Simulation of Streamflow Constraints in the MODFLOW-2005 version of GWM with the Streamflow-Routing (SFR) Package

Streamflow and streamflow-depletion constraints specified in the initial versions of the Groundwater Management (GWM) Process for MODFLOW (Ahlfeld and others, 2005) were calculated by use of the original MODFLOW Streamflow-Routing Package called STR (Prudic, 1989). The MODFLOW-2005 version of GWM (MF2005-GWM) has now been updated to allow representation of streamflow and streamflow-depletion constraints using either the original STR Package or the updated SFR Package developed by Prudic and others (2004) and Niswonger and Prudic (2005); however, the user cannot simultaneously use the STR and SFR Packages in a model run. The SFR Package is similar in most aspects to the STR Package. For example, the SFR Package uses the continuity equation to route surface-water flow through one or more simulated rivers, streams, canals, or ditches. One of the most significant differences between the two packages is that in SFR, stream depth is calculated at the midpoint of each reach instead of the beginning of each reach, as was done in the original STR Package. This approach allows for the addition and subtraction of water from runoff, precipitation, and evapotranspiration within each stream reach. Because the SFR and STR Packages use different methods to calculate stream depth within each reach, the model-calculated flow rates across streambeds will likely differ between the SFR and STR Packages. The SFR Package also simulates unsaturated flow beneath streams, which cannot be simulated by the STR Package (Niswonger and Prudic, 2005).

As with the STR Package, the SFR Package is best suited for modeling long-term changes (months to hundreds of years) in groundwater flow using averaged flows in streams; the packages are not recommended for modeling the transient exchange of water between streams and aquifers when the objective is to examine short-term (minutes to days) effects caused by rapidly changing streamflows (Prudic and others, 2004).

Streamflow Constraints (STRMCON) File

As with previous versions of GWM, the streamflow constraints (**STRMCON**) file is used to define streamflow and streamflow-depletion constraints. Either the STR (Prudic, 1989) or SFR (Prudic and others, 2004; Niswonger and Prudic, 2005) Streamflow-Routing Packages may be used to simulate streamflow, but both packages cannot be used simultaneously. GWM will know which package is being used to simulate streamflow by the file types specified in the MODFLOW **NAME** file; if GWM detects that both STR and SFR have been made active in the **NAME** file, the code will stop and an error message will be printed to the GWM **OUT** file.

The input structure of the **STRMCON** file is the same regardless of which streamflow-routing package is being used. The input instructions are unchanged from the original report (Ahlfeld and others, 2005, p. 44-45) with the exception that the SEG and REACH integer variables now refer to the segment and reach numbers of the model cells in which the streamflow or streamflow-depletion constraints are located, as specified in *either* the STR *or* SFR Packages.

SUPPLY2 Sample Problem with STR and SFR Streamflow-Routing Packages

The SUPPLY Sample Problem described in the original GWM documentation (Ahlfeld and others, 2005, p. 82) describes a transient water-supply problem in which total groundwater withdrawals over a 3-year period are limited by the amount of streamflow depletion allowed in two streams that are in hydraulic connection with the simulated aquifer. Experience with the sample problem indicated that there could be numerical-stability issues associated with its solution that resulted from streamflow-depletion constraints that were nearly redundant from one year to the next. Because of these numerical-stability issues, the sample problem was revised, and is now referred to as the SUPPLY2 problem. The changes to formulation of the management problem are: (1) flow-rate decision variable *Q3* was dropped from the formulation, (2) water-supply demands in the second year were removed, and (3) streamflow-depletion constraints in the first two years were removed. These changes resulted in a reduction in the numbers of (1) candidate flow-rate decision variables from 8 to 7, (2) specified water-supply demand constraints (which are specified using the summation constraints option of GWM) from 24 to 16, and (3) streamflow-depletion constraints from 36 to 12. The revised problem was run with version 1.1 of MF2005-GWM first using the STR Package to simulate streamflow. The new solution obtained using GWM is nearly identical to the original SUPPLY problem, although decision variable *Q3* is no longer active in the solution. The value of the objective function at the optimal solution is $53,022 for both the original and revised problems.

The SUPPLY2 sample problem was further revised to demonstrate use of the SFR Streamflow-Routing Package in place of the STR Streamflow-Routing Package to simulate groundwater/surface-water interactions and streamflow routing. The only changes that were required to the input files for the sample problem were (1) the STR file type was replaced by the SFR file type in the MODFLOW **NAME** file and (2) an SFR input file was used in place of an STR input file. The SFR input file prepared for the sample problem is shown in figure 1 at the end of this document.

Although there are several differences in the structure of the input files between the STR and SFR Packages, for the most part, the type of information that is specified for both packages is the same. The two differences that affect the sample problem relate to the specification of stream-channel slope and streambed conductance. In the SFR file, stream-channel slope, which affects calculation of stream depth in each simulated stream reach, is not specified, as it is for the STR Package. Instead, stream-channel slope is calculated by SFR on the basis of streambed elevations and stream-channel lengths specified for each stream segment and reach, respectively. Also, streambed conductance is not specified directly in SFR, as it is for STR. Instead, the user must specify the hydraulic conductivity (*K*) and thickness (*M*) of the streambed in each stream segment, the width (*W*) of the stream channel for each stream segment, and the length (*L*) of the stream channel in each stream reach. SFR then calculates the streambed conductance for each stream reach on the basis of the relation $\frac{KLW}{M}$.

Because it was not possible to specify streambed elevations and stream-channel lengths in the SFR input file such that calculated stream-channel slopes were exactly equal to those specified in the STR input file, there were small differences in the computed values of streamflow, stream depth, and groundwater discharge to the simulated streams between the STR and SFR simulations. Nevertheless, the differences in the optimal solution to the management formulation using the STR and SFR Packages were small. The value of the objective function at the optimal solution is $53,022 using the STR Package and $53,028 using the SFR Package. All seven flow-rate decision variables and two of the four external decision variables are active in each of the STR and SFR solutions, and the optimal values calculated for each of the decision variables in the two solutions are virtually identical.

Both the STR and SFR Package input files for this sample problem are distributed with the MF2005-GWM software.

References

Ahlfeld, D.P., Barlow, P.M., and Mulligan, A.E., 2005, GWM--A groundwater management process for the U.S. Geological Survey modular groundwater model (MODFLOW-2000): U.S. Geological Survey Open-File Report 2005-1072, 124 p.

Niswonger, R.G., and Prudic, D.E., 2005, Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams—A modification to SFR1: U.S. Geological Survey Techniques and Methods 6-A13, 48 p.

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, groundwater flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.

Prudic, D.E., Konikow, L.F., and Banta, E.R., 2004, A new Streamflow-Routing (SFR1) Package to simulate stream-aquifer interaction with MODFLOW-2000: U.S. Geological Survey Open-File Report 2004-1042, 95 p.

Figure 1. Input file for SFR Streamflow-Routing Package for SUPPLY2 sample problem.

```
#SUPPLY2 Sample Problem using SFR                         Record 0
 40   3  0  0  128390.  0.0001   -1  81                   Record 1
    1   13    1    1    1          200.0                  Record 2
    1   13    2    1    2          200.0
    1   14    3    1    3          200.0
    1   15    4    1    4          200.0
    1   16    5    1    5          200.0
    1   16    6    1    6          200.0
    1   16    7    1    7          200.0
    1   16    8    1    8          200.0
    1   16    9    1    9          200.0
    1   16   10    1   10          200.0
    1   16   11    1   11          200.0
    1   16   12    1   12          200.0
    1   15   13    1   13          200.0
    1   14   14    1   14          200.0
    1   13   15    1   15          200.0
    1   12   16    1   16          200.0
    1   12   17    1   17          200.0
    1   12   18    1   18          200.0
    1   12   19    1   19          200.0
    1   13   20    1   20          200.0
    1   14   21    1   21          200.0
    1   14   22    1   22          200.0
    1    9   30    2    1          200.0
    1    9   29    2    2          200.0
    1    9   28    2    3          200.0
    1    9   27    2    4          200.0
    1   10   26    2    5          200.0
    1   11   25    2    6          200.0
    1   12   24    2    7          200.0
    1   13   23    2    8          200.0
    1   14   22    2    9          200.0
    1   14   22    3    1          200.0
    1   15   23    3    2          200.0
    1   15   24    3    3          200.0
    1   15   25    3    4          200.0
    1   15   26    3    5          200.0
    1   16   27    3    6          200.0
    1   17   28    3    7          200.0
    1   18   29    3    8          200.0
    1   18   30    3    9          200.0
    3    0    0                                           Record 5: St.Prd. 1
    1    1    3    0 100000.0  0.0  0.0  0.0  0.05        Record 6a: Seg. 1
       5.0       1.0     48.50      20.0      3.0         Record 6b
       5.0       1.0     38.00      20.0      3.0         Record 6c
    2    1    3    0  50000.0  0.0  0.0  0.0  0.05        Record 6a: Seg. 2
       5.0       1.0     40.25      20.0      3.0         Record 6b
       5.0       1.0     38.00      20.0      3.0         Record 6c
    3    1    0    0      0.0  0.0  0.0  0.0  0.05        Record 6a: Seg. 3
       5.0       1.0     38.00      20.0      3.0         Record 6b
       5.0       1.0     30.00      20.0      3.0         Record 6c
        -3         0         0                            Record 5: St.Prd. 2
       (Records for Stress Periods 3-11 deleted here.)
        -3         0         0                            Record 5: St.Prd.12
```