## *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.