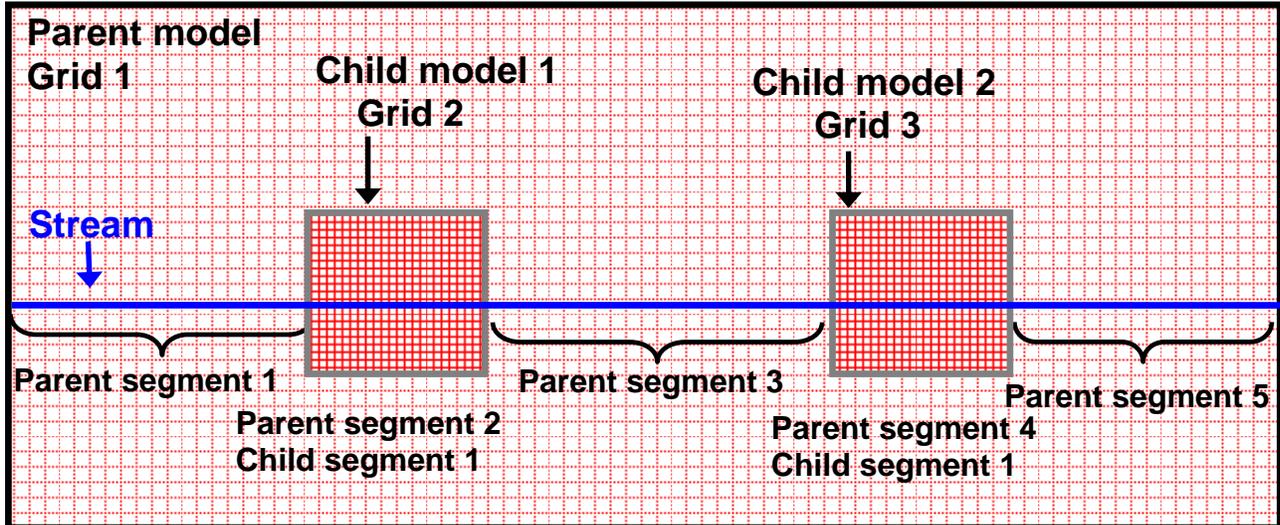


A Product of the Groundwater Resources Program

# MODFLOW–LGR—Modifications to the Streamflow-Routing Package (SFR2) to Route Streamflow through Locally Refined Grids

Chapter 34 of

Book 6, Modeling Techniques, Section A, Groundwater



Techniques and Methods 6-A34

**Cover:** Schematic of a stream intersected by two locally refined child grids embedded within a coarse parent grid with details indicating renumbering of stream segments represented by the child grids.

# **MODFLOW–LGR—Modifications to the Streamflow-Routing Package (SFR2) to Route Streamflow through Locally Refined Grids**

**By Steffen W. Mehl and Mary C. Hill**

A Product of the Groundwater Resources Program

**Techniques and Methods 6-A34**

**U.S. Department of the Interior  
U.S. Geological Survey**

**U.S. Department of the Interior**  
KEN SALAZAR, Secretary

**U.S. Geological Survey**  
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

Suggested citation:

Mehl, S.W., and Mary C. Hill, 2010, MODFLOW–LGR—Modifications to the Streamflow-Routing Package (SFR2) to Route Streamflow through Locally Refined Grids: U.S. Geological Survey Techniques and Methods 6-A34, 15 p.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government

Although this report is in the public domain, permission must be secured from the individual copyright owners to reproduce any copyrighted material contained within this report.

For more information about the USGS and its products:

Telephone: 1-888-ASK-USGS

World Wide Web: <http://www.usgs.gov/>

# Preface

This report describes modifications to the Streamflow-Routing Package (SFR2) of MODFLOW-2005 (Niswonger and Prudic, 2005) to allow streamflow to be routed through a locally refined grid using the Local Grid Refinement (LGR) capability (Mehl and Hill, 2005) of MODFLOW. The modifications allow streamflow to be routed across interfaces between parent and child grids. The current version is compatible with MODFLOW-2005 version 1.8 (Harbaugh, 2005) and MODFLOW-LGR version 1.2 (Mehl and Hill, 2007) with support for multiple areas.

The performance of the program has been tested in a variety of applications. Future applications, however, might reveal errors that were not detected in the test simulations. Users are requested to notify the U.S. Geological Survey of any errors found in this document or the computer program by using the e-mail address available at the Web address below. Updates might occasionally be made to both this document and to LGR and the SFR2 Package. Users can check for updates on the Internet at URL [http://water.usgs.gov/software/ground\\_water.html/](http://water.usgs.gov/software/ground_water.html/).

# CONTENTS

Preface.....	iii
Abstract.....	1
Introduction.....	1
Purpose and Scope.....	2
Acknowledgments.....	2
Approach for Modifying SFR for Compatibility with LGR.....	3
Coupling Implementation.....	3
Compatibility Issues.....	4
Streamflow-Routing Examples.....	5
Example 1 – Transient Simulation of a Two-Dimensional, Heterogeneous Confined Aquifer with Two Areas of Pumping.....	5
Streamflow Comparisons.....	6
Example 2 – Steady-State Simulation of a Three-Dimensional, Homogeneous, Unconfined Aquifer.....	8
Modified Input Instructions for SFR2 Package.....	9
Changes to Stream Numbering – Item 2.....	10
Changes to Allow Routing Between Grids – Items 1 and 4b and(or) 6a.....	10
Sample Output for Example 2.....	12
References Cited.....	14
Appendix 1. Changes to gwf2sfr7.f.....	15
Additional Variables in Fortran Module GWFSFRMODULE.....	15
Additional Variables in Argument List for GWF2SFR7FM and GWF2SFR7BD.....	15
Additional Local Variables in GWF2SFR7FM and GWF2SFR7BD.....	15
Additional Local Variables in SGWF2SFR7RDSEG.....	15

## Figures

1. Schematic of a parent grid with two child areas of local grid refinement and a stream intersecting all three grids.....	4
2. Heterogeneity structure, stream location, and areas of local refinement around the simulated wells.....	5
3. Simulated steady-state hydraulic-head contours for the system shown in figure 2.....	6
4. Simulated streamflows at four times using a coarse grid, local grid refinement (LGR) with a single area of refinement, LGR with two areas of refinement, and a globally refined grid.....	7
5. Plan view of a three-dimensional aquifer system including streamflow routing between parent and child grids.....	8
6. Simulated streamflow in relation to distance along the stream using the coarse grid, local grid refinement (LGR), and a globally refined grid.....	9
7. Annotated example of the parent SFR2 input file for the example shown in figure 1 and figure 2.....	11
8. Annotated example of the second child SFR2 input file for the example shown in figure 1 and figure 2.....	12

## Tables

1. Comparison of minimum simulated streamflow and computer processing time for four grids, for the results shown in figure 4. ....	7
2. Additional variables in Fortran module GWFSFRMODULE. ....	15
3. Additional argument-list variables in Fortran subroutines GWF2SFR7FM and GWF2SFR7BD. ....	15
4. Additional local variables in Fortran subroutines GWF2SFR7FM and GWF2SFR7BD. ....	15
5. Additional local variables in Fortran subroutine SGWF2SFR7RDSEG. ....	15

## Conversion Factors

	<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
meter (m)		3.281	foot
meter per second (m/s)		3.281	foot per second
square meter per second (m <sup>2</sup> /s)		10.76	square foot per second
cubic meter per second (m <sup>3</sup> /s)		35.31	cubic foot per second

## Acronyms

LGR Local Grid Refinement  
BFH Boundary Flow and Head  
SFR2 Streamflow-Routing

# **MODFLOW–LGR—Modifications to the Streamflow-Routing Package (SFR2) to Route Streamflow through Locally Refined Grids**

**By Steffen W. Mehl and Mary C. Hill**

## **Abstract**

This report documents modifications to the Streamflow-Routing Package (SFR2) to route streamflow through grids constructed using the multiple-refined-areas capability of shared node Local Grid Refinement (LGR) of MODFLOW-2005. MODFLOW-2005 is the U.S. Geological Survey modular, three-dimensional, finite-difference groundwater-flow model. LGR provides the capability to simulate groundwater flow by using one or more block-shaped, higher resolution local grids (child model) within a coarser grid (parent model). LGR accomplishes this by iteratively coupling separate MODFLOW-2005 models such that heads and fluxes are balanced across the shared interfacing boundaries. Compatibility with SFR2 allows for streamflow routing across grids. LGR can be used in two- and three-dimensional, steady-state and transient simulations and for simulations of confined and unconfined groundwater systems.

## **Introduction**

Hydrologic simulations that include substantial surface-water and groundwater interactions often need highly refined grids in local areas of interest to improve simulation accuracy. In particular, refined grids may be needed to represent hydraulic gradients that change substantially over short distances, as can occur near streams. Furthermore, the hydraulic-response times of surface-water phenomena commonly differ from those of the corresponding groundwater system, which can affect the dynamics of their interaction. Addressing the scale issues of these interactions requires the ability to incorporate local-scale phenomena within a regional-scale framework while accurately accounting for the differing physics and time scales of the surface-water and groundwater systems. This report focuses on one aspect of this challenge; namely, stream/aquifer interactions. Both the Streamflow-Routing (SFR2) Package (Niswonger and Prudic, 2005) and Local Grid Refinement (LGR) capability of MODFLOW–LGR (Mehl and Hill, 2005, 2007) obey mass conservation and therefore account for the volume of stream gain/loss in a physically consistent way. LGR accomplishes this by iteratively coupling separate MODFLOW-2005 models such that heads and fluxes are balanced across the shared interfacing boundaries. By modifying SFR2 to allow streams to be represented on a locally refined grid using LGR, better simulation of the dynamics between stream/aquifer systems is possible.

## **Purpose and Scope**

The purpose of this report is to document modifications to SFR2 (Niswonger and Prudic, 2005) to be compatible with the local grid refinement capability of MODFLOW–LGR (Mehl and Hill, 2005). These modifications allow users of MODFLOW-2005 (Harbaugh, 2005) to simulate streamflow routing through multiple areas of grid refinement. This report first discusses the coupling strategy followed by the compatibility issues of the method. Two example applications are presented to demonstrate the performance of the method for two-dimensional confined-aquifer and three-dimensional unconfined-aquifer situations. Input instructions and important information to programmers are presented in the Appendix.

## **Acknowledgments**

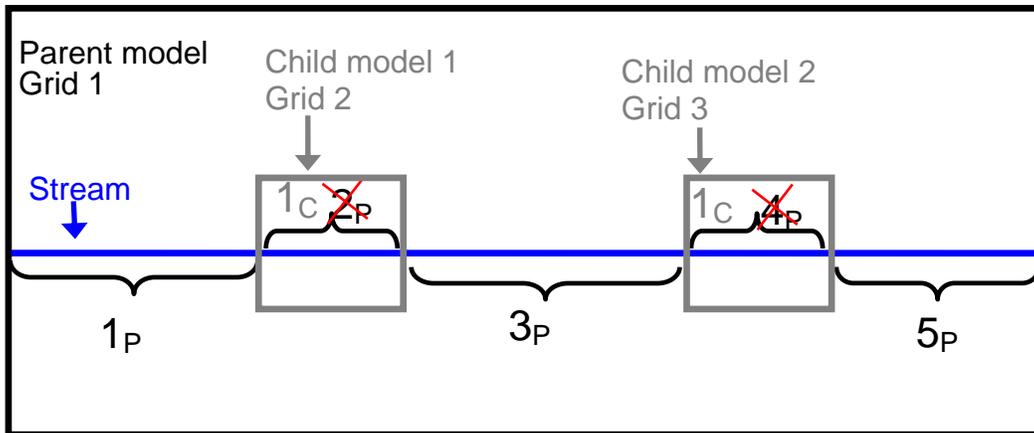
Compatibility of SFR2 and LGR was developed with support from the U.S. Geological Survey (USGS) Office of Groundwater and the USGS Groundwater Resources Program. Arlen Harbaugh (USGS) suggested the use of auxiliary variables for connecting streamflow across grids. Richard Niswonger and David Prudic (USGS) provided valuable suggestions for model testing and assistance with SFR2 programming. Christopher Hoard (USGS) provided useful beta testing of the code, and Paul Barlow (USGS) provided several suggestions to help clarify the documentation.

## **Approach for Modifying SFR for Compatibility with LGR**

The version of MODFLOW–LGR (Mehl and Hill, 2007) used here can simulate multiple areas of grid refinement, as shown in figure 1. Therefore, the method of linking streamflow between grids must accommodate multiple grids and multiple inflows and outflows from grids. Coupling SFR2 with MODFLOW-LGR requires that stream segments are properly connected between regional and locally refined grids such that flow can be routed consistently through the stream network. This is established by requiring two additional inputs to the SFR2 Package input files for each grid. These additional inputs define the corresponding grid number and segment number from which inflow into the segment is obtained. By defining a new stream segment at each stream crossing of the parent/child grid interface, outflows from a segment are used as inflows to the corresponding segment of the adjacent grid. The following sections describe the approach used to link streamflows across grids.

### **Coupling Implementation**

The input files for SFR2 require modifications for use with LGR. The modifications are implemented through auxiliary variables. Auxiliary variables are user-specified optional variables that are supported in many MODFLOW Packages and typically used for postprocessing. Their implementation here differs from other Packages in that the variables are used by the Ground Water Flow Process (Harbaugh, 2005) rather than a postprocessor. Two auxiliary variables, “LGRGRID” and “LGRSEG”, which, when specified at the end of Item 1 of the SFR2 input file, indicate these additional variables will be read at the end of Item(s) 4b and(or) 6a after all variables needed for a particular segment have been listed. LGRGRID and LGRSEG are the corresponding grid and segment numbers from which inflow is obtained. If the segment in the parent grid is represented by the child grid, a negative value is used for LGRGRID in the parent-grid SFR2 input file. In this case, the value specified for LGRSEG in the parent-grid SFR2 file is not used and can be any value. If no inflow is obtained from a different grid, values of 0 are used for both LGRGRID and LGRSEG. New stream segments need to be defined in the parent grid for stream segments that will be covered by a child grid. This will often require renumbering of the stream segments in a stream network as shown in figure 1. An annotated example of the required changes to the SFR2 input file is provided in the section “Modified Input Instructions for SFR2 Package.”



**Figure 1.** Schematic of a parent grid with two child areas of local grid refinement and a stream intersecting all three grids. Stream segment numbers for the parent and child grids are indicated with a subscript of “P” and “C”, respectively. A new segment begins at the interface between parent and child grids. The red X’s indicate that this stream segment is not represented in the parent grid and will be represented by the corresponding segment in the child grid.

## Compatibility Issues

The modifications are in general compatible with both SFR2 and LGR, including options for unsaturated-zone flow beneath streams and transient routing. The exceptions and other compatibility issues are listed below.

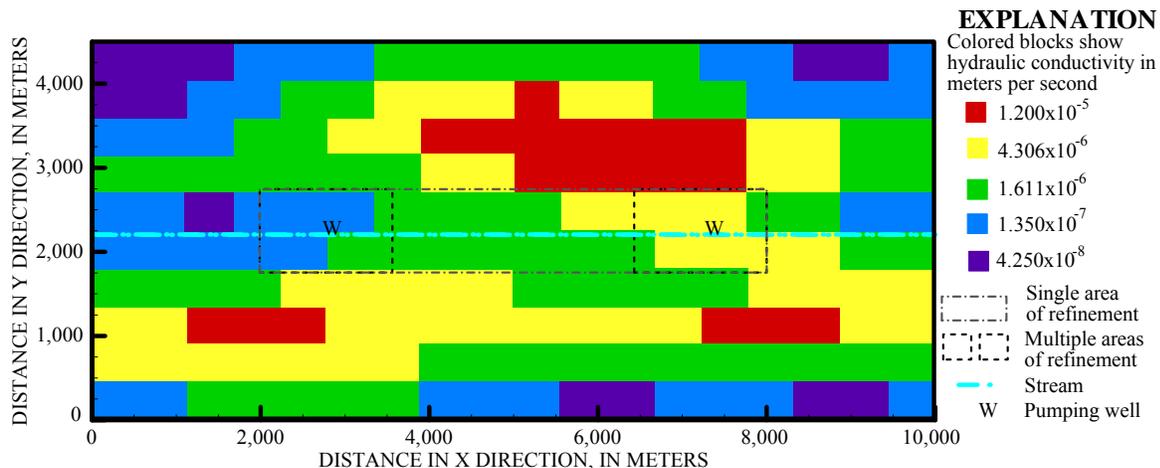
- (1) No streambed flows at specified-head boundaries along parent-child interfaces. As currently implemented, SFR2 does not calculate flows between stream segments and adjoining aquifers for constant-head cells. For the shared-node method of LGR in which the child models use specified-head boundary conditions, there is no gain or loss of streamflow at these interface cells.
- (2) Streamflow not routed across grids when using BFH. The BFH (Boundary Flow and Head) Package (Mehl and Hill, 2005) is not fully compatible with SFR2. If using the BFH Package to simulate the parent or child model separately, streamflow that crosses between grids will not be routed correctly. Future modifications to BFH could address this issue by storing the streamflow at the interface between grids.
- (3) Inflow from or outflow to lakes cannot cross grids. SFR2 allows stream inflows and outflows to be connected to lakes represented by the LAK Package (Merrit and Konikow, 2000). Currently (2010), stream segments with connections to lakes must be on the same grid as the lake. For example, a stream segment in the child grid cannot derive inflow from a lake represented only in the parent grid.
- (4) SFR2 input files require modification. Previously constructed SFR2 input files cannot not be used directly. For the parent grid, the stream network needs to be divided into new segments where the stream crosses the interface to a child grid. This requires renumbering the stream segments and corresponding reaches. In both the parent and child SFR2 input files, the auxiliary variables need to be added.

## Streamflow-Routing Examples

Two examples are used to demonstrate streamflow routing across multiple grids. The first example is a transient simulation of a two-dimensional (single layer), heterogeneous, confined aquifer and illustrates the multiple-refined-areas capability with streamflow routed through two child grids. This example also is simulated with a single area of refinement that covers a larger portion of the stream length to illustrate tradeoffs in accuracy and computer processing (CPU) time when selecting an area of refinement near a stream. The second example is a steady-state simulation of a three-dimensional, homogeneous, unconfined aquifer and illustrates a more typical stream/aquifer modeling condition.

### Example 1 – Transient Simulation of a Two-Dimensional, Heterogeneous Confined Aquifer with Two Areas of Pumping

This example is a modification of “example 1” described by Mehl and Hill (2005, p. 30) and is shown in this report in Figure 2. The parent model grid cells are 92.5 m by 90 m, which produces a grid that has 50 rows and 108 columns. The grid cells for both child models are 10.28 m by 10 m, producing a 9:1 refinement ratio. The hydraulic conductivity values are shown in figure 2 for the five different zones of heterogeneity. The pumping rate of each well is 0.85 m<sup>3</sup>/s. A straight stream runs through the center of the model from left to right with a specified inflow of 5.0 m<sup>3</sup>/s at the left boundary. A streambed hydraulic conductivity of 0.2 m/s and Manning’s *n* of 0.040 are used for all segments. Constant-head boundaries of 12 m and 8 m are used along the left and right sides, respectively; all other boundaries are no flow. The system is simulated with an initial steady-state stress period with no pumping followed by a transient stress period with pumping. The steady-state solution with pumping is shown in Figure 3. The stream is losing for approximately the first 6,000 m and gaining thereafter.



**Figure 2.** Heterogeneity structure, stream location, and areas of local refinement (indicated by dashed rectangles) around the simulated wells.

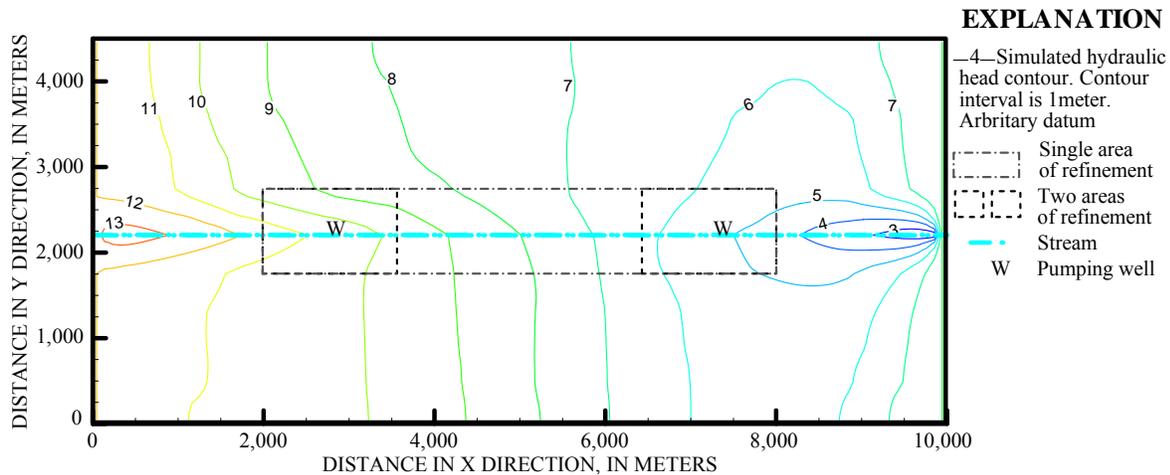


Figure 3. Simulated steady-state hydraulic-head contours for the system shown in Figure 2.

### Streamflow Comparisons

Comparisons are made using a globally refined grid model (same discretization as the child models but extending over the entire domain) as the reference solution. This solution is compared to two LGR solutions and the solution obtained using a coarse discretization of the parent grid only (no refinement). Calculated streamflow is the metric used for comparison; results for the four simulations are shown in Table 1 and Figure 4 at four different times.

Table 1 and Figure 4 show that streamflow calculated for the locally refined grids better matches that calculated for the globally refined grid than that calculated for the coarse grid, particularly at early time when the pumping transients are substantial. At later time, the system nears steady state and there is little difference among the four models.

The solution using the coarse grid throughout the model has difficulty representing the correct streamflow at early time for all segments downstream from the first pumping well (Figure 4). For simulations with two locally refined grids, the refinement leads to some improvement in the region of no refinement between the two grids (approximately between 4,000 m and 6,000 m in Figure 4), but this improvement rapidly diminishes upon crossing the interface to the coarse grid. This can be seen in Figure 4 at time step 5 where the LGR solution with two grids initially follows the globally refined grid solution, but after crossing into the parent grid, it begins to deviate at 4,000 m. A similar phenomenon occurs at time step 15 near 9,000 m.

These results support the idea that the best refinement strategy when modeling stream/aquifer interactions is a refinement structure that follows the stream for as many reaches as possible, particularly those downstream from reaches where substantial gains/losses occur. This approach was tested by using a single refinement that spans the same area as the two locally refined grids and the area in between the grids (in total, the area between 2,000 m and 8,000 m). These results are shown in Figure 4 and Table 1 and have the best agreement with the globally refined grid for all time steps. However, this additional refined area results in an increase in computer processing time, as shown in Table 1. Clearly, there is a tradeoff between the amount of refined area, accuracy, and computer processing time.

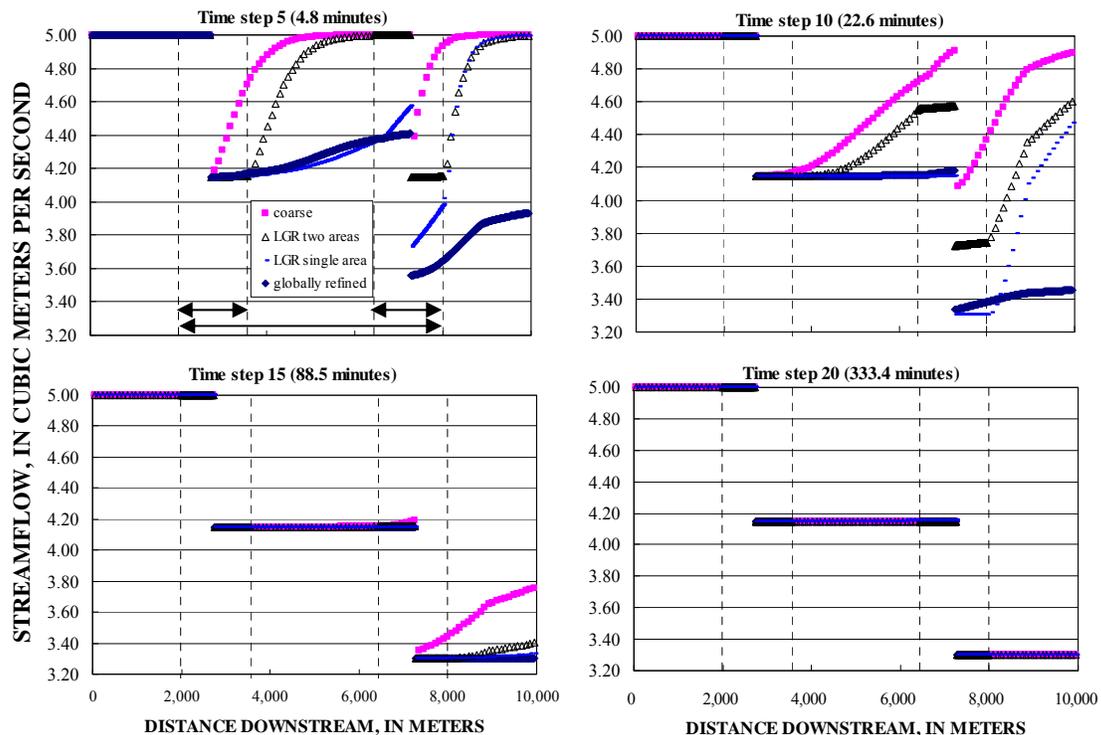
The superposition-based error analysis presented in Appendix 3 of Mehl and Hill (2005) describes how errors in hydraulic head at the interface between grids are diffused through the child grid according to the governing groundwater flow equation. With SFR2, errors in the coupling between grids can propagate into streams and be routed through the grid by way of the

stream network. Therefore, there is a tendency for errors in the coupling between grids to be carried in the downstream direction rather than being diffused in all directions through the grid as is the case when only groundwater flow is simulated.

**Table 1.** Comparison of minimum simulated streamflow and computer processing time for four grids, for the results shown in Figure 4.

[ Computer processing times using a Linux workstation, Opeteron 246 – 2.0 gigahertz]

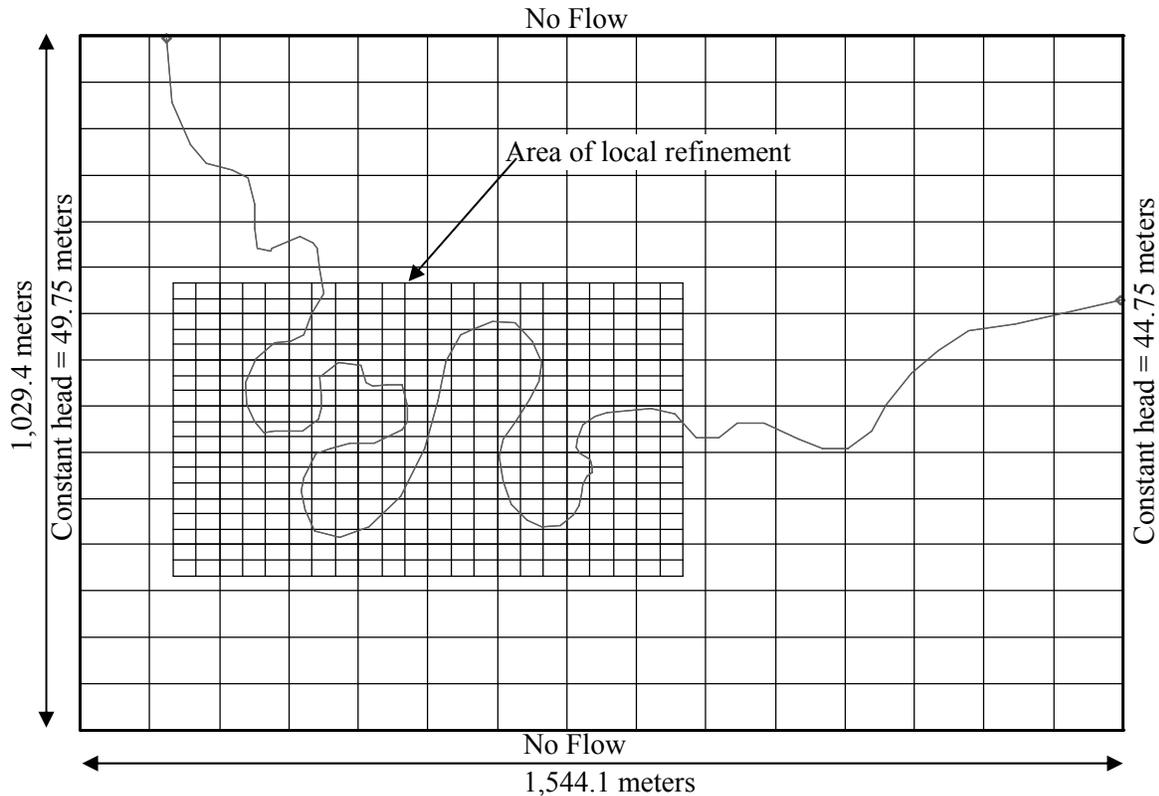
Grid	Minimum streamflow at time step 5 (cubic meters per second)	Minimum streamflow at time step 10 (cubic meters per second)	Minimum streamflow at time step 15 (cubic meters per second)	Minimum streamflow at time step 20 (cubic meters per second)	Computer processing time (seconds)
Coarse (no refinement)	4.18	4.08	3.35	3.30	3.94
Locally refined with two areas of refinement	4.15	3.72	3.30	3.30	87
Locally refined with a single area of refinement	3.73	3.30	3.30	3.30	102
Globally refined	3.56	3.33	3.30	3.30	158



**Figure 4.** Simulated streamflows at four times using a coarse grid, Local grid refinement (LGR) with two areas of refinement, LGR with a single area of refinement, and a globally refined grid. The extent of the refined areas are shown using arrows in the graph for time step 5; the pumping wells are located at the center of the two refined areas.

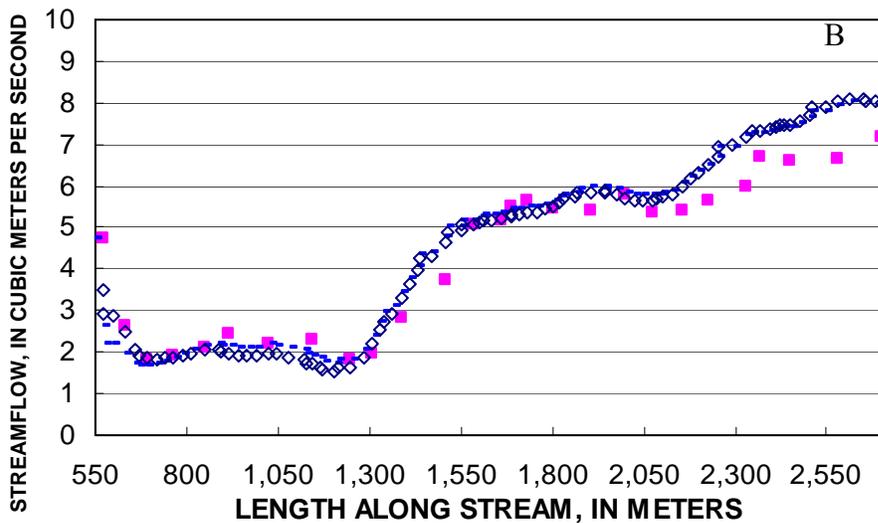
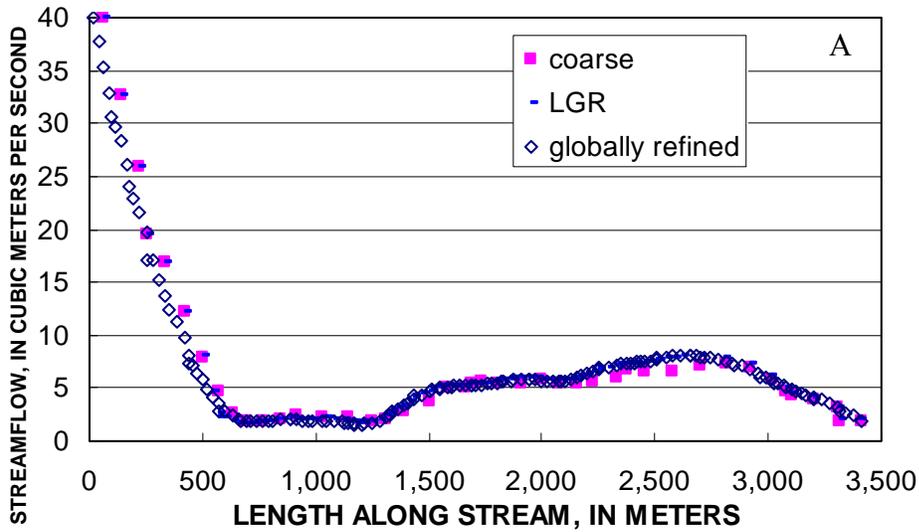
## Example 2 – Steady-State Simulation of a Three-Dimensional, Homogeneous, Unconfined Aquifer

This example is a modification of “example 3” described by Mehl and Hill (2005, p. 42) and is shown in this report in Figure 5. The aquifer is unconfined and homogeneous with a hydraulic conductivity of 1.0 m/s. A streambed hydraulic conductivity of 0.01 m/s, a streambed thickness of 1.5 m, and Manning’s  $n$  of 0.040 are used for all segments. A streamflow of 40 m<sup>3</sup>/s is specified as the inflow condition. Constant-head boundaries span the left and right sides; all other boundaries are no flow.



**Figure 5.** Plan view of a three-dimensional aquifer system including streamflow routing between parent and child grids. A 15×15 horizontal grid discretization is shown for the parent grid, and the locally refined grid (19×22) spacing is equivalent to a 45×45 discretization over the whole domain.

Unlike the previous example, there is no pumping, but the meandering of the stream produces substantial stream/aquifer interaction, causing changes in streamflow. The streamflow in each reach is compared using a coarse grid (grid spacing equivalent to the parent), a locally refined grid using LGR, and a globally refined grid (same grid spacing as the child model, but extending over the entire domain). The globally refined grid is the basis for comparison. The results are shown in Figure 6 and indicate that in the area of local grid refinement, the streamflow simulated by LGR more closely matches the globally refined grid. As with the previous example, in areas that are not refined, the results are not as accurate. This corroborates the previous refinement strategy of extending over as much of the stream as possible if accurate simulation of stream/aquifer interaction is important.



**Figure 6.** Simulated streamflow in relation to distance along the stream using the coarse grid, local grid refinement (LGR), and a globally refined grid. Results are shown for (A) the entire stream length and (B) only the locally refined area.

## Modified Input Instructions for SFR2 Package

This section contains an annotated example of SFR2 input-file modifications needed for compatibility with LGR. If the stream does not cross into another grid, no modifications are necessary and the standard SFR2 input file can be used. The changes indicated in this section are for situations where LGR is used and a stream crosses into another grid.

## Changes to Stream Numbering – Item 2

Figure 1 shows a simple stream network that could be represented by a single stream segment in the parent grid. For compatibility with LGR, a new stream segment is started at locations where the stream crosses a grid interface cell. In this example, a second stream segment ( $2_p$ ) is started when crossing into the first child grid. A third segment ( $3_p$ ) is started when exiting the first child grid. A fourth stream segment ( $4_p$ ) is started when crossing into the second child grid. A fifth segment ( $5_p$ ) is started when exiting the second child grid. In this example, stream segments within the child model boundaries and represented in the child grid are numbered starting with 1, but this is not required. That is, if the child model has a different stream originating inside of the child area, it could be numbered first and the stream originating from the parent grid could be numbered subsequently. Furthermore, the child model can use multiple segments to represent the same length of stream that was perhaps represented as a single segment in the parent grid. This might be useful in situations where, for example, multiple stream segments and reaches could be used in the child grid to take advantage of the higher grid resolution to better represent topography of the streambed.

## Changes to Allow Routing Between Grids – Items 1 and 4b and(or) 6a

The cells of the parent model that are within the child model are deactivated after the first LGR iteration and therefore cannot route streamflow, as indicated by the red crosses in Figure 1. The routing of streamflow through these deactivated segments is represented by the child model. This requires the ability to pass inflows and outflows between segments of parent and child models. For example, in Figure 1, outflow from segment 1 of the parent model ( $1_p$ ) is used as an inflow to segment 1 of child model 1 ( $1_c$ ). Outflow from segment 1 of child model 1 ( $1_c$ ) is used as inflow to segment 3 of the parent model ( $3_p$ ). The routing between grids is controlled using two new auxiliary variables in item 1 of the SFR input file: LGRGRID and LGRSEG. In item 4b and(or) 6a, these variables function similarly to input variable IUPSEG in the SFR2 Package, which is used to indicate the upstream segment from which flow is supplied from a diversion. LGRGRID and LGRSEG indicate the grid and segment number, respectively, whose outflow will be used as an inflow for the current segment. Segments of the parent grid that are represented by the child grid are inactive after the first LGR iteration, which is indicated by setting LGRGRID to a negative value in the parent-grid SFR2 input file. In this case, the value specified for LGRSEG in the parent-grid SFR2 input file is not used and can be set to any value. Zeros are used for any active segments that do not receive inflow from another grid.

Figure 7 is an annotated example of the parent grid SFR2 input file for the example shown in Figure 1 and Figure 2. The stream segments (fourth column in item 2) are renumbered when crossing into or out of a new grid. The auxiliary variables LGRGRID and LGRSEG are used to indicate the grid and segment numbers for obtaining inflow to the current grid and are boxed. Parameters are not used in this model, so only item 6a is modified. If parameters were used, then similar modifications would be needed for item 4b.

The child grid SFR2 files require similar modifications for the auxiliary variables LGRGRID and LGRSEG but do not require renumbering of the stream segments. Figure 8 is an annotated example of the SFR2 input file for the second child grid.

Item 1	108	5	0	0	1.	1.E-6	0	19	AUX LGRGRID AUX LGRSEG	
Item 2	1	26	1	1	1	1	9.25			
Item 2	1	26	2	1	2	2	9.25			
...	...	...	...	...	...	...	...			
Item 2	1	26	22	1	22	22	9.25			} Start a new segment when crossing into another grid
Item 2	1	26	23	2	1	1	9.25			
Item 2	1	26	24	2	2	2	9.25			
...	...	...	...	...	...	...	...			
Item 2	1	26	38	2	16	16	9.25			} Start a new segment when crossing into another grid
Item 2	1	26	39	3	1	1	9.25			
Item 2	1	26	40	3	2	2	9.25			
...	...	...	...	...	...	...	...			
Item 2	1	26	70	3	32	32	9.25			} Start a new segment when crossing into another grid
Item 2	1	26	71	4	1	1	9.25			
Item 2	1	26	72	4	2	2	9.25			
...	...	...	...	...	...	...	...			
Item 2	1	26	86	4	16	16	9.25			} Start a new segment when crossing into another grid
Item 2	1	26	87	5	1	1	9.25			
Item 2	1	26	88	5	2	2	9.25			
...	...	...	...	...	...	...	...			
Item 2	1	26	108	5	22	22	9.25			
Item 3	5	1	0							
Item 6a	1	1	2	0	5.0	0.	0.	0.	0.04	<input type="text" value="0"/> <input type="text" value="0"/> ← No inflow to segment 1 from other grids
Item 6b	0.2	1.5	14.	20.	1.2					
Item 6c	0.2	1.5	11.6449	20.	1.2					
Item 6a	2	1	3	0	0.	0.	0.	0.	0.04	<input type="text" value="-1"/> <input type="text" value="0"/> ← Segment 2 is represented by the child grid
Item 6b	0.2	1.5	11.5327	20.	1.2					
Item 6c	0.2	1.5	9.85047	20.	1.2					
Item 6a	3	1	4	0	0.	0.	0.	0.	0.04	<input type="text" value="2"/> <input type="text" value="1"/> ← Inflow to segment 3 from grid 2, segment 1
Item 6b	0.2	1.5	9.73832	20.	1.2					
Item 6c	0.2	1.5	6.26168	20.	1.2					
Item 6a	4	1	5	0	0.	0.	0.	0.	0.04	<input type="text" value="-1"/> <input type="text" value="0"/> ← Segment 4 is represented by the child grid
Item 6b	0.2	1.5	6.14953	20.	1.2					
Item 6c	0.2	1.5	4.46729	20.	1.2					
Item 6a	5	1	0	0	0.	0.	0.	0.	0.04	<input type="text" value="3"/> <input type="text" value="1"/> ← Inflow to segment 5 from grid 3, segment 1
Item 6b	0.2	1.5	4.35514	20.	1.2					
Item 6c	0.2	1.5	2.	20.	1.2					
Item 6a	-5	1	0							

**Figure 7.** Annotated example of the parent SFR2 input file for the example shown in Figure 1 and Figure 2. Boxed values are modification needed for auxiliary variables LGRGRID and LGRSEG. The remaining modifications are related to renumbering the stream segments (fourth column of item 2) when crossing into a new grid.

Item 1	154	1	0	0	1.	1.E-6	0	39	AUX LGRGRID	AUX LGRSEG
Item 2	1		55	1	1		1		1.027778	
Item 2	1		55	2	1		2		1.027778	
:	:		:							
Item 2	1		55	154	1		154		1.027778	
Item 3	1	1	0							
Item 6a	1	1	0	0	0.00	0.	0.	0.	0.04	1 3 ← Inflow to segment 1 from grid 1, segment 3
Item 6b	0.2	1.5	6.26168	20.	1.2					
Item 6c	0.2	1.5	4.35514	20.	1.2					
Item 6a	-1	1	0							

**Figure 8.** Annotated example of the second child SFR2 input file for the example shown in Figure 1 and Figure 2. Boxed values are modifications needed for auxiliary variables LGRGRID and LGRSEG. No renumbering of stream segments is required for the child grid.

## Sample Output for Example 2

The parent grid output from SFR2 when running with local grid refinement differs from simulations with no refinement because the segments that are represented by the child grid are made inactive in the parent. In the reaches that comprise these segments there is no exchange flow between the stream and aquifer. Flow out of these segments is used as inflow to the segments of the child grid that represent these adjoining segments. Likewise, flow out of child segments is used as inflow to adjoining segments of the parent grid.

The volumetric budget printed at the end of the listing file includes the stream leakage only for the active segments in each grid. That is, the stream leakage within the child grid is not accumulated and applied to the parent's stream leakage budget. Volumetric budget output for the parent and child grids for Example 2 (Figure 5) is shown below:

Parent model output:

•••

```

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 1
-----

```

CUMULATIVE VOLUMES	L**3	RATES FOR THIS TIME STEP	L**3/T
-----		-----	
IN:		IN:	
----		----	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	147.8467	CONSTANT HEAD =	147.8467
STREAM LEAKAGE =	43.3488	STREAM LEAKAGE =	43.3488
PARENT FLUX B.C. =	44.5197	PARENT FLUX B.C. =	44.5197
TOTAL IN =	235.7152	TOTAL IN =	235.7152
OUT:		OUT:	
----		----	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	185.8729	CONSTANT HEAD =	185.8729
STREAM LEAKAGE =	0.0000	STREAM LEAKAGE =	0.0000
PARENT FLUX B.C. =	49.8530	PARENT FLUX B.C. =	49.8530
TOTAL OUT =	235.7259	TOTAL OUT =	235.7259
IN - OUT =	-1.0712E-02	IN - OUT =	-1.0712E-02
PERCENT DISCREPANCY =	-0.00	PERCENT DISCREPANCY =	-0.00

Child model output:

•••

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 1

CUMULATIVE VOLUMES	L**3	RATES FOR THIS TIME STEP	L**3/T
IN:		IN:	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	97.4155	CONSTANT HEAD =	97.4155
STREAM LEAKAGE =	1.7531	STREAM LEAKAGE =	1.7531
TOTAL IN =	99.1686	TOTAL IN =	99.1686
OUT:		OUT:	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	92.0600	CONSTANT HEAD =	92.0600
STREAM LEAKAGE =	7.1086	STREAM LEAKAGE =	7.1086
TOTAL OUT =	99.1686	TOTAL OUT =	99.1686
IN - OUT =	-1.5259E-05	IN - OUT =	-1.5259E-05
PERCENT DISCREPANCY =	-0.00	PERCENT DISCREPANCY =	-0.00

•••

FLUX ACROSS PARENT-CHILD INTERFACE AT TIME STEP 1 IN STRESS PERIOD 1

CUMULATIVE VOLUMES	L**3	RATES FOR THIS TIME STEP	L**3/T
TOTAL IN TO CHILD =	49.8530	TOTAL IN TO CHILD =	49.8530
TOTAL OUT TO PARENT =	44.5197	TOTAL OUT TO PARENT =	44.5197

Examination of the volumetric budget of the child model shows that the difference in stream leakage ( $7.1086 \text{ m}^3/\text{s} - 1.7531 \text{ m}^3/\text{s} = 5.3555 \text{ m}^3/\text{s}$ ) is equal to the reduced flow to the constant head boundary ( $97.4155 \text{ m}^3/\text{s} - 92.0600 \text{ m}^3/\text{s} = 5.3555 \text{ m}^3/\text{s}$ ). Comparing this value to the difference in flux across the parent/child interface ( $49.8530 \text{ m}^3/\text{s} - 44.5197 \text{ m}^3/\text{s} = 5.3333 \text{ m}^3/\text{s}$ ) shows a 0.42-percent difference. Decreasing the closure criteria of the LGR iterations will reduce this discrepancy.

## References Cited

- Harbaugh, A.W., 2005, MODFLOW-2005, The U.S. Geological Survey modular ground-water model—the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6–A16, 9 chapters.
- Mehl, S.W., and Hill, M.C., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model—Documentation of shared node local grid refinement (LGR) and the boundary flow and head (BFH) package: U.S. Geological Survey Techniques and Methods 6–A12, 68 p.
- Mehl, S.W., and Hill, M.C., 2007, MODFLOW-2005, the U.S. Geological Survey modular ground-water model—Documentation of multiple-refined area capability of local grid refinement (LGR) and the boundary flow and head (BFH) package: U.S. Geological Survey Techniques and Methods 6–A21, 13 p.
- Merrit, M.L., and Konikow, L.F., 2000, Documentation of a computer program to simulate lake-aquifer interaction using the MODFLOW ground-water model and the MOC3D solute-transport model: U.S. Geological Survey Water-Resources Investigations Report 2000–4167, 146 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 Techniques and Methods 6–A13, 47 p.

## Appendix 1. Changes to gwf2sfr7.f

The changes to the SFR2 Fortran source code are described here.

### Additional Variables in Fortran Module GWFSFRMODULE

There are two new variables in GWFSFRMODULE. They are listed in Table 2.

**Table 2. Additional variables in Fortran module GWFSFRMODULE.**

Variable name	Size	Description
NSFRAUX	Scalar	Number of auxiliary variables.
SFRAUX	C*16,20	The names of the auxiliary variables.

### Additional Variables in Argument List for GWF2SFR7FM and GWF2SFR7BD

There are three new variables in the argument list of GWF2SFR7FM and GWF2SFR7BD. They are listed in Table 3.

**Table 3. Additional argument-list variables in Fortran subroutines GWF2SFR7FM and GWF2SFR7BD.**

Variable name	Size	Description
llgr	Scalar	Flag indicating if LGR is active ( $\neq 0$ ) or inactive ( $=0$ ).
Lgriter	Scalar	Current number of LGR iterations.
Ngrids	Scalar	Number of grids

### Additional Local Variables in GWF2SFR7FM and GWF2SFR7BD

There are four new local variables in GWF2SFR7FM and GWF2SFR7BD. They are listed in Table 4.

**Table 4. Additional local variables in Fortran subroutines GWF2SFR7FM and GWF2SFR7BD.**

Variable name	Size	Description
lgrgrid	Scalar	Grid number from which the current segment receives inflow. Values less than 0 indicate segment is inactive and is represented in a child grid.
lgrseg	Scalar	Segment number from which the current segment receives inflow.
lgrgridprv	Scalar	Grid number of the previous segment.
lint	Scalar	Flag indicating if a cell is interior to a child grid ( $=1$ ) or not ( $=0$ )

### Additional Local Variables in SGWF2SFR7RDSEG

There are two new local variables in SGWF2SFR7RDSEG. They are listed in Table 5.

**Table 6. Additional local variables in Fortran subroutine SGWF2SFR7RDSEG.**

Variable name	Size	Description
jfst	Scalar	Starting value of loop index. The number of segment variables plus one.
jlst	Scalar	Ending value of loop index. The number of the auxiliary variables plus jfst.