Local Grid Refinement

Introduction

Simulations of groundwater flow and transport often need highly refined grids in local areas of interest in order to improve simulation accuracy. For example, refined grids may be needed in:

- regions where hydraulic gradients change substantially over short distances, as would be common near pumping or injecting wells, rivers, drains, and focused recharge;
- regions of site-scale contamination within a regional aquifer where simulations of plume movement are of interest; and,
- regions requiring detailed representation of heterogeneity, as may be required to simulate faults, lithologic displacements caused by faulting, fractures, thin lenses, pinch outs of geologic units, and so on.

Refinement of the finite-difference grid used by MODFLOW can be achieved using several methods; the advantages and disadvantages of each are explained below.

Globally Refined Grid

In this case, the grid is refined over the entire domain.

Advantages:

- Easy to build the grid
- Can yield reliable results
- No limitations for contaminant transport or particle tracking simulations

Disadvantages:

- Creates a needless amount of grid cells outside the area of interest, resulting in longer simulation times.

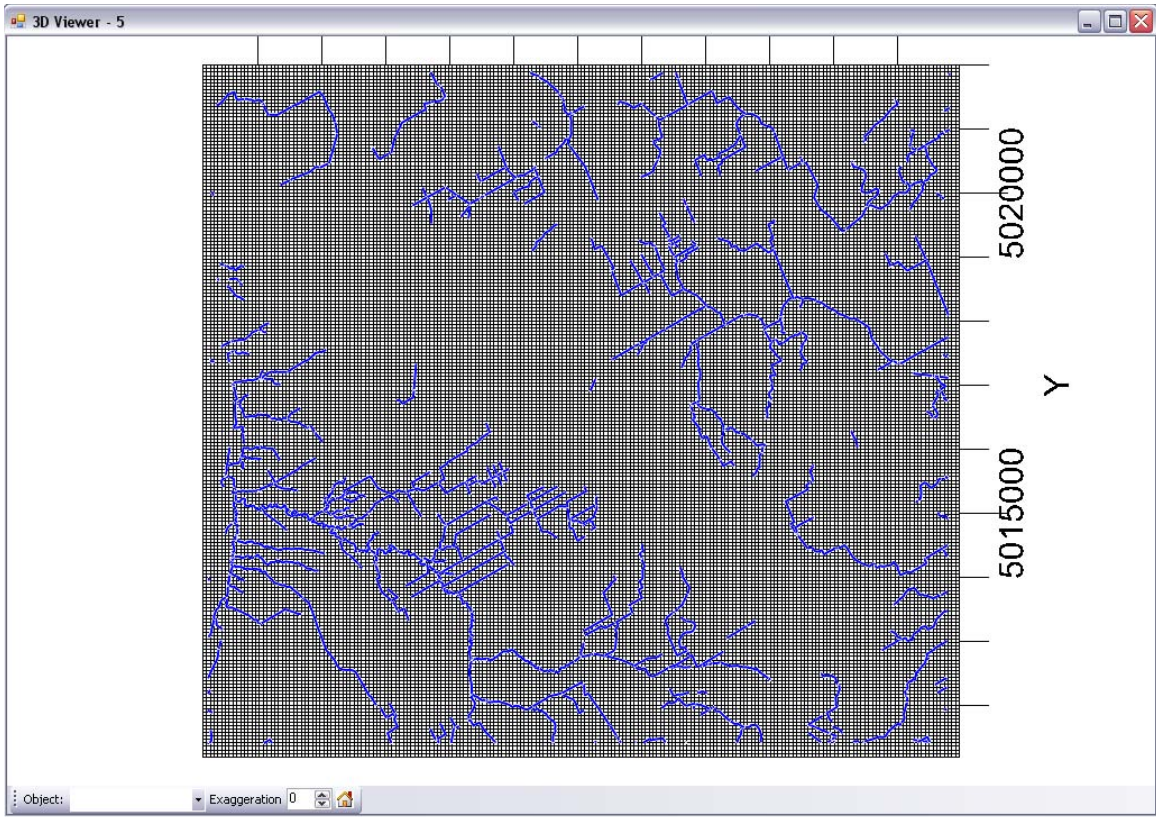


Figure 1: Globally refined grid in VMOD Flex

Variably-Spaced Grid

Using a variably spaced grid, the grid spacing is small around the area of interest, and gradually increases in size away from this area, out to the boundary of the model domain. Also referred to as Gradational Mesh Refinement (GMR), this is the most commonly used method.

Advantages:

- Ideal method for some cases
- A regular structure between adjacent cells
- A single model that is solved in a single (iterative) matrix equation; and hence "real-time" feedback between the coarse and fine grid areas through this single matrix solution.
- Ideal for contaminant transport and particle tracking simulations

Disadvantages:

- Not ideal if refinement is needed in multiple areas of the domain (for example, a number of well fields scattered throughout the study area) as it can result in a fine grid over the entire domain)
- Creates a needless amount of grid cells outside the area of interest, resulting in longer simulation times
- Can result in cells with large aspect ratios at the boundary of the domain, which can lead to numerical errors
- Working with these grids (construction, data input, and post-processing) is more arduous than with uniformly spaced grids.
- No vertical refinement (of a localized area)

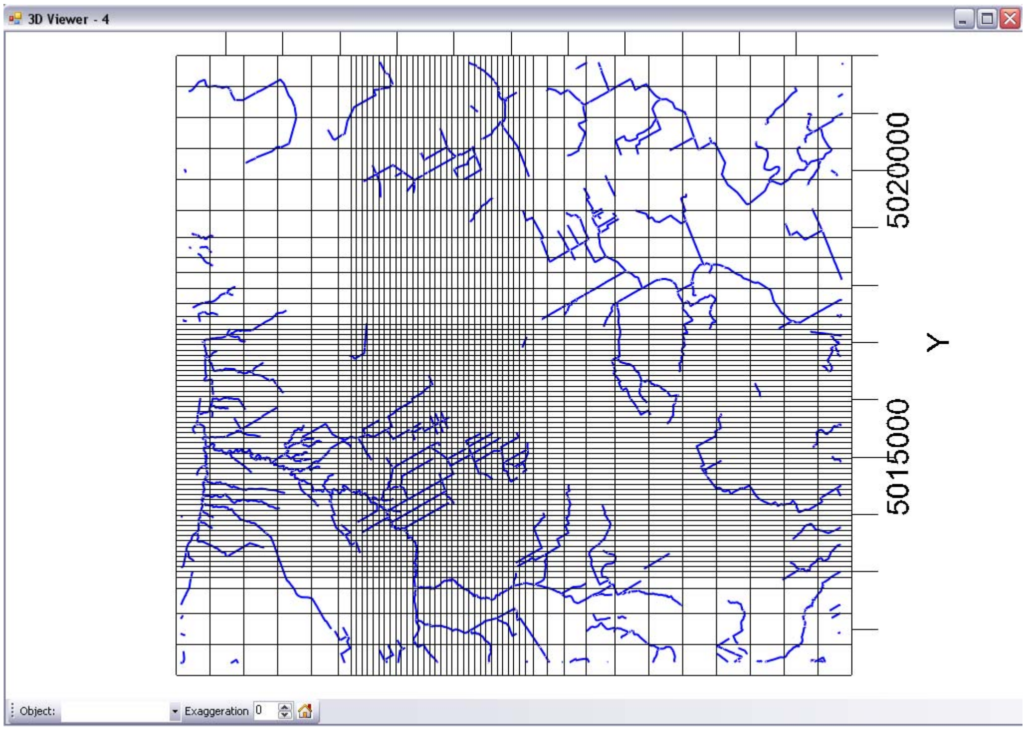


Figure 2: Numerical grid with refinement around area of interest

Telescopic Mesh Refinement (TMR)

The TMR (telescopic mesh refinement (TMR) approach combines two or more different-sized finite-difference grids—usually a coarse grid, which incorporates regional boundary conditions, and a locally refined grid, which focuses on the area of interest. The link between the coarse and local grids is most commonly accomplished by first simulating the coarse grid and using its results to interpolate heads and fluxes, or a combination of both, onto the boundaries of the local grid.

Advantages:

- Straightforward, flexible, and easy
- Works well for some (but not all) problems
- Computationally efficient

Disadvantages:

- No vertical refinement (of a localized area, that differs from the background grid)
- No support for contaminant transport or particle tracking simulations across the local-child grid interface.
- This approach is one-way coupling only (from the coarse grid to the local grid) and does not allow for feedback from the local grid to the coarse grid. Therefore, after running both models, the burden is placed on the modeler to check if heads along and fluxes across the interfacing boundary is consistent for both models. If they do not match, there is no formal mechanism for adjusting the models to achieve better agreement

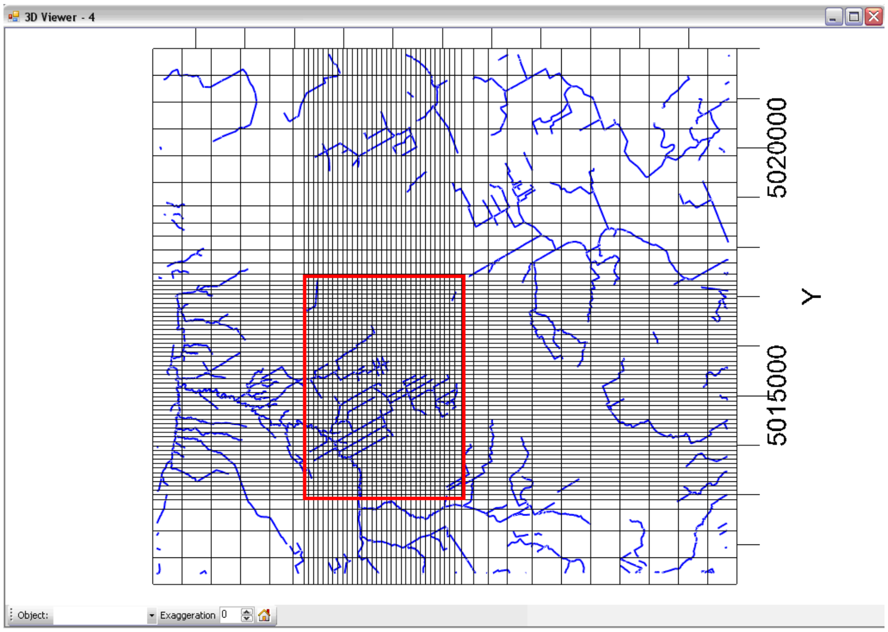


Figure 3: Coarse and fine grid.
NOTE: This figure is a demonstration only of the TMR concept.

Local Grid Refinement (LGR)

This method links two or more different-sized finite-difference grids: a coarse (parent) grid covering a large area which incorporates regional boundary conditions, and a fine (child) grid covering a smaller area of interest. The grid refinement covers only the area of interest. In Visual MODLOW Flex, the implementation is based on the USGS MODFLOW-LGR code.

Advantages:

- Create cells only in the area of interest, therefore less computationally intensive
- Support for refinement in multiple areas (create up to 9 child grids)
- Define a vertical refinement in the child grid that is different from the parent grid
- Two-way feedback between the coarse and local grids, ensures that the models have consistent boundary conditions along their adjoining interface.
- Easy to design the child grids
- Offers immediate results

Disadvantages:

- No support for contaminant transport or particle tracking simulations across the local-child grid interface. (However, the parent and child models can be run separately in these cases, using the generated BFH (Boundary Flow and Head) package files.

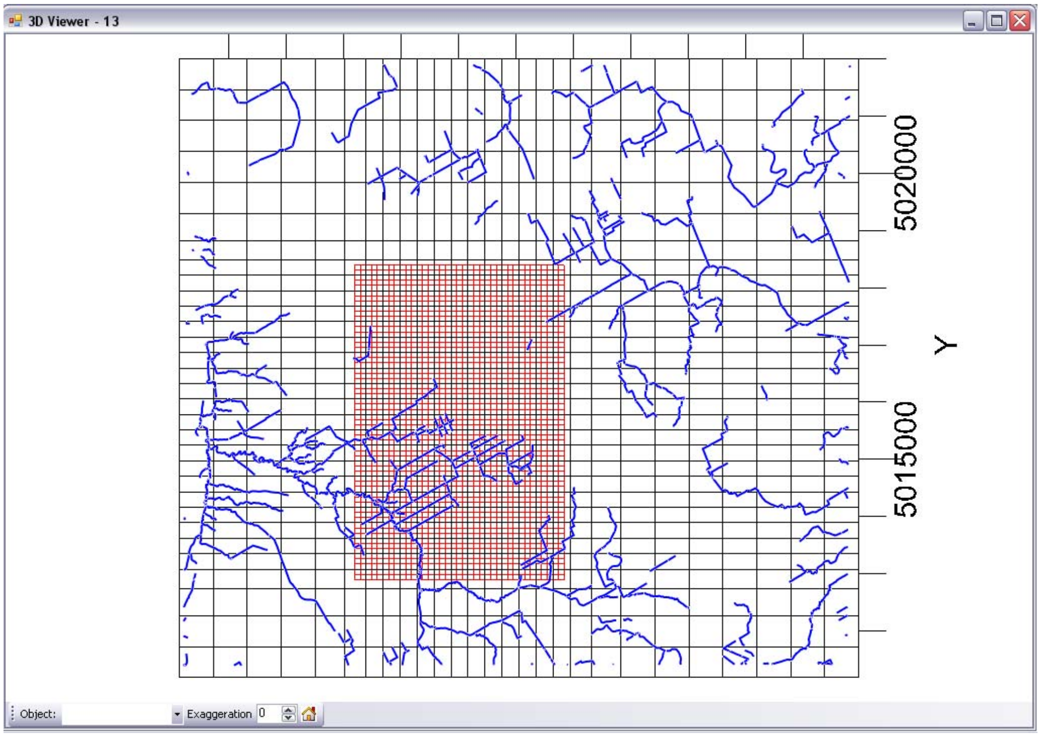


Figure 4: 2D Viewer showing parent grid (grey gridlines) and child grid (red grid lines) in Visual MODFLOW Flex

Example

The following example is based on the Benchmark Example 3 included with the MODFLOW-LGR documentation. Note, that a river boundary condition is used in place of the stream boundary for this test case.

The meandering river has a total length of 3,409 m and has a linear drop in stage along the length of the river from the inlet at 50.0 m to the outlet at 45.0 m. This results in a gradient along the river of 0.00147. The width, thickness of the riverbed and the riverbed hydraulic conductivity are constant throughout the length at 1.0 m, 0.5 m, and 1.0 m/day, respectively. The land-surface elevation of the model domain follows a linear profile from 50 m at the left boundary and drops to 45 m at the right boundary. The bottom elevation also follows this linear profile such that the model has a uniform thickness of 50 m throughout the domain. The specified-head boundaries at both ends provide a background gradient equal to the slope of the top and bottom of the model (0.00347). The aquifer is homogeneous and isotropic with a hydraulic conductivity of 1.0 m/day. The system is unconfined, which causes nonlinearity in the flow because the saturated thickness depends on the value of head, which is not known beforehand.

Inputs

The river boundary condition was defined in the conceptual model using a polyline shapefile that was imported. The parameters for the river can be defined manually or mapped to attributes in the shapefile, (or using a DEM for calculating river stage). The following figures illustrate the conceptual model (Figure 5) and and the corresponding numerical realization (see Figure 6). The child grid is shown in red and encompasses a small region of the meandering river. The child grid is refined at a factor of 3:1 over the parent grid.

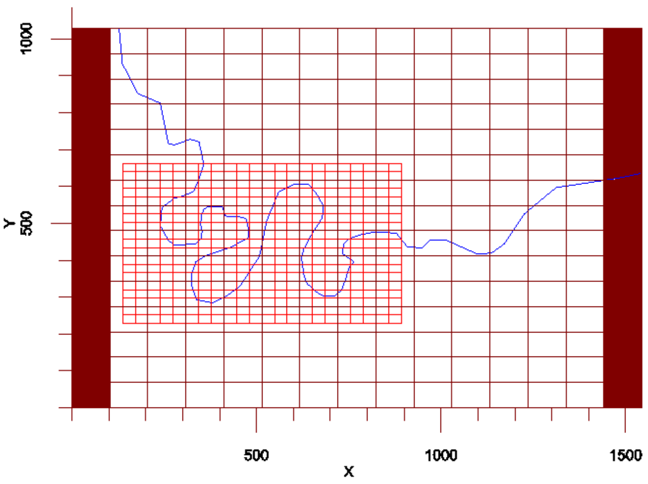


Figure 5: Conceptual boundary conditions with parent and child grid.

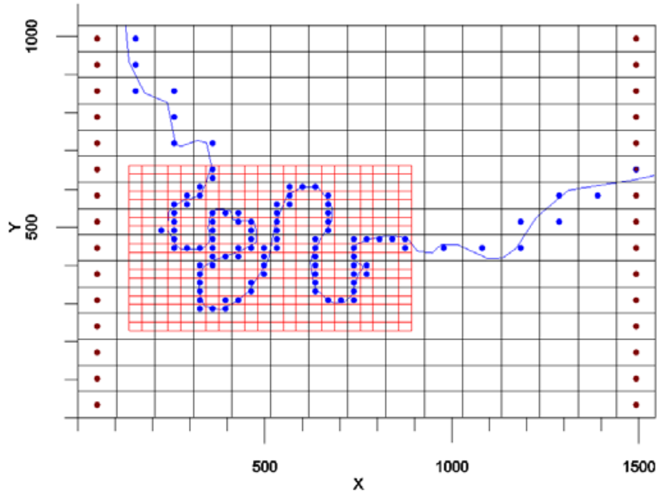
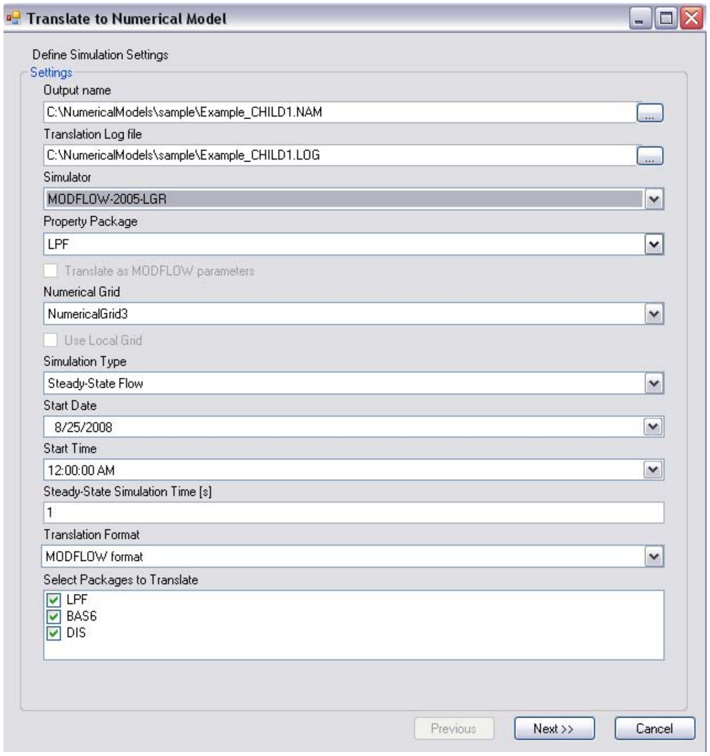


Figure 6: Numerical model equivalents; blue points are river cells, red are constant heads.

In this scenario, the properties are constant across both the parent and child grids.

Translation and Running the Model

After defining the numerical inputs, these can then be "translated" to MODFLOW-LGR format and run with the engine. The translation settings are show below:



After you complete the translation, the following files will be generated:

- MODFLOW files for the Parent Grid (Example_PARENT.NAM, Example_PARENT.LPF, Example_PARENT.BAS, Example_PARENT.DIS, Example_PARENT.RIV, etc.
- MODFLOW files for each of the Child Grid(s) (Example_CHILD1.BAS, Example_CHILD1.DIS, Example_CHILD1.LPF, Example_CHILD1.NAM, Example_CHILD1.RIV
- Example.LGR - this is the Control File, that contains details on the linkages between the parent and child grid(s)
- The Boundary Flow and Head (BFH) Package file, which allows the child and parent models to be simulated independently using the boundary conditions obtained through the iterative process of LGR.

Results

Once the simulation is complete, a set of heads will be generated for the parent grid and each of the child grids. In VMOD Flex, these heads can be visualized in 2D, Cross-section, or 3D Views, and animated in the case of a transient model. If you select the Parent heads, you will see a smooth transition of heads including the area covered by the child grid. This is shown in Figure 7 below. This is done to provide an effective presentation of the results. Tri-linear interpolation is used to calculate the heads on the parent grid cells that overlap with the child grid. In addition, you can show just the child grid heads on their own, using both color shading and contours; this is show in Figure 8 below.

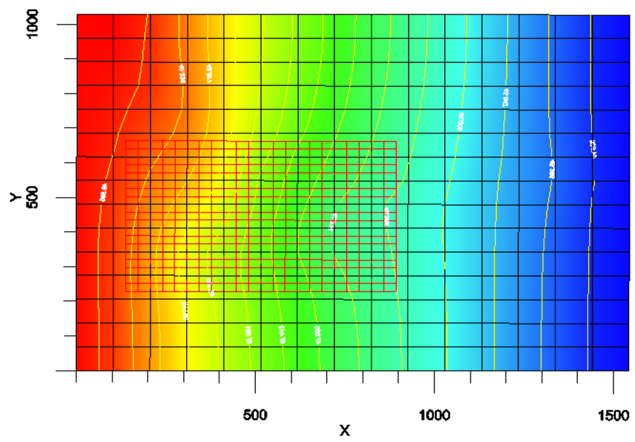


Figure 7: Combined parent and child grids heads with contours

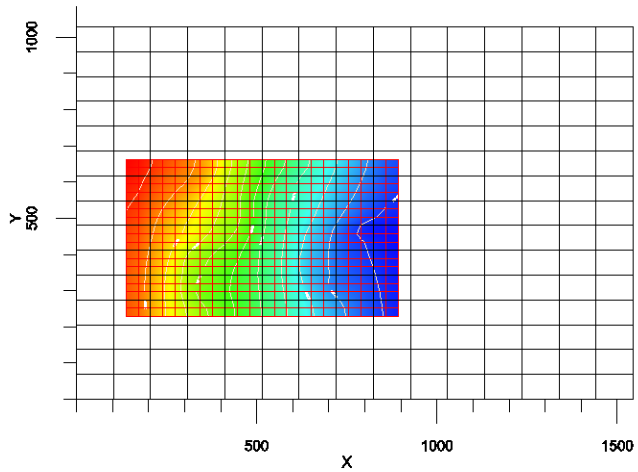


Figure 8: Child grid heads with contours

You can also analyze the Volumetric Budget in the .LST file. An entry for the Parent Flux boundary condition will be included (an example from the Parent model is below).

```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP   1 IN STRESS PERIOD   1
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    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                    IN:
          ---                                    ---
            STORAGE =           0.0000             STORAGE =           0.0000
      CONSTANT HEAD =         158.2277       CONSTANT HEAD =         158.2277
      RIVER LEAKAGE =         142.0706       RIVER LEAKAGE =         142.0706
   PARENT FLUX B.C. =          51.2186    PARENT FLUX B.C. =          51.2186

           TOTAL IN =         351.5168            TOTAL IN =         351.5168

         OUT:                                   OUT:
         ----                                   ----
            STORAGE =           0.0000             STORAGE =           0.0000
      CONSTANT HEAD =         154.0517       CONSTANT HEAD =         154.0517
      RIVER LEAKAGE =          22.3512       RIVER LEAKAGE =          22.3512
   PARENT FLUX B.C. =         175.5873    PARENT FLUX B.C. =         175.5873

          TOTAL OUT =         351.9903           TOTAL OUT =         351.9903

           IN - OUT =          -0.4734            IN - OUT =          -0.4734

PERCENT DISCREPANCY =          -0.13   PERCENT DISCREPANCY =          -0.13
```

Conclusions

The various methods of grid refinement all have advantages and disadvantages. The appropriate method selected should be based on your project objectives and application. Using Visual MODFLOW Flex, it is possible to design globally refined grids and variably spaced grids for simulation with MODFLOW 2000,2005. It is also possible to define local grids for simulation using MODFLOW-LGR.

For more information, please visit our website: www.vmodflex.com

References

Steffen Mehl, Mary C. Hill. 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 Office of Ground Water and U.S. Department of Energy, 2005.

Steffen Mehl, Mary C. Hill, and Stanley A. Leake . Comparison of Local Grid Refinement Methods for MODFLOW. GROUND WATER 44, no. 6: 792–796, 2006

Matthew Tonkin, Marinko Karanovic, Andrew Hughes, Christopher Jackson. New and Contrasting Approaches to Local Grid Refinement, MODFLOW and More 2006: Managing Ground-Water Systems - Conference Proceedings. 2006

Online Guide to MODFLOW-LGR: http://water.usgs.gov/nrp/gwsoftware/modflow2005_lgr/Guide/index.html