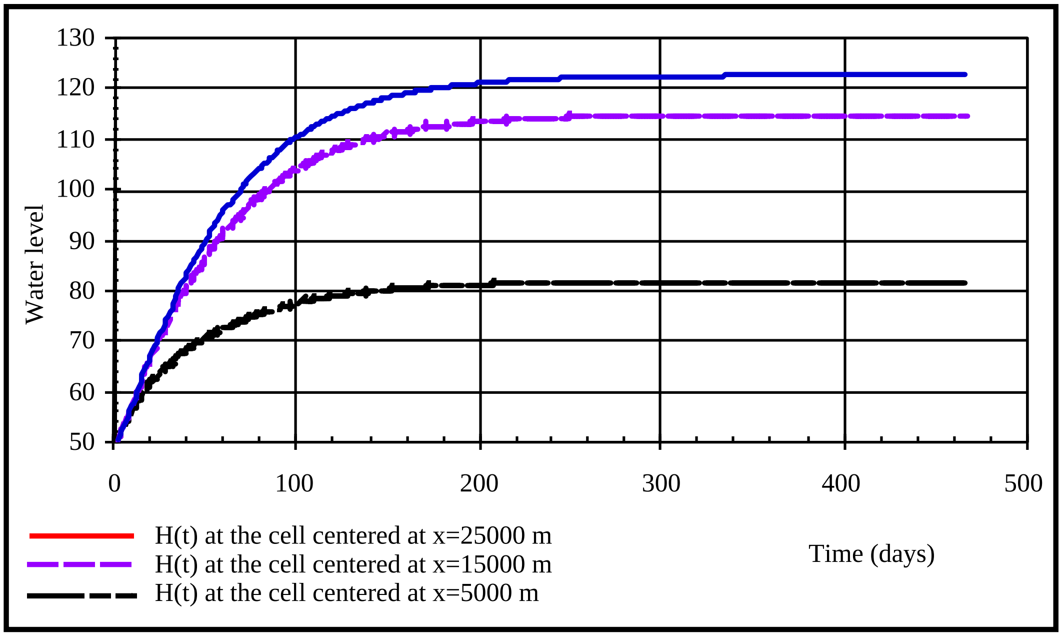


Figure 4.8. The water levels vs. time

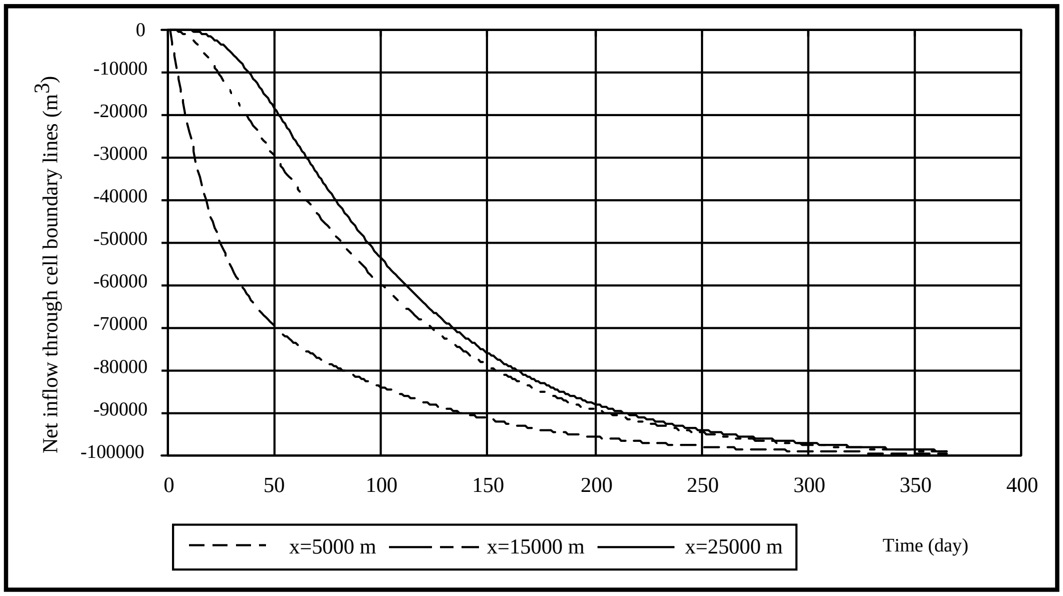


Figure 4.9. The net in-flow through the boundaries of a cell

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.

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.

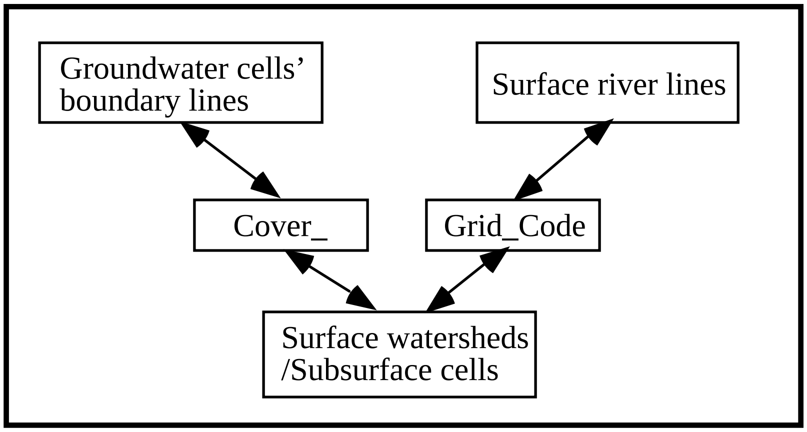

Groundwater cells' boundary lines
Surface river lines
Cover_
Grid_Code
Surface watersheds /Subsurface cells

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.

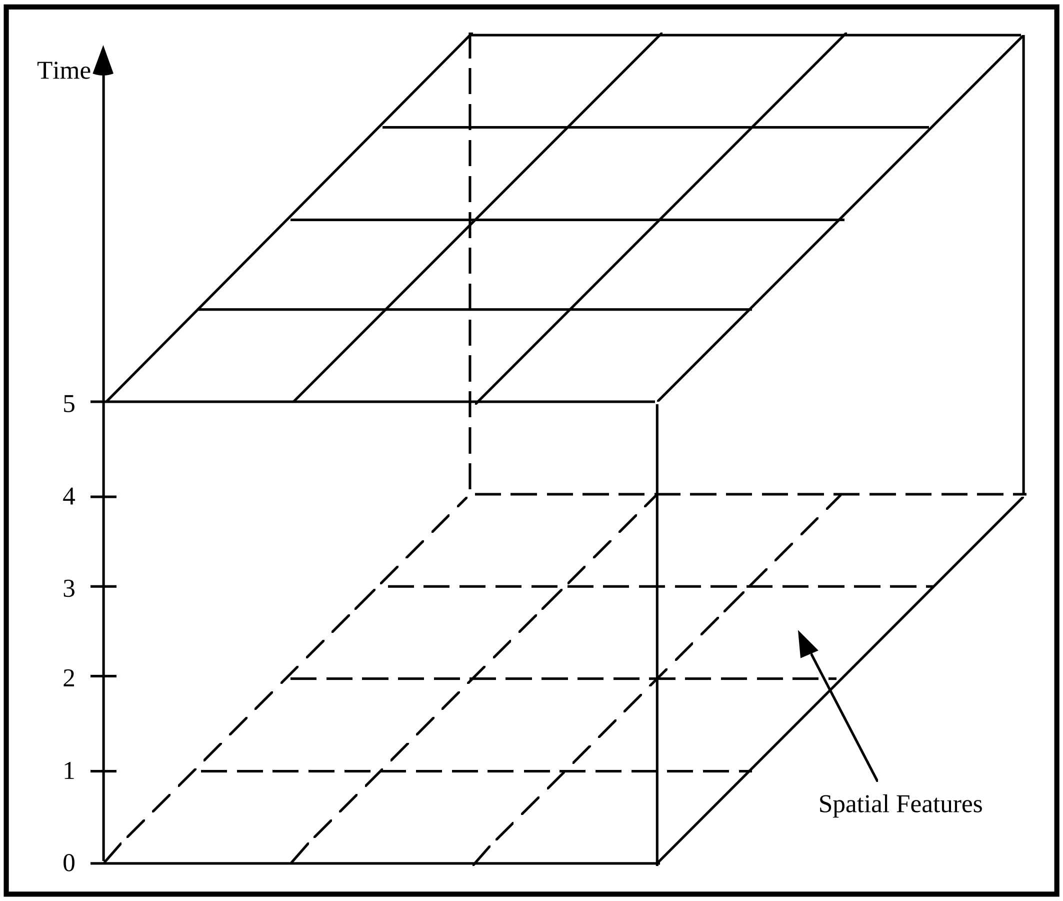


Figure 5.2. The spatial and time domains of a simulation model

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.

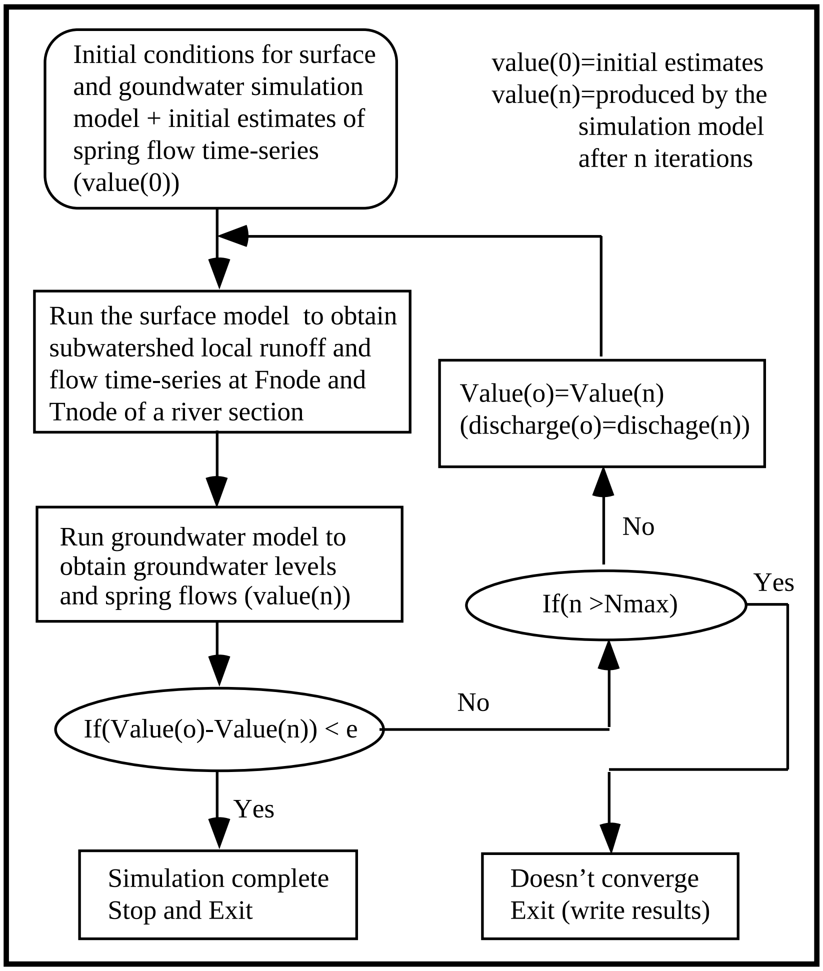

Initial conditions for surface and goundwater simulation model + initial estimates of spring flow time-series (value(0))
value(0)=initial estimates
value(n)=produced by the simulation model after n iterations
Run the surface model to obtain subwatershed local runoff and flow time-series at Fnode and Tnode of a river section
Value(o)=Value(n)
(discharge(o)=dischage(n))
Run groundwater model to obtain groundwater levels and spring flows (value(n))
No
If(n >Nmax)
Yes
If(Value(o)-Value(n)) < e
No
Yes
Simulation complete
Stop and Exit
Doesn’t converge
Exit (write results)

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).

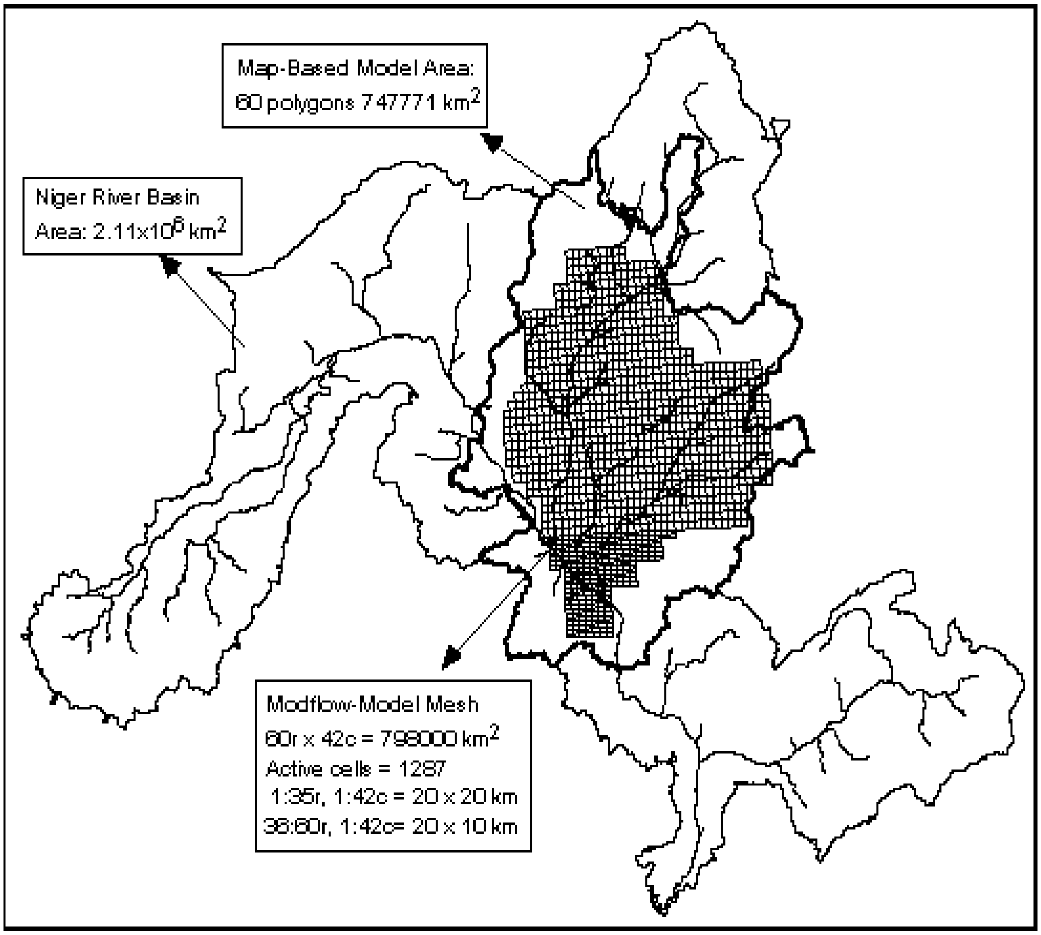

Map-Based Model Area:
60 polygons 747771 km^2
Niger River Basin
Area: 2.11x10^6 km^2
Modflow-Model Mesh
60r x 42c = 798000 km^2
Active cells = 1287
1:35r, 1:42c = 20 x 20 km
36:60r, 1:42c= 20 x 10 km

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

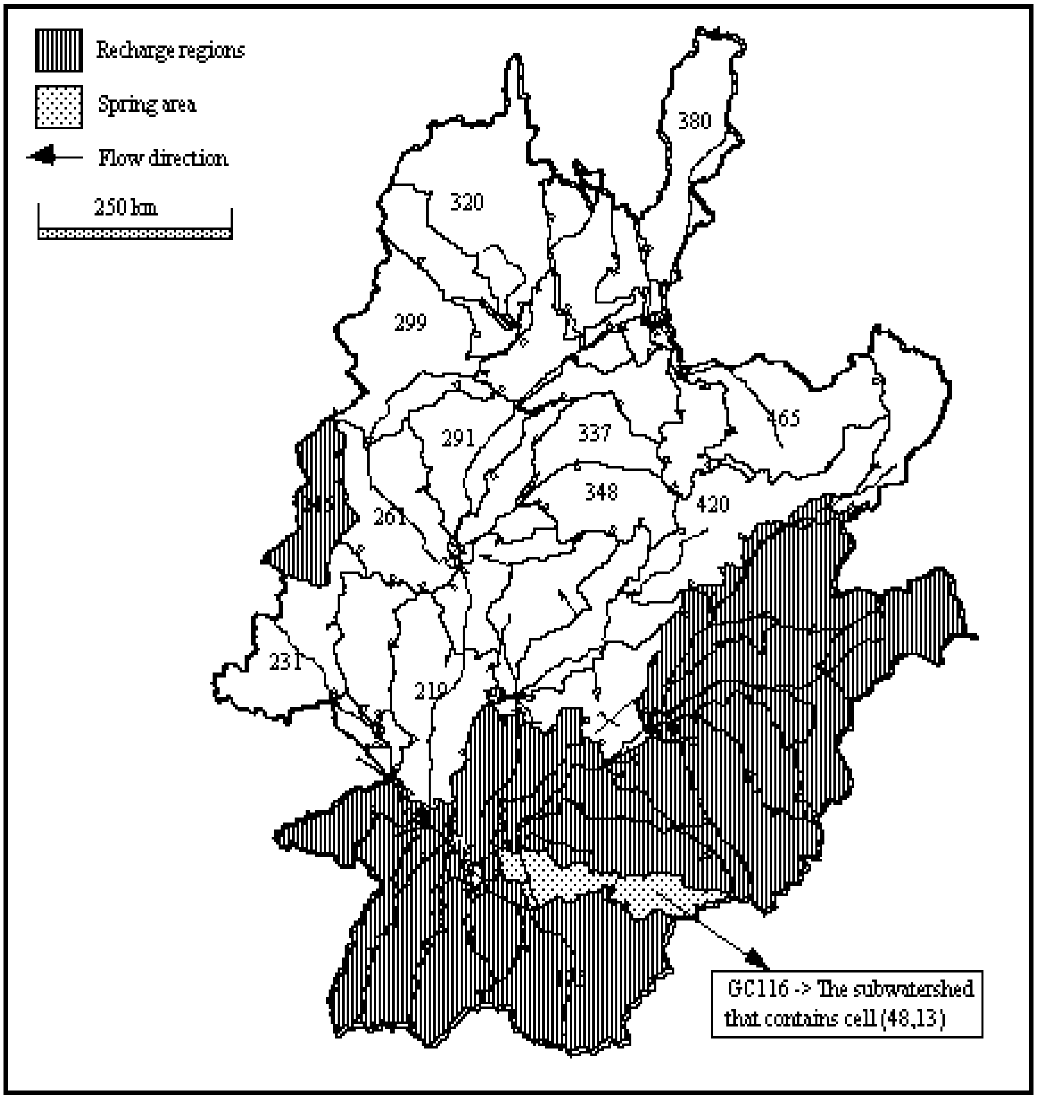


Figure 5.5. The polygons of the map-based groundwater simulation model

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.

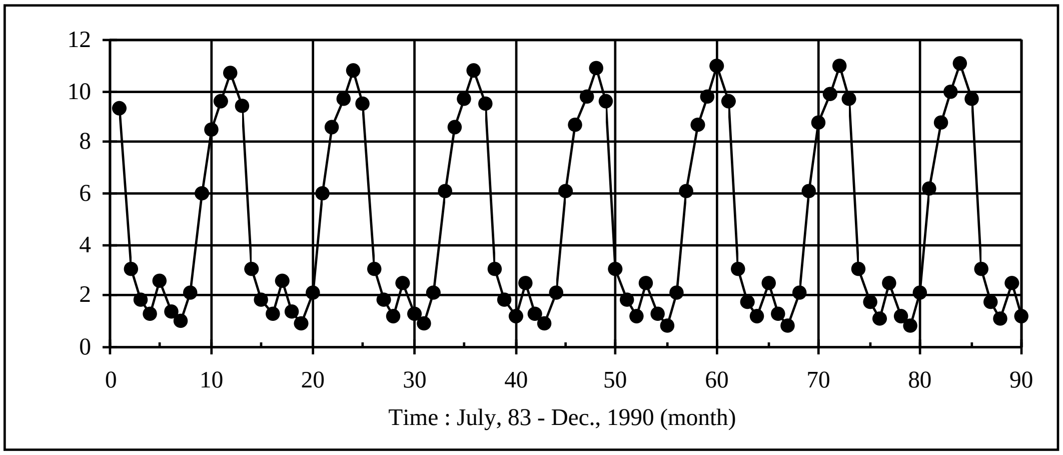


Figure 5.6. The spring flow time-series at GC116 produced by the Map based model

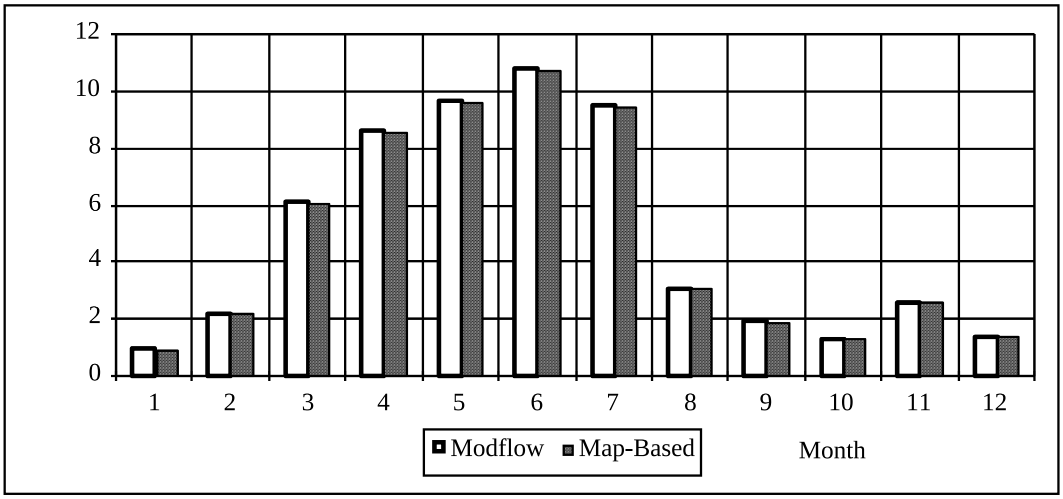


Figure 5.7. The monthly-average spring flows at GC116 produced by the Map based model and at cell (48,13) by the Modflow model

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 ground-water 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.

Chapter Six. Summary and Conclusions

As stated in Chapter One, the principal purpose of this research is to design map-based surface and subsurface simulation models that have all three model components - programs, maps and databases - integrated. As a result of this research, a map-based surface water flow simulation model and a map-based groundwater flow simulation model are constructed. Both models are based on the concepts of object-oriented programming (OOP) and geographic information systems (GIS). Listed below are conclusions that can be drawn from this research:

1. Using the concepts of object-oriented programming and relational databases, it is possible to design an efficient map-based simulation model for surface and subsurface water flows under the environment of a geographic information system (GIS).
2. In order to design a map-based flow simulation model under GIS environment, it is necessary to design an efficient data structure to manage the spatially-referenced time-series data. A data structure has been designed and used successfully to manage all the spatially-referenced time-series data sets for the simulation models. The data structure has the following features (Chapter Three):
   (a) One data table is created for each data item with the table name reflecting the item name.
   (b) The fields (columns) are related to the spatial features on the map with the field names constructed from the feature identifications. The number of fields equals the number of features on the map that have time-series data defined on them.

(c) The records (row) of the table store the time steps of the spatially-referenced time-series data.

3. Due to the integration of its three model components, the map-based surface water flow simulation model has the following capabilities:

   (a) The base maps of the model and the simulation model itself can be constructed using an interactive and menu-driven user interface. Thanks to the programs developed for the base map and simulation model construction, this map-based water flow simulation model can be recursively applied to different regions with very little model modification.

   (b) Once the base maps and the simulation model are constructed, the modeling procedure can be activated from the maps with its progress being monitored on the maps.

   (c) The model results can be displayed, retrieved, and analyzed on the maps. Displaying and analyzing the model results on the model maps make it easier for a model user to understand and interpret the model results.

   (d) Model conditions can be modified directly from the maps, i.e. when a map is altered, its associated data tables and programs will also be modified accordingly to reflect the change. Due to this type of model design, a portion of study region (subregion) can be isolated and cut to create a "sub-model" for more detailed analysis.

4. The experience of constructing these map-based models shows that the "one-to-one" condition imposed on the relationship between objects among different classes can greatly improve the efficiency and portability of the model programs. In fact, it is generally true that when applying the concept of object-oriented programming to

construct a model, it is more efficient to use combinations of many simple objects rather than to use a single complex object to simulate complex situations. If the simple-single object method is used, a new complex situation can usually be simulated with the combinations of these simple-single objects or with the creation of new simple-single objects, while if a complex single object is used then it may not be reusable for another new situation because it is inefficient, if not impossible for an already complex object to be modified to fit a new situation.

5. The map-based groundwater simulation model is constructed by applying the continuity equation (Equation 2.23) to the polygons and the momentum equation (Darcy's Law) to the boundary lines of these polygons. Because such a design is consistent with the data structures of the polygon and line attribute tables in ARC/INFO GIS, the model and its data sets are fully integrated with the basic maps. In addition to the features listed above for the map-based surface water flow simulation model, the following features are specific to the groundwater simulation model:

   (a) The base maps and model can be constructed from a given polygon coverage.

   (b) The meshes (polygons) used for the simulation model can be of any shape, which makes it possible for groundwater model meshes to take the shapes of subwatershed polygons of the surface water flow simulation model.

   (c) Under this design, the continuity and momentum equations are defined separately on the polygon and polygon boundary line objects and the problems of assembling and solving large set of linear equations are avoided.

6. The application of the concepts of object-oriented programming and GIS approach makes it possible to construct a model not in terms of state variables but in terms of problems and problem objects.

7. The one-to-one relationship between the surface and subsurface objects are emphasized in designing the integrated surface and subsurface water flow simulation model. A simulation model procedure that keeps the one-to-one relationship between the modeling objects can greatly simplify the data exchange procedure and make the simulation program efficient. Technique exist, however, to design an integrated model with one-to-many type spatial relationships. For example, if it is desired to have a model with one surface object to many groundwater objects, the model can be designed as described below. Two pointer states can be created for each of the subsurface objects and one for each of the surface objects. The first pointer of a subsurface object is used to point to next subsurface object that is spatially connected to the same surface object. A zero value of the first point indicates that the object is the last of the subsurface objects connected to the same surface object. The second pointer of a subsurface object is used to point to its connected surface object. The pointer of a surface object is used to point to the first of the subsurface objects connected to it. This way, a surface object only needs to know the first in the list of subsurface objects that are related to it, which converts the original one-to-many relation into a one-to-one relation.

8. Because the map-based surface and subsurface models are constructed based on the map topology of ARC/INFO, the model programs must

be designed internally within the ArcView environment. Although using the programs internal to ArcView greatly enhances the models graphical presentation, e.g. allowing the simulation results to be monitored and displayed on the base map while the simulation is in progress, the model runs slowly when compared to models written with external programming languages, such as FORTRAN and C++. Possible solutions to the problem of model speed could be found by either exporting the ARC/INFO map-topology for use by external programs or creating other ways to connect the model objects for use in external programs.

With the successful design and construction of these map-based simulation models, this research has shown that using the techniques of object-oriented programming, relational databases management, and GIS, it is feasible to construct a model with all three of its components integrated. By applying the model to the Niger River Basin, this research has also demonstrated the effectiveness of the map-based model in surface water flow simulation.

Appendix I. The Map-Based Surface Water and Subsurface Water Flow Simulation Models

User's Manual

1. Model Installation

All model programs are contained in the project file HYDRO.APR. To test the model, two coverages in ARC/INFO export format are provided. These two files are NGBASIN.e00 and NGRIVER.e00. NGBASIN.e00 contains subwatershed polygon and polygon boundary line coverages of the Niger river basin in the west Africa and NGRIVER.e00 contains the river line coverage of the Niger river basin. These coverages are created by applying a delineation procedure to the 5 minute DEM of the region. The delineation procedure are given in Figure 2.

To install the coverages on a UNIX workstation, from under the ARC/INFO's ARC prompt, type in:

IMPORT COVER NGBASIN NGBASIN and

IMPORT COVER NGRIVER NGRIVER

To install the coverages on a PC with ArcView version 2.1 or later, from DOS prompt, type in:

IMPORT C:\WIN32APP\ArcView\BIN\IMPORT.EXE C:\NGFLOW\NGBASIN.E00 C:\NGFLOW\NGBASIN and

IMPORT C:\WIN32APP\ArcView\BIN\IMPORT.EXE C:\NGFLOW\NGRIVER.E00 C:\NGFLOW\NGRIVER

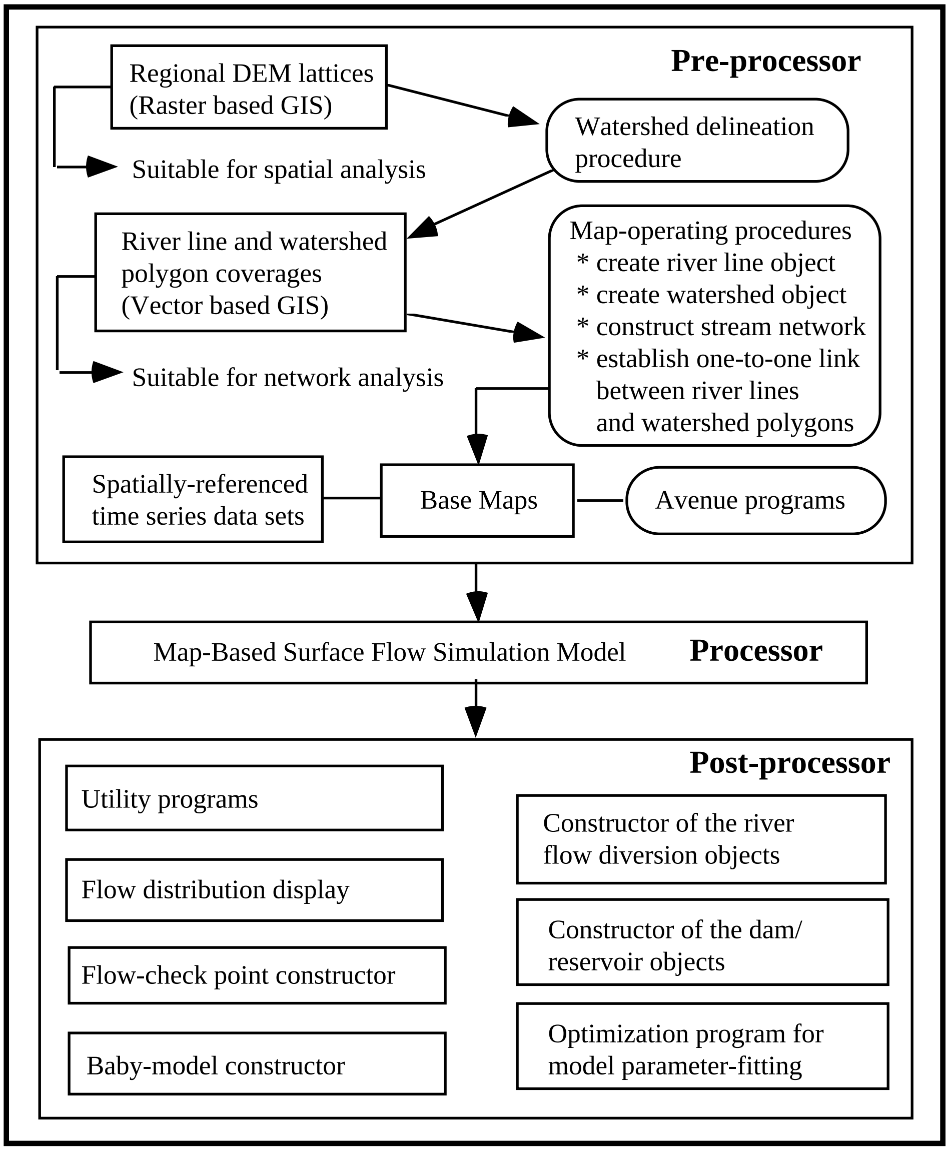
assuming your ArcView is installed under C:\WIN32APP, your *.E00 files are in C:\NGFLOW and your coverages are to be stored under C:\NGFLOW.

After restoring these coverages, following the procedure described on next section to construct and run the map-based surface water and groundwater flow simulation model.

2. Model Description

2.1. General description

The integrated map-based surface and subsurface water flow simulation model is contained in the HYDRO.APR project. To construct a map-based surface and subsurface water flow simulation model for a region (using the Niger River Basin as an example), three coverages are required, a polygon coverage (NGBASIN), a line coverage constructed using the ARC command: build NGBASIN line, from the NGBASIN polygon coverage, and NGRIVER line coverage. All these three coverages are created by applying the watershed delineation procedure to the DEM's in the Niger river basin area. Figure 1. shows the components of a map-based surface water flow simulation model.



Pre-processor
Regional DEM lattices (Raster based GIS)
Suitable for spatial analysis
Watershed delineation procedure
River line and watershed polygon coverages (Vector based GIS)
Suitable for network analysis
Map-operating procedures
* create river line object
* create watershed object
* construct stream network
* establish one-to-one link between river lines and watershed polygons
Spatially-referenced time series data sets
Base Maps
Avenue programs
Map-Based Surface Flow Simulation Model
Processor
Post-processor
Utility programs
Flow distribution display
Flow-check point constructor
Baby-model constructor
Constructor of the river flow diversion objects
Constructor of the dam/ reservoir objects
Optimization program for model parameter-fitting

Figure 1. The components of a map-based surface water flow simulation model

As shown in Figure 1, a map-based surface water flow simulation model is supported by both spatial-data sets (maps) and spatially-referenced time-series data sets. Section 2.2 describes both the model base-map construction procedure and the time-series data preparation procedure.

2.2. THE CONSTRUCTION OF BASE-MAPS AND SPATIALLY REFERENCED TIME-SERIES DATA SETS

2.2.1. Construction of model base-maps

Step 1. Applying watershed delineation procedure to the DEM of the study region.

The base-maps are acquired by applying a watershed delineation procedure to the digital-elevation model (DEM) of the region. Figure 2 gives a sample river basin delineation procedure.

```
‘************************************
‘A sample delineation procedure - deline.aml
‘************************************
demprj = project ( demorg, project. prj,  #, 100)
fill demprj demprj
demfdr = flowdirection ( demfil )
demfac = flowaccumulation ( demfdr )
&sv thres =10000
demstr = con(demfac > %thres%, 1)
demlnk = streamlink ( demstr, demfdr)
NGRIVER = streamline ( demlnk, demfdr, grid-code, #)
demacc = zonalmax ( demlnk, demfac)
demout = con (demacc == demfac, demlnk)
demshd = watershed ( demfdr, demout)
NGBASIN = gridpoly ( demshd )
quit
```

Figure 2. A sample delineation procedure

As a result of applying the delineation procedure, two coverages are generated, NGBASIN representing the subwatershed polygons and NGRIVER representing the river lines. Since the GRIDPOLY function produced only the polygon coverage, the following ARC command needs to be applied to build the accompany line coverage:

BUILD NGBASIN LINE

Step 2. Dissolving the single-cell-polygons

To dissolve the single-cell-polygon, using the ARC command:

```
DISSOLVE incov outcov GRID-CODE poly
```

This command dissolves all the single-cell polygons into its adjacent polygons with the same grid-code that share at least one common boundary line. Because some single-cell polygons share no common boundary with their adjacent polygons, they will not be dissolved by the ARC's dissolving procedure. In this case, NGBASIN.ply, NGBASIN.lin and NGRIVER need to be added to the HYDRO.apr so that the SFdslv.pre (avenue program designed to modify the GRID-CODE assignment) can be applied to the NGBASIN.ply. To add the themes to an active view, use the + button from the View button bar. Once all three coverages are added, using the ★ button to setup the control data sets (associated with the project-level ObjectTag). Once this is done, click the 🏃 tool from the View tool bar followed by click on the cursor-sensitive area of the view that contains NGBASIN.ply, NGBASIN.lin, and NGRIVER themes. When prompted with the list of the programs that are available from the 🏃 tool, select the program SFdslv.pre, which will reassign the appropriate grid-code values to all the single-cell polygons so that they will share a common boundary line with their adjacent polygons.

After running SFdslv.pre, exit ArcView and from ARC, apply the DISSOLVE procedure again, which should dissolve all the unwanted single-cell-polygons.

Step 3. Modifying the feature attribute tables (FTABs) of the subwatershed polygon and river line coverages (SFmdflds.pre)

The purpose of adding additional fields to the FTABs is to create river line and subwatershed polygon objects for the map-based surface water flow simulation model. The procedure starts with using the + button from the View button bar to add NGBASIN.ply, NGBASIN.lin, NGRIVER to an active-view, then from View menu bar, click ***SFwModel***, and select ***MdfyFtabs(pre-1)***. The program will prompt the user to select from a list of the themes the names of river line coverage (NGRIVER), subwatershed polygon coverage (NGBASIN.ply) and subwatershed boundary line coverage (NGBASIN.lin) and proceed to add the necessary attributes to these three coverages. The program SFmdflds.pre also sets up the control-list and attaches the list to the project-level OBJECT-TAG. The control-list is shown below in Figure 3. Items are delimited by "=".

```
NGBASIN.ply=NGBASIN_=Grid_Code
NGRIVER.shp=NGRIVER_=Grid_Code
NGBASIN.lin=NGBASIN_
```

Figure 3. Control-list set to the object-tag at the project level (3 parameters)

Step 4. Sorting nodes and vertices of river lines [SFsortr.pre].

This procedure sorts the nodes of the river lines so that the direction of From-Node (FNode) to To-Node (TNode) (Figure 4) of a river line section is always pointing in the downstream direction. The program also sorts the vertices of a river line so that the vertex with zero-index is located at the FNode of the line. Before the sorting program could be run, you need to identify the outlet river section by setting the attribute ISOUTLET of the outlet section to 1 (one). To do this, make sure the river theme (NGRIVER) is active and visible. Then from View button bar, click the button to get the FTAB associated with the river theme and while the F-Table is active, click the button to promote all the selected records to the top and change the ISOUTLET attribute to 1 (one). Once this is done, the sorting procedure can start. To perform the task of sorting, click ***SFwModel*** followed by selecting menu item ***LineSortR(pre-2)***.

When running SFsortr.pre, an error message (something like ERROR ON EXECUTING LINE X ON PROGRAM XXXX.c) may appear, which may be caused by the protection of NGRIVER coverage. When this happens, we need to used the CONVERTTOSHAPEFILE option from THEME menu from the View menu bar to covert NGRIVER coverage to a shape file with the same name. Then add the NGRIVER.shp file to the view as a new theme, reset the control-list by clicking at and select NGRIVER.SHP and the river theme. Then rerun the program SFSortR.

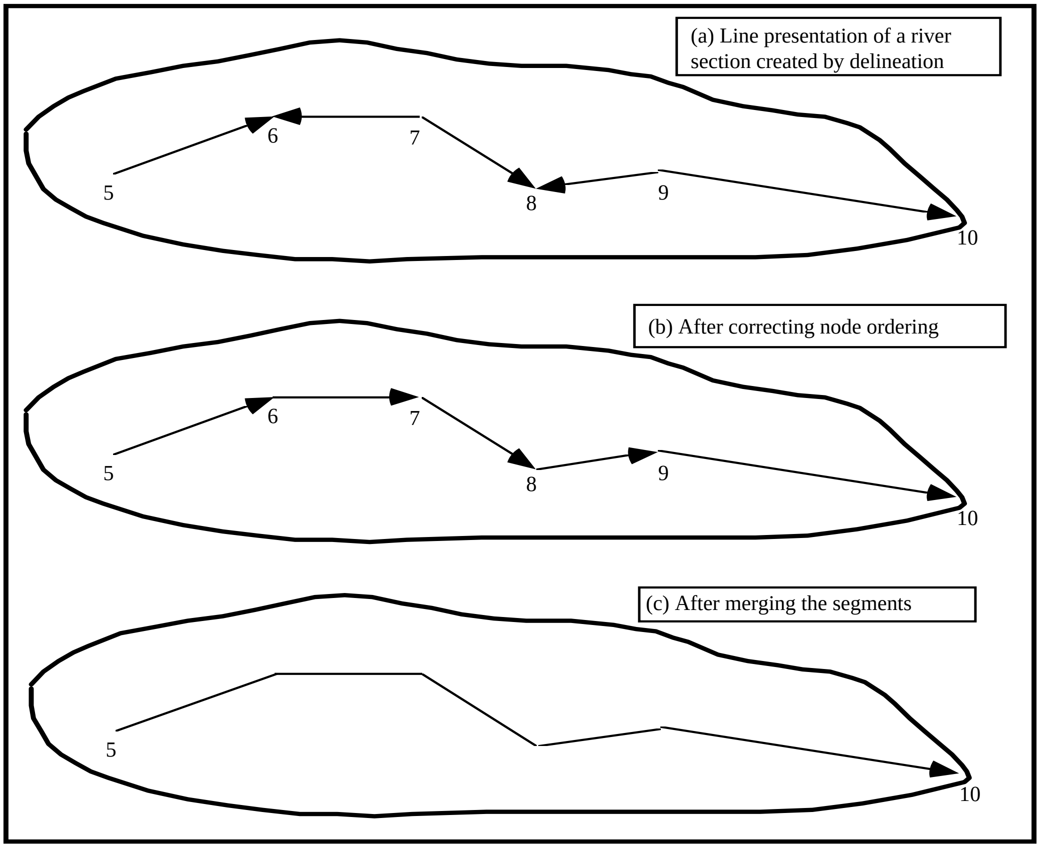

(a) Line presentation of a river section created by delineation
5
6
7
8
9
10
(b) After correcting node ordering
5
6
7
8
9
10
(c) After merging the segments
5
10

Figure 4. Sorting and merging multiple river segments into one river section

Step 5. Cleaning the river line splits (SFsplit.pre)

The purpose of the river split cleaning program is to remove any river splits that are contained in one subwatershed polygon so that each subwatershed polygon contains only the river segments that form a single line. A split is defined as three river segments forming a “Y” shape and contained by a single subwatershed (Figure 5). Without correcting them, the polygon that contains the split river lines will have a one-to-many relation with the river line database, which violates the ‘one-to-one’ condition necessary for the flow routing system. To perform the task, from View menu bar click ***SFwModel***, followed by selecting the menu item ***RmvSplits(pre-3)***.

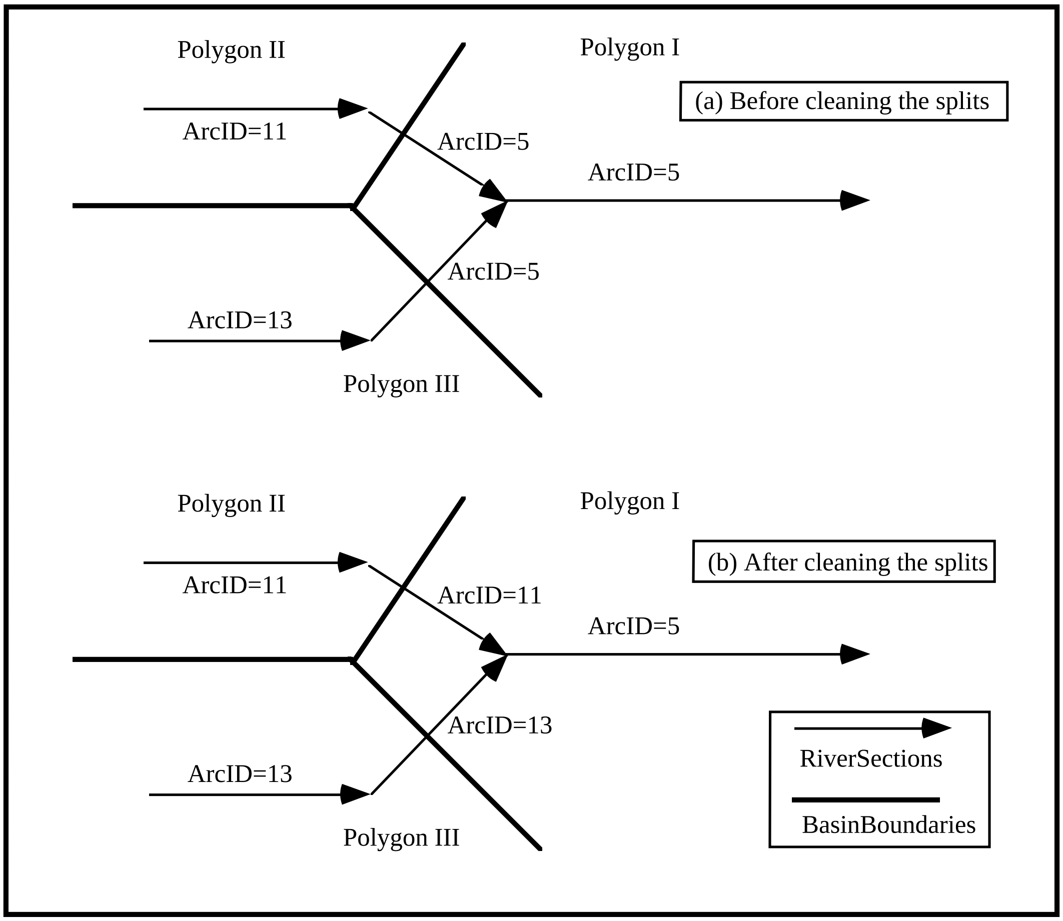


Figure 5. Rearranging river sections

Step 6. Merging multiple river segments into one river section (SFmg1ln.pre)

The purpose of the segment merging program is to merge any multiple line segments contained by a single subwatershed polygon into one single line object so that each polygon contains only one line section (Figure 3). To do this, from the View menu bar click ***SFwModel***, followed by selecting the menu item ***Mg1Line(pre-4)***. This procedure also reset the control-list to 16 parameters to be used later by the program SFmktmtb.pre to create time-series data tables. The control-list is shown below in Figure 6. Items are delimited by "=".

```
NGBASIN.ply=NGBASIN_=Grid_Code
NGRIVER.shp=NGRIVER_=Grid_Code
NGBASIN.lin=NGBASIN_
dhtb.dbf=NGBASIN.ply=NGBASIN_=8,4=View1
fflow.dbf=NGRIVER1.shp=Grid_code=9,2=View1
gfvtb.dbf=NGBASIN.ply=NGBASIN_=14,11=View1
headtb.dbf=NGBASIN.ply=NGBASIN_=8,2=View1
pflow.dbf=NGBASIN.ply=Grid_code=8,3=View1
pmptb.dbf=NGBASIN.ply=NGBASIN_=14,11=View1
psurp.dbf=NGBASIN.ply=Grid_code=14,11=View1
rchtb.dbf=NGBASIN.ply=NGBASIN_=14,11=View1
respvt.dbf=NGRIVER1.shp=Grid_code=7,4=View1
sprtb.dbf=NGBASIN.ply=NGBASIN_=8,3=View1
tflow.dbf=NGRIVER1.shp=Grid_code=9,2=View1
xfluxtb.dbf=NGBASIN.lin=NGBASIN_=14,11=View1
yfluxtb.dbf=NGBASIN.lin=NGBASIN_=14,11=View1
```

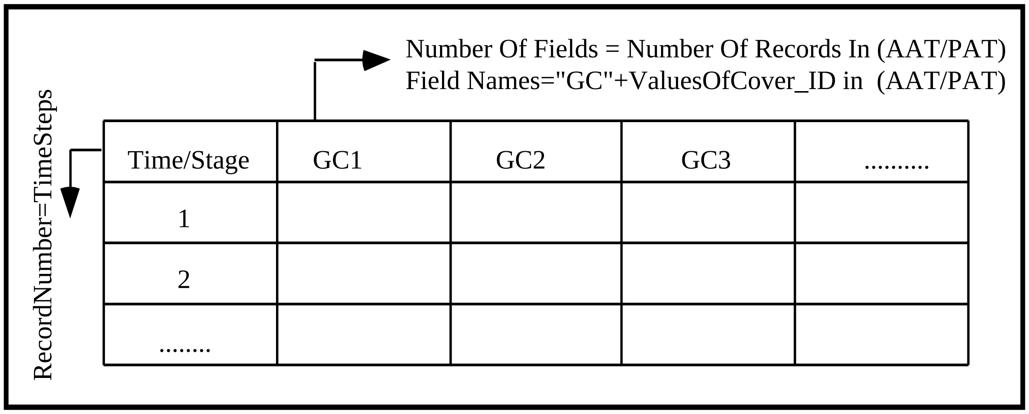
Figure 6. Control-list set to the object-tag at the project level (16 parameters)

Step 7. Identifying the head and outlet sections on the river network (SFchkout.pre)

This procedure identifies the outlet (by setting ISOUTLET=1) and head (by setting ISHEAD=1) sections on the river network. To do this, from the View menu bar click ***SFwModel***, followed by selecting the menu item ***ChkInOut(pre-5)***.

Step 8. Creating data structure to hold spatially-referenced time-series tables

Altogether 13 database tables are created to hold spatially-referenced time-series tables (Figure 6). These time-series tables are used by both map-based surface and subsurface simulation models. To perform this task, from the View menu bar click ***SFwModel***, followed by selecting menu item ***Crtmtb(pre-6)***. All the databases holding the spatially-referenced time-series tables have the data structure shown in Figure 7.



Number Of Fields = Number Of Records In (AAT/PAT)
Field Names="GC"+ValuesOfCover_ID in (AAT/PAT)

RecordNumber=TimeSteps

Time/Stage	GC1	GC2	GC3	....
1				
2				
....				

Figure 7. Database Structure for spatially-referenced time-series data

Step 9. Creating other model supportive files

This procedure creates 8 files/coverages used by the model. These files are (1) dams.shp, (2) flowchk.shp, flowdist.dbf, flowtime.dbf, optmass.dbf, optsrme.dbf, mflowfit.dbf, and target.dbf. To start the procedure, from the View menu bar, click ***SFwModel*** followed by selecting the menu item ***MkFVtbls(pre-7)***.

Step 10. Creating polygon/line objects for GFlowSim

This procedure appends the fields needed for the map-based groundwater simulation model (GFlowSim) to the polygon (NGBASIN.ply) and line (NGBASIN.lin) coverages. To perform the task, from the View menu bar, click ***GFwModel***, and select the menu item ***GFmdfld(pre-1)***.

Step 11. Setting up polygon coverage for GFlowSim

Click ***GFwModel***, and select the menu item ***SetPlyFld(pre-2)*** to set up the polygon coverage (NGBASIN.ply) for GFlowSim.

Step 12. Setting up boundary line coverage for GFlowSim

Click ***GFwModel*** and select the menu item ***SetLneFld(pre-3)*** to set up the boundary line coverage (NGBASIN.lin) for GFlowSim. This procedure calculates the boundary-line parameters, such as dlx, dly, fcosx, fcosy, and slength which are used in GFlowSim.

Step 13. Setting up boundary line coverage for multiple GFlowSim models.

The GFlowSim model allows the simulation of multiple, mutually-independent aquifers simultaneously. To construct multiple groundwater simulation models that share a single polygon and line coverage, one has to first select the polygons that make up each groundwater model, and set their HasGrd attribute to 1 (one). To perform this task, (1) make the polygon theme active and visible, and use from the View tool bar to select the polygons (holding down shift key to perform multiple selections), (2) click on the button to get the FTAB associated with the polygon theme, (3) click on the button to promote the selected records, and (4) set HasGrd=1 in all the selected records. Once this is done, click ***GFwModel***, and select the menu item ***SetPModel(pre-4)*** to set up the boundary line coverage (NGBASIN.lin) for multiple model areas. This procedure is necessary only when there are more than one aquifers coexist in a single polygon coverage or one aquifer only covers part of the region the polygon coverage covers.

Up to this point (step 13), the basic-maps for the map-based surface and subsurface water flow simulation models are properly set. The following steps describe the procedure (1) to set-up time-series data sets for the computation of PFlow(t) (PFLOWVT.dbf), (2) set-up some subwatershed polygon related parameters, such as DIFFUSION-NUMBER, FLOWTIME for surface water flow simulation and HYDRAULIC CONDUCTIVITY, AQUIFER-TOP, and BOTTOM ELEVATIONS for groundwater simulation.

Step 14. Interpolating the missing observation points for rainfall data (Cmprain.pre)

Assuming the locations of all rain gage stations are in a rainfall station (rainst) point coverage and the rainfall time-series are stored on a time-series table in the format shown in Figure 7, that is, the connection between the time-series table and rain gage station is established through the gage station's identification number and the header of the time-series table. To interpolate the missing rainfall data, click the tool and select the program **CMPRAIN.PRE.** (Some program variables, such as ThmName, RainTbName, "RainId", may need to be modified to point at the correct data sets before the program can be run). Because the procedure uses a squared-inverse-distance scheme for the missing data point and all the distance are dynamically computed at the run-time, running the interpolation program can be very time consuming if the rainfall data come from a large set of rain gage stations with long observing periods. Therefore, it may be desirable to cut the rainfall data to the simulation interval for rainfall interpolation.

Step 15. Interpolating the rainfall time-series to the center points of subwatersheds or cells for soil-water-balance computation (cmpsurp.pre)

The purpose of this procedure is to interpolate the rainfall time-series (stored in a data table in the format given in Figure 7) to the time-series defined on the center points of each subwatershed to be used as water-surplus for PFlow(t) computation, or to the centers of the cells used for soil-water balance computation. To activate the procedure, click the tool, select the program **CMPSURP.PRE,** and follow the procedures provided by the pop-up menus. (Again, some variables in **CMPSURP.PRE** may need to be modified to match the names of the data sets and themes).

Step 15. Computing DiffNum, FlowTime for subwtershed polygons

If PFlow(t) is to be computed using a convolution procedure, then the parameters, DiffNum, FlowTime of the subwatershed polygons need to be set. To compute the parameters necessary to compute Flowtime and Diffnum, the program listed in Figure 8 written by Seann Reed can be used (The program needs to be run under ARC/GRID using DemFil, DemFdr, and DemShd as input grids (See Figure 2).

The program listed in Figure 8 produces the mean flow distance and standard deviation of the distance for each polygon. Once this two parameters are computed, the DiffNum (D_i) and FlowTime can be computed using the following formula:

$$D_i = \frac{\sigma_i^2}{2(l_i^2)} \qquad (1)$$

$$T_i = l_i/\text{Vfact} \qquad (2)$$

where, l_i = average flow length of polygon i (m),

σ_i = standard deviation of the flow length for polygon i (m),

Vfact = average overland flow velocity (m/s)

Both l_i and σ_i are stored in file length.dat by the procedure listed in Figure 8.

```
 /*******************************************************
 /* Name: pac_par.aml
 /* Purpose: Determine the parameters necessary to calculate
 /* a "flowtime" and a "diffusion number".
 /******************************************************
 /** FOR THE CASE OF THE MISSION RIVER, THE ARGUMENTS
ARE:
 /* dem = demfil  /* DEM
 /* sheds = missub  /* Mask of watersheds
 /* fd = misfdns    /* Flowdirection grid
 /*&args dem sheds
 /** SET VARIABLES FOR INPUT GRIDS
 &sv fd = misfdns
 &sv sheds = missub
 fl = flowlength ( %fd%, #, downstream )
 flmin = zonalmin ( %sheds%, fl, data )
 flsub = fl - flmin
 length.dat = zonalstats ( %sheds%, flsub, moment, data )
```

Figure 8. Code for polygon related parameter computation

2.2 THE MAPS OF THE SIMULATION MODEL

Figure 9 shows the view containing the themes upon which the simulation model is constructed. The themes contained in the Niger-View and their functions are discussed below.

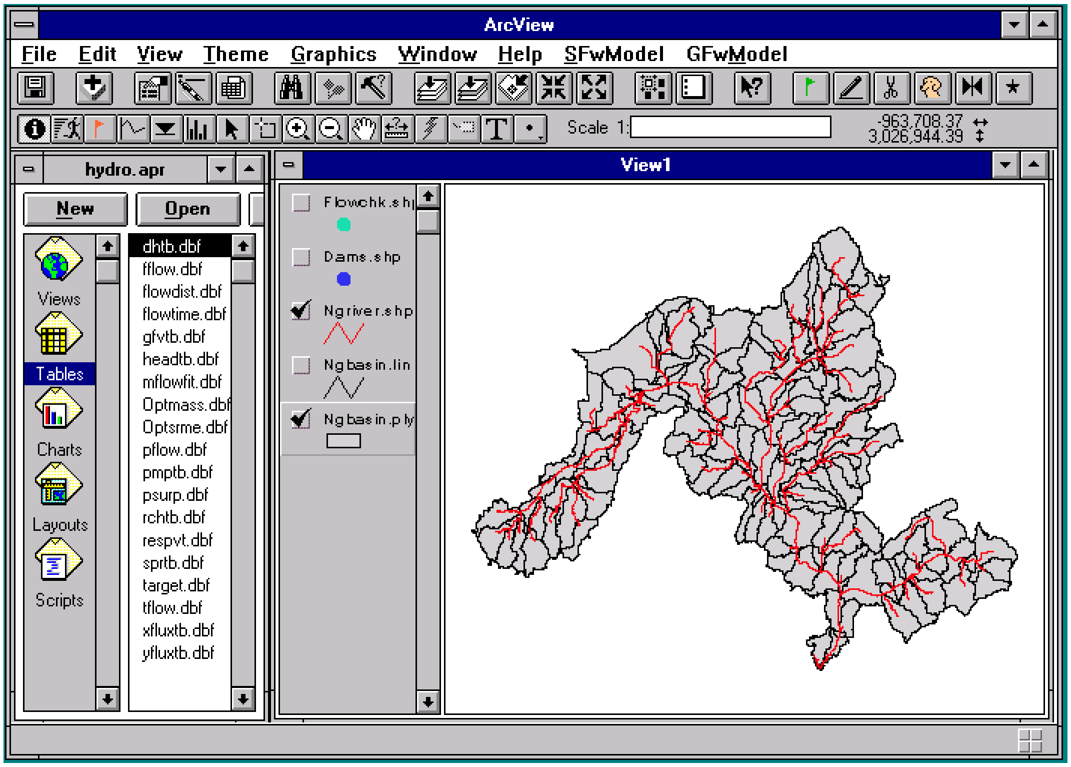


Figure 9. The view containing the base maps of the simulation model

Listed below are the coverages representing the base maps upon which the surface water flow simulation model is constructed.

- •NGRIVER.shp - An arc coverage representing the river network. This line coverage is essential for the construction of the map-based surface water flow simulation model (SFlowSim)
- •NGBASIN.ply - A polygon coverage representing the subwatershed of the river basin for surface water flow simulation model and representing cells for the groundwater simulation model. This coverage is essential for the construction of both surface water flow simulation model and groundwater flow simulation model.
- •NGBASIN.lin - An arc coverage representing the boundary lines of subwatershed polygons (NGBASIN.ply). This coverage is needed for the construction of the groundwater simulation model (GFlowSim)

- Dams.shp - Point coverage representing locations of dams and reservoirs
- Flowchk.shp - Point coverage representing the locations where the flow interpolation will be computed

The coverages that are essential for the map-based surface water flow simulation models are NGRIVER.shp and NGBASIN.ply. The coverages essential for the map-based groundwater simulation model are NGBASIN.ply and NGBASIN.lin. Dams.shp and flowchk.shp are needed if these objects present. As Dams.shp, flowchk.shp and other non-essential model data files are generated by the program SFMkFtab.pre from the pre-processor module, the coverages necessary to construct base maps for the integrated surface and subsurface water flow simulation model are (1) NGBASIN.ply, NGRIVER, and NGBASIN.lin.

2.3. The Model's Graphical User Interface

The graphical user interface of the simulation model (**SFlowSim**) is designed to provide easy access to the simulation model and its related programs. A user can use these graphical interfaces to activate the simulation model, modify the model conditions, add flow check points, flow diversion points, or add dam/reservoir objects. This section describes the functions associated with each user interface.

2.3.1. View Menu

Two menu sections, SFwModel and GFwModel have been added to the standard View menu bar GUI provided by the ArcView. SFwModel menu runs the surface water flow simulation model and its related programs while GFwModel menu runs the groundwater flow simulation model and its related programs. Figure 10 shows the menu items contained in SFwModel and GFwModel menu.

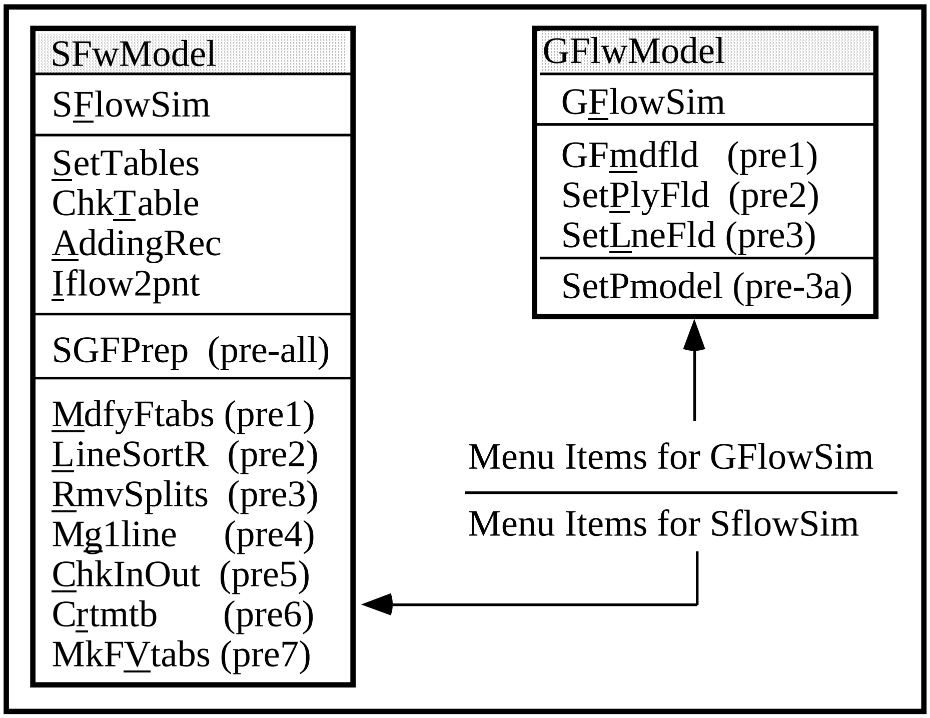


Figure 10. Menu items of SFwModel and GFwModel

SFwModel contains twelve menu items and these items are divided into the simulation model, utility and preprocessor sections. The utility section is shared by the groundwater simulation model and post-processors of surface water flow simulation model. The functions of the menu items contained in each section are described below, with the title of the program it activates shown in [ ].

1. SFlowSim - [SFlowSim.prc] activates the map-based surface water flow simulation model.
2. SetTables - [Rinifld.utl] initializes the fields of a table. When this item is selected, a pop-up menu with four options is presented and based on the user selection, Rinifld.utl will call one of the four programs. These four programs are:

   (1) Iniflds.utl which sets selected records of a user selected field to a single or multiple values.

   (2) Inif lda.utl which sets all records of a user selected field to a single or multiple values.

   (3) Initbl.utl which sets all records of whole table or multiple user selected fields to a single value.

(4) Inifdfd.utl which initializes a field of a table with the values of a field of another table based on the user selected key fields on both tables. These two key fields can have different field name, but their values need to have a one-to-one relation.

3. ChkTable - [Rchktbl.utl] displays the data structure of a value attribute table or a feature attribute table. When this item is selected, a pop-up menu with two options is presented and based on the user selection, the program [Rchktbl.utl] will call one of the two programs. These programs are:

   (1) [Chktbl.utl] which checks and displays the data structure of a value attribute table.

   (2) [Chkftab.utl] which checks and displays the data structure and the shape type of a feature attribute table.

4. AddingRec - [tbaddrec.utl] appends a user specified number of records to a time-series table.

5. Iflow2pnt - [Iflw2pnt.utl] interpolates flow rates to the locations given by a point coverage.

6. SGFPrep (pre-all) [preproc.pre] processes all the pre-processing procedure for both surface and subsurface water flow simulation models.

7. MdfyFtabs (pre-1) - [SFmdfld.pre] appends fields to line/polygon attribute tables to create river and river basin objects.

8. LineSortR (pre-2) - [SFsortR.pre] sorts nodes and vertices of a river line coverage to create the river network. After sorting, the direction of From-Node to To-Node of a river section always points in the downstream direction and the vertices with index 0 is at the From-Node of the arc.

9. RmvSplits (pre-3) - [SFsplit.pre] cleans the splits of a river network so that “Y” shaped streams do not occur within a subwatershed.

10. Mg1line (pre-4) - [SFmg1ln.pre] merges multiple segments contained by a single subwatershed (polygon) into one single river section so that the relation between river section and subwatershed polygon is One-to-One.

11. ChkInOut (pre-5) - [SFchkout.pre] identifies head sections and outlet sections of the river network. The head sections are defined as the river sections with no other river sections that flow into them and the outlet section is defined as the river section that discharges to no other river sections but out of the river basin.

12. Crtmtb [pre-6] - [SFmktmtb.pre ->wrtmfile.pre] creates time-series tables, e.g., FFlowTb, TFlowTb, PFlowTb, etc., for the simulation model.
13. MkFvtabs [pre-7] - [MkFtab.pre] creates dams.shp, flowchk.shp and other data tables for the simulation model.

The five pre-processor programs (pre-1 to pre-5) need to be run in the same sequence as they are presented in the SFwModel ViewMenu.

GFwModel contains 5 menu items and these items are divided into simulation mode and preprocessor sections. The functions of the menu items are described below, with the title of the program it activates put in [ ].

1. GFlowSim - [GFlowSim.prc] activates the map-based groundwater simulation model.
2. GFmdfld (pre-1) - [GFmdfld.pre] appends fields to polygon and polygon-boundary-line attribute tables to make cell and cell boundary objects for the map-based groundwater simulation model.
3. Setplyfld (pre-2) - [GFplyfld.pre] computes and fills in the states of the existing cell objects for the groundwater simulation model.
4. Setlnefld (pre-3) - [GFlnefld.pre] computes and fills in the states of the cell-boundary-line objects for the groundwater simulation model.
5. SetPmodel (pre-4) - [GFlnsfld.pre] constructs multiple groundwater simulation models. Before running the program, one has to select all the polygons in the model-regions and set their attribute: HasGrd=1 (has-ground = one).

All the pre-processor programs should be run only once to set up the map-based models unless the base maps of the model are modified.

2.3.2. View Button Bar

Four buttons are added to the standard View button bar GUI provided by the ArcView. The functions and programs associated with these buttons are explained below (immediately following each icon is the icon name given by ArcView's icon manager)

- PennantGreen, interpolates flow rates to the points given by FlowChk.shp coverage [SFsegmt.pst].

- Pen, writes selected or all the scripts contained in the project's SEd to a designated location on a disk [wrtfiles.utl].

- Cut, cuts selected portion of the active coverages and sends them to a new view to create a sub-model for either detailed study of the region or for model parameter fitting [clipmdl.utl].

- Dog, runs interactive optimization programs to search for the parameters that give the best fit between observed-flow-time-series and simulation model generated flow-time-series[Optimize.ave]. The best fit is defined either by least sum of square errors or least sum of mass differences. When running the model, at least one coverage theme must be active and at least one feature of the coverage has to be selected, because the parameters to be fitted are those of the active coverages and selected features.

- STAR, sets up the control list (ctrllist) or model's time dimension (model interval) [setctrl.utl] & [setmctrl.utl - set-time-ctrl].

2.3.3. View Tool Bar

Four buttons are added to the standard view button bar GUI provided by the ArcView. The functions and programs associated with these buttons are explained below.

- Execute, runs all the programs available to the Script Editor (SEd) of the project [Main.utl - activated by apply event]. When the tool is selected, the program, Main.utl is loaded and activated when the mouse is clicked in the cursor sensitive area of the active view. The last program run by the Main.utl is the default program to be run again. If the user wants to run other programs, select NO option, and a pop-up menu will appear with a list of programs for the user to choose. The selected program will then run with the cursor position taken into consideration.

- PennantRed (red color), creates dam, reservoir, flow diversion, or flow-check point objects on a location selected by the program user. Programs associated with click and apply events are listed below.

CLICK - [SFclsset.pst] provides options for a user to select what kind of object (dam, flowchk, or flow-diversion points) to create, and if the user would like to start with new sets or append more objects to the existing set. The program passes the user selection through the tool's object-tag to [SFRaddpt.pst].

APPLY - [SFRaddpt.pst] runs one of the three programs, [SFaddpt.pst], [SFDFlow.pst], or [SFaddDam.pst], depending on the value of the object-tag (representing the user selection) passed on to it from [SFclsset.pst].

[SFaddpt.pst] - creates flow check points at user specified locations and adds them to the FLOWCHK.SHP coverage. The flow rates at the flow check points will later be computed using the program [SFsegmt.pst] activated by the button (green color) on the View-Button-Bar.

[SFDFlow.pst] - creates a flow diversion object at a user specified location on a river. For now, only one diversion flow rate is allowed at one location, later on, a diversion flow rate time-series can be associated with the diversion object.

[SFaddDam.pst] - creates a dam/reservoir object at a user specified location on a river, and the time-series data table associated with the dam object so that each time step, the simulation results of the dam operation can be recorded.

- Icon12, plots either the longitudinal flow profile along a user selected river or a flow time-series (PFlow(t), FFlow(t), TFlow(t), or SurpF(t)), at a user selected location. Programs associated with click and apply events are listed below.

CLICK - [SFsetplt.pst] provides options for a user to select which type of flow curves to plot and passes on the selection through the tool's object-tag to [SFRplt.pst].

APPLY - [SFRplt.pst] runs one of the three programs, [SFtrplt.pst], [SFtmplt.pst], or [Sfptflow.pst] based on the value of the object-tag passed on to it from [SFsetplt.pst].

[SFtrplt.pst] - plots the longitudinal flow profile along a selected river.

[SFtmplt.pst] - plots the flow time-series at a user selected location.

[Sfptflow.pst] - plots the interpolated flow time-series at a user designated location

⤓ - AlingBottom, plots flow vectors on groundwater simulation cell's boundaries or plots time-series of head(t), dh(t), spr(t), pmp(t), etc., of a cell at a user selected location. Programs associated with click and apply events are described below.

CLICK - [GFsetplt.pst] provides options for a user to select which type of flow curves to plot and passes on the selection through the tool's object-tag to [GFRplot.pst]

APPLY - [GFRplot.pst] runs one of the two programs, [GFptflx.pst] or [GFpthead.pst], based on the value of the object-tag passed on to it from [GFsetplt.pst].

[GFptflx.pst] - plots flux, water level distributions, or both for the groundwater flow simulation model. Under steady state, it plots flux, and water level distributions based on the final results of simulation run and under steady state, it plots the above values at a user designated time step.

[GFpthead.pst] - plots water level (head(t)), spring flow (spr(t)), water level variations (dh(t)) at a user selected location.

2.4. MODEL PROGRAMS

The map-based surface water flow simulation model contains a total of 46 programs. Some of these programs are essential programs for model construction and model simulation and some of these programs are merely written to speed up routine spatial data processing. This section describes these programs and their functions. The number in the bracket following the program indicates the number of lines of the program code.

1. chkctrl.utl [14] - checks the model's control set. Control set contains the information of coverage name, key-field-name, grid-code, and model time-steps.
2. chkftab.utl[34] - checks the data structures and shape type of a feature attribute table.
3. chktbl.utl[35] - checks the data structures of a value attribute table.
4. clipmdl.utl[184] - clips off a selected portion of the active coverage and sends it to a new view to create a clipped model for either detailed study of the region or for model parameter fitting
5. cmprain.pre[118] - fills in missing rainfall time-series data at a point by interpolating the rainfall time-series from other rain-gage stations

6. cmpsurp.pre[152] - estimates moisture surplus for each subwatershed from the rainfall time-series data defined on the rain-gage stations in the region.
7. convert.utl [587] - converts parameter set between spatial features on which they are defined.
8. Damrt.ave[208] - simulates dam/reservoir operation. This program is called by SFlowSim.prc when HASDAM attribute of a river line object is non-zero.
9. GFcntpnt.utl[132] - computes the center location of each arc on a selected line coverage and creates a point coverage showing all the central points based on the computation results. The program also computes and creates a line coverage showing the arcs normal to the original line coverage with each normal vector originates at the center of each line on the original line coverage.
10. GFlnfld.pre[291] - computes and fills in the states of each boundary lines of the existing cells for the groundwater simulation model.
11. GFlnsfld.pre[232] - computes and fills in the states of each boundary lines when the groundwater model does not cover the same area of the surface water flow simulation model.
12. GFlowSim.prc[916] - simulates groundwater flow. This is the main program of the map-based groundwater flow simulation model.
13. GFmdfld.pre[79] - appends fields to the standard polygon/arc coverage to create cells and cell boundary line objects for the map-based groundwater simulation model.
14. GFplyfld.pre[51] - computes and fills in the states of the existing cell objects for the groundwater simulation model.
15. GFptflx.pst[266] - plots flux on the cell boundaries, water levels on the cells or both for a user selected simulation time step or of final results of the groundwater simulation model. This is a post processor program of GFlowSim.
16. GFpthead.pst[141] - plots time-series of water levels (head(t), dh(t), pmp(t)) of a user selected location. This is a post processor program of GFlowSim.
17. GFRplot.pst[36] - runs either [GFpthead.pst] or [GFptflx.pst] based on the user's selection.

18. GFsetplt.pst[17] - provides user with options of plotting groundwater flow time-series of a location or groundwater flux/water level of a designated time step and passed user's selection to [GFRplot.pst]
19. IDextply.pst[88] - identifies the external boundaries of the groundwater simulation model. This program is used mainly on the clipped portion of the river basin to form a clipped-groundwater simulation model.
20. Iflw2pnt.utl[341] - interpolates flow rates to the points given by a point coverage.
21. Inifdfd.utl[58] - initializes a field of a table with the values of a field of another table based on the user selected key fields on both tables. These two key fields can have different field name, but their values need to have a one-to-one relation.
22. Iniflda.utl[159] - sets all records of a user selected field to single or multiple values.
23. Iniflds.utl[82] - sets selected records of a user selected field to single or multiple values.
24. Initbl.utl[134] - sets all records of whole table or multiple user selected fields to a single value.
25. Main.utl[46] - runs a user selected program.
26. MKarrow.utl[61] - makes an arrow head on a line coverage. This program is downloaded from ESRI user network and has been slightly modified.
27. mkftab.pre[239] - creates dams.shp, flowchk.shp and data tables (optmass.dbf, optsrme.dbf, target.dbf, flowdist.dbf, and flowtime.dbf) for the simulation model.
28. Optimize.ave[855] - this is a directional optimization program used to search for the parameters that give the best fit between observed-flow-time-series and simulation model generated flow-time-series at a user-specified location. The best fit is given by the simulated flow time-series that has SMD=0 and min.RMSE. When running the model, at least one coverage theme must be active and at least one feature of the coverage has to be selected, because the parameters to be fitted are those of selected features on the active coverages (Themes). This program calls SFlowSim.prc to simulate the surface water flow for each parameter change.
29. preproc.pre [16] - calls other pre-processing programs of surface and subsurface water flow simulation models for model setup.
30. Rchktbl.utl[25] - Runs either [chkftab.utl] or [chktab.utl] based on the user's selection.

31. Rinifld.utl[31] - Runs one of the four programs, [Inifldа.utl], [Iniflds.utl], [Initbl.utl], or [Inifdfd.utl] based on the user's choice.

32. setctrl.utl [219] - creates model control set, which contains cover-name, cover-id, grid-code, and time-steps.

33. setmctrl.utl [149] - resets model's time-step control.

34. SFAdddam.pst[270] - creates a dam/reservoir object and puts it in the location designated by the user. The program also creates a time-series table associated with the dam object to record the simulation results of dam operation.

35. SFaddpt.pst[54] - creates a flow check point and puts it to a location designated by the user.

36. SFchklin.utl[85] - retrieves all the vertex points used to form a line and puts the points shape into flowchk.shp file.

37. SFchkout.pre[156] - searches and identifies the head sections and outlet sections of a river basin.

38. SFclsset.pst[131] - gets the user's choice regarding the type point objects, dam, flow-check, or flow-diversion, to create and passes on the user's selection to [SFRaddpt.pst].

39. SFDflow.pst[52] - creates a flow diversion points and puts a mark on the map to indicate its location.

40. SFdslv.utl[186] - assigns single cell ploygons with appropriate Grid-Codes so that they can be dissolved.

41. SFlowSim.prc[1244] - simulates surface water flows on a river network based on the local flow time-series defined on the subwatershed polygons. This is the major program of this map-based surface water flow simulation model. This model can be activated by [Main.utl] from a tool-bar, SFlowSim on the SFwModel view menu, or called by [Optimize.ave], the interactive optimization program. SFlowSim.prc can detect from which source it is activated and act accordingly. For example, when it is activated by from the View tool bar, the program will takes the cursor's location into consideration, and as a result, it provides the user with choices of either simulating the whole river basin or the portion of the river basin that is above the user selected point (cursor location). When it is activated by from the view-menu, it can only simulate the river

basin. When it is called by the optimization program, it skips over all the codes that requires user interaction so that the simulation program can run uninterruptedly.

42. SFmdfld.pre[160] - appends fields to attribute tables of the arc/polygon coverage created by the river delineation procedure to create river and watershed objects.
43. SFmg1ln.pre[361] - merges multiple segments contained by a single subwatershed (polygon) into one single river section so that the relation between river section and subwatershed polygon is one-to-one [SFmg1ln.pre].
44. [Sfptflow.pst] - plots the interpolated flow time-series at a user designated location.
45. SFRaddpt.pst[39] runs one of the three programs, [SFaddpt.pst], [SFDFlow.pst], or [SFaddDam.pst], based on the user's selection.
46. SFRplot.pst[36] - runs one of the two programs, [GFptflx.pst] or [GFpthead.pst], based on the value of the object-tag passed on to it from [GFsetplt.pst].
47. SFSegmt.pst[333] - linearly interpolates the flow rates to the user selected location.
48. SFsetplt.pst[17] - gets the choice from a user on which type of curve to plot and pass on the selection to [SFRplot.pst] through the form of object-tag.
49. SFsortr.pre[531] - sorts nodes and vertices of river line coverage to create the river network [SFsortR.pre]. After sorting, the direction of From-Node to To-Node of a river section is always pointing in the downstream direction and the vertex with index 0 is at the From-Node of the arc.
50. SFsp2pf.121[84] - computes local generated flow based on the moisture surplus defined on the subwatershed polygons.
51. SFsplit.pre[532] - cleans the splits of the river sections so that "Y" shaped streams do not occur within a subwatershed [SFsplit.pre].
52. SFthmplt.pst[97] - calls the program wrtmfile.pre based on the parameters provided by the control file, sfdbfs.ctl to create time-series data tables.
53. SFtmplt.pst[134] - plots time-series of a selected attribute at a selected location.
54. SFtrplt.pst[402] - plots flow rate changes along a user selected river.
55. tbaddrec.utl[69] - appends records to a time-series data table. The number of records is given by the user.
56. tbsvgd.utl[28] - closes all the open value attribute tables (VTab) and feature attribute tables (Ftab).

57. Wrtfiles.utl[85] - writes either selected or all the scripts contained in the project’s SEd to a designated location of a disk
58. wrtmfile.pre[82] - called by SFmktmtb.pre to write a program that create the template for a time-series database table.
59. Wrtprogs.utl[71] - writes an Avenue code that can be later run to create the template of a time-series database table.

3. Performing Tasks under SFlowSim/GFlowSim

This section gives a brief description of the procedures to perform tasks using **SFlowSim**, the map-based surface water flow simulation model.

3.1. Surface Water Flow Simulation

The map-based surface water flow simulation model is designed to simulate surface water flow runoff based on the excess precipitation defined on the subwatersheds of a river basin. Running the simulation model generates three flow time-series: PFlow(t) associated with a subwatershed polygon representing the flow contribution of the polygon, FFlow(t) and TFlow(t) associated with the From-Node and To-Node of a river line representing the flow rates on the river line at these two locations. Two procedures can be used to run the simulation model.

Procedure (1): while model-map view is an active document, do the following: from View menu bar, **SFlwModel** -> **SFlowSim**

Procedure (2): while model-map view is an active document, click from the View tool bar, followed by clicking at a river line, selecting ***SFlowSim.prc*** from the program list presented, and following the instructions. Using procedure (2), you can simulate either the portion of the river basin above the river line selected or the whole river basin, while using procedure (1) you can only simulate the whole river basin.

Regardless of which procedure is used to run the simulation model, a user will be presented with a multiple input table containing the model control parameters. Under most cases, the default value can be used to run the model unless it is desired otherwise. The meanings of the parameters are described below:

(1) Optimization=0, indicates if the run is for optimization (value 1) or for simulation only (value 0)

(2) CalPflow=0, indicates if PFlow will be re-computed [value 1], or not [value 0]

(3) Nresp=12, number of steps in polygon response function (SurpF(t) -> PFlow(t)), Nresp=0, indicating PFlow(t) is estimated from SurpF(t) without using a response function.

(4) IniTmStep=1, Starting time step

(5) EndTmStep=365, Ending time step

(6) ToSub=0.1, the fraction of surplus that goes to groundwater, 0<=ToSub<=1

(7) Muskingum=0, indicates if Muskingum river routing will be considered (=1) or not (=0)

(8) Pltply=1, indicating polygons will be highlighted during simulation.

The value following the equal sign of each parameter indicates the program default.

3.2. Creating Dam/Flowchk/Diversion objects

The simulation model can simulate the effect of dams and flow diversions on the river flow. The simulation model can also interpolate the flow rate to any user selected point (flowchk) on a river line. The procedure used to create a Dam/FlowChk/Diversion object and add it to the map is:

Click 🚩 (RedFlag) from the View tool bar, select the type of the object to be added, and then click on a location on the stream network where you would like to have the object inserted. After the selection, the user is prompted to select whether to start a new set of the object or append to the existing set. If starting a new set is selected, then all the objects of the selected class will be cleaned from the system. This is also the correct method if one wants to erase the existing object sets.

3.3. Interpolating the Flow Rates to Flowchk Points

This program interpolates the flow rates at all user selected points contained in FLOWCHK.SHP theme. To activate the program, a user can click on the ⚑ (GreenFlag) in the View button bar.

3.4. Plotting Surface Water Flow Profiles

To plot the flow distribution, click 📈 on the View tool bar. Options for either plotting the flow distribution along a selected stream or flow time-series at a location are presented prompted. If the longitudinal flow profile is selected, a user can then click any location on the river network to plot the longitudinal flow profile along the river selected stream between the selected point and the outlet. If a flow time-series plot is selected when the user clicks on a location, the user is prompted to select if FFlow(t), TFlow(t), PFlow(t), or SurpFlow(t) will be plotted.

3.5. Plotting Groundwater Flow Related Items

To make a plot, click ▼ on the View tool bar. Options for either plotting flux/head level distributions on groundwater cells at a given time or time distributions of water levels, water level variations, etc., at a location will be presented. After making a selection, the user will then need to click on the basin map to activate the program and follow the instructions on the screen. For the Niger river model, the groundwater model exists only under a portion of the river basin.

3.6. Creating a Sub-Model

From time to time, it is necessary to perform more detailed studies of a specific portion of a river basin. The map-based surface water flow model allows a part of a river basin to be clipped to form a separate model for more detailed studies. Niger river basin is used as an example to describe how to create a workable sub-model.

1. Make NGRIVER.shp, NGBASIN.ply themes active. If it is desired to have other themes included in the sub-model, then make them active as well. But the river line

theme (NGRIVER.shp) and subwatershed polygon theme (NGBASIN.shp) are the essential themes and they have to be included to create a sub-model.

2. Select the river lines graphically from NGRIVER.shp theme and NGBASIN.ply theme by using the selection tool in View tool bar. Hold down the shift key to perform multiple selections.
3. Click ✂ on the View button bar. The program will prompt for the location to put the shape files holding the selected features of the selected themes (NGRIVER.shp, NGBASIN.ply). In most cases, a user can take the default prompted by the program. When prompted with the destination View to which the clipped themes will be added, the user should select NewView. The program will detect all the source arcs on the sub-model. The sources are defined as those river lines that require FFlow(t) supplied by the user or provided from the “base-model” simulations.
4. Up to this point, a sub-model that contains the selected portion of the selected themes is created. All the surface model simulation programs can be run following exactly the same procedures as those for the “base-model”. One of the purpose of creating sub-model is to run the interactive optimization program that is discussed below.

3.7. Model Parameter Optimization (Model calibration)

The optimization model is created to search for the model parameters that produce flow time-series that best fit the historically observed time-series in terms of sum of root mean square errors (RMSE) and mass conservation (SMD). The results of the optimization are shown in four tables, optmass.dbf, optsrme.dbf, mfitflow.dbf and target.dbf, and four charts, optrmse.cht, optmass.cht, tarteg.cht, and mfitflow.cht. Optmass.cht, created from optmass.dbf, gives the changes of SMD as each optimization parameter changes. Optsrme.cht, created from optrmse.dbf, gives the changes of RMSE as each optimization parameter changes. Target.cht, created from target.dbf, gives the comparison between the observed and simulated river flow time-series. Mfitflow.cht, created from Mfitflow.dbf, gives the comparison of observed and simulated monthly average flows.

1. Create a sub-model following the procedures described in Section 3.6.
2. Initialize the Target field of Target.dbf table using :

SFlwModel -> **SetTables** ->**FillOneFieldWithAnother** (option3)

The program, **FillOneFieldWithAnother** requires a user to identify a target table whose field is to be set, a source table where the source data are stored, a target field and a key field of the target and source tables. The key fields for target and source tables do not need to have the same name, but need to have the same data structure and unique one-to-one relation.

3. Make the themes whose parameters are to be optimized active. For example, if the parameters of NGRIVER.shp are to be optimized, then NGRIVER.shp theme has to be active.
4. Select the features (river lines or subwatershed) whose parameters are to be optimized using ViewFeatureSelectTool, because the optimization is only applied to the selected features (records) of the active themes.
5. Click on the View button bar to start the optimization program, and follow the instructions prompted by the program. The optimization can be controlled by a control file (optctrl.ctl). A sample control file is created by the program SFmkFtab.pre activated by ***SFVtbls*** from under ***SFwModel*** menu. The files can be modified to suit a specific need. If no sample control file is available, then select CANCEL button when prompted for the control file name and follow the procedure provided by the optimization program to create a new control file.

   For each parameter to be optimized, the program requires a user to provide the upper and lower bounds and optType. optType equals either 1, indicating that the parameter goes to minimize RMSE or 0, indicating that the parameter goes to make SMD=0.

3.8. MAP-BASED GROUNDWATER MODEL

The map-based groundwater model (***GFlowSim***) is created to account for groundwater flows in cooperation with the map-based surface water flow simulation model (***SFlowSim***). The groundwater model usually uses the same subwatersheds as its cells and cell boundaries. The groundwater model can cover the same area of the whole river basin or several separate groundwater models can coexist under one single large river basin to simulate separate groundwater systems. For the Niger River Basin Model presented, only one groundwater model is created to simulate the Iullemeden aquifer system. The region that the groundwater model covers can be seen by making NGBASIN.lin active and querying with the condition of [Hasgrd=1 and Isbnd=1]. The procedure to run the groundwater model is: (from View menu bar)

GFlwModel->**GFlowSim** and follow the instructions provided by the program.

3.9. Writing Scripts Contained in the Project to Disk

This program is written to facilitate writing all or selected script programs to a designated location at a computer disk. To activate the program, click ✎ on the View button bar and follow the instructions on the screen.

3.10. Creating Time Series Database Template

This program [***Wrtprogs.utl***] is written to create the template (class) of a time-series database. To run the program, click 🏃 on the View tool bar followed by clicking at the View window. Select [***Wrtprogs.utl***] as the running program from the program list provided. Then select the theme that the time-series data is associated with and the key field that contains unique feature ID of the theme e.g. Cover_, or Cover_ID. The program will then write another program name [***Atmp.ave***] and running program [Atmp.ave] will create the time-series database template needed.

To create all the standard time-series data tables, refering to step 8 above for a proper procedure.

3.11. Setting up Model's Control List

To setup the model's control list, click on the ★ - STAR button and follow the instructions provided by the program.

3.12. Running the Groundwater Simulation Model

The procedure to simulate groundwater flow with GFlowSim is, from View menu bar, **GFwModel** -> **GFlowSim** . After the program starts, you will be presented with a multiple input table containing the model control parameters. These parameters are described below:

(1) FluxPlot=100, A proportion used to scale the flux value so that the plot fits the screen.

(2) BndFact=1.12, A fraction number accounting for effects of boundaries

(3) Sctrl=0.003, Storativity adjusting factor

(4) YesColor=5, plot the flux and water level as simulation proceeds; =0, do not plot.

(5) Pmodel=true, indicating there are more than one groundwater models running simultaneously, Pmodel=false, indicating the model covers the whole study area.

(6) IsSteady=true, simulate steady state, =False, simulate unsteady state.

3.13. Other Programs

This map-based simulation model also provides utility programs to perform various simulation model related tasks. These tasks include checking the data structure, field types of a value attribute table or feature attribute table, disintegrating a line into points, appending records to an existing database table, and flux line integration. More information about the utility programs can be found in section two of this document.

Appendix II. The Spatially Referenced Time-Series Data Tables

TimeTblName	Field	SpFeature	Model	StateName	KeyField
DHTB.DBF	(8.4)	BasinPoly	GFlow	Dh(t)	Cov# or Cov_
FFLOW.DBF	(8.2)	RiverLine	SFlow	FFlow(t)	Grid-Code or Grie_Code
GFVTB.DBF	(14.11)	BasinPoly	GFlow	DeltV(t)	Cov# or Cov_
HEADTB.DBF	(8.2)	BasinPoly	GFlow	Head(t)	Cov# or Cov_
PFLOW.DBF	(8.3)	BasinPoly	SFlow	PFlow(t)	Grid-Code or Grie_Code
PMPTB.DBF	(8.3)	BasinPoly	GFlow	Pump(t)	Cov# or Cov_
PSURP.DBF	(14.11)	BasinPoly	SFlow	PSurp(t)	Grid-Code or Grie_Code
RCHTB.DBF	(14.11)	BasinPoly	S-GFlow	Rech(t)	Cov# or Cov_
RESPVT.DBF	(7.4)	RiverLine	SFlow	Resp(t)	Grid-Code or Grie_Code
SPRTB.DBF	(8.3)	BasinPoly	S-GFlow	Spring(t)	Cov# or Cov_
TFLOW.DBF	(8.2)	RiverLine	SFlow	TFlow(t)	Grid-Code or Grie_Code
XFLUXTB.DBF	(8.3)	BasinLine	GFlow	X-Flux(t)	Cov# or Cov_
YFLUXTB.DBF	(8.3)	BasinLine	GFlow	Y-Flux(t)	Cov# or Cov_

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