

# Appendix J

## Data Centered Groundwater Modeling Enhancements

### 1.0 Purpose

The South Platte Decision Support System (SPDSS) Alluvial Groundwater Model was developed as part of Colorado's Decision Support Systems (CDSS) using a data centered approach. To facilitate the data centered approach the CDSS has developed several tools to assist the modeling process. In the SPDSS the tools for the groundwater model were evaluated and enhanced under Task 50 (SPDSS, 2007).

The objectives of this task are as follows:

1. *Enhance the data centered groundwater modeling process*
2. *Utilize standard packages, where applicable, to minimize development and maintenance costs*
3. *Develop a process specific for the SPDSS but flexible enough to be applied to other Colorado river basins.*

Task 50 incorporates the existing HydroBase data structures, supplemented by an additional database to store other types of data and engineering estimates necessary to define model characteristics. These two data sources are combined using procedures defined in this document into a modeling geodatabase used with a series of Data Management Interfaces (DMIs) to create package files for MODFLOW-2000, the groundwater flow model used in the SPDSS. The commercial model interface program Department of Defense Groundwater Modeling System (GMS Version 6.0) is used to create additional MODFLOW-2000 package files. **Figure 1** illustrates the general concept of the data centered modeling flow process.

This appendix supplements information presented in prior Task 50 technical memoranda, presenting documentation, source code and example files for the data centered process tools. Documentation for previously submitted tools is repeated in this Appendix for completeness.

### Approach

The following table summarizes the sections contained in this Appendix.

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2.3	SPDSS_GW_geodatabase
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To accomplish the objectives, Task 50 required the following:

- *development of a database for measured and engineering control data,*
- *creation of an ArcGIS geodatabase for groundwater spatial data,*
- *development of custom ArcGIS tools to facilitate the development of the MODFLOW Streamflow Routing (SFR2) package,*
- *creation of a Data Management Interface (DMI) for the generation of a SFR2 package,*
- *development of procedures to create and process data through GMS, and*
- *development or modification of modeling related DMIs.*

A detailed flow diagram of the data centered modeling flow process is shown in **Figure 2**, while **Figure 3** shows the process for generation of MODFLOW datasets. The databases, data management interface programs (DMIs), procedures, and tools enhanced or developed under Task 50.4 are described in the remainder of this Appendix.

## 2.0 Groundwater Data Repositories

The data centered modeling process requires the model to be based on measured data and easily updated when new measured data become available. This approach requires the data to reside in a central storage location that can be easily accessed. To accomplish this, three databases are used in the groundwater data centered modeling process: HydroBase, SPDSS\_GW\_database, and the SPDSS\_GW\_geodatabase. **Figure 2** illustrates the components of the data repositories and how they fit in the data centered modeling process.

### 2.1 HydroBase

HydroBase is the State of Colorado’s hydrologic database. Among other water resources data types, it contains data pertinent to groundwater, which includes: groundwater levels, aquifer configuration data, and aquifer hydraulic properties data.

The data centered modeling process can either work directly with HydroBase or with a stored procedure copy of HydroBase. In the remainder of this TM, the name HydroBase refers to either of these scenarios. Documentation of HydroBase can be found on the Colorado's Decision Support Systems website at <http://cdss.state.co.us/onlineTools/Pages/OnlineToolsHome.aspx>.

## 2.2 SPDSS\_GW\_database

This database was developed under Task 50.4 to store tables of control data (engineering estimates), exclusion data, measured data that do not reside in HydroBase, and model-specific data. Each of these is discussed below. A full listing of datasets included in the SPDSS\_GW\_database is found in **Attachment A**. In addition to local data tables, the database also contains links to tables in HydroBase. Finally the SPDSS\_GW\_database has queries that combine data in the local tables with linked tables to create datasets for export to the geodatabase.

When developing groundwater models, physically measured data is often not available in sufficient density. Therefore engineering control data must be used to increase the data density for interpolation onto the model grid. The control tables possess the same structure as their related measured data table in HydroBase.

Exclusion tables identify the measured data reported in HydroBase that are not suitable for modeling. Data not suitable for modeling are identified by an analyst during data analysis and model setup. Examples include anomalous aquifer configuration picks or extreme hydraulic conductivity data. If a data value marked as excluded in the exclusions table is modified in HydroBase and becomes suitable for modeling, the exclusion table can be modified to note this change and accept the previously excluded data for future use.

Some measured hydrogeologic datasets are not included in HydroBase because its current structure does not accommodate these types of data; however, they are still necessary for SPDSS groundwater modeling. Example datasets include stream channel cross sections, streambed conductance data, and municipal and industrial pumping data. New tables were designed to store these data in the SPDSS\_GW\_database.

Model-specific data tables in the SPDSS\_GW\_database contain data specific to modeling setup. These data include boundary conditions, hydrostratigraphic units, and the characteristics for the SFR2 package.

The SPDSS\_GW\_database has queries programmed to initiate through the database's Main Switchboard, which is further explained in **Attachment A**. These queries are used to create tables for exporting out of the database for model processing in the SPDSS\_GW\_geodatabase. Queries access the data from the linked HydroBase tables, exclude the values identified in exclusion tables and then append the data from control tables.

**Attachment A** outlines the structure of the SPDSS\_GW\_database and the steps required to load and maintain data, link the database to external data sources, and run queries to

combine data for export to the SPDSS\_GW\_geodatabase. It also includes a data dictionary that defines the fields of each table in the database.

### 2.3 SPDSS\_GW\_geodatabase

The final database is called the SPDSS\_GW\_geodatabase. A geodatabase is an ArcGIS database used to manage spatial and relational data and can contain feature classes (fc), feature datasets (fd), rasters, and tables. A feature class is an ArcGIS format that contains points, polylines, or polygons. A feature datasets, at its most basic level, is similar to a folder in the Windows operating system and can be used to thematically group feature classes in a geodatabase. Rasters are comprised of regularly spaced grids. GIS can facilitate the development of groundwater models because of its ability to allow viewing and processing of spatial data.

The SPDSS\_GW\_geodatabase stores two basic categories of spatial data: Static Data and Dynamic Data. Dynamic Data are broken into two sub-categories: Database and Analysis. **Figure 2** illustrates these categories.

Static Data imported from outside sources, such as from CDSS datasets or from the USGS National Hydrography Dataset (NHD), would consist of reference and base map data, such as roads, counties, cities, and streams. It could also include model specific data such as the aquifer boundary or the model area. These types of data are imported into the geodatabase at the start of the modeling process and will likely not change during model development.

Dynamic Data are more likely to change during the modeling process and be updated as new data become available. The Dynamic Data are generated from two sources: Database and Analysis of data in the geodatabase, and are used for development of model inputs. Database data are imported from the SPDSS\_GW\_database and then converted to spatial datasets. The types of data include, for example, groundwater level measurements, aquifer framework elevations, aquifer hydraulic properties, and the SFR segmentation points. These datasets may be periodically updated in the future as new data become available in HydroBase.

Analysis Data are created from the analysis of the data in the geodatabase, which were imported from the SPDSS\_GW\_database or other sources. These data may include, for example, the datasets created in the SFR2 package development. The analysis is performed using several tools including GMS, ArcToolbox geoprocessing tools, or the custom SFR tools coded in ArcMap VBA.

The geodatabase also includes a log table that tracks the creation and modification of the data within the geodatabase. The log table must be manually updated by the analyst.

Spatial data contained in the geodatabase will be used to create, update, and display modeling datasets. **Attachment B** documents the structure of the SPDSS\_GW\_geodatabase and the steps required to load and maintain spatial datasets in the SPDSS\_GW\_geodatabase.

## 3.0 Streamflow-Routing Package Development

One of the more complicated model input packages, the Streamflow-Routing (SFR2) package is used to simulate streams and diversions. At the time of initial model development, graphical user interface programs to facilitate use of this package were not available commercially, so a specific tool was developed for the SPDSS. A brief description of SFR2 and the tools developed to create this model input package are presented in this section.

### 3.1 Description of SFR2 Package

MODFLOW-2000 uses a streamflow-routing package (SFR2) to simulate the stream-aquifer interaction (Niswonger and Prudic, 2006). For the RGDSS groundwater model an older stream package was utilized. Therefore, the data centered modeling process was modified for the SPDSS to incorporate the SFR2 package.

The SFR2 package defines the characteristics of the modeled stream and diversions. These stream characteristics include the stream depth calculation method, Manning's roughness for the channel and overbank areas, the power coefficients relating streamflow to stream depth and width, hydraulic conductivity, streambed thickness, streambed elevation, streambed width, streambed depth, and 8-point streambed geometry cross section data. These are the parameters used by the SFR2 package to compute the stream-aquifer interaction in the model.

The SFR2 package divides the stream system into segments, which are portions of a stream with constant or linearly varying characteristics. The segments must be numbered in ascending order from upstream to downstream. Segments are then broken into reaches, which are defined by the intersection of segments and model grid cells. The reaches of each segment must also be numbered in ascending order from upstream to downstream.

Custom ArcGIS tools were created under this task to assist in defining the segments, reaches, and their respective characteristics for developing the SFR2 package. The first set of tools referred to as the SFR GIS processor are used to pre-process data in the SPDSS Groundwater geodatabase and once the inputs are configured the SFR2 file is generated using the SFR Generator. These tools and the development of the SFR2 package are highlighted in **Figure 4** and discussed in the paragraphs below.

### 3.2 Input Data Sources for SFR2 Package Development

The development of the SFR2 package requires two input datasets:

- the framework for the stream system, and
- the points attributed with the SFR2 required parameters used to segment the framework and define the characteristics of each segment at its upstream and downstream end.

The framework of the stream system is stored as a feature class, *Streams*, in the SPDSS\_GW\_geodatabase database (Figure 2). The polyline features in the feature class represent the streams and diversions that will be explicitly simulated in the model. The requirements for developing this stream framework are found in **Attachment C**. The *Streams* (fc) is represented by the light blue box with the title *Streams* (fc) shown in **Figure 4**.

The second dataset used to create the SFR2 package consists of the points that break the features in the *Streams* feature class into segments. These points are located where there is a diversion, tributary, streamflow gage, or significant change, as determined by the analysts, in a stream characteristic. To create the dataset of segmentation points, an analyst must populate the table *Streams\_segmentation\_pts* in the SPDSS\_GW\_database with the location and characteristics of the segmentation points (see **Attachment A**). This table can then be imported into the geodatabase and converted to a feature class as outlined in **Attachment B**. The feature class should be called *Streams\_segmentation\_pts* and should be stored in the Streams feature class dataset. This feature class is represented by the green box with the title *SFR\_segmentation\_pts* (fc) shown in **Figure 4**.

### 3.3 ArcGIS Tools used to Develop the SFR2 Package

To facilitate the SFR2 package development the following customized ArcGIS tools and manual steps were developed: Snap and Split, Network Creation, Segment Numbering, Reach Creation, and Attribute Fill. The tools are coded in Visual Basic for Applications (VBA), and are preserved in an ArcMap document called “CDSS\_SFR2\_Development.mxd”. The tools can be accessed via a custom toolbar, named CDSS SFR Tools. The purpose of each tool is described below and more detailed user documentation can be found in Appendices C to G. **Figure 4** identifies the flow of data from one tool to the next for generating the SFR2 package.

#### 3.3.1 Snap and Split Tool (Attachment C)

*Input Data:* Streams (fc), Stream\_segmentation\_pts (fc)

*Description:* This tool creates the segments for the SFR2 package by splitting the stream and diversion line features into segments based on the location of the segmentation point data. The tool will first move each point from its original locations to a location on the nearest stream or diversion line following the shortest distance from the point to the line. The point will only be moved if the point and the line share the same unique identifier in their respective attribute tables. The user can specify the maximum tolerance a point can be moved. If the point is within approximately 3 feet of the endpoint of a line it will be moved to the endpoint so that features with lengths of less than 3 feet will not be created.

*Output Data:* Streams\_segments (fc), Stream\_segmentation\_pts\_snap (fc)

#### 3.3.2 Network Creation (Attachment D)

*Input Data:* Streams\_segments (fc)

*Description:* In order to run the Segment Numbering tool it is necessary that the Streams\_segments (fc) be converted to a network dataset. **Attachment D** identifies the procedure to create a network dataset.

*Output Data:* Streams\_Net (network), which includes Streams\_segments (fc) and Streams\_Net\_Junctions (fc)

### **3.3.3 Segment Numbering (Attachment E)**

*Input Data:* Streams\_Net (network)

*Description:* This tool numbers the segments in ascending order from upstream to downstream. Additionally, fields are added to capture the upstream and downstream segments a segment is connected to. Finally, the endpoints of each segment are exported out as a point feature class: Streams\_segments\_endpoints (fc). This feature class maintains some of the attributes of the Streams\_segments (fc). A field is added to the attribute table of Streams\_segments\_endpoints (fc) that identifies if the point is the fnode (or starting point) or the tnode (or ending point) of a line.

*Output Data:* Streams\_segments\_endpoints (fc)

### **3.3.4 Create Reaches (Attachment F)**

*Input Data:* Streams\_segments (fc), Model\_grid (fc)

*Description:* This tool creates reaches by intersecting the Streams\_segments (fc) with the Model\_grid (fc). After creating reaches, the reaches are then numbered in ascending order from upstream to downstream and the length of each feature is added to the attribute table in feet.

*Output Data:* Streams\_segments\_reaches (fc)

### **3.3.5 Attribute Fill (Attachment G)**

*Input Data:* SFR\_segmentation\_pts\_snap (fc), Streams\_segments\_endpoints (fc)

*Description:* The SFR\_segmentation\_pts\_snap (fc) contains the attributes required by SFR2 at key segment locations. This tool performs a spatial and attribute join to assign attributes from SFR\_segmentation\_pts\_snap (fc) to Streams\_segments\_endpoints (fc). Attributes of Streams\_segments\_endpoints (fc) are then linearly or constantly interpolated at points where no data exists. Only the hydraulic conductivity and elevation characteristics are linearly interpolated.

*Output Data:* Fields are added to Streams\_segements\_endpoints (fc)

## **3.4 Generation of SFR2 Package**

A program was developed to convert the SFR2-related geodatabase files generated with the ArcGIS SFR tools into MODFLOW format. This program is represented by the grey box in Figure 3 called *SFR Generator*. The development and use of this program is

documented in **Attachment H**. This and the other programs described in this section were tested and used in the development of the model inputs.

## **4.0 Development of New DMIs and Procedures**

Additional Data Management Interfaces and procedures were developed to manipulate data in the modeling process. A DMI was created to export the model grid from GMS as a feature class to be stored in the SPDSS\_GW\_geodatabase database. Procedures were created to document the process to create and activate a model grid with a polygon feature class and to create modeling layers in GMS with xyz datasets. The functionality of this tool is available in current versions of GMS (8.2), so future application of the grid is not necessary if current versions of GMS are available.

### **4.1 GMS Grid Conversion**

Visual Basic was used to develop a program to export the model grid from GMS to a geodatabase polygon feature class. The feature class is attributed with the grid properties, row identifier, column identifier, and the cells activity code (either active or inactive). This feature class will be used for model display, and developing model data such as the SFR2 package. The development and use of this program is documented in **Attachment I**.

### **4.2 Creating and Activating the Model Grid**

In GMS, a model grid can be developed and grid cells can be activated by importing a polygon feature class into GMS and intersecting the grid with the polygon. This process establishes the foundation for the model. Detailed steps for this procedure are found in **Attachment J**.

### **4.3 Creating Model Layers with XYZ Datasets**

A model includes data layers for the aquifer top and bottom, the starting water level, recharge, and various hydraulic properties. These layers can be developed in GMS by importing xyz, horizontal and vertical datasets, and then interpolating the data onto the model grid. The xyz datasets can be imported as text files, shapefiles or feature classes. Once the datasets are interpolated and assigned to a data layer, GMS will then write the layer to the appropriate MODFLOW package file. Detailed steps for this procedure are found in **Attachment K**.

### **4.4 Modification of Program StatePP**

Modifications were made to the existing DMI: StatePP to add MODFLOW's multi-node well (MNW) package capability (Halford and Hanson, 2002). The program StatePP was modified to read in the additional required data to generate the MNW, and StatePP provides the additional processing required to generate the MNW input file. The DMI modifications are described in the following sections.

#### **StatePP Modifications**

The existing program StatePP (version 2.31) was upgraded to include the option to generate a file for the MODFLOW multi-node well (MNW) package. The multi-node



well package allows users to simulate wells that extend beyond a single model node. Multi-node wells dynamically distribute flow between nodes under pumping, recharging, or non-pumping conditions (Halford and Hanson, 2002).

In comparison to previous versions of StatePP, additional data are required in the agricultural and municipal and industrial pumping input files to generate the MNW file. In addition to data provided to previous versions of StatePP, agricultural well data must include top and bottom model layers in which a given well is completed, unique well ID, and a multi-parcel flag. Municipal and industrial pumping must include model layer top and bottom in which a given well is completed. Details about the specific content and formatting of the additional data and a description of the various assumptions used in generating the MNW file can be found in the updated StatePP documentation found in **Attachment L** which is reproduced from earlier version presented in the RGDSS, with the addition of specific sections related to the MNW package.

The MNW file is generated by StatePP if the MNW flag is set to 1 in the control file. There are also several output options for the MNW package that must be specified in the control file, and are documented in **Attachment L**. The modifications to StatePP was carried out in such a way that input files used and designed for previous versions of StatePP will run as before if the MNW flag is set to zero or omitted in the control file.

#### **4.5 Lateral Boundary Processor**

Significant recharge to the alluvium of the South Platte and tributaries occurs from inflow of recharge from areas adjacent to the main alluvial deposits that define the model extent. Much of this originates as deep percolation of applied irrigation water and canal seepage. Minor amount will also occur from infiltration of native precipitation. A data management interface was developed to track these components of recharge and use a time lag method to route these flows to boundary cells in the model. **Attachment M** provides documentation for this program.

#### **4.6 Bedrock Flux Interface**

The SPDSS uses information generated by the Denver Basin groundwater model, developed by the USGS (USGS, 2011), in order to quantify flow between the bedrock aquifers of the Denver Basin and overlying alluvial aquifers. The primary tool for accomplishing this are programs developed by the USGS and documented in Techniques and Methods 6-A28, developed with funding from the CWCB. Since the active areas in the Denver Basin model and the SPDSS model do not exactly overlap due to different levels of discretization, an a utility was developed to process bedrock flows for use in the SPDSS alluvial model. **Attachment N** documents use of this supplemental utility.

#### **4.7 Rainfall Pre-Processor**

This utility processes precipitation time series data and land use to create files for use with StatePP and with the ungaged surface water utility described in section 4.8. Use of this program is described in **Attachment O**.

#### **4.8 Ungaged Surface Water Runoff Processor**

This utility processes ungaged surface water runoff quantities generated in the rainfall pre-processor to distribute to the nearest stream reach in the SFR package. Use of this program is documented in **Attachment P**.

### **5.0 Summary and Conclusions**

These enhancements will allow modelers to more quickly create and update model files. Detailed procedures used to implement each of these enhancements are included in Attachments A through P.

### **6.0 Recommendations**

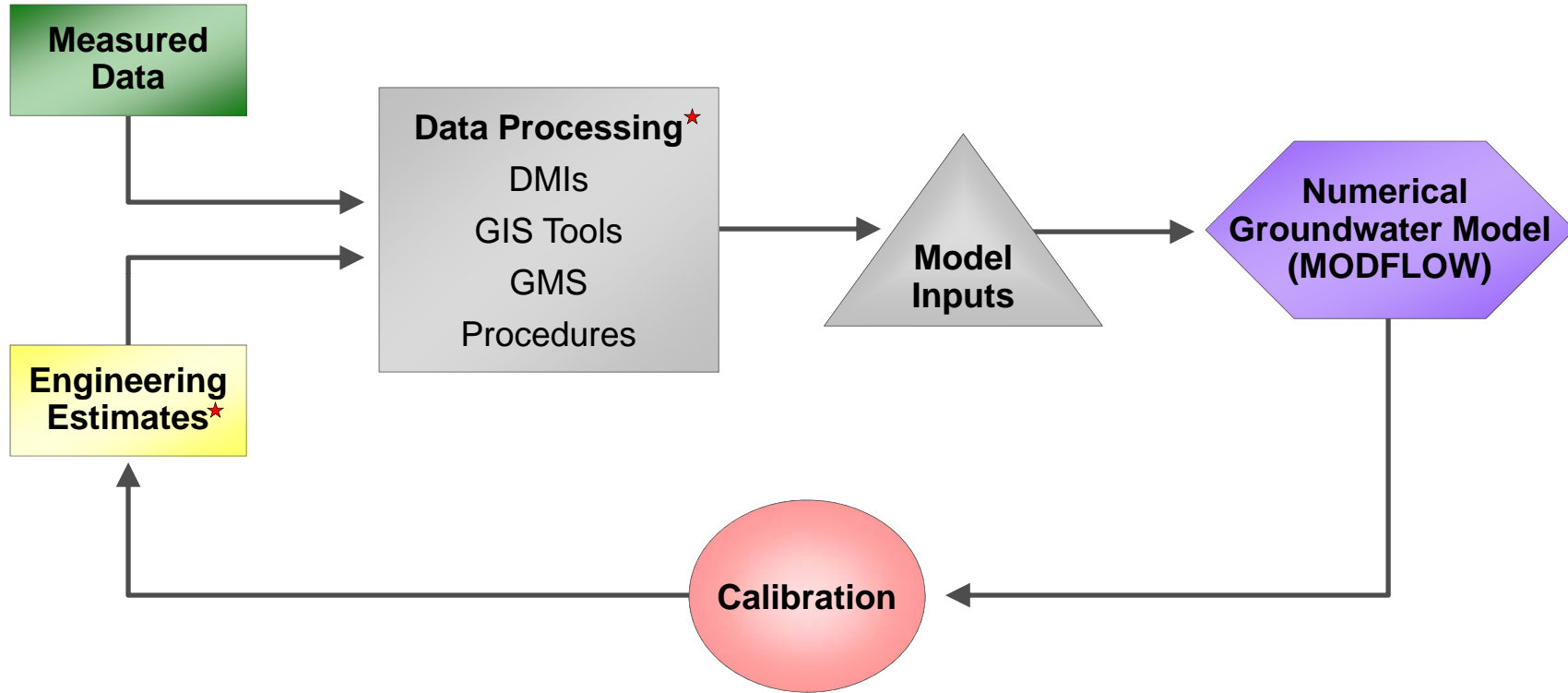
A guiding principle in the modifications to the data-centered groundwater modeling process was to automate steps in the process that were considered to be repetitive and where automation would streamline the modeling process. Therefore, many modeling steps were left as manual procedures because the effort to automate them did not justify the efficiency gained through automation. As the data-centered modeling process is implemented it may become apparent that some of the manual procedures should be automated. It is recommended such procedures be considered for automation as they are encountered in the future.

### **7.0 References**

- Halford, K.J. and Hanson R.T., 2002, User Guide for the Drawdown-Limited, Multi-Node Well (MNW) Package for the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, Versions MODFLOW-96 and MODFLOW-2000: U.S. Geological Survey Open-File Report 02-293, 33 p.
- Niswonger, R.G. and Prudic, D.E., 2006, Documentation of the Streamflow-Routing (SFR2) Package to Include Unsaturated Flow Beneath Streams--A modification to SFR1 Techniques: U.S. Geological Survey Techniques and Methods, Book 6, Chap. A13. April.
- Banta, E. R., Paschke, S. S., and Litke, D. W., 2008, User Guide and Documentation for Five MODFLOW Groundwater Modeling Utility Programs, U. S. Geological Survey Techniques and Methods 6-A28.
- Paschke, S.S. ed., 2011, Groundwater availability of the Denver Basin aquifer system, Colorado: U.S. Geological Survey Professional Paper 1770, 274 p.
- SPDSS (South Platte Decision Support System). 2007. SPDSS Phase 3 Task 50.4 Technical Memorandum Data Centered Groundwater Modeling Enhancements. Prepared for the CWCB and DWR by CDM Smith. March.

# SPDSS

Figure 1: Overview of SPDSS Groundwater Data Centered Modeling Process



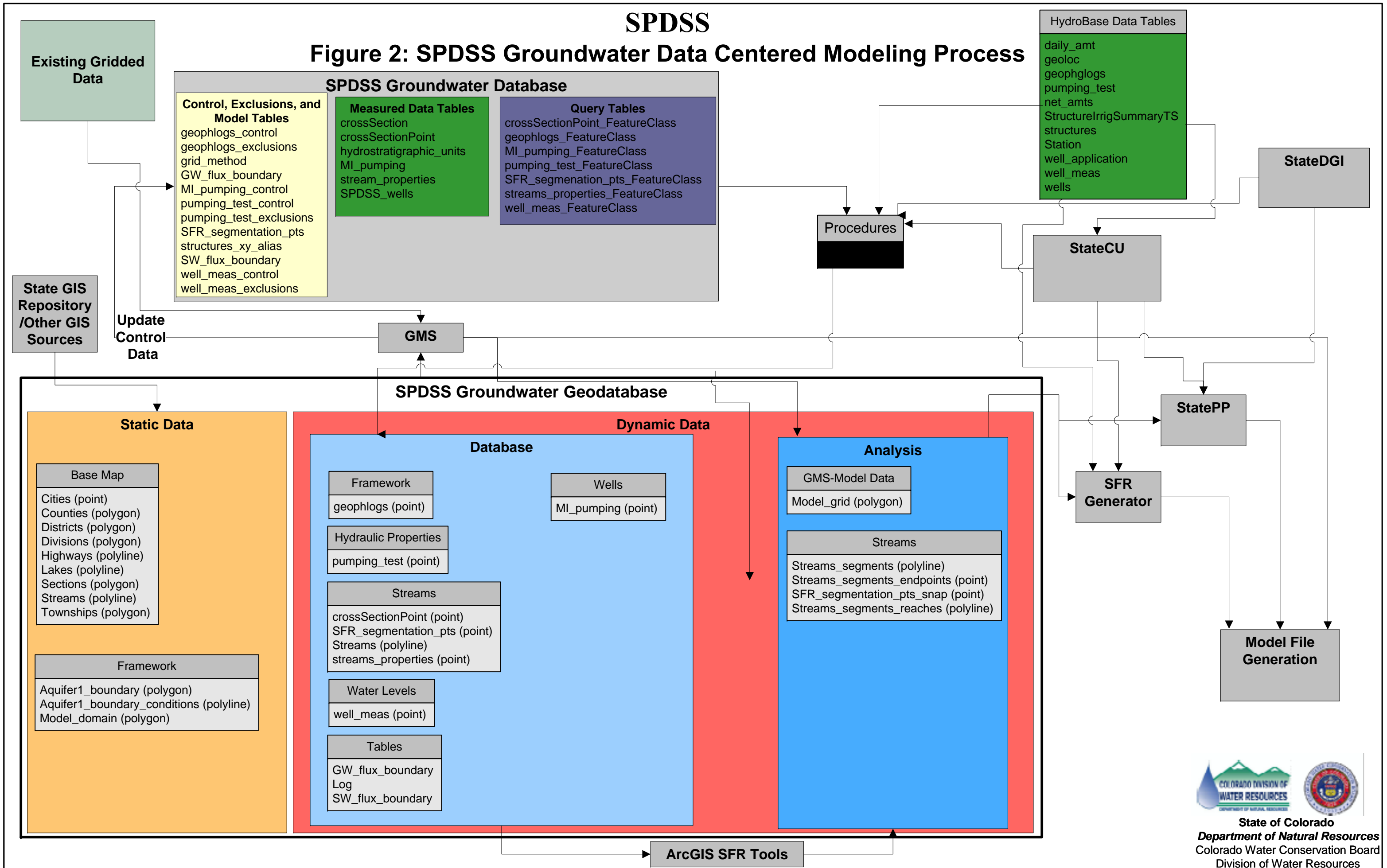
\*Enhanced in Task 50.4



State of Colorado  
Department of Natural Resources  
Colorado Water Conservation Board  
Division of Water Resources

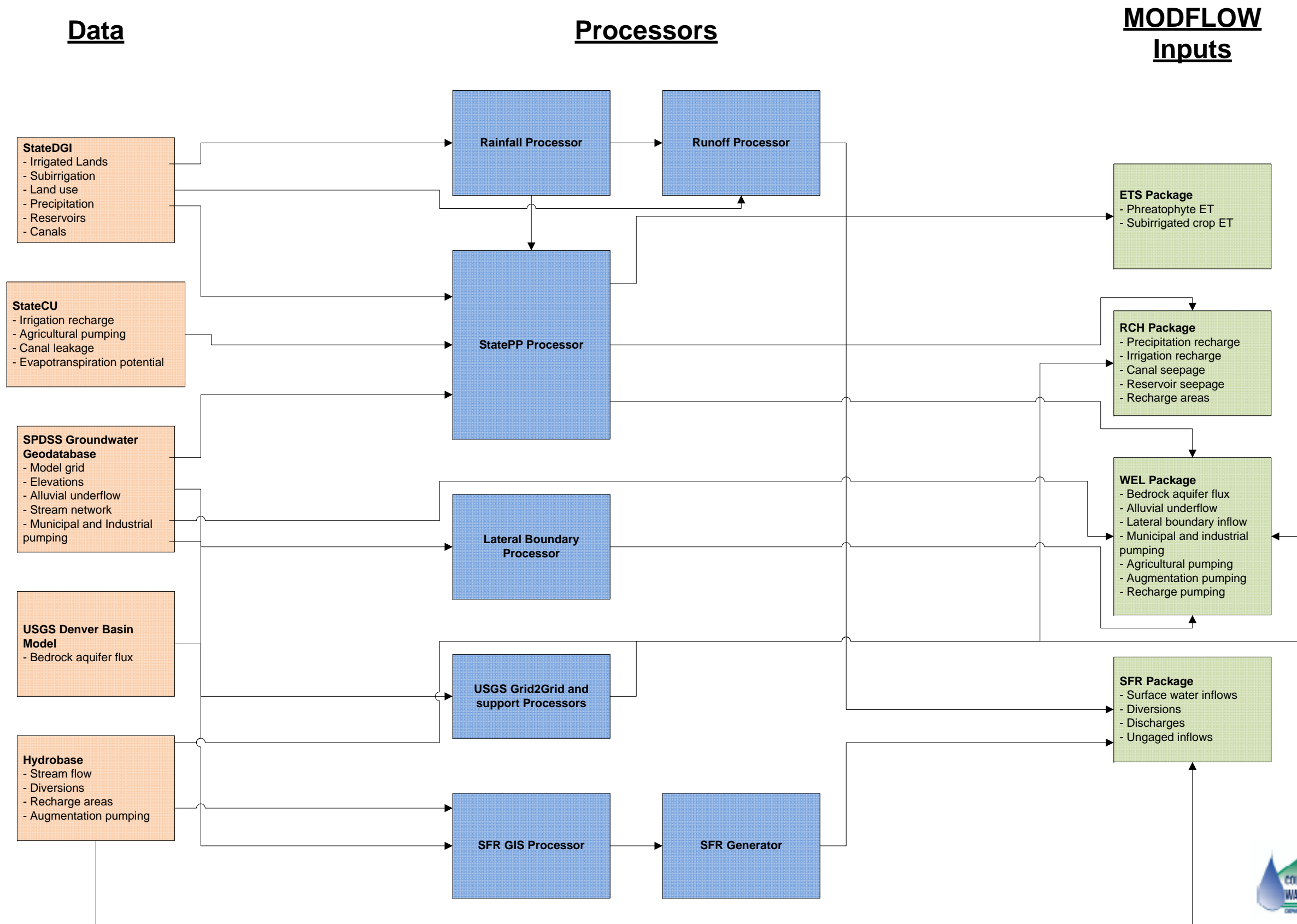
# SPDSS

## Figure 2: SPDSS Groundwater Data Centered Modeling Process



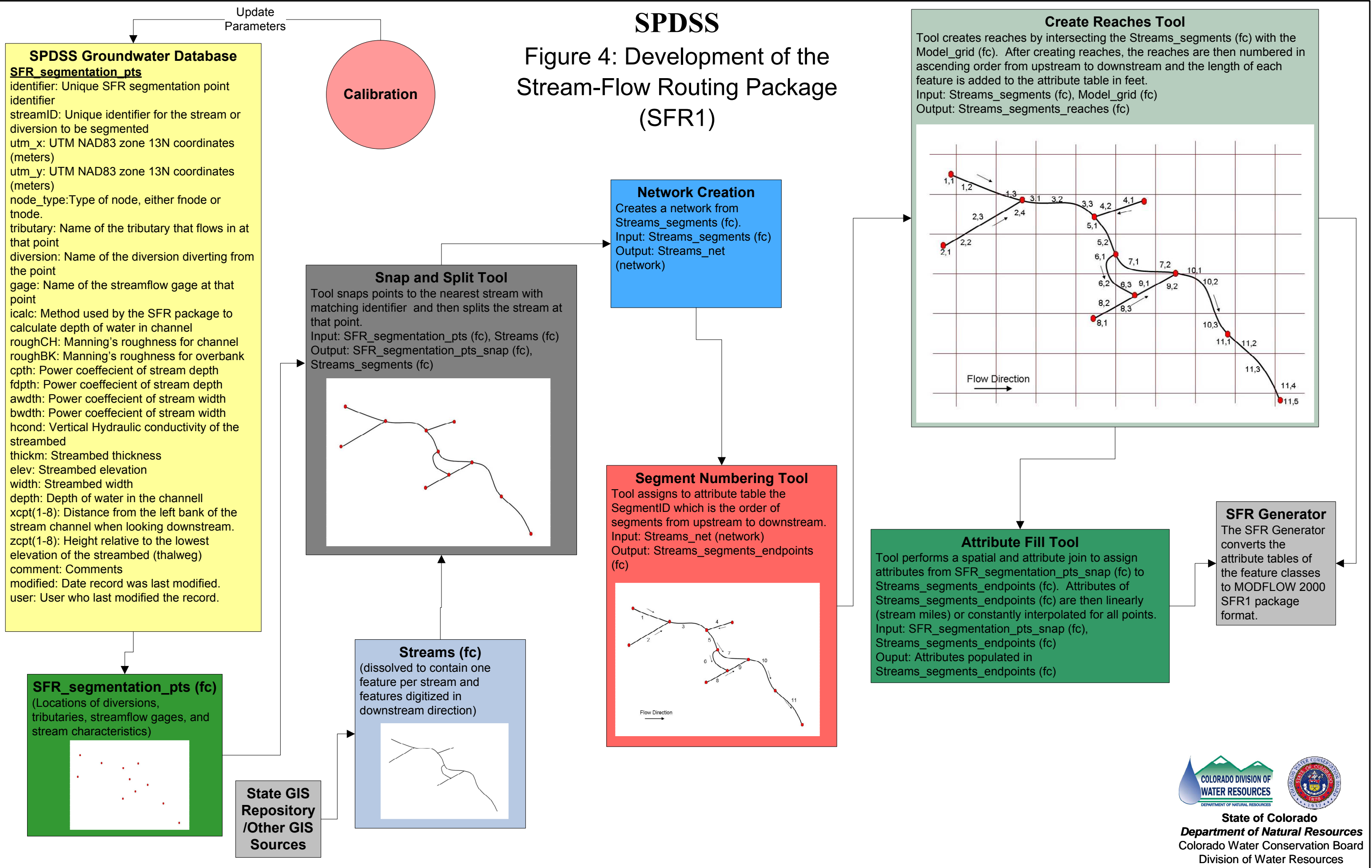
# SPDSS

## Figure 3: SPDSS Groundwater Model Data Set Generation Process



# SPDSS

## Figure 4: Development of the Stream-Flow Routing Package (SFR1)



State of Colorado  
 Department of Natural Resources  
 Colorado Water Conservation Board  
 Division of Water Resources