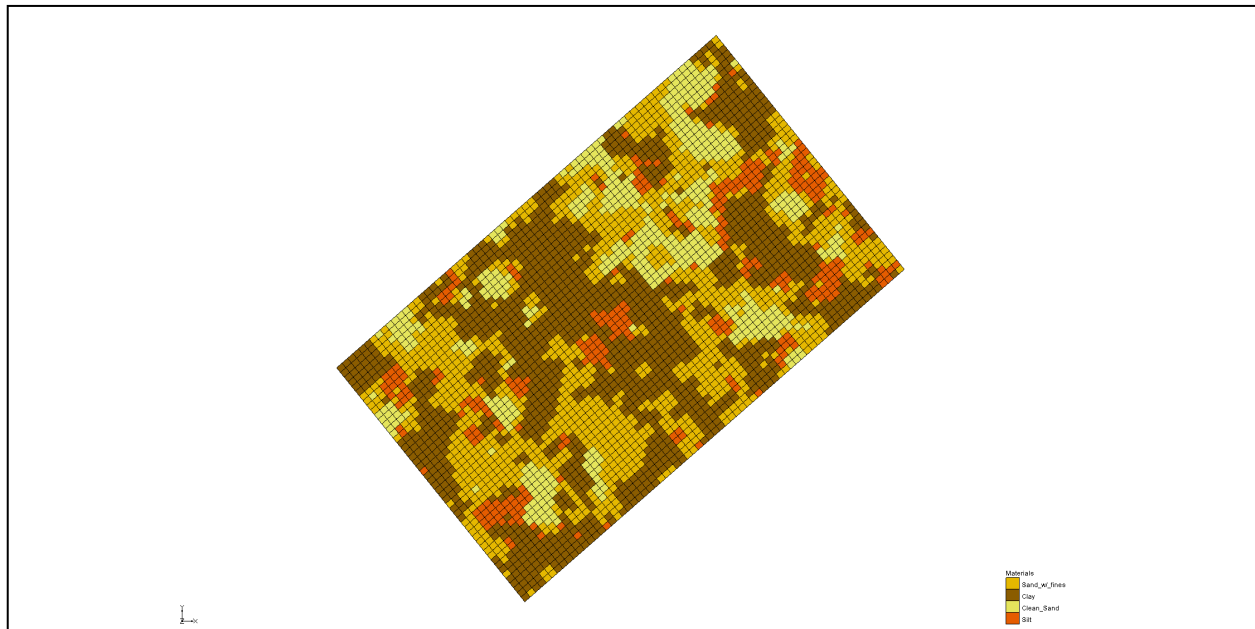*GMS 9.2 Tutorial*

T-PROGS

Use T-PROGS to generate multiple material sets on a 3D grid from borehole data

Objectives

Learn to use the T-PROGS interface in GMS to create multiple material sets on a 3D grid, each equally likely, based on borehole data. Learn how T-PROGS can create data for the MODFLOW HUF package.

Prerequisite Tutorials

- None

Required Components

- Gostatistics
- Grid
- Map
- MODFLOW
- Stochastic Tools
- Sub-surface Characterization

Time

- 30-60 minutes

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1   Contents

2   Introduction

This tutorial describes how to use the T-PROGS interface in GMS. T-PROGS is a software package that performs transition probability geostatistics to generate multiple, equally probable models of aquifer heterogeneity, all of which can be conditioned to borehole data. T-PROGS is generally used in a stochastic modeling approach with MODFLOW. T-PROGS can be used to generate multiple material sets which, in GMS, can be used to create input data for the Layer Property Flow (LPF) package in MODFLOW. T-PROGS can also be used to generate multiple instances of HUF data used in the Hydrogeologic Unit Flow (HUF) package in MODFLOW 2000. This tutorial will demonstrate the application of T-PROGS in generating material sets for both a multi-layer grid and a one-layer grid. In addition, this tutorial will demonstrate how to generate multiple sets of HUF data.

T-PROGS was originally developed by Graham Fogg and Steven Carle at UC Davis. For more information, consult the T-PROGS User Manual (Carle, Steven F., T-PROGS:

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Transition Probability Geostatistical Software Version 2.1, Hydrologic Sciences Graduate Group University of California, Davis, 1999.)

2.1   Outline

This is what you will do:

1.   Import Borehole data.

2.   Create a bounding grid.

3.   Develop vertical Markov chains and define additional parameters.

4.   Run TSIM for 3D and 2D cases.

5.   Import a scatter point set.

6.   Interpolate and redistribute elevations.

7.   Run TSIM and compare data.

3   Problem Description

The problem we will be modeling in this tutorial is illustrated in Figure 1. The objective is to set up a stochastic simulation for a local scale model of a site in Texas. The grid for the local scale model will be oriented in the general direction of the ground water flow at the site and the two ends of the model will be marked as constant head boundaries.
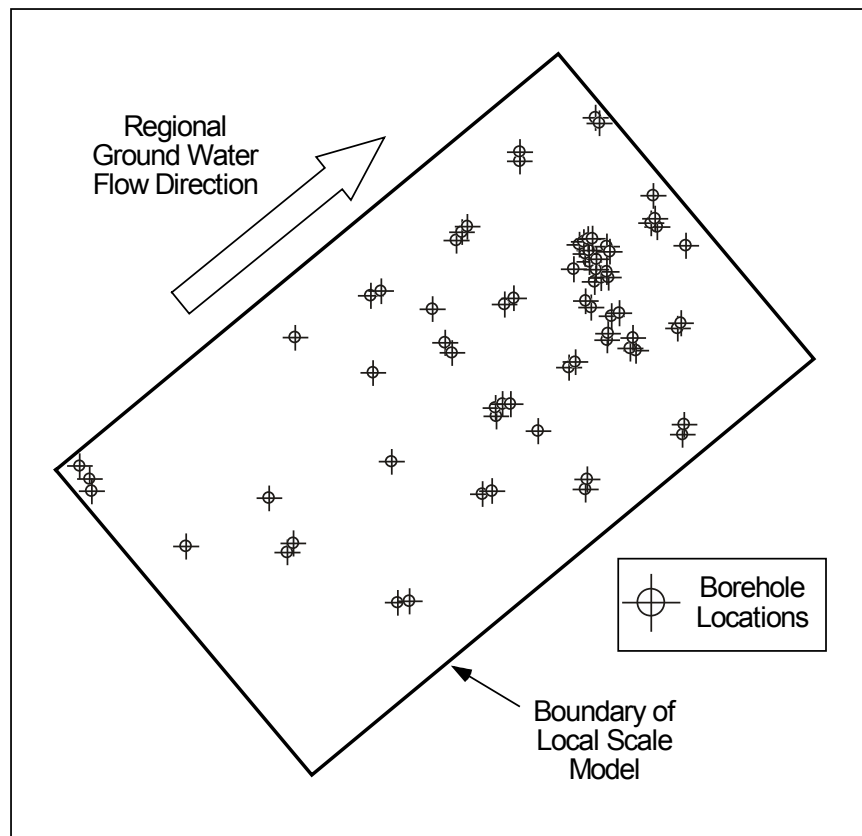
Figure 1.   Conceptual representation of site to be modelled.

Seventy-four borehole logs are available in the vicinity of the site. A 3D oblique view of the borehole data is shown in Figure 2. The borehole logs indicate that the geology corresponds to an alluvial system with considerable heterogeneity. One approach for dealing with such a site in GMS would be to create a solid model of the site stratigraphy, including a detailed 3D representation of each of the lenses. However, the solid modeling approach will not work at this site since the heterogeneity is too complex and there is not sufficient correlation between the boreholes to develop meaningful cross-sections. By contrast, the transition probability geostatistics approach is ideally suited for this type of situation. With this approach, we will first analyze the borehole data to determine transitional tendencies, proportions, and mean lens lengths. These data will then be used to generate multiple realizations of the site heterogeneity as input for a stochastic simulation. Each of the realizations will preserve the geologic tendencies inherent in the borehole data and will be conditioned to the borehole data (the cells coinciding with borehole locations will match the stratigraphy in the borehole log).
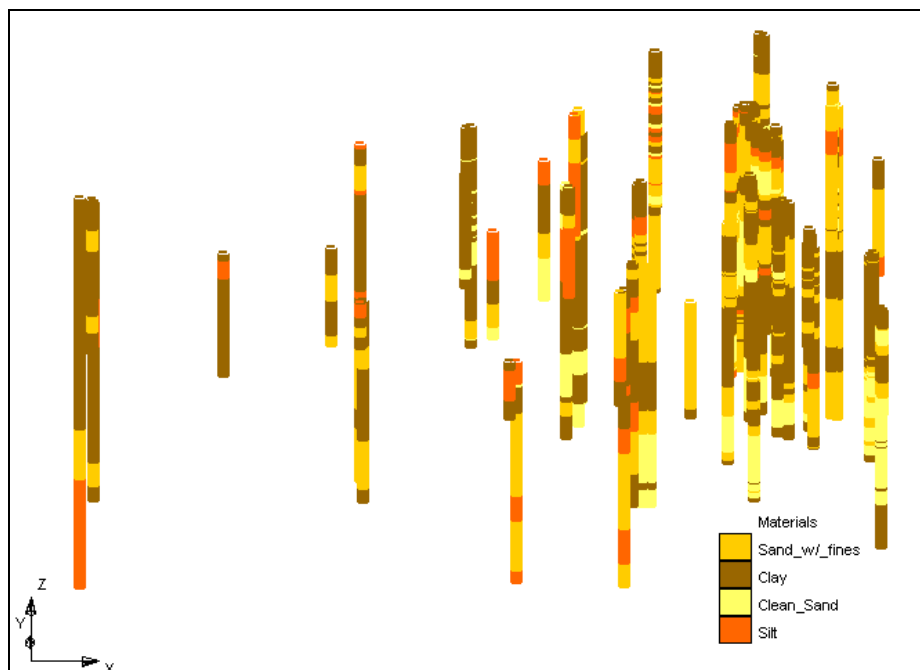
Figure 2.   3D oblique view of borehole data.

This tutorial will be completed in three phases. In the first phase, we will develop the input for a stochastic MODFLOW model using the LPF package and a 3D (multi-layer), orthogonal grid. In the second phase, we will again use the LPF package but we will use a 2D (single-layer) grid. In the third phase, we will use the HUF package with a 3D grid with non-uniform layer elevations. The second and third phases of the tutorial can be completed relatively quickly since we can re-use the transition probability data developed during the first phase.

While this tutorial illustrates how to use the T-PROGS interface to develop the input data for a stochastic MODFLOW simulation, we will not actually run the MODFLOW simulation. The steps involved in running a stochastic MODFLOW simulation using either the T-PROGS approach or a "Monte Carlo" style approach are described in the *MODFLOW - Stochastic Modeling – Indicator Simulations* tutorial.

4   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.

5   Phase I – Multi-Layer Orthogonal Grid

The underlying equations solved by the T-PROGS software require an orthogonal grid with constant cell dimensions (ΔX, ΔY, and ΔZ). The ΔX values can be different from

the ΔY and ΔZ values, and the ΔY values can be different from the ΔZ values, but all cells must have the same ΔX, ΔY, and ΔZ dimensions. However, GMS can be used with T-PROGS with both uniform and non-uniform grids. If a uniform grid is used, the T-PROGS calculations are carried out directly on the grid cells. If a non-uniform grid is used, the T-PROGS calculations are carried out on a uniform background grid which bounds the user-defined grid. After the calculations are complete, the material ids are transferred from the background grid to the user-defined grid by comparing the coordinates of the cell center for each cell in the user-defined grid to determine which cell in the background grid contains the cell center. The material id for this cell is then inherited by the cell in the foreground grid. Best results are obtained when the user-defined grid is uniform. When the HUF package is used, a more sophisticated approach is used to handle the stratigraphic layering in the vertical direction. The heterogeneity from the background grid is preserved in a set of HUF input arrays.

In the first phase of this tutorial, we will run T-PROGS on a multi-layer orthogonal MODFLOW grid. The MODFLOW model will use the *Layer Property Flow (LPF) Package* with the *Material ID* option for assigning aquifer properties. With this option, each cell in the grid is assigned a material id and the aquifer properties (Kh, Kv, etc.) associated with each material are automatically assigned to the layer data arrays for the LPF package when the MODFLOW files are saved. The T-PROGS software generates multiple material sets (arrays of material ids), each of which represents a different realization of the aquifer heterogeneity. When running a MODFLOW simulation in stochastic mode, GMS automatically loads each of the N material sets generated by the T-PROGS software and saves N different sets of MODFLOW input files. The N solutions resulting from these simulations can be read into GMS and used to perform risk analyses such as probabilistic capture zone delineation.

5.1   Loading the Borehole Data

The first step in setting up the T-PROGS simulation is to read in the borehole data.

1. Select the *Open* button .

2. Locate and open the directory entitled **Tutorials\T-PROGS\t-progs**.

3. Select the file named **LH 3D.gpr**.

4. Click on the *Open* button.

5.2   Saving the Project

We want to save the changes to our project as we go, but leave the original project unchanged. So, we will create a new project.

1. Select the *File | Save As* menu command.

2. Save the project with the name **tprob3d.gpr**.

As you continue with the tutorial, you may wish to periodically save changes to the project using the *Save* command in the *File* menu or the *Save* button 💾.

5.3   Viewing the Borehole Data

At this point you should see a set of boreholes displayed in plan view. To view the heterogeneity in the borehole logs, we will view the boreholes in oblique view.

1. Select the *Oblique View* button 🔷.

Notice that the most common material at the site is clay and the least common material is clean sand. It can also be seen that there is considerable heterogeneity at the site. It should be noted that the current display has a z magnification factor of 5.0. This factor can be adjusted using the *Display | Display Options* menu command. To return to plan view:

2. Select the *Plan View* button 🔲.

5.4   Building the 3D Grid

Before editing the T-PROGS data we must first create the 3D grid. For sites such as this one where the grid must be rotated to align it with the regional ground water flow direction, the best approach is to use the grid frame to define the grid location. The grid frame is located in the Map Module of GMS and is used to define the location, size, and orientation of the grid. To create the grid frame:

1. In the *Project Explorer* right-click on the empty space and then, from the pop-up menu, select the *New | Grid Frame* menu command.

At this point, you should see the outline of the grid frame appear. The size, location, and orientation of the grid frame can be edited in two ways: 1) by editing the values in the *Grid Frame* dialog, and 2) by click and dragging on the control points displayed on the grid frame. The symbols and the corners of the grid frame can be dragged to resize the grid frame and the small circle just to the side of the lower right corner of the grid frame can be used to rotate the frame. Clicking and dragging anywhere in the middle of the frame drags the entire frame to a new location.

2. Select the *Map Data* Folder 📁 in the *Project Explorer*.

3. Select the *Select Grid Frame* 🔲 tool.

4. Select the grid frame by clicking on it in the *Graphics Window*.

5. Double click on the grid frame to bring up the *Grid Frame Properties* dialog.

6. Enter the following values for the origin, dimension and rotation angle of the grid frame:

Origin x:	**3313550**

Origin y:	6952450
Origin z:	130
Dimension x:	1710
Dimension y:	1010
Dimension z:	80
Rotation Angle:	40

7. Select the *OK* button to exit the dialog.

8. Select the *Frame* button.

Now we are ready to create the grid:

9. Select the *Feature Objects | Map → 3D Grid* menu command.

10. Enter **70**, **50**, and **20** for the number of cells in the X, Y, and Z-dimensions respectively.

11. Select the *OK* button.

After a few moments the grid should appear.

5.5   Initializing the T-PROGS Simulation

The next step is to initialize the T-PROGS simulation and define some general options including the azimuth angle, background material, and materials included in the simulation.

1. Select the *Borehole Data* folder in the *Project Explorer*.

2. Select the *T-PROGS | New Simulation* menu command.

3. Select the *Next* button since we will be using all of the boreholes.

The *T-PROGS Materials* dialog lists the materials in use on the boreholes, and an *Azimuth* angle. The azimuth angle represents the angle corresponding to the *Strike (X)* direction. If there is anisotropy in the xy plane, this angle should be set to the principle direction of the anisotropy. If anisotropy is not present, this angle should be coincident with the x-axis (the rows or j-direction) of the grid. By default, the azimuth angle is defaulted to a value that aligns it with the x-axis of the grid. This value corresponds to the negative grid rotation angle we entered in the grid frame. This is because the grid rotation angle is counterclockwise from the x-axis, but the azimuth angle is clockwise from the y-axis.

The upper part of the dialog lists the materials in the boreholes. The first column of toggles indicates which materials are to be used in the analysis. By default, all materials associated with the boreholes are selected. These toggles are necessary since it is possible that there may be materials defined in the materials list that are not associated with boreholes. Furthermore, a T-PROGS simulation can be performed without borehole

data. In such a case, the user would define the mean proportions and lens lengths for each material.

The second column in the top section of the dialog lists the background material. By default, the material type that had the predominant occurrence in the boreholes (greatest proportion) is marked as the background material. When defining the transition probability data in the next section, the input parameters do not need to be edited for the background material. The parameters for this material are automatically adjusted to balance the equations.

To proceed to the next step:

4.   Select the *Next* button.

5.6   Developing the Vertical Markov Chains

The most important step in setting up the T-PROGS data is to define the transition probability data for each material located in the boreholes in the three primary directions: vertical, strike, and dip. The vertical transition trends are developed first, based on the borehole data. The data in the strike and dip directions can then be derived from the vertical data.

The first step in setting up the transition data is to run a utility within T-PROGS called GAMEAS that computes a set of transition probability curves as a function of lag distance for each material for a given sampling interval. GAMEAS is launched as follows:

1.   Select the *Compute* button in the upper left corner of the dialog.

At this point, a window should appear listing the output from the GAMEAS utility. For this problem, GAMEAS may take up to 2-3 minutes to run, depending on the speed of your computer. When it finishes, "Successful Completion" should be written to the window and the *Abort* button should switch to say *Close*.

2.   When GAMEAS finishes, select the *Close* button.

At this point, the plots in the upper right corner of the dialog should be updated. These plots display the transition probabilities for each material with respect to each of the other materials. The rows correspond to *Clean_Sand*, *Sand_w/_fines*, *Silt*, and *Clay*, respectively. Likewise, the columns correspond to *Clean_Sand*, *Sand_w/_fines*, *Silt*, and *Clay* in that order. Thus, the plot in the first row and first column represents the probability of transitioning from clean sand to clean sand. The plot in the first row and second column represents the probability of transitioning from clean sand to sand w/ fines, etc. The plots can be better viewed by maximizing the plot:

3.   Right click on any of the plots and select the *Maximize Plot* command from the pop-up menu.

4.   Select the *Esc* button to minimize the plot.

You may wish to use this feature to view other plots.

Each of the plots contains two curves depicting the transition probability. The dashed line represents the transition probability measured from the borehole data by the GAMEAS utility. In general, this curve represents the transition probability from material j to material k. The transition probability t_{jk}(h) is defined by:

t_{jk}(h)= Pr{k occurs at $\mathbf{x} + \mathbf{h}$ | j occurs at $\mathbf{x}$}..1

where x is a spatial location, h is the lag (separation vector), and *j,k* denote materials. The lag is defined by the *Lag spacing* item in the upper left corner of the *Vertical (Z) Markov Chains* dialog. The curve shown with the solid line is called a "Markov Chain". The Markov Chains are used to formulate the equations used by T-PROGS to generate the multiple material sets during the simulation stage. The objective of this stage of the analysis is to fit the Markov Chain curves as accurately as possible to the measured transition probability curves. This process is similar to fitting a model variogram to an experimental variogram in a kriging exercise. Mathematically, a Markov chain model applied to one-dimensional categorical data in a direction ϕ assumes a matrix exponential form:

$\mathbf{T}(h_\phi) = \exp(\mathbf{R}_\phi h_\phi)$...2

where ϕ denotes a lag in the direction h_ϕ, and $\mathbf{R}_\phi$ denotes a transition rate matrix

$$\mathbf{R}_\phi = \begin{bmatrix} r_{11,\phi} & \cdots & r_{1k,\phi} \\ \vdots & \ddots & \vdots \\ r_{k1,\phi} & \cdots & r_{kk,\phi} \end{bmatrix}$$ 3

with entries $r_{jk,\phi}$ representing the rate of change from category j to category k (conditional to the presence of j) per unit length in the direction ϕ. The transition rates are adjusted to ensure a good fit between the Markov Chain model and the observed transition probability data.

It should be noted that the self-transitional curves on the diagonal start at a probability of 1.0 and decrease with distance and the off-diagonal curves start at zero probability and increase with distance. In both cases, the curves eventually flatten out at some distance. The probability corresponding to the flat part of the curve represents the mean proportion of the material. All curves on a particular column should flatten out to the same proportion. The proportions are displayed in the lower left corner of the dialog. As expected, clay has the highest proportion of the four materials. The point where a tangent line from the early part of the curves on the diagonal intersects the horizontal (lag distance) axis on each curve represents the mean lens length for the material. The mean lens lengths are shown just to the right of the mean proportions in the lower left part of the dialog. The slope at the beginning of each of the Markov Chains represents the transition rate. Together, the proportions, lens lengths, and transition rates define the Markov Chains.
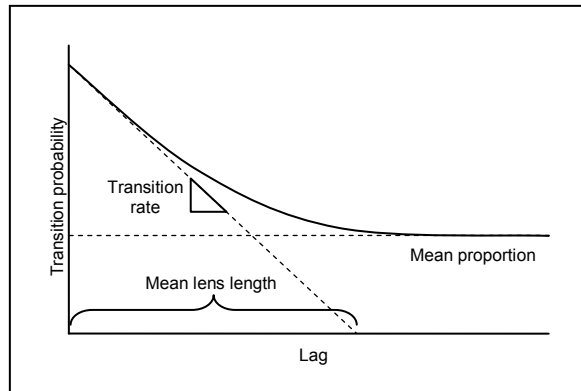
Figure 3.   *Markov chain curve diagram.*

Several methods are provided for fitting the Markov Chains to the measured transition probability curves. These methods are listed in the section of the dialog titled "Markov Chains". By default, GMS automatically makes an attempt to fit the curves using the *Edit maximum entropy factors* option. In many cases, this fit is sufficiently accurate and we can proceed to the next step. However, it is often useful to explore the other options for fitting the curves.

     5.   Select the *Edit the transition rates* option.

With this option, the user directly edits the transition rates and the mean proportions using the two spreadsheets at the bottom of the dialog. The proportion and rates for the background material need not be defined. The proportion for the background material is adjusted so that the proportions sum to 1.0. The transition rates involving the background material are adjusted so that the row sums obey:

$$\sum_{k=1}^{K} r_{jk,\phi} = 0 \qquad \forall j \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.4$$

and the column sums obey

$$\sum_{j=1}^{K} p_j r_{jk,\phi} = 0 \qquad \forall k \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.5$$

where j is the row index, k is the column index, p is the proportion, and r is the transition rate.

     6.   Select the *Edit embedded transition probabilities* option.

With both this option and the next option (*Edit embedded transition frequencies*), GMS parses the borehole data and computed embedded transition probabilities (or transition frequencies) and displays the results in the matrix in the lower right part of the dialog. The transition rates can be computed from the transition probabilities (or frequencies). This option is described in more detail in the T-PROGS Users Guide.

7. Select the *Edit maximum entropy factors* option.

With this option, the diagonal terms of the rate matrix are computed from the mean lens lengths using the relationship:

$$r_{kk,\phi} = -\frac{1}{\overline{L_{k,\phi}}}$$ 6

where L is the mean lens length. The off-diagonal terms represent the ratio of the current transition rate to the transition rate corresponding to maximum entropy. When this factor is equal to 1.0, the probability that a given material is adjacent to another material is consistent with a random distribution of the materials. In other words, the probability will be dependent only on the proportions of the two materials. Viewing these factors illustrates the juxtapositioning tendencies in the borehole data. For example, the *Silt $\rightarrow$ Clean_Sand* factor (in the *Silt* row and the *Clean_Sand* column) should be equal to 0.39. This factor represents the transition from silt to clean sand moving in the +Z (upwards) direction. The *Clean_Sand $\rightarrow$ Silt* factor is 1.01. With factors less than 1.0, we can conclude that the type of transition occurs less frequently than one might expect, given the proportions of the materials. Since the *Clean_Sand $\rightarrow$ Silt* factor is greater than the *Silt $\rightarrow$ Clean_Sand* factor, we can conclude that it is less likely to transition from *Silt* to *Clean_Sand* than from *Clean_Sand* to *Silt* when moving in the +Z direction. In other words, these two materials exhibit a fining-upwards tendency. The maximum entropy factors provide a simple and intuitive way to view and edit the transition rates.

8. Select the *Fit curves to a discrete lag* option.

This option is the simplest to use. With this option, a curve fitting process is used to adjust the transition rates and proportions so that the curve coincides exactly with the measured transition probability at the selected lag interval. By adjusting the lag interval, an excellent fit can often be obtained. We will use this option to fit our curves and proceed to the next step.

9. Enter **17** for the *Lag #* and select the *Tab* key. This number produces a good fit between the measured transition data and the Markov Chains.

10. Select the *Next* button.

5.7   Define the Strike/Dip Transition Trends

The next step is to define the Markov Chains in the strike and dip directions. In theory, the GAMEAS utility could be run in the strike and dip directions to develop measured transition probability data which could then be modeled with Markov Chains. However, borehole data are not sufficiently dense in these directions to develop meaningful data. Therefore, we apply *Walther's Law* to develop the strike and dip Markov Chains. Walther's Law states that vertical successions of deposited facies represent the lateral succession of environments of deposition. In other words, the transition rates in the horizontal directions can be derived from the transition rates in the vertical direction. To begin with, we can assume that the proportions are the same in all three directions. The

Lens length ratios method is then used to define the transition rate matrix. With this method, the diagonal transition rates are defined from the lens lengths using equation 6. The lens lengths in the horizontal directions are derived from the lens length ratios entered by the user for each material using the spreadsheet on the bottom left of the dialog. These ratios represent the lens length in the horizontal direction vs. the lens length in the vertical direction. GMS sets up the matrix using a default ratio of approximately 10.0. The off-diagonal terms in the rate matrix are then inherited from the vertical transition rates and then scaled by dividing by the lens length ratio.

Once the Markov Chains have been defined by the Lens length ratios method, the other four methods listed in the *Markov Chains* section of the dialog can be used to view/edit the Markov Chain data. In this case we will accept the default data for both the strike and dip directions.

1. Select the *Next* button to exit the *Strike (X) Markov Chains* dialog and proceed to the *Dip (Y) Markov Chains* dialog.

2. Select the *Finish* button.

3. Select the *Save* button 💾.

5.8   Run TSIM

With the Markov Chains defined in all three primary directions, we are now ready to select the *Run TSIM* command to generate the material sets. The Run TSIM command actually launches up to three different utilities: GAMEAS, MCMOD, and TSIM. If the *Fit curve to a discrete lag* option is used (as is the case with our simulation), GAMEAS is launched first to develop the transition trends from the borehole data. GAMEAS only runs if this option is used for the vertical Markov Chains. MCMOD then takes the one-dimensional Markov Chains defined in the three primary directions and formulates a three-dimensional Markov Chain. This Markov Chain is then read into TSIM and TSIM generates the material sets.

Running TSIM can take anywhere from several minutes to several hours depending on the number of materials, the resolution of the grid, and the number of material sets desired. To ensure that this tutorial can be completed in a reasonable amount of time, we will only create five material sets.

1. Select the *T-PROGS | Run TSIM* menu command.

2. Make sure the *Launch TSIM internal in GMS* option is selected and select the *Next* button.

3. Change the simulation name to **sim3d**.

4. Enter **5** for the *Number of realizations*.

5. Accept the other defaults and select the *Finish* button.

6. When the GAMEAS utility finishes, select the *Close* button.

The MCMOD and TSIM utility are then executed. The output from MCMOD and TSIM is displayed in the bottom part of the progress dialog.

7. Select the *Close* button when TSIM finishes.

5.9   Viewing the Results

The output from T-PROGS is a series of material sets. The material sets are organized in the *Project Explorer* associated with the *3D Grid* Module. The first material set is automatically loaded and the *Cell faces* display option is turned on. The material set simulations are organized into a *Material Sets* folder in the *Project Explorer*.

1. In the *Project Explorer*, expand the *Material Sets* folder under the *3D Grid Data* folder .

2. Expand the *sim3d* folder .

All five material sets are listed under the *sim3d* folder. The active material set, *sim3d 1*, is bold.

3. Change material sets by selecting the material set named *sim3d 2* . Notice the grid display is updated.

4. In the mini-grid display, change to the second layer.

5. View the side of the grid by selecting the *Front View* button .

6. Use the arrow buttons in the *Mini-Grid Plot* section of the *Tool Palette* to view different cross-sections.

7. Return to plan view by selecting the *Plan View* button .

8. View the material set properties by right-clicking on any of the material sets and selecting the *Properties* command from the pop-up menu. (You may wish to repeat this with other material sets to confirm that all material sets have the same proportions.)

9. Select the *OK* button to exit the *Material Set Info* dialog.

A probability data set for each material can also be created and displayed. We will first save our current display settings and then change the setting to view the probability data sets.

10. Right-click in the empty space of the *Project Explorer* and select the *New | Display Theme* command (A display theme is used to save the current display settings).

11. Select *OK* to accept the defaults of the display template.

12. Right-click on the *sim3d* folder 📁 in the *Project Explorer* and select the *Create Probability Data Sets* command.

13. Select the **Clean_Sand** dataset in the *Project Explorer*.

14. Select the *Display Options* button 🔧.

15. Turn on the *Contours* options and select the *Options…* button.

16. Change the *Contour Method* to be **Color Fill**.

17. Turn on the display of the *Legend*.

18. Select *OK* two times to exit all dialogs.

The probability of the *Clean_Sand* material existing in each grid cell is now contoured. You can now select the other datasets to view the different material probabilities.

19. Select the **Display (1)** display theme 🖼 in the *Project Explorer* to reset the display settings.

This completes the 3D grid portion of this tutorial.

6   Phase II – Single Layer Grid

This portion of the tutorial will demonstrate the generation of multiple material sets for a single-layer model. When developing a single layer model, the modeler must determine how to distribute the hydraulic conductivity values within the layer. A common approach is to delineate zones of hydraulic conductivity by examining the subsurface stratigraphic data. The modeler often faces a difficult task of trying to determine a reasonable strategy for delineating two-dimensional zones of hydraulic conductivity based on complex 3D borehole data.

The 2D T-PROGS approach provides a simple, rational approach to representing borehole data in a single layer MODFLOW model. The 2D T-PROGS approach is similar to the 3D approach. The first step is to generate the Markov chains in the three principal directions. Since these data have already been generated in the first phase of the tutorial, we will reuse the Markov Chain information for this phase. The main difference between the two approaches is what happens when TSIM is executed. For the 2D case, GMS determines the predominant material at each borehole and creates a single sample at the xy location of the borehole corresponding to the predominant material type. These samples are input to TSIM in the place of the entire borehole log that is input to TSIM in the 3D case. TSIM then performs a 2D indicator simulation in the xy plane and each of the resulting material sets is conditioned to the simplified borehole data.

6.1   Building the Single Layer Grid

First, we will use the same grid frame created in the first phase of the tutorial and create a single layer grid.

1. Right-click on the *Grid Frame* ⊡ in the *Project Explore*r and select the *Map to | 3D Grid* menu command.

2. Select *OK* at the prompt to confirm that we are creating a new grid.

3. Enter **70**, **50**, and **1** for the number of cells in the X, Y, and Z-dimensions respectively.

4. Select the *OK* button.

6.2   Saving the Project

Before continuing, we will save the project under a new name.

1. Select the *File | Save As* menu command.

2. Save the project with the name **tprob2d.gpr**.

6.3   MODFLOW Layer Elevations

Grid layer elevations could be interpolated from scatter point data using the *to MODFLOW Layers* command in the *2D Scatter Point* module. However, for the sake of simplicity, we will use constant top and bottom elevations with our model.

6.4   Run TSIM

We will use the same transition probability data developed in the first phase of this tutorial for the 2D case. Therefore, we can proceed directly to running TSIM.

1. Select the *T-PROGS | Run TSIM* menu command.

2. Select the *Next* button.

3. Enter simulation name as **sim2d**.

4. Enter **5** for the *Number of realizations*. Accept the other defaults and select the *Finish* button.

5. Select *OK* at the prompt to confirm that each borehole will be simplified to a single sample in the calculations.

6. When the GAMEAS utility finishes, select the *Close* button.

The MCMOD and TSIM utility are executed. Helpful information is displayed at the top of the dialog including *Elapsed Time* and *Time Remaining*. This simulation runs much faster than the 3D case.

7. Select the *Close* button when TSIM finishes.

8. View the results by following the procedure outlined in section 5.9 *Viewing the Results* in phase I of this tutorial.

7   Phase III – Generating Multiple HUF Data Sets

In the final phase of this tutorial, we will generate HUF data using T-PROGS. Using HUF arrays overcomes the main limitation of T-PROGS. The limitation is that grid cell dimensions must be kept small to capture the heterogeneity. This results in thin cells at the top of the grid that are prone to wetting and drying problems. With the HUF approach, larger cell thicknesses can be used.

When using the HUF approach, the user first creates a grid with constant row and column widths. The layer elevations are then interpolated as desired to match aquifer boundaries. When TSIM is executed in the HUF mode, GMS creates a background grid that has the same dimensions as the primary grid in terms of rows and columns, but has a greater number of layers than the primary grid resulting in greater detail or resolution in the vertical direction. The background grid is then an orthogonal grid compatible with the T-PROGS interpolation algorithm. The T-PROGS simulation is then performed on the background grid. The heterogeneity resulting from the dense background grid is then translated by GMS into a set of grid independent HUF units.

Once again, we will reuse the transition probability data created in the first phase of the tutorial.

7.1   Turn off Cell faces

Before continuing, we will turn off the display of the grid cell materials.

1. Select the *Display Options* button .

2. Select the *3D Grid Data* item in the list box.

3. Turn off the *Cell faces* item on the *3d Grid* tab and select *OK*.

7.2   Building the Grid

First, we will create a four-layer grid using the grid frame.

1. Right-click on the *Grid Frame* in the *Project Explore*r and select the *Map to | 3D Grid* menu command.

2. Select *OK* at the prompt.

3. Enter **70**, **50**, and **4** for the number of cells in the X, Y, and Z-Dimensions respectively.

4. Select the *OK* button.

7.3   Saving the Project

Before continuing, we will save the project under a new name.

1. Select the *File | Save As* menu command.

2. Save the project with the name **tprobhuf.gpr**.

7.4   Initializing MODFLOW

Before interpolating the top and bottom elevations for the grid, we will first initialize the MODFLOW data.

1. Select the *MODFLOW | New Simulation* command to initialize MODFLOW.

2. Select the *Packages* button.

3. In the *Flow Package* section, select the *HUF* package, then click *OK*.

4. Select the *OK* button again to exit the *MODFLOW Global/Basic Package* dialog.

7.5   Interpolating the Layer Elevations

Next, we will import a set of scatter point data and interpolate the top and bottom elevations for the four layers of the MODFLOW grid. To do this, we will first interpolate the elevations for the top of the grid. Although we could also interpolate the elevations at the bottom of the grid, we will leave these values at a constant value for simplicity. We will then use the *Redistribute Layers* command to evenly distribute the elevations for the interior layer boundaries.

Importing the Scatter Point Data

We will import the scatter data from a tabular text file:

1. Select the *Open* button 📂.

2. In the *Files of type* combo box, at the bottom of the *Open* dialog, select the **Text Files (*.txt)** filter.

3. Select and open the file **topo.txt**.

4. Turn on the *Heading row* toggle in the first page of the *Text Import Wizard*.

5. Select the *Next* button.

6. Confirm that the *GMS data type* selection at the top of the dialog is **2D Scatter Points**.

7. The spreadsheet at the bottom of the dialog enables you to specify what types of data are in each column. In the *Type* row, make the id column (first column) a **Label** type and the elevation column (fourth column) a **Data set** type. This indicates that the fourth column represents an elevation data set.

8. Select the *Finish* button.

A set of scatter points should appear in the vicinity of the grid.

Interpolating the Layer Elevations

Next, we will interpolate the elevations associated with the scatter point set to the top of the MODFLOW grid using the default interpolation options.

1. Right-click on the **topo** scatter set in the *Project Explorer* and select the *Interpolate To→MODFLOW layers* command.

2. In the *Scatter point data sets* list select the **elevation** item, and in the *MODFLOW data* list, select the **Top Elevations Layer 1** item.

3. Select the *Map* button.

4. Select the *OK* button.

To view the results:

5. Turn off the display of the scatter points by turning off the **topo** toggle in the *Project Explorer*.

6. Hide all the boreholes by unchecking the box next to the *Borehole Data* folder in the *Project Explorer*.

7. Select the 3D Grid Data Folder in the Project Explorer.

8. Select a cell somewhere near the center of the grid.

9. Select the *Front View* button .

10. Select the *Side View* button .

Redistributing the Interior Layer Elevations

We will now use the *Redistribute Layers* command to distribute the elevations of the interior layer boundaries between the current elevations at the top and bottom of the grid. We will make the top layer a little larger than the other three layers. The other three layers will be evenly distributed.

1. Select the *Grid | Redistribute Layers* menu command.

2. Enter a value of **0.35** in the *Fraction* column for layer 1 and select the *Tab* key. Note how the fractions for the other layers are automatically updated.

3. Select the *OK* button.

4. Select *Yes* at the prompt to confirm that we are overwriting the MODFLOW elevations.

Note the change in the layer elevations. Having a thicker layer at the top reduces difficulties caused by cell wetting and drying.

7.6   Run TSIM

We are now ready to run TSIM.

1. Select the *T-PROGS | Run TSIM* menu command.

2. Select the *Next* button.

3. Change the *Simulation name* to **simhuf**.

4. Enter **5** for the Number of realizations.

5. Select the *Generate HUF arrays* option in the *TSIM output* section.

6. Enter **20** in the *Num Z* edit field. This defines the number of layers in the background grid and controls the level of detail in the resulting HUF units.

7. Accept the other defaults and select the *Finish* button.

8. When the GAMEAS utility finishes, select the *Close* button.

9. The MCMOD and TSIM utilities are executed. Select the *Close* button when TSIM finishes.

7.7   Viewing the Results

The output from T-PROGS is automatically converted to a series of HUF data sets. The HUF data sets are organized in the *3D Grid Project Explorer*. The first HUF data set is automatically loaded and the *Display hydrogeologic units* option is turned on. Note that the stratigraphic definition is independent of the MODFLOW grid boundaries.

1. Expand the *HUF Data* folder under the *3D Grid Data* folder . Next, expand the *simhuf* folder.

All five realizations are listed under the *simhuf* folder. The active HUF data set, *simhuf 1,* is identified by a bolded name and selected icon. You may wish to view other HUF data sets by clicking on the other items in the list. You may wish to also view different columns and rows of the MODFLOW grid. As you view the results, the solid lines represent the boundaries of the MODFLOW grid cells. The filled colors in the background represent the HUF units.

As you view the cross sections, keep in mind that the vertical scale is currently magnified by a factor of 5.0. If you wish, you can change back to the true scale using the *Display Options* command in the *Display* menu.

This completes the HUF portion of this tutorial.

8   Conclusion

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

- T-PROGS can be used to help create single or multi-layer MODFLOW model that uses the Material IDs approach with the LPF package. It can also be used with the MODFLOW HUF package.