Appendix G
Streamflow-Routing Package Development

1.0 Purpose

Stream-aquifer interactions were simulated using the MODFLOW-2000 Streamflow Routing package (SFR2) (Niswonger and Prudic 2010). This package defines the properties of the stream system such as stream geometries, stream connectivity, stream inflows, and physical properties of the streambed. Diversions and discharges can also be simulated using the SFR2 package.

The purpose of this appendix is to supplement the description of the SFR2 package in the Task 50.4 Technical Memorandum (TM) (South Platte Decision Support System [SPDSS] 2008) with additional details on the creation of the SFR2 package for the calibrated SPDSS model. The supplemental description includes additional detail on the data sources, processing of the components of the SFR2 package, populating the SPDSS_GW_database with SFR2 data, and using Task 50 SFR2 tools to build the SFR2 package input file.

2.0 SFR2 Package Description

The Streamflow-Routing package (SFR2) defines the characteristics of streams used in the groundwater model. Each stream is discretized into segments, which are a portion of the stream with constant or linearly varying properties. These segments are overlaid on the model grid, and the intersection of a segment with these cells is referred to as a reach. Segment boundaries are defined when there is a tributary, diversion, streamflow gage, or a non-linear change in a stream property. These locations used to define segments will be referred to as segmentation points in portions of this report. The segments must be numbered in ascending order from upstream to downstream for the SFR2 package.

The physical properties of each segment are defined at the upstream and downstream end of a segment. If the upstream value differs from the downstream value, then the value is linearly interpolated along the segment. The properties of each segment may include the stream depth calculation method, point streambed geometry cross-section data, streambed thickness, roughness coefficients for the channel and overbank, vertical hydraulic conductivity, streambed elevation, streambed width, streambed depth, and power coefficients relating streamflow to stream depth. A subset of these parameters may be used, depending on the method selected to relate stream depth to flow.

Segments are split into reaches, which are defined by the intersection of segments and model grid cells. The SFR2 package requires reaches of each segment to be numbered in increasing order from upstream to downstream. Additionally, the length channel within each reach must be calculated. Inflows and outflows for the stream are specified at the upstream end of a segment

3.0 SFR2 Components

The components of the SFR2 package include the stream network split into segments, the properties of each segment, segment reaches and streamflows at the model boundary, and diversions and discharges within the model. Each of these components is discussed in the Task 50.4 TM and additional details for selected components are discussed in the following paragraphs.

Stream Network

The Colorado Division of Wildlife (CDOW) shapefile of the hydrography of Colorado was used as the starting point for defining the stream network. The shapefile was first clipped to the South Platte River Basin. Features were selected so at least one stream covered each drainage area within the model domain. These features were exported to a new shapefile.

Some tributaries in the CDOW shapefile did not connect to the South Platte River. Therefore, ground surface contours developed from the U.S. Geological Survey (USGS) 30-meter National Elevation Dataset (NED) were used to refine the path of the tributaries and to determine the confluence with the South Platte River.

To use the Task 50 tools for developing the SFR2 package, each stream in the network must have a unique identifier and be comprised of only one feature. There were some duplicate names in the CDOW streams shapefile. For example, there were multiple Sand Creeks. To make the stream names unique, the Sand Creek identifiers were changed to Sand Creek 1, Sand Creek 2, etc. In the Cache la Poudre area, two Spring Creeks existed within the CDOW streams shapefile. To make each creek unique, one identifier was kept as Spring Creek, and the other was changed to Spring Creek 2. Additionally, a couple of un-named tributaries existed within the stream network. These creeks were arbitrarily named Trib 1 and Trib 2.

After each stream was given a unique identifier, ArcToolbox in ArcGIS was used to dissolve the features based on the stream name. This processing step created just one feature per unique stream. Each unique stream was given a stream order – the mainstem was given an order of one, a tributary an order of two, a tributary of a tributary on order of three, and so on. The stream order information is one component required to run the Task 50 SFR2 Segment Numbering Tool, further described in the Task 50.4 TM.

Braided Channel Areas

Some of the streams obtained from the CDOW shapefile contained braided channels. These areas with braided channels were inspected to determine if they needed to be modeled as separate channels or if they could be aggregated together and modeled as one channel. These areas were evaluated based on the width between the separated channels and length of the separated channels.

Using ArcGIS, the braided areas were evaluated using the CDOW shapefile and 1:24K USGS Digital Raster Graphics (DRGs). The width between braided channels was measured and the lengths of the braided channels were measured. Considering the model cell size of 1,000 feet, it was found that no braided channels were sufficiently long or separated to warrant modeling the channel individually. Therefore, all braided channels are represented as a single channel in the model.

Stream Segment Properties

The stream segment properties include stream depth calculation method, streambed thickness, roughness coefficients for the channel, vertical hydraulic conductivity of streambed material, streambed elevation, streambed width, and streambed depth. These properties are discussed in the Task 50.4 TM, and only additional detail for selected properties not discussed in the Task 50.4 TM is included below.

Stream Depth Calculation Method

The SFR2 package has five options for computing stream depth: a specified value, Manning's equation using a wide rectangular channel, Manning's equation using an eight-point cross-section, a power equation, or a table of values relating flow to depth and width (Niswonger and Prudic 2010). Several methods for relating stream depth to flow were tested during early phases of the modeling, including the power equation and eight point cross-sections. These methods were found to create solution difficulties in the model. The selected method for the calibrated model used an assumption of a constant channel width, calculating the depth using Manning's equation.

Roughness Coefficient

Manning's n roughness coefficients were estimated using the following sources:

- Prudic (1989)
- Chow (1959)
- Gingery Associates, Inc. (1980, 1979)
- Engineering Professionals, Inc. (1987)
- Soil Conservation Service (1982)
- Various HEC models of South Platte tributaries received from Urban Drainage and Flood Control District (UDFCD)

Based on the inspection of the various data sources mentioned above, the streams were divided into three categories—South Platte River, its mountain tributaries, and other tributaries. Based on the sources, a minimum n value of 0.030 and maximum n value of 0.050 for the mountain tributaries were averaged to result in an n of 0.040. Likewise for the other tributaries, the minimum and maximum values of 0.030 and 0.045, respectively, were averaged for a final n of 0.038. The mainstem South Platte River n values were considered to be 0.035 based on Prudic 1989 for a natural channel in a major river. A summary table of n values based on the various sources is presented below in Table G-1.

Table G-1: Summary of Manning's Roughness Coefficient Values Researched for SFR2 Input

Manning's n Value for Active Channel				
Mainstem	**Mountain Tributary**	**Other Tributary**	**Notes**	**Source**
0.035 +/- 0.010			Natural channel - major river	4
		0.030 +/- 0.005	Natural channel - clean and straight	4
		0.040 to 0.045		6, 7
		0.035 to 0.040		1
		0.035 to 0.040		5
	0.035 to 0.040			1
	0.030 to 0.050			2
	0.030 to 0.050			3

Sources:

1) Engineering Professionals, Inc. July 1987. Manning's N-Value Report-Floodplain Information and Drainage Plan for St. Vrain Creek and North St. Vrain Creek
2) Gingery Associates, Inc. February 1980. Spring Creek Major Drainageway Planning Study Manning's N-Value Report.
3) Gingery Associates, Inc. August 1979. Hydraulic Roughness Value Analysis -Manning's N-Dry Creek.
4) Prudic, David E. 1989. Documentation of a Computer Program to Simulate Stream-Aquifer Relations Using a Modular, Finite-Difference, Ground-Water Flow Model. U.S. Geological Survey, Open-File Report 88-729. Table 1, pg. 10.
5) Soil Conservation Service. August 1982. Documentation for Selection of Manning's Roughness Coefficient for Boxelder Floodplain Management Study.
6) Urban Drainage and Flood Control District. Cherry Creek to Scott Road Reservoir HEC Model. URS. May 2003.
7) Urban Drainage and Flood Control District. Box Elder Creek HEC Model. Box Elder Floodplain Future. Wright Water Engineers. September 2001.

Vertical Hydraulic Conductivity

Vertical hydraulic conductivity values for the streambed were determined from Task 34, streambed conductance testing. Since the regional SPDSS model uses a model cell size of 1,000 by 1,000 feet, the streambed conductance term is scale-dependent (Mehl and Hill 2010). For the large cell size, the vertical hydraulic conductivity was reduced from observed field values to avoid generation of streambed conductance terms that were too high for a stable solution to be calculated in the model.

This parameter is used to calculate a conductance term in the model to quantify the stream leakage. The conductance term that is calculated in the model is a function of streambed area and thickness of streambed materials. The conductance term calculated in the SFR package is calculated using the following equation.

$$C = \frac{K \bullet w \bullet L}{m}$$

C – Conductance
w – Channel width
L – Length of channel in grid cell
m – Stream bed thickness

The conductance term is used within the model to calculate the leakage into or out of the stream, based on the groundwater elevation and stream elevation, including consideration of the potential for the groundwater elevation falling below the base of the streambed material. This parameter should be considered an approximation of the physical parameters that control stream leakage, since the complexities of the three dimensional flow proximal to the stream bed are difficult to represent when the stream dimension is small compared to the dimension of the grid cells. The streambed conductance term will need to be modified if refined models are developed from the SPDSS model with a smaller grid dimension, since the streambed conductance will typically increase as the grid dimension approaches the stream width. Table G-2 summarizes the stream parameters in the calibrated model.

Table G-2 Streambed Vertical Hydraulic Conductivity in Model

Tributary Name	**Streambed Vertical Hydraulic Conductivity (ft/day)**
Ashcroft Draw	0.5
Badger Creek	0.5
Bear Creek	0.5
Beaver Creek	5
Beebe Draw	5
Big Dry Creek	5
Big Thompson River	5
Bijou Creek	5
Boulder Creek	10
Box Elder Creek	5
Boxelder Creek	5
Cache la Poudre River Reach	5
Camp Creek	0.5
Cedar Creek	0.5
Cherry Creek	0.5
Cherry Creek Reach	0.5

Table G-2 Streambed Vertical Hydraulic Conductivity in Model

Tributary Name	Streambed Vertical Hydraulic Conductivity (ft/day)
Clear Creek	5
Coal Creek	5
Comanche Creek	0.5
Cottonwood Draw	0.5
Crow Creek	5
Dry Creek	5
East Bijou Creek	5
Eaton Draw	5
First Creek	0.5
Graham Seep	5
Kiowa Creek	0.5
Little Dry Creek	5
Little Thompson River	5
Lodgepole Creek	0.5
Lonetree Creek	5
Lost Creek	4
Middle Bijou Creek	0.5
Muddy Creek	0.5
Owl Creek	5
Pawnee Creek	0.5
Plum Creek	0.5
Poudre River	0.5
PR1	2
PR2	2
Ralston Creek	5
Saint Vrain Creek	5
Sand Creek 1	0.5
Sand Creek 2	5
Sand Creek 3	5
Sand Creek 4	0.5
Second Creek	5
Sheep Draw	0.5

Table G-2 Streambed Vertical Hydraulic Conductivity in Model

Tributary Name	Streambed Vertical Hydraulic Conductivity (ft/day)
South Platte River	0.5
South Platte River NE	0.5
SPR: Balzac to Julesburg Reach	5
SPR: Denver to Henderson Reach	5
SPR: Fort Lupton to Kersey Reach	5
SPR: Henderson to Fort Lupton Reach	5
SPR: Kersey to Weldona Reach	5
SPR: Waterton to Denver Reach	5
SPR: Weldona to Balzac Reach	5
Spring Creek	0.5
Spring Creek 2	0.5
The Slough	5
Third Creek	5
Toll Gate Creek	0.5
Trib 1	0.5
Trib 4	0.5
Twentytwo Slough	0.5
West Bijou Creek	0.5
West Sand Creek	0.5
Wildcat Creek	0.5
Wolf Creek	0.5

Streambed Elevation

Elevation profiles along the stream network were inspected to identify where elevation segmentation points were needed in the SFR2 input to maintain a linear slope in elevation for each segment. The following steps were implemented to develop the elevation profiles and identify the locations where elevation segmentation points were needed.

1) The stream network, a point feature class, and the USGS 30-meter NED were added to an ArcGIS project.

2) A point was created at each tributary intersection and each Task 34 location. The points were identified with the name of the nearest stream.

3) The ArcGIS SFR2 Snap and Split tool created as part of Task 50 was used to snap the points to the stream network and split the stream at the location of each point. This created the initial network of segments.

4) A field called "From_To" was added to the newly created "streams_segments" layer to allow for the identification of the stream segment based on the tributaries or cross-sections that were upstream and downstream of the segment. For example, the segment along the South Platte River defined by the Task 34 cross-section location SC-21 upstream and Badger Creek downstream was named "SC-21 to Badger Creek" in the "From_To" field.

5) The ET GeoWizards tool was used to create station points along the stream segments layer every 100 meters.

6) The station points were converted to 3D features based on the USGS 30-meter NED using the 3D Analyst extension.

7) The z value was added to the attribute table of the stations points 3d layer using a custom script.

8) The attribute table of the stations points 3d layer with x, y, and z values was then opened in *Excel* and profiles were created for each unique value in the "From_To" field.

9) For each profile, a line was connected between the first point and last point in the profile. If the profile deviated by more than 20 feet vertically from the line, then a segmentation point at that location was added to the table of segmentation points to be used for creating segments.

In all, 65 elevation segmentation points were identified and added to the table of segmentation points. Streambed elevations were refined based on survey information available from Task 34 and from wells located near the stream channel.

Streambed Width

Streambed widths were estimated based on examination of aerial photos, maps, and the measured cross-sections from Task 34. These widths were generalized for regional modeling purposes, using a typical width of 20 feet for western tributaries, 15 feet for plains tributaries, 50 feet for the Cache La Poudre, and 150 feet for the South Platte.

3.0 SFR2 Network Refinement

As mentioned above, the SFR2 package requires segments to contain constant or linearly varying variables. Therefore, additional segmentation points were added at stream network confluences, diversions and discharge locations, and critical elevation change points. Segmentation points were also added at Task 34 streambed conductance study locations, since surveyed elevations for the streambed were available. The seven main gage locations on the South Platte River—Henderson, Kersey, Weldona, Fort Morgan, Balzac, Atwood, and Julesburg—were defined as segmentation points in the SFR2 package to allow comparison of gage records and modeled flows at these locations during the calibration process.

4.0 Model Inputs

Database Preparation

The development of the SFR2 package requires two input datasets for the Task 50 SFR2 Tools:

- 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 was developed as described in Section 2.1.1 and then added as a feature class, *Streams*, in the SPDSS_GW_geodatabase.

The second dataset used to create the SFR2 package is the points that will split the features in the *Streams* feature class into segments. These points are identified where there is a diversion, tributary, streamflow gage, or significant change, as determined by the analysts, in a stream property. The table *Streams_segmentation_pts* in the SPDSS_GW_database was populated with these points using the following rules:

1. The unique identifier of the stream which will be segmented by the point must be specified.
2. Stream depth calculation method and all required properties are specified for the most upstream point (fnode) of every stream or diversion.
3. At any location where an analyst determines there is a significant change in a stream property, a point must be generated and that stream property must be given a value.
4. If the analyst changes the stream depth calculation method, a point is created and all properties unique to that calculation method must be defined in the table.
5. Properties such as vertical hydraulic conductivity and streambed elevation that can be linearly interpolated between segments must be specified at the most downstream point (tnode) of every stream or diversion. If no downstream vertical hydraulic conductivity value is specified then the value will be populated as a constant for downstream segments.
6. The streambed elevation must be specified at the confluence of all streams.

7. All points must be identified as an fnode, starting point, or tnode, ending point, of a segment. All points should be set to fnode unless the point specifies the vertical hydraulic conductivity or streambed elevation values for the most downstream point of the stream or diversion.

8. A point must be specified at all streamflow gaging stations where streamflow output from the model is required.

9. A point must be specified at all diversion locations.

After the table was populated it was then converted to a feature class, *Streams_segmentation_pts,* in the *Streams* feature dataset of the SPDSS_GW_geodatabase.

Task 50 Tools

After the input datasets, *Streams* and *SFR2_segmentation_pts*, were created and added to the geodatabase, the Task 50 SFR2 tools were used to generate the SFR2 package. The first tool used was the Snap and Split tool, which partitions the streams into segments defined by the segmentation points. The second step created a network from the output of the Snap and Split tool. Then next step used the Segment Numbering tool to number all segments in ascending order from upstream to downstream. The Reach Creation tool split the segments into reaches with the model grid. The Attribute Fill tool calculated the segment properties at the upstream and downstream end of each segment using the data supplied in the *SFR2_sementation_pts* feature class. Finally, the SFR2 Generator was used to convert the data in the attribute tables of the geodatabase files to the required MODFLOW SFR2 package format.

References

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