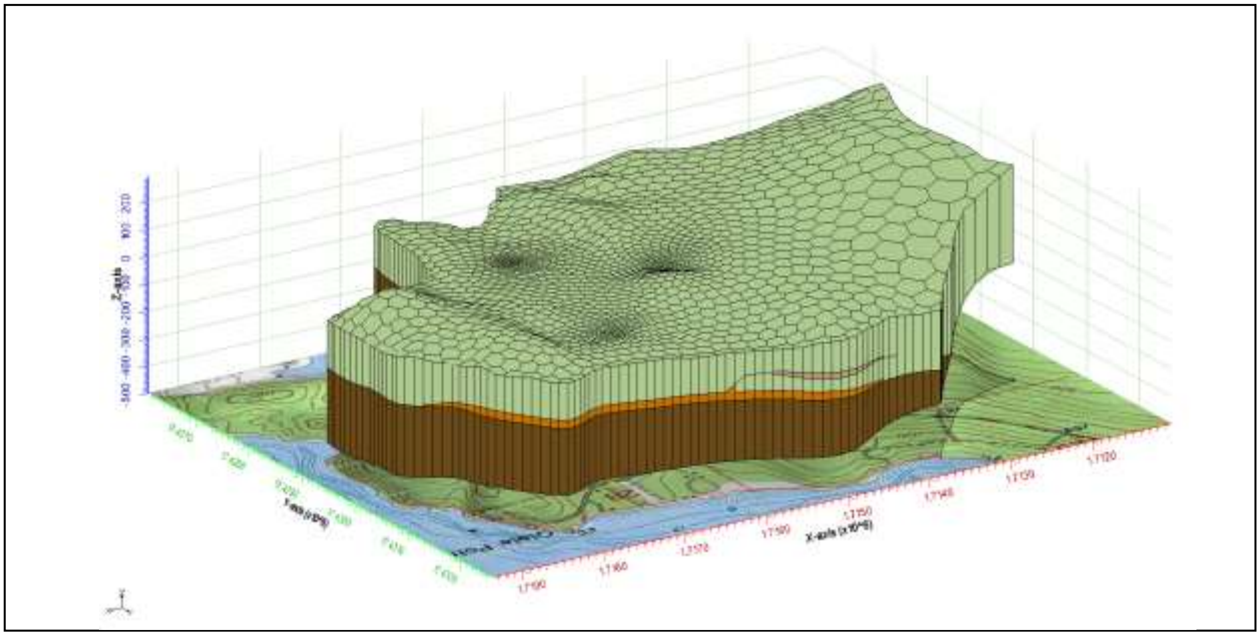
v. 10.0

GMS 10.0 Tutorial

MODFLOW-USG – Complex Stratigraphy

Create a MODFLOW-USG model of a site with complex 3D stratigraphy using GMS



Objectives

GMS supports building MODFLOW-USG models with multiple types of unstructured grids. This tutorial shows how to generate 3D unstructured grids of complex stratigraphy.

Prerequisite Tutorials

- Stratigraphy Modeling – Horizons and Solids
- MODFLOW – Conceptual Model Approach I
- UGrid Creation

Required Components

- Map Module
- Subsurface Char
- MODFLOW
- MODFLOW-USG

Time

- 30–50 minutes

1 Introduction

MODFLOW–USG (for UnStructured Grid), was developed to support a wide variety of structured and unstructured grid types, including nested grids and grids based on prismatic triangles, rectangles, hexagons, and other cell shapes. Flexibility in grid design can be used to focus resolution along rivers and around wells, for example, or to subdiscretize individual layers to better represent hydrostratigraphic units.**Error! Reference source not found.**

MODFLOW-USG's subdiscretization capability to better represent hydrostratigraphic units is an extremely powerful feature. Traditional MODFLOW requires that grid layers be continuous throughout the model domain even if the particular stratigraphic unit ends or pinches out (see Figure 1).

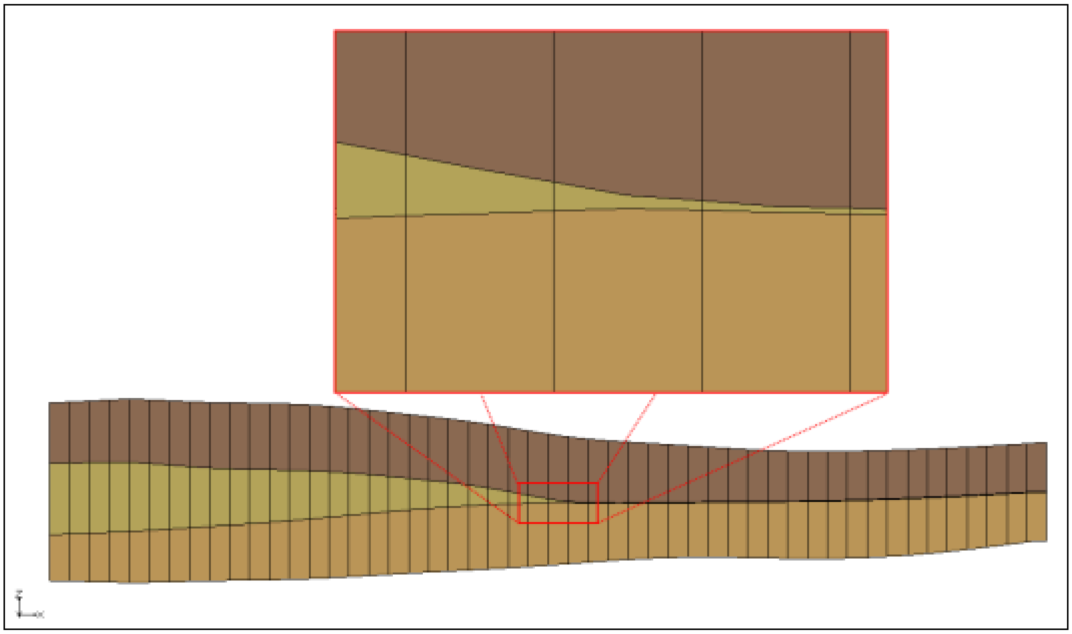


Figure 1 MODFLOW 2000 finite difference grid with pinching layer

With MODFLOW-USG the grid layer can simply end. The following figures from the MODFLOW-USG documentation show examples of complex gridding.

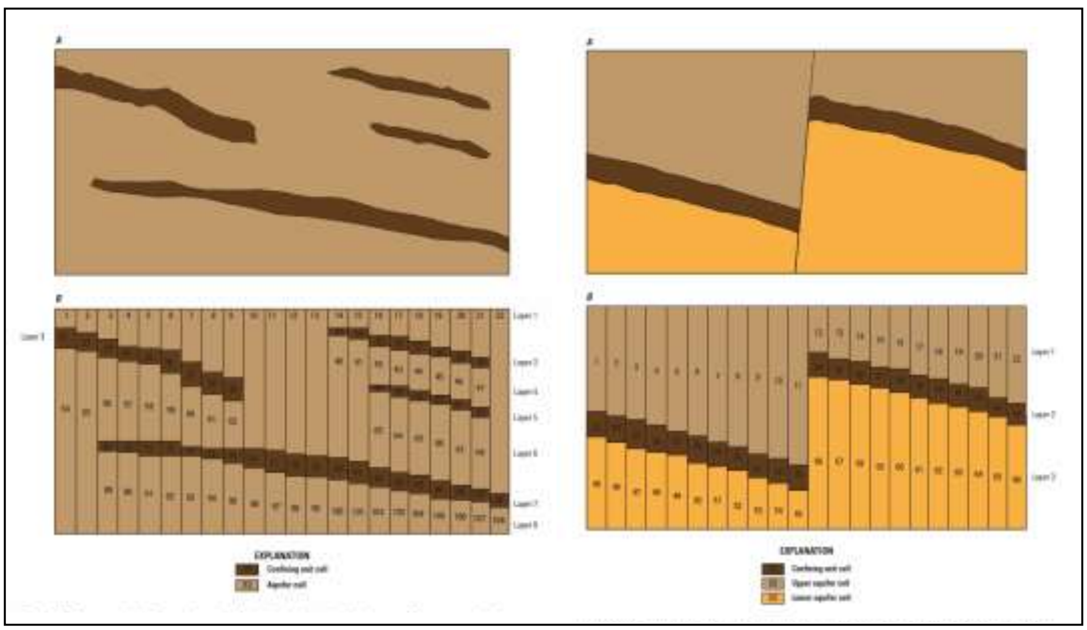


Figure 2 Complex gridding examples (MODFLOW-USG manual)

As the user can see from the figures, MODFLOW-USG allows layers to be discontinuous or even offset from one another. Figure 3 (below) shows the same model as Figure 1 created using a MODFLOW-USG compatible UGrid. Notice how the pinching layer is discontinuous and stops upon reaching a minimum thickness.

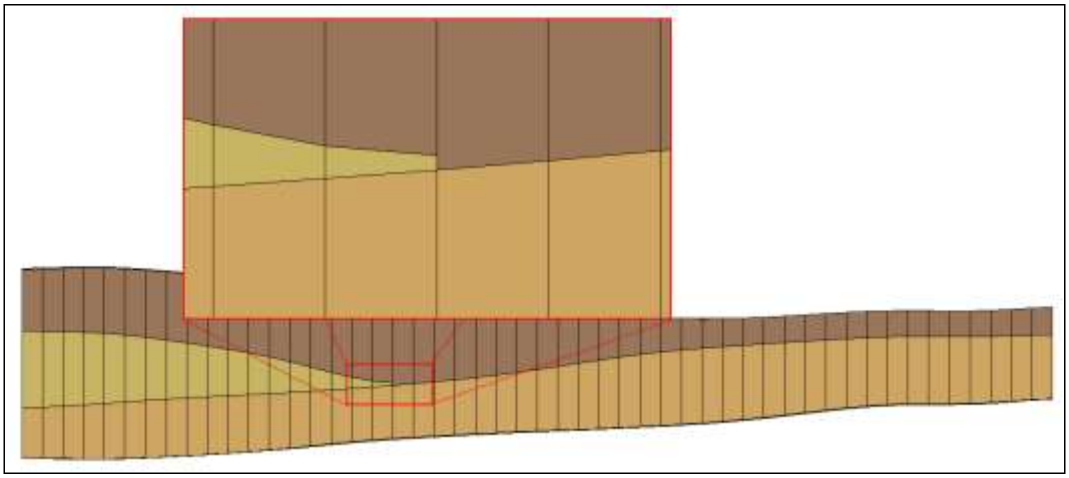


Figure 3 Example of a UGrid with pinching layer

This tutorial will focus on using the horizons approach in GMS to generate a 3D unstructured grid for complex stratigraphy. Using GMS, the user can quickly and easily generate complex 3D unstructured grids from a variety of subsurface data including: boreholes, user-defined cross sections, TINs, Rasters, and conceptual models. Since this tutorial assumes that the user understands how to use the horizons method to create subsurface models and the conceptual modeling approach for assigning MODFLOW model properties, the user should complete the "Stratigraphy Modeling – Horizons and Solids" and the "MODFLOW-USG – Quadtree" tutorials prior to beginning this tutorial.

1.1 Outline

Here are the steps to this tutorial:

1. Read in an existing GMS project.
2. Generate a 2D Quadtree UGrid.
3. Generate a 3D Quadtree UGrid using the Horizons method.
4. **Map → MODFLOW** and run the model.
5. Generate a 2D Voronoi UGrid.
6. Generate a 3D Voronoi UGrid using the Horizons method.
7. **Map → MODFLOW** and run the model.
8. Import a VTK unstructured grid file (*.vtu)
9. Generate a 3D UGrid using the Horizons method.
10. **Map → MODFLOW** and run the model.

2 Description of Problem

The site to be modeled in this tutorial is shown in Figure 4. The site is a small coastal aquifer with three production wells. The no-flow boundary on the upper left corresponds to a parallel-flow boundary, and the no-flow boundary on the left corresponds to a thinning of the aquifer due to a high bedrock elevation. A stream provides a river boundary condition on the lower left, and the remaining boundary is a coastal boundary simulated with a specified head condition.

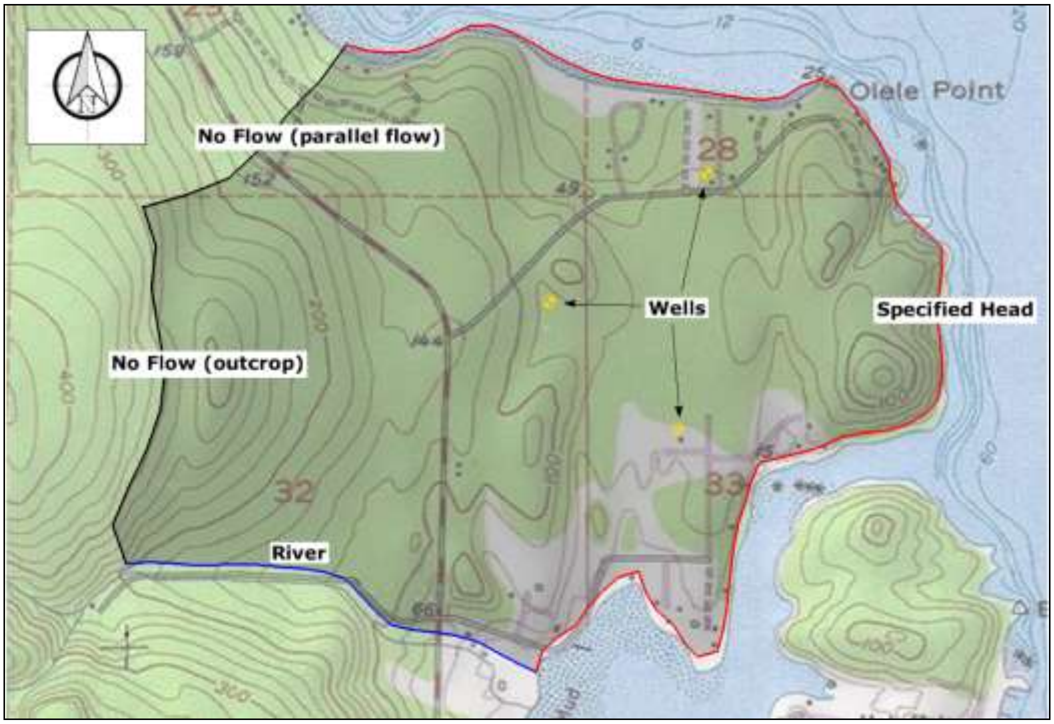


Figure 4 Site conceptual model

A fence diagram of the site is shown below. The stratigraphy of the site mainly consists of an upper and lower aquifer. There are also minor semi-confining units at the site with significantly lower hydraulic properties. The upper aquifer has a hydraulic conductivity of 10 ft/day and the lower aquifer has a hydraulic conductivity of 30 ft/day. The wells extend to the lower aquifer. The recharge to the aquifer is about one foot per year.

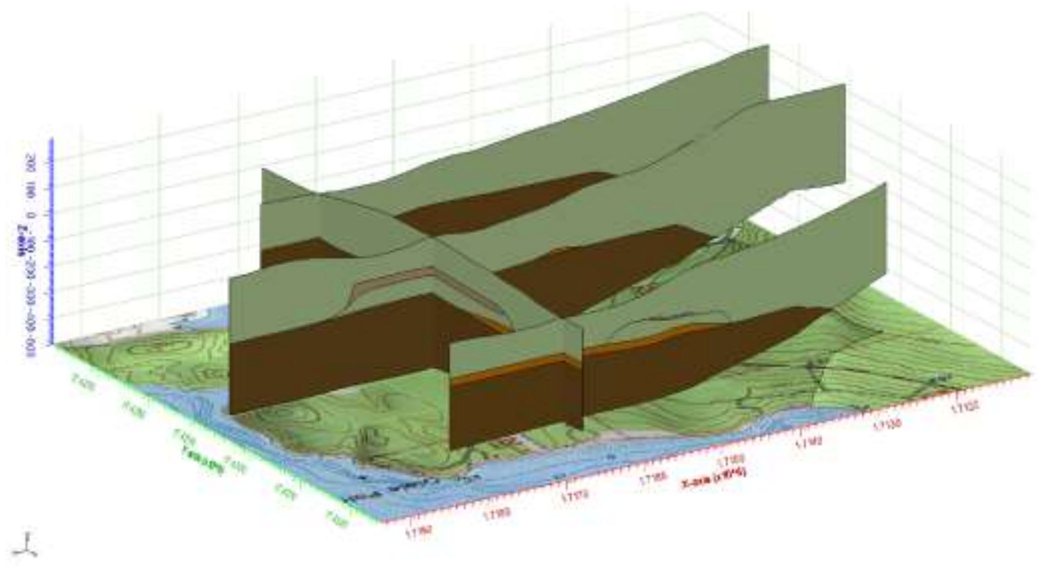


Figure 5 Fence diagram of site's subsurface

3 Getting Started

Do the following to get started:

1. If necessary, launch GMS.

2. If GMS is already running, select the *File* | **New** command to ensure that the program settings are restored to their default state.

4 Open the Starting Project

The user will start by opening a GMS project that already has the shape files, which contain the model geometry.

1. Select the **Open** button.

2. Locate and open the directory entitled *Tutorials\MODFLOW-USG\ComplexStratigraphy*.

3. Select the file entitled "start.gpr."

4. Click **Open**.

5 Save with a Different Name

Before making any changes, save the project under a new name.

1. Select the *File* | **Save As** command.
2. Change the project name to "olele.gpr."
3. Click **Save**.

Be sure to hit the **Save** button periodically as the model is developed.

6 Create a 2D Quadtree UGrid

This project already contains a conceptual model of both map data and subsurface data. Therefore, the user can start by generating the grid.

1. Right-click in the blank space in the Project Explorer.
2. Select the *New* **| Grid Frame** command.
3. Right-click on the "Grid Frame" .
4. Select the **Fit to Active Coverage** command.

This will ensure that the grid will be big enough to include the site.

5. Right-click on the "Grid Frame" .
6. Select the *Map to* **| UGrid** command to open the *Map → UGrid* dialog.

This command brings up a dialog for the creation of a UGrid. The user will create a 2D Quadtree grid with a base cell size of 500 ft, and the grid will be refined around the wells, the river, and the coastal boundary.

7. Change the *Dimension* dropdown to "2D."
8. Change the *UGrid type* to "Quadtree/Octree."
9. Under the *X-Dimension*, change the *Cell size method* to *Cell size*.
10. Enter "500.0" for the *Cell Size*.
11. Repeat the previous two steps for the items under the *Y-Dimension*.
12. Click **OK**.

The user should see a new 2D UGrid in the graphics display similar to Figure 6. The large cells in the UGrid have a cell size of about 500.[1] If the user zooms in around the wells or the river/coastal boundary, the user will see the smaller cells. The size of the cells around the boundary conditions are specified in the *"Refine"* attributes of those boundary conditions.[2]

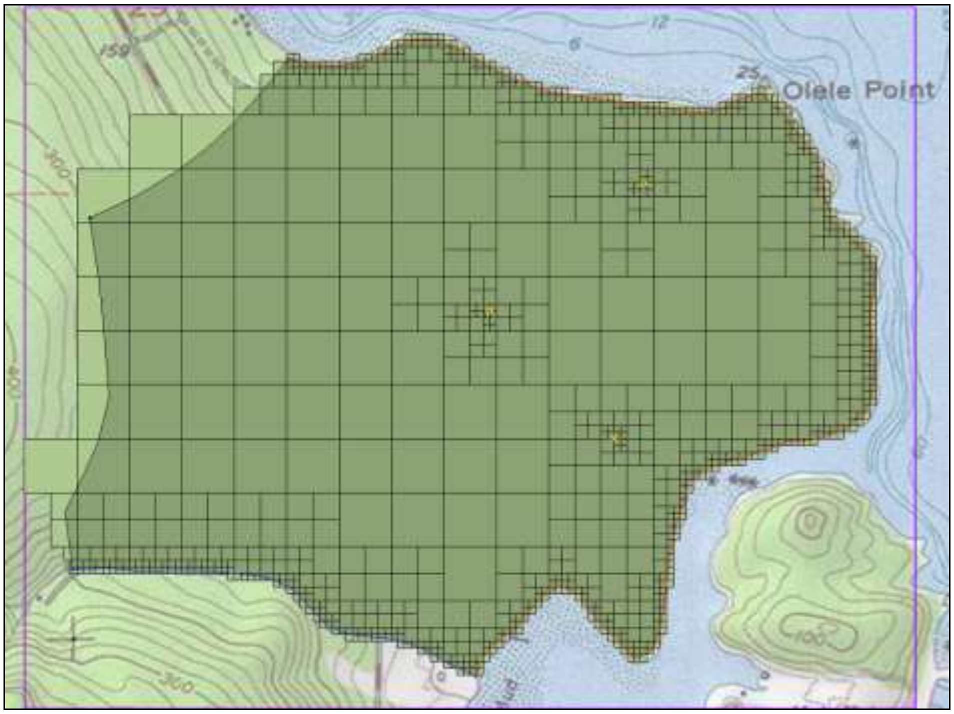


Figure 6 2D quad tree UGrid

Now rename the UGrid that was just created.

13. Right-click on "ugrid" .
14. Select the **Rename** command.
15. Enter "quadtree" for the name.

1. The size will *not* be exactly 500 because the grid frame defines the extents of the grid. If the user wanted the cells to be exactly 500 ft square, then the user would need to adjust the extents of the grid frame to be a multiple of 500.

2. Grid refinement is explained in the "MODFLOW-USG – Quadtree" tutorial.

7 Create a 3D Quadtree UGrid

It is now possible to use the 2D Quadtree UGrid and the subsurface data (boreholes, cross sections, and conceptual model) to create a 3D Quadtree UGrid. This is done using the **Horizons → UGrid** command. At this point, the user may wish to explore the borehole and cross section data to see the current subsurface conceptual model. In the interest of time, the tutorial will not go through any of the steps to explore the subsurface data; instead, the user will move on to creating the 3D UGrid.

1. Select the "Borehole Data" folder in the Project Explorer.
2. Select the *Boreholes* | **Horizons → UGrid** menu command.

This command brings up the *Horizons to UGrid – Horizons Elevations* wizard. Here, the user will select the data and the options used to generate the UGrid. In the first step of the wizard, the user specifies the subsurface data to be used. In this example, the user will use the borehole data, the user-defined cross sections, and the conceptual model.

3. Under the *Boreholes* section of the dialog, make sure the *Use boreholes* and *Use borehole cross sections* toggles are on.
4. Under the *Conceptual model* section, turn on the *Use horizons conceptual model*.
5. Click the **Next** button to proceed to the next step in the wizard.

In this step in the wizard, the user will select a 2D UGrid that will be extruded into a 3D UGrid. Since the user currently has only 1 UGrid in the project, it won't be necessary to change the selected UGrid. The user will also select how the top and the bottom of the UGrid will be defined. In this case, the user has a TIN that defines the ground surface of the site, and the user will use the bottom of the boreholes for the bottom of the UGrid.

6. Under the *Top elevation* section, select the "TIN elevations" option.
7. Click the **Next** button to proceed to the next step in the wizard.

In the final step of the wizard, the user will specify the interpolation option (this tutorial will use the default) as well as various *Meshing options*. The *Minimum element thickness* option will ensure that all cells/elements in the UGrid will have a thickness greater than or equal to the specified minimum.

8. Under the *Meshing options* section, turn on the *Minimum element thickness*.
9. Enter a value of "2.0" for the *Minimum element thickness*.
10. Click on the **Finish** button to create the 3D UGrid.

7.1 View the 3D Quadtree UGrid

The 3D UGrid generation should complete quickly. The user will now rename the new UGrid and view it in 3D.

1. Right-click on “quadtree (2)”.
2. Select the **Rename** command.
3. Enter “quadtree-3d” for the name.
4. Uncheck the “Grid Frame” in the Project Explorer.
5. Select the **Oblique View** button to view the UGrid in 3D.

The user should see the 3D UGrid in the graphics display similar to the figure below.

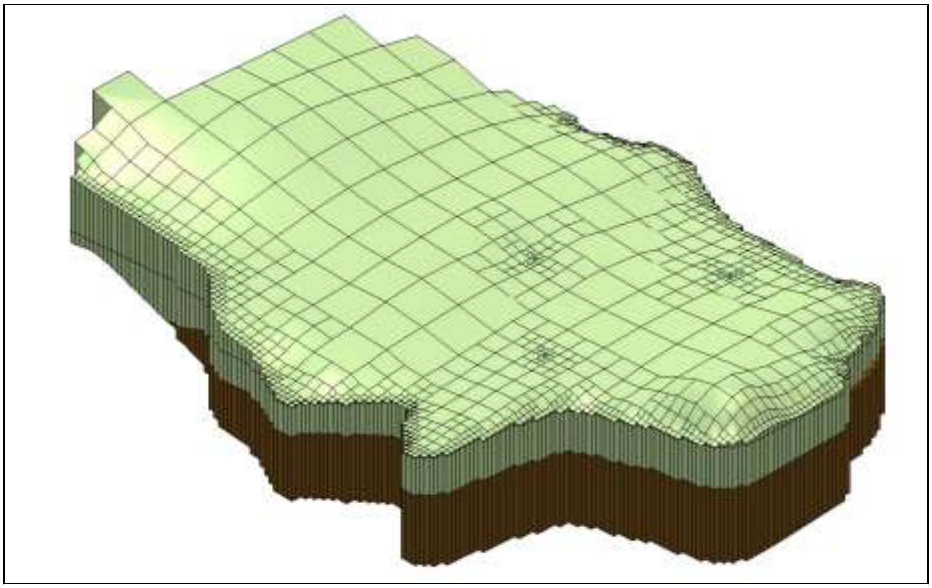


Figure 7 3D quadtree UGrid

The user will now examine the properties of the newly created UGrid.

6. Uncheck the “quadtree” item in the Project Explorer.
7. Right-click on the “quadtree-3d” item in the Project Explorer.
8. Select the **Properties** menu command to open the *UGrid Properties* dialog.

This dialog provides information on the extents of the UGrid and the number of cells and nodes as well as the type of cells (2D/3D). The user should see about 2693 cells and 5265 nodes.

9. Select **Done** to exit the dialog.

Now the user will view the different layers of the UGrid. The grid that was created has 5 layers. In the previous figure, the user could clearly see the light green layer and the brown layer. These are layers 1 and 5 respectively. There are 3 other layers that are not as easy to see. The user will use the single layer viewing option to see the different layers of the UGrid. This option is found near the top of the GMS window as shown in the next figure.

Figure 8 Single layer viewing toolbar

10. Turn on the check box next to *Single layer* 

on the tool bar.

The view of the UGrid has now changed and only the cells in layer 1 are visible.

11. Change the *Layer* value to “2.”

The view of the UGrid should now look similar the left side of the following figure.

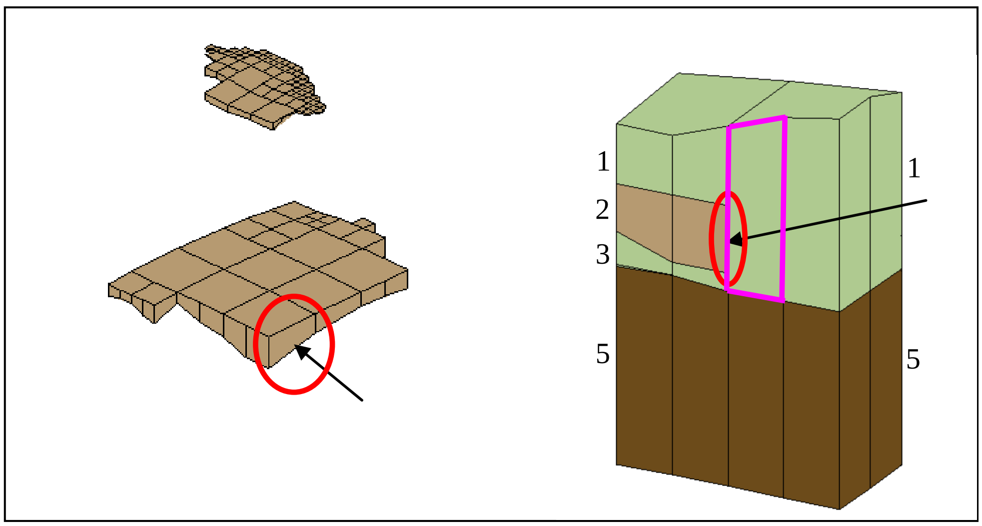


Figure 9 Layer 2 of 3D quadtree UGrid and side view cells

This layer represents 2 low permeability lenses at this site. These lenses are disjointed from one another and they cover only a portion of the modeled site. This is an example of how a 3D UGrid supports discontinuous layers. Note that all of the cells in this layer have a thickness of at least 2 feet (this was part of the input to the **Horizons → UGrid** command). These lenses do not extend any further because any cells beyond the current extent would have had a thickness of less than 2 feet.

Look at the cell face that is circled on the left side of the figure. This face is adjacent to another cell face in a different layer; the user can see this in the right side of the figure. The adjacent cell outlined in pink is in layer 1; the pink-outlined cell is adjacent to cells in layers 1, 2, and 3. The information concerning cell face adjacency and face areas is written to the DISU package. MODFLOW-USG uses the information in the DISU package to allow flow between these cells.

At this point, the user can view the other layers included in the UGrid by changing the *Layer* value. When finished, the user will turn off the single layer view.

12. Uncheck the *Single layer* viewing option.
13. Click on the **Plan View** button.

8 Create a MODFLOW-USG Model

Now create the MODFLOW-USG model.

1. Select the *MODFLOW* | **New Simulation** menu item.

Notice in the dialog that under the *MODFLOW version* section that the only version available is USG. This is because the user is creating the MODFLOW simulation on a UGrid. All of the other versions of MODFLOW can only be used on a structured 3D Grid.

2. Click **OK** to exit the dialog.

The user will also need to define the aquifer properties. In this example, the user will use materials to assign aquifer properties. The user needs to go into the LPF package and select the *Use materials* option.

3. Select the *MODFLOW* | **LPF – Layer Property Flow** menu item to open the *LPF Package* dialog.
4. In the *Layer property entry method* section (near the top of the dialog), select the “Use material IDs” option.
5. Click **OK** to exit the dialog.

9 Map to MODFLOW

Now assign the conceptual model values to the MODFLOW model.

1. Right-click on the “MODFLOW” conceptual model in the Project Explorer.
2. Select the *Map To* **| MODFLOW/MODPATH** menu item.
3. In the *Map* → *Model* dialog, leave the values at their defaults.
4. Click **OK**.

Boundary condition symbols for specified head, rivers, and wells should appear. To see the symbols better, the user will turn off the cell faces on the UGrid.

5. Right-click on “UGrid Data” folder in the Project Explorer.
6. Select the **Display Options** menu command.
7. Turn off the *Cell faces* option.
8. Select **OK** to exit the dialog.

The user should see the MODFLOW boundary conditions as shown in the following figure. The river boundary (blue symbols) on the south is assigned only to layer 1 of the UGrid. The coastal, specified head boundary (purple symbols) is assigned to layers 1 to 5. The wells were assigned to layer 5. The user can use the single layer viewing option to see the boundary conditions in particular layers.

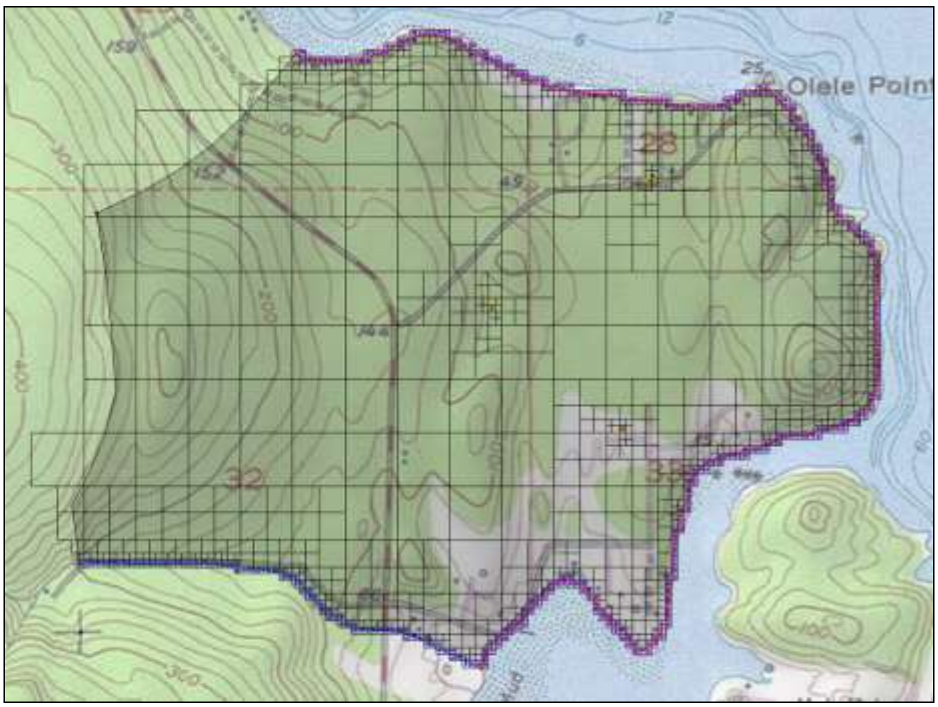


Figure 10 Quadtree UGrid with MODFLOW boundary conditions

10 Save and Run MODFLOW

Now it is possible to run MODFLOW. At this point, it is a good idea to run the MODFLOW Model Checker to make sure that the user does not have any obvious errors in the model.

1. Select the *MODFLOW* | **Check Simulation** menu command.
2. Click the **Run Check** button.

This command will search through the MODFLOW inputs for obvious errors such as negative values for hydraulic conductivity, etc. The model should not have any warnings or errors.

3. Click the **Done** button to exit the dialog.
4. Click the **Save** button.
5. Click the **Run MODFLOW** button.
6. When the model finishes, click **Close**.

GMS reads in the solution and displays the contours similar to the figure below. The user can see that there is some drawdown around the wells.

Figure 11 MODFLOW head contours

11 Create the 2D Voronoi UGrid

The user will now create another MODFLOW-USG model using a Voronoi UGrid. Since all of the model data is defined using the conceptual model approach, this process is very fast. The user will follow the same procedure that the user employed to create the 3D Quadtree UGrid.

1. First, uncheck “quadtree-3d” to hide the 3D Quadtree UGrid.

2. If necessary, expand the "MODFLOW" conceptual model below the "Map Data" item in the Project Explorer.
3. Right-click the "SourceSink" coverage in the Project Explorer.
4. Select the *Map To* | **UGrid** menu command.
5. Make sure that the *Dimension* is set to "2D."
6. Change the *UGrid type* to "Voronoi."
7. Select **OK** to generate the Voronoi UGrid.
8. Right click on the "ugrid" item in the Project Explorer.
9. Select the **Rename** command.
10. Enter "voronoi" for the name.
11. Right-click on "UGrid Data" folder in the Project Explorer.
12. Select the **Display Options** menu command to open the *Display Options* dialog.
13. Turn on the *Cell faces* option.
14. Turn off the *Contours*.
15. Select **OK** to exit the dialog.

The user should now see a 2D Voronoi grid as shown in the figure below. Notice that like the Quadtree grid, the Voronoi grid is refined around the wells and the other boundary condtions.

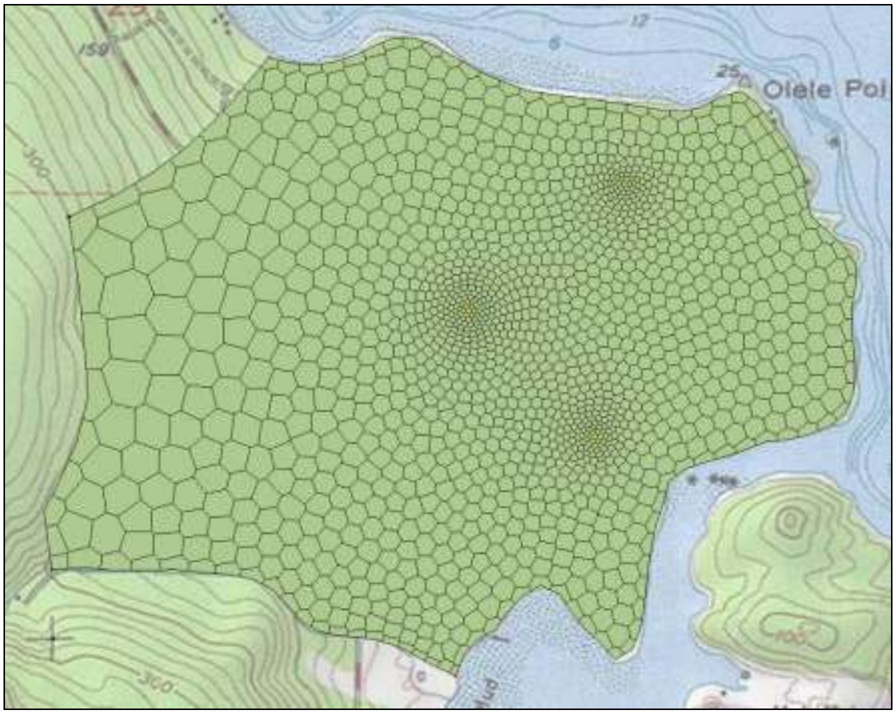


Figure 12 2D Voronoi UGrid

12 Create a 3D Voronoi UGrid

It is now possible to create the 3D Voronoi UGrid.

1. Select the "Borehole Data" folder in the Project Explorer.
2. Select the *Boreholes* | **Horizons → UGrid** menu command.
3. Click the **Next** button to proceed to the next step in the wizard.
4. Under the *Primary UGrid* section, select the "voronoi" item.
5. Click on the **Finish** button to create the 3D UGrid.
6. Uncheck the "voronoi" item in the Project Explorer to hide the 2D UGrid.
7. Right-click on the "voronoi (2)" item.
8. Select the **Rename** command.
9. Enter "voronoi-3d" for the name.
10. Select the **Oblique View** button to view the UGrid in 3D.

The user should now see a 3D Voronoi grid similar to the figure below. This grid looks similar to the 3D Quadtree UGrid. The user can view the different layers of this UGrid using the single layer viewing option just like the user did with the 3D Quadtree UGrid.

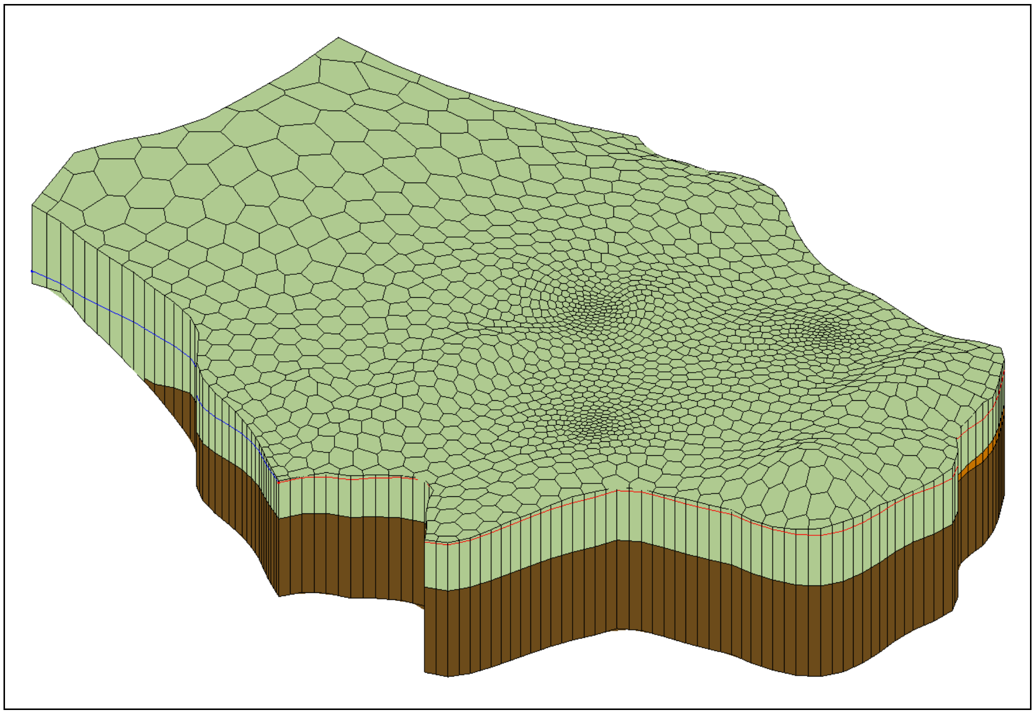


Figure 13 3D Voronoi UGrid

13 Create a MODFLOW-USG Model

Now create the MODFLOW-USG model.

1. Right-click on “voronoi-3d.”
2. Select the **New MODFLOW** menu item to open the *MODFLOW Global/Basic Package* dialog.
3. Click **OK** to exit the dialog.
4. If necessary, turn on the check box next to the **“**MODFLOW” item below the “voronoi-3d” UGrid in the Project Explorer. This will make sure that the boundary condition symbols are visible.

Again, it is necessary to define the aquifer properties for this model like the user did previously.

5. Select the *MODFLOW* | **LPF – Layer Property Flow** menu item to open the *LPF Package* dialog.
6. In the *Layer property entry method* section, select the “Use material IDs” option.

7. Click **OK** to exit the dialog.

14 Map to MODFLOW

Now assign the conceptual model values to the MODFLOW model.

1. Click on the “MODFLOW” conceptual model in the Project Explorer.
2. Select the *Feature Objects* | **Map → MODFLOW** menu item.
3. In the *Map → Model* dialog, leave the values at their defaults.
4. Click on the **OK** button.
5. Right-click on the “UGrid Data” folder in the Project Explorer.
6. Select the **Display Options** menu command to open the *Display Options* dialog.
7. Turn off the *Cell faces* option.
8. Select **OK** to exit the dialog.
9. Click on the **Plan View** button.

Boundary condition symbols for specified head, rivers, and wells should appear similar to the following figure.

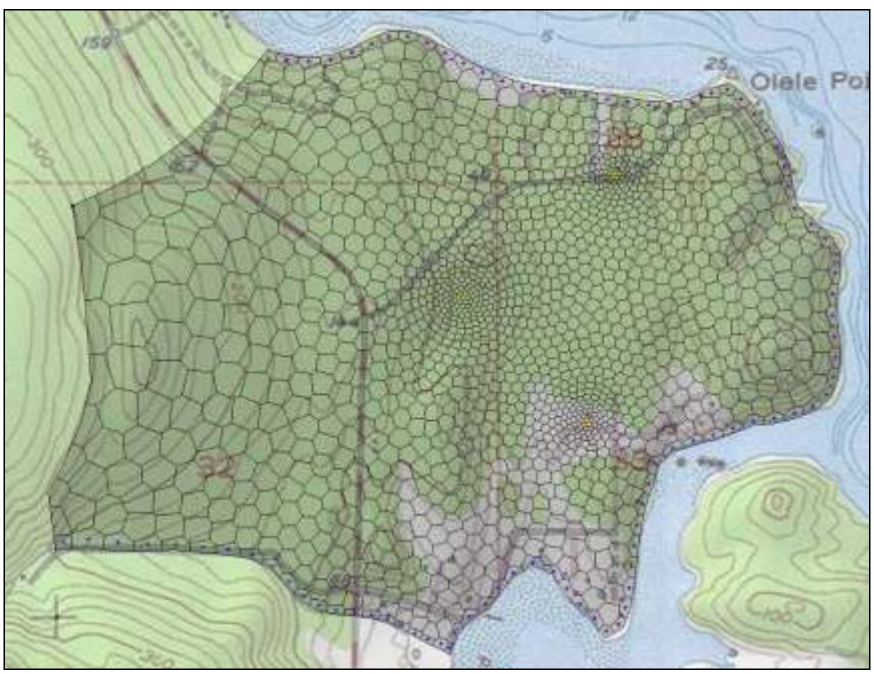


Figure 14 MODFLOW boundary conditions on a Voronoi UGrid

15 Save and Run MODFLOW

Now it is possible to run MODFLOW.

1. Click the **Save** button.
2. Click the **Run MODFLOW** button.
3. When the model finishes, click **Close**.

GMS reads the solution and displays the contours similar to the figure below.

Figure 15 MODFLOW computed head contours on Voronoi UGrid

At this point, the user may wish to compare the solution from the Quadtree UGrid with the Voronoi UGrid.

16 Import VTK Unstructured Grid File

In the last part of this exercise, the user will import a VTK Unstructured Grid that matches the site boundary. Then the user will use the **Horizons → UGrid** command to make a 3D UGrid for the site.

1. Uncheck the "voronoi-3d" item in the Project Explorer to hide the UGrid.
2. Select the **Open** button.

3. Locate and open the directory entitled *Tutorials\MODFLOW-USG\complex-stratigraphy*.

4. Change the *Files of type* to “All Files (*.*).”

5. Select the file entitled **“**tri-quad.vtu.”

6. Click **Open**.

The user should now see a UGrid similar to the following figure. VTK unstructured grids are very flexible and can contain many different types of cells (1D, 2D, 3D). The **Horizons → UGrid** command will work with any UGrid that contains only 2D cells. This particular UGrid contains only triangles and quadrilaterals.

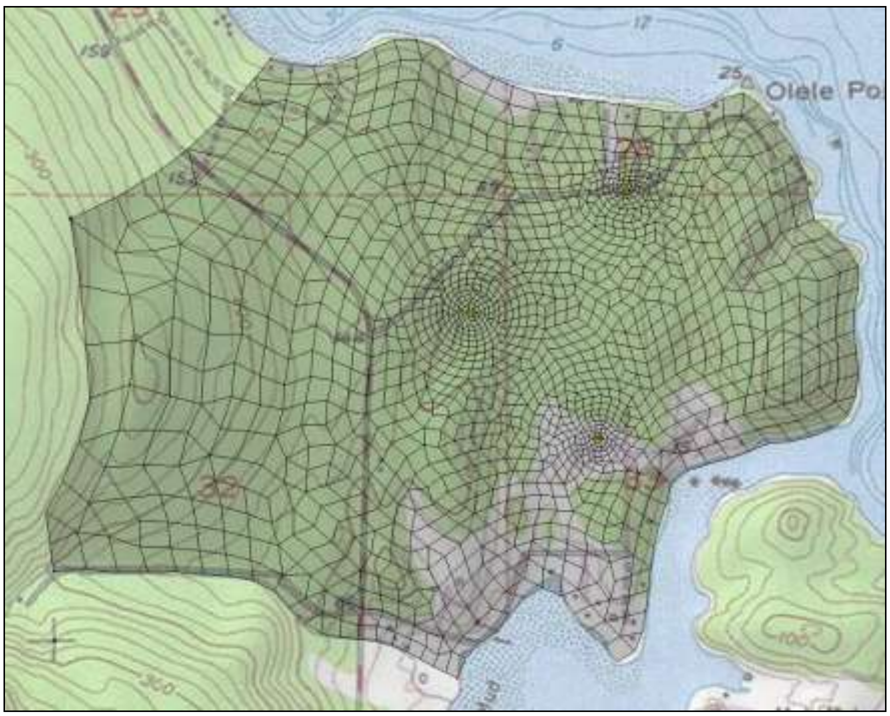


Figure 16 UGrid comprising triangle and quadrilateral cells

17 Create a 3D UGrid

It is now possible to create the 3D UGrid.

1. Select the “Borehole Data”  folder in the Project Explorer.

2. Select the *Boreholes* | **Horizons → UGrid** menu command.

3. Click the **Next** button to proceed to the next step in the wizard.

4. Under the *Primary UGrid* section, select the “tri-quad” item.

5. Click on the **Finish** button to create the 3D UGrid.
6. Uncheck the "tri-quad" item in the Project Explorer to hide the UGrid.
7. Right-click on the "tri-quad (2)" item.
8. Select the **Rename** command.
9. Enter "tri-quad-3d" for the name.
10. Right-click on "UGrid Data" folder in the Project Explorer.
11. Select the **Display Options** menu command.
12. Turn on the *Cell faces* option.
13. Turn off the *Contours*.
14. Select **OK** to exit the dialog.
15. Select the **Oblique View** button to view the UGrid in 3D.

The user should now see a 3D UGrid similar to the figure below. This grid looks similar to the previous 3D UGrids that the user has created. The user can view the different layers of this UGrid just like the user did previously.

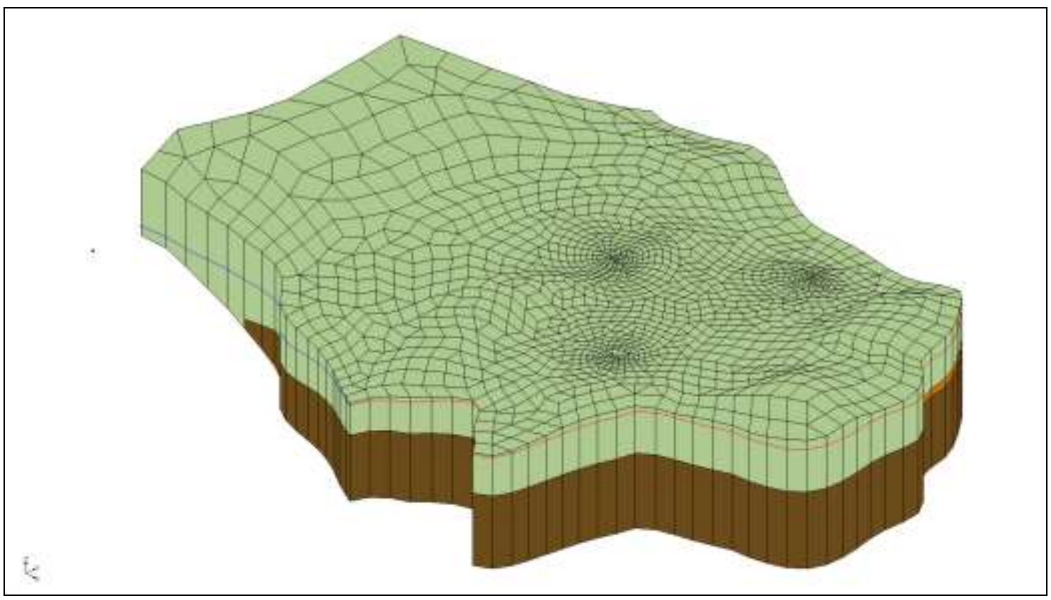


Figure 17 3D UGrid created from tri-quad 2D UGrid

18 Create a MODFLOW-USG Model

Now create the MODFLOW-USG model.

1. Right-click on "tri-quad-3d."
2. Select the **New MODFLOW** menu item.
3. Click **OK** to exit the dialog.
4. Turn on the check box next to the "MODFLOW" item below the "tri-quad-3d" UGrid in the Project Explorer. This will make sure that the boundary condition symbols are visible.

Again, the user needs to define the aquifer properties for this model like the user did previously.

5. Select the *MODFLOW* | **LPF – Layer Property Flow** menu item to open the *LPF Package* dialog.
6. In the *Layer property entry method* section select the "Use material IDs" option.
7. Click **OK** to exit the dialog.

19 Map to MODFLOW

Now assign the conceptual model values to the MODFLOW model.

1. Click on the **MODFLOW** conceptual model in the Project Explorer.
2. Select the *Feature Objects* | **Map → MODFLOW** *menu item*.
3. In the *Map → Model* dialog, leave the values at their defaults.
4. Click on the **OK** button.
5. Right-click on the **UGrid Data** folder in the Project Explorer.
6. Select the **Display Options** menu command.
7. Turn off the *Cell faces* option.
8. Select **OK** to exit the dialog.
9. Click on the **Plan View** button.

Boundary condition symbols for specified head, rivers, and wells should appear in graphics view similar to the following figure.

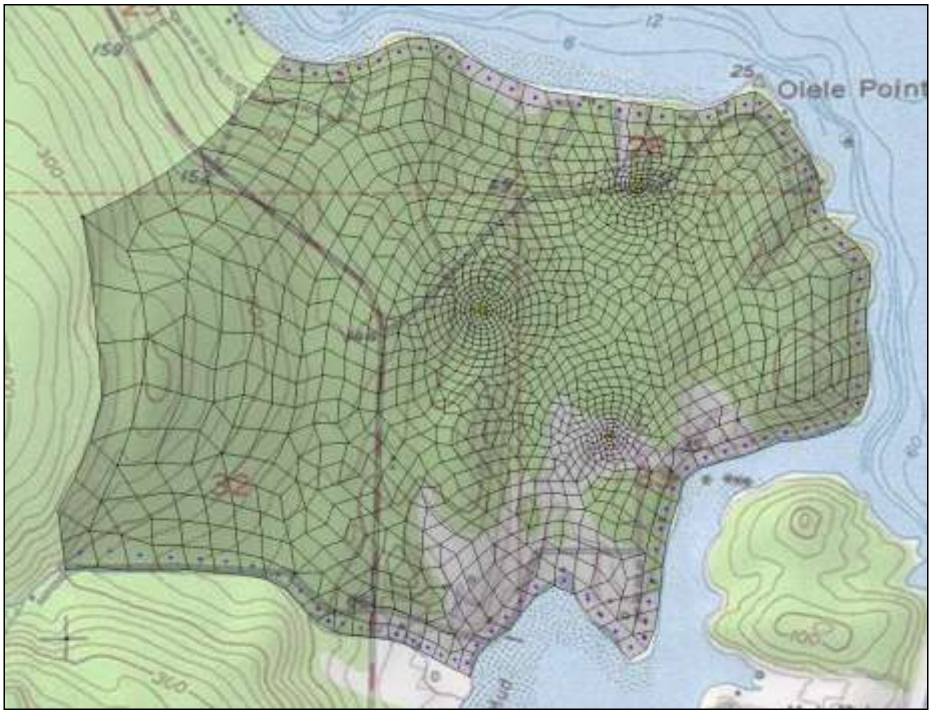


Figure 18 MODFLOW boundary conditions on a 3D UGrid

20 Save and Run MODFLOW

Now it is possible to run MODFLOW.

1. Click the **Save** button.
2. Click the **Run MODFLOW** button.
3. When the model finishes, click **Close**.

GMS reads the solution and displays the contours similar to the figure below.

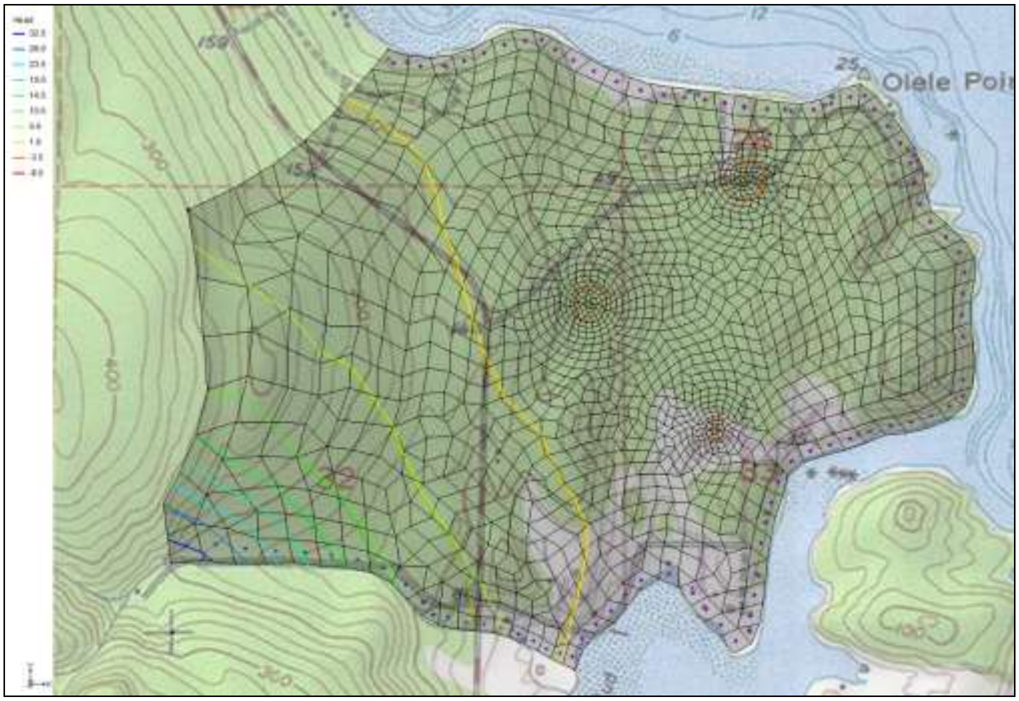


Figure 19 MODFLOW computed head contours on 3D UGrid

At this point, the user may wish to compare the solution from the different MODFLOW simulations.

21 Conclusion

This concludes the tutorial. Here are the key concepts in this tutorial:

- The **Horizons→ UGrid** command can create 3D UGrids of complex stratigraphy.
- The **Horizons → UGrid** command can create a variety of 3D UGrids.
- The **Horizons → UGrid** command will work on imported VTK unstructured grids that are comprised of 2d cells.
- Multiple UGrids and multiple MODFLOW-USG simulations can exist in the same GMS project.