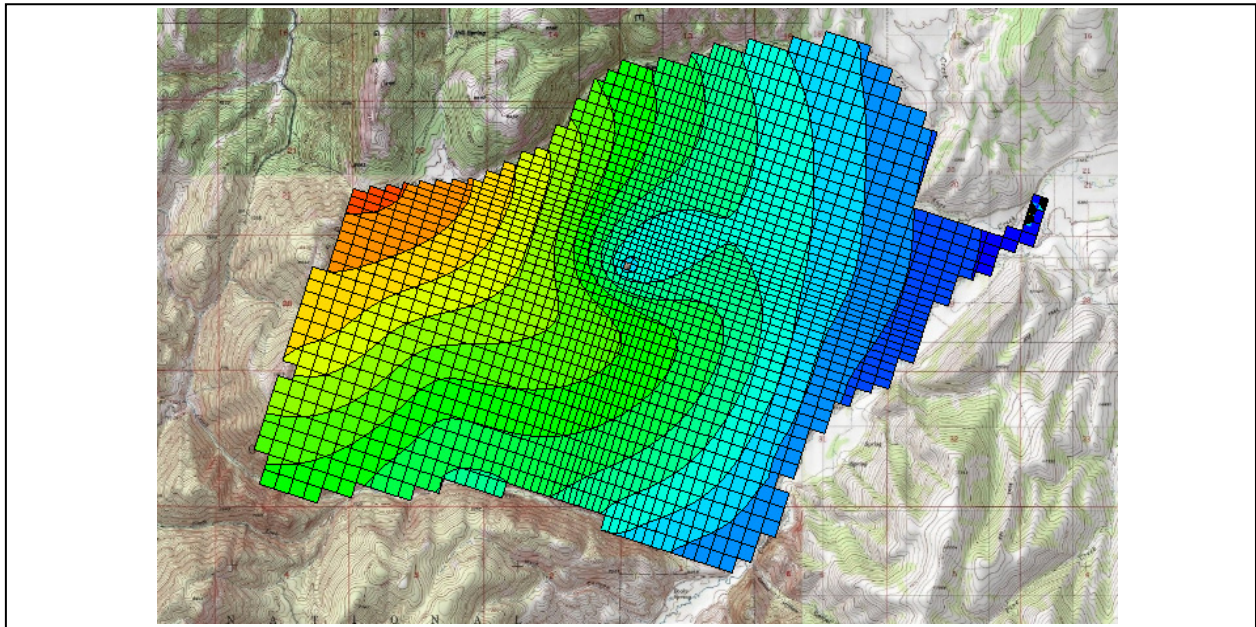


GMS 8.2 Tutorial **MODFLOW – LAK Package**

Use the MODFLOW Lake (LAK3) package to simulate mine dewatering



Objectives

Learn the steps involved in using the MODFLOW Lake (LAK3) package interface in GMS. Use the LAK3 package to simulate the dewatering of a deep excavation associated with a mining operation.

Prerequisite Tutorials

- None

Required Components

- Sub-surface Characterization
- Geostatistics
- GIS, Grid
- Map
- MODFLOW

Time

- 30-60 minutes



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2 Introduction

This tutorial illustrates the steps involved in using the Lake (LAK3) Package as part of a MODFLOW simulation. The Lake Package is a more sophisticated alternative to the typical approach of using the General Head Package to simulate the lake-aquifer interactions. Comparing the Lake package to the GHB package is similar to comparing the River package to the Stream package. With the GHB package, the user defines the stage in the lake and MODFLOW computes the flow required to maintain that stage, given the head losses that occur as the water flows through the lake bottom sediments. With the Lake package, the stage in the lake is computed by MODFLOW based on the water budget. The water budget is a function of inflow/outflow resulting from head differences between the aquifer and the lake. The flow budget also includes the effect recharge, evaporation, and anthropogenic inflow and discharge. The storage capacity of the lake is determined automatically based on the lake geometry. The Lake Package can be used for either steady state or transient simulations.

The Lake package represents a lake using a set of inactive cells as shown in Figure 1:

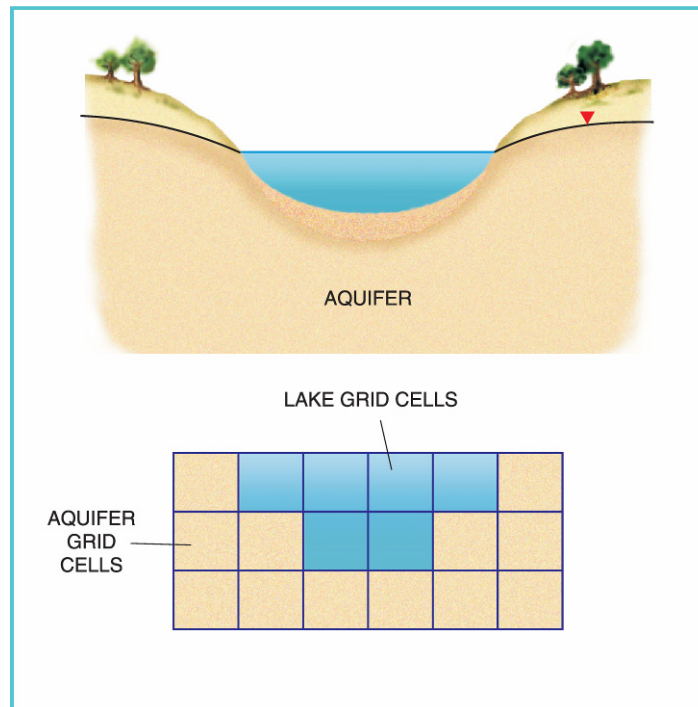


Figure 1. Cell discretization used by the Lake package (taken from Merritt, L.M. and Konikow, L.F., 2000, *Documentation of a computer program to simulate lake-aquifer interaction using the MODFLOW ground-water flow model and the MOC3D solute-transport model: U.S. Geological Survey Water-Resources Investigations Report 00-4167*).

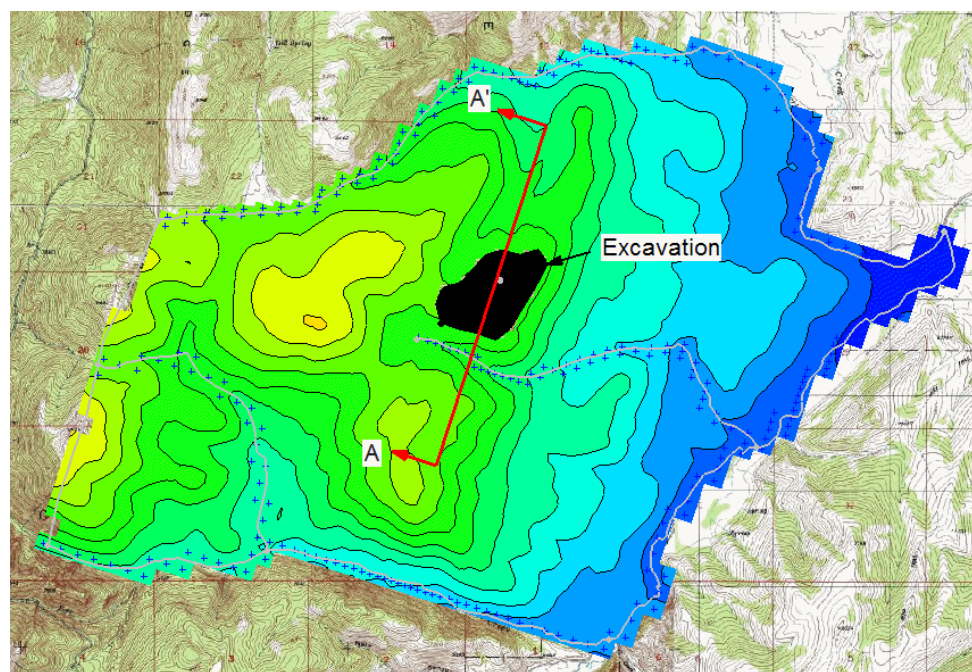
The blue cells correspond to the lake and have an IBOUND value of zero (the cells are “inactive”). Defining the lake in this fashion allows the lake to interact with lower layers and it allows lateral inflow to the lake.

The lake is also assumed to have lakebed sediments which affect the flow between the aquifer and the lake. The effect of the lakebed sediments is represented with a lakebed leakance term which includes the thickness and the hydraulic conductivity. The flow from the aquifer into the lake is a function of both the lakebed leakance and the conductance of aquifer cells adjacent to the lake.

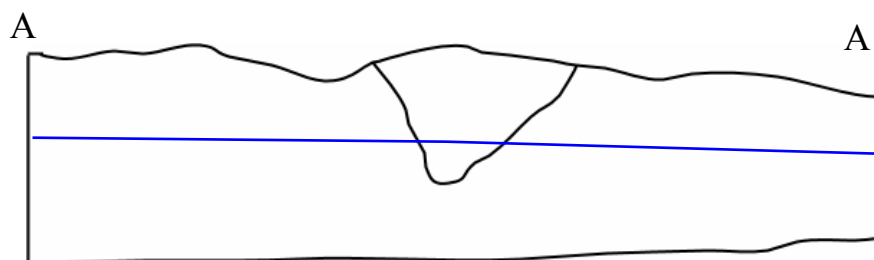
The Lake Package includes an option for simulating “sublakes”. This option makes it possible for the lake to partition into smaller, separated lakes as the lake stage drops.

2.1 Problem Description

In this tutorial exercise we will be using the Lake Package to simulate the dewatering of a deep excavation associated with a mining operation. The model domain is shown in Figure 2. The contours in the map represent ground surface elevation. The aquifer consists primarily of fractured limestone. An excavation has been proposed in the region indicated in the figure. When fully excavated, the mine will be approximately 700 meters wide and 1200 meters long, and will be about 600 meters deep at the deepest point. The objective of this exercise is to estimate the amount of water that will need to be pumped out of the bottom of the excavation in order to dewater the site.



(a)



(b)

Figure 2. Map of region containing the proposed mine (a) Plan view (b) Cross-section corresponding to A-A' with water table shown.

To perform the simulation, we will first read in a GMS project file containing a MODFLOW simulation of the site calibrated to existing conditions. We will then turn on the Lake Package option and use a TIN to adjust the MODFLOW grid to define a “lake” coincident with the proposed excavation. We will first estimate a pumping rate for dewatering the excavation and assign that pumping rate as a user-specified “outflow” from the lake. We will run MODFLOW and examine the resulting stage in the lake. We then adjust the pumping rate and run the model again. This process will be repeated until we find a pumping rate that results in a stage corresponding to the bottom ten meters of the excavation (~1810 m).

NOTE: The “mine” and excavation described in this tutorial are hypothetical. No such excavation is planned for the area.

Although not required, it may be useful to complete the *MODFLOW – Conceptual Model Approach* tutorial before doing this tutorial.

2.2 Outline

These are the major steps involved in this tutorial exercise:

1. Open a file containing a calibrated MODFLOW simulation of the groundwater flow in the region surrounding the proposed excavation site.
2. Turn on the Lake Package option.
3. Define the elevations of the bottom of the lake (excavation) using a TIN.
4. Define the location of the lake using a polygon in the Map Module.
5. Assign a set of lake properties to the lake polygon in the Map Module, including a “withdrawal rate” representing the pumping rate used by the dewatering wells.
6. Use the Map → MODFLOW command to discretize the lake data from the polygon to the grid cells.
7. Run the MODFLOW simulation.
8. Read in the solution and examine the resulting lake stage.
9. Repeat steps 5-8 until the resulting stage is within ten meters of the bottom of the lake (excavation).


3 Getting Started

Let’s get started.

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

4 Reading the MODFLOW Model

First, we will read in a file containing a previously completed MODFLOW model of the site

1. Select the *Open* button .
2. Locate and open the directory entitled **tutfiles\MODFLOW\modflake**.


3. Open the file named **start.gpr**.

You should see a set of contours on the grid. These contours represent the computed head from the MODFLOW simulation. This model has been calibrated to pre-excavation conditions. We will now modify the model to simulate the effect of the mine.

5 Saving a Copy of the Project

Before continuing, we will save a copy of the project under a different name.

1. Select the *File | Save As* menu command.
2. Save the project with the name **mine01.gpr**.

As you go through the tutorial, you may want to periodically select the Save button  to save your changes.

6 Turning on the Lake Package


Next, we will turn on the Lake Package option in the MODFLOW interface.

1. Select the *MODFLOW | Global Options* menu command.
2. Select the *Packages* button.
3. Turn on the *Lake (LAK3)* option.
4. Select the *OK* button twice to exit both dialogs.

7 Creating the Lake Coverage

The easiest way to build Lake Package data in GMS is to use conceptual modeling tools in the Map Module. This allows us to define the boundary of the mine using a polygon and to define the geometry of the mine (the elevations) using a TIN.

First, we need to create a coverage for the lake polygon:

1. In the *Project Explorer*, expand the  *Map Data* folder if necessary.
2. Right-click on the *Conc. Mod* item in the *Map Data* section of the *Project Explorer* and select *New Coverage...* in the resulting pop-up menu.
3. In the *Coverage Setup* dialog, change the *Coverage name* to **lake**.
4. In the *Source/Sink BC's* category, scroll down and turn **on** the toggle by the *Lake* option.



5. Turn **off** the *Use to define model boundary* toggle.
6. Click *OK* to exit the dialog.

8 Importing the Lake Polygon

Next, we need to create a polygon representing the boundary of the mine. To do this, we will import a shapefile.

7. Select the *File | Open* menu command.
8. In the *Files of type* combo box at the bottom of the *Open* dialog, select the *Shapefiles (*.shp)* option.
9. Select the file named **mine_bound_poly.shp**.



At this point, a new item called *GIS Layers* should appear in the *Project Explorer*. Just under this item, you should see a layer named **mine_bound_poly.shp**. It is behind the grid and the map coverages so it is partially obscured. To see the polygon better:

10. Turn **off** the  *3D Grid Data* item in the *Project Explorer*.
11. Turn **off** the  *Map Data* item in the *Project Explorer*.

You should now see the polygon displayed with a black line. In order to use this polygon in our conceptual model, we need to convert it from a shapefile to a GMS feature object in the *lake* coverage. To convert the polygon:

12. Click on the *GIS Layers* item in the *Project Explorer*.
13. Select the *GIS | Shapes → Feature Objects* menu command.
14. Select *Yes* at the prompt to use all the shapes.
15. Select the *Next* button to begin the *GIS to Feature Objects Wizard*.
16. Click the *Next* button again to skip this step (there are no attributes with the shapefile).
17. Click the *Finish* button to complete the process.

Note that the *Shapes → Feature Objects* command adds the new feature objects to the active coverage. Since the lake coverage is currently active, the mine boundary polygon should have been added to the lake coverage. To confirm, do the following:


18. Turn **off** the  *GIS Layers* folder in the *Project Explorer*.
19. Turn **on** the  *lake* coverage folder in the *Project Explorer*.

Since the lake is still visible, we are now viewing the polygon in the *lake* coverage.

9 Setting up the Lake TIN



Before we enter the lake properties, we need to create a TIN representing the geometry (elevations) of the bottom of the mine. This TIN is used during the *Map* → *MODFLOW* process to mark the lake cells and assign the proper layer elevations to the cells in the MODFLOW grid in the vicinity of the bottom of the mine. To build the TIN, we will first create the TIN from the mine boundary polygon and then we will interpolate the elevations to the TIN from a scatter point set.

To build the TIN:



1. Select the  lake coverage in the *Project Explorer*.
2. Select the *Feature Objects* | *Map* → *TIN* menu command.
3. Change the name of the TIN to **mine bottom**.
4. Select the *OK* button.

At this point, you should see a new TIN appear. The density of the triangles in the TIN is a function of the vertex spacing on the arcs defining the polygon boundary. If necessary, the spacing can be adjusted using the *Redistribute Vertices* command. However, our spacing looks fine so we will accept this TIN and continue.

To interpolate the elevations:

5. Expand the  *2D Scatter Data* section of the *Project Explorer* if necessary.
6. Right-click on the  excavation 2d scatter set in the *Project Explorer* and select the *Interpolate To* | *Active TIN* menu command.
7. Change the *Interpolated data set name* to **elevations** and select the *OK* button.

You should see some contours appear on the TIN. Before continuing, let's view the TIN in oblique view to confirm the interpolation results.


8. Click on the *Ortho/General Mode* button  at the top of the GMS window to switch to *General Viewing Mode*.
9. Click on the *Oblique View* button .

At this point, you may wish to use the *Zoom*  and *Rotate*  tools to view the shape of the mine in 3D. When finished:

10. Click on the *Plan View* button .
11. Click on the *Ortho/General Mode* button  to switch back to *Ortho Viewing Mode*.

10 Assigning the Polygon Properties

We are now ready to assign the lake properties to our mine polygon.

1. Select the  lake coverage in the *Project Explorer*.
2. Double-click on the lake polygon to bring up the *Properties* dialog.
3. Enter **mine** in the *Name* column.
4. Change the *Type* to **lake**.
5. Enter **2300** for the *Initial Stage*.
6. Enter **1801** for the *Min. Stage*.
7. Enter **2460** for the *Max. Stage*.
8. Click on the button in the *Bathymetry* column, select the TIN named **mine bottom**, and click *OK* to exit the dialog.

The *Lake Leakance* represents the leakance (K/thickness) of the lake bottom sediments. Since we are simulating an excavation, there are no lake bottom sediments, so we will input an arbitrarily large leakance value to simulate minimal resistance to flow.

9. Enter **1e6** for the *Lake Leakance*.

For the precipitation, we will enter a value in units of *m/d* that corresponds to a rate of just under 0.5 m/yr. Since the excavation will be dewatered, we will be conservative and leave the evaporation at zero.

10. Enter **0.0013** for the *Precipitation*.

The *Runoff* term represents the volumetric inflow from the adjacent watershed. The basin feeding into the mine has an area of about 3,000,000 m², so we will assume that about 1/5 of the precipitation in this area turns into runoff, giving us a volumetric rate of $0.0013/5 * 3e6 = 780 \text{ m}^3/\text{d}$.

11. Enter **780** for the *Runoff*.

The *Withdrawal* rate represents the volumetric extraction rate due to anthropogenic activities. We will use this term to represent the pumping rate used to dewater the well. We will start with an estimate and then re-run the model until the stage is near the bottom of the mine. We will enter the number as a positive value since it is assumed to be extracted by default.

12. Enter **2000** for the *Withdrawal*.

Finally, there are two columns for the *Parent Lake* and *Sill Elevation*. These properties are used to link multiple lakes together into a system where a large lake can change into multiple smaller lakes as the water level drops. We will not need to use this feature.

There is also an option called “Adjust cell elevations”. This option is used to modify the top elevations of the active cells just beneath the lake cells so that the elevations match the lake bathymetry. This option leads to more accurate stage-volume relationships, but it can make the model less robust. We will leave the option off for our study.

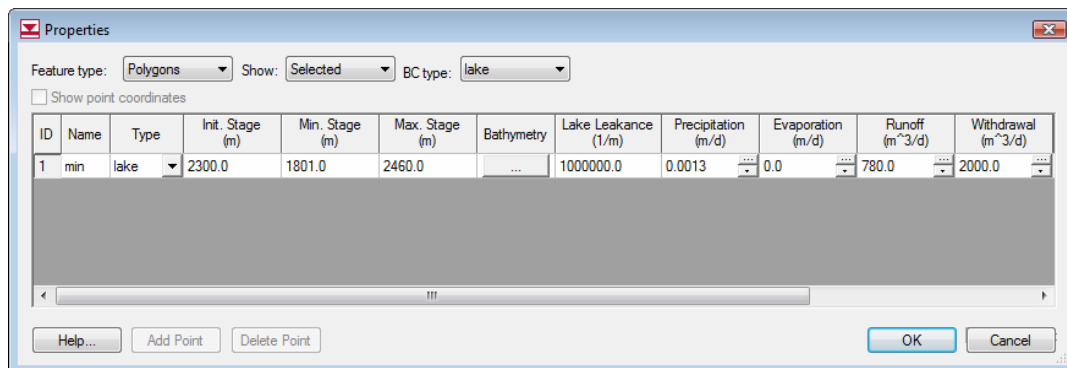




Figure 3. Lake properties.

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

11 Map → MODFLOW

At this point, we are finally ready to run the *Map → MODFLOW* command to discretize our conceptual model data to the MODFLOW input arrays on the 3D grid. The mine boundary polygon and the mine bottom TIN are used to identify the set of cells that lie inside the body of the mine. These cells are marked as lake cells and are set to be inactive ($IBOUND = 0$) and the elevations of the cells adjacent to the bottom of the mine are adjusted up or down to match the mine bottom when the user selects the *Adjust Cell Elev.* field in the polygon attributes table. A lake object is also created in the Lake Package and the lake properties entered in the previous section are inherited by this object. Also, the leakance values entered in the previous step are assigned to all grid cells on the perimeter of the lake.

1. Turn **on** the  *3D Grid Data* item in the *Project Explorer*.
2. Turn **off** the  **mine bottom** TIN in the *Project Explorer*.
3. Select the *Feature Objects | Map → MODFLOW* menu command.
4. Select the *OK* button.

12 The Lake Package Dialog

Let's take a look at the Lake Package dialog to see how the conceptual model was mapped to the grid.

1. Select the *MODFLOW | Source/Sink Packages | Lake (LAK) Package* menu command.

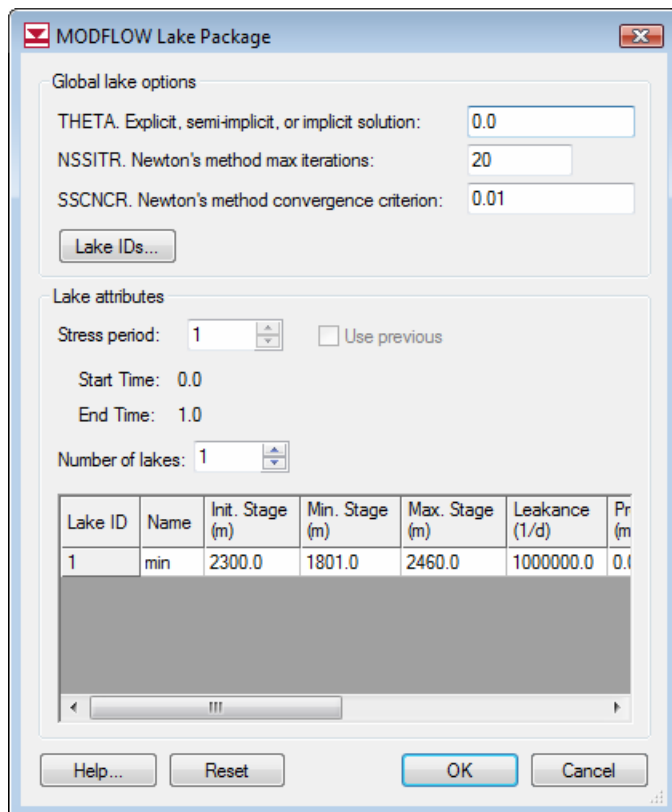


Figure 4. MODFLOW Lake Package dialog.

The dialog has some global options at the top and a list of lakes at the bottom. Notice there is one lake listed and it has the values we entered into the conceptual model.

Lakes are located in the grid using 2D arrays of lake IDs.

2. Click the *Lake IDs* button.
3. Use the scroll bars to find the area of the 2D array where there are 1s (about in the middle).

This is where the lake is in the grid. Each lake has a unique ID number. If there was more than one lake there would be other areas with different ID numbers (2, 3 etc).

4. Change the *Layer* field to **2**.

Notice the values are all 0 in this layer meaning the lake does not extend into the second layer of the model.

5. Select the *OK* button twice to exit both dialogs.

13 Changing the Solver

Before continuing, we will change the solver option to use the SIP solver. This solver seems to work better than the other solvers for this particular problem.



1. Select the *MODFLOW | Global Options* command.
2. Select the *Packages* button.
3. Select the *Strongly Impl. Procedure (SIP1)* option in the *Solvers* section.
4. Select the *OK* button twice to exit the dialogs.

Next, we will adjust the maximum number of iterations.

5. Select the *MODFLOW | SIP1 Package* command.
6. Change the *MXITER. Maximum iterations per time step* value to **1000**.
7. Select the *OK* button.

14 Running the MODFLOW Simulation

We are now ready to save our changes and run MODFLOW.

1. Select the *Save* button .
2. Select the  *Run MODFLOW* button.
3. When MODFLOW has finished running, select the *Close* button. The MODFLOW solution will automatically be read in.

Notice that the head contours indicate drawdown of the water table around the mine.

15 Viewing the Results

Next we need to determine the stage in the mine as a result of our selected pumping rate. The LAK3 package generates a text file called a “gage” file for each lake in the simulation that contains a list of stage vs. time step (we are doing a steady state simulation). We can access the gage file from the *Project Explorer*:

1. Click on the + symbol to the left of the **mine01 (MODFLOW)** item in the *Project Explorer* to expand the list of items in the solution.
2. Click on the + symbol to the left of the **Gage Files** item in the *Project Explorer* to show the list of gage files.
3. Double click on the **mine01.gag** item to open it in a text editor.

Note that the stage value listed on the last line is approximately 2257 m. We have caused some drawdown but still have a long ways to go to dewater the mine.


4. Close the text editor.

16 Modifying the Model


Next, we will increase the pumping rate and run the model again to see the effect on the stage. However, we must be careful as we proceed. The LAK3 package is quite sensitive to the initial conditions. For example, if we change the pumping rate to 10,000 m³/d, the solution will not converge. We will make smaller changes to the pumping rate and we will also adjust the starting heads and the initial stage to improve convergence.

At this point we can either edit the conceptual model and again map it to the grid, or we can edit the lake values on the grid directly in the *MODFLOW Lake Package* dialog. Either way is acceptable but if we edit the lake on the grid our conceptual model will not be in sync with the grid. That's fine as long as we don't forget and map it again later thus overwriting our changes on the grid. For this tutorial we will stick with editing the conceptual model but you are welcome to edit the lake values directly in the *MODFLOW Lake Package* dialog if you wish.

To change the lake properties:

1. Select the  lake coverage in the *Project Explorer*.
2. Double-click on the lake polygon to bring up the *Properties* dialog.
3. Enter **2200** for the *Initial Stage*.
4. **2500** for the *Withdrawal*.
5. Select the *OK* button to exit the dialog.

Now we must map our changes from the conceptual model to the grid:

6. Select the  *Map → MODFLOW* button.
7. Select *OK* at the prompt.


Next we will change the starting heads to match our current solution.

8. Select the *MODFLOW | Global Options* command.
9. Click on the *Starting Heads* button.
10. Select the *3D Data Set → Grid* button.
11. Since the **Head** data set is already selected, select the *OK* button to copy the head solution to the starting heads array.

12. Select the *OK* button twice to exit both dialogs.

17 Running the MODFLOW Simulation

We are now ready to save our changes and run MODFLOW again.

1. Select the *Save* button .
2. Select the *MODFLOW | Run MODFLOW* menu command.
3. When MODFLOW has finished running, select the *Close* button. The MODFLOW solution will automatically be read in.

18 Viewing the Results

Notice that there is now a little more drawdown around the mine.

1. Click on the + symbol to the left of the **mine01 (MODFLOW)** item in the *Project Explorer* to expand the list of items in the solution.
2. Click on the + symbol to the left of the **Gage Files** item in the *Project Explorer* to show the list of gage files.
3. Double click on the **mine01.gag** item to open it in a text editor.

Note that the stage value listed on the last line is approximately 2230 m. This represents a drop from the previous iteration of 27 m.

4. Close the text editor.

19 Iterating the Solution Process

At this point, you must iteratively increase the pumping rate and re-run the model until we reach the desired stage level (~1810 m). To do this, you would repeat the previous steps, gradually adjusting the pumping rate while updating the initial stage and starting heads array. You may wish to continue this process to see what pumping rate is required. If your solution does not converge for a particular iteration, you will need to make a smaller change to your withdrawal rate.

As you iterate, you will need to be careful. In some cases the model will appear to converge but the solution will not be valid. If you have any doubt about the solution, you need to open up the **model01.out** file in the **mine01 (MODFLOW)** folder in the *Project Explorer* and look at the lake package iteration output about 2/3 of the way down the file.

As you iterate, you may find it easier to edit the lake in the *MODFLOW Lake Package* dialog instead of in the conceptual model. Editing the lake in the Lake Package dialog allows you to skip the Map → MODFLOW step and thus save a little time. There is

nothing wrong with that but you should remember that the values in the conceptual model will be out of sync with the values on the grid.

The final withdrawal rate to get to a stage of about 1810 m is 6340 m³/d.

20 Conclusion

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

- To use the Lake Package, you must create both a TIN representing the lake bathymetry and a polygon representing the lake boundary.
- The lake properties are assigned to the lake polygon in Map module.
- The flow between the aquifer and the lake is a function of both the aquifer conductance and the lakebed leakance.
- The Lake Package computes the stage in the lake based on a flow budget for the lake and the lake geometry.
- To determine the amount of pumping required for an excavation, you can simulate the excavation using the Lake Package and adjust the withdrawal rate until the desired stage is found.