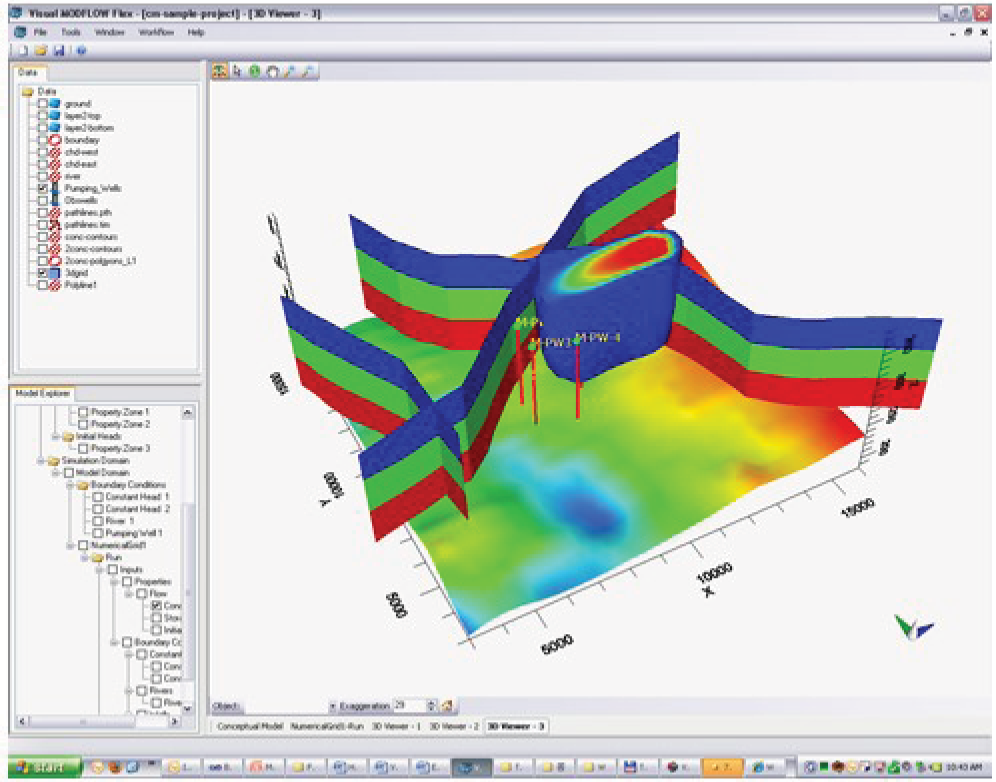
An Overview of MODFLOW FLEX



By:

Dr. Surjeet Singh

Scientist 'F'

Email: surjeet.nihr@gov.in

Mobile: +91-9456134747

Ground Water Hydrology Division

National Institute of Hydrology

Jalvigyan Bhawan, Roorkee-247 667

Uttarakhand (INDIA)

Presentation Overview

- Modeling Process & Flow Equation
- Visual MODFLOW FLEX
- Comparison with Visual MODFLOW Classic
- Additional Options in MODFLOW FLEX
- Various Packages in FLEX
- FLEX Overview

Modeling - Governing Equation

Governing flow equation, PDE

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + W = S_s\frac{\partial h}{\partial t}$$

- K_{xx}, K_{yy} & K_{zz} are hydraulic conductivity along x, y, and z coordinate axes (L/T)
- h is the potentiometric head (L)
- W is volumetric flux per unit volume representing sources and/or sinks of water, where *negative* values are extractions, and *positive* values are injections (T^{-1})
- S_s is the specific storage of porous material (L^{-1})
- t is time (T)

MODFLOW

- **Developed by USGS (1984)**
  - A 3-D Finite Difference groundwater model;
  - Simulates and predicts groundwater conditions.

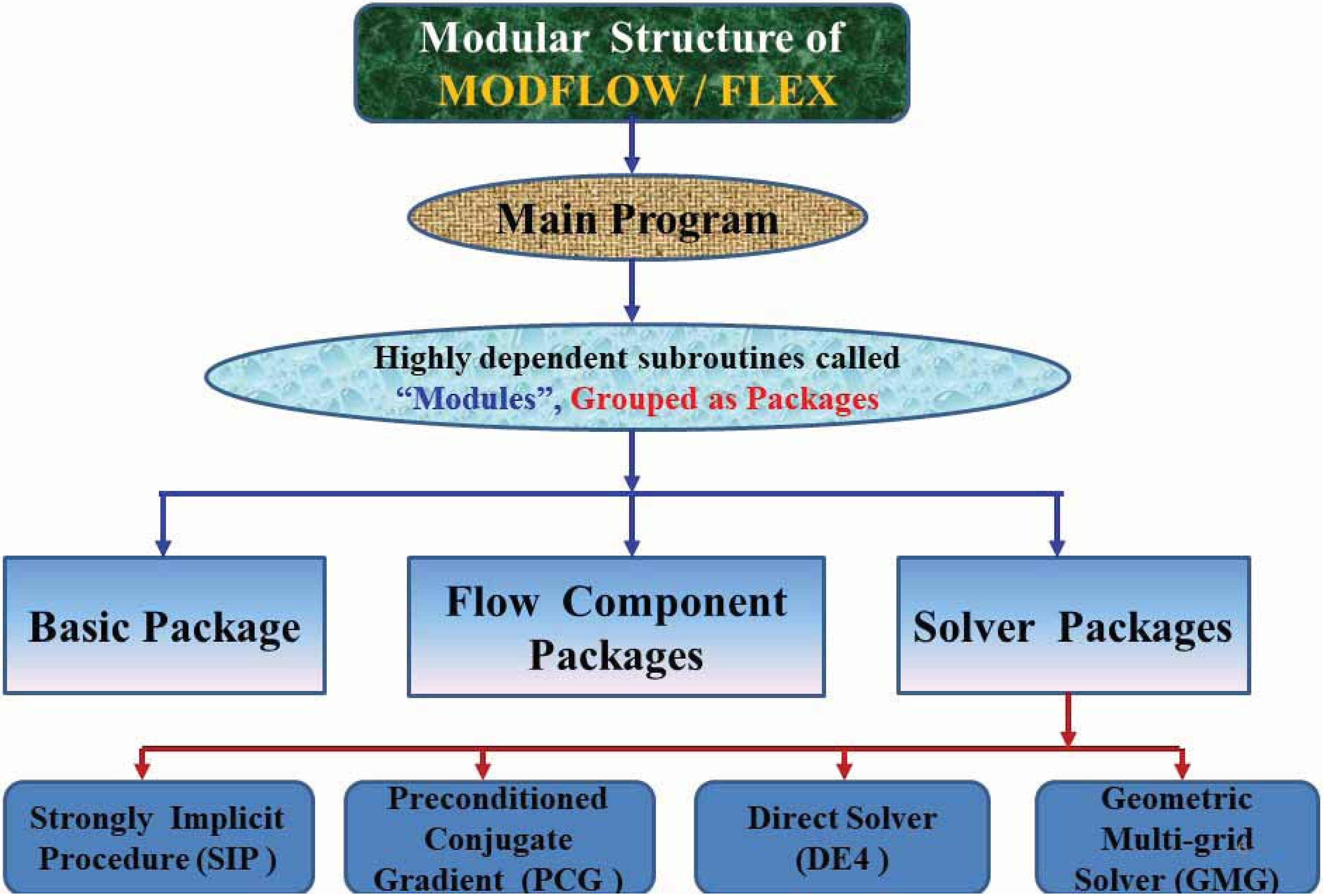
- **MODFLOW Packages include:**
  - Capabilities to simulate coupled groundwater/surface water systems, solute transport, variable-density flow (including saltwater), parameter estimation, and groundwater management.

- **MODFLOW-2005** – Most stable and well tested; simulates steady and non-steady flow in irregularly shaped flow system.
  (For both confined & unconfined or combined system)

MODFLOW Releases ...

MODFLOW-88	Written in FORTRAN 77, and its version 2.6, released in September, 1996.
MODFLOW-96	Released in December, 1996.
MODFLOW-2000	Released in July, 2000, and merged MODFLOWP and HYDMOD codes into the main program.
MODFLOW-2005	Standard version of MODFLOW.
Visual MODFLOW	Released in 1994 and based on the USGS MODFLOW-88 code and MODPATH code. Visual MODFLOW supports MODFLOW-2000, MODFLOW-2005, MODFLOW-NWT, MODFLOW-LGR, MODFLOW-SURFACT, and SEAWAT.
Conduit Flow Process for MODFLOW-2005	Simulates laminar and turbulent flow conditions within preferential flow layers and within single- and dual-porosity aquifers, as occuring in karst, fractured rock, and basalt aquifers.
GSFLOW	A coupled Groundwater and Surface water flow model based on the integration of MODFLOW-2005 with USGS Precipitation-Runoff Modeling System (PRMS).
Visual MODFLOW Flex	A graphical interface for MODFLOW. The program also combines proprietary extensions, such as MODFLOW-SURFACT, MT3DMS (mass-transport 3D multi-species) and a 3D model explorer.

MODFLOW Packages



Packages

Visual MODFLOW Flex has a no. of tools for analyzing water quality, groundwater supply, and source water protection.

Tools	Features
MODFLOW-2000, 2005, NWT	Standard Engine for groundwater flow modeling.
MODFLOW-USG	Finite volume version of MODFLOW with unstructured grids.
MODFLOW-LGR	Local grid refinement (LGR) for regional-local scale simulations.
MODFLOW-SURFACT	Saturated/ unsaturated subsurface flow and transport processes.
MT3DMS	Multi-species contaminant transport simulations.
SEAWAT	Variable-density groundwater flow coupled with multi-species solute and heat transport.
RT3D	Multi-species reactive contaminant transport simulations.
MODPATH	Standard package for forward and reverse particle tracking.
MOD-PATH3DU	Package for forward and reverse particle tracking supporting Un-Structured Grids.
Zone Budget	Package for sub-regional water budget calculations.
PEST v.12.3	Automated calibration and Sensitivity analysis tool.

MODFLOW Engines

- **MODFLOW-2000, 2005, NWT:** Standard for groundwater flow simulations.
- **MODFLOW-USG:** Finite volume version of MODFLOW that uses unstructured grids.
- **MODFLOW-LGR:** Shared-node local grid refinement (LGR) for regional-local scale simulations.
- **MODFLOW-SURFACT:** Enhanced simulations of complex saturated/unsaturated subsurface flow and transport processes
- **MODPATH:** Standard package for forward and reverse particle tracking.
- **Zone Budget:** Standard package for sub-regional water budget calculations.
- **MGO*:** For determining the optimal well pumping and/or injection rates at one or more wells, in order to achieve a specific objective while maintaining reasonable system responses.

* *Available with the Classic interface.*

MODFLOW Packages

RIV – River package
CHD – Constant-Head boundary package
DRN – Drain package
WEL – Well package
LAK – Lake Package
EVT – Evapotranspiration package
STR* – Streamflow-Routing package
RCH – Recharge package
FHB – Flow and Head boundary package
ETS1* – Evapotranspiration Segments package
MNW* – Multi-node Well Package
HFB – Horizontal Flow Barrier Package
UZF – Unsaturated Zone Flow Package

* *Available with the Classic interface.*

Transport Packages

- **MT3DMS:** Three-dimensional transport model for simulating advection, dispersion, and chemical reactions of dissolved constituents.
- **MODFLOW-SURFACT:** Enhanced simulations of complex saturated/unsaturated subsurface flow and transport processes.
- **SEAWAT:** Three-dimensional variable-density groundwater flow coupled with multi-species solute and heat transport.
- **RT3D:** Reactive transport simulations.
- **MT3D99*:** An enhanced version of MT3DMS, that includes support for implicit solver, TVD Solution scheme, dual-porosity advection-diffusion, Non-equilibrium Sorption and Monod Kinetics, and Multi-species Reactions, including First-Order Parent-Daughter chain reactions, and Instantaneous Reactions among species.
- **PHT3D*:** A multi-component transport model for three-dimensional reactive transport in saturated porous media.

* *Available with the Classic interface.*

Parameter Estimation and Sensitivity Analysis

PEST v12.3: Automated parameter estimation, calibration and sensitivity analysis

Defining PEST inputs & interpreting results is easy with an intuitive, easy-to-use interface that guides you through the PEST process from start to finish.

Data Visualization

Designed with 3D Visualization Technology:

- Visualize all data, including conceptual objects, numerical grids, input data (property zones, boundary condition cells) and output data (calculated heads, pathlines, water table) in 2D, 3D & multi-view (FlexViewer) displays.
- Create cut-away & cross-sectional views that allow you to see inside of the model.
- Generate 3D animations & movies for reports or for web publishing.
- Add isolines, contours, pathlines & color shading to viewers.
- Drape raster images (site maps, satellite imagery) over 3D surfaces to show relief.

Uncertainty & Multiple Scenarios

Visual MODFLOW Flex allows to assess uncertainty & comparisons of multiple modeling scenarios – all within a single project.

- Manage multiple model scenarios in a single project.
- Easily generate multiple models in parallel for evaluating alternative hydrogeologic interpretations and hypotheses.
- Direct visual and numerical comparisons between different modeling scenarios.
- Calculate head differences between multiple model runs, with the same or different grid sizes.
- Compare & analyze multiple modeling scenarios for selecting the best, and most realistic model.

Flexible Grid Options

Visual MODFLOW Flex provides different grid types and choose the best, & most stable model.

- Choose various structured and unstructured grid types to accommodate a wide range of applications and geologic conditions (e.g., pinch outs, discontinuities).
- Improve simulation accuracy, reduce runtimes and increase model stability with unstructured grid types (MODFLOW-USG).
- Generate multiple grids within the same project and compare side-by-side in 2D or 3D.
- Perform grid refinement around areas of interest.
- Create faster & more stable models with nested child grids that contain local horizontal & vertical refinement (MODFLOW-LGR).

GIS Integration

- Easy to construct grid-independent hydrogeologic conceptual model using existing GIS datasets.
- Quick & easy data import facility from all common file types and formats.
- Automatic conversion of coordinate system & units on import.
- Automatic data validation & error checking on import.
- Option to define model boundaries, property zones, boundary conditions & attributes from imported GIS data.

Integrated 3D Conceptual & Numerical GW Modeling

Visual MODFLOW Flex provides a seamless transition from raw data through conceptualization model to numerical model in a single modeling environment:

- Define complex geology & model layers using borehole log data and cross-sections.
- Interpret GIS data to define hydrogeologic properties & boundaries independent of the grid.
- Run, analyze, & validate model results with raw data in 2D, 3D, & cross-sectional views.
- Create multiple conceptualizations; generate numerous grids & model scenarios in parallel all in a single project.
- Assess uncertainty though comparing heads from multiple model runs in 2D, 3D or chart views.

Visual MODFLOW Flex: Feature Comparison

Features	Basic	Professional	Premium
MODFLOW-2000, 2005, NWT	√	√	√
MODFLOW-USG (Un-Structured Grids)		√	√
ZoneBudget	√	√	√
MODPATH	√	√	√
MOD-PATH3DU		√	√
Enhanced 3D Visualization	√	√	√
MT3DMS	√	√	√
RT3D	√	√	√
Local Grid Refinement (MODFLOW-LGR)		√	√
Conceptual Modeling		√	√
Multiple Grid Types		√	√
Compare results from multiple model runs		√	√
Modeling Scenarios in a Project	One	Unlimited	Unlimited
Build and run bigger models (Native 64-bit Support)		√	√
3D Animation and Movie Generation		√	√
PEST		√	√
SEAWAT		√	√
SAMG Solver (Serial)		√	
SAMG Solver (Parallel)			√
FEFLOW Model Generation (.FEM file)			√
MODFLOW-SURFACT	Add-On	Add-On	Add-On

MODFLOW Packages

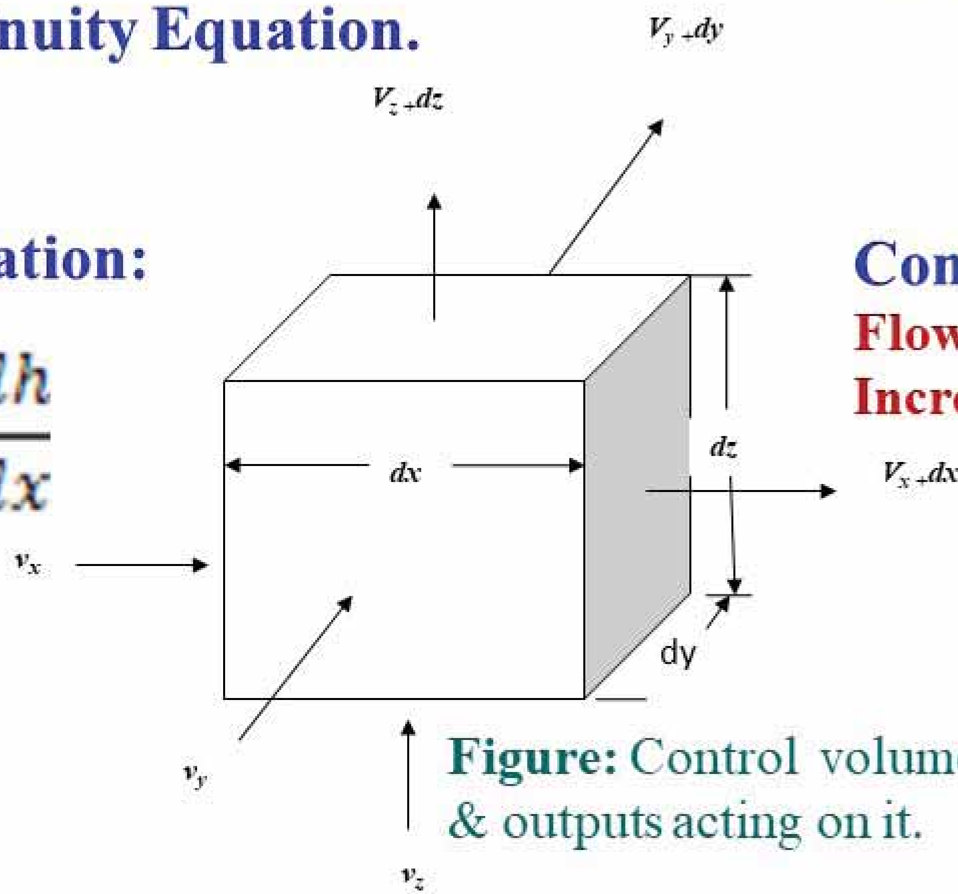
Functionality	Package & Processes Name	Purpose
BAS	Basic Package	These include • model domain (X,Y,Z extents), no. of layers, etc. • locations of active, inactive, and specified head cells • head stored in inactive cells, and • initial heads in all cells. • Includes boundary locations, time-step length, initial conditions, and printing of results.
Flow component packages: account all groundwater flow components.		
BCF	Block-Centered Flow Package	Specify properties controlling flow between cells.
LPF	Layer-Property Flow Package	Specify properties of porous media of cells
HFB	Horizontal Flow Barrier Package	Simulate barriers to flow such as slurry walls by reducing the conductance between individual pairs of cells.
CHD	Time-Variant Specified-Head Option	Simulate specified head boundaries that can change within or between stress periods.
RIV	River Package	Simulate head-dependent flux boundaries.
DRN	Drain Package	Simulate head-dependent flux boundaries.
WEL	Well Package	Simulate a specified flux to individual cells and specified in units of length^3/time.
GHB	General Head Boundary Package	Simulate head-dependent flux boundaries.
RCH	Recharge Package	Simulate a specified flux distributed over the top of the model and specified in units of length/time.
EVT	Evapotranspiration Package	Simulate a head-dependent flux out of the model distributed over the top of the model and specified in units of length/time. .

Numerical Schemes

- Groundwater equation follows: Integration of **Darcy's Equation** into **Continuity Equation.**

Darcy's equation:

$$V_x = K_{xx}\frac{dh}{dx}$$



Continuity equation:

Flow in – Flow out = Increase in storage

Figure: Control volume showing inputs & outputs acting on it.

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right) = S_s\frac{\partial h}{\partial t}$$

Finite Difference Scheme in MODFLOW

$$CR_{i,j-\frac{1}{2},k}\left(h^m_{i,j-1,k} - h^m_{i,j,k}\right) + CR_{i,j+\frac{1}{2},k}\left(h^m_{i,j+1,k} - h^m_{i,j,k}\right) +$$
$$CC_{i-\frac{1}{2},j,k}\left(h^m_{i-1,j,k} - h^m_{i,j,k}\right) + CC_{i+\frac{1}{2},j,k}\left(h^m_{i+1,j,k} - h^m_{i,j,k}\right) +$$
$$CV_{i,j,k-\frac{1}{2}}\left(h^m_{i,j,k-1} - h^m_{i,j,k}\right) + CV_{i,j,k+\frac{1}{2}}\left(h^m_{i,j,k+1} - h^m_{i,j,k}\right) +$$
$$P_{i,j,k}\, h^m_{i,j,k} + Q_{i,j,k} = SS_{i,j,k}\left(\Delta r_j \Delta c_i \Delta v_k\right) \frac{h^m_{i,j,k} - h^{m-1}_{i,j,k}}{t^m - t^{m-1}}$$

- $\mathbf{h^m_{i,j,k}}$ is the hydraulic head at cell *i,j,k* at time step *m;*
- ***CV*, *CR*** and ***CC*** are the hydraulic or branch conductances between node *i,j,k* and a neighbouring node;
- $\mathbf{P_{i,j,k}}$ is the sum of coefficients of head from source and sink terms;
- $\mathbf{Q_{i,j,k}}$ is the sum of constants from source and sink terms; for flow out of the groundwater system (such as pumping) and flow in (such as injection);
- $\mathbf{SS_{i,j,k}}$ is the specific storage;
- $\Delta c_i\, \Delta r_j$ **and** Δv_k are the dimensions of cell *i,j,k*, which, when multiplied, represent the volume of the cell; and
- $\mathbf{t^m}$ is the time at time step *m.*

Finite Difference Scheme in MODFLOW

$$CV_{i,j,k-\frac{1}{2}} h^m_{i,j,k-1} + CC_{i-\frac{1}{2},j,k} h^m_{i-1,j,k} + CR_{i,j-\frac{1}{2},k} h^m_{i,j-1,k}$$

$$+ \left(-CV_{i,j,k-\frac{1}{2}} - CC_{i-\frac{1}{2},j,k} - CR_{i,j-\frac{1}{2},k} - CR_{i,j+\frac{1}{2},k} - CC_{i+\frac{1}{2},j,k} - CV_{i,j,k+\frac{1}{2}} + HCOF_{i,j,k} \right) h^m_{i,j,k}$$

$$+ CR_{i,j+\frac{1}{2},k} h^m_{i,j+1,k} + CC_{i+\frac{1}{2},j,k} h^m_{i+1,j,k} + CV_{i,j,k+\frac{1}{2}} h^m_{i,j,k+1} = RHS_{i,j,k}$$

Where,

$$HCOF_{i,j,k} = P_{i,j,k} - \frac{SS_{i,j,k} \Delta r_j \Delta c_i \Delta_k}{t^m - t^{m-1}}$$

$$RHS_{i,j,k} = -Q_{i,j,k} - SS_{i,j,k} \Delta r_j \Delta c_i \Delta v_k \frac{h^{m-1}_{i,j,k}}{t^m - t^{m-1}}$$

In matrix form: $\mathbf{A}\,\mathbf{h} = \mathbf{q}$

Where,

A is a matrix of the coefficients of head for all active nodes.

h is a vector of head values at the end of time step ***m*** for all nodes.

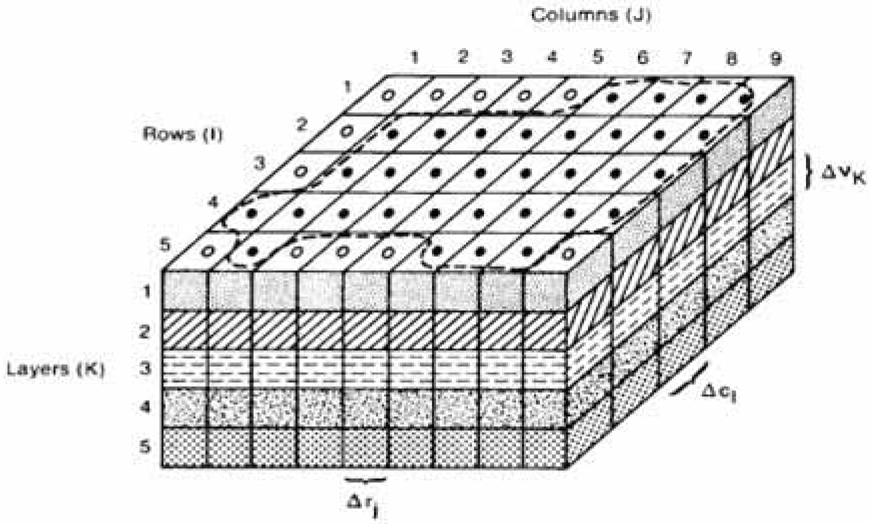
q is a vector of the constant terms, *RHS*, for all nodes of the grid.

MODFLOW Solvers

Functionality	Package Name	Purpose
Solver Packages		
SIP	Strongly Implicit Procedure	Iteratively solves the system of finite-difference equations.
PCG	Preconditioned-Conjugate Gradient	Solve the finite difference equations in each step of a MODFLOW stress period.
DE4	Direct Solver	Solve the finite difference equations in each step of a MODFLOW stress period.
GMG	Geometric Multi-Grid	Solve the finite difference equations in each step of a MODFLOW stress period.
Other Flow Packages		
STR	Stream	Simulate streams in a model.
FHB	Flow and Head Boundary	Used for specified head cells and specified flow cells, whose properties can vary within a stress period
IBS	Inter-Bed Storage	Simulate compaction of low-permeability interbeds within layers.
HUF	Hydrogeologic-Unit Flow	Used to specify properties controlling flow between cells.
RES	Reservoir	Simulates leakage between a reservoir and an underlying groundwater system .
OBS	Observation	Compare model-generated values of head, flux, or advective transport with observed values.
SFR	Stream Flow-Routing	Simulate streams in a model. Unsaturated flow beneath streams can also be simulated.
LAK	Lake	Used to simulate lakes.
UZF	Unsaturated Zone	Simulates vertical flow of water through unsaturated zone to the saturated zone.
SWI2	Seawater Intrusion	Allows three-dimensional vertically integrated variable-density groundwater flow and seawater intrusion in coastal multi-aquifer systems.

Schematization in MODFLOW

3–Dimensional grids considered in schematization.



Explanation

- - - - Aquifer Boundary

• Active Cell

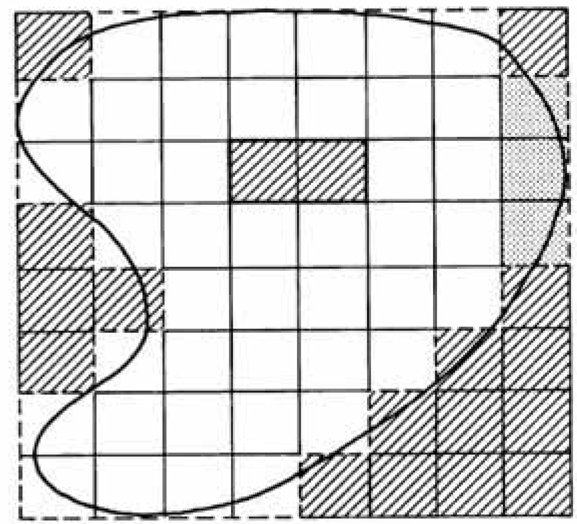
o Inactive Cell

Δr_J Dimension of Cell Along the Row Direction. Subscript (J) Indicates the Number of the

Δc_I Dimension of Cell Along the Column Direction. Subscript (I) Indicates the Number of

Δv_K Dimension of the Cell Along the Vertical Direction. Subscript (K) Indicates the Numbe

Discretized aquifer showing boundaries and cell designations.



Explanation

—— Aquifer Boundary

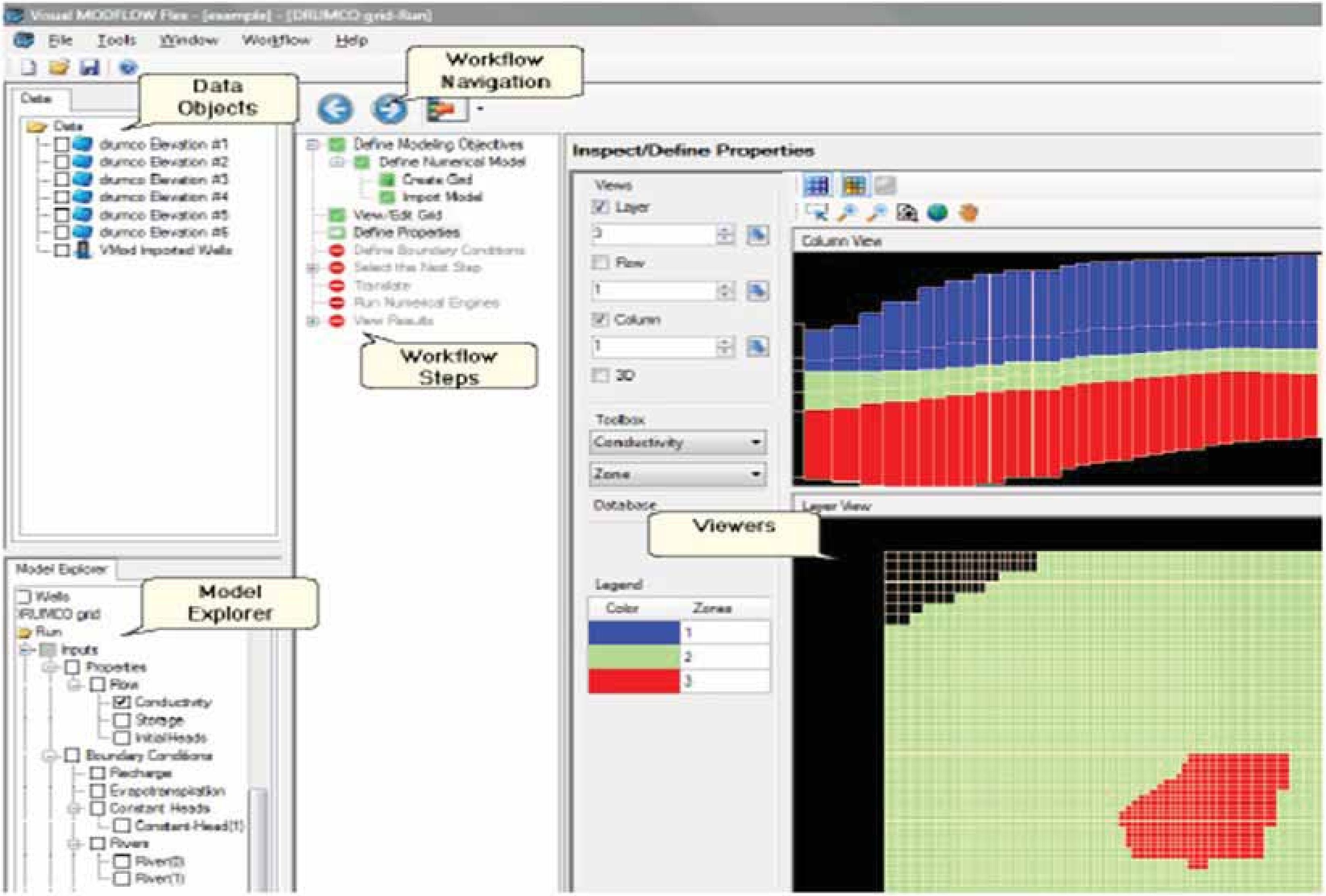
- - - Model Impermeable Boundary

Inactive Cell

Constant-Head Cell

Variable-Head Cell

Modflex Overview



- Data Objects

Features

VMOD Flex supports the following coordinate systems:

- Geographic coordinate systems (data import only)
- Projected coordinate systems: UTM, StatePlane
- Local Cartesian

Data Import Formats

Import spatial and attribute data from a wide variety of data types including:

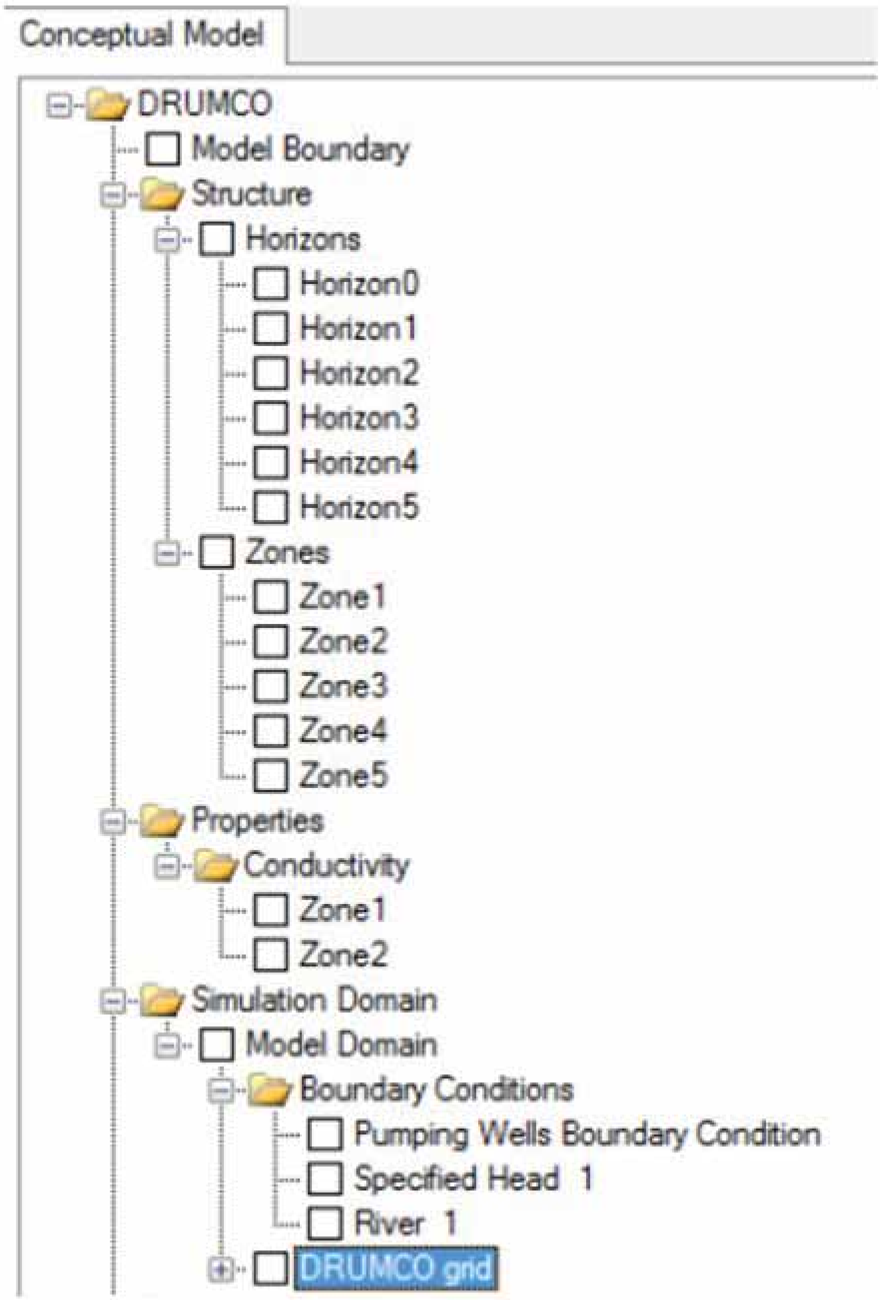
- Points (.XLS, .TXT, .CSV, .MDB, .SHP, .DXF, .TRP)
- Polygons (.SHP, .DXF)
- Polylines (.SHP, .DXF)
- 3D Gridded Data (.HDS, .DAT)
- Raster Images (.BMP, .TIF, .JPG)
- Time Schedules (.XLS)
- Surfaces (.DEM, .GRD, .TXT. ,.ASC)
- Hydro GeoAnalyst (HGA) Cross Sections (.3XS)
- Vertical and Horizontal Wells (.XLS)

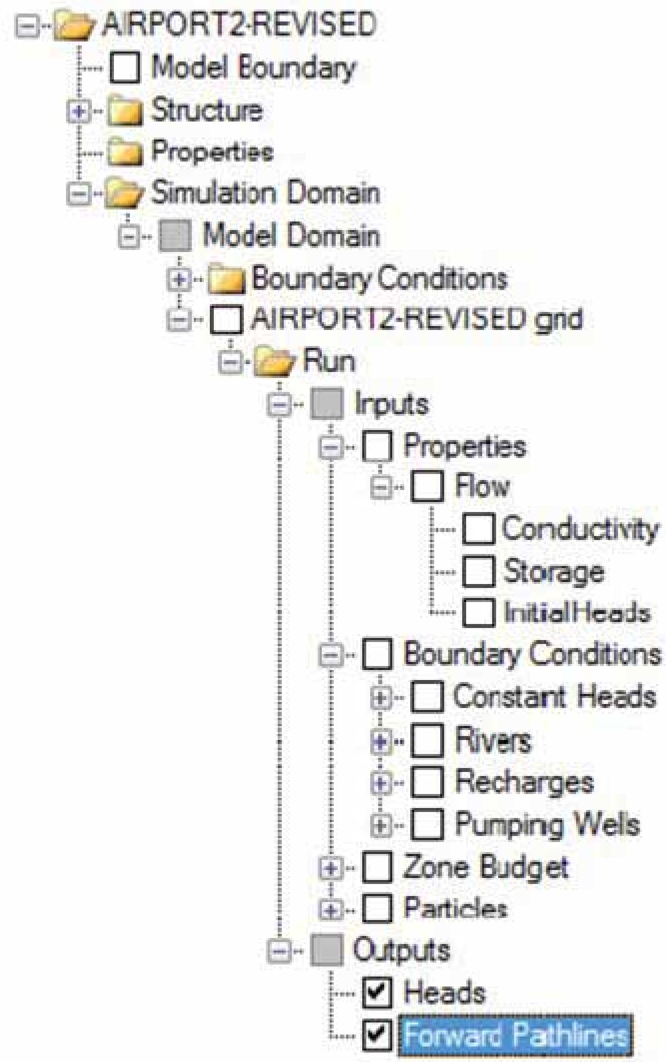
Boundary Conditions in Flex

Support for the following boundary conditions:

- Pumping Wells
- Specified Head
- River
- General Head
- Drain
- Recharge
- Evapotranspiration
- Lake
- Specified Flux
- Streams

Model Tree for Conceptual & Numerical Model



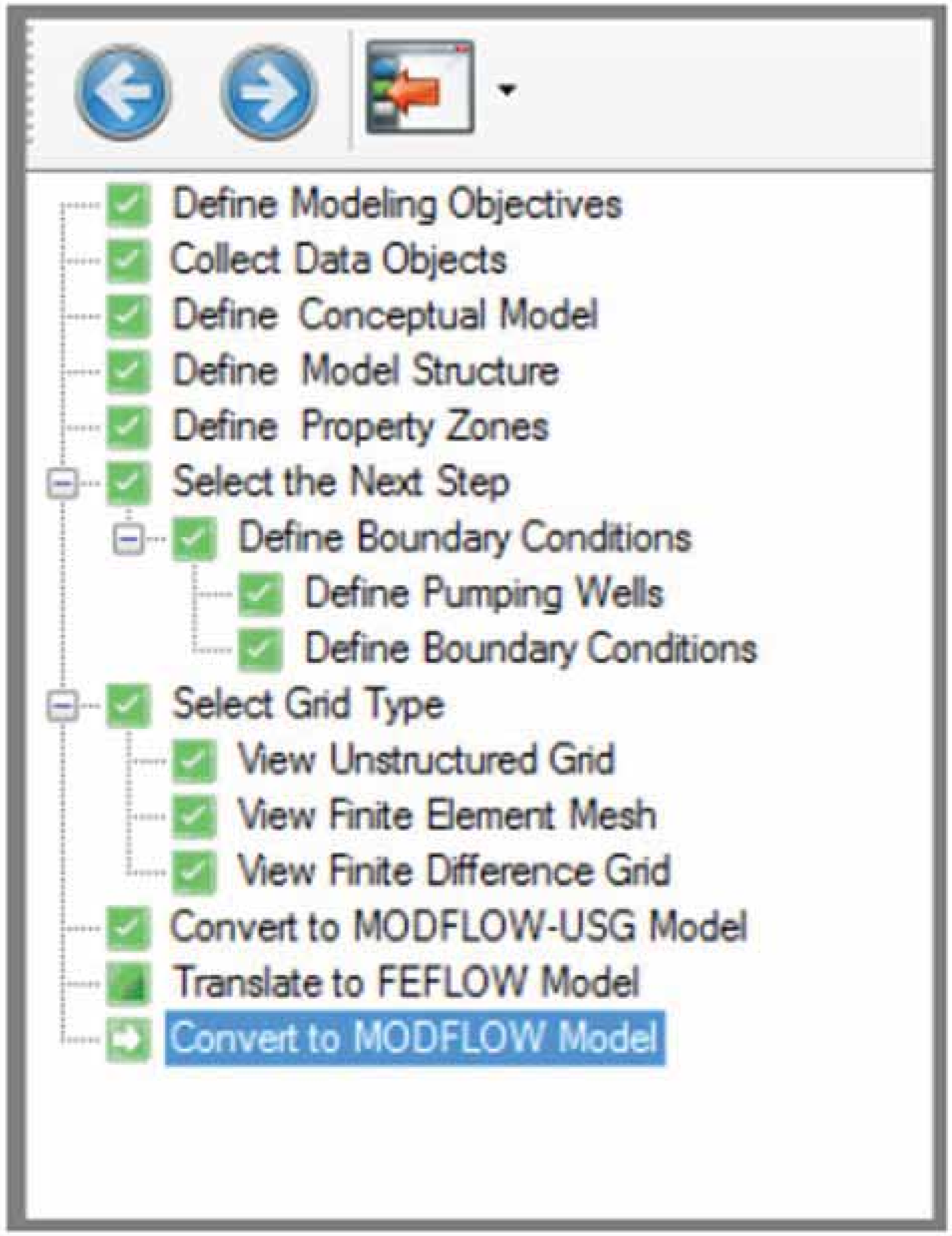


Flex Viewer

The "Flex" Viewer: which is available in the numerical modeling workflow, and consists of a combination of a Layer, Row and Column view and 3D View; the individual views can be shown/hidden.

Workflows

GW Modeling consists of a series of steps that must be completed in a particular sequence.



Navigation of Workflow

Go to the Previous Step in the workflow

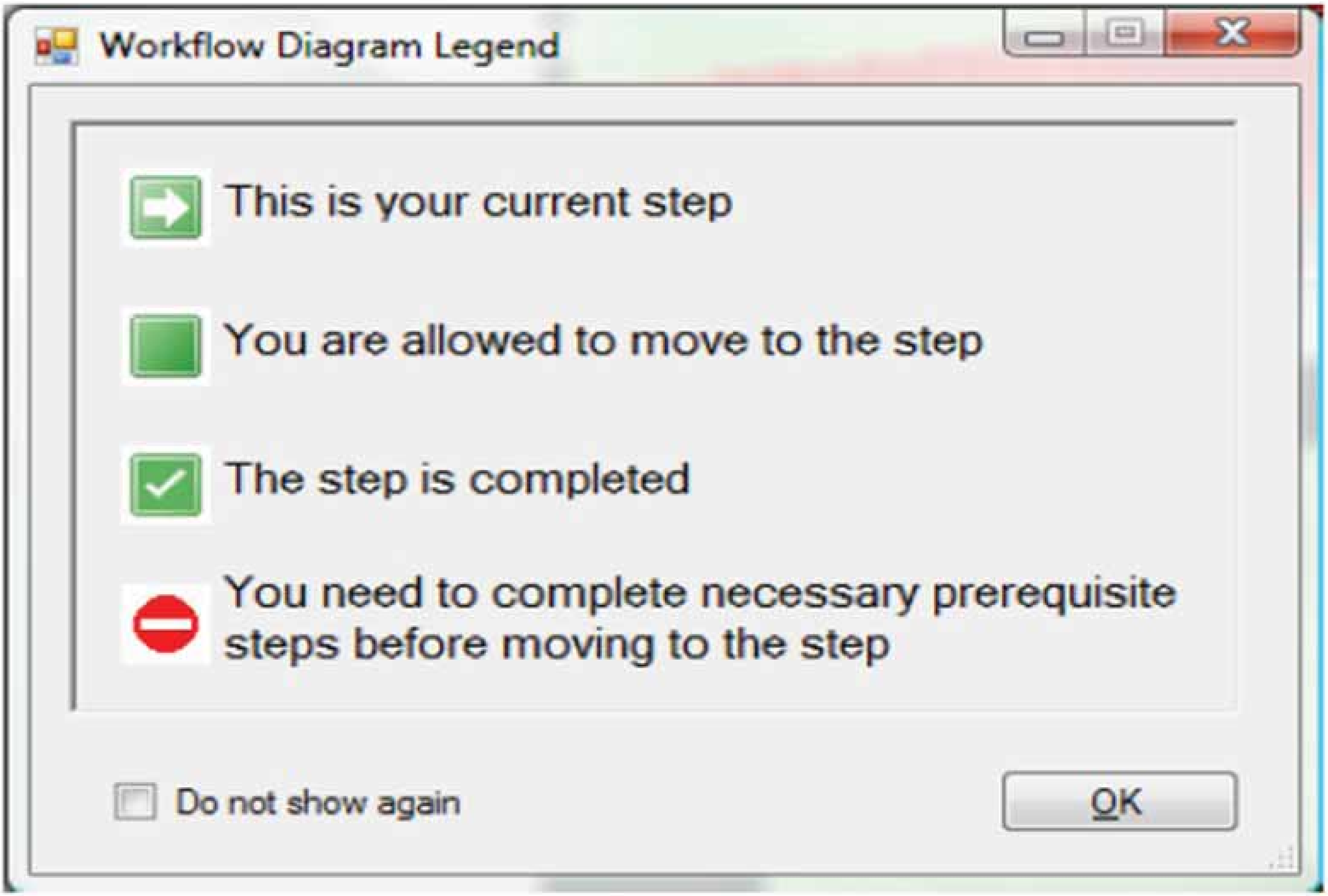
Go to the Next Step in the workflow

Hide the workflow panel; ideal when you want to maximize the viewing space for visualization and editing.

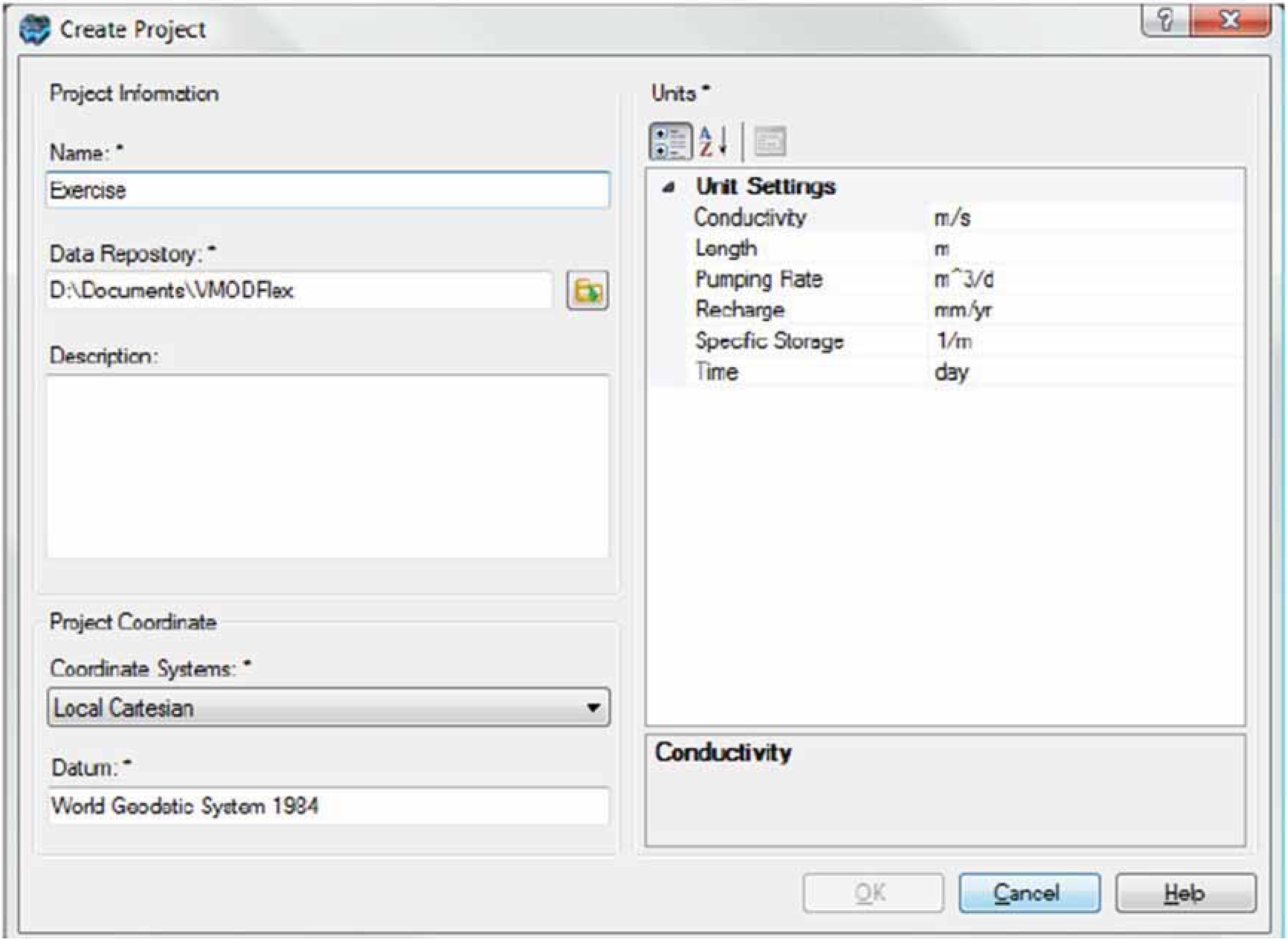
Expand the workflow panel; this button is only available when the workflow panel has been collapsed.

Workflow States

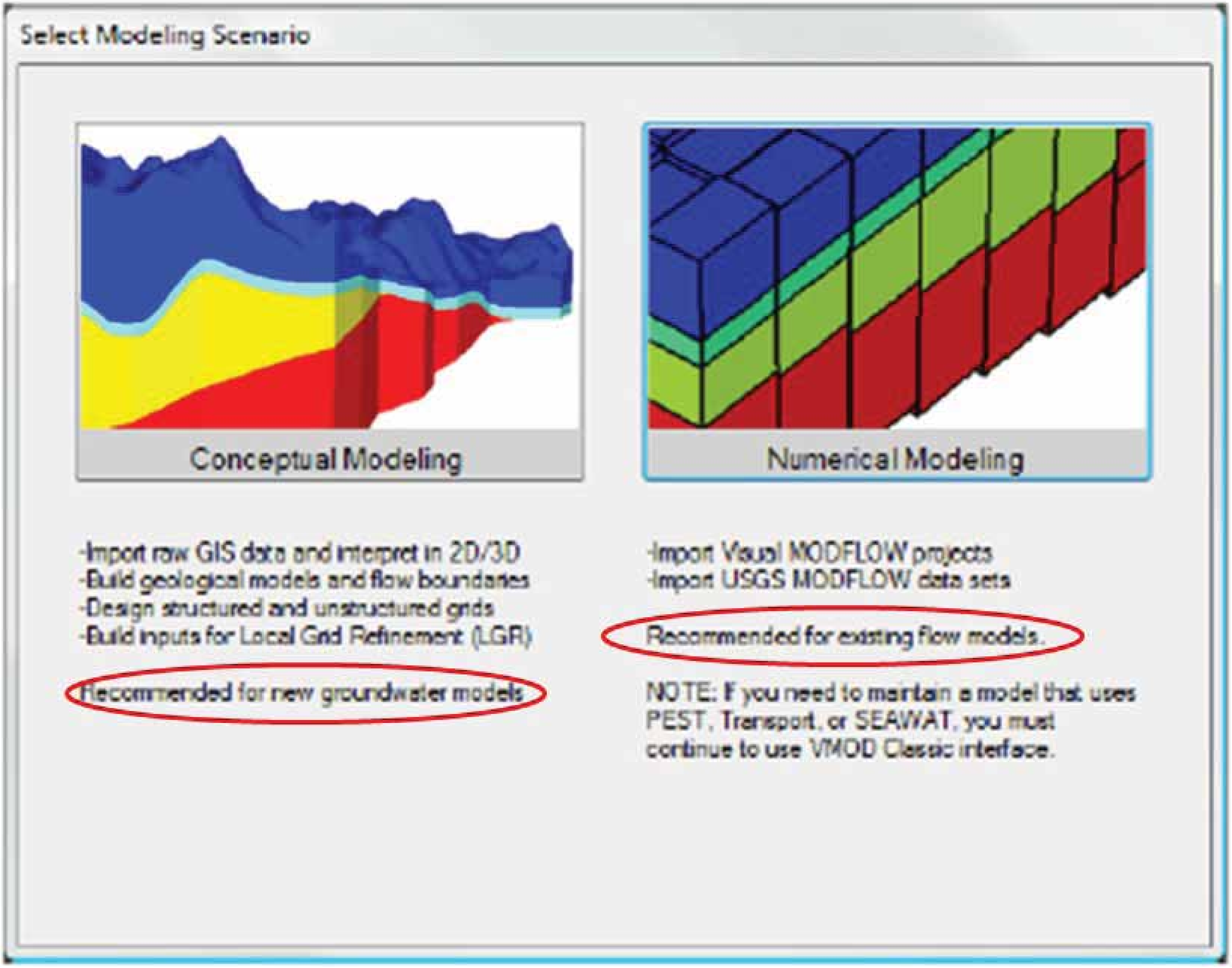
Beside each state in the workflow there is a corresponding icon. The icon helps you to identify which is your current step, which steps have been completed, and which steps you may proceed to next. The image below provides an explanation of this.



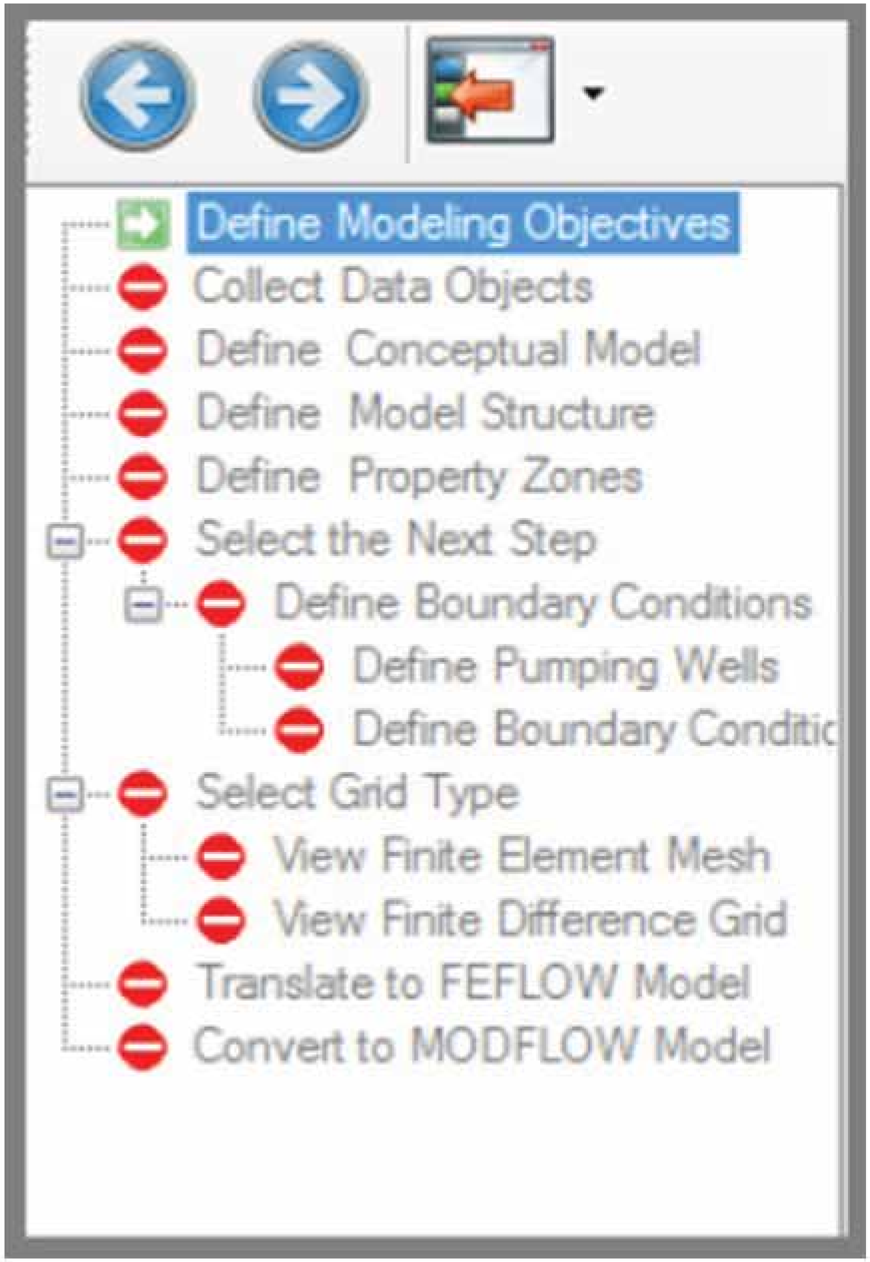
Project Creation



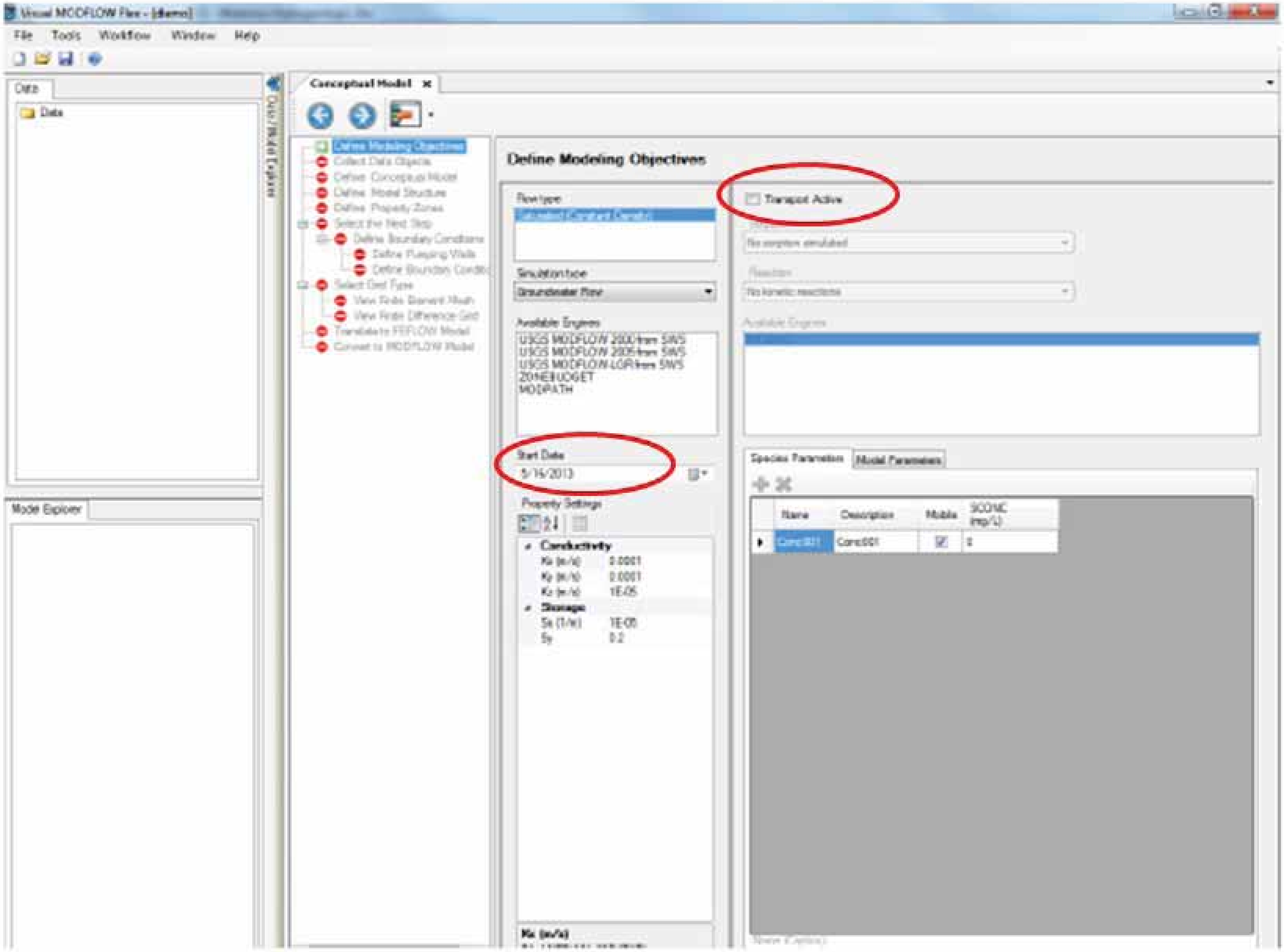
Type of Model



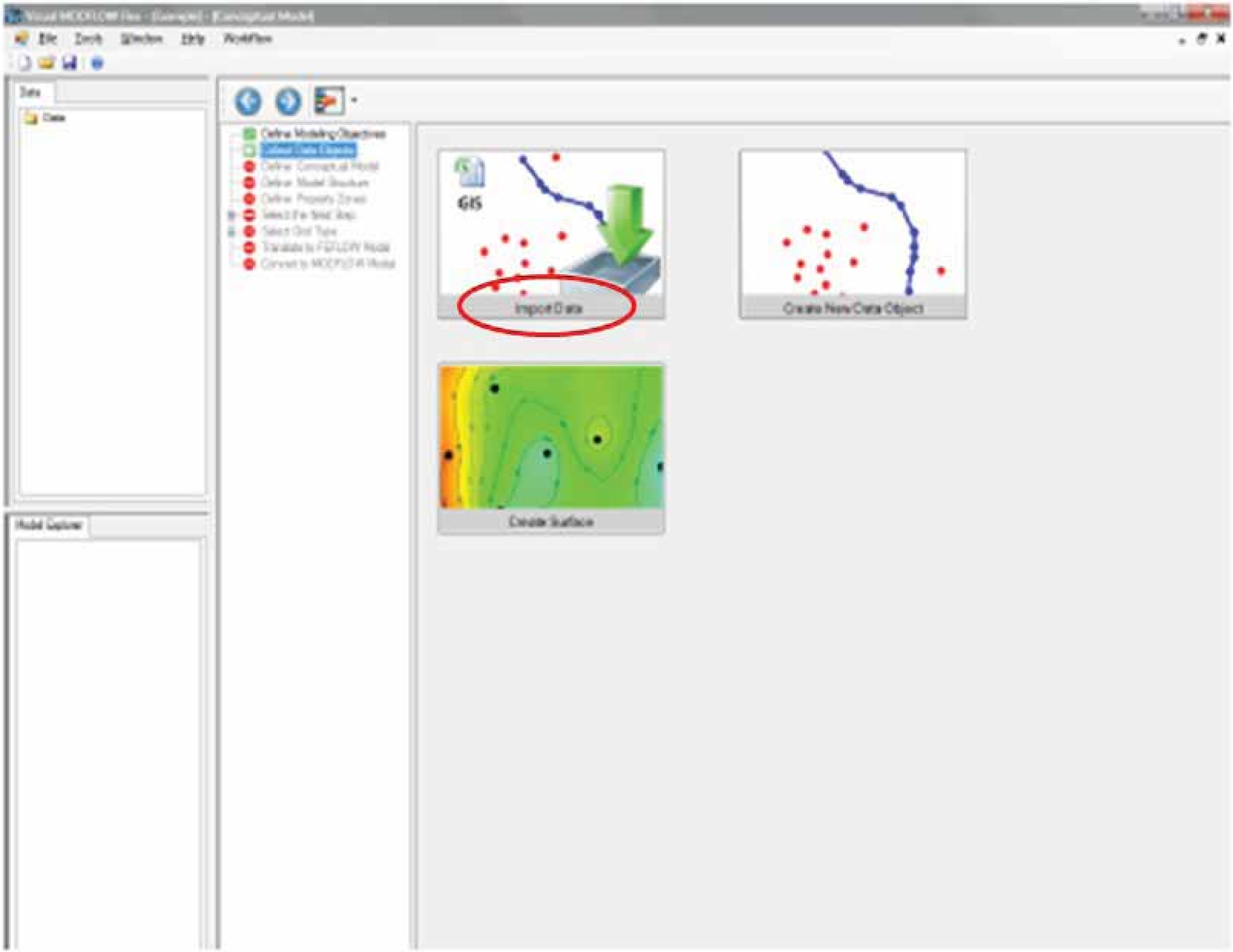
Steps to Follow



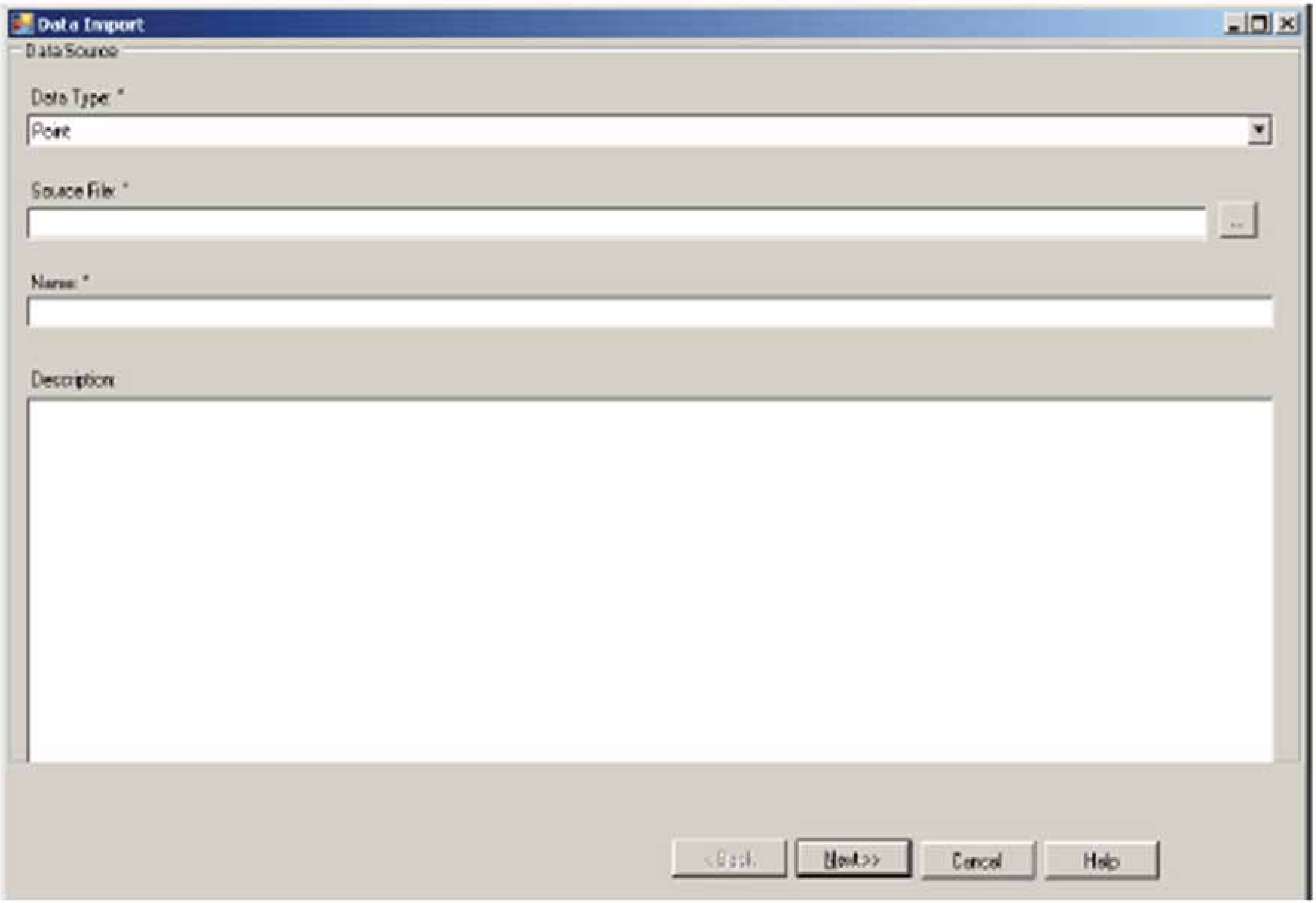
Define Objective of Model



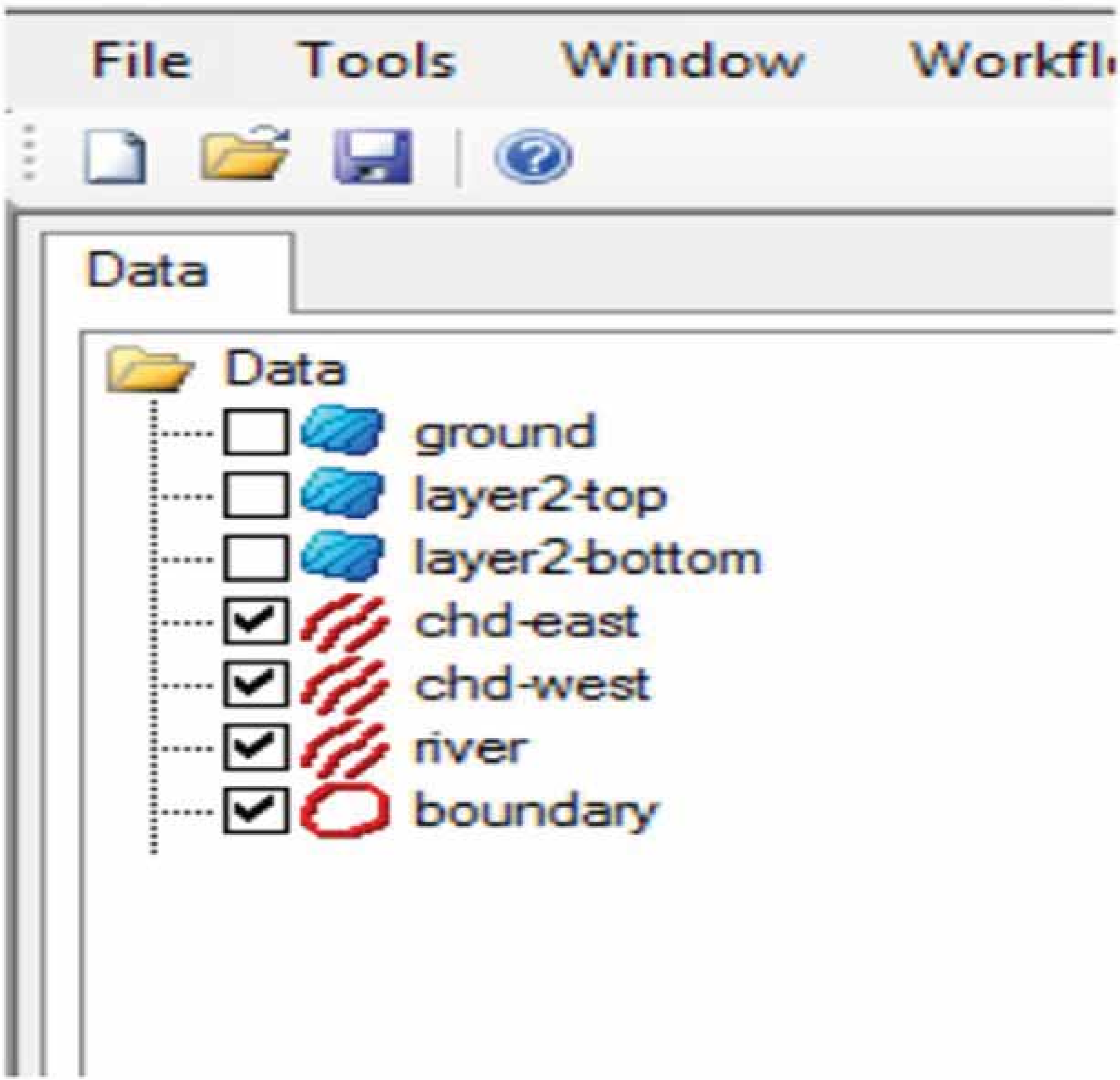
All Types of Data Import



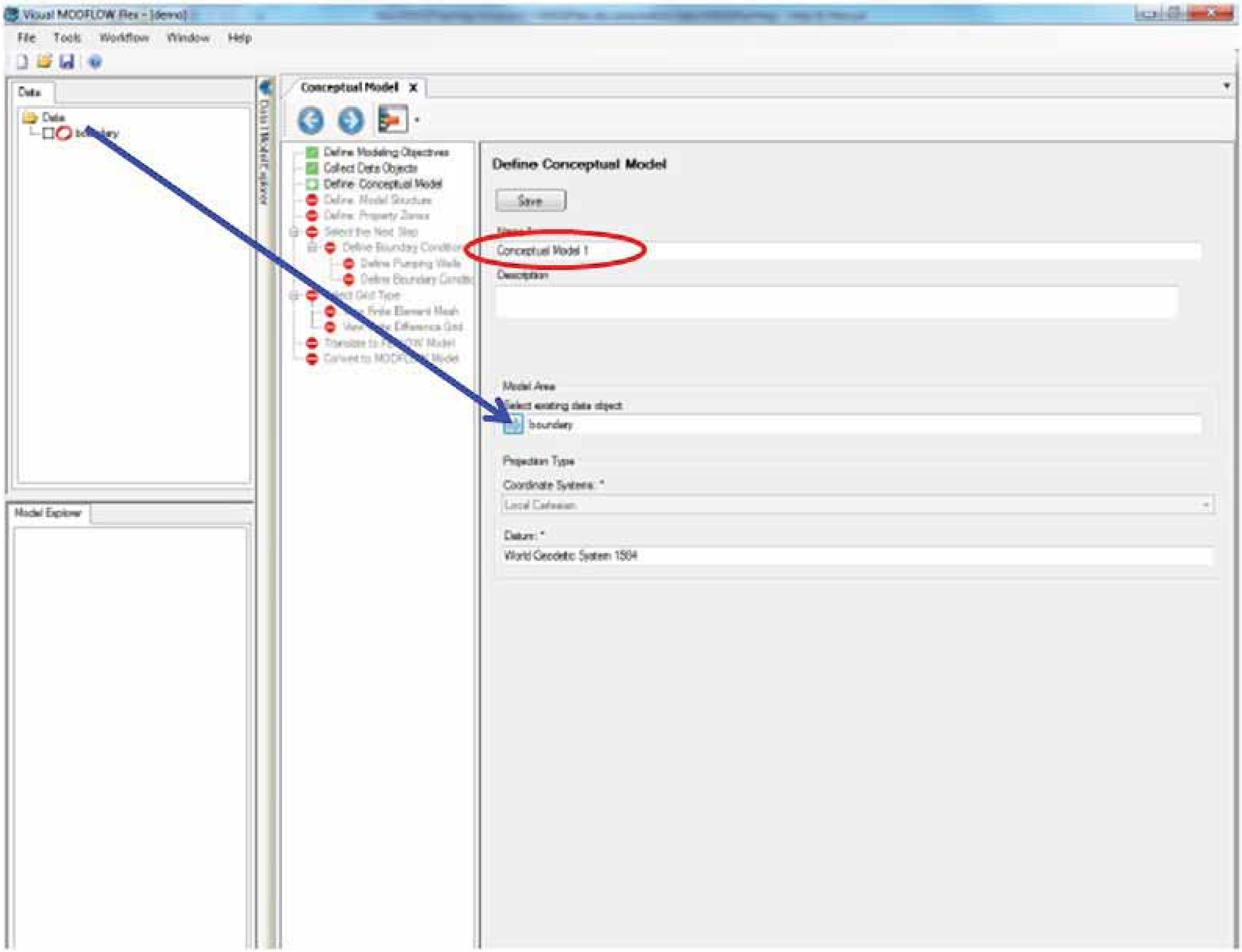
Data Type Selection



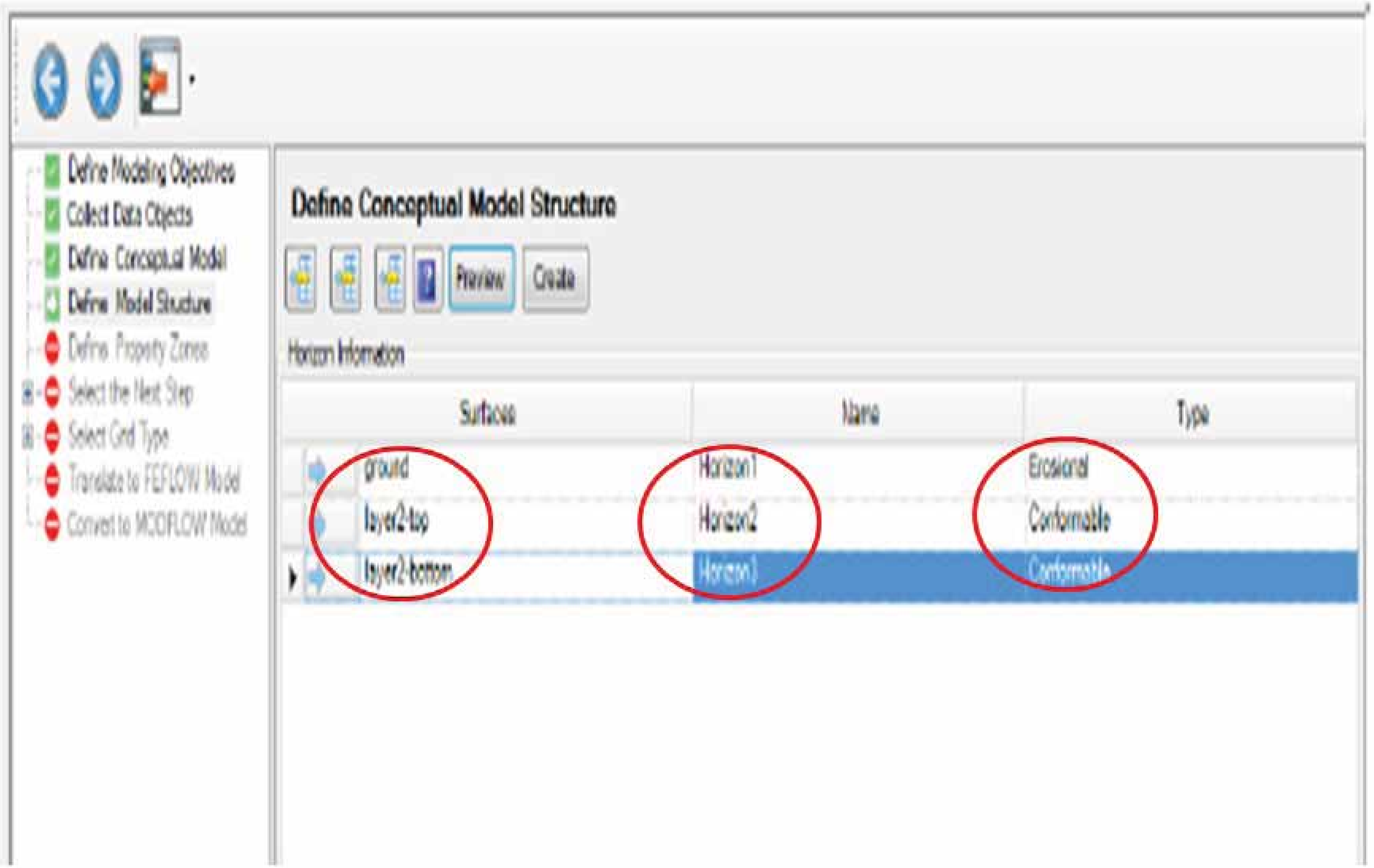
Imported Data



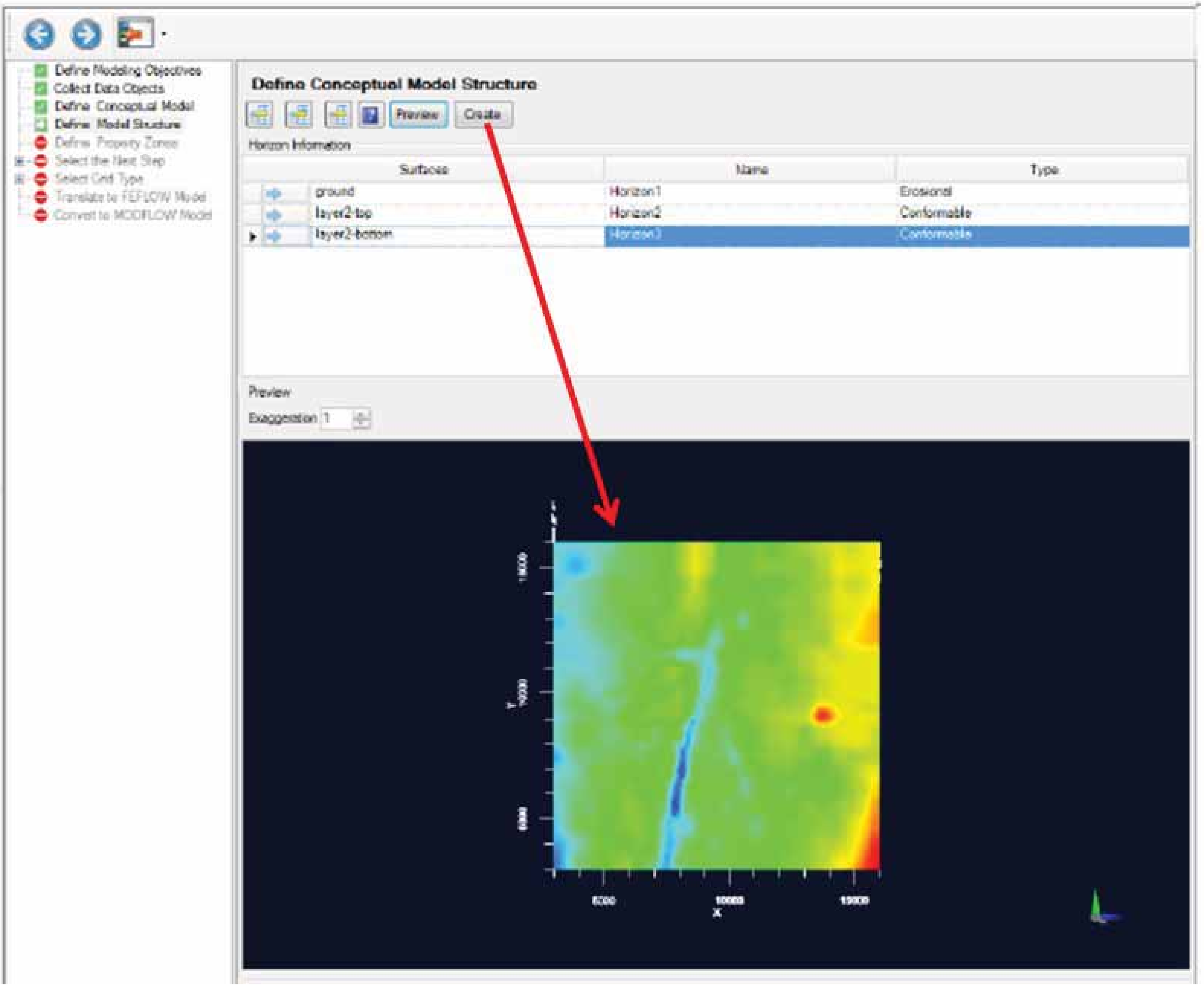
Add Imported Data to the Conceptual Model



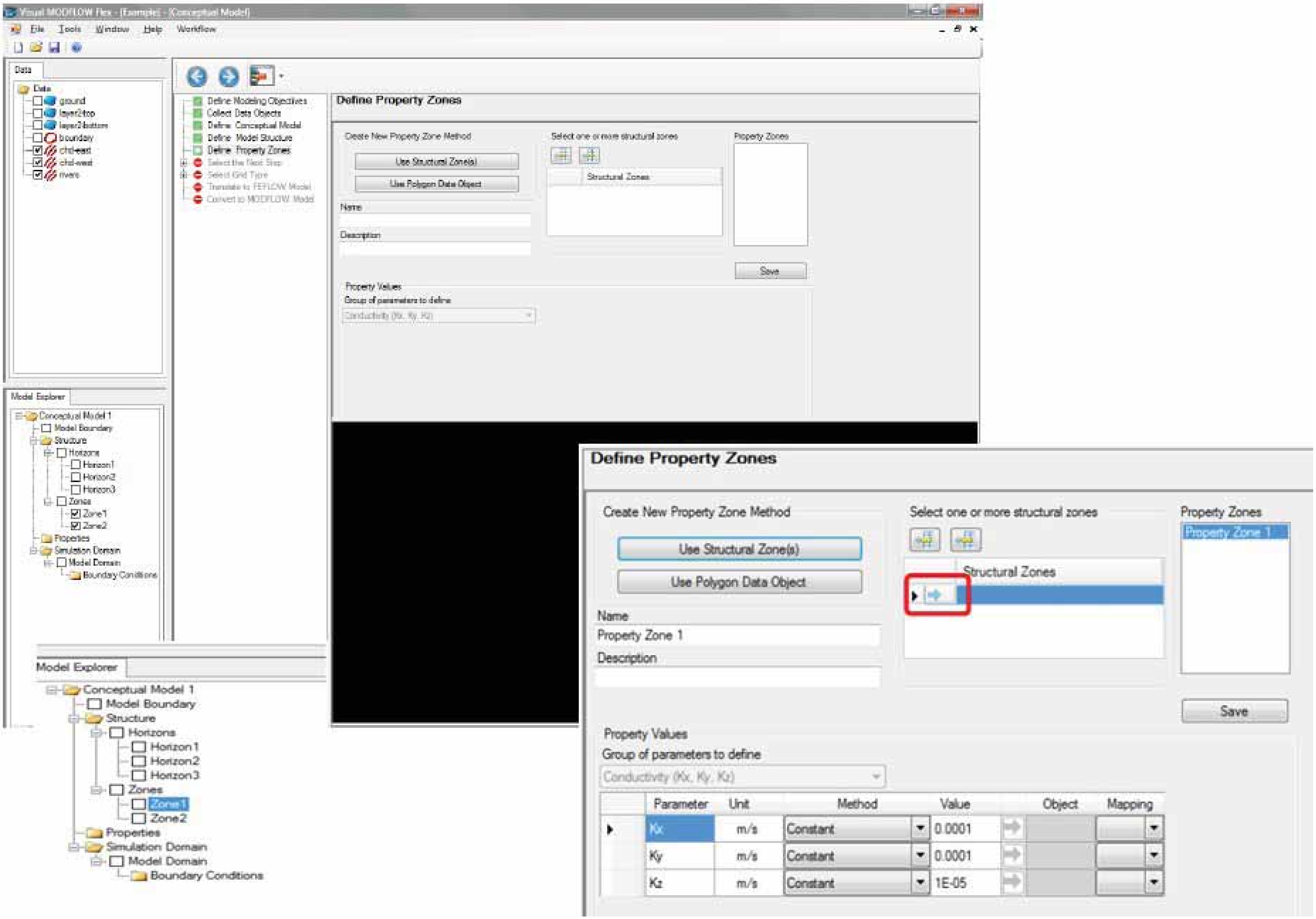
Define Structure



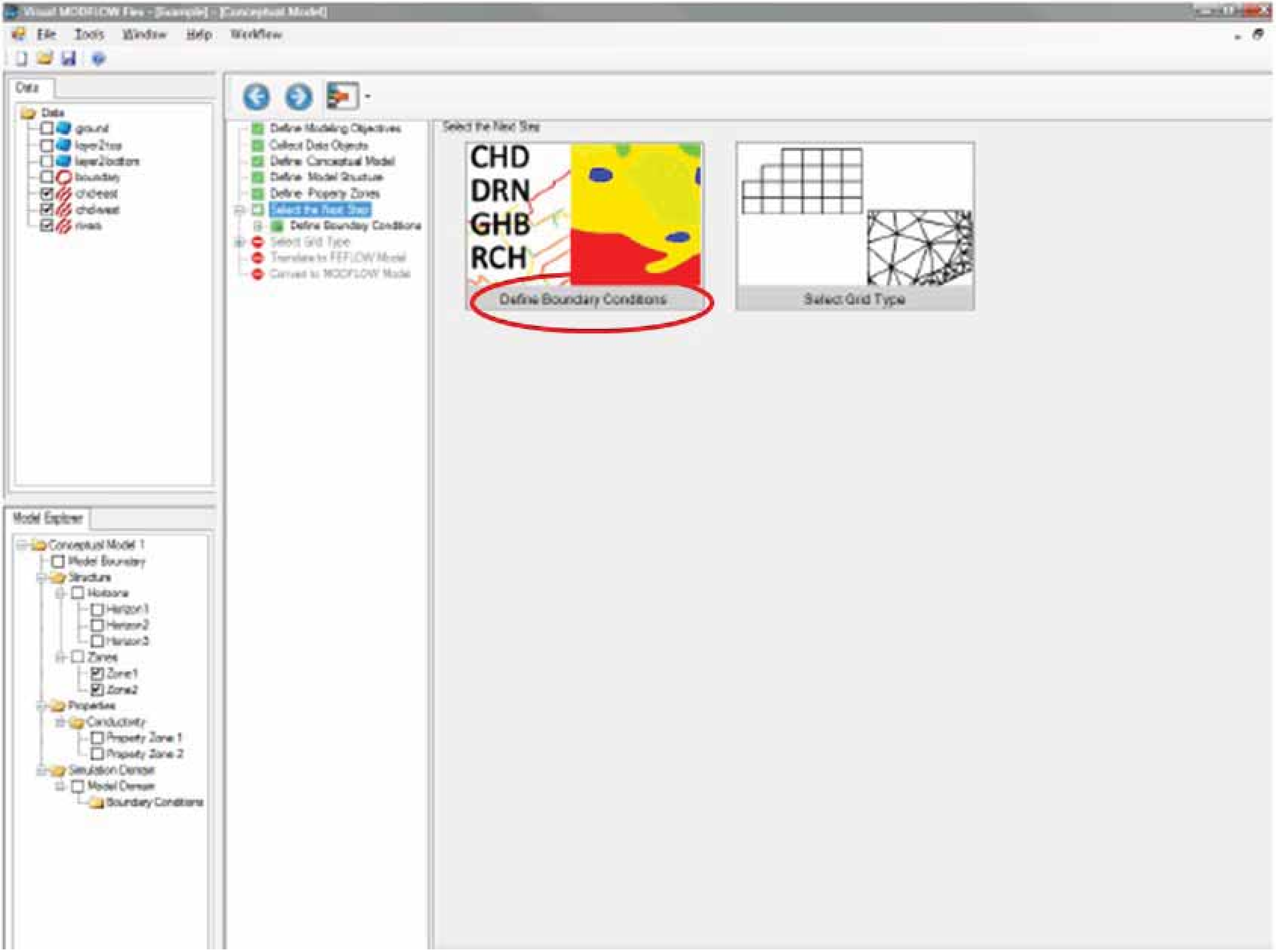
Preview of Imported Data



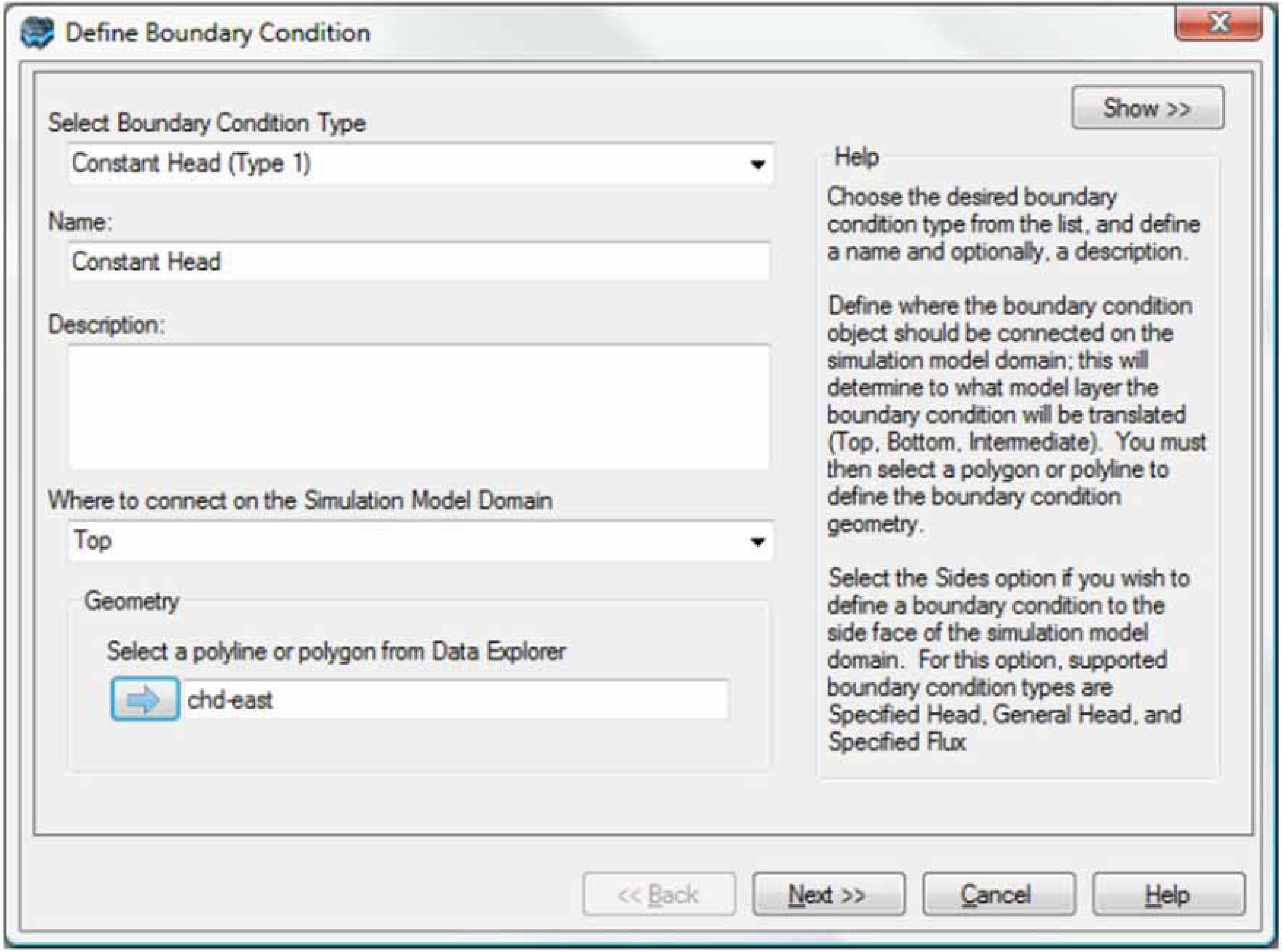
Prepare Property Zones & Assign Data



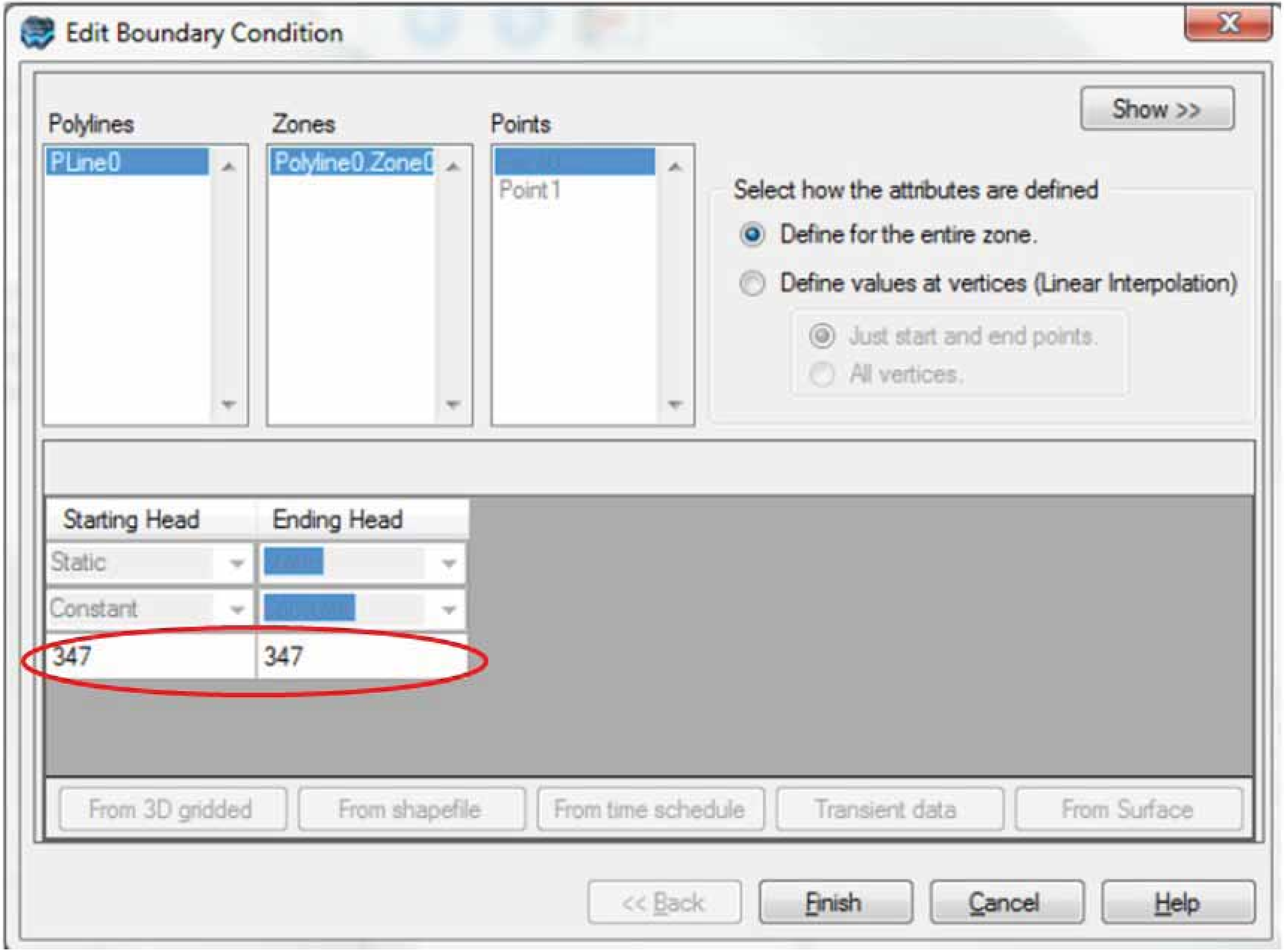
Assign Boundaries



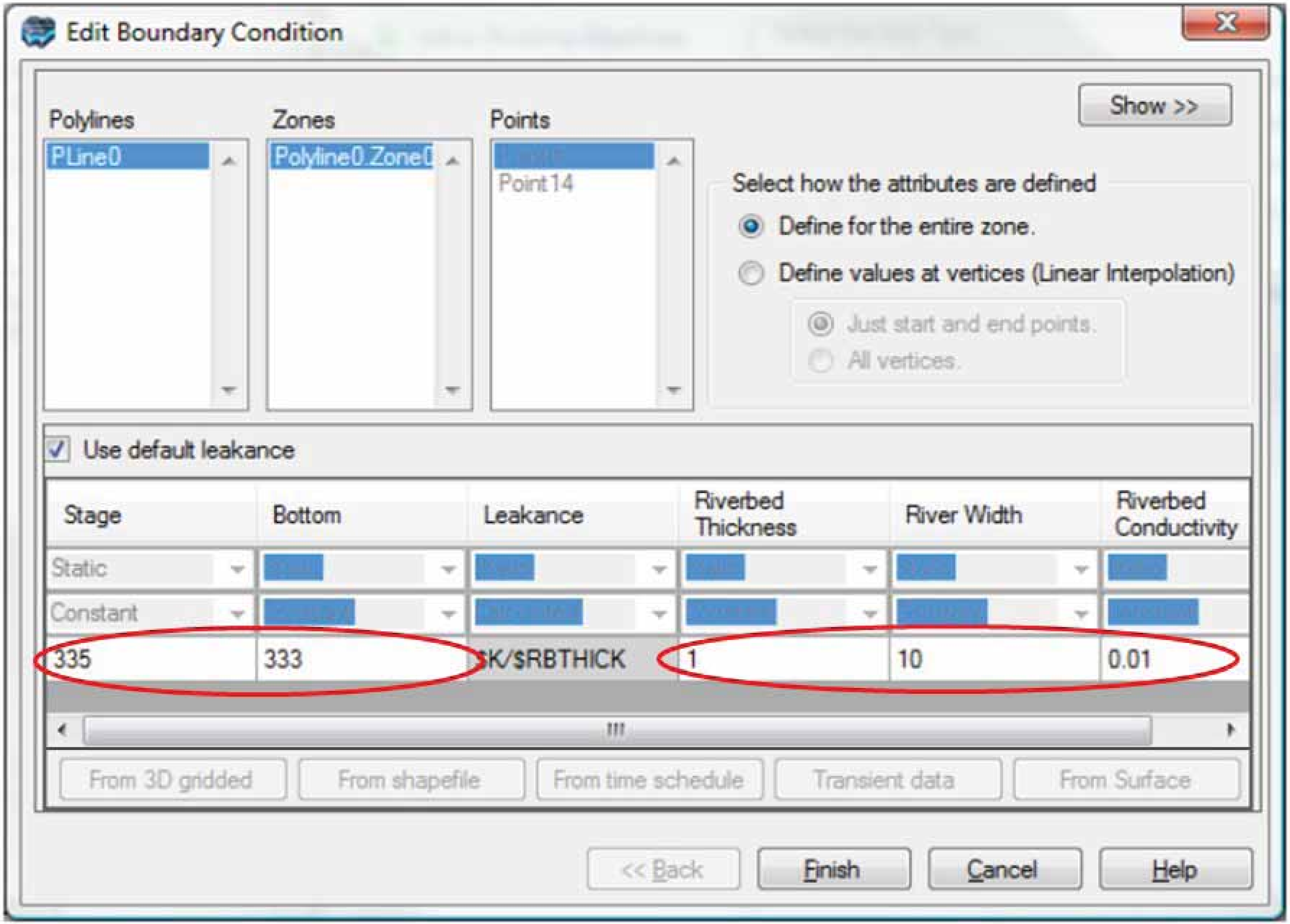
Constant Head Boundary



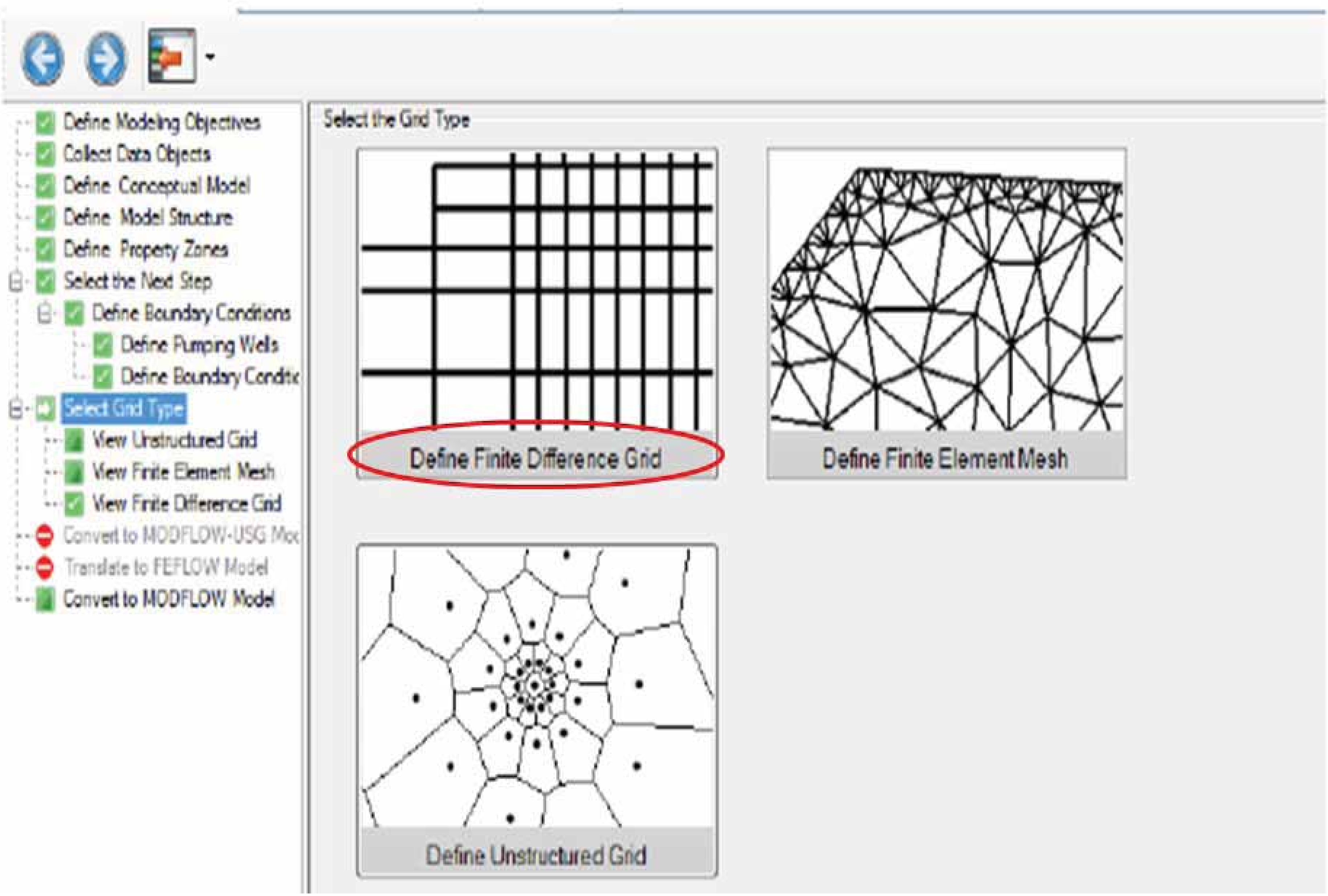
Edit Boundary Condition



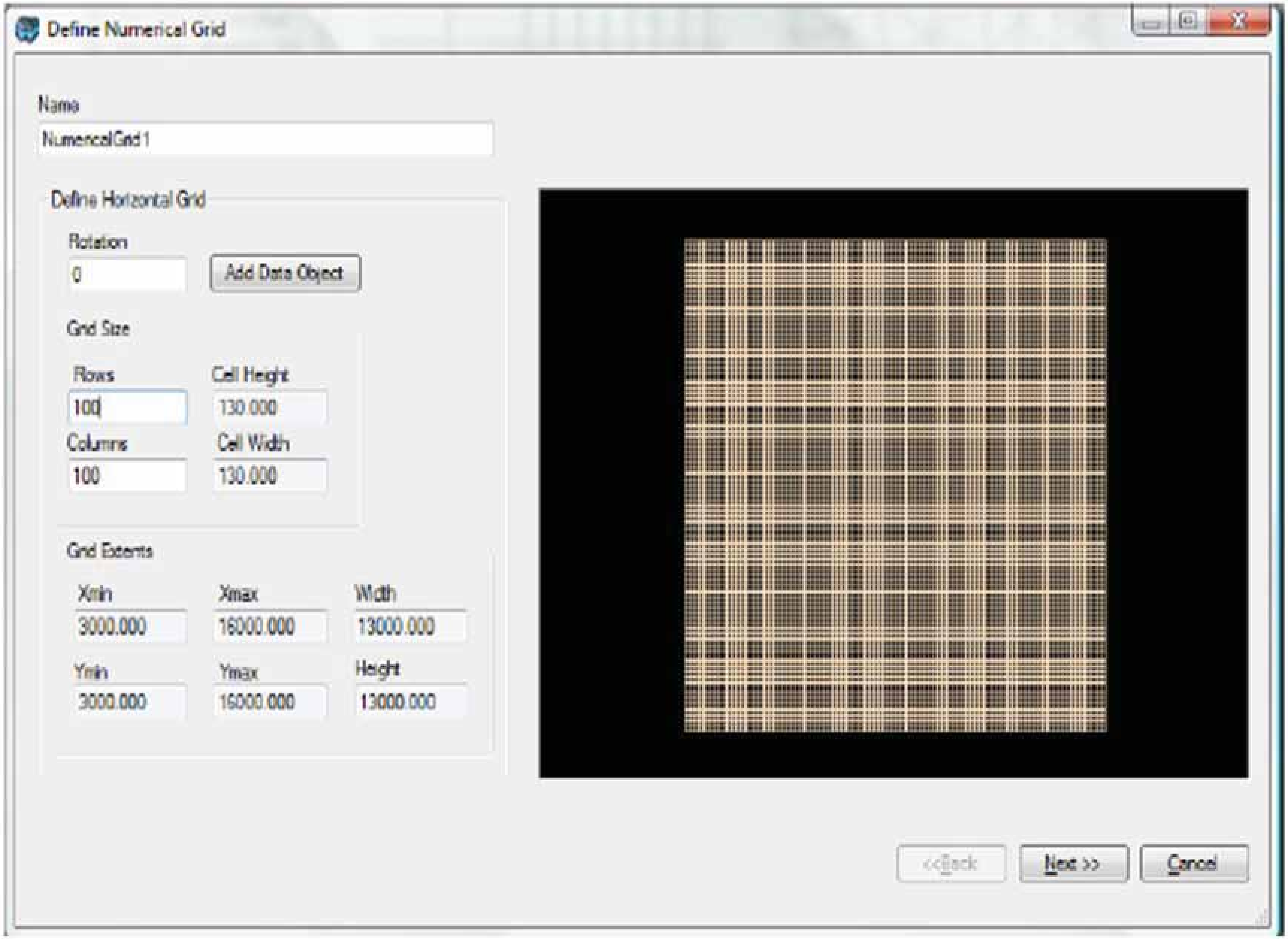
River Boundary



Model Grid Selection

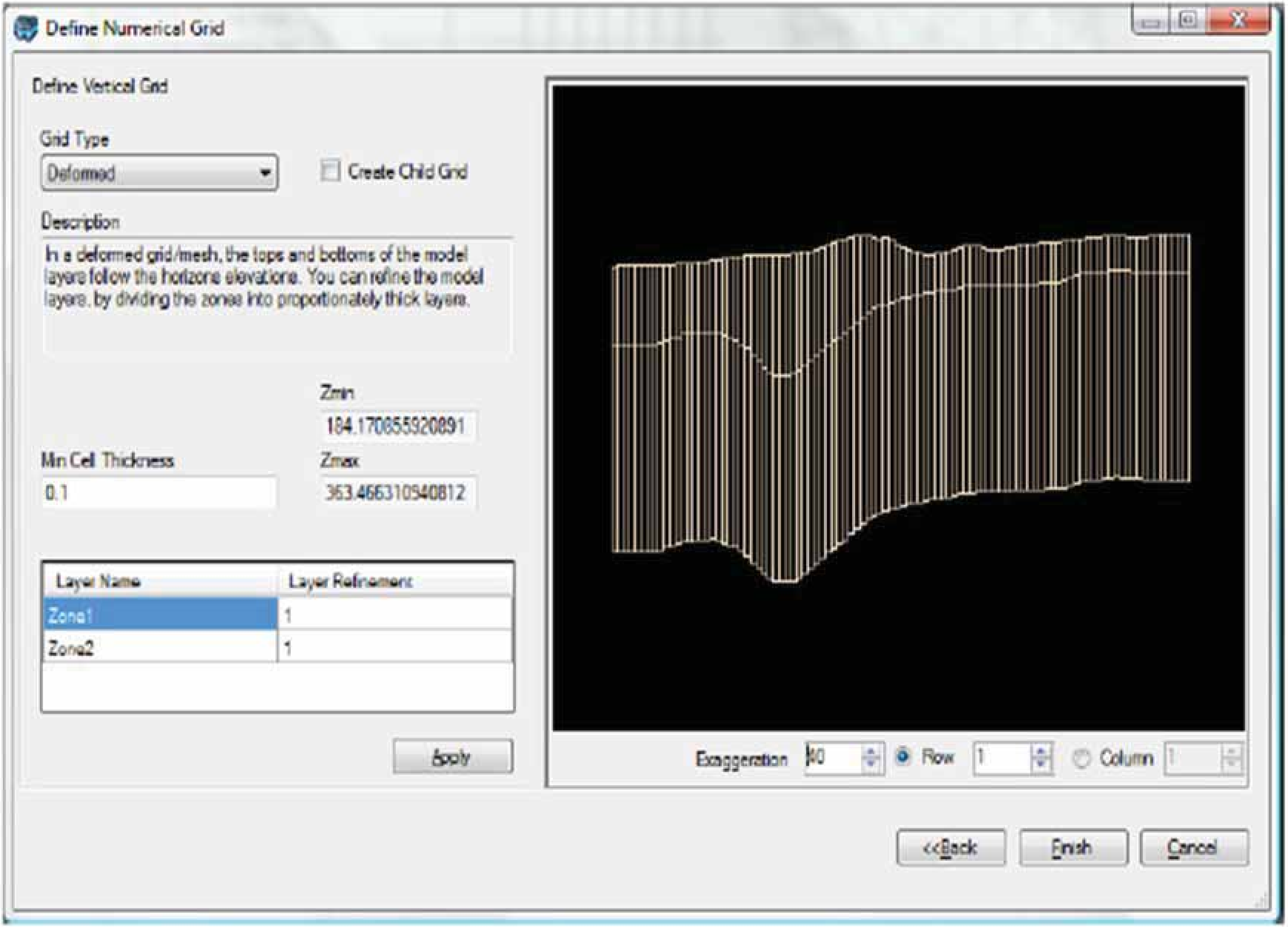


Grid Design

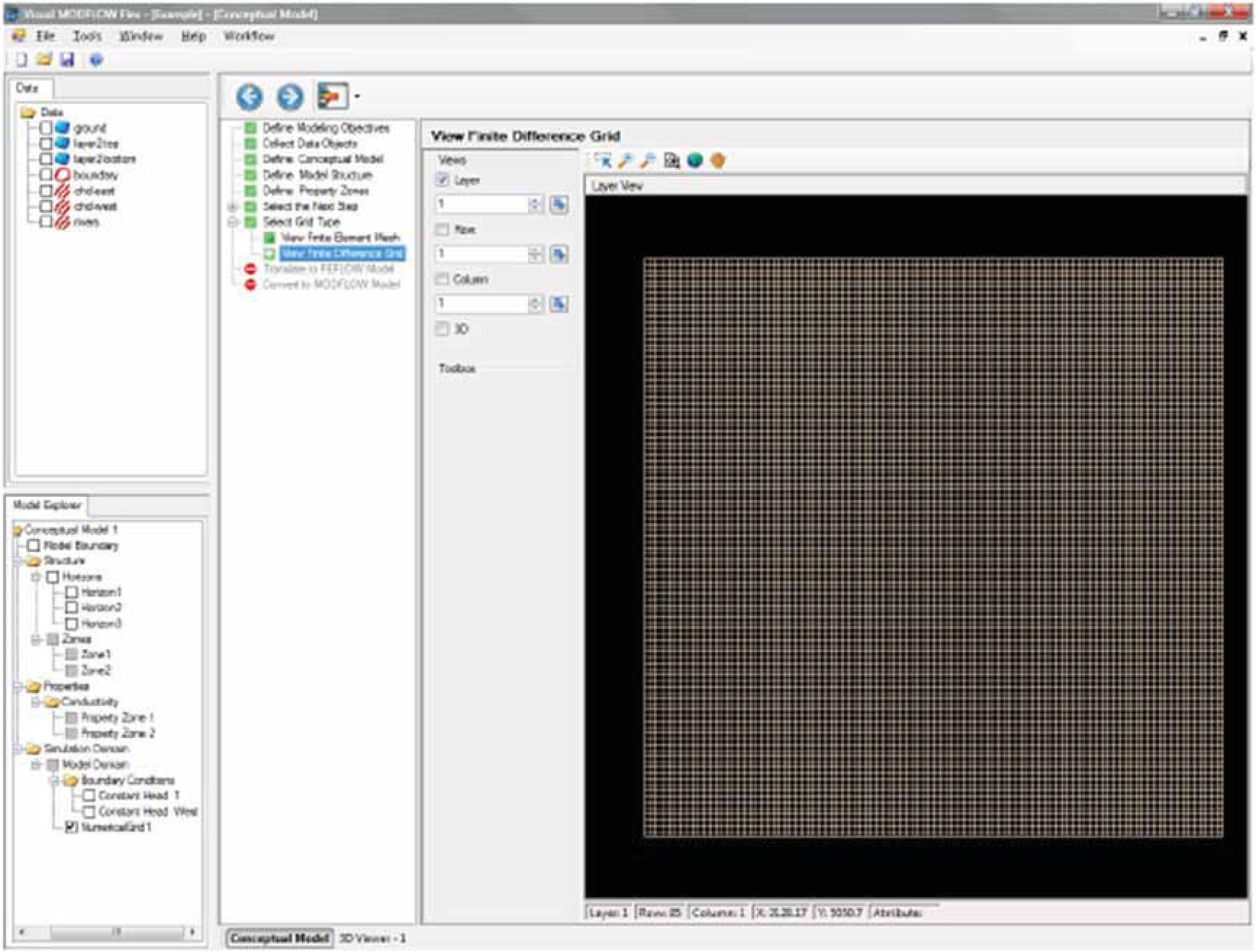


Define Numerical Grid
Name
NumericalGrid1
Define Horizontal Grid
Rotation
0
Add Data Object
Grid Size
Rows
100
Cell Height
130.000
Columns
100
Cell Width
130.000
Grid Extents
Xmin
3000.000
Xmax
16000.000
Width
13000.000
Ymin
3000.000
Ymax
16000.000
Height
13000.000
<< Back
Next >>
Cancel

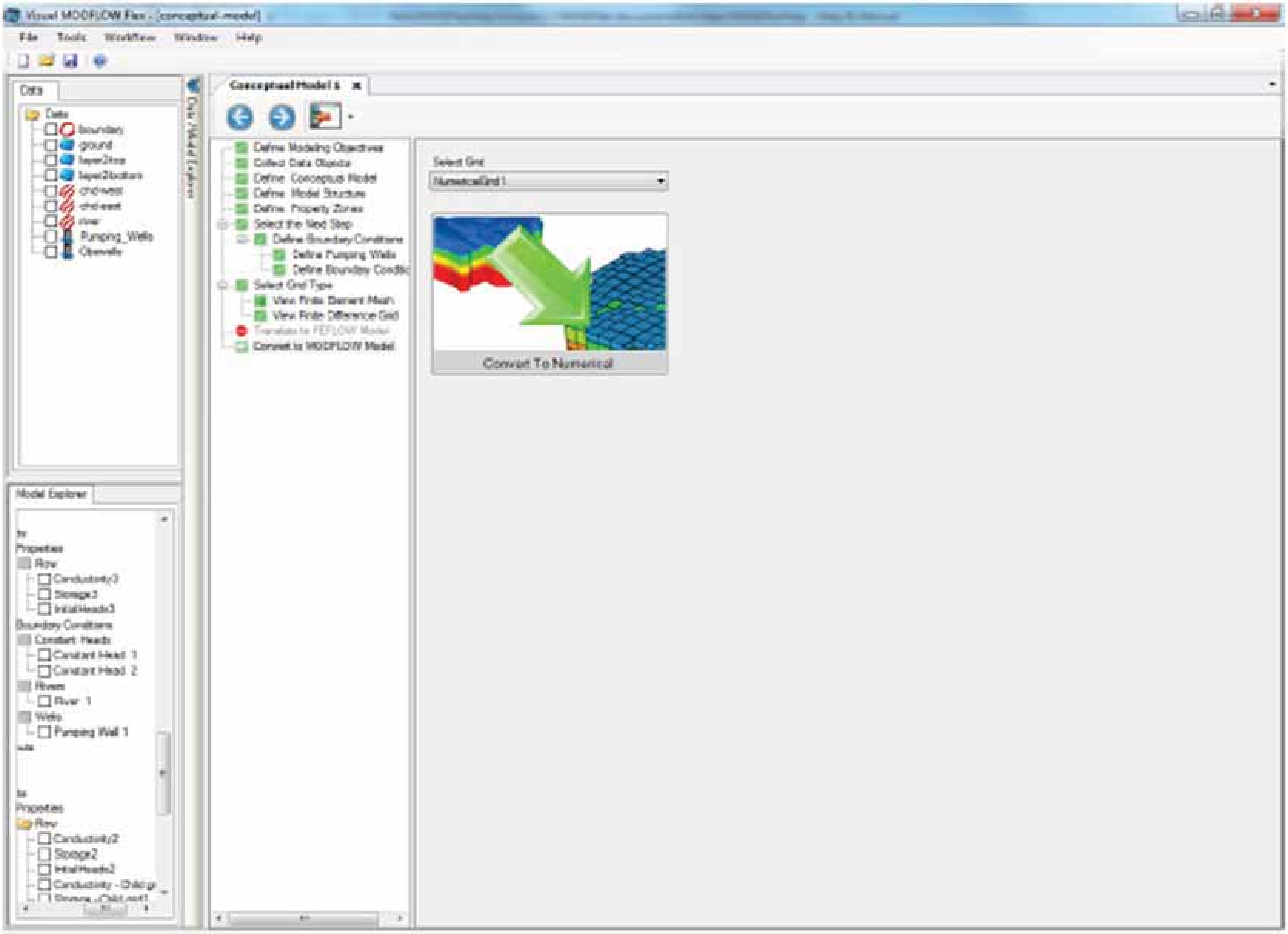
Grid Type & Model Thickness



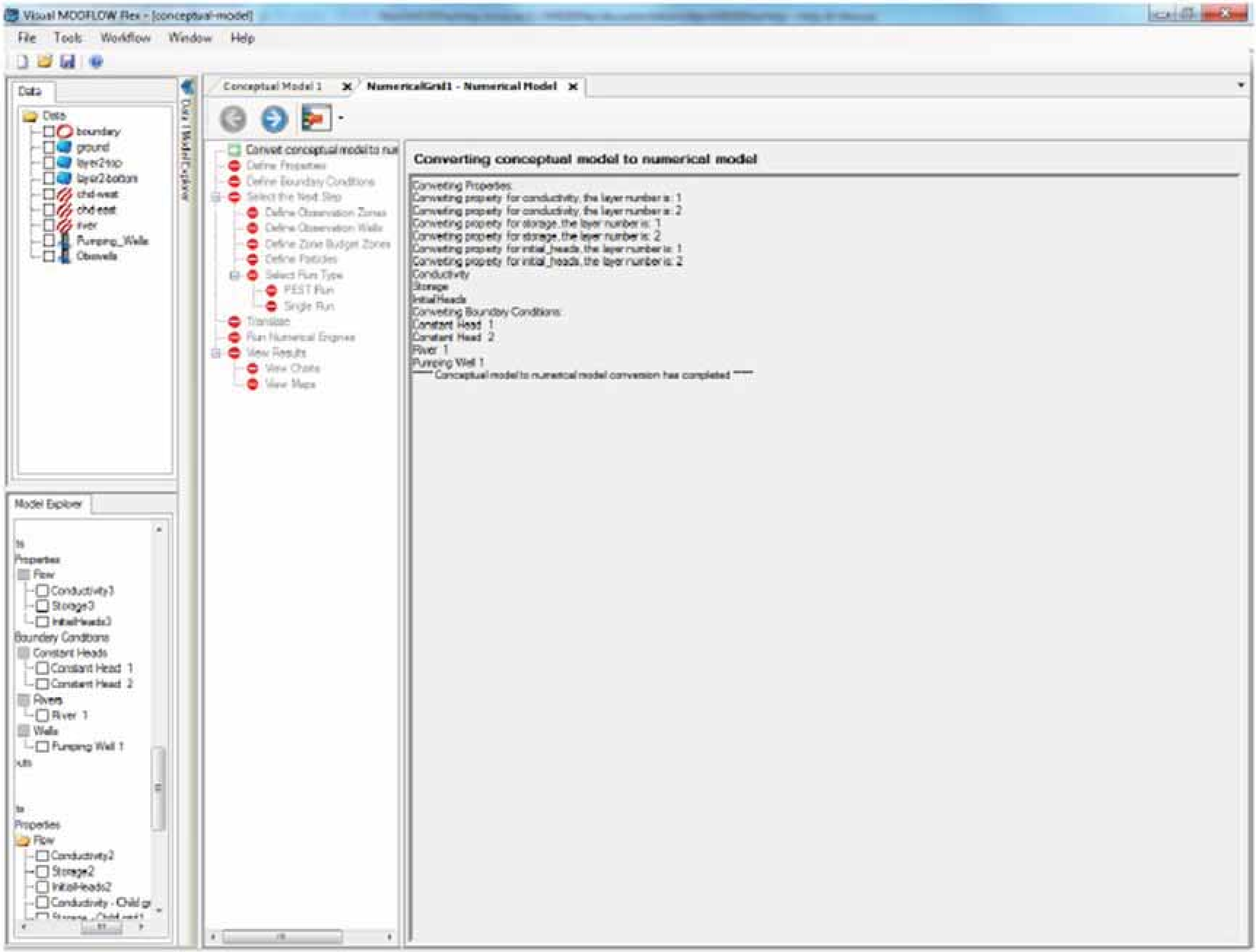
3D Visualization



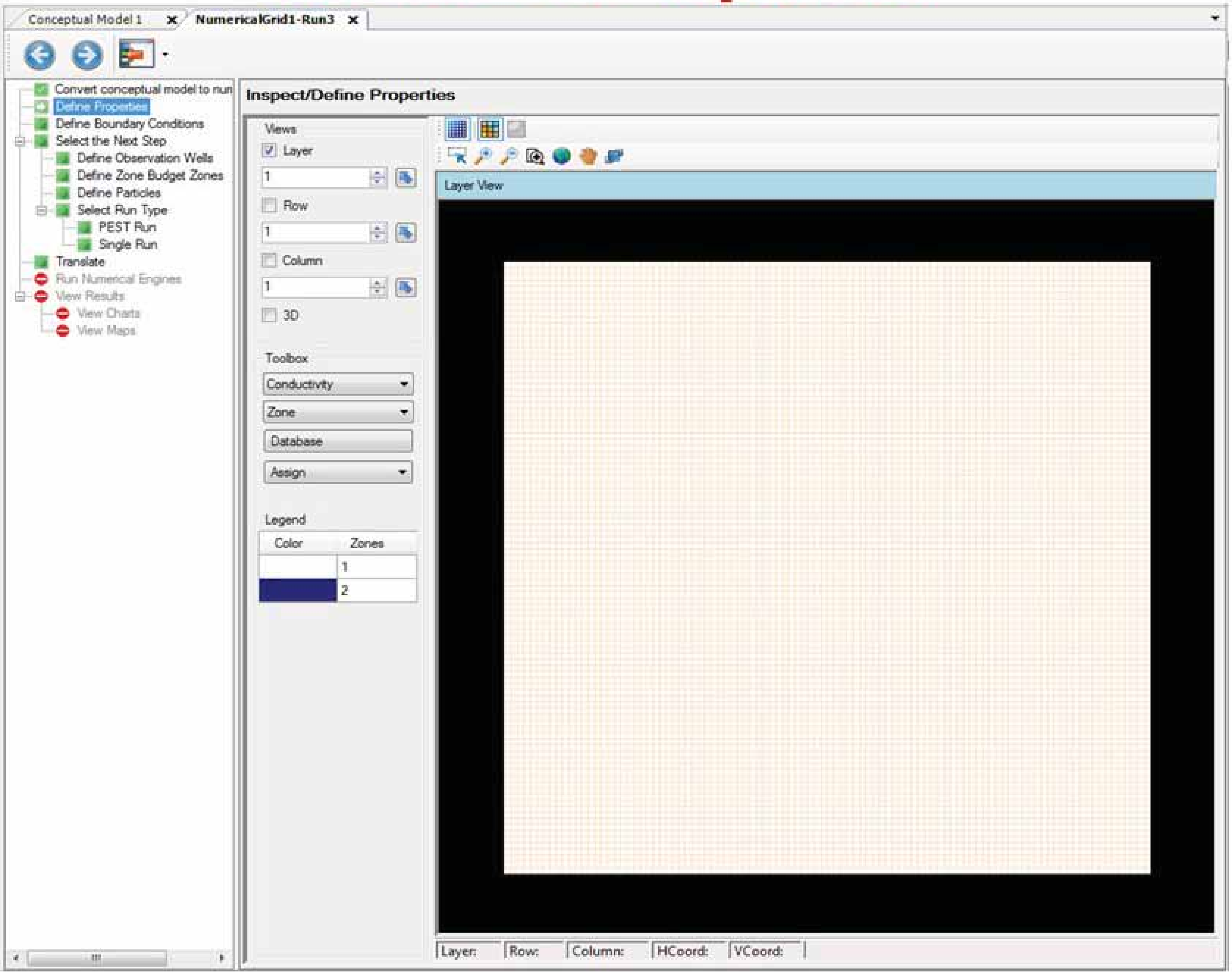
Conversion of Conceptual Model into Numerical Model



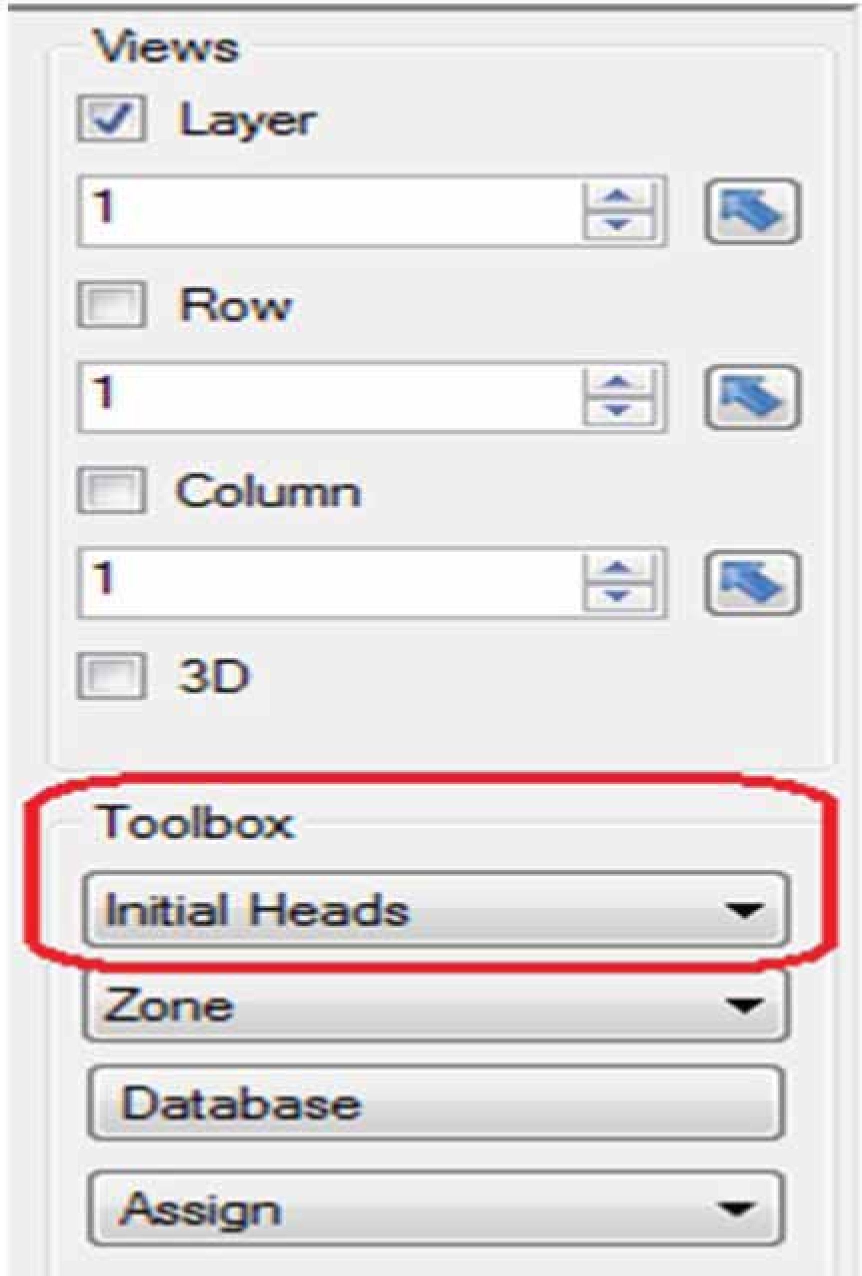
Processing Conversion



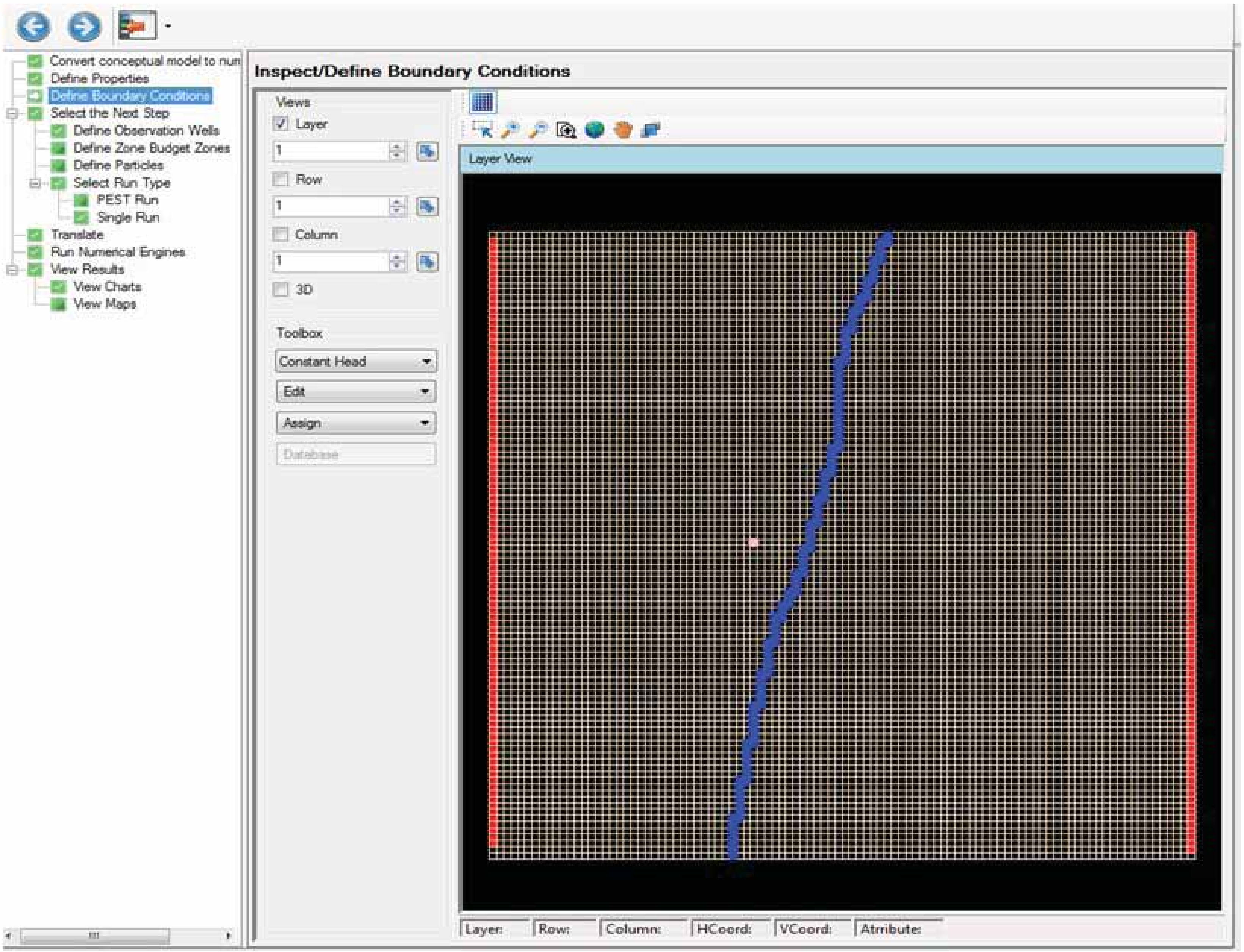
View & Edit Properties



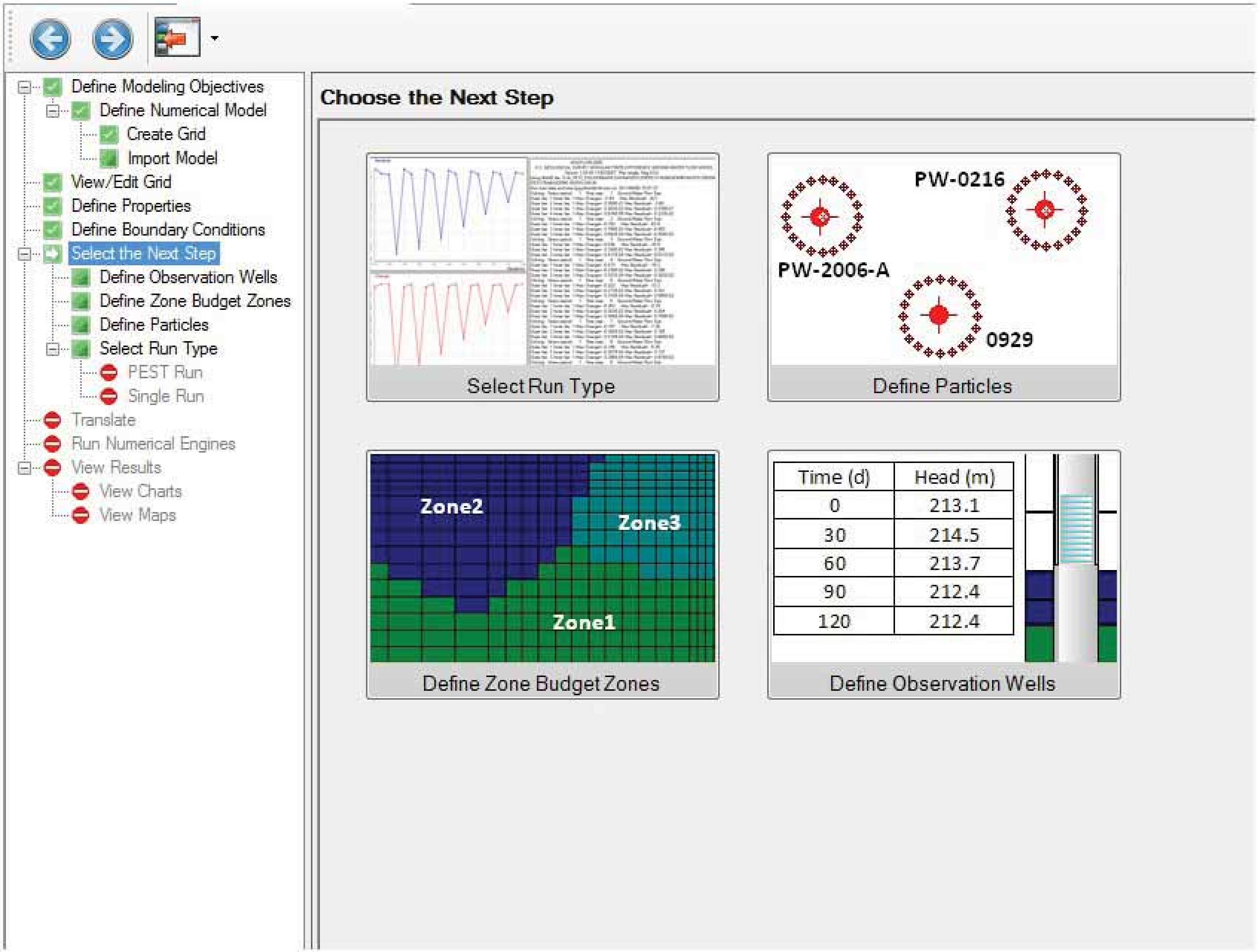
Property Views



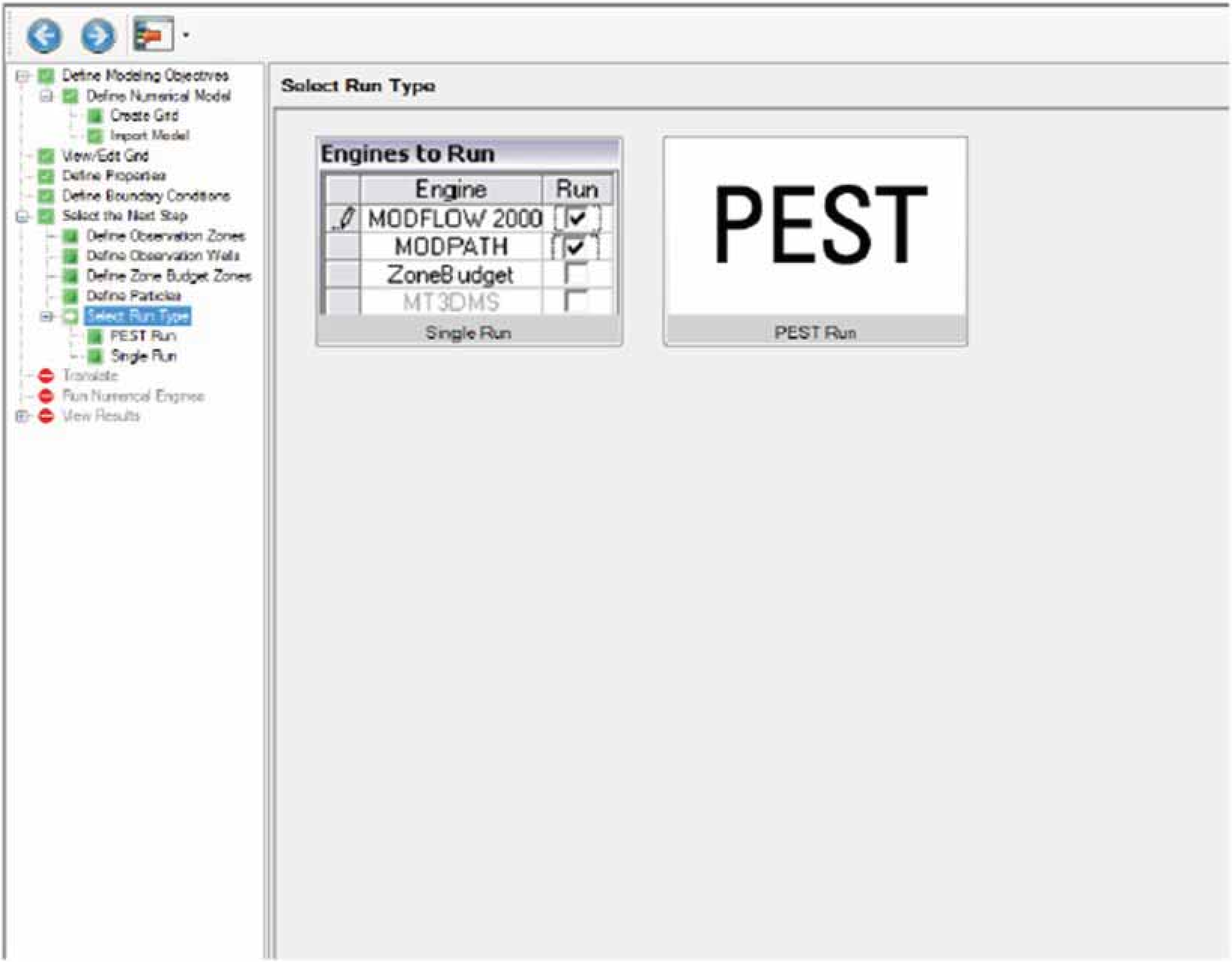
View & Edit Boundary Condition



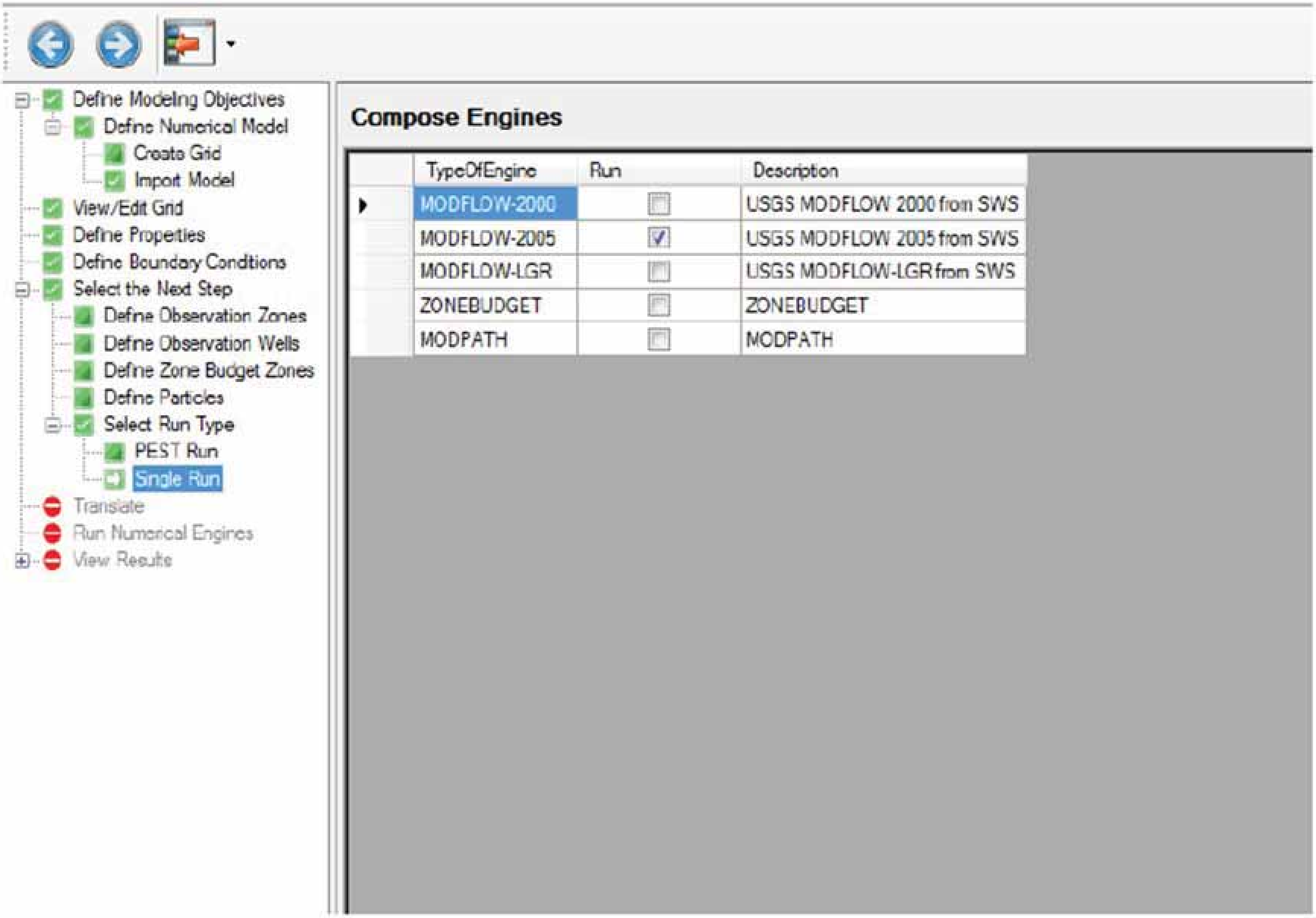
Creation of Zones for Zone Budget



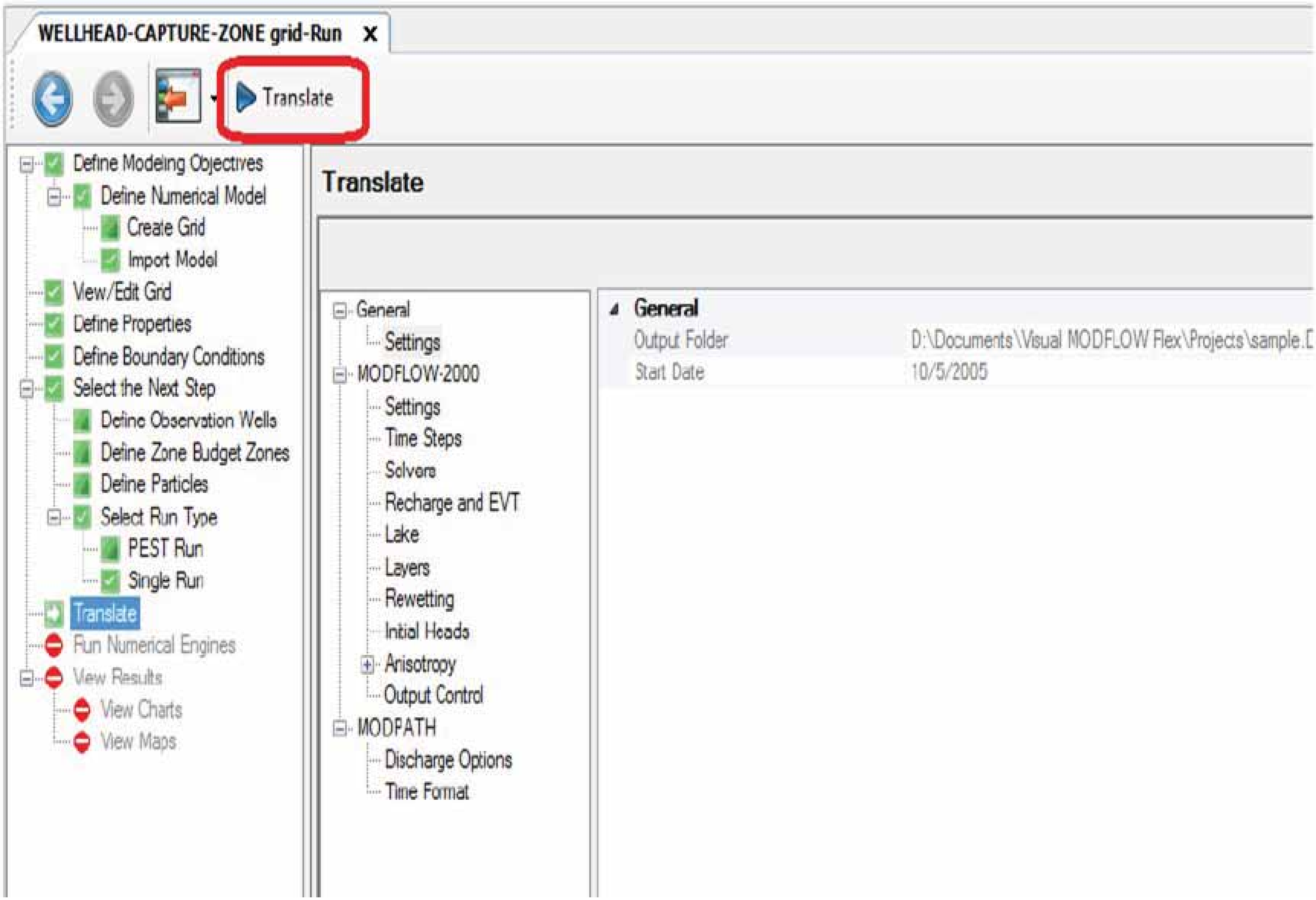
Select Run Type



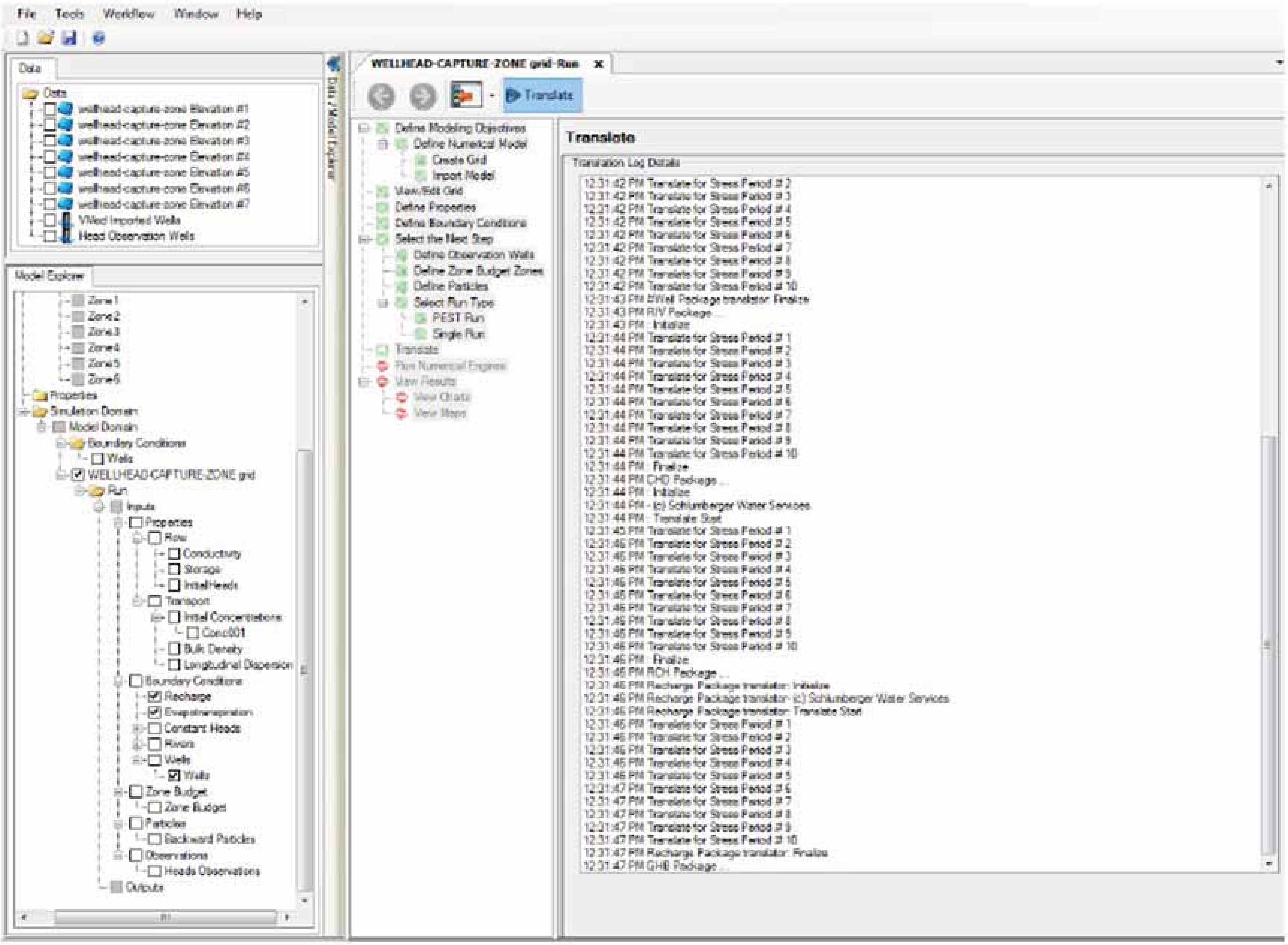
Select Modflow Engine



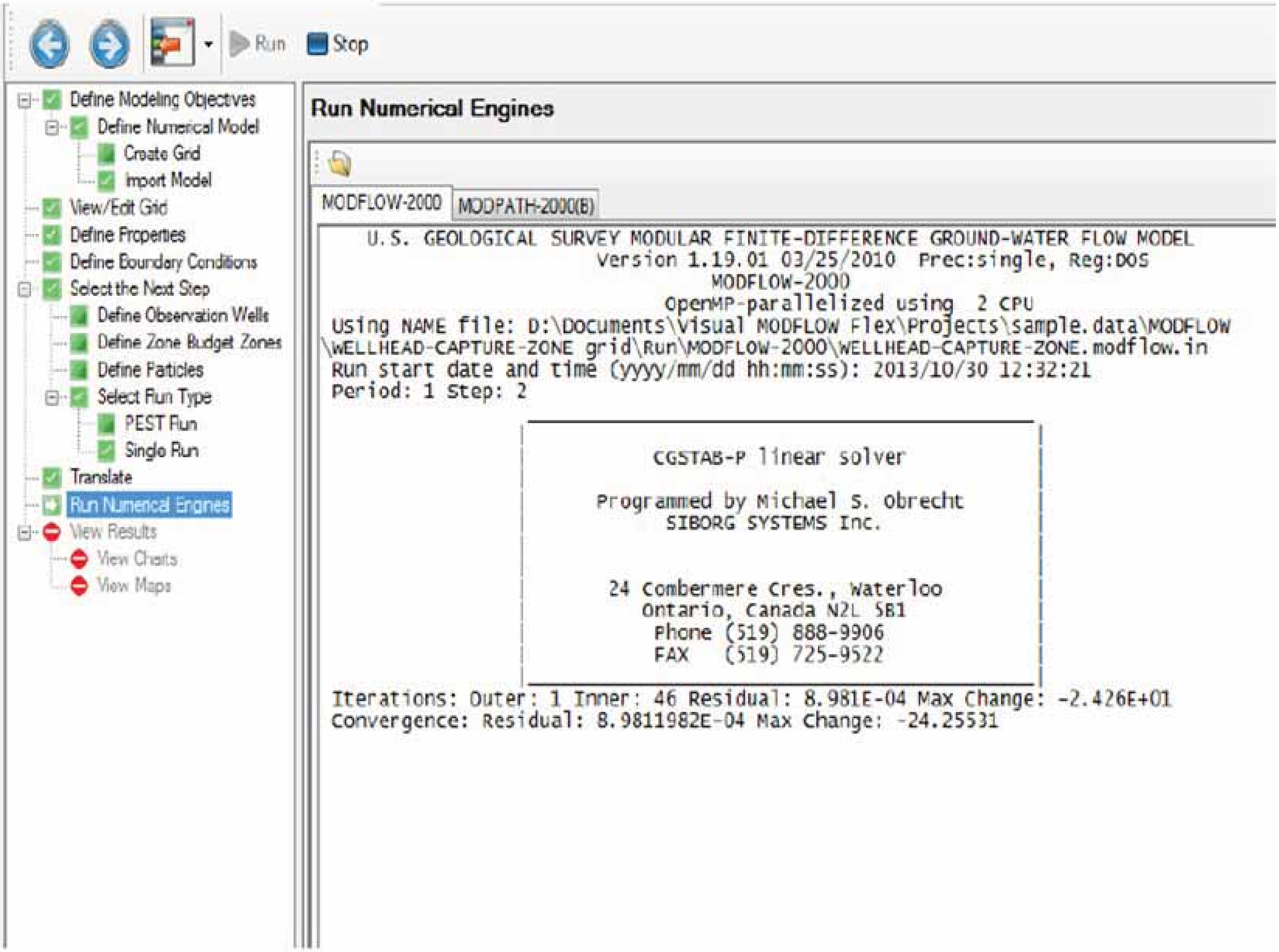
Translate Model



Model Translation in Progress

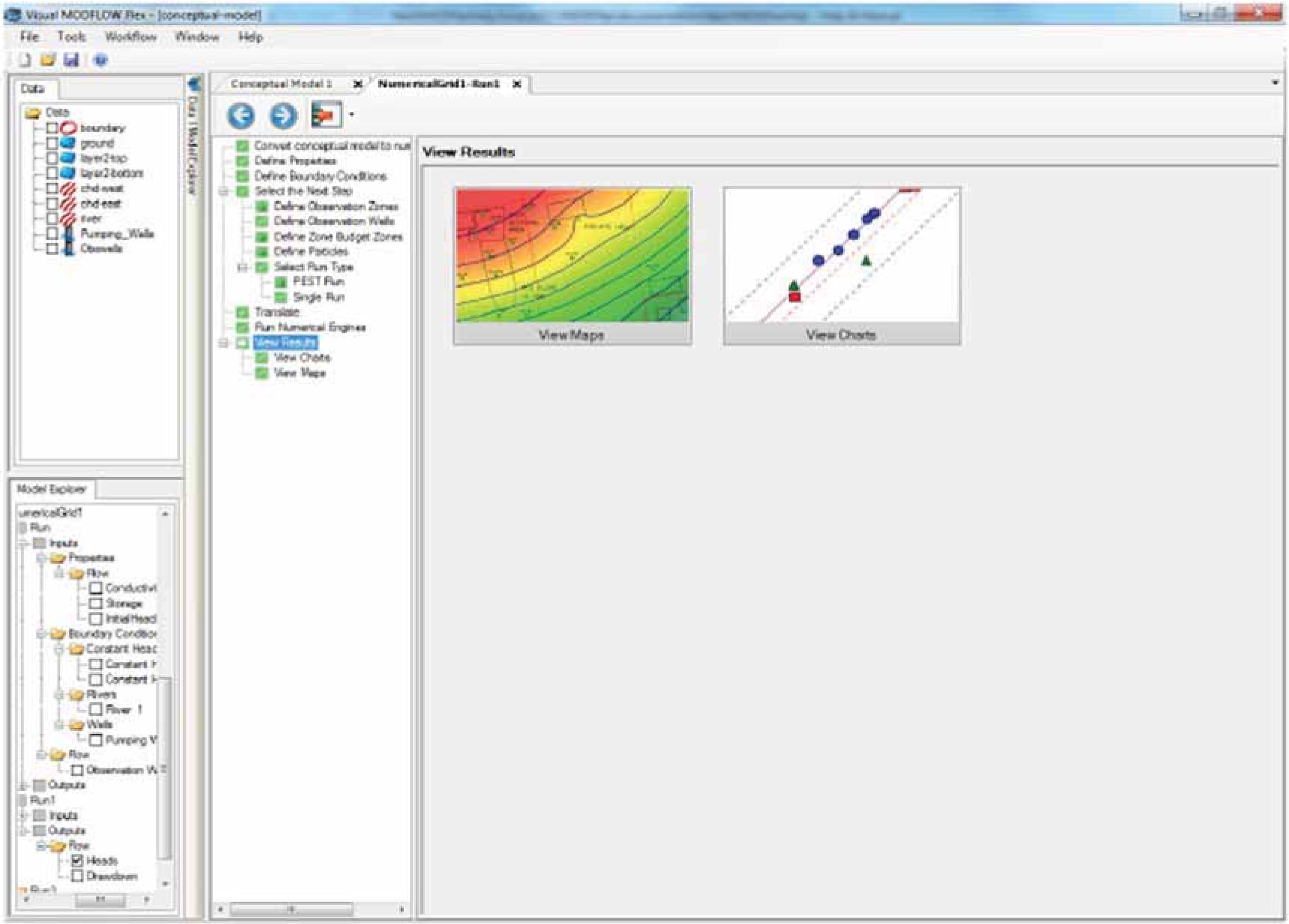


Run Engine

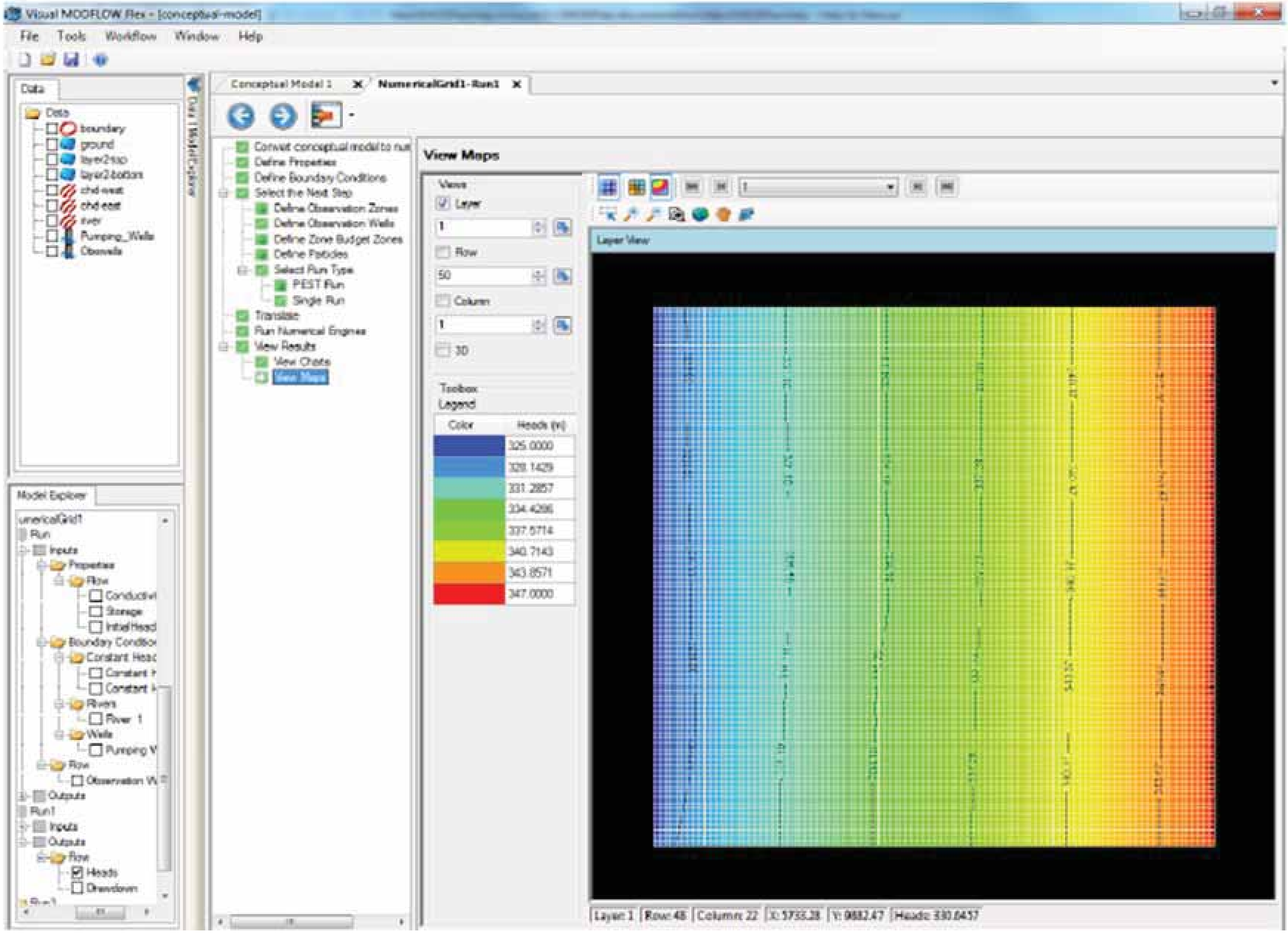


Run
Stop
Define Modeling Objectives
Define Numerical Model
Create Grid
Import Model
View/Edit Grid
Define Properties
Define Boundary Conditions
Select the Next Step
Define Observation Wells
Define Zone Budget Zones
Define Particles
Select Run Type
PEST Run
Single Run
Translate
Run Numerical Engines
View Results
View Charts
View Maps
Run Numerical Engines
MODFLOW-2000
MODPATH-2000(B)
U.S. GEOLOGICAL SURVEY MODULAR FINITE-DIFFERENCE GROUND-WATER FLOW MODEL
Version 1.19.01 03/25/2010 Prec:single, Reg:DOS
MODFLOW-2000
OpenMP-parallelized using 2 CPU
Using NAME file: D:\Documents\Visual MODFLOW Flex\Projects\sample.data\MODFLOW
\WELLHEAD-CAPTURE-ZONE grid\Run\MODFLOW-2000\WELLHEAD-CAPTURE-ZONE.modflow.in
Run start date and time (yyyy/mm/dd hh:mm:ss): 2013/10/30 12:32:21
Period: 1 Step: 2
CGSTAB-P linear solver
Programmed by Michael S. Obrecht
SIBORG SYSTEMS Inc.
24 Combermere Cres., Waterloo
Ontario, Canada N2L 5B1
Phone (519) 888-9906
FAX (519) 725-9522
Iterations: Outer: 1 Inner: 46 Residual: 8.981E-04 Max Change: -2.426E+01
Convergence: Residual: 8.9811982E-04 Max Change: -24.25531

View Results



View Maps



Visual MODFLOW Flex - [conceptual-model]
File
Tools
Workflow
Window
Help
Data
boundary
ground
layer2-top
layer2-bottom
chd-west
chd-east
river
Pumping_Wells
Obswells
Conceptual Model 1
NumericalGrid1-Run1
Convert conceptual model to numerical
Define Properties
Define Boundary Conditions
Select the Next Step
Define Observation Zones
Define Observation Wells
Define Zone Budget Zones
Define Particles
Select Run Type
PEST Run
Single Run
Translate
Run Numerical Engines
View Results
View Charts
View Maps
View Maps
Views
Layer
Row
Column
3D
Toolbox
Legend
Color
Heads (m)
325.0000
328.1429
331.2857
334.4286
337.5714
340.7143
343.8571
347.0000
Layer View
Model Explorer
Run
Inputs
Properties
Flow
Storage
Boundary Conditions
Rivers
Wells
Outputs
Run1
Heads
Drawdown
Layer: 1
Row: 48
Column: 22


Thank You!