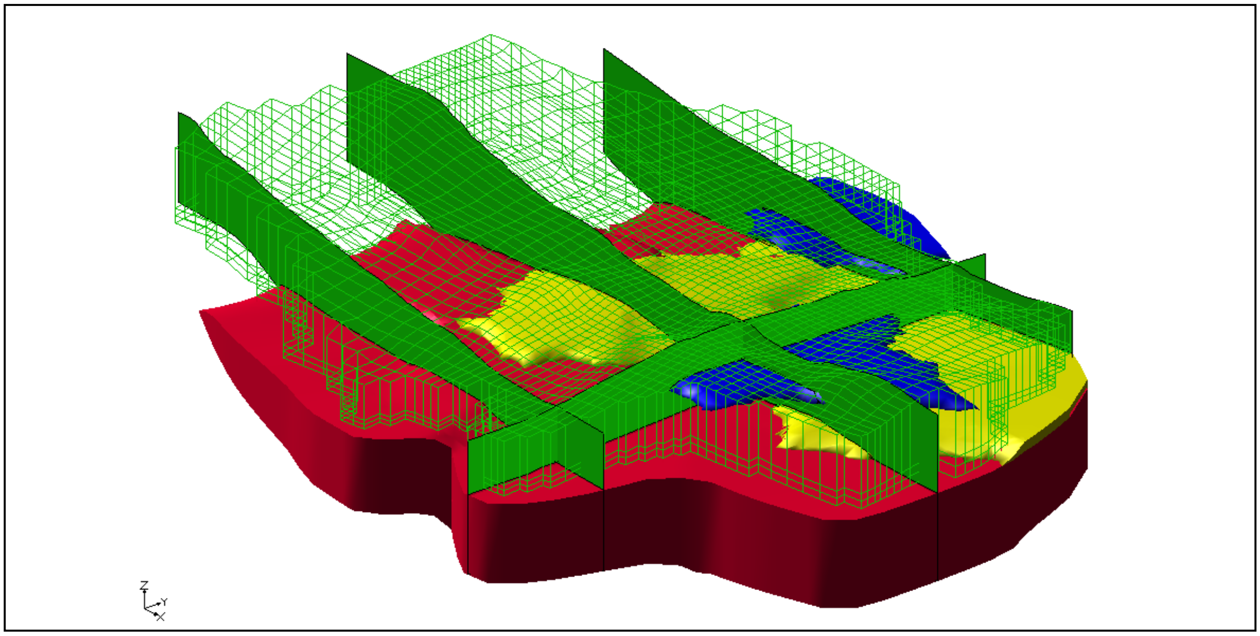
v. 10.3

GMS 10.3 Tutorial

MODFLOW – Generating Data from Solids

Using solid models to represent complex stratigraphy with MODFLOW



Objectives

Learn the steps necessary to convert solid models to MODFLOW data on a 3D grid, and adjust elevations associated with the grid to match the elevations defined by the solid models.

Prerequisite Tutorials

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

Required Components

- Sub-surface Characterization
- Grid Module
- Map Module

Time

- 40–60 minutes

1 Introduction

Complex stratigraphy can be difficult to simulate in MODFLOW models. MODFLOW uses a structured grid that requires each grid layer be continuous throughout the model domain. This makes it difficult to explicitly represent common features such as pinchouts and embedded seams in a MODFLOW model.

Solid models can be used to represent arbitrarily complex stratigraphy. Figure 1 shows a cross section through a solid model where different stratigraphic units pinch out. Designing a MODFLOW compatible grid for this type of stratigraphy is very difficult.

This tutorial covers the steps necessary to convert solid models (Figure 1) to MODFLOW data. The elevations associated with the finite-difference grid will be adjusted to match the elevations defined by the solid models. The material assigned to each grid cell will be inherited from the solid encompassing the cell. Figure 2 shows a MODFLOW compatible grid of the cross section shown in Figure 1.

Figure 1 Cross section through a solid model

One of the main benefits of using solid models to define stratigraphy for MODFLOW models is that it provides a grid-independent definition of the layer elevations that can be used to immediately re-create the MODFLOW grid geometry after any change to the grid resolution. Solid models of stratigraphy can be easily created in GMS using the "horizons approach". The tutorial entitled "Stratigraphy Modeling – Horizons and Solids" explains how to create solid models using GMS.

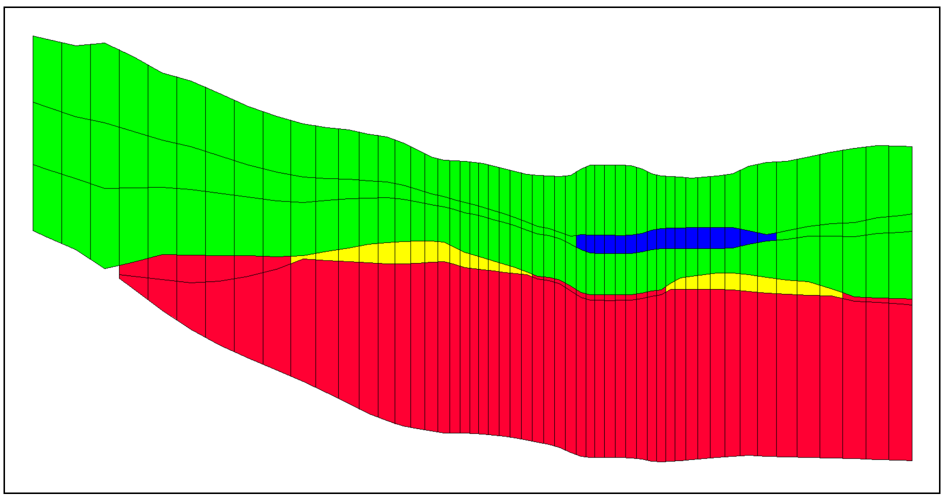


Figure 2 Finite difference grid with elevations and materials inherited from the solid model

This tutorial discusses and demonstrates opening a file containing solids data, using the **Solids → MODFLOW** command with the *Grid Overlay* and *Boundary Matching* options, assigning grid layers to the solids, fixing problems associated with thin cells, converting the conceptual model to MODFLOW and running MODFLOW, converting the solids to HUF data, and convert the conceptual model again and running MODFLOW.

1.1 Getting Started

Do the following to get started:

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

2 Importing the Solids

First, import a file containing a set of solids for the site being modeled:

1. Click **Open** to bring up the *Open* dialog.
2. Select "Project Files (*.gpr)" from the *Files of type* drop-down.
3. Browse to the *Tutorials\MODFLOW\sol2mf* directory and select "start.gpr".
4. Click **Open** to import the file and close the *Open* dialog.

The imported cross sections show the stratigraphy for the example site (Figure 3).

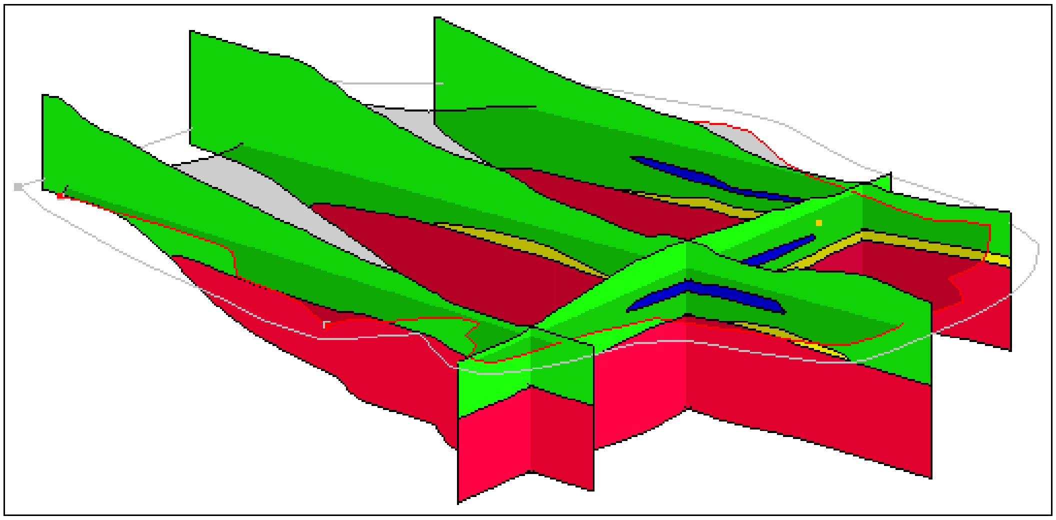


Figure 3 Initial view after opening the project

There are five different solids in this project file. There are two main units labeled upper_aquifer (green) and lower_aquifer (red). There are two silty-clay (blue) units inside of the upper_aquifer, and there is a clay (yellow) unit between the upper_aquifer and lower_aquifer.

3 Boundary Matching Versus Grid Overlay

There are three options when using the **Solids → MODFLOW** command: the *Boundary Matching* option, the *Grid Overlay* option, and the *Grid Overlay with K Equivalent* option (Figure 4).

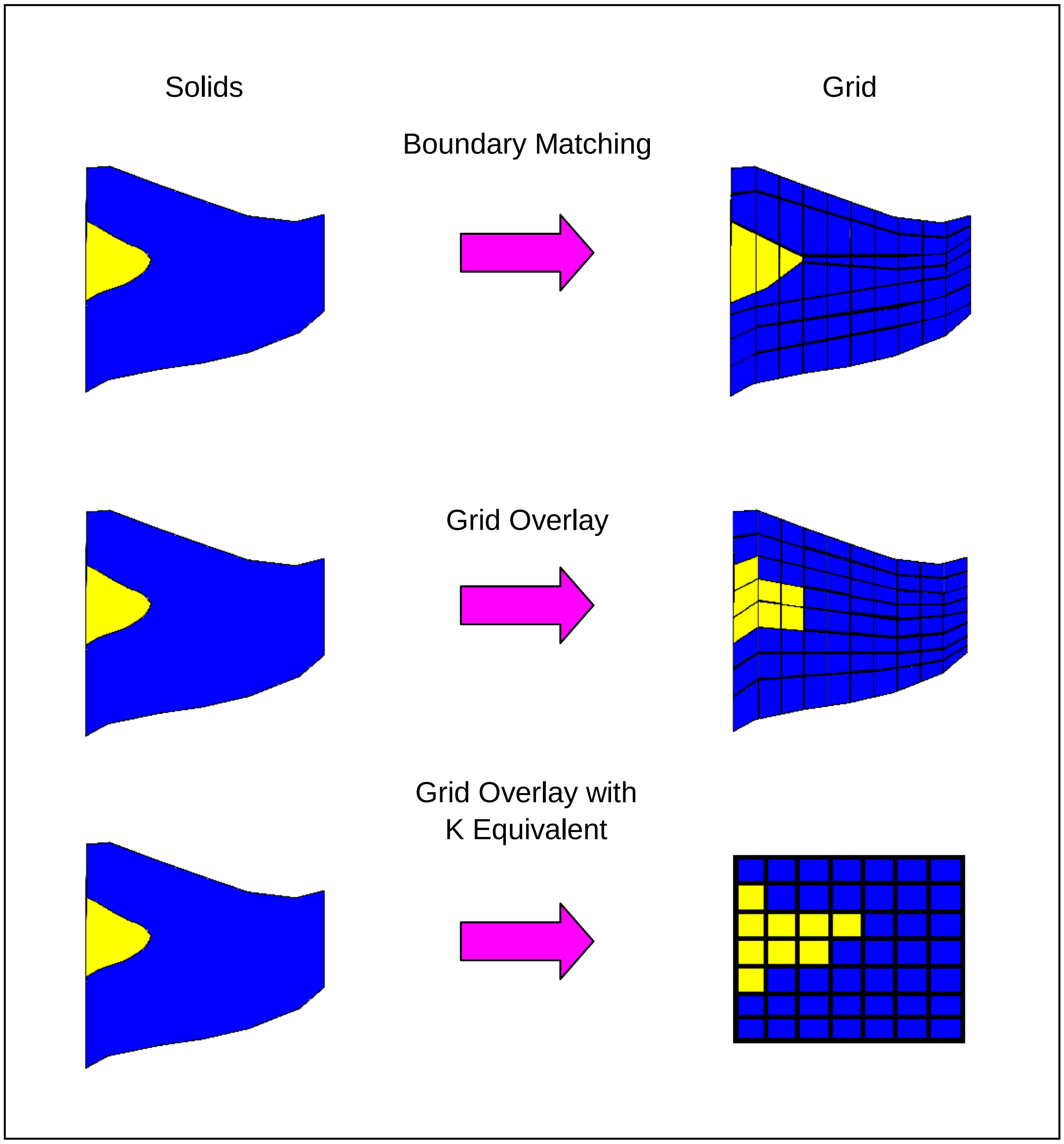


Figure 4 Solids → MODFLOW options illustrated (side view)

3.1 Boundary Matching

With the *Boundary Matching* option, the top and bottom of the grid are deformed to match the tops and bottoms of the solids. The interior grid layers are also deformed to match the boundaries of the solids. The grid cell materials are set to match the material of the solid of the grid cell center.

This option results in a close fit between the grid and the solids, but it can result in thin cells which can cause stability problems or dry cell issues when running MODFLOW. This option requires determining which grid layers should be associated with which solids.

3.2 Grid Overlay

The *Grid Overlay* option deforms the top and bottom of the grid to match the tops and bottoms of the solids. The interior grid layer boundaries are deformed to be evenly spaced between the top and bottom of the grid using a simple linear interpolation. The interior grid layers are not changed to match the solid boundaries. As with the *Boundary Matching* option, the grid cell materials are set to match the material of the solid of the grid cell center.

This option does not result in as close a fit between the grid and the solids as the boundary matching option, but it may avoid the thin cell problems associated with the *Boundary Matching* option. The *Grid Overlay* option does not require assigning grid layer ranges to each solid.

3.3 Grid Overlay with K Equivalent

This option is very similar to the *Grid Overlay* option. One of the problems with the *Grid Overlay* option is that if there is a relatively thin layer in the solids and the layer does not happen to encompass any cell centers or it encompasses few cell centers, the layer will be under-represented in the MODFLOW grid. This becomes particularly important if the layer is meant to represent a low permeability layer. For such cases, the *Grid Overlay with K Equivalent* (or Grid Overlay with Keq) option may give superior results.

The Grid Overlay with Keq method is identical to the *Grid Overlay* method in terms of how the elevations of the grid cells are defined. The two methods differ in how the material properties are assigned. Rather than simply assigning materials based on which solid encompasses the cell centers, the Keq method attempts to compute a custom K_h and K_v value for each cell.

When assigning the material properties to a cell, GMS computes the length of each solid in the cell (from a vertical line at the cell center that intersects the solids) and computes an equivalent K_h, K_v, and storage coefficient for the cell that takes into account each of the solids in the cell. Thus, the effect of a thin seam in a cell would be included in the K_h and K_v values for the cell.

4 Solids → MODFLOW Using Grid Overlay

This tutorial will first examine the *Grid Overlay* option. With this option, all that is needed are a set of solids and a grid in the same location.

4.1 Displaying the 3D Grid

The grid was imported as part of the project, but the display of the grid cells was turned off. To turn it back on, do the following:

1. In the Project Explorer, turn on the " 3D Grid Data" folder.
2. Expand the " 3D Grid Data" folder by clicking on the plus symbol next to it.
3. Turn on the " grid" item within that folder.

The 3D grid should now be visible (Figure 5).

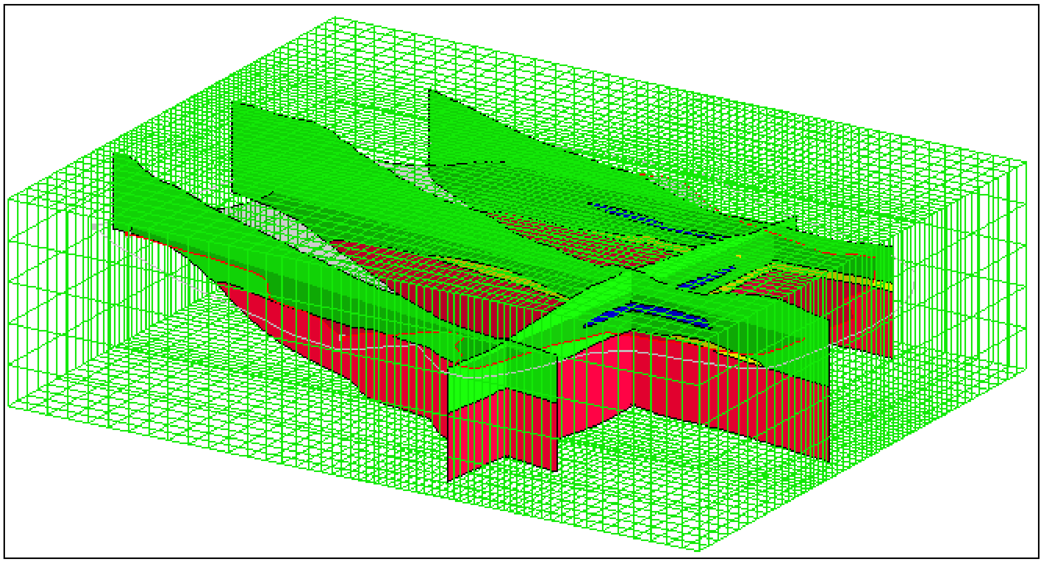


Figure 5 Initial view with 3D grid visible

4.2 Initializing MODFLOW

It is necessary to initialize MODFLOW before executing the **Solids** → **MODFLOW** menu command.

4. Right-click on " grid" and select **New MODFLOW…** to bring up the *MODFLOW Global/Basic Package* dialog.
5. Click **OK** to accept the defaults and close the *MODFLOW Global/Basic Package* dialog**.**

Normally, the starting heads would be set here. Since they are set to be equal to the grid top elevation (300) by default, there is no need to do so in this case.

4.3 Activating Cells

It is necessary to inactivate the cells outside the model domain.

1. In the Project Explorer, select the " Map Data" folder to make it active.
2. Select *Feature Objects* | **Activate Cells in Coverage(s)**.

The cells outside the model domain will disappear (Figure 6).

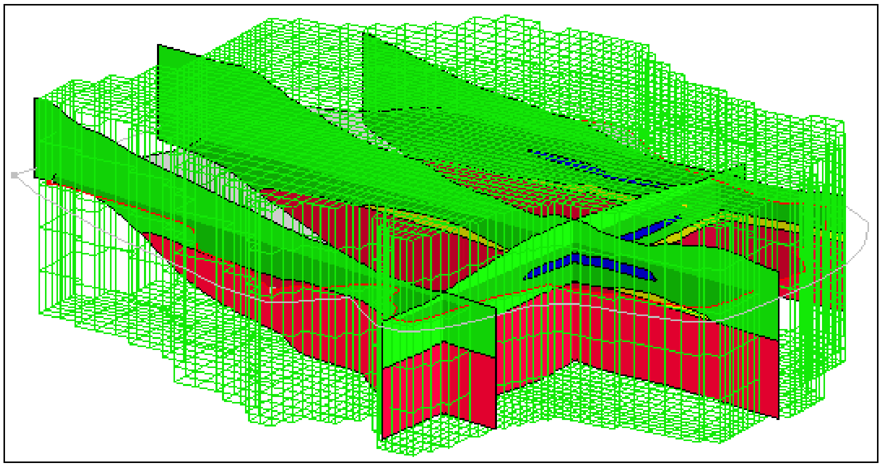


Figure 6 3D grid showing only active cells

4.4 Solids → MODFLOW

1. In the Project Explorer, select the " Solid Data" folder to make it active. Notice that labels for each solid appear (Figure 7).
2. Select *Solids* | **Solids → MODFLOW…** to bring up the *Solids →MODFLOW* dialog.
3. Select *Grid Overlay* under *Solids →MODFLOW Mode*.
4. Click **OK** to close the *Solids →MODFLOW* dialog and execute the deformation.

The deformation may take a few moments to complete. The 3D grid should appear deformed to match the top and bottom of the solids (Figure 7).

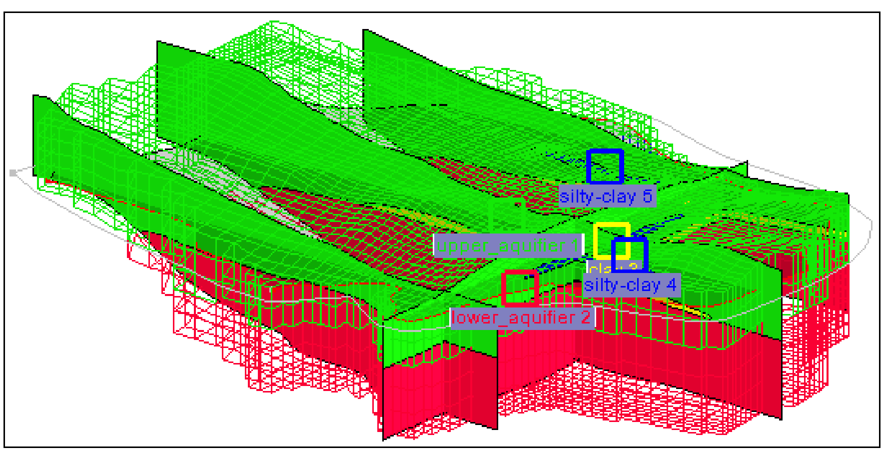


Figure 7 The 3D grid has been deformed

4.5 Viewing the Grid

Do the following to examine the grid:

1. Click **Display Options** to bring up the *Display Options* dialog.
2. Select " 3D Grid Data" from the list on the left.
3. On the *3D Grid* tab, turn on *Cell faces*.
4. Click **OK** to close the *Display Options* dialog.
5. Select the " 3D Grid Data" folder to make it active.

Notice that the solid cross sections are now mostly obscured from view by the grid, but are still poking out in places. Looking closely, notice that the top of the grid matches the top of the solid cross sections quite well. The grid and cross sections should appear as shown in Figure 8.

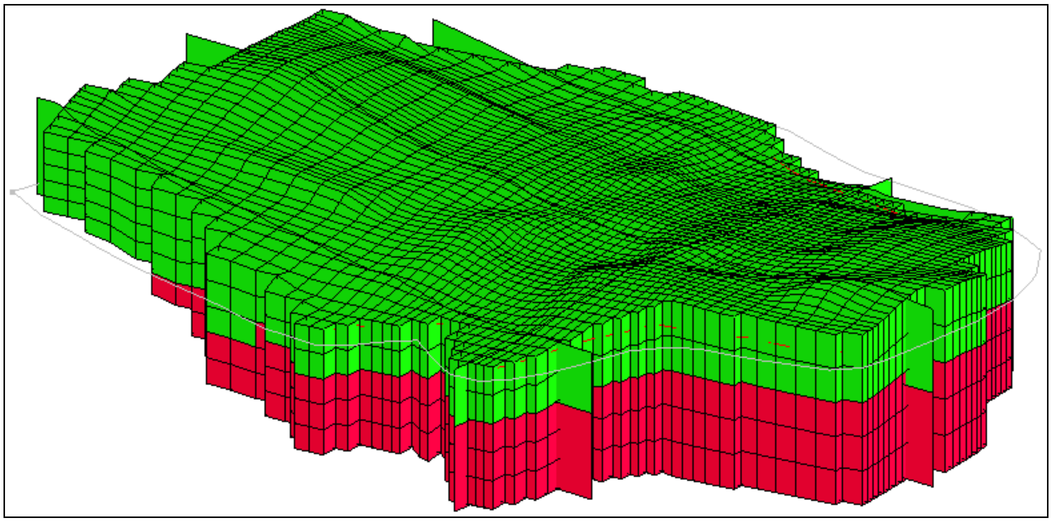


Figure 8 After executing Solids → MODFLOW using grid overlay

Do to the following to look at the grid from the side:

1. Switch to **Ortho Mode** .
2. Using the **Select Cells** tool, select a cell somewhere near the middle of the grid.
3. Switch to **Front View** .

The solid cross sections are in front of the grid row.

4. In the Project Explorer, turn off the " Solid Data" folder.
5. In the Mini Grid Toolbar, use the arrow buttons to view the grid along different rows.

The grid at row 14 should appear similar to Figure 9.

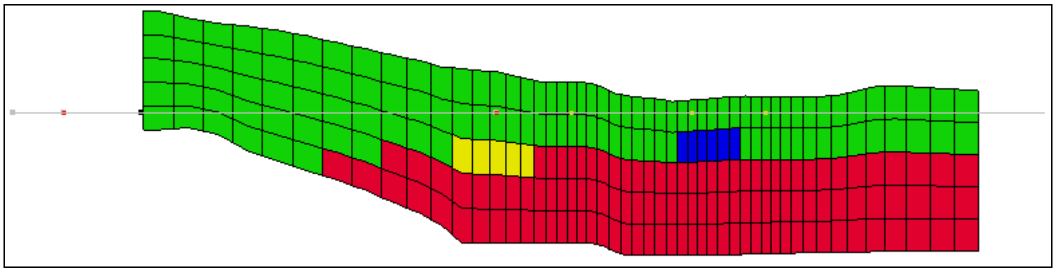


Figure 9 Grid row 14 after Solids → MODFLOW using grid overlay

Feel free to continue reviewing the MODFLOW model at this point before moving on.

5 Solids → MODFLOW Using Boundary Matching

The *Boundary Matching* option results in a close fit between the solid boundaries and the grid layer, but it requires a bit more work.

5.1 Layer Ranges

It is necessary to assign a layer range to each of the solids before converting the solids to MODFLOW data using the *Boundary Matching* option. The layer range represents the consecutive sequence of layer numbers in the MODFLOW grid that should coincide with the solid model.

A sample set of layer range assignments is shown in Figure 10. The first example, (a), is a case where each solid is continuous through the model domain with no pinchouts. Each of the solids is given a layer range defined by a beginning and ending grid layer number. The resulting MODFLOW grid is shown in Figure 10(b).

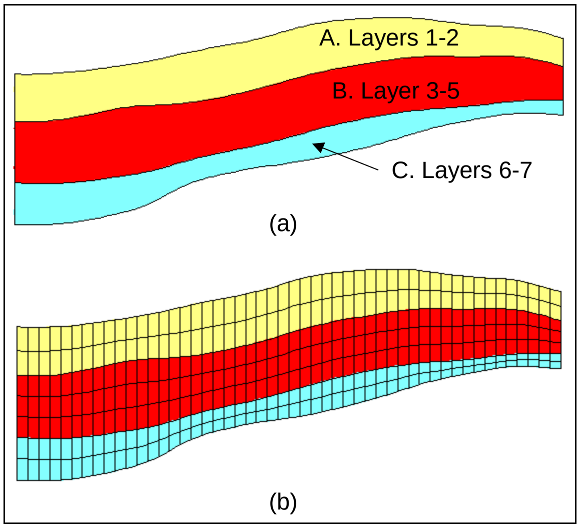


Figure 10 (a) A set of simple solids with grid layer assignments
(b) The MODFLOW grid resulting from the layer assignments

A more complex case with pinchouts is illustrated in Figure 11(a). Solid A is given the layer range 1–4, and the enclosed pinchout (solid B) is given the layer range 2–2. The set of grid layers within the defined range that are actually overlapped by the solid may change from location to location. The layer range represents the set of grid layers potentially overlapped by the solid anywhere in the model domain.

For example, on the left side of the problem shown in Figure 11(a), solid A covers grid layers 1, 2, 3 and 4. On the right side of the model, solid A is associated with grid layers 1, 3 and 4 since the enclosed solid (solid B) is associated with layer 2. Likewise, Solid C is associated with grid layers 5 and 6 on the left side of the model but only with layer 6 on the right side of the model where solid D is associated with layer 5. The resulting MODFLOW grid is shown in (b).

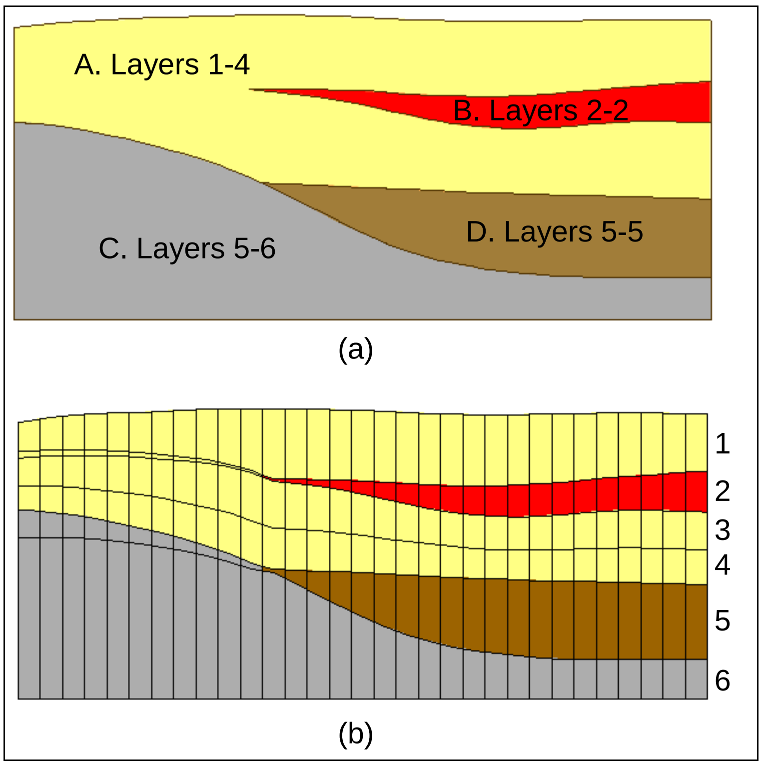


Figure 11 (a) Grid layer assignments for a set of solids with pinchouts
(b) The MODFLOW grid resulting from the layer assignments

When assigning layer ranges to solids, care must be taken to define associations that are topologically sound. For example, since solid B in Figure 11(a) is enclosed by solid A, solid B could not be assigned a layer range that is outside the layer range of solid A.

5.2 Assigning Layers to Solids

Now it is possible to assign the grid layers to the solids. Figure 12 is a cross section through the site. Notice that the project must have a minimum of five grid layers in order to represent all of the layers present in this cross-section. In this case, the upper_aquifer (green) will be assigned to layers 1–3. The silty-clay (blue) will be assigned to layer 2.

The clay (yellow) will be assigned to layer 4, and the lower_aquifer (red) will be assigned layers 4–5.

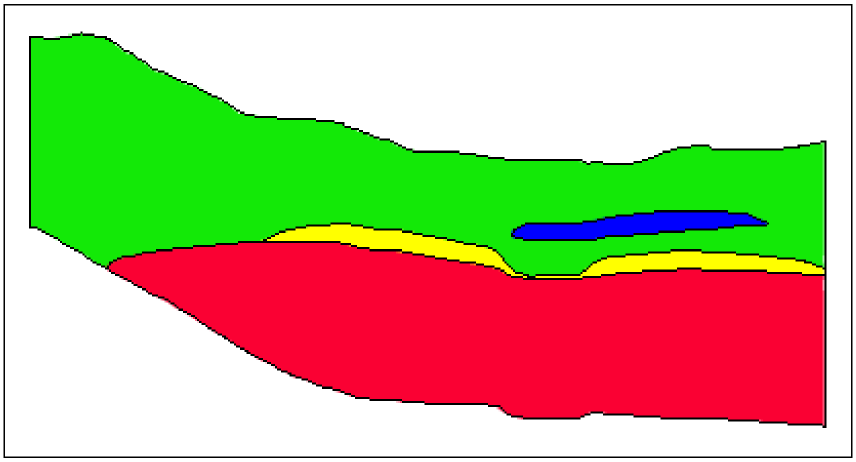


Figure 12 Cross-section through the model domain

1. In the Project Explorer, expand the " Solid Data" folder if necessary.
2. Double-click on " upper_aquifer 1" solid in the Project Explorer to bring up the *Properties* dialog.
3. Enter "1" for *Begin layer* and "3" for *End layer*.
4. Click **OK** to close the *Properties* dialog.
5. Repeat steps 2–4 for the remaining solids, using the values shown in the following table.

	upper_aquifer 1	lower_aquifer 2	clay 3	silty-clay 4	silty-clay 5
Begin layer	1	4	4	2	2
End layer	3	5	4	2	2

5.3 Solids → MODFLOW

1. Select *Solids* | **Solids → MODFLOW…** to bring up the *Solids → MODFLOW* dialog.
2. Under *Solids → MODFLOW Mode*, select *Boundary Matching*.
3. Click **OK** to close the *Solids → MODFLOW* dialog and initiate the conversion.

The **Solids → MODFLOW…** command may take a few moments to complete.

6 Viewing the Grid

See how the grid has changed by doing the following

1. Select the "3D Grid Data" folder to make it active.
2. Switch to **Plan View**.
3. Turn on **Ortho Mode**.
4. Using the **Select Cells** tool, select a cell somewhere near the middle of the grid.
5. Switch to **Front View**.
6. Use the arrow buttons in the Mini Grid Toolbar, to view row 30 (Figure 13).

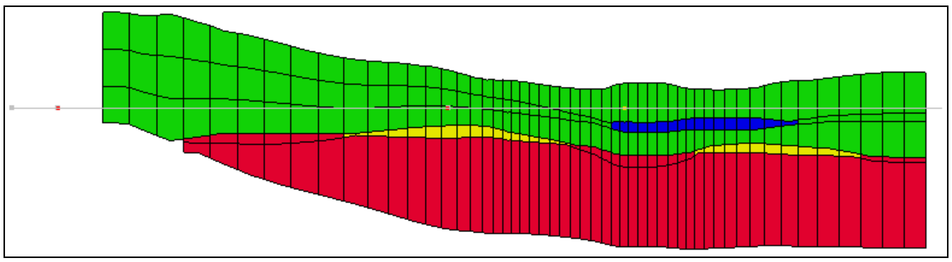


Figure 13 Row 30 of grid after Solids → MODFLOW using boundary matching

Notice that the second layer has both silty-clay (blue) and upper_aquifer (green) materials assigned to it.

7. Use the arrow buttons to view the grid along different rows.
8. Switch to **Side View**.
9. Use the arrow buttons in the Mini-Grid Toolbar to view the grid along different columns.
10. Switch back to **Front View**.

7 Thin Cells

The purpose of boundary matching is to ensure that each upper and lower boundary defined by the solid model is precisely matched by a layer boundary in the MODFLOW grid. As a result of this approach, thin cells often occur where solids pinchout. Notice the thin cells on the edges of the clay (yellow) and silty-clay (blue) solids in Figure 13. If wanting to limit the effect of the thin cells in the model grid, set a minimum target thickness for each of the solids.

7.1 Assigning Minimum Thickness

To limit the thin cells in the model, do the following:

1. Double-click on the "upper aquifer 1" solid in the Project Explorer to bring up the *Properties* dialog.

2. Enter "20" for *Target min. cell thickness*.

3. Click **OK** to exit the *Properties* dialog.

4. Repeat steps 1–3 for each of the remaining solids.

7.2 Top Cell Bias

Another problem that may occur with boundary matching is that the cells in the top layer of the grid may be too thin and subject to wetting and drying. To ensure that the top layer of the grid is sufficiently thick, do the following:

1. Double-click on the "upper_aquifer 1" solid in the Project Explorer to bring up the *Properties* dialog.

2. Select "Yes" from the *Use top cell bias* drop-down.

3. Click **OK** to exit the *Properties* dialog.

4. Select *Solids* | **Solids → MODFLOW…** to bring up the *Solids → MODFLOW* dialog.

5. Select **OK** to close the *Solids → MODFLOW* dialog and execute the **Solids → MODFLOW** menu command.

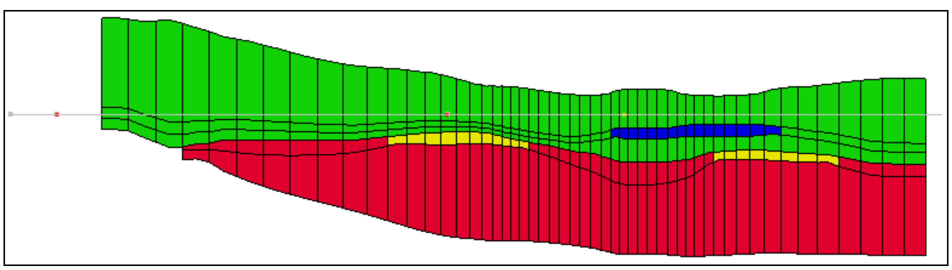


Figure 14 Row 30 of the model grid using target minimum thickness and top cell bias

The grid should now look similar to Figure 14. Notice how the top row is thicker, and the thin cells in the yellow and blue areas are now thicker.

8 Converting the Conceptual Model

It is now possible to finish developing the MODFLOW model. In the interest of time, the conceptual model has already been built. It was imported with the project file. For more information on conceptual models, refer to the "MODFLOW – Conceptual Model Approach" tutorial.

1. In the Project Explorer, select the "Map Data" folder to make it active.

2. Switch to **Plan View** .
3. Select *Feature Objects* | **Map → MODFLOW** to bring up the *Map → MODFLOW* dialog.
4. Select *All applicable coverages* and click **OK** to close the *Map → MODFLOW* dialog.

The grid should appear similar to Figure 15.

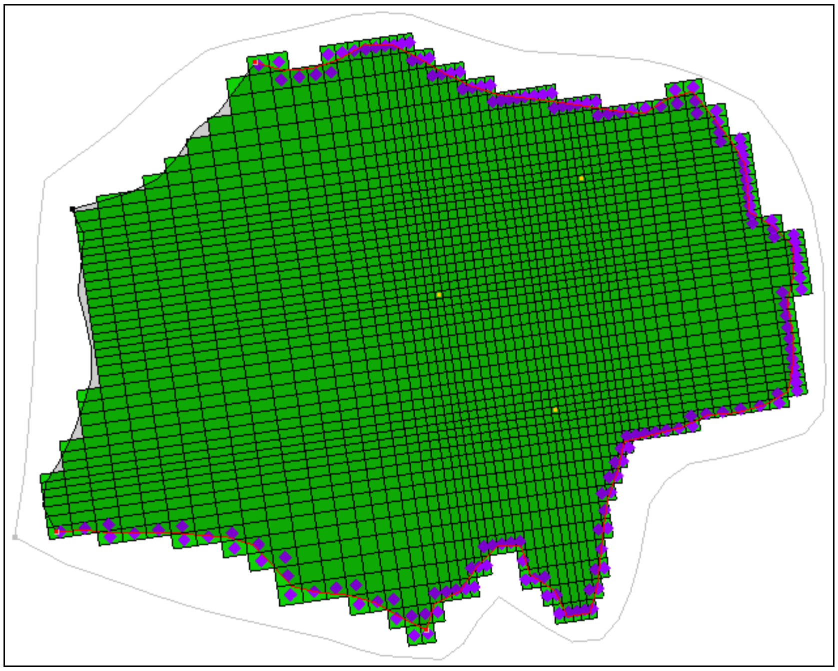


Figure 15 Plan view after map converted to MODFLOW

8.1 Using Materials to Define Hydraulic conductivity

Next, set the option for MODFLOW to use the material assigned to the grid cell to define the hydraulic conductivity for the cell.

1. Select *MODFLOW* | **LPF – Layer Property Flow** to bring up the *LPF Package* dialog.
2. In the *Layer property entry method* section, select *Use Material IDs*.
3. In the *Layer data* section, click **Material Properties…** to bring up the *Materials* dialog .
4. On the *MODFLOW* tab, select each material in the table below and enter the values for the properties shown in the table below:

Material Name	*Horizontal k (ft/d)*	*Vert. anisotropy (Kh / Kv)*
upper_aqufier	15.0	3.0
lower_aquifer	30.0	3.0
clay	0.5	3.0
silty-clay	1.0	3.0

5. Click **OK** to exit the *Materials* dialog.
6. Click **OK** to exit the *LPF Package* dialog.

9 Running MODFLOW and Viewing the Solution

It is now possible to run MODFLOW. Before doing so, save the MODFLOW simulation.

1. Select *File* | **Save As…** to bring up the *Save As* dialog.
2. Select "Project Files (*.gpr)" from the *Save as type* drop-down.
3. Enter "run1_lpf.gpr" as the *File name*.
4. Click **Save** to save the file and close the *Save As* dialog**.**
5. Select *MODFLOW* | **Run MODFLOW** to bring up the *MODFLOW* model wrapper dialog.
6. When MODFLOW has finished running, turn on *Read solution on exit* and *Turn on contours (if not on already)*.
7. Click **Close** to close the *MODFLOW* model wrapper dialog and import the MODFLOW solution.
8. Click **Display Options** to bring up the *Display Options* dialog.
9. Select " 3D Grid Data" from the list on the left.
10. On the *3D Grid* tab, turn off *Cell faces*.
11. Click **OK** to exit the *Display Options* dialog.

The head contours are visible on the grid (Figure 16). Cycle through the layers to see how the head contours change within the different layers. Switch to **Side View** to see the contours on the rows or columns.

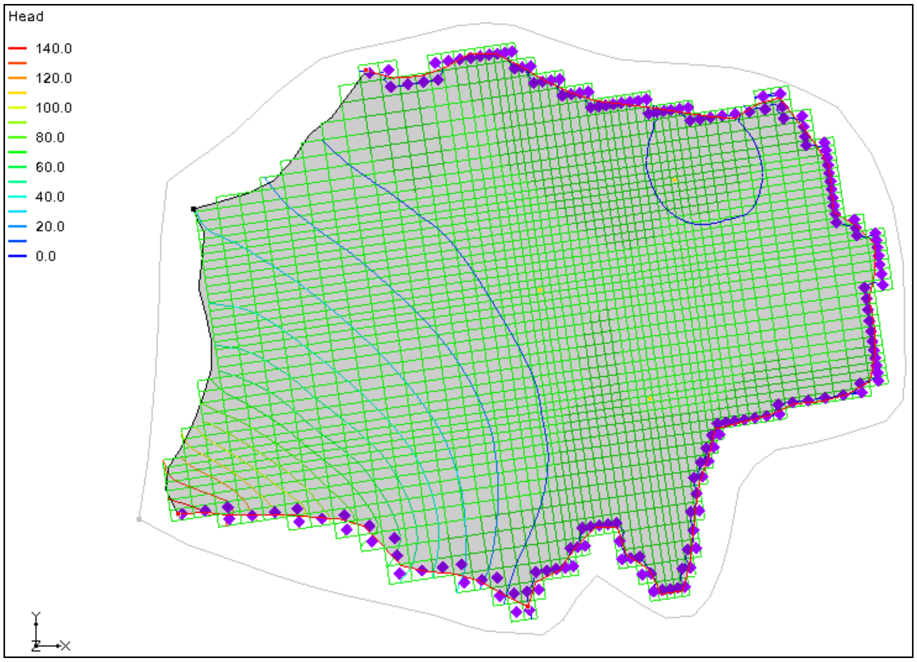


Figure 16 MODFLOW solution with contours visible

10 Solids → HUF

Now use the HUF package in MODFLOW to define the hydraulic properties of the grid cells instead of the LPF package. This package is designed to represent complex stratigraphic relationships in a grid independent fashion.

The hydrostratigraphy is represented using a set of hydrogeologic units. Each unit is defined by two arrays: one for the top elevation and one for the thickness. The thickness values can be set to zero in regions of the model where the unit is not present. When MODFLOW is executed, each cell is compared to the corresponding unit elevation arrays and equivalent hydraulic properties are assigned to the cell. Figure 17 shows an example of HUF units on a MODFLOW grid.

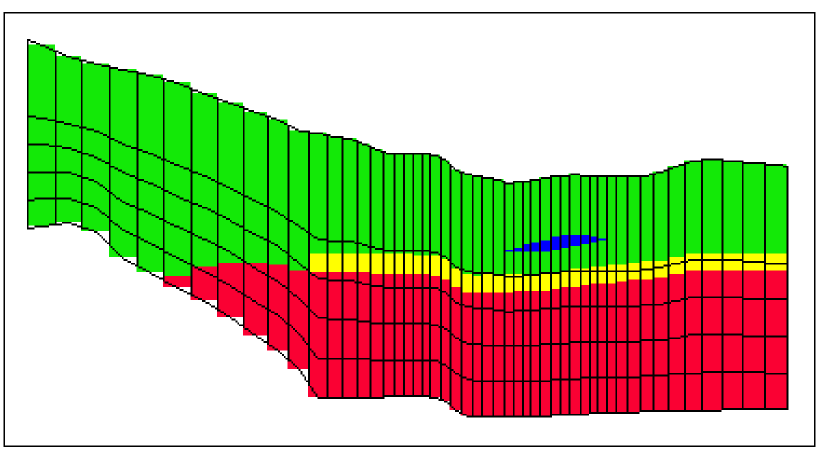


Figure 17 HUF data

10.1 Selecting the HUF Package

First, select the HUF package as the flow package.

1. Select *MODFLOW* | **Global Options** to bring up the *MODFLOW Global/Basic Package* dialog.
2. Click **Packages…** to bring up the *MODFLOW Packages / Processes* dialog.
3. In the *Flow package* section select *HUF – Hydrogeologic Unit Flow.*
4. Click **OK** to exit the *MODFLOW Packages / Processes* dialog.
5. Click **OK** to exit the *MODFLOW Global/Basic Package* dialog.

10.2 Converting the Solids to HUF Data

It is now possible to convert the solids to HUF data. However when the **Solids → MODFLOW** command ran, some of the cells were inactivated in layers 4 and 5. It is necessary for those cells to be active for this new model.

1. In the Project Explorer, select the " Map Data" folder to make it active.
2. Select *Feature Objects* | **Activate Cells in Coverage(s)**.
3. In the Project Explorer, select the " Solid Data" folder to make it active.
4. Select *Solids* | **Solids → HUF** to bring up the *Solids → HUF* dialog.
5. Turn on *Adjust grid cell elevations*.

The MODFLOW top elevation array of the top layer and the bottom elevation array of the bottom layer are adjusted to match the tops and bottoms of all the solids. The interior top and bottom elevation arrays are assigned based on the proportions entered in the *Elevation bias* spreadsheet. The entire grid depth for each grid column is distributed according to the entries in the spreadsheet for each layer.

6. In the *Elevation bias* spreadsheet, enter "0.4" in the *Fraction* column of row *1*.
7. Click **OK** to execute the **Solids → HUF** command and close the *Solids → HUF* dialog.

10.3 Viewing the HUF Data

To view the HUF data, do the following:

1. In the Project Explorer, select the " 3D Grid Data" folder to make it active.
2. Click **Display Options** to bring up the *Display Options* dialog.
3. Select "3D Grid Data" from the list on the left.

4. On the *3D Grid* tab, select "Specified" from the *Color* drop-down under *Cell edges*.
5. On the *MODFLOW* tab, turn on *Display hydrogeologic units*.
6. Click **OK** to exit the *Display Options* dialog.

The display should appear similar to Figure 18.

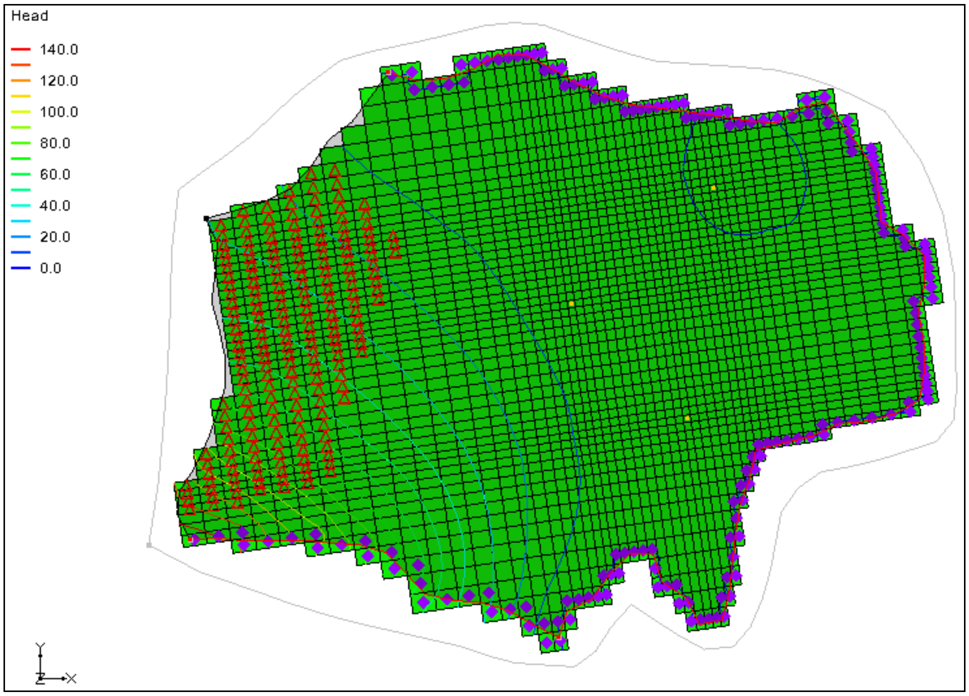


Figure 18 The HUF data is now visible

7. Using the **Select Cells** tool, select a cell somewhere in the middle of the grid.
8. Switch to **Front View**.
9. Use the arrow buttons in the Mini-Grid Toolbar to view the grid along different columns (Figure 19).

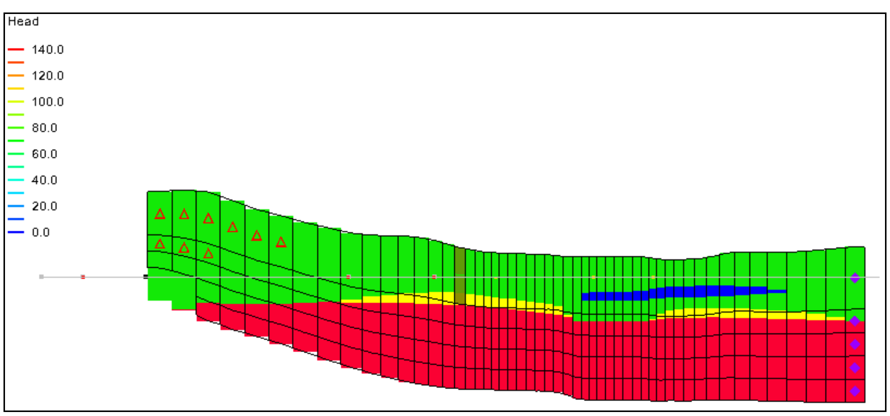


Figure 19 HUF data visible in front view

10.4 Converting the Conceptual Model

It is necessary to convert the conceptual model again to ensure that any cells that were inactive will have the correct boundary conditions.

1. Switch to **Plan View**.
2. In the Project Explorer, select the " Map Data" folder to make it active.
3. Right-click on the " MODFLOW" conceptual model and select **Properties** from the menu to bring up the *Conceptual Model Properties* dialog.
4. Select "HUF" from the *Flow package* drop-down.
5. Click **OK** to exit the *Conceptual Model Properties* dialog.
6. Select *Feature Objects* | **Map → MODFLOW** to bring up the *Map → MODFLOW* dialog.
7. Select *All applicable coverages* and click **OK** to execute the **Map → MODFLOW** command and close the *Map → MODFLOW* dialog.

10.5 Running MODFLOW

It is now possible to save the project and run MODFLOW.

1. Select *File* | **Save As…** to bring up the *Save As* dialog.
2. Select "Project Files (*.gpr)" from the *Save as type* drop-down.
3. Enter "run1_huf.gpr" as the *File na*me.
4. Click **Save** to save the project and close the *Save As* dialog.
5. Select *MODFLOW* | **Run MODFLOW** to bring up the *MODFLOW* model wrapper dialog.
6. When MODFLOW has finished running, turn on *Read solution on exit* and *Turn on contours* (if not on already).
7. Click **Close** to close the *MODFLOW* model wrapper dialog and import the MODFLOW solution..

The head contours are visible on the grid (Figure 20). Some red triangles may appear on certain grid cells. These cells have gone dry (the water table is below the bottom of the cell) in this simulation. Cycle through the layers to see how the head contours change within the different layers. It is also possible to switch into side view to see the contours on the rows or columns.

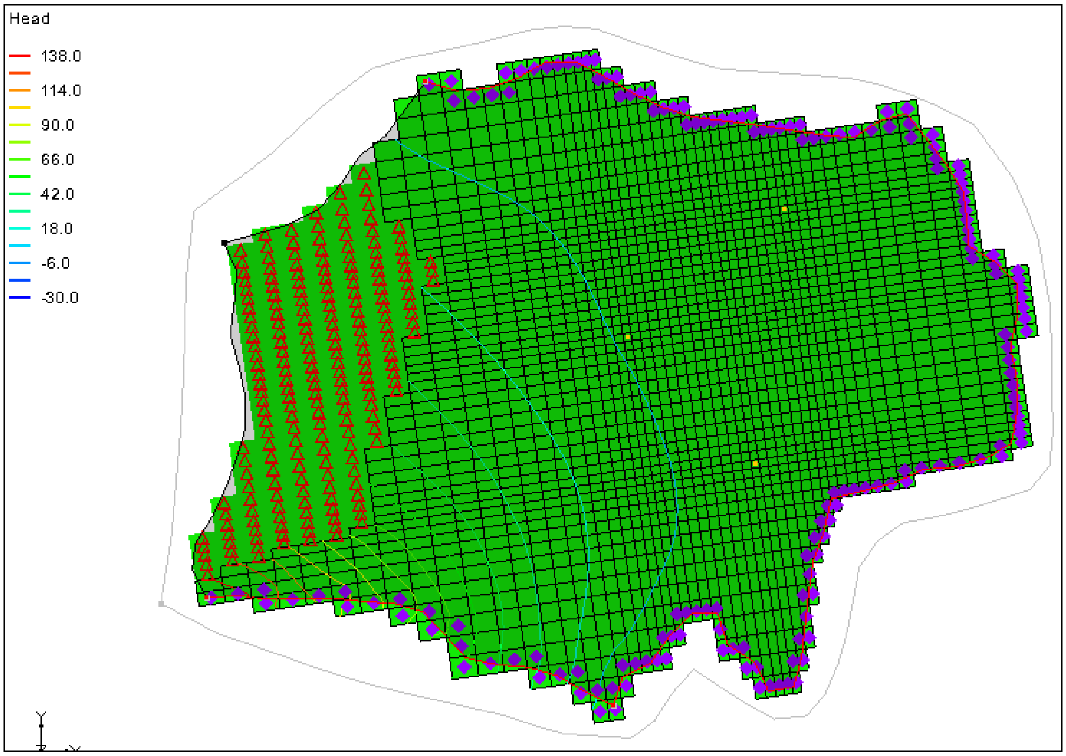


Figure 20 Head contours of the HUF data after MODFLOW is run

11 Conclusion

This concludes the "MODFLOW – Generating Data from Solids" tutorial. The following concepts were discussed and demonstrated:

- Solids can be used to define the MODFLOW layer elevations. They can also be used to create MODFLOW HUF data.
- It is necessary to assign layer ranges to the solids before using them to create a layered grid if using the **Solids → MODFLOW** *Boundary Matching* option.
- It is possible to use a minimum thickness to avoid thin cells. It is also possible to specify a top cell bias to make the top grid layer thicker.
- If using solids to define the MODFLOW layer data, it is probably best to use the Material IDs approach to define the hydraulic properties of grid cells based on their material.

