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.
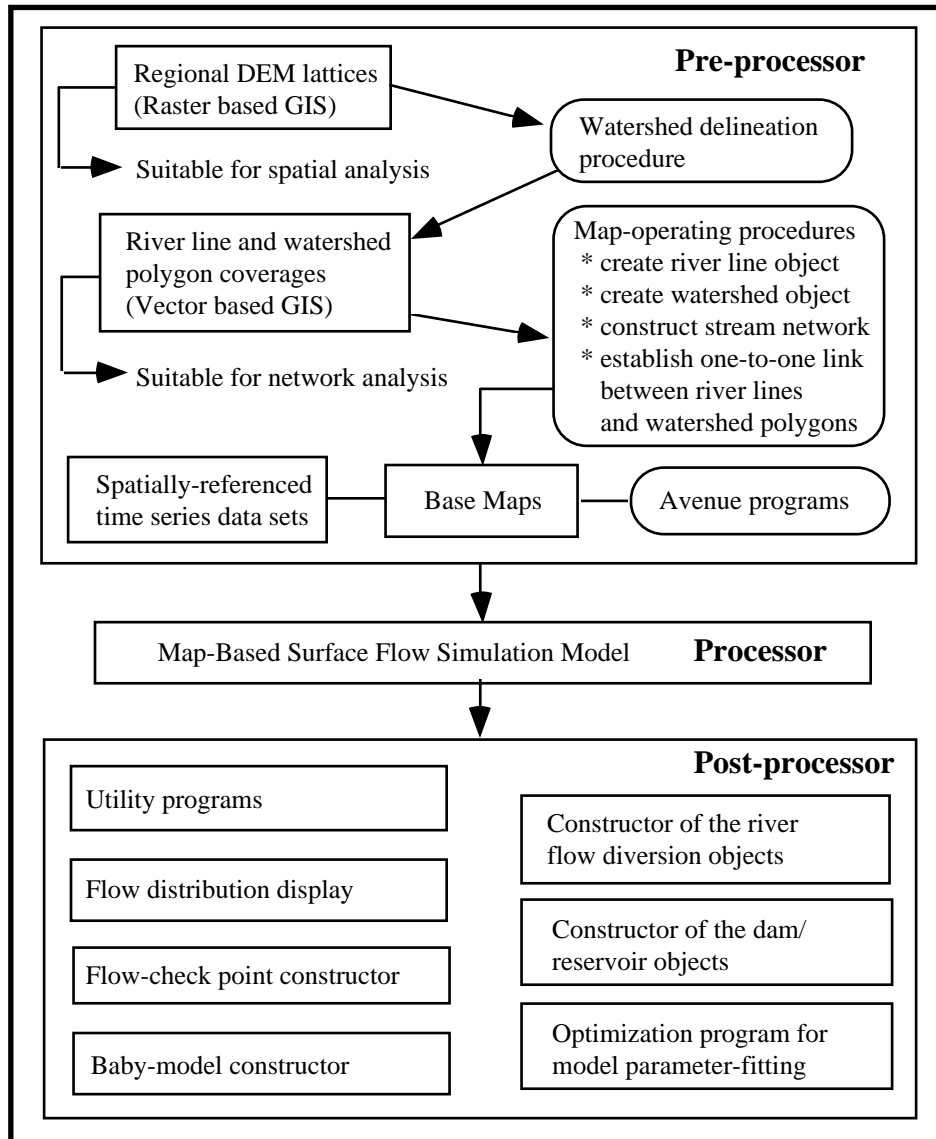

Figure 1. The components of a map-based surface water flow simulation model

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

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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.

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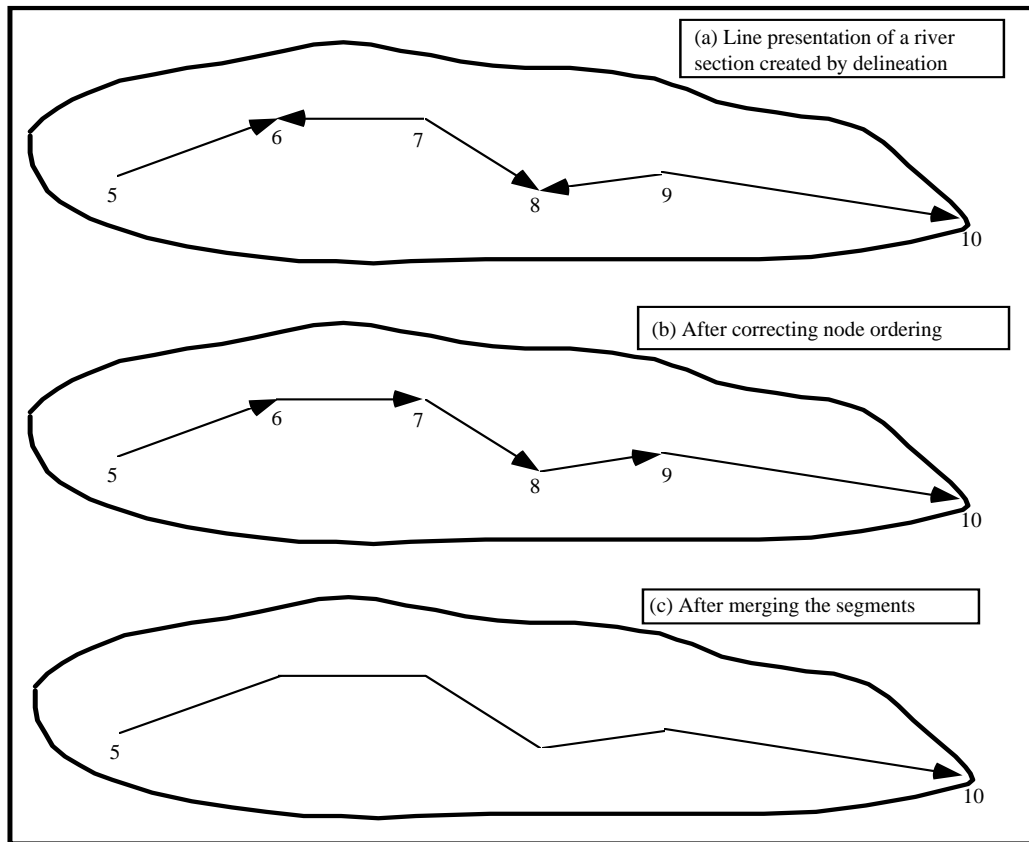
Figure 4. Sorting and merging multiple river segments into one river section

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)***.

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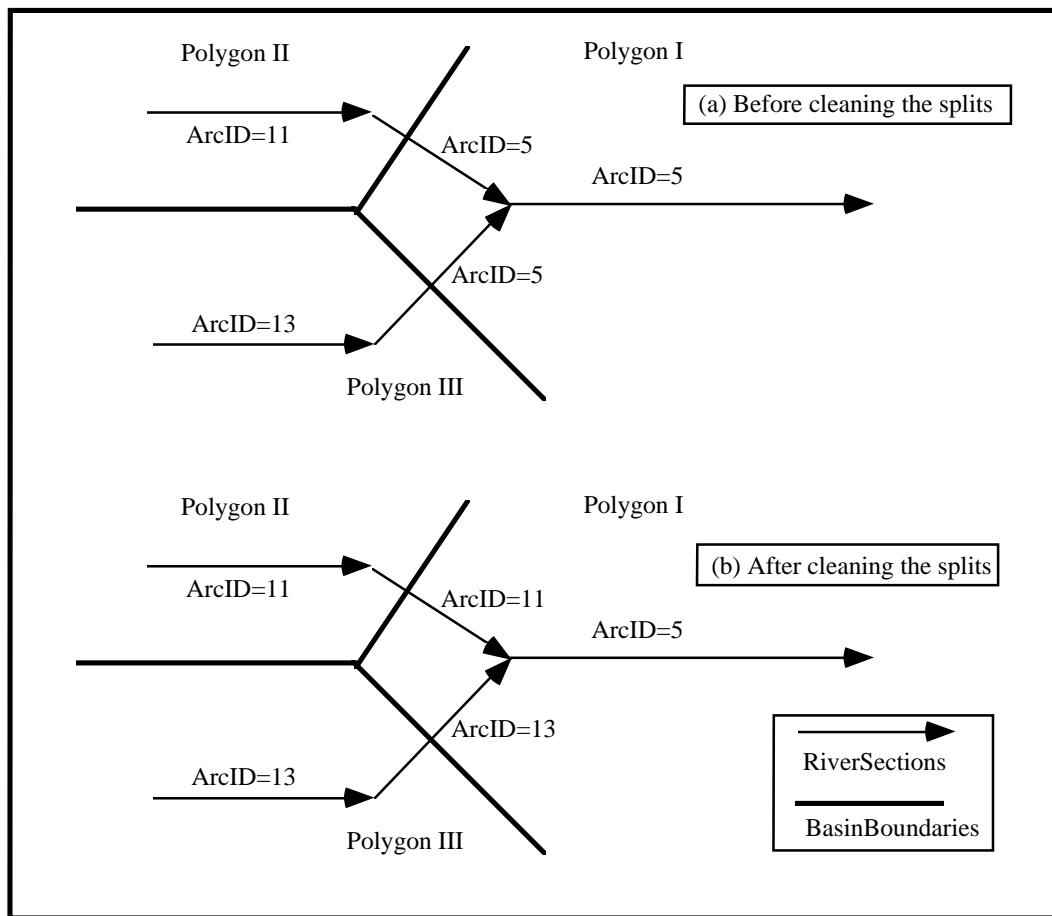
Figure 5. Rearranging river sections

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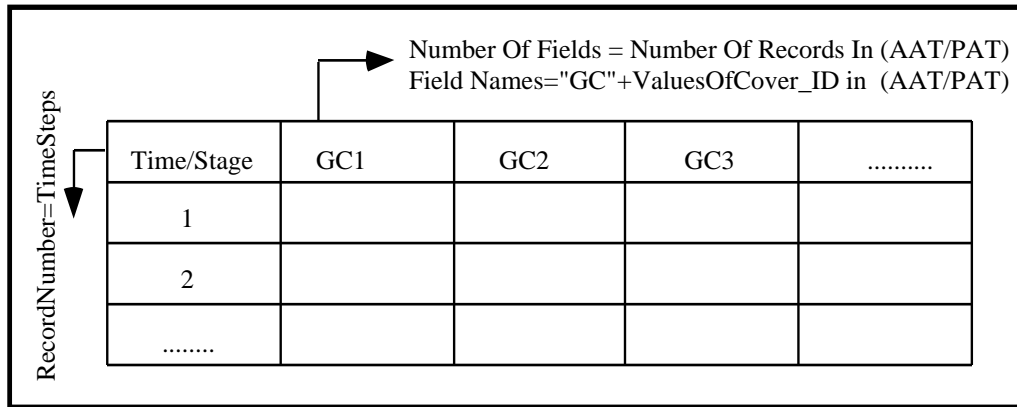
Figure 7. Database Structure for spatially-referenced time-series data

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:

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

$$T_i = l_i/\text{Vfact} \tag{2}$$

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.

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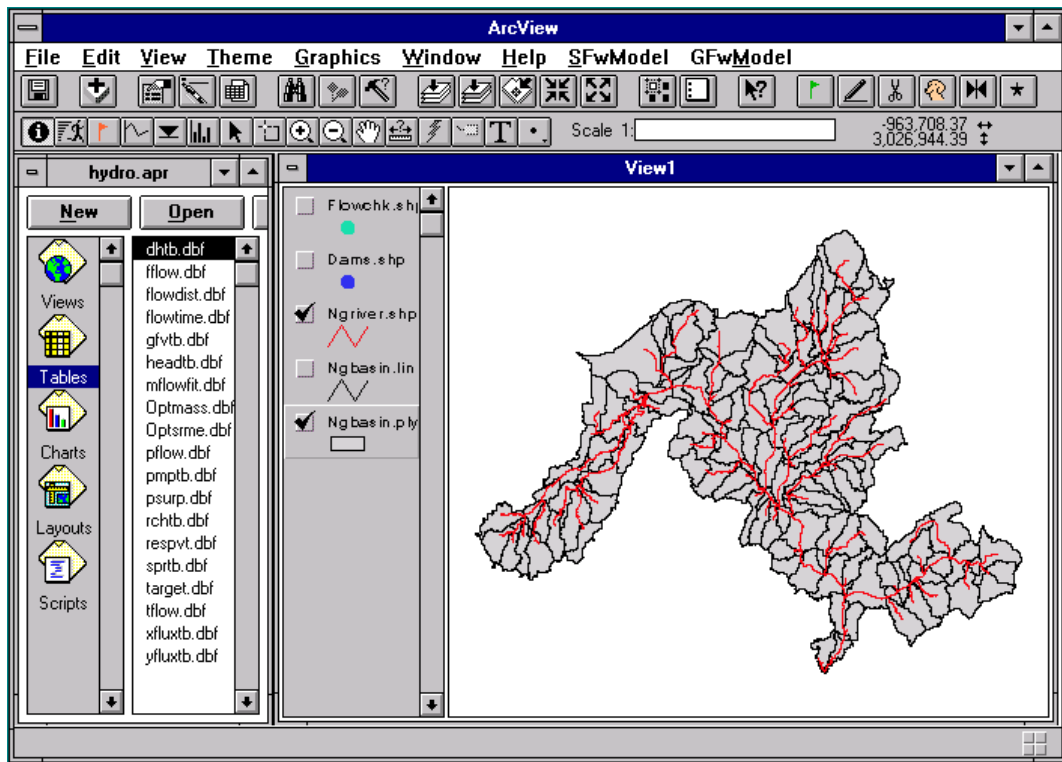
Figure 9. The view containing the base maps of the simulation model

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.

```
┌─────────────────────────────────────────────────────────────────────┐
│  ┌──────────────────────────┐      ┌──────────────────────────┐      │
│  │ SFwModel                 │      │ GFlwModel                │      │
│  ├──────────────────────────┤      ├──────────────────────────┤      │
│  │ SFlowSim                 │      │  GFlowSim                │      │
│  ├──────────────────────────┤      ├──────────────────────────┤      │
│  │ SetTables                │      │  GFmdfld   (pre1)        │      │
│  │ ChkTable                 │      │  SetPlyFld  (pre2)       │      │
│  │ AddingRec                │      │  SetLneFld (pre3)        │      │
│  │ Iflow2pnt                │      ├──────────────────────────┤      │
│  ├──────────────────────────┤      │  SetPmodel (pre-3a)      │      │
│  │ SGFPrep  (pre-all)       │      └──────────────────────────┘      │
│  ├──────────────────────────┤                                        │
│  │ MdfyFtabs (pre1)         │                                        │
│  │ LineSortR  (pre2)        │      Menu Items for GFlowSim           │
│  │ RmvSplits  (pre3)        │      ─────────────────────────         │
│  │ Mg1line    (pre4)        │      Menu Items for SflowSim           │
│  │ ChkInOut  (pre5)         │                                        │
│  │ Crtmtb     (pre6)        │                                        │
│  │ MkFVtabs (pre7)          │                                        │
│  └──────────────────────────┘                                        │
└─────────────────────────────────────────────────────────────────────┘
```
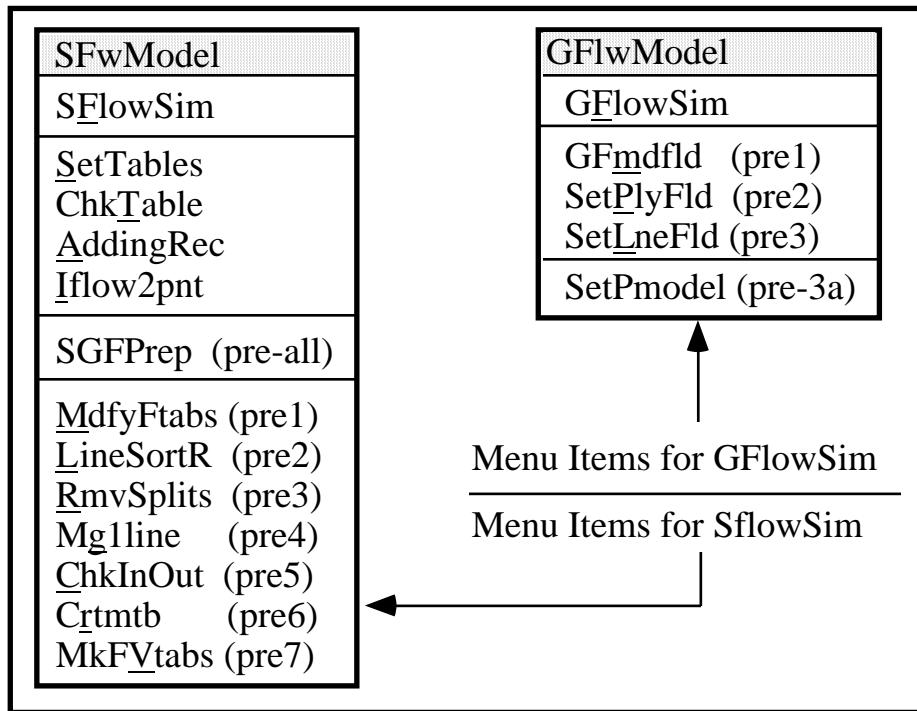
Figure 10. Menu items of SFwModel and GFwModel

       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) Iniflda.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.

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12. <u>Crtmtb</u> [pre-6] - [SFmktmtb.pre ->wrtmfile.pre] creates time-series tables, e.g., FFlowTb, TFlowTb, PFlowTb, etc., for the simulation model.

13. <u>MkFvtabs</u> [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 <u>SFwModel</u> ViewMenu.

<u>GFwModel</u> 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. <u>GFlowSim</u> - [GFlowSim.prc] activates the map-based groundwater simulation model.

2. <u>GFmdfld</u> (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. <u>Setplyfld</u> (pre-2) - [GFplyfld.pre] computes and fills in the states of the existing cell objects for the groundwater simulation model.

4. <u>Setlnefld</u> (pre-3) - [GFlnefld.pre] computes and fills in the states of the cell-boundary-line objects for the groundwater simulation model.

5. <u>SetPmodel</u> (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.

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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

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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, [Iniflda.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 <u>SFwModel</u> 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 [image] 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.

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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

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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_