Integrating GIS Methods for the Analysis of GeoSystems

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Dedicated to my mother and father.

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Zusammenfassung

Die Nachfrage nach Simulationen nimmt in der Hydrologie und Umweltforschung zu. Diese Simulationen beinhalten die Abbildung von Oberflächen- und Grundwasserströmungen.

Daten über die betrachteten Systeme stehen nur in beschränktem Umfang zur Verfügung. Außerdem weisen die Systeme eine hohe Komplexität auf. Verschiedene hydrogeologische Daten können in GIS verwaltet und dargestellt werden und werden daher als nützliches Modellierwerkzeug herangezogen. Die Daten aus einem GIS Projekt dienen dann als Eingabeparameter zur numerischen Simulation. Das heutige GIS kann Strukturen noch nicht in ihrer eigentlichen 3-dimensionalen Gestalt bearbeiten. Stattdessen stellt es die Geometrie von Oberflächen – und Grundwassersystemen in 2 und 2.5 Dimensionen. Die Generierung 3-dimensionaler Modelle ist jedoch erforderlich, um hinreichend genaue Ergebnisse bei der Modellierung von Hydrosystemen zu erhalten. Die vorliegende Arbeit behandelt wird die Einbindung des GIS in das numerische Softwarepaket GeoSys/Rockflow (Kolditz et al. 2004). Gezeigt wird auch inwiefern somit die Erstellung 2- und 3-dimensionaler numerischer hydrologischer Modelle vereinfacht wird. Ein 3-dimensionales Model wurde exemplarisch mithilfe einese GIS-Datensatzes erstellt. Der Datensatz beinhaltet hydrogeologische Ränder, digitale Höhenmodelle (DEM), Rasterkarten, Kluftsysteme, Flussnetze, Lithologien (Querschnitte), Bohrlöcher und Quellen. Diese GIS-Daten werden als geometrische Objekte in der geometrischen Programmbibliothek GEOLib gespeichert. Fundamentale geometrische Objekte sind dabei Punkte, Polylinien, Oberflächen, Volumen und Gebiete. Diese Objekte werden zur Definition der Modellgeometrie, Anfangs- und Randbedingungen, Quelltermen verwendet. Darüber hinaus wird ein Konzept für Schichtenmodellierung aus Schicht-Polylinien, Schicht-Oberflächen (TINs) und Schicht-Volumen ins Finite Elemente Programm implementiert. Um die genannten Ziele zu erreichen, wurde die geometrische Bibliothek GEOLib entwickelt und wurde das bestehende Graphical User Interface (GUI) erweitert und verbessert. Die Neuerungen wurden anhand einiger Fallbeispiele entwickelt und getestet. Diese Fallstudien betrachten Gebiete im Mittleren Osten, Europa und dem Tübinger Umland. Letztere wurden auch zur Lehre herangezogen.

Abstract

Modelling of hydrosystems is of increasing demand in fields of water and environmental research and basically includes modelling of surface water and groundwater flow. Due to the limitation of available data and the complexity of geo-systems themselves in most modelling tasks, Geographical Information System (GIS) is taken as a useful tool due to the ability to store diverse kinds of hydrogeological information in a common understandable structure combined with its capabilities. The GIS data are served as the input parameters for the numerical modelling. Modern GIS , not yet based on a real 3D spatial representation, focus on 2 and 2.5 dimensions to represent surface and groundwater system. The construction of 3D model is challenging and of vital importance in order to accurately simulate hydrodynamic flow. This work presents the integration implementation of GIS methods within the numerical modelling software GeoSys/Rockflow (Kolditz et al. 2004) and demonstrates how GIS technology and its integration make the geometric construction of 2D and 3D hydrosystem models easier. The 3D structural model was built based on the implemented integration techniques using existing GIS data. The GIS project contains hydrogeological boundaries extracted from geological maps, Digital Elevation Model (DEM), raster maps for the aquifer layers, fault system, river network, lithology (cross section), boreholes, and springs. The data are kept in a GIS project and converted into geometric components of the modeling system – GEOLib, and then can be used as boundary conditions, initial conditions, source sink terms, material groups and model domain. Fundamental geometric objects are points, polylines, surfaces, volumes and domains. In addition, the concept of advanced layer models, such as layer polylines, layer surfaces with Triangulated Irregular Network (TIN), layer volumes are implemented in the finite element program, which are the methodology for the construction of a 3D structural model. In order to accomplish these aims described above, the following contributions were achieved: To design and implement the geometric objects library (GEOLib) within GeoSys/RockFlow; to create the interface between GIS data and GeoSys/RockFlow; to extend the existing Graphical User Interface (GUI) of GeoSys/RockFlow for the features mentioned. As a result, the GIS integrated concept was demonstrated in several case studies in Middle East, Europe, and in local area Tübingen, which was also used as an education example for the students.

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1 INTRODUCTION

In recent years, the use of Geographic Information System (GIS) in hydrosystem modeling has grown rapidly. Hydrosystem modeling is a complex task, which in general includes surface and subsurface water modeling. The spatial nature of geological objects making up these systems encourages the inclusion of GIS to be part of the modeling system (Setijadji, 2003). GIS technology allows for organization, quantification, and interpretation of large quantities of hydrogeological data accurately and with minimal risk of human error (Pinder, 2002). GIS provides a means of representing the real world by using integrated layers of constituent spatial information (Corwin 1996). The Data required for hydrogeological applications are complex; information from the fields of geology, hydrology, geomorphology, soil science, climatology, land use and topography are needed. Geographic information can be represented in GIS as objects, such as points, lines, and areas. However, this is still a difficult task for a GIS, because of the limited data and the complexity of geo-objects themselves. Another limitation of modern GIS are not yet capable of a three-dimensional (3D) spatial representation and mainly deal with two-dimensional (2D) modeling which is often inappropriate for hydrosystem modeling applications. Turner (1989,2000) emphasized the importance of 3-dimensional characterizations in subsurface studies. He stressed the need for accurate 3D data to describe depositional systems and aquifer heterogeneity in order to accurately simulate hydrodynamic flow. The current GIS standards allow data sharing with other system and integration with specialized programs for hydrosystem modeling.

This work presents the integration of GIS methods within the numerical modeling program GeoSys/RockFlow (Kolditz et al. 2004) and demonstrates how GIS technology and its integration make the geometric construction of 2D and 3D hydrosystem models more easy and accurate. The hydrogeological conceptual model is converted to a GIS project using the ArcGIS software. The required data for modeling, such as geometric data describing geological layers, initial conditions, boundary conditions, source sink terms and the model domain are kept in a GIS project. These GIS data, together with an external database (e.g. MS Excel data), of the material properties, and well information, can be directly imported to GeoSys/RockFlow; as a result, a GeoSys project is created for modeling purposes (Kalbacher et al. 2005, Chen et al. 2005). Furthermore, GIS supports the surface model like regular grid digital elevation model (DEM). The DEM data is used to create an accurate 3D topographical surface model, which is important for surface water modeling in the case that the topographical parameters play an important role in the surface modeling. This thesis introduces a method, based on an interface with GeoSys/RockFlow, to map existing 2D triangulated surface using DEM data. The mesh density during mesh generation in GeoSys/RockFlow using an object-oriented concept could change the resolution of the surface model.

The following objectives were identified and pursued in order to accomplish these aims: (1) To understand finite element programming (2) To understand the programming language C and C++. (3) To understand the techniques of windows desktop software development in the Visual Studio.NET environment. (4) To contribute to the implementation of a Graphical User Interface (GUI) of the numerical modeling program GeoSys/RockFlow. (5) To design and implement the geometric objects library (GEOLib) within GeoSys/RockFlow. (6) To create the interface between GIS data and GeoSys/RockFlow. (7) To demonstrate the utility of the above achievements through several case studies.

The processes for integrating GIS and GeoSys/RockFlow are demonstrated step by step with example modeling tasks from Tübingen, the Zarqa ma'in Jiza area in Jordan, the Jericho area in Palestine, the Gallego catchment in Spain and Brand area in Germany.

2 GIS CONCEPT AND GEOSYSTEMS

2.1 GIS with GeoSystems Modeling

A GIS is a powerful set of tools for collecting, storing, retrieving, transforming and displaying spatial data from the real world (Burrough 1986). There are six core activities of GIS that can be applied in geoscience application: (1) data organization, (2) data visualization, (3) spatial data query, (4) integration of diverse data types, (5) data analysis, and (6) prediction (Bonham-Carter 1994, Setjiadji 2003). GIS has been particularly important for hydrosystem modeling applications for data collection, data organization, distribution of hydrogeological data and construction of maps. The modeling projects often maintain data of many sources (geology, geophysics, geochemistry, hydrology, wells, etc.) and GIS is an invaluable tool for integration of many different data types. The required data for modeling purpose can be prepared in GIS as layer models. Layers can be represented in two ways: in vector format as points, lines, polygons and in raster format as pixels. Figure 2.1 shows an example of a 3D groundwater model with boundary conditions, source terms and fault systems created for GeoSys/RockFlow using the GIS interface and the GIS data sources.

Another feature of a typical GIS, which is used for surface water modeling, is its spatial analysis features. For example in ArcGIS, the 3D Analyst extension enables users to effectively visualize and analyze surface data. There are two surface models being used: regular raster or the grid model DEM and Triangulated Irregular Network (TIN) (Bratt and Booth, 2002). In general, each has its own methodology for creation, data structure access and analysis. The use of these two kinds of data is to create 3D topographical surface model with higher accuracy. DEM is a simple, regularly spaced grid of elevation points. DEM data provides accurate topographical information which is important for the surface water modeling and the resampling of high-resolution grid data sometimes are required to effectively use models concerning about the computer limits. In addition, the functionality of hydrological processing is available in ArcGIS, which can be used, for example, for the delineation of watersheds and streams from the DEM data. Figure 2.2 shows a one-layer 3D model with river networks using the DEM data in the Gallego catchment.

Moreover, the construction of solid 3D model depends on the layer models. For the layer model of each geological formation, a regular raster is created from sparse and irregular data using available interpolation techniques: inverse distance weighted, spline, kriging, and natural neighbors. For the subsurface modeling, the data from the underground study is always limited. So, using these interpolation tool results in more trendy information underground.

Lastly, an open GIS allows for the sharing of geographic data, cooperation of different GIS technologies, and integration with other non-GIS application by the specific customization for ArcGIS with visual basic for application (VBA) is needed to fulfill some functions, which are not available from the standard ArcGIS environment. Section 2.4 demonstrates the open GIS concept, which customizes ArcGIS for the use of TIN for the special GeoSystems modeling purpose.

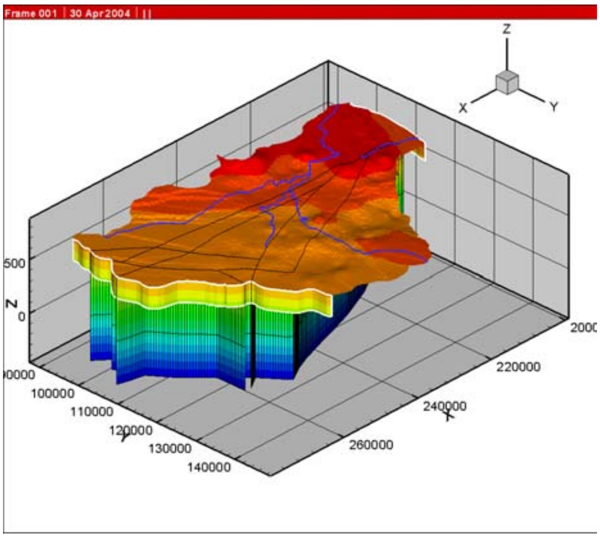


Figure 2.1: Use of polyline for boundary condition

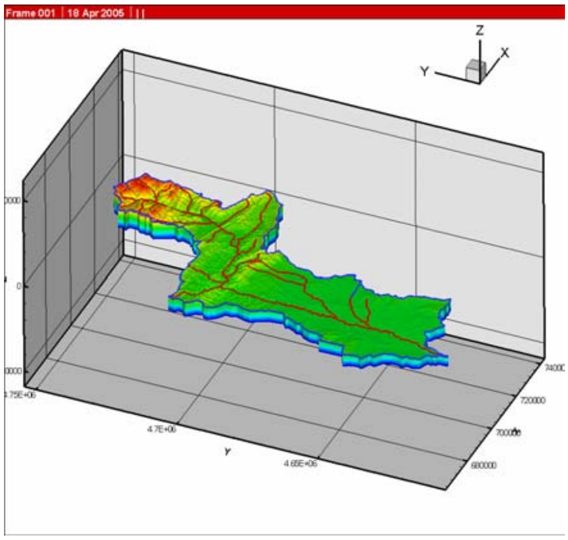


Figure 2.2: Mapped result using DEM

2.2 GIS Data Types

There are several GIS data types which can be used for hydrosystem modeling; in general, they are subdivided into two types: raster data and vector data.

2.2.1 Raster Data

In a raster model, the area is covered by a grid with (usually) equal-sized, square cells. The attributes are recorded by assigning each cell a single value based on the majority feature (attribute) in the cell. The most common raster models used in the hydrosystem modeling are:

2.2.1.1 Digital Elevation Model (DEM)

A DEM file is a simple, regularly spaced grid of elevation points. In hydrosystem modeling, DEM is used to create a topographical surface for the modeling area. Figure 2.3 shows part of the DEM for the Gallego catchment.

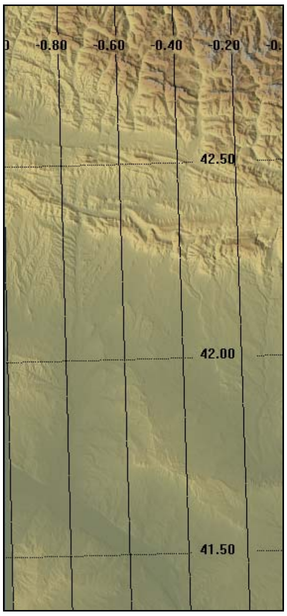


Figure 2.3: Corrected SRTM DEM
(http://glcf.umiacs.umd.edu/data/srtm/desc.shtml)

2.2.1.2 Digital Terrain Model (DTM)

A digital terrain model (DTM) is a digital file consisting of terrain elevations for ground positions at regularly spaced horizontal intervals. DTM may be used in the same way as DEM to generate the topographical surface of a modeling area. Figure 2.4 shows an example of a DTM.

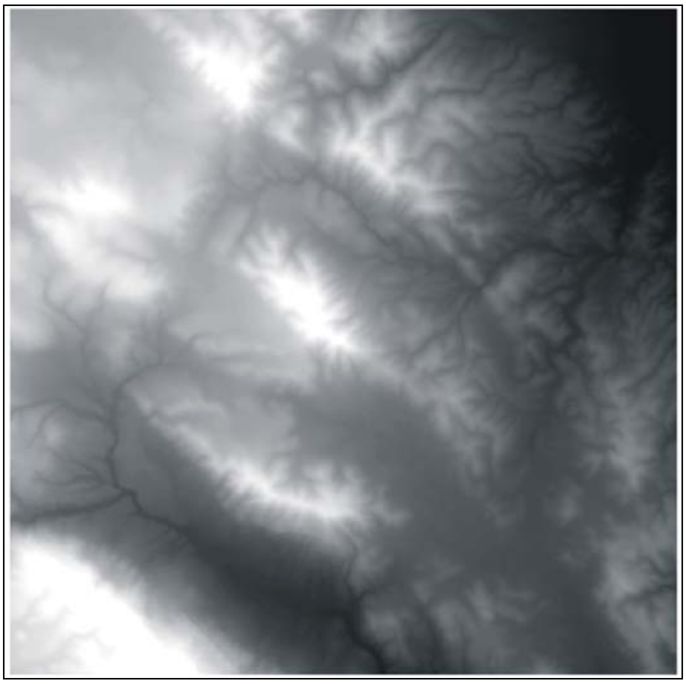


Figure 2.4: DTM (Anker 2005)

2.2.1.3 Raster Data – Lithological Layer Data

ArcGIS handle two kinds of raster maps in ASCII and binary format. The ASCII file, which is used in this thesis is shown in Figure 2.5:

```
ncols     464
nrows     314
xllcorner    193089.182283
yllcorner    87150
cellsize     200
NODATA_value    -9999
187.7918 187.8328 187.8743 187.9161 187.9583 188.0008 188.0437
188.087 188.2922 186.2334 188.0229 187.3221 188.4321 ……
```

Figure 2.5: One example of ASC file

The description of the file is in the following table (Table 1):

ncols	number of columns in the data set.
nrows	number of rows in the data set.
xllcenter or **xllcorner**	x-coordinate of the center or lower-left corner of the lower-left cell.
yllcenter or **yllcorner**	y-coordinate of the center or lower-left corner of the lower-left cell.
cell size	cell size for the data set.
nodata_value	value in the file assigned to cells whose value in unknown. This keyword and value is optional.

Table 1: ASC file description

Normally, for the generation of a 3D subsurface model, lithological information of each geological layer is required. Observation wells (boreholes) are used to get the geometric information of some locations, but because of the data limitation for both subsurface and surface layer; interpolation tools are used to estimate between known points. The interpolation method is also implemented in ArcGIS spatial analysis. Figure 2.6 shows an example of an interpolated raster map for the surface layer; Figure 2.7 shows the mapped result. The raster maps from all the layers can be used to generate a 3D geometric structural model.

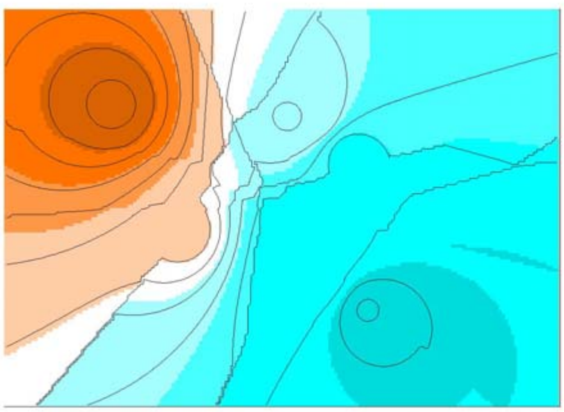


Figure 2.6: Surface raster map

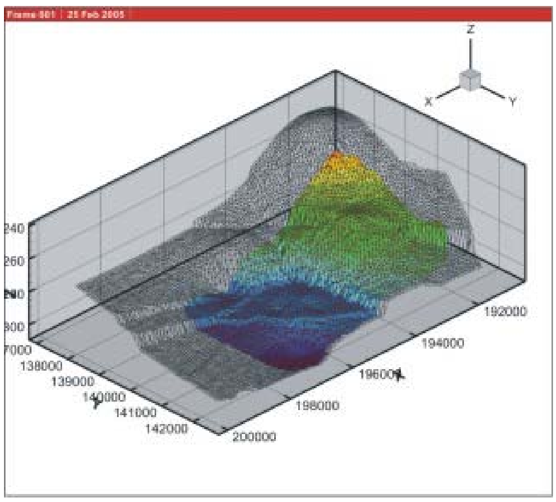


Figure 2.7: Mapped result using raster map

2.2.2 Vector Data

In addition to the raster model, the vector type model is also utilized for hydrosystem modeling purposes. The fundamental concept of vector GIS is that all geographic features in the real world can be represented as points, either polylines or surfaces.

2.2.2.1 Point Data

There are several uses of point data from GIS for hydrosystem modeling:

- Pumping wells: source term,
- Boreholes: lithological information of surface and subsurface layer,
- Wells for boundary condition,
- Wells for initial condition.

Figure 2.8 shows the boreholes containing the lithological information for the modeling project.

2.2.2.2 Polyline Data

There are several uses of polyline data from GIS for the geo-system modeling:

- Delineation of source term (Fig 2.9),
- Representation of faults (Fig 2.10),
- Localization of boundary condition (Fig 2.11),
- Localization of initial condition.

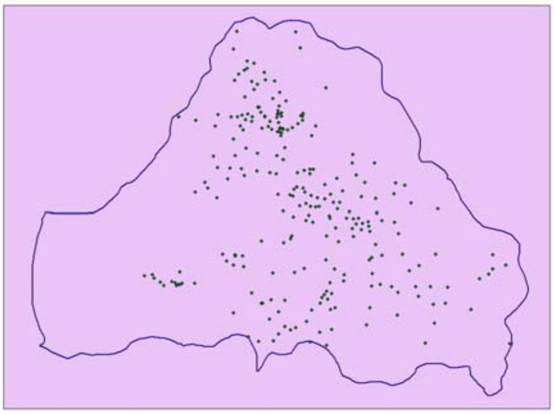


Figure 2.8: Wells for lithological information (Sawarieh 2004)

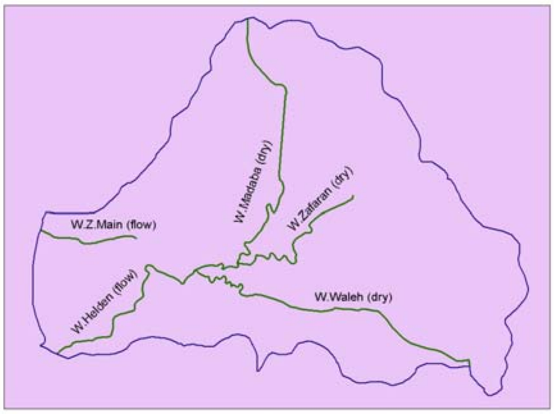


Figure 2.9: Polylines for wadi network

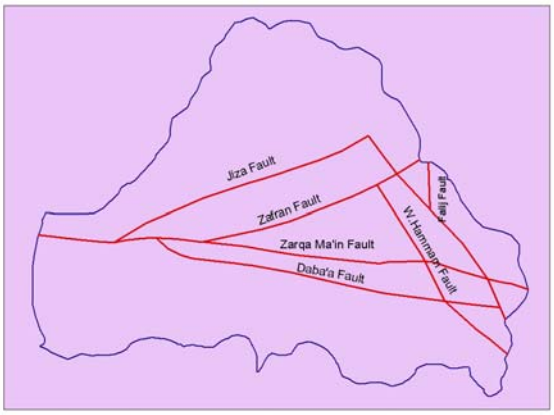


Figure 2.10: Polylines for fault system

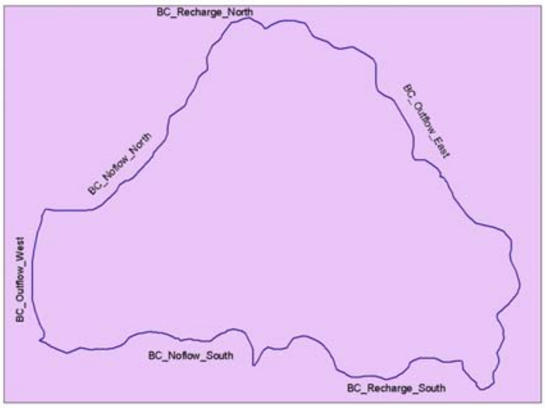


Figure 2.11: Polylines for boundary condition

2.2.2.3 Surface Data

There are several uses of surface data from GIS for the hydrosystem modeling:

- Areal distribution of initial conditions (Fig 2.12),
- Localization of boundary conditions,
- Areal distribution of material properties (Fig 2.13).

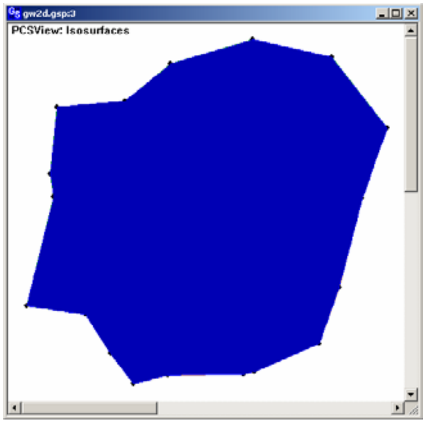


Figure 2.12: Surface for initial conditions

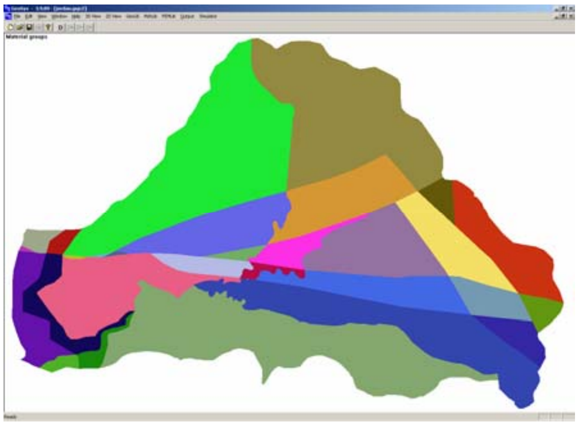


Figure 2.13: Surfaces for material groups

2.2.2.4 Volume Data

Volume data is 3D data. However, the restriction of the current GIS technology does not allow the full 3D data functionalities, which are very important for the analysis of GeoSystems. Here the integration of GIS with GeoSys/RockFlow was able to solve such a problem by creating a 3D structural model. Figure 2.14 shows the 3D volume data for the whole modeling domain.

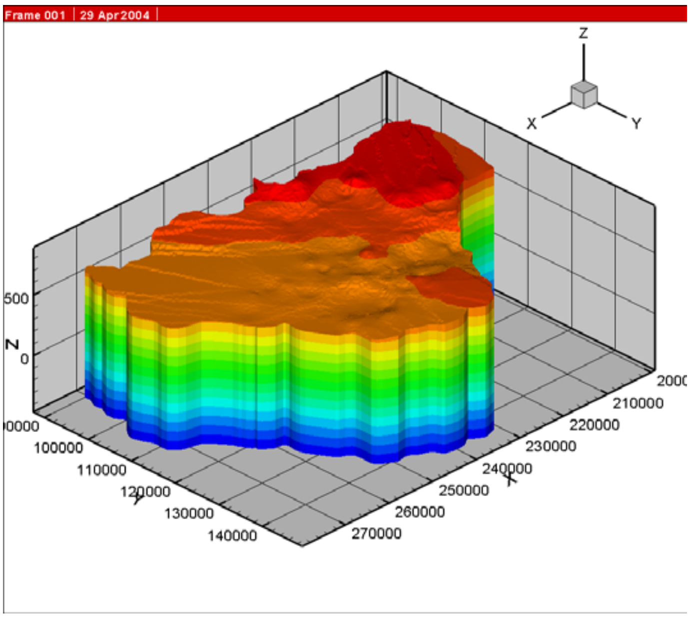


Figure 2.14: 3D volume of the whole domain

2.3 GIS Interface with GeoSystems

The communication between generic ArcGIS applications and the specialized GeoSys/RockFlow modeling program can be accomplished in several ways. The First is by standardization of data formats. For example, the shape file is a well-known spatial data format that allows data sharing among applications. For raster data, a format such as DEM can be used to share interpreted geophysical images between specialized software to GIS. The second approach of integration is by creating a direct extension to ArcGIS. The core technology of ArcGIS is the ArcObjects, which is a collection of COM features. You can customize these applications using a common Visual Basic for Applications (VBA) environment. The customization can vary from creating a script for a specific task to highly customized and stand-alone applications based on the ArcObjects software components. Developers have a choice of development environments when using ESRI software including VB, C++, .NET, and Java. The significant weakness of GIS for subsurface modeling is that GIS does not support solid 3D modeling, so, based on the object-oriented technology, a structural 3D model can be built based on the concept of integrating GIS and GEOLib (Geometric object library of the modeling program GeoSys/RockFlow). The figure 2.15 shows the interface concept between a GIS and GEOLib, as well as the structure of geometric modeling part of the whole system.

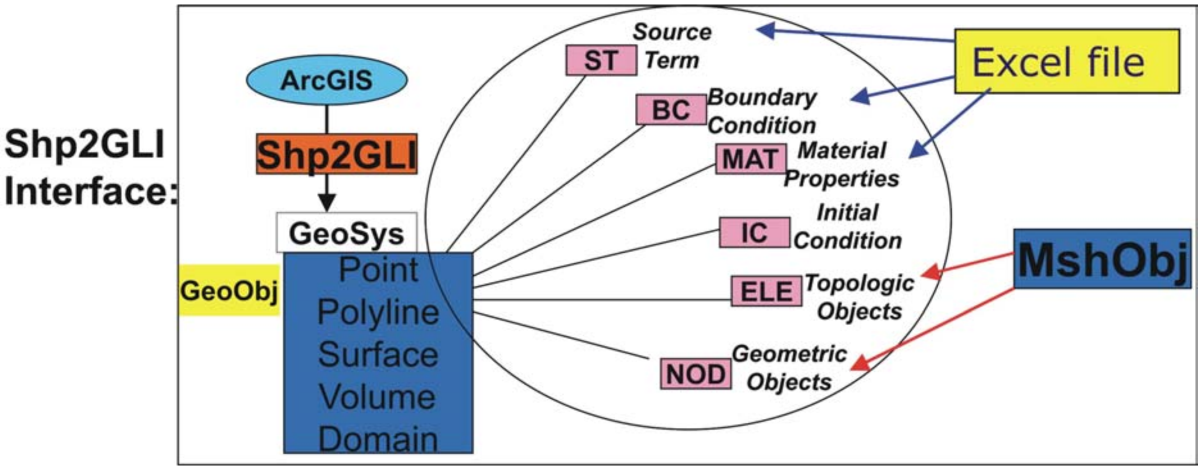


Figure 2.15: Interface of GIS and GEOLib and the geometric modeling part of the whole system

Because of the data format differences between a typical GIS and GeoSys/RockFlow, an Shp2GLI interface is built. After importing the GIS Shape file into GeoSys/RockFlow, the interface converts the Shape file into the GeoSys/RockFlow geometric data structure – GLI. GLI is the file extension of the GEOLib data. The 2D Geo-Objects in GeoSys/RockFlow such as point, polyline, and surface together with an external Excel file which describes the temporal information, could be used not only for locating source terms (ST), boundary conditions (BC), material properties (MAT), initial conditions (IC), but also for creating nodes and elements that form a finite element mesh.

2.3.1 Import ArcGIS (SHP) data

The figure 2.16 shows the dialog for importing ArcGIS SHP data. After the shape files have been imported, the point and polyline data from the shape file are displayed in the corresponding combo box within the SHP Data frame. Each 2D shape file describes the geometric information for a certain layer. In order to handle the layer information in an efficient way, the layer number is appended to the name of the point and polyline objects. New geometric features can also be created using this dialog.

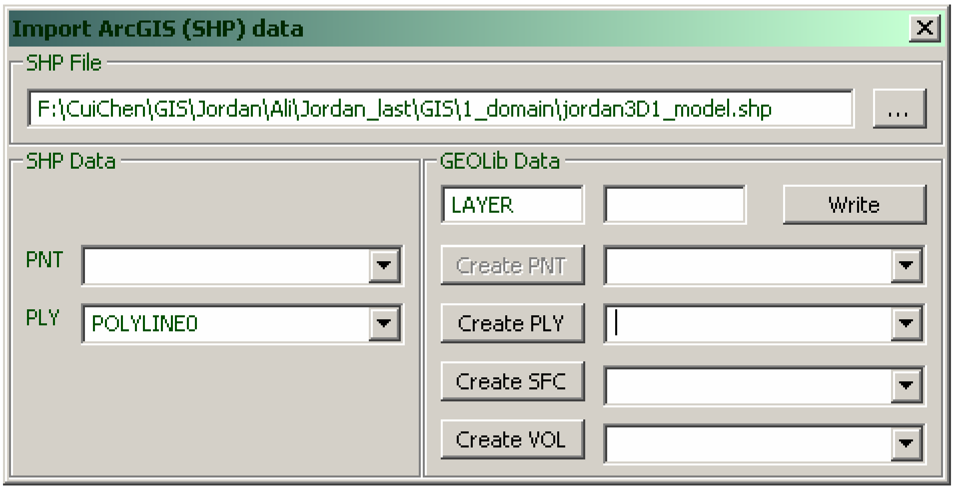


Figure 2.16: Importing SHP data dialog

2.3.2 From 2D to 3D

GIS traditionally tends to view the world from above, either as flat surfaces or as discrete horizontally oriented surfaces such as topography. The term "2.5D" is often used to describe the way in which GIS views natural phenomena. Currently, variety of software is already capable of handling a wide range of spatial problems. Among all types of systems dealing with spatial information, GIS has proved to be the most sophisticated system that operates with the largest scope of objects. 3D information is very important in the GeoSystems analysis. Unfortunately, such 3D systems are still not available on the market. For example, one system is used for data storage and another for 3D visualization, which leads to inconsistency problems; as a result, extra time and effort were given to find the appropriate solution (Zlatanova, 2002).

By implementing GIS tools within GeoSys/RockFlow, a 3D hydrogeological model can be built to analyze hydrogeological systems. The generation of the 3D model relies heavily on data from boreholes and geologic cross sections; in addition, the existing 2D GIS database, the hydrogeological boundaries, and the DEM are important data sources for the building of a 3D model. The following section describes the finite element components used in GeoSys/RockFlow and how these elemental shapes link to the concept of layer models. Such layer models are made up of layer polylines, layer surfaces (TINs), and layer volumes, all of which are required for the construction of a 3D structural model.

2.3.2.1 Finite Element Library

The finite element library consists of 1-D, 2-D and 3-D finite elements.

- 1-D: Line elements,
- 2-D: Triangles, Quadrilaterals,
- 3-D: Prism, Tetrahedral, and Hexahedra.

All elements can be used in combination within one mesh. Figure 2.17 shows the geometrical presentation of those elements inside one 3D finite element:

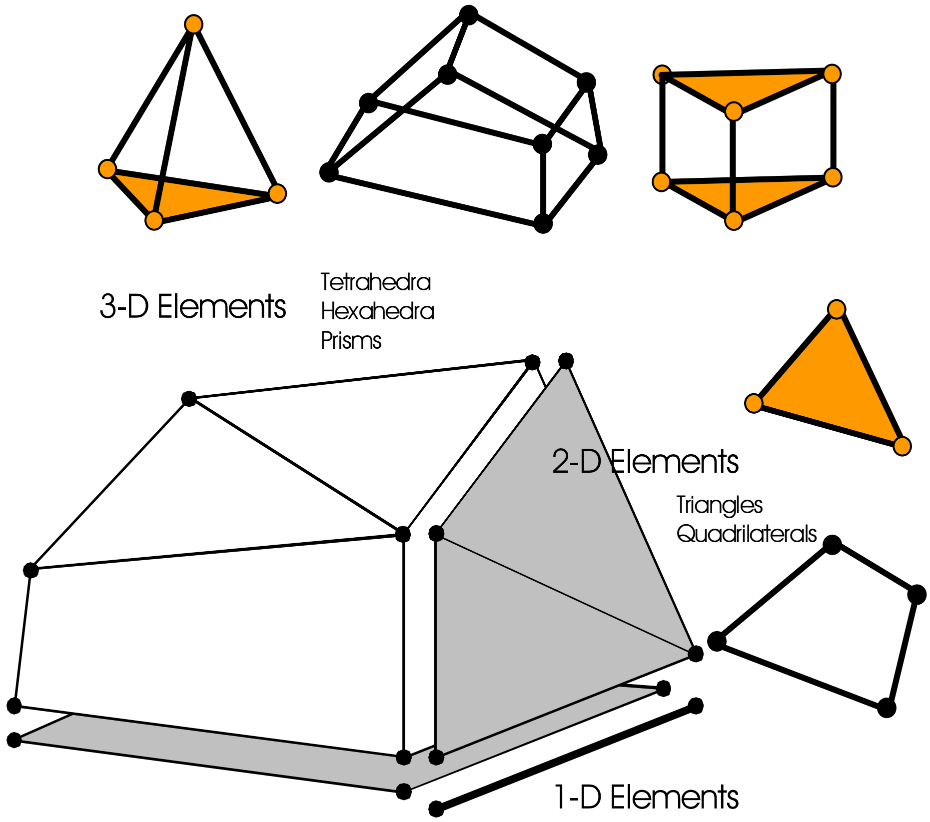


Figure 2.17: Geometrical presentation of finite element library (Beinhorn 2004)

The 3D structural model is built based on the available geometric data. Consistency of geometric model is very important, in particular, for the meshing procedure. The spatial discretization (finite elements and differences) is assembled from coupled line (for wadi), triangular (for surface), quad (for faults) and prismatic (for aquifers) elements are summarized in Figure 2.18 (Beinhorn 2004).

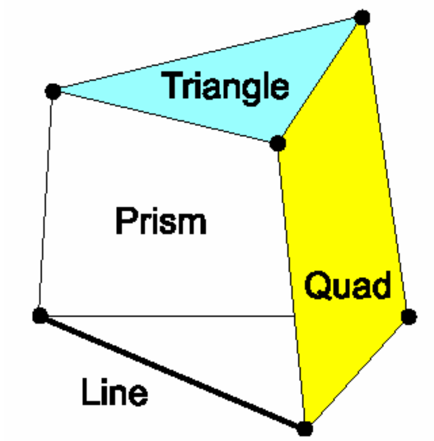


Figure 2.18: Combination of multi-dimensional finite elements (Beinhorn 2004)

In this way, linear elements can be used to model channel flow or unsaturated zone, triangles for overland flow, triangular prisms for saturated groundwater flow and quadrilaterals for fractured flow (Beinhorn 2004).

2.3.2.2 Layer Polylines

For 2.5D vertically extended models, model boundaries can best be defined by layer polylines (see also section 4.2.2.2). In contrast to a geometric polyline, a layer polyline consists of finite element nodes, which are linked to a polyline by using a nearest neighbor search algorithm. These layer polylines are duplicated and moved to the corresponding z-coordinate of each layer. Layer polylines can then be used to define boundary conditions along complex vertical surfaces (section 4.2.3.3).

2.3.2.3 Layer Surface with TIN

A Tin is a set of adjacent, non-overlapping triangles computed from irregularly spaced points, with x, y horizontal coordinates and z vertical elevations, which can be used for a discrete geometric description of surfaces and volumes. The generation of TINs for surfaces requires an existing triangule mesh. A layer surface is described as a TIN file. Layer surfaces are used to create solid volumes. See also section 4.2.3.2. Figure 2.19 shows the mapped layer surfaces with TIN.

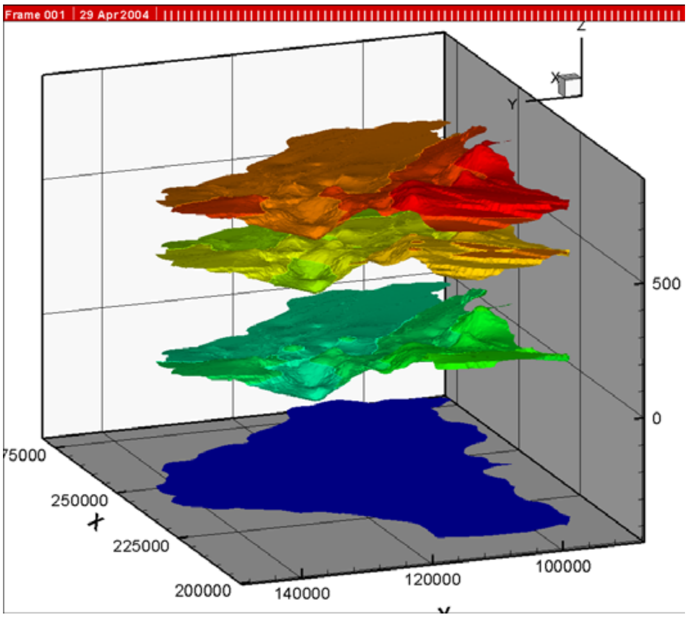


Figure 2.19: Mapping result for each layer

2.3.2.4 Layer volumes

A layer volume is built based on layer surfaces. The layer volume concept is very useful in the object-oriented program for the identification of corresponding finite volumes and for the assignment of the material properties to the finite element components (See also section 4.2.4.2). Figure 2.20 shows an example of a layer volume.

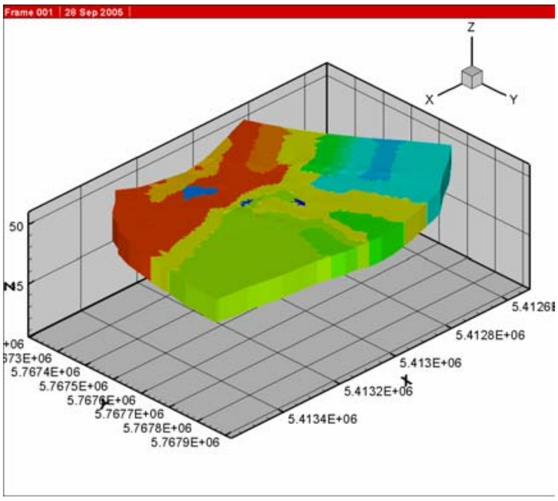


Figure 2.20: A layer volume

2.4 Customizing ArcGIS with VBA for Importing TIN data

2.4.1 Introduction

GIS supports two types of surface models: a triangulated irregular network (TIN) or a regular grid digital elevation model (DEM). However, the disadvantage of the DEM is its inherent spatial invariability, since the structure is not adaptive to the irregularity of the terrain. This may produce a large amount of data redundancy especially where the topographic information is minimal. An ArcGIS methodology is used for constructing TIN terrain model from DEM. The resulting terrain models are computationally feasible comparing to the original DEM by significantly reducing the number of nodes while preserving the terrain attributes that are typically lost when coarsening raster-based elevation models. Customization for ArcGIS with visual basic for application (VBA) is needed to fulfill some functions, which are not available from the standard ArcGIS environment, and here the elements of TIN, like the nodes and triangles are exported into GeoSys/RockFlow finite element data Structure to create a surface model in GeoSys/RockFlow.

2.4.2 TIN

TINs (triangulated irregular networks) are used primarily for surface modeling. They represent surfaces by dividing them into a set of non-overlapping triangle facets. ArcObjects offers the possibility to customize ArcGIS in a com-based programming environment such as, C++, VB, VBA, VB.net etc. Three notable interfaces implemented by the TIN object are ITinAdvanced, ITinEdit, and ISurface. ITinAdvanced provides access to basic properties and is a jump off point for getting at the underlying data structure. ITinEdit is used for TIN construction and editing. ISurface provides surface analysis functions such as contouring, profiling, and volumetrics. Triangles, edges, and nodes are the basic elements that comprise a TIN. For advanced TIN editing and analysis, it should access to these elements and the relationships between them. The TIN object model includes TinTriangle, TinEdge, and TinNode objects for this purpose as well as helper objects such as TinElementEnumerators and TinFilters that support iterative processing.

2.4.3 Customizing ArcGIS by programming ArcGIS with VBA

In the following it shows one small part of DEM of Meuse basin (Fig 2.21), and DEM data is available from the Internet website (http://glcf.umiacs.umd.edu/data/srtm/desc.shtml). TIN is created in ArcGIS by using the function from 3D spatial analyst: Raster to TIN, and in the next step converted into GeoSys/RockFlow triangle mesh structure by using user-implemented method.

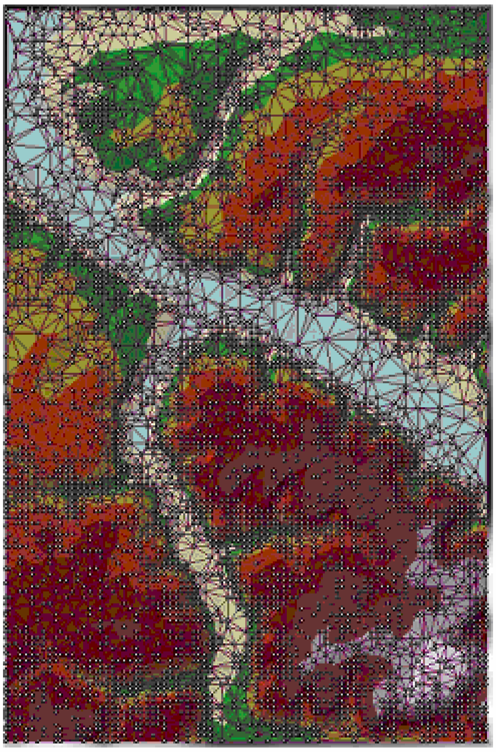


Figure 2.21: Part of DEM for Meuse basin

2.4.4 Visual Basic for Application with ArcObjects

In the following, it shows the procedure how to build a user defined functions in ArcGIS desktop working environment using programming technique of VBA.

- Create new toolbar,
- Create new command buttons on the toolbar,
- Go to VBA to edit the event of the button,
- Add reference for ItinAdvanced: ItinAdvanced is an important object from ArcObjects, and the reference need to be added for it so that it can be used. The reference is a file with extension as OLB.

User Interface

This is the new toolbar in ArcGIS: Export TIN elements to GeoSys/RockFlow RFI. It is shown in the Figure 2.22.

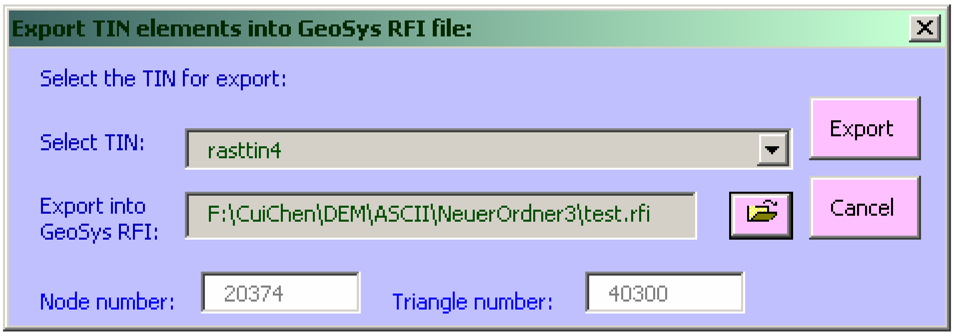


Figure 2.22: Convert TIN elements into GeoSys RFI file format

The TIN file is selected which was converted from DEM data using ArcGIS 3D spatial analyst, and then the triangles of the TIN are exported into GeoSys/RockFlow RFI data structure. Converting the Unicode Text document into MS-DOS format text document are necessary.

Export the MSH File into Tecplot

Using the Tecplot (Tecplot, Inc, 2005) interface, the RFI data can be exported into Tecplot file for displaying purposes. Figure 2.23 shows the TIN in Tecplot interface. Here it shows a 3D visualization, since DEM is not so preventative in a 2D sense.

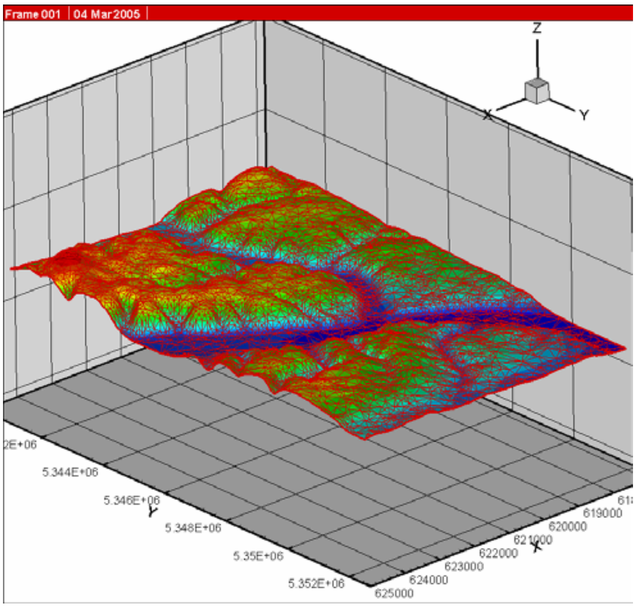


Figure 2.23: TIN in Tecplot

3 GEOSYS/ROCKFLOW SOFTWARE CONCEPT

Object-oriented software concept becomes increasingly important in order to meet scientific computing challenges, such as the treatment of coupled non-linear multi-field problems with extremely high resolutions. GeoSys/RockFlow is an object-oriented program to simulate flow, mass, heat transport and deformation as well as chemical reaction processes in porous and fractured media. The implementation of numerical methods involving geometric description of geo-systems with the application of finite element meshes is of vital importance for investigation and modeling of complex coupled nature or man-induced processes. An overview of the object-oriented concept for multi-process systems is introduced in this section.

3.1 Object-Orientation in Finite Element Analysis

Almost all numerical methods eventually have to deal with the solution of algebraic equation systems. The basic algorithms for the discretization of partial differential equations (PDEs) resulting from the initial-boundary-value-problems (IBVPs) of continuum mechanics can be generalized in principle as follows: time discretization, calculation of problem-specific node (finite difference method - FDM), element (finite element method - FEM), volume (finite volume method - FVM) contributions, incorporating initial and boundary conditions, assembling and solving the resulting equation system. For non-linear problems, iteration schemes, such as Picard or Newton methods, have to be used.

The general solution algorithm for the finite element method is given in Table 2.

Domain disretization (i.e. mesh generation): Creation of individual geometric elements (e.g. triangles, tetrahedral) and their topological relationships (mesh topology).
Local element assembly: Depending on PDE types all element matrices and vectors have to be computed. The element integration requires geometric operations such as interpolation with shape functions, calculation of inverse Jacobians and determinants. Additionally material functions have to be computed in Gauss points. Material functions can depend on field variables. Geometric element operations (shape functions, Jacobian), Material parameter calculation at Gauss points, Global assembly of the algebraic equation Ax=b: The local element entries are assembled into the global system matrix A and global RHS vector b. The equations systems are established after incorporating boundary conditions and source/sink terms. Assembly of system matrix A (including incorporation of boundary conditions), Assembly of RHS vector b (including incorporation of source/sink terms), Solving the system equations,
Iterative methods to handle non-linearities,
Iterative methods to handle couplings (partitioned and monolithic schemes).

Table 2. General solution procedure of the finite element method (Wang and Kolditz 2005)

The implementation of the general solution algorithm for multi-field IBVPs according to Table I is illustrated in Fig. 3.1. The time loop represents time discretization. Within the time loop, specified physical processes (e.g. flow, transport, deformation) are solved using the finite element method (left box). The solution procedure of each process is unique (middle box). The basic part is the calculation and assembly of element contribution (right box).

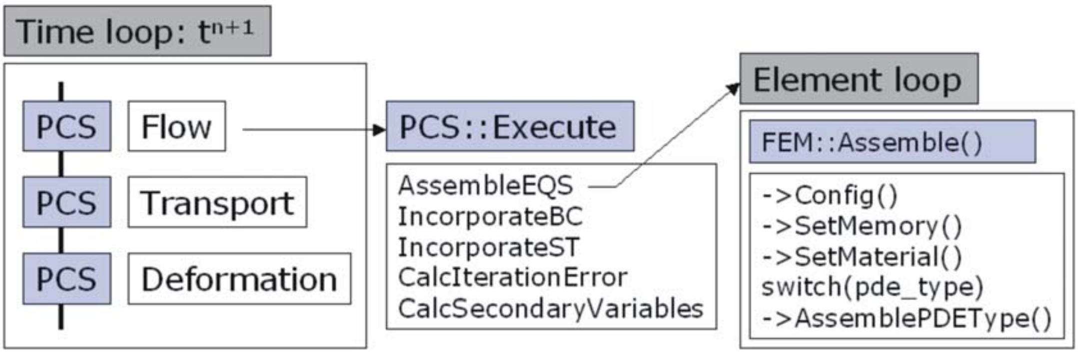


Figure 3.1: Implementation of solution algorithm (Wang and Kolditz 2005)

Based on above described general solution algorithm for multi-field IBVPs, the fundamental concept of object-orientation in finite element analysis is the generalization of

- Process (PCS) types (section 3.1.1),
- Equation (PDE) types (section 3.1.2),
- Element (ELE) types (section 3.1.3).

3.1.1 Process (PCS) Types

The central idea behind object-orientation of processes is that the basic steps of the solution procedure: calculation of element contributions, assembly of equation system (including treatment of boundary conditions and source terms), solution of the equations system, linearization methods and calculation of secondary variables, are independent of the specific problem (e.g. flow, transport, deformation processes). The process (PCS) class provides basic methods in order to solve a PDE in a very general way. The central part of the PCS object is the member function PCS::Execute() (Fig. 3.1 middle box) conducting these basic steps. Specific properties of the mechanical problem, such as PDE type, primary and secondary variables and material functions, are assigned during process configuration (member function PCS::Config()). In order to configure PCS instances polymorphism is used.

Fig. 3.2 illustrates the object-orientation of PCS types for the solution of IBVPs. The PCS object was designed to manage the complete solution algorithm in order to build the global equation system (EQS). In fact, the PCS object 'only' administrates references to geometric (GEO) objects (points, polylines, surfaces, volumes); MSH objects (mesh nodes and elements), node-related data such as initial (IC) and boundary (BC) conditions as well as source terms (ST); material data of porous media (fluid (MFP), solid (MSP), medium (MMP) and chemical (MCP) properties); parameters of the different numerical methods (NUM). PCS instances have 'only' pointers to the related objects as members.

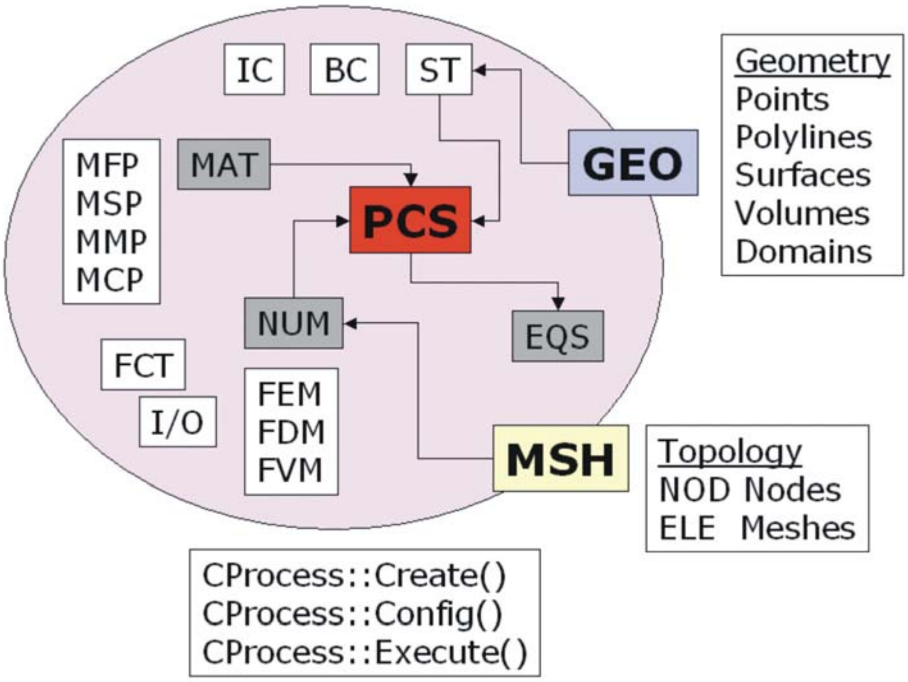


Figure 3.2: Structure of the process (PCS) object (Wang and Kolditz 2005)

3.1.2 PDE Types

IBVPs in porous media mechanics, such as fluid flow, mass and heat transport, deformation can be categorized into elliptic, parabolic, hyperbolic or mixed equation types.

As an example to explain to the generalization of PDE types, illustrate the treatment of Laplace terms, which appear in flow, transport as well as deformation processes, illustrate. In Fig. 3.3 the evaluation of finite element matrices for Laplace terms, i.e. $\mathbf{D}\partial^2 / \partial x^2$ is given, where **D** is a problem-specific material tensor. The special part of diffusion terms is the calculation of second order space derivatives. The second line of the equation in Fig. 3.3 represents the numerical integration of matrix being transformed into reference coordinates. From the view point of object-orientation the following operations are used: tensor coordinate transformation (**T**), Jacobian (**J**), integration ($\int$) and computation of material properties (**D**). The latter is the only problem-specific.

Fig. 3.3 shows the implementation of the Laplace term calculation, in which Ωr is the domain by the reference element. The **CalLaplace**() member function of the finite element class works for different processes with different material functions (Fig. 3.4) and geometric element types. A short description is given in the table below.

Code	Description
gp	Gauss integration points
GaussData()	Calculation of Gauss weights
Jacobian()	Calculation of Jacobian determinant and inverse
GradShapeFunction()	Calculation of shape function derivatives
LaplaceMATFunction()	Calculation of material coefficients
(∗Laplace) (i,j)	Finite element matrix

$$\mathbf{K}_e = \int_{\Omega_e} \nabla \boldsymbol{N} \mathbf{D} (\nabla \boldsymbol{N})^{\mathsf{T}} \, \mathrm{d}\Omega$$
$$= \sum_{gp=1}^{no\_gp} \int_{\Omega_r} w_{gp} \left[\nabla \boldsymbol{N} \mathbf{D} (\nabla \boldsymbol{N})^{\mathsf{T}} \mathrm{d}et \ \mathbf{J} \right] |_{gp} \, \mathrm{d}\Omega$$

```
void CFiniteElement::CalcLaplace()
{
  // Loop over Gauss points
  for (gp = 0; gp < no_gp; gp++)
  {
    GaussData();               // Integration points and weights
    Jacobian();                // det J, J^-1
    GradShapefct();            // ∇N
    LaplaceMATFunction();      // Material parameters, D
    for (i=0; i<nnodes; i++) // Loop over element nodes
      for (j = 0; j < nnodes; j++)
      {
        if(j>i) continue;     // Symmetry
        for (k = 0; k ¡ ele_dim; k++)
          for(l=0; l¡ele_dim; l++)
            (*Laplace)(i,j) += fkt * dshapefct[k*nnodes+i]
                                 * mat[ele_dim*k+l]
                                 * dshapefct[l*nnodes+j];
      }
  }
}
```

Figure 3.3: Finite element Laplace matrix and implementation (Wand and Kolditz 2005)

```
void CFiniteElementPCS::LaplaceMATFunction()
{
  // Calculate conductivity tensor D for Laplacian
   switch(PcsType){
      case L: // Liquid flow
      case U: // Unconfined flow
      case G: // Gas flow
      case T: // Two-phase flow
      case C: // Componental flow
      case H: // Heat transport
      case M: // Mass transport
      case O: // Overland flow
      case R: // Richard flow
   }
}
```

Figure 3.4: Implementation of process dependent material functions (Wang and Kolditz 2005)

3.1.3 Element (ELE) Types

The basic concept, which is applied, is that: element data, such as geometrical and topological properties, as well as operations of elements, such as element matrix calculations and treatment of boundary conditions, can be generalized.

The element object is the fundamental entity in both PDE and element types. In Fig. 3.5 the structure of the element object is illustrated. The element has two kinds of properties connected geometry and PDE types.
Element geometry includes the geometric type (line, triangle, quad, tetrahedron, prism, hexahedron), node coordinates, edges, faces and volume. Coordinate transformation functionalities are considered as geometric element properties. Element topology is defined by element neighbor relationships. Patch properties are available for finite volume approaches and flux calculations. The elements form the mesh topology. Different geometric element types can be combined (Fig. 3.5) together to establish a mesh. Additionally, elements can be assigned to different meshes.
Depending on PDE type (elliptic, parabolic, hyperbolic, mixed), different first or second order differential terms have to be evaluated ($\partial/\partial t$, $\partial/\partial x$, $\partial^2/\partial t^2$, $\partial^2/\partial x^2$). These differential terms are categorized in corresponding FE matrix types, mass matrix, Laplacian matrix, tangential matrix and coupling matrices. An obvious advantage of this element concept is that, depending on the geometric element type, interpolations (shape functions) and derivations as well as tensor operations and Gaussian integrations are conducted automatically in a correct. For material tensor properties in 1D, 2D or 3D (**A**, **B**, **C**, **D** (x) in Fig. 3.5), the correct matrix multiplications are conducted automatically. Material functions (*A*, *B*, *C*, *D*(u) in Fig. 3.5) are evaluated accordingly at corresponding Gaussian points of the selected element.

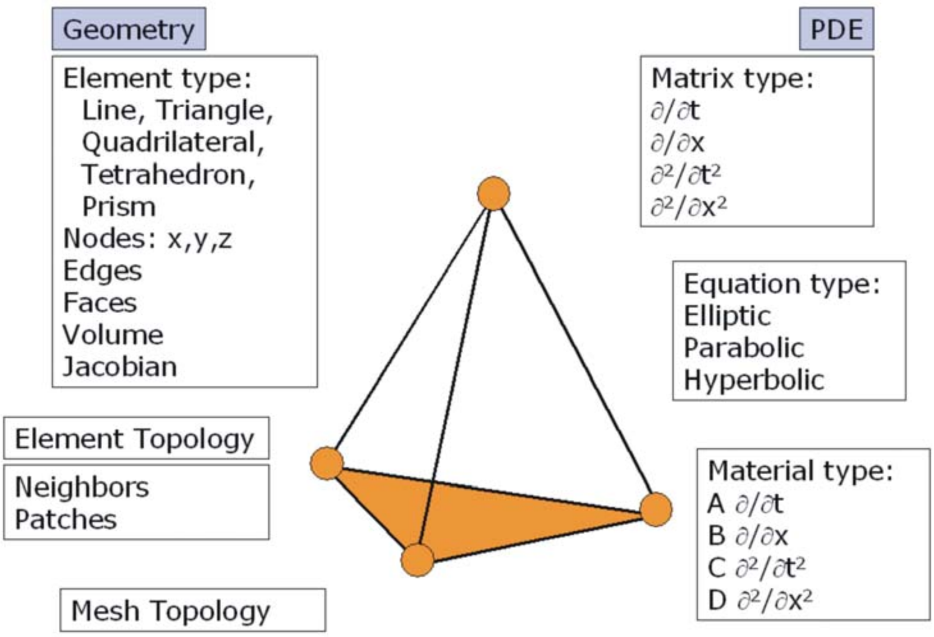


Figure 3.5: Structure of element object (Wang and Kolditz 2005)

For the sake of object-orientation for numerical methods, a so-called process (PCS) object was designed, implemented and successfully applied to different numerical methods (FEM, FDM, FVM).

3.2 GeoSys/RockFlow Structure

The main concept of GeoSys/RockFlow is the separations of geometrical, topological and physical data. They are:
GEOLib contains the basic geometric entities such as points, polylines, surfaces, volumes, and domains.

MshLib contains the basic topological entities such as finite elements (line, triangles, prism, quadrilateral, tetrahedron, hexahedron, etc).
PCSLib contains the numerical methods for solving partial differential equations (PDEs) such as the finite element methods and other component like boundary condition (bc), source term (st), fluid property (mfp), medium property (mmp), initial condition (ic), and time step (tim) if it is a transient simulation.
Those three basic modules can be connected via a Graphical User Interface (GUI).
The figure 3.6 focus on the above three modules and their relationship between them.

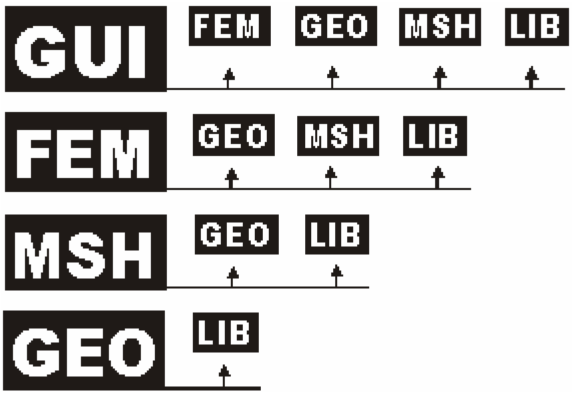


Figure 3.6: hierarchical relationship between GeoSys/RockFlow components

3.3 Process of a GeoSys/RockFlow Project and its Interface

3.3.1 File Concept

The general steps to create a GeoSys/RockFlow project are as follows:

1. Create geological features as layers for the study domain in ArcGIS by using feature creation tool, saved as shape files. Import shape files into GLI - our input file format of GEOLib and served as the input geometric data of modeling area.

2. Based on the geometric objects (e.g. domain boundary), a finite element mesh has to be created. As a result, a MSH file is created containing node geometry and element topology as well as the material group connected with the elements.

3. Create and edit the process data. The concept of GeoSys/RockFlow is based on a multi-phase / multi-component approach. The physical and chemical properties of fluid and solid phases as well as material properties representing e.g. geologic formations are specified. Moreover, initial and boundary conditions for the unknown field functions (e.g. pressure, temperature, concentrations) related to the selected process are also defined. Finally, numerical method is managed. As a result, output data of each process is saved in MSH file.

During the model set-up a project file is generated, which contains a list of data files. The final project file (GSP) looks like that (Fig 3.7):

```
#PROJECT_MEMBER
gw.bmp  // map
gw.gli  // geometric (GEO) data
gw.msh  // mesh (MSH) data
gw.pcs  // process (PCS) data
gw.num  // numerical (NUM) parameter
gw.tim  // time discretization (TIM) data
gw.ic  // initial conditions (IC) data
gw.bc  // boundary conditions (BC) data
gw.st  // source terms (ST) data
gw.mfp  // fluid properties (MFP) data
gw.mmp  // porous medium properties(MMP)data
gw.out  // output control (OUT) data
gw.fct  // functions (FCT) data
#STOP
```

Figure 3.7: GeoSys/RockFlow project file components

3.3.2 GeoSys/RockFlow Graphical User Interface

3.3.2.1 Views

According to the data concept of GeoSys/RockFlow the GUI provides corresponding views of the GS/RF libraries: GEOView, MSHView and PCSView. Figure 3.8 show the multiple document interface (MDI) of GeoSys/RockFlow.

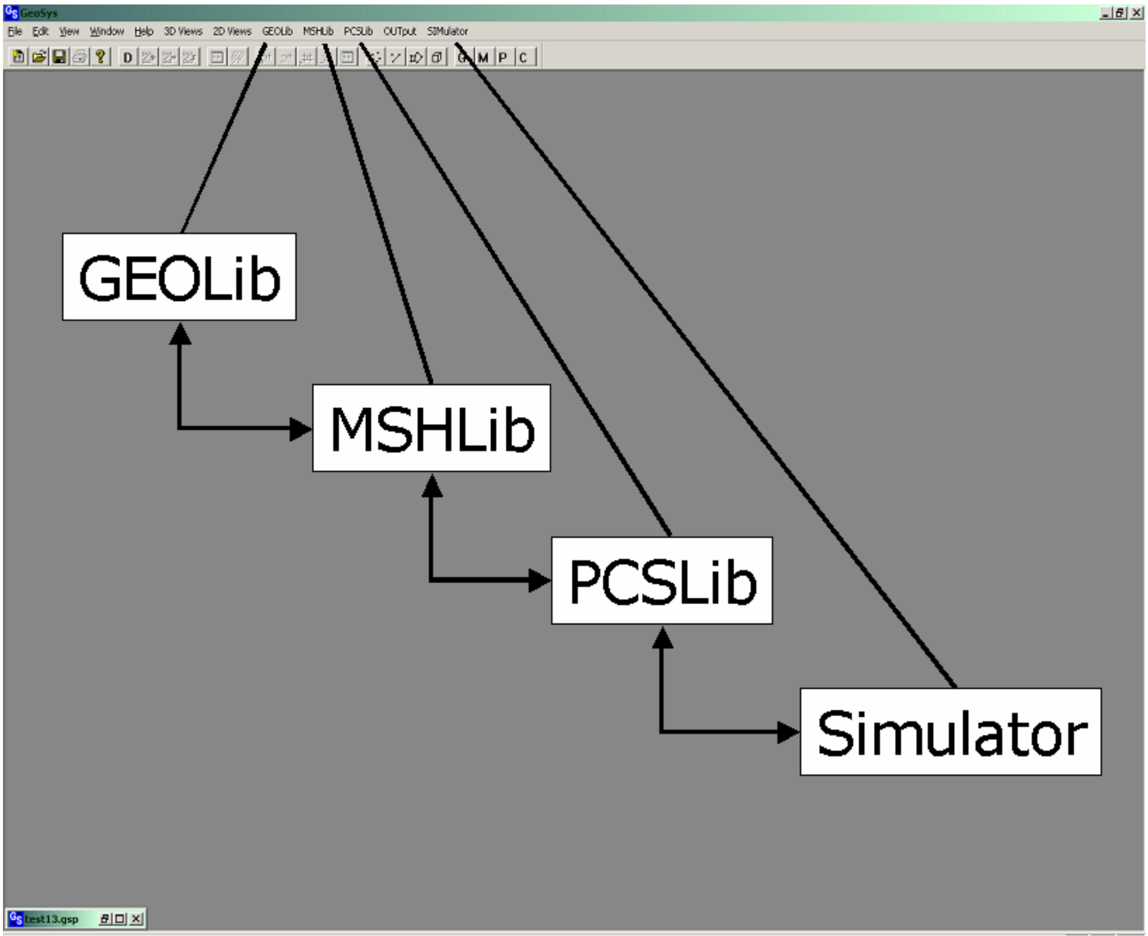


Figure 3.8: GeoSys/RockFlow user interface

3.3.2.2 Tool Bar

The tool bar is designed for convenient data access to project data, display methods, GEOLib, MSHLib, and PCSLib data and methods.

File handling: create, open, and save project file.

Display methods: zoom in, zoom out and zoom fit for the views.

GEOLib methods

 Create GEOView

 Point Editor

 Polyline Editor

 Surface Editor

 Volume Editor

MSHLib methods

PCSLib methods

3.3.2.3 Menus

Data and methods from the menus are available if the corresponding view is active. The following figures (Fig 3.9, Fig 3.10, Fig 3.11) show the relationship between GEOLib menu and GEOView, MSHLib menu and MSHView, and PCSLib menu and PCSView.

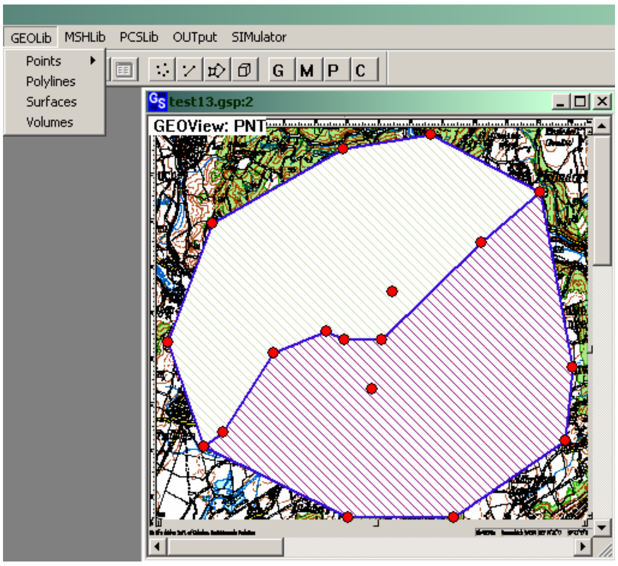


Figure 3.9: GEOLib menu and GEOView

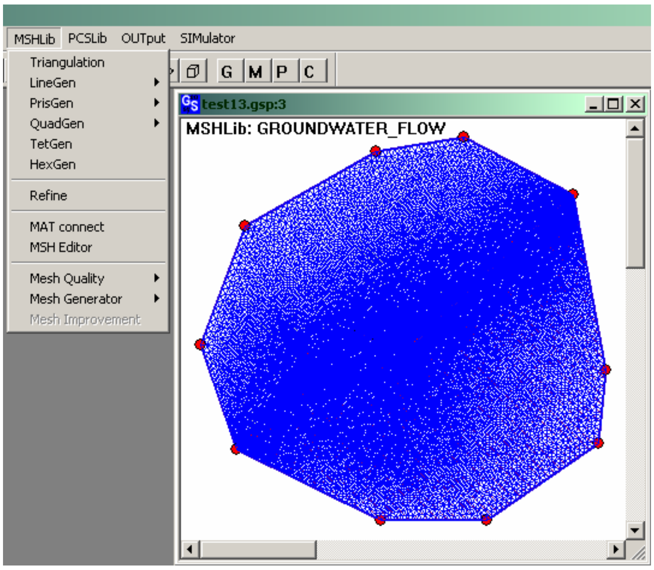


Figure 3.10: MSHLib menu and MSHView

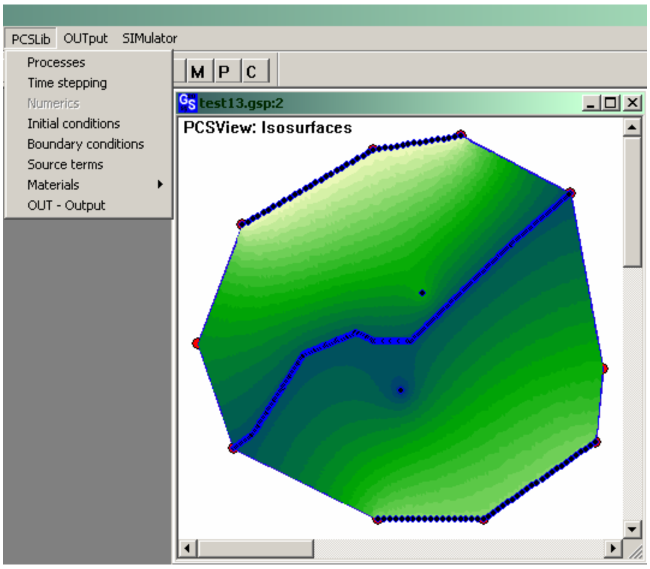


Figure 3.11: PCSLib menu and PCSView

3.3.2.4 Control Panel

During the session, a control panel is available to show the present data status and guide the user. The whole control panel (Fig 3.12) consist of four parts for data handling: GEO data, MSH data, PCS data, and other parts like TIM data for time steps guiding, FCT data for checking functions, DOM data for controlling the whole modeling domain displaying, and MAT data for checking the material groups.

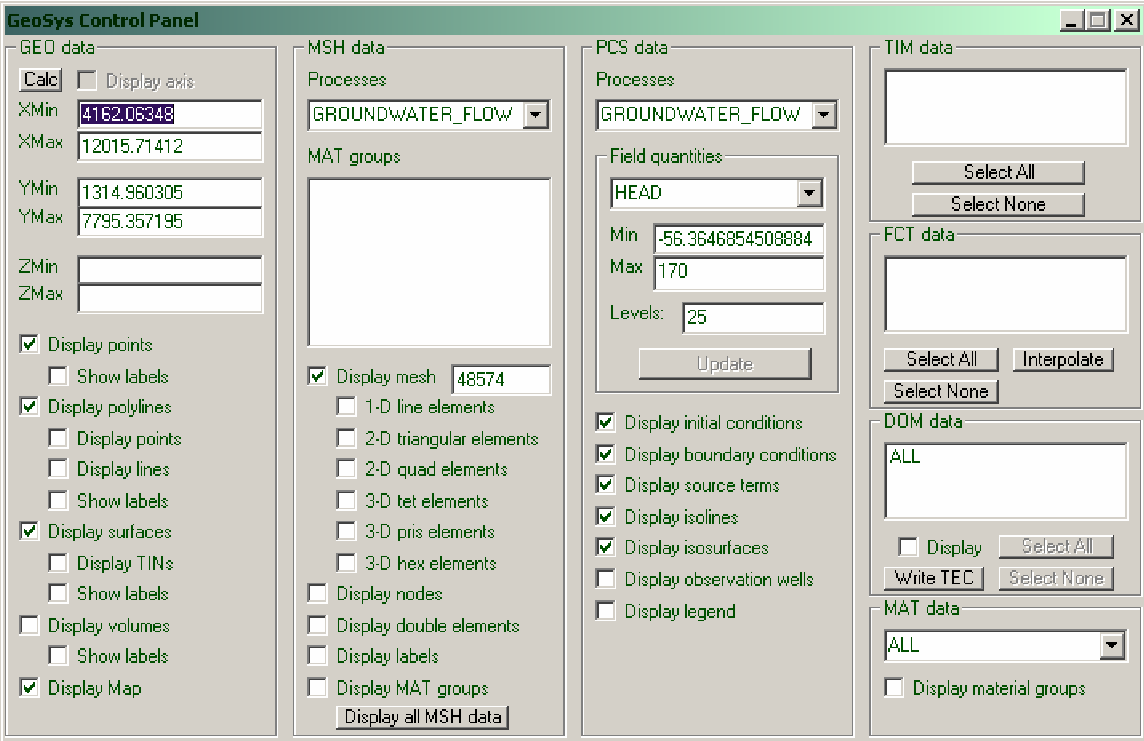


Figure 3.12: Control panel

4 GEOMETRIC MODELING – GEOLIB

4.1 Introduction

This section introduces the geometric data structure of GeoSys/RockFlow – GEOLib. GEOLib is the geometric library for the whole GeoSys/RockFlow model, which contains the input data for the model domain. The input file for GEOLib is the GLI file, which is an ASCII file. Those geometric objects of GEOLib are: point, polyline, surface, volume and domain. All these geometric entities are implemented as C++ classes: CGLPoint, CGLPolyline, CGLSurface, CGLVolume, CGLDomain. Instances of these objects are stored in vectors.

4.2 Modeling Geometric Object and Geometric Relationships

The following section describes the relationship between geometric objects according to the normal concept of geometry, *i.e.* an object is a component of another object. The hierarchical relationship between points, polylines, surfaces, volumes and domains is shown in figure 4.1: Points are the basic element of all other geometry types. Polylines are composed of an array of points. Surfaces consist of closed polylines, i.e. the last point of polyline is connected to the first one. Volumes consist of two surfaces and the domain consists of several volumes.

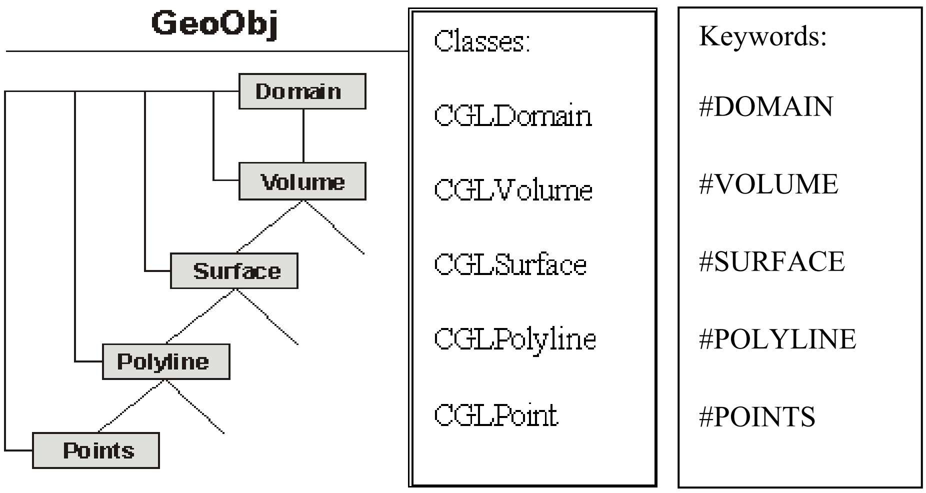


Figure 4.1: Hierarchical relationship between geometric objects

4.2.1 Points

The point is the basic element of all other geometric objects. Points can be used to define the following 1-D geometry elements: Source term, boundary condition.

Definition of a Point Class

The C++ definition of the point class is shown in the figure 4.2.

```
class CGLPoint
{
  public:
    // ID
   string name;
   long id;
    // Geometry
    double x;
    double y;
    double z;
    double epsilon;
    double length;
    // Meshing
    int index_msh; //WW
    double mesh_density;
    // Properties
    double value;
    double property;
    …..//other variables
  // Methods
    // Create
       CGLPoint(void);//  constructor
    ~CGLPoint(void); //destructor
    // I/O
    void Write(char*); //write points
    ios::pos_type Read(ifstream*,int*);// read points
    // GEO
    double PointDis(CGLPoint*); //distance between two points
    boolIsInsidePolygonPlain(double*,double*,double*,long);
    bool IsInsideTriangle(double*,double*,double*);
    bool IsInsideRectangle(double*,double*,double*);
    bool IsInsidePrism(double*,double*,double*);
    ......//other functions
};
```

Figure 4.2: Point class definition

Keywords

The point object in a GLI file starts with a keyword followed by the description of the point, which includes point number, coordinates (x, y, z), and properties (mesh density and point name).

Keyword: #POINTS

$MD is the mesh density,

$ID is the name of a point.

Example

The following shows an example of points in the gli file:

#POINTS

0	5148.4127	2703.1746	0.00000000 $MD 25 $ID POINT0
1	5488.8889	2919.8413	0.00000000 $MD 25 $ID POINT1
2	6386.5079	4147.6190	0.00000000 $MD 25 $ID POINT2
3	7315.0794	4477.7778	0.00000000 $MD 25 $ID POINT3
4	7634.9206	4343.6508	0.00000000 $MD 25 $ID POINT4
5	8284.9206	4353.9683	0.00000000 $MD 25 $ID POINT5
6	10059.524	5850.0000	0.00000000 $MD 25 $ID POINT6
7	11091.270	6613.4921	0.00000000 $MD 25 $ID POINT7

4.2.2 Polylines

A polyline consists of an array of points. Polylines are important geometry objects used to define the following:

- GEOLib: Definition of plane surfaces,
- MSHLib: Surface boundaries for 2-D meshing, creation of line elements along polylines (e.g. rivers),
- PCSLib: Assign boundary condition and source/sink terms along polylines; assign material properties along polylines.

Definition of the Polyline Class

The C++ definition of the polyline class is shown in figure 4.3.

```
class CGLPolyline
{
  private:
    long number;
    friend class Surface;
  public: //properties
    // ID
    long id;//CC
    string name;
    int type;
    int data_type;
    double epsilon;
    int mat_group;
    double minDis;
    //components
    bool computeline;
    int number_of_points;
    string ply_file_name;
    vector<CGLPoint*> point_vector;//point vector of polyline
    vector<CGLLine*> line_vector;
    ……//other variables
    //method
    CGLPolyline(void);  // constructor
    ~CGLPolyline(void); // destructor
      //I/O
    ios::pos_type Read(ifstream*,string);//read polylines
    void Write(char* file_name); //write polylines
    void ComputeLines(CGLPolyline*);
    bool PointExists(CGLPoint* point,CGLPoint* point1);
    void AddPoint(CGLPoint* m_point);
    CGLPoint* CenterPoint(void);
      //point vector
    void WritePointVector(string);//
    void ReadPointVector(string);//
    void SortPointVectorByDistance();
    // Meshing
    vector<long>msh_nodes_vector;
    vector<double*> msh_coor_vector;
    vector<int> OrderedPoint;
    void GetPointOrderByDistance();
    void SetPointOrderByDistance(CGLPoint*); //
    ......//other functions
  };
```

Figure 4.3: Polyline class definition

4.2.2.1 Topological Polylines

In general, there are two types of polylines: topological polylines and layer polylines. The topological polyline definition is shown as follows. Figure 4.4 shows the relationship between points and topological polyline:

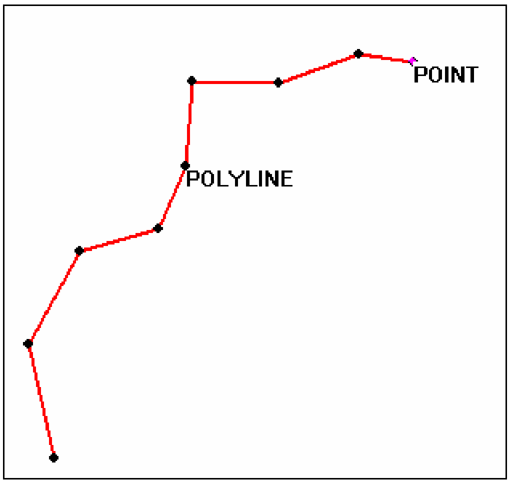


Figure 4.4: Relationship between points and a topological polyline

Keywords

Topological polylines are built from points specified in the sub-keyword $POINTS. The polyline objects in a GLI file starts with a keyword followed by some sub-keywords. Keyword: #POLYLINE Sub-keyword description is shown Table 3:

Sub-keyword	Objective
$ID	Id
$NAME	Name for identification
$TYPE	Type for use
$EPSILON	ε environment
$MAT_GROUP	Material group
$POINTS	List of points building the polyline

Table 3: Sub-keywords for a polyline object

Example

The following shows an example of a topological polyline:

```
#POLYLINE
 $ID
  0
 $NAME
  Neckar
 $TYPE
  2
 $EPSILON
  1
 $MAT_GROUP
  -1
 $POINTS
 0
```

4.2.2.2 Layer Polylines

The second type of polyline is layer polyline. The layer polylines are necessary to (for example) assign boundary conditions to the vertical faces of a 3D model domain. A standard polyline has elevation z = zero. In creating layer polylines, for each interface between layers of the model a line is created with elevations according to the nearest nodes in the existing 3D mesh. Figure 4.5 shows the relationship between finite element nodes and layer polyline.

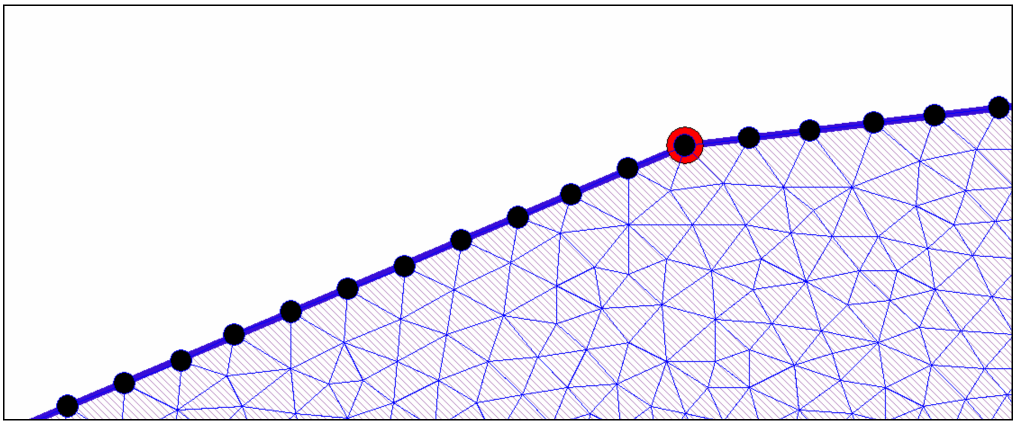


Figure 4.5: Relationship between finite element nodes and layer polyline

Keywords

The layer polyline is stored in the GLI file with a sub-keyword as $POINT_VECTOR, which is a file including an array of points with the extension .PLY.

Example

The description of the layer polyline in GLI file is shown below:

```
#POLYLINE
 $ID
  160
 $NAME
  BC_SOUTH_L6
 $EPSILON
  2.22613
 $MAT_GROUP
  -1
 $POINT_VECTOR
  BC_SOUTH_L6.ply
```

Figure 4.6 shows the layer polylines in a 3D model.

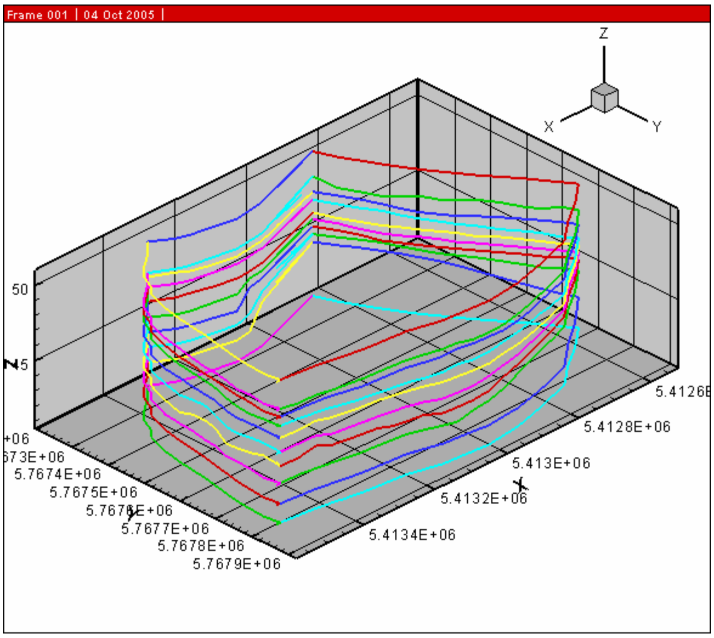


Figure 4.6: Layer polyines

4.2.3 Surfaces

Surfaces are closed polylines, i.e. the last point of polyline is connected to the first one. A surface can be used as:

- GEOLib: geometric basis of volumes,
- MSHLib: for 2-D meshing purposes,
- PCSLib: Assign boundary condition and source/sink terms at surfaces; Assign material properties to surfaces.

Definition of the Surface Class

The C++ definition of the surface class is shown in the following Figure 4.7.

```
class Surface{
    public:
       //ID
    long id;//CC
    string name;
    int type;
    string type_name;
    double epsilon;
    int mat_group;
    string mat_group_name;
    double Radius;
    //topology
    bool order;
    bool createtins;
    double center_point[3];
    CTIN *TIN;
    vector<CGLPoint*>polygon_point_vector;
    vector<CGLPolyline*> polyline_of_surface_vector;
    vector<int> polyline_of_surface_orient;
    vector<double*>nodes_coor_vector;
    ….//other variables
    //Method
    Surface(); //constructor
    ~Surface();//destructor
    // I/O
    void output(FILE* geo_file, int &p_index, int &l_index,
                                 int &pl_index,int &s_index);
    void Write(string);
    ios::pos_type Read(ifstream*,string);
    //Topology
    void PolylineOrientation();//CC
    void ReArrangePolylineList();
    void PolygonPointVector();//OK/CC
    void CalcCenterPoint(void);
    void CreateTIN(void);
    void ReadTIN(string);//CC
    void WriteTIN(string);//CC
    bool PointInSurface(CGLPoint*); //OK
    private:
    friend class CGLLine; //WW
    ….//other functions
};
```

Figure 4.7: Surface class definition

4.2.3.1 Topological Surfaces

In general, there are two types of surfaces: topological surfaces and layer surfaces. A topological surface can be created from one closed polyline (polygon) or from several polylines. Figure 4.8 shows the relationship between the polyline and topological surface.

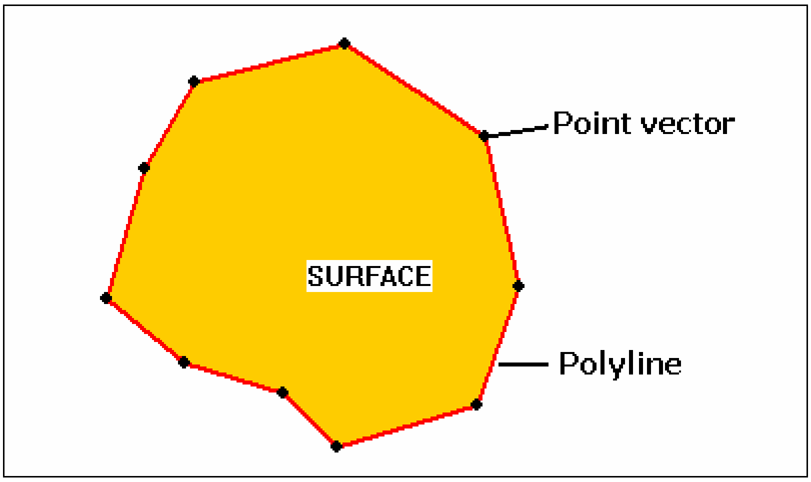


Figure 4.8: Relationship between polyline and topological surface

The following is a brief description of creating a surface using several polylines. The polylines should close together, but it does not work when polylines cross each other as shown in Figure 4.9a. These polylines should surround a close area as shown in Figure 4.9b.

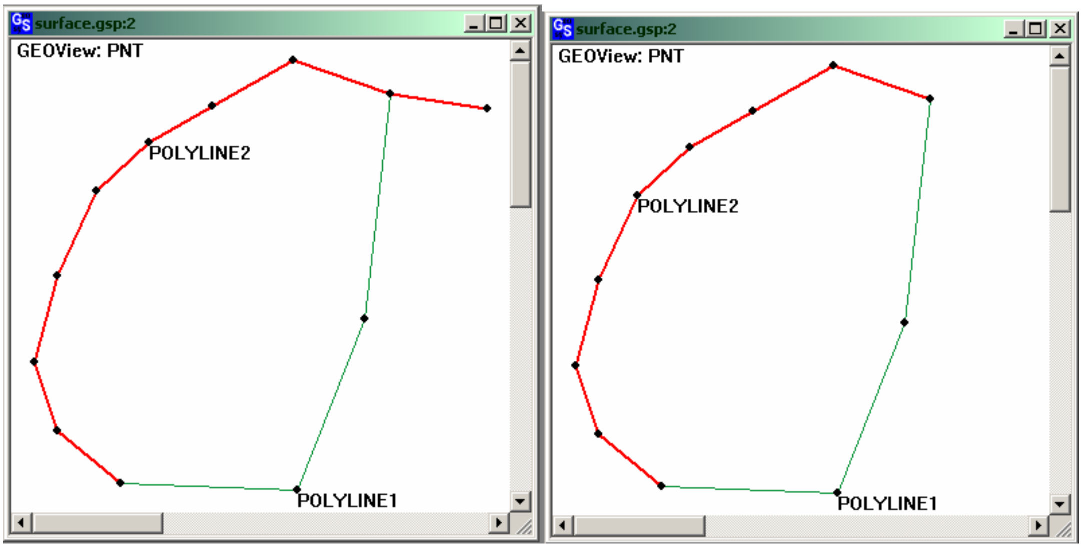


Figure 4.9 (a, b): Surface creation from closed polylines

Keywords

Surfaces are built from polylines specified by the sub-keyword $POLYLINES. The surface objects in a GLI file start with a keyword followed by some sub-keywords.
The sub-keyword description is shown in Table 4:

Sub-keyword	Objective
$ID	Id
$NAME	Name for identification
$TYPE	Type for use
$MAT_GROUP	Material group
$POLYLINES	List of polylines building the surface

Table 4: Sub-keywords for a surface object

Example

The topological surface definition is as follows.

Keyword: #SURFACE

```
#SURFACE
 $ID
  0
 $NAME
  SURFACE0
 $TYPE
  0
 $MAT_GROUP
  0
 $POLYLINES
  Neckar
  POLYLINE_NORTH
```

4.2.3.2 Layer Surface with TINs

The basic principle behind a layer surface is the TIN. A TIN is a set of adjacent, non-overlapping triangles computed from irregularly spaced points, with x, y horizontal coordinates and z vertical elevations, which can be used for a discrete geometric description of surfaces and volumes. One kind of layer surface is the surface with TINs, which need the existing triangulations. Figure 4.10 shows the relationship between one-layer surfaces with TINs

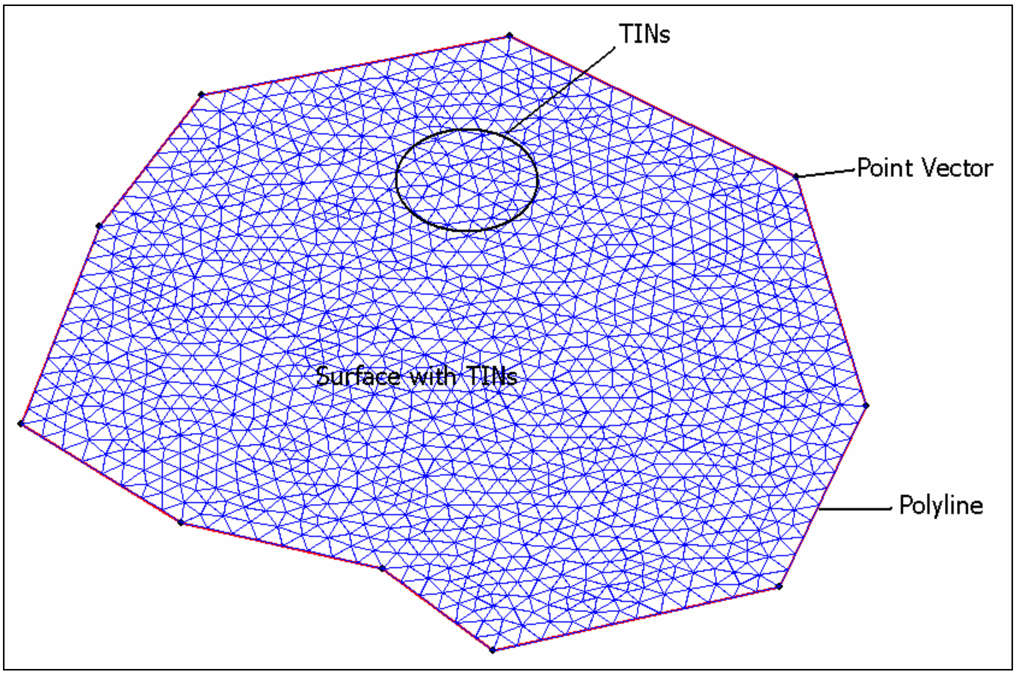


Figure 4.10: Relationship between layer surfaces with TINs

Figure 4.11 shows the layer surfaces, which are later used for creating volumes.

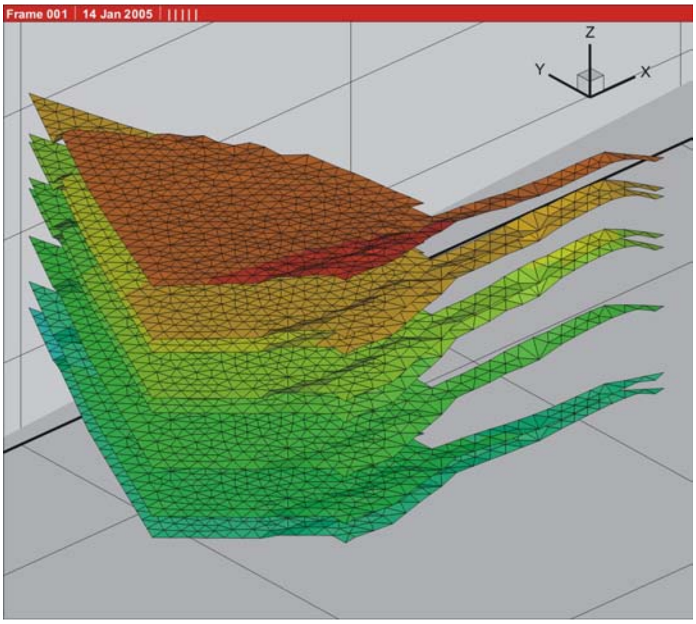


Figure 4.11: Layer surface TINs

Keywords
The sub-keyword for a TIN surface is $TIN.

Example
The description of a TIN surface in the GLI file is shown below:

```
#SURFACE
 $NAME
  SURFACE3_layer_4
 $TYPE
  -1
 $MAT_GROUP
  -1
 $TIN
  SURFACE3_layer_4.tin
```

4.2.3.3 Vertical Layer Surfaces

Another kind of layer surfaces is vertical surfaces in a 3D model domain, necessary for assigning boundary conditions etc. Figure 4.12 shows the relationship between the vertical surface and the 2D geometric model in a 3D view. One layer surface consists of two layer polylines, and one TIN (Fig. 4.13) created from the points on the layer polylines.

Keywords
The layer surface is stored in the GLI file with two important sub-keywords: $POLYLINES and $TIN.

Example

```
#SURFACE
 $ID
  151
 $NAME
  SFC_BC_SOUTH_L1
```

```
$TYPE
 1
$MAT_GROUP
 -1
$POLYLINES
 BC_SOUTH_L0
 BC_SOUTH_L1
$TIN
 SFC_BC_SOUTH_L1.tin
```

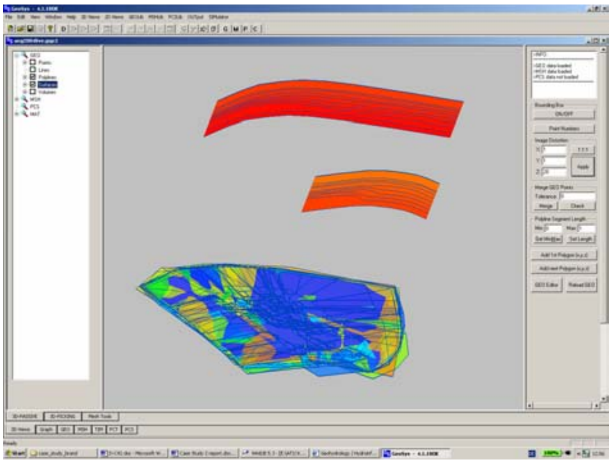


Figure 4.12: Layer surface in GeoSys 3D view (Kalbacher 2005)

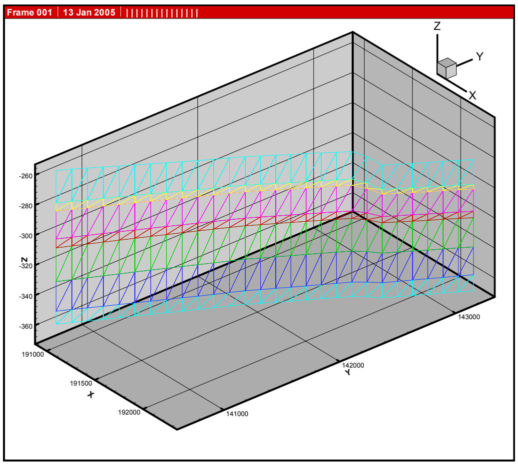


Figure 4.13: TIN from the layer surfaces in Tecplot

4.2.4 Volumes

Volumes are composed of two surfaces with a closed boundary and should be completely enclosed by the set of surfaces.

Definition of a Volume Class

The C++ definition of the volume class is shown in the Figure 4.14.

```
class CGLVolume
{
  public:
    // ID
    string name;
    int type;
    string type_name;
    // GEO
    int display_mode;
    int data_type;
    Surface* m_sfc;
    vector<Surface*>surface_vector;
    int layer;
    // MAT
    int mat_group;
    string mat_group_name;
    bool selected;
  // Methods
  private:
  public:
    CGLVolume(void);  // construction
    ~CGLVolume(void); // destruction
   // Access
    long GEOInsertVolume2List(CGLVolume*);
    void AddSurface(Surface* P_Surface);
    // I/O
    ios::pos_type Read(ifstream*);
    void Write(string);
    // GEO
    bool PointInVolume(CGLPoint*,int);
};
```

Figure 4.14: Volume class definition

4.2.4.1 Topological Volumes

There are two types of volumes: topological volumes and layer volumes. The topological volume consists of two surfaces with TINs (Fig 4.15), and it can be called surface volumes.

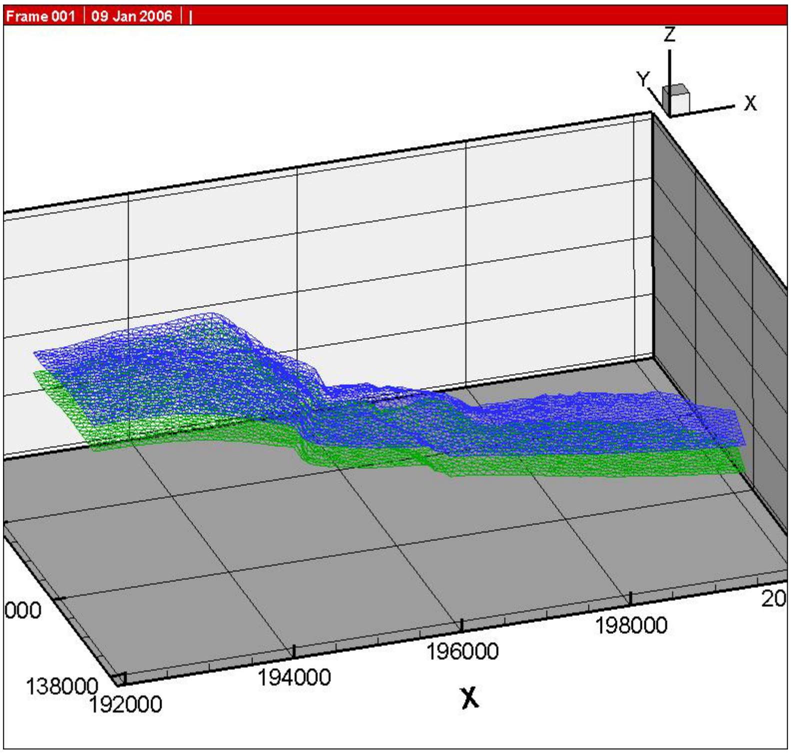


Figure 4.15: Topological volume

Keywords

Volumes are built from surfaces specified by the sub-keyword $SURFACES.

Example

The description of a topological volume is stored in the GLI file as follows:

```
#VOLUME
 $NAME
  VOLUME_SURFACE0_layer_3
 $SURFACES
  SURFACE0_layer_2
  SURFACE0_layer_3
```

4.2.4.2 Layer Volumes

The layer volume is created by connecting the mesh file (prismatic element, for example), the number of the layer and the surface file.

Keywords

Sub-keyword description is shown in the following table (Table 5):

Sub-keyword	Objective
$NAME	Name for identification
$SURFACES	Surfaces building the volume
$MAT_GROUP	Material group
$LAYER	Layer number of the surface building the volume

Table 5: Sub-keywords for a volume object

Example

The layer volume objects in a GLI file start with a keyword followed by some sub-keywords.

Keyword: #VOLUME

```
#VOLUME
 $NAME
  LAYER4_23
 $SURFACES
  LAYER4_23
 $MAT_GROUP
  SAND_FINE
 $LAYER
  4
```

Figure 4.16 shows the layer volumes in a 3D model.

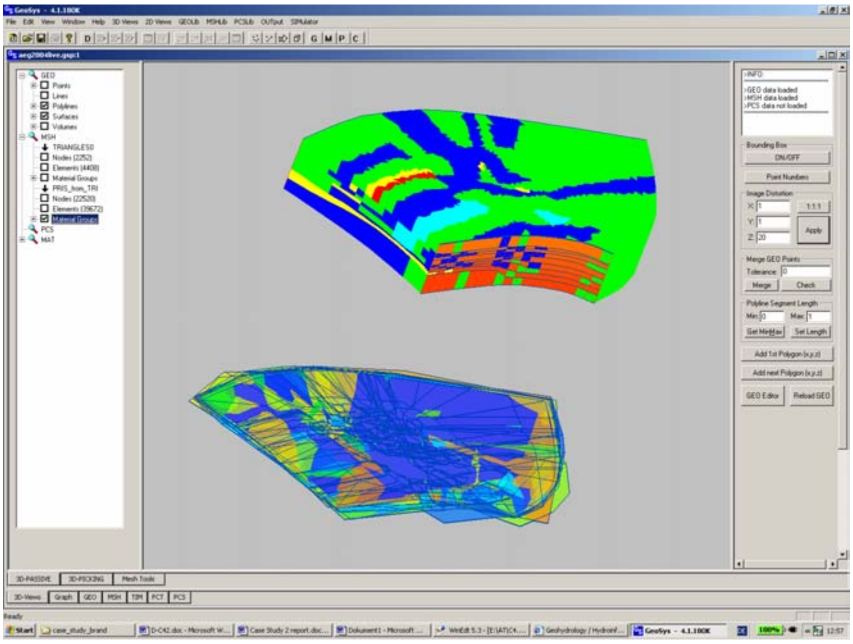


Figure 4.16: Layer volumes in 3D view (Kalbacher 2005)

4.2.5 Domains

A domain includes all of the above objects inside the modeling area. Figure 4.17 shows a domain.

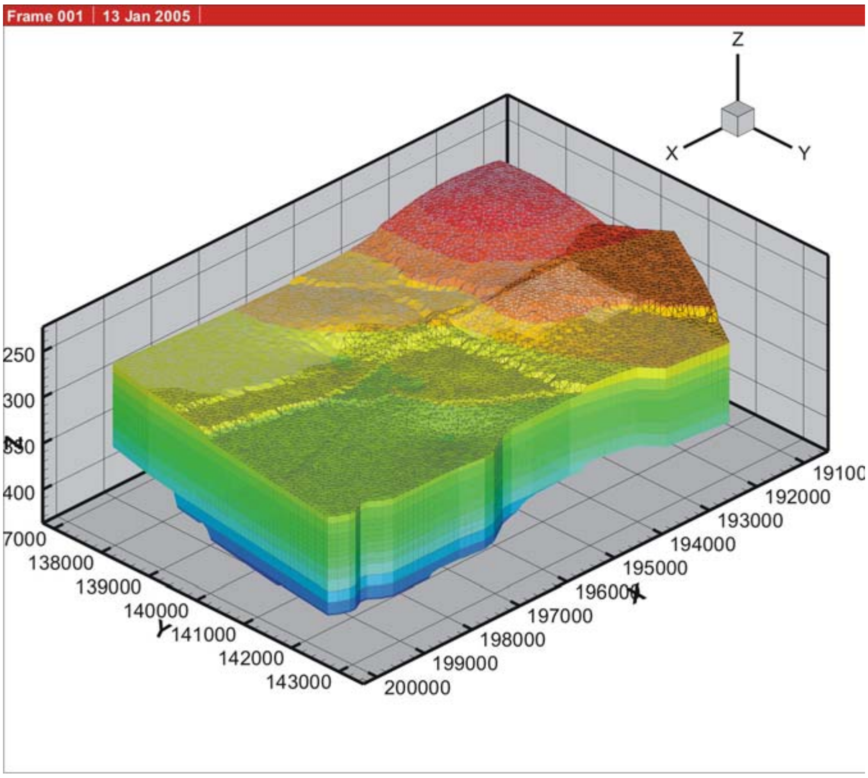


Figure 4.17: The model domain

Definition of a Domain Object

The C++ definition of the domain class is shown in the Figure 4.18.

```
class CGLDomain
{
  private:
    string name;
    long Insert(CGLDomain *);
    vector<CGLDomain*> GetVector(void);
  public:
    double x_min,x_max;
    double y_min,y_max;
    double z_min,z_max;
    //method
    CGLDomain(void); // constructor
    ~CGLDomain(void);// destructor
    int Read(char *,FILE *);
    CGLDomain* Get(string);
};
```

Figure 4.18: Domain class definition

Keywords

The volume objects in a GLI file starts with a keyword followed by some sub-keywords.
Keyword: #DOMAIN
The sub-keyword description is shown in the following table (Table 6):

Sub-keyword	Objective
$NAME	Name for identification
$COORDINATES	xmin, xmax, ymin, ymax of the domain

Table 6: Sub-keywords of a domain object

Example

The following shows one example of a domain object:

```
#DOMAIN
 $NAME domain
 $COORDINATES
-10000. 10000. –10000. 10000.
```

4.3 Object-Oriented Implementation

All of the geometric entities described above are implemented as C++ classes: CGLPoint, CGLPolyline, CGLSurface, CGLVolume, CGLDomain. Instances of these objects can alternatively be stored in vectors and lists for convenience and specific purposes. Table 7 shows the description for those objects, the class definition, geometric dimension and their corresponding keywords.

Object	**Keyword**	**Class**	**Dimension**
Points	#POINT	CGLPoint	0
Polylines	#POLYLINE	CGLPolyline	1
Surfaces	#SURFACE	CGLSurface	2
Volumes	#VOLUME	CGLVolume	3
Domains	#DOMAIN	CGLDomain	3

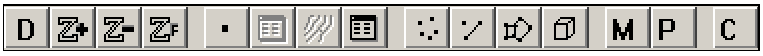
Table 7: Description of those GEOLib objects

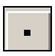
4.4 GEOLib - Graphical User Interface

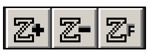
This section will describe the creation of geometric data for the model, and the filling of the GeoSys/RockFlow GEOLib library. Point is the basic element for other geometric types. Therefore, the first step is the creation of points.

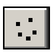
4.4.1 Toolbar

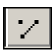
There are tools on the toolbar which are used to handle geometry data

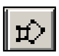


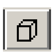
 Draw point

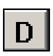
 Zoom in, Zoom out and Zoom full

 Point Dialog, handles point data, add, edit, update, and remove.

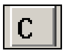
 Polyline Dialog, handles polyline data, add, edit, update, remove.

 Surface Dialog, handle surface data, add, edit, update, remove, etc.

 Volume Dialog, handles volume data, add, edit, update, remove, etc.



Refresh the drawing; redraw the window when some changes are done.



Control panel; control all the data (Geo, MSH, PCS) for displaying purpose.

4.4.2 Multiviews

The graphical user interface (GUI) of GeoSys/RockFlow is based on the concept of windows multiple-document interface (MDI), which is a specification that defines a user interface for applications that enable the user to work with more than one document at the same time. For the document components of GeoSys/RockFlow: GEO data, MSH data and PCS data, multi views are implemented for the purpose of displaying and checking. These multiviews are: GEOView, MSHView and PCSView.

Figure 4.19 shows the multiview concept in GeoSys/RockFlow.

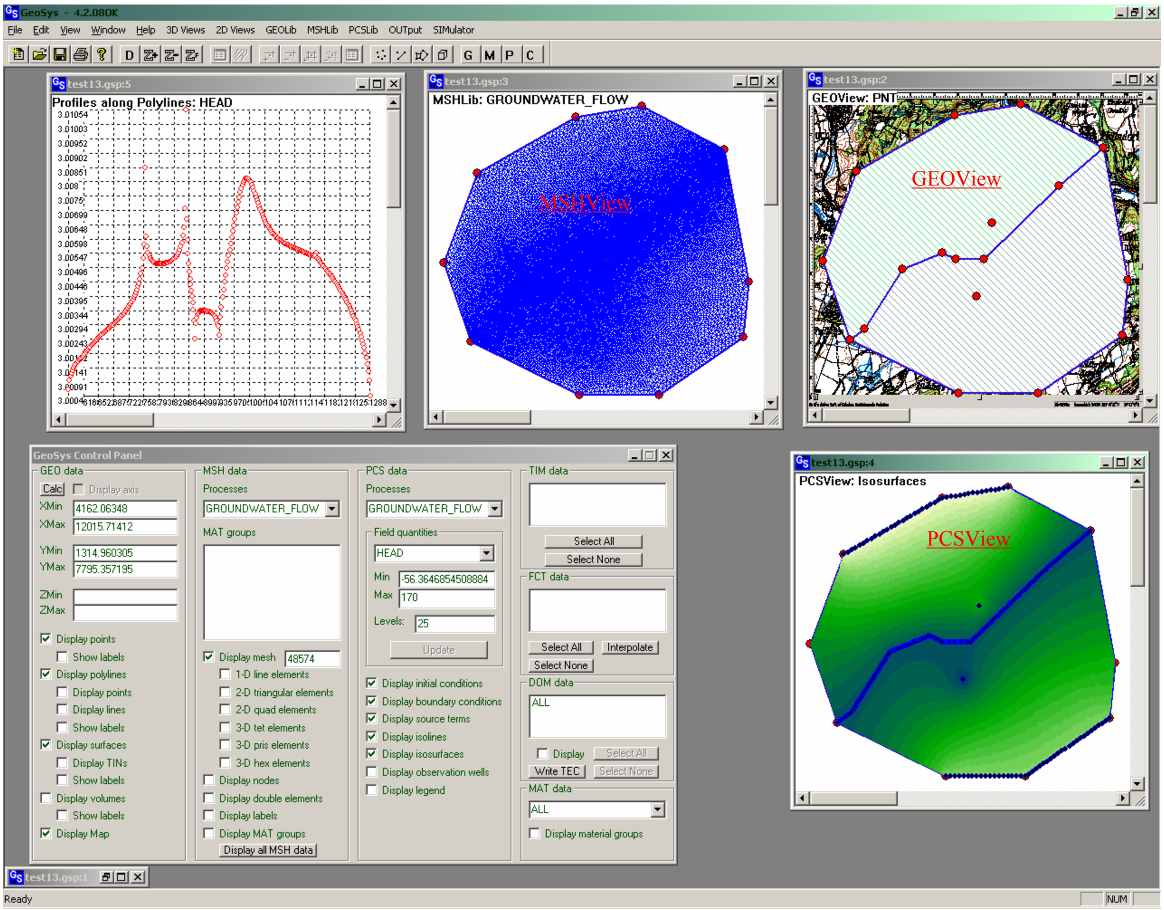


Figure 4.19: Multiviews

4.4.3 Zoom Functions

For checking data, the zoom functions are implemented within GeoSys/RockFlow: zoom in, zoom out and zoom full. Zoom functions are very useful especially when the details of the finite element meshes and the process data need to be checked for consistency. This can be used for all the views. Figure 4.20 and Figure 4.21 show the result of the finite element nodes of the boundary conditions for the model domain before and after using the zooming function.

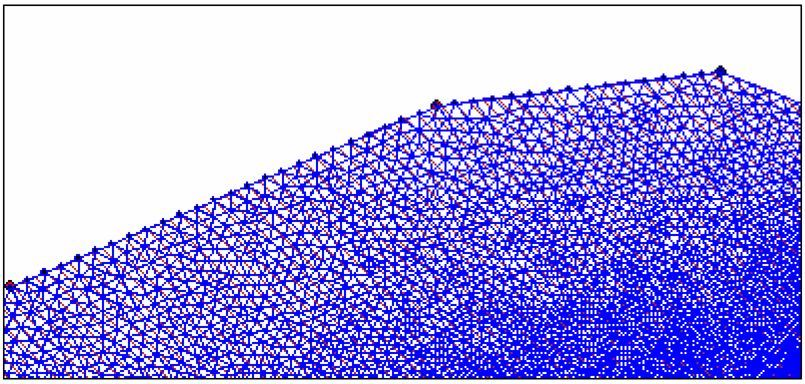


Figure 4.20: Display boundary conditions before zooming

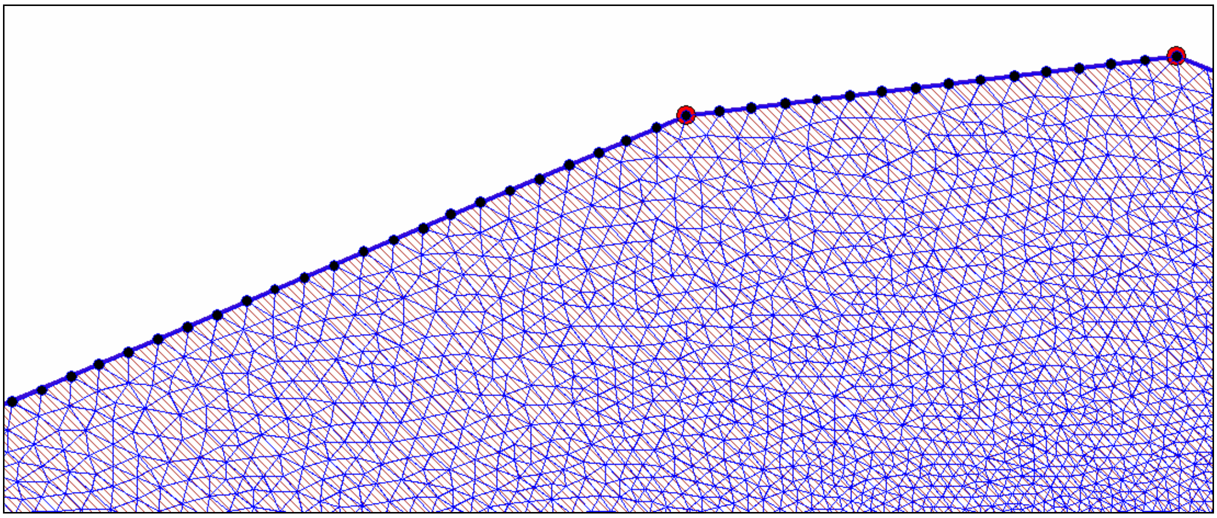


Figure 4.21: Display boundary conditions after zooming

4.4.4 Dialogs

4.4.4.1 Point Dialog

Create point

Points are created in the point dialog. The created points are automatically added to the point list in the point editor (Fig 4.22).

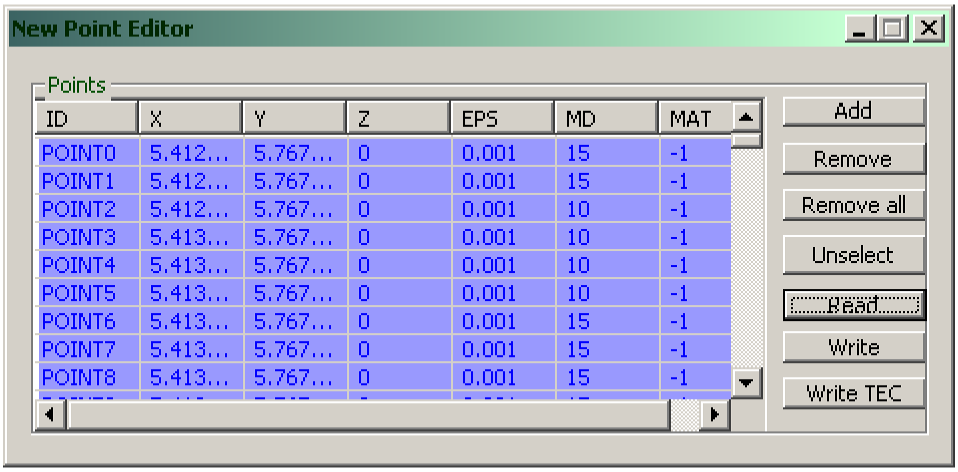


Figure 4.22: Point editor

Edit Point

The point dialog includes the following editing options:

- Change the ID name, x, y, z, epsilon, mesh density and material property.
- Remove Point: Selected points or all the points can be removed in this dialog. When removing all the points, the point vector is destructed.
- Read/Write Point data: As a result, the created points can be written in the GLI file. The existing point data can also be read into this dialog.
- Write Tecplot file: Another option of displaying point data is that the points can be converted into a Tecplot file format.

4.4.4.2 Polyline Dialog

Create Polyline

Polyline consists of an array of existing points. The existing points create a new polyline. The polyline is automatically assigned a name as Polyline0. The index from the polylines starts from zero. Figure 4.23 shows the polyline editor.

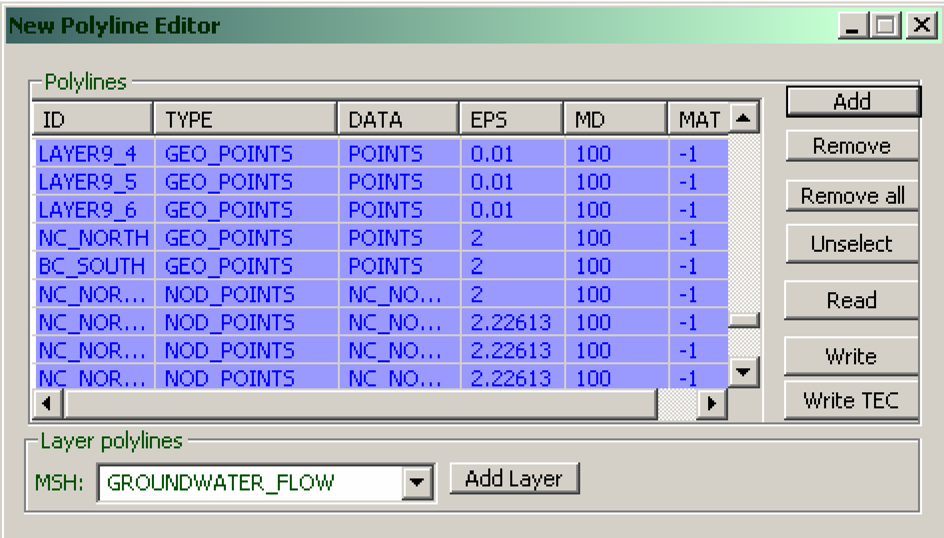


Figure 4.23: Polyline editor

Edit Polyline

The polyline dialog includes the following editing options:

- Change the ID name, type, data name, epsilon, mesh density and material property.
- Remove polyline: Selected polylines or all the polylines can be removed in this dialog. When removing all the polylines, the polyline vector is destructed.
- Read/Write polyline data: As a result, the created polylines can be written in the GLI file. The existing polyline data can also be read into this dialog.
- Write Tecplot file: Another option of displaying polyline data is that the polylines can be converted into a Tecplot file format.
- Create layer polylines: Layer polylines are created based on the selected mesh file.

4.4.4.3 Surface Dialog

Create Surface

Existing polylines are used to create surfaces. It assigns automatically the surface name starting with index as 0: surface0. Figure 4.24 shows the surface editor.

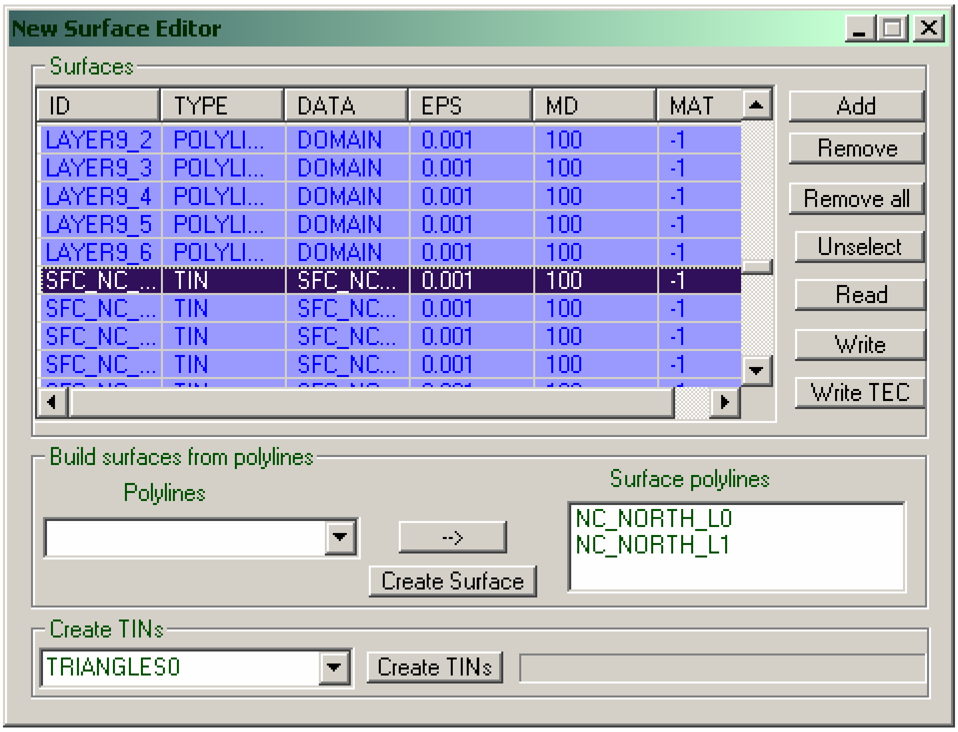


Figure 4.24: Surface editor

Edit Surface

The surface dialog includes the following editing options:

- Change the ID name, type, data, epsilon, mesh density and material property.
- Remove surface: Selected surfaces or all the surfaces can be removed in this dialog. When removing all the surfaces, the surface vector is destructed.
- Read/Write surface data: As a result, the created surfaces can be written in the GLI file. The existing surface data can also be read into this dialog.
- Write Tecplot file: Another option of displaying surface data is that the surfaces can be converted into a Tecplot file format.
- Create surface TINs: Surface TINs are created based on the selected mesh file.

4.4.4.4 Volume Dialog

Create Volume

In the volume editor shown in Figure 4.25, two types of volumes can be created: layer volume and surface volume.

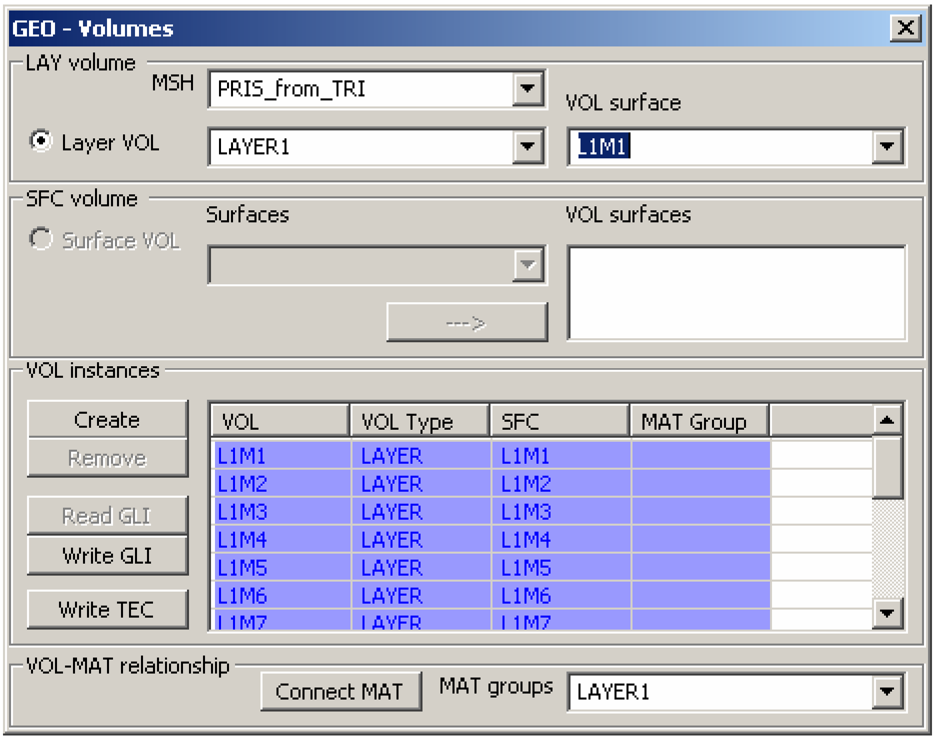


Figure 4.25: Volume editor

Edit Volume

The volume dialog includes the following editing options:

- Change the type, surface and material property.
- Remove volume: Selected volumes can be removed in this dialog.
- Read/Write volume data: As a result, the created volumes can be written in the GLI file. The existing volume data can also be read into this dialog.
- Write Tecplot file: Another option of displaying volume data is that the volumes can be converted into a Tecplot file format.
- Connect material group: A material group can be assigned to a volume by the connecting function.

4.5 Independency of GEOLib

The main concept of GeoSys/RockFlow is the separation of GEOLib, MSHLib and PCSLib. GEOLib is an independent part of the whole system. However, other parts, like the GUI and FEM projects, are both dependent on GEOLib. Figure 4.26 shows the independent GEOLib components in a GeoSys/RockFlow project and Figure 4.27 shows the dependency of the GeoSys/RockFlow GUI project on GEOLib. Figure 4.28 shows the dependency of the FEM project on GEOLib.

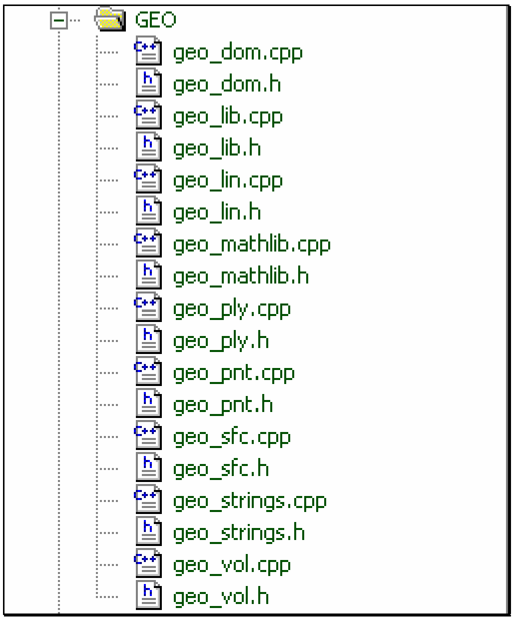


Figure 4.26: GEOLib project

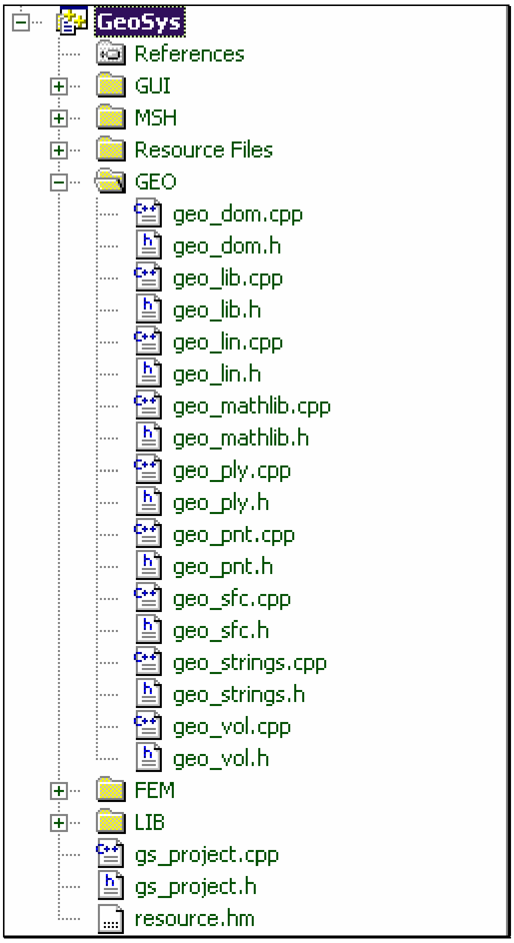


Figure 4.27: Dependency of GeoSys/RockFlow GUI project on GEOLib

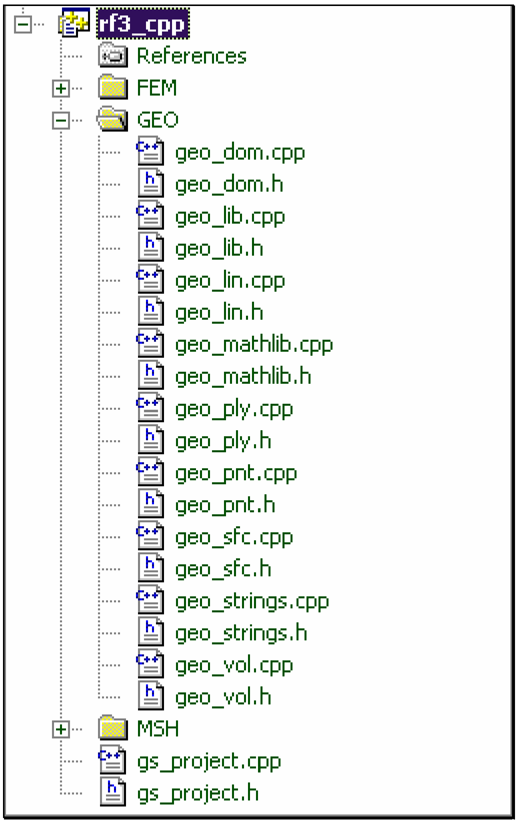


Figure 4.28: Dependency of GeoSys/RockFlow FEM project on GEOLib

4.5.1 A GeoSys/RockFlow Project with GEOLib

The following example is to demonstrate the independency of GEOLib. The GSP project file includes only GLI data and has the structure:

GEOLibtest.gsp
#PROJECT_MEMBER
GEOLibtest.gli
#STOP

The GEOLibtest.gli includes the data of points, polylines, surfaces, and volumes.

After read the gsp data into GeoSys/RockFlow, the result displayed in the 2D GEOView, and from the control panel, it shows that the point, polyline, surface and volume data are available. See figure 4.29.

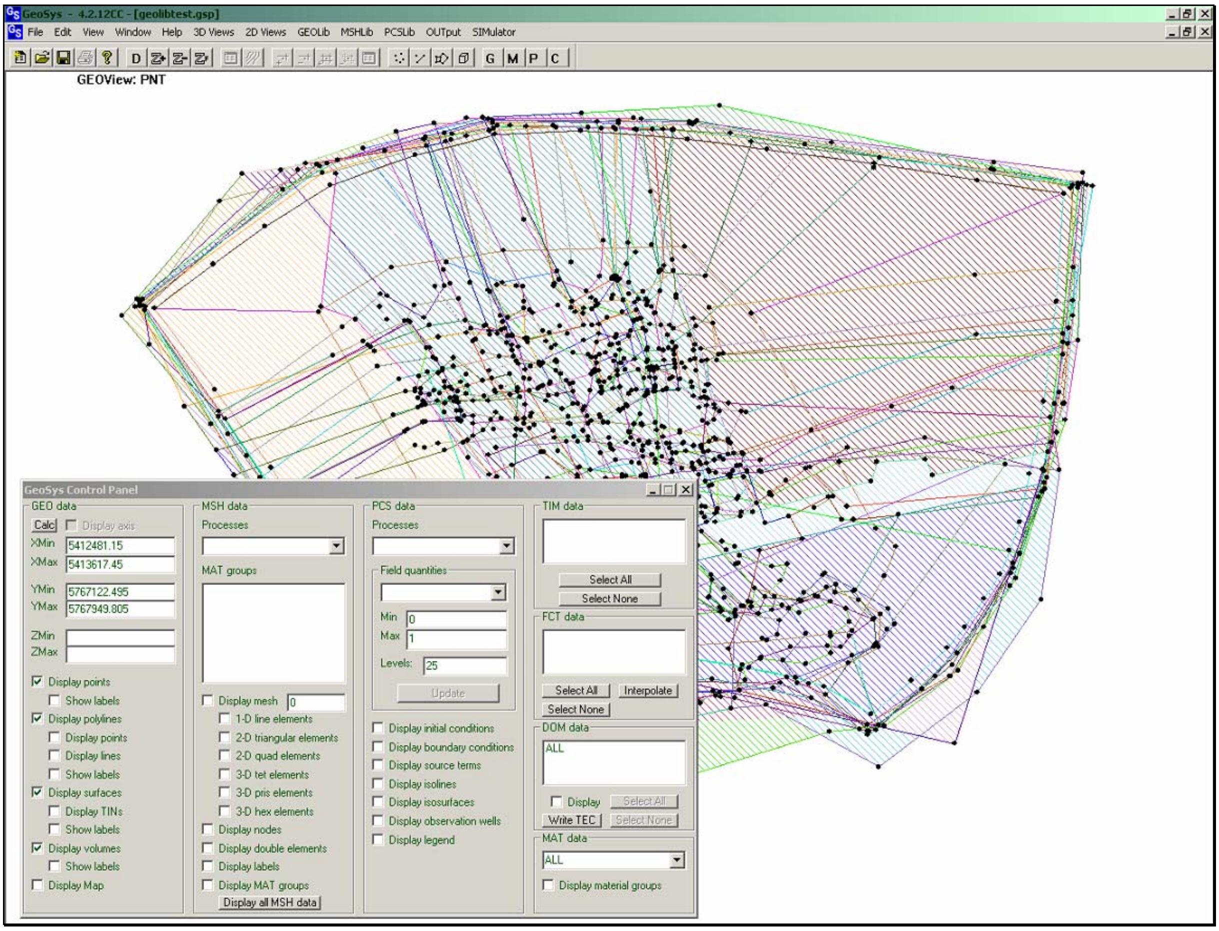


Figure 4.29: Display of GEO data

5 APPLICATIONS OF GIS-BASED GEOSYSTEMS ANALYSIS

This section summarizes the main features of five applications, which are described in the following chapters from six to ten. The cased studies introduced in these chapters are based on the concept and method explained in the above sections. The first application in chapter six presents the features in GeoSys/RockFlow by creating a 2D Tübingen groundwater model in details using its Graphical User Interface. It gives the user a general overview on the aspects of the numerical modeling program. Furthermore, it also offers the opportunities for the user to understand the basic principles and techniques of groundwater modeling. Chapter seven to nine cover the technical concept to integrate GIS within GeoSys/RockFlow to create 2.5D and 3D hydrological models for the analysis of GeoSystems. Chapter seven presents the details to develop a numerical groundwater flow in the study location in the Zarqa Ma'in – Jiza areas in Central Jordan to model a mixing process between water from upper and lower aquifers. Based on this groundwater model, a heat transport between the two aquifers in the study area is considered to show the thermal water from the lower aquifer to flow up via faults (conduits) to the upper aquifer. The result gives a better understanding of groundwater resources in this arid area for the water resource management. Chapter eight introduces a 2.5D groundwater flow model in the Jericho plain area of Palestine built in GeoSys/RockFlow using the GIS based concept. The flow model is then used to visualize the effect of the well pumping on the water level in summer and winter seasons right after the pumping event to maintain a sustainable exploitation of the groundwater resources in the study area. Moreover, a modeling routine was carried out in order to suggest alternatives for a better understanding of the mixing mode of the possible recharge mechanisms for the aquifer. Chapter nine introduces a 3D groundwater model in the Brand area. Chapter ten aims to create a river network using the DEM data with the multiple resolution method for the triangulation.

The description of the features of these applications is listed in the table 8.

Chapter	**Case**	**Features**
6	2D Tübingen groundwater model	Case study for students, education example
7	Flow and Heat Transport Model in the Zarqa Ma'in – Jiza Areas in Central Jordan	3 layers, GIS and database TINs, 27*3 volumes, Mapping, 2.5D
8	Groundwater Model for the Jericho Plain Area of Palestine / Lower Jordan Rift Valley	7 layers, GIS and database Interpolated raster maps Time dependent ST Wells, 2.5 D
9	3D Groundwater Model in Brand Area	Layer volume Layer material properties 3D model
10	Multiple Resolution Method for River Network Extraction in the Gallego Catchment	DEM Multiple mesh density

Table 8: The description of case studies

6 2D GROUNDWATER MODEL IN TÜBINGEN

This chapter explains GeoSys/RockFlow GUI from its basics up to the software file handling concept, including basic concepts such as installation and software concept such as the architecture and user guide of the GUI and the file concept for a modeling task. This was used as a tutorial for the education purpose for the students. The tutorial is oriented in a practical way, with an example, which aims to create a 2D groundwater model in Tübingen area.

6.1 Installation

6.1.1 GeoSys/RockFlow-Win

The following files are necessary to run GeoSys/RockFlow –GUI, and these files should be whether altogether in one directory or in the system directory. The files are listed in Table 9:

GeoSys.exe	Windows application
mfc71d.dll, msvcp71d.dll, msvcr71d.dll	MFC libraries
shapelib.dll	Data import from ArcGIS
gmsh.exe, cygwin1.dll	Meshing tools

Table 9: Library files for GeoSys/Rockflow

6.1.2 Meshing Tools

For triangulation, gmsh (http://www.geuz.org/gmsh/) can be used. The following files should be in the same directory as GeoSys.exe is.

- gmsh.exe
- cygwin1.dll

6.2 GeoSys/RockFlow project

During the model set-up a project file is generated, which contains a list of data files. The final project (GSP) file looks like that:

```
#PROJECT_MEMBER
gw.bmp  // map
gw.gli  // geometric (GEO) data
gw.msh  // mesh (MSH) data
gw.pcs  // process (PCS) data
gw.num  // numerical (NUM) parameter
gw.tim  // time discretization (TIM) data
gw.ic   // initial conditions (IC) data
gw.bc   // boundary conditions (BC) data
gw.st   // source terms (ST) data
gw.mfp  // fluid properties (MFP) data
gw.mmp  // porous medium properties (MMP) data
gw.out  // output control (OUT) data
gw.fct  // functions (FCT) data
#STOP
```

Figure 6.1: Description of a GeoSys/RockFlow project file

6.3 New Project

At the beginning of a new session, a new project has to be created using the File new option from the toolbar. After a new project has been created (clicking OK button), a project folder has to be generated. All project data are stored in a separate folder. The project folder will be created automatically in the directory chosen as project folder path. The name of the directory is the name of the project. The steps are as follows:

- Select base directory (Fig 6.2) using the file browser

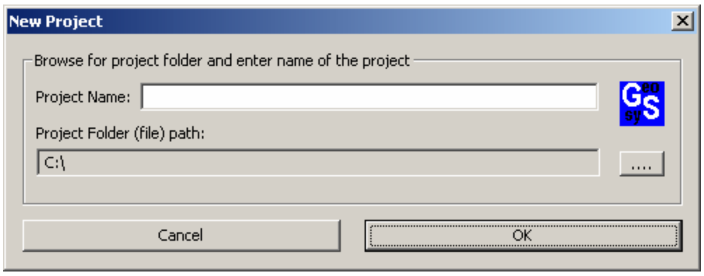


Figure 6.2: New project dialog

- Select base directory (Fig 6.3).

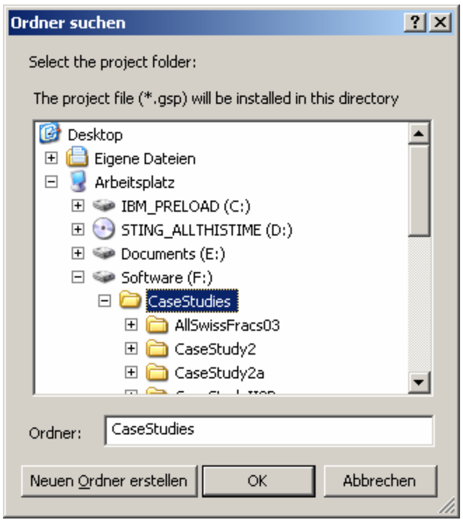


Figure 6.3: Base file directory

- Select project name and confirm with OK (Fig 6.4).

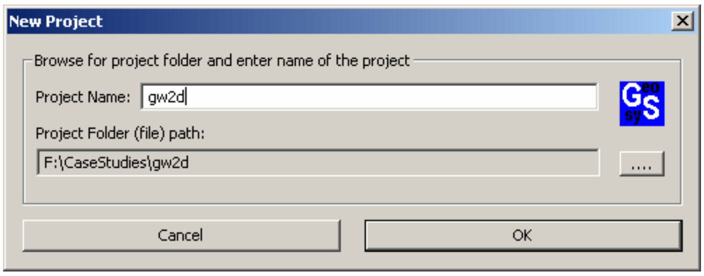


Figure 6.4: Select project name

- Store project file: gw2d.gsp.

After the above steps, the GUI should appear (Fig 6.5).

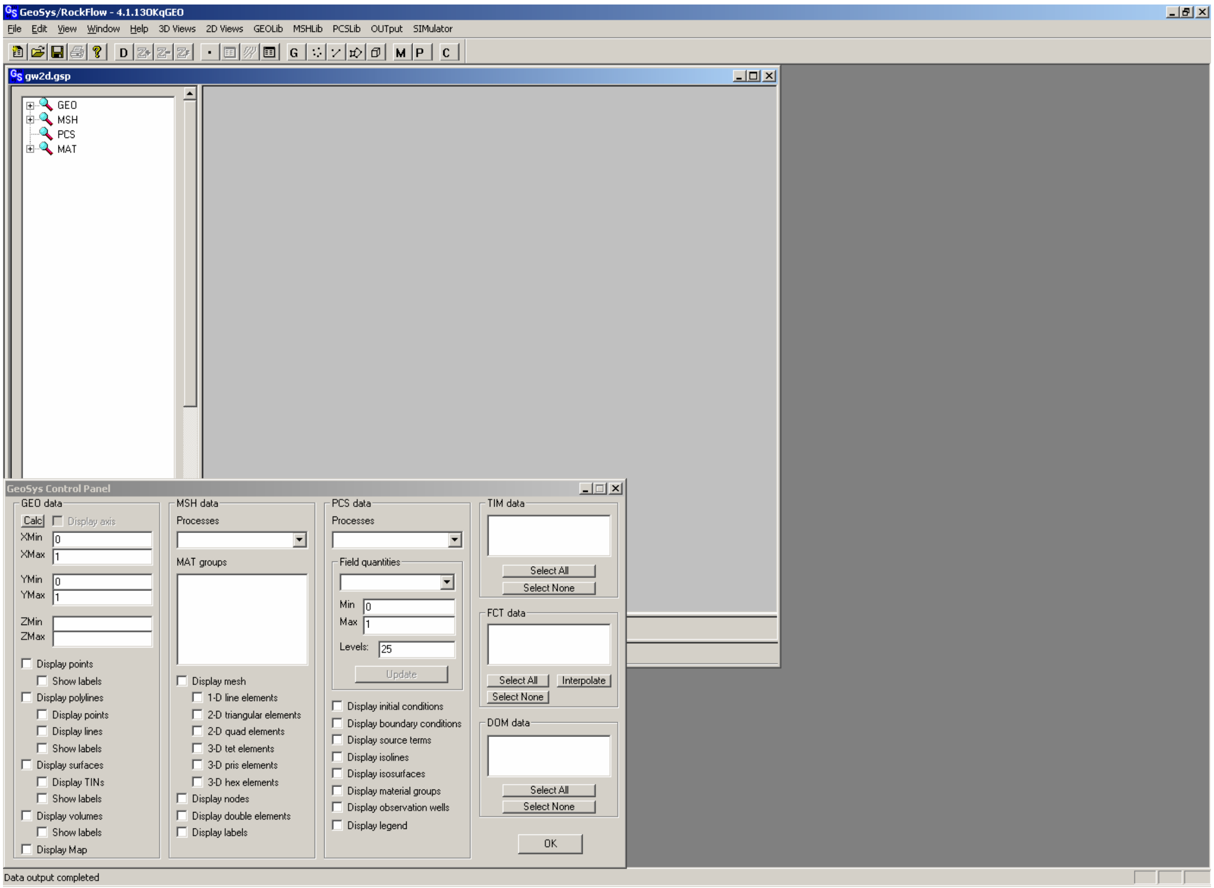


Figure 6.5: GUI after creating a new project

6.4 Import Map (BMP)

Using the File-Import option (Fig 6.6), BMP files for maps can be imported. The BMP file is copied to the project folder and renamed according to the project name.

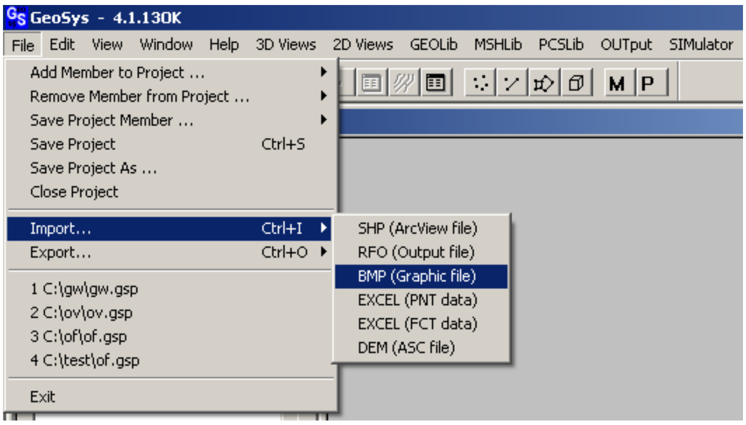


Figure 6.6: Import BMP option

- Select BMP file (Fig 6.7).

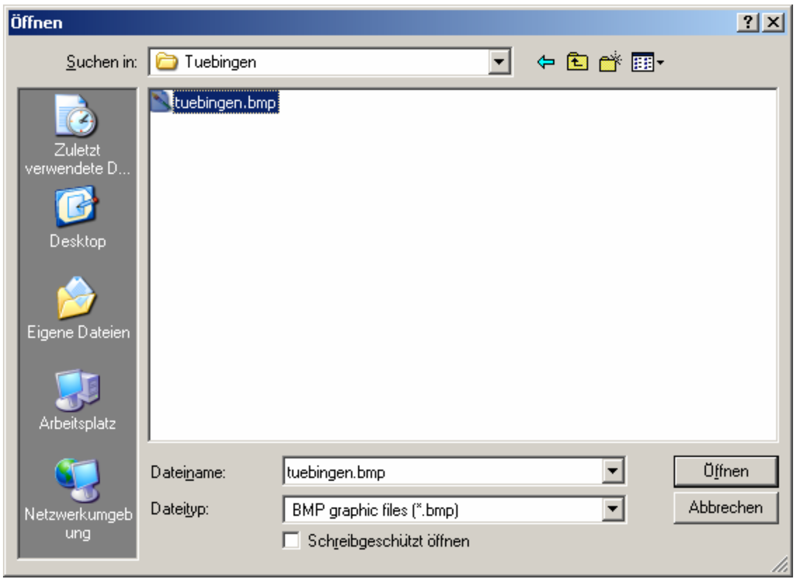


Figure 6.7: Select BMP file

BMPs are displayed in the GEOView (Fig 6.8). Using the Display Map option in the Control Panel BMPs can be switched on or off.

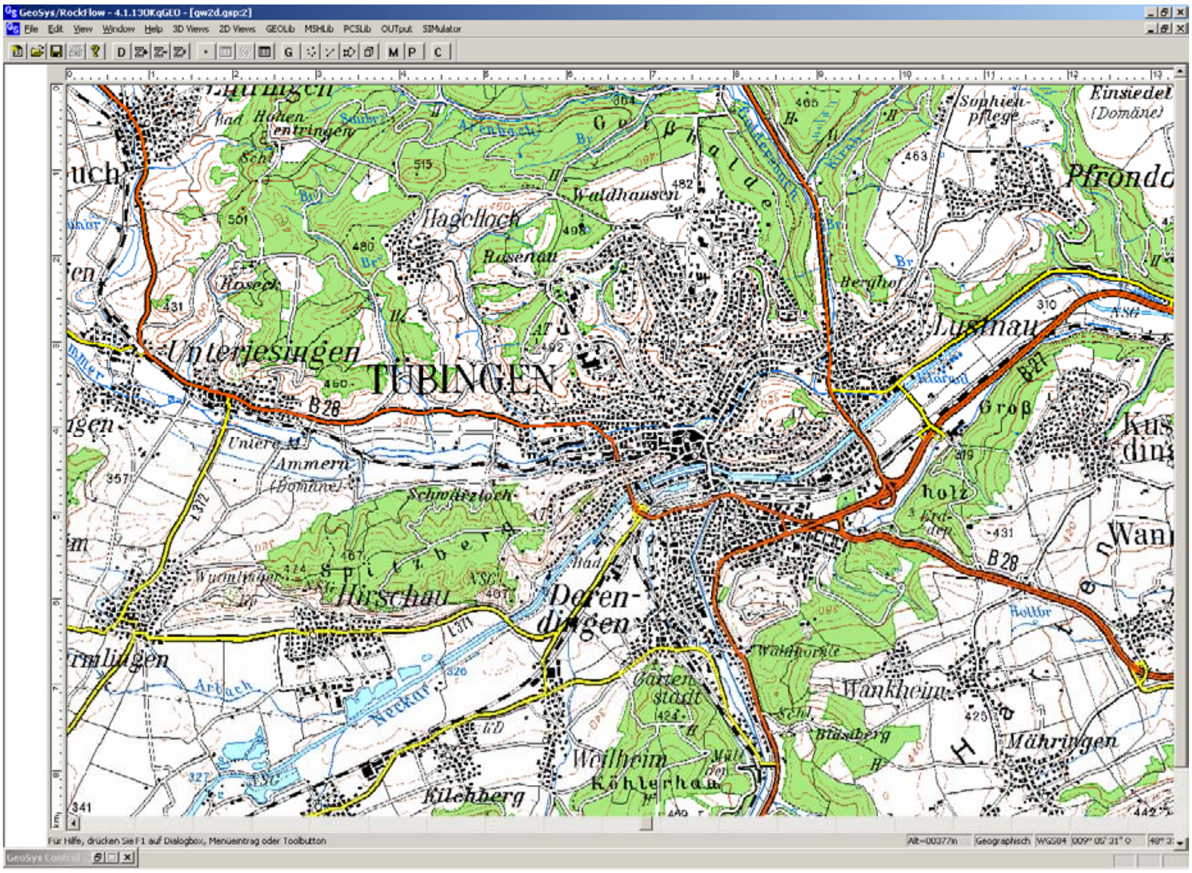


Figure 6.8: Display BMP map in GEOView

6.5 GEOLib Data - Geometry

In this part, 2D geometric objects (points, polylines, surfaces) for the modeling purposes using the creation tools are created.

6.5.1 Set Scale

The first step of dealing with GEO data is defining a scale in the Control Panel (Fig 6.9). Set Xmin and Xmax values (in meter), Y values are calculated correspondingly (based on the GEOView window size).

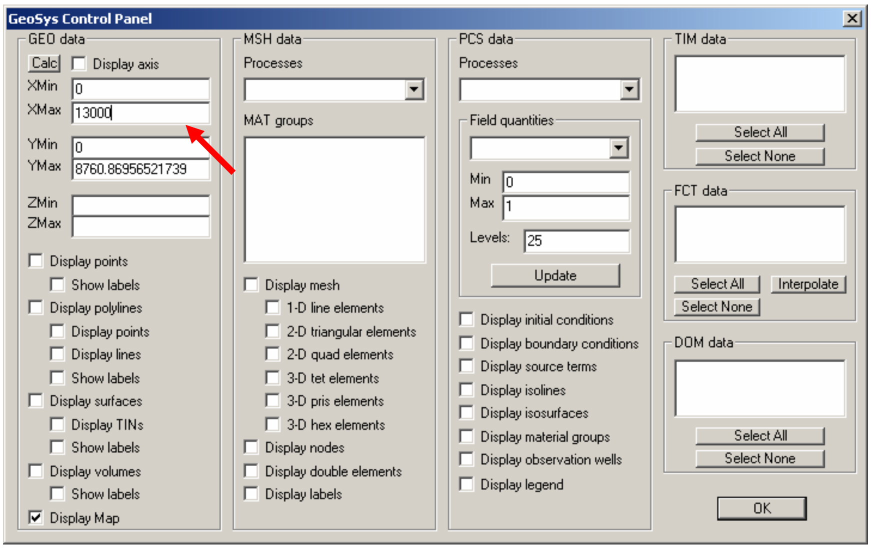


Figure 6.9: Set geometry scale of modeling area

6.5.2 Points

Points are the basic elements of all geometry types. They are used in all libraries:

- GEOLib: forming polylines,
- MSHLib: meshing density for triangulations,
- PCSLib: boundary conditions, source/sink terms (such as wells).

Create Points

Points can be created in the GEOView by left mouse clicks using the Set Point option in the tool bar. Every time when a new point is created, it will be automatically added to the GEOLib point vector. See Figure 6.10.

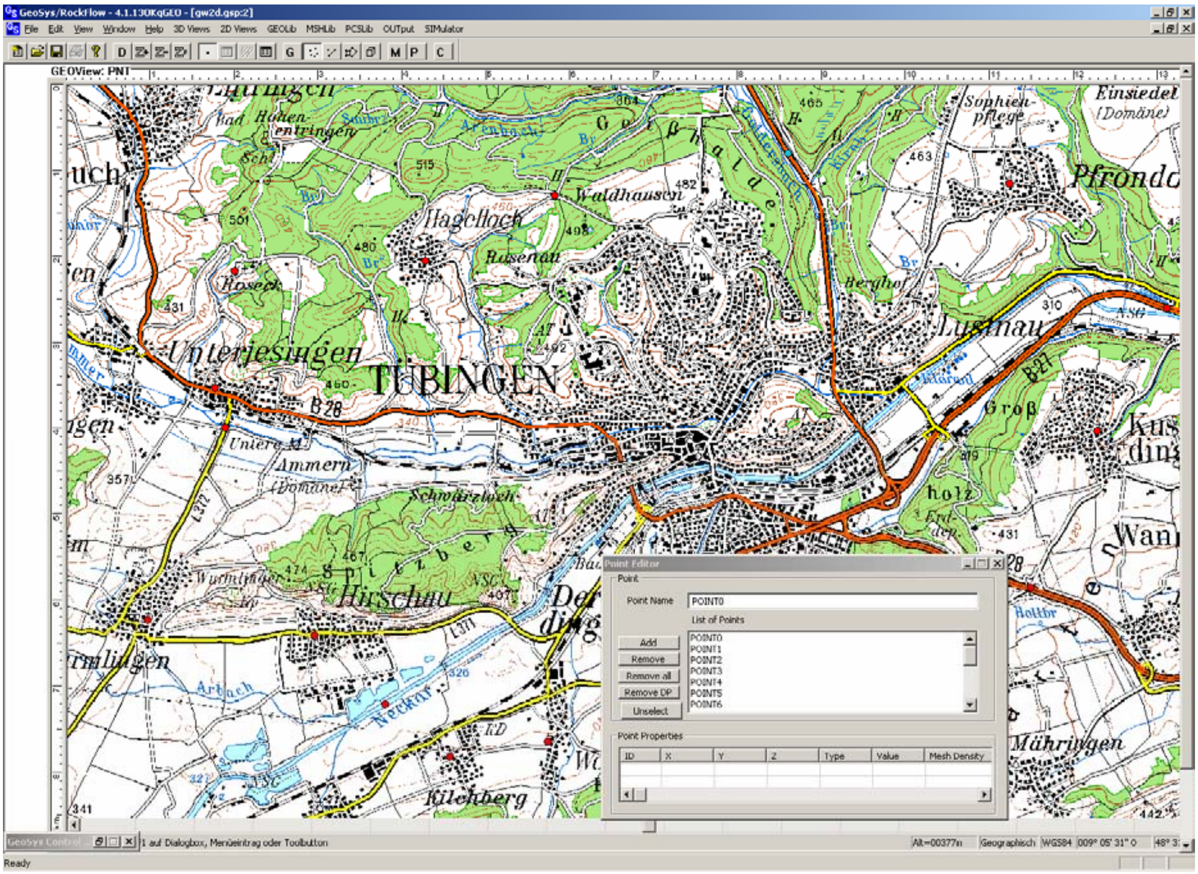


Figure 6.10: Create points in GEOView

Edit Points

It includes:

- Remove one selected point,
- Remove all points,
- Remove double points,
- Click on the point list to highlight the point (light blue),

Unselect point.

- Editing the properties of one point, like the name, x, y, z, type, mesh density could be done by the following steps:
- Click on the cell to be edited,
- Input the new value,
- Click on other cell to finish the update.

6.5.3 Polylines

Polylines consist of an array of existing points. They can be used for e.g.:

- GEOLib: definition of plane surfaces,
- MSHLib: surface boundaries for 2-D meshing, creation of line elements along polylines (e.g. rivers),
- PCSLib: assign boundary condition and source/sink terms along polylines; assign material properties along polylines.

Create Polylines

Polylines are created using the existing points. Polyline consists of an array of existing points. Open polyline dialog (Fig 6.11), click on button "Add" to add new polyline, the polyline is automatically assigned a name as Polyline0. The index from polyline starts from zero. Then snap the points and left click to create point. The snapped point is displayed with a pink color. Finish creating a polyline by a right button click.

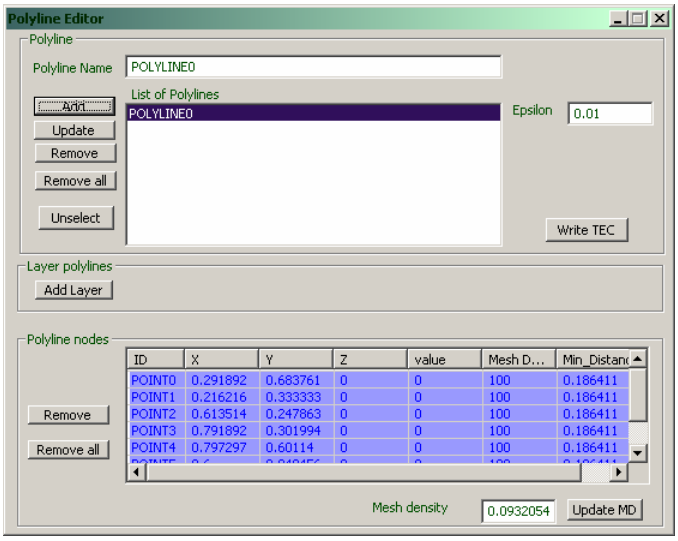


Figure 6.11: Create new polyline

Here three polylines are created for the northern and southern domain separated by the Neckar river, as well as a polyline for the river itself. See Figure 6.12.

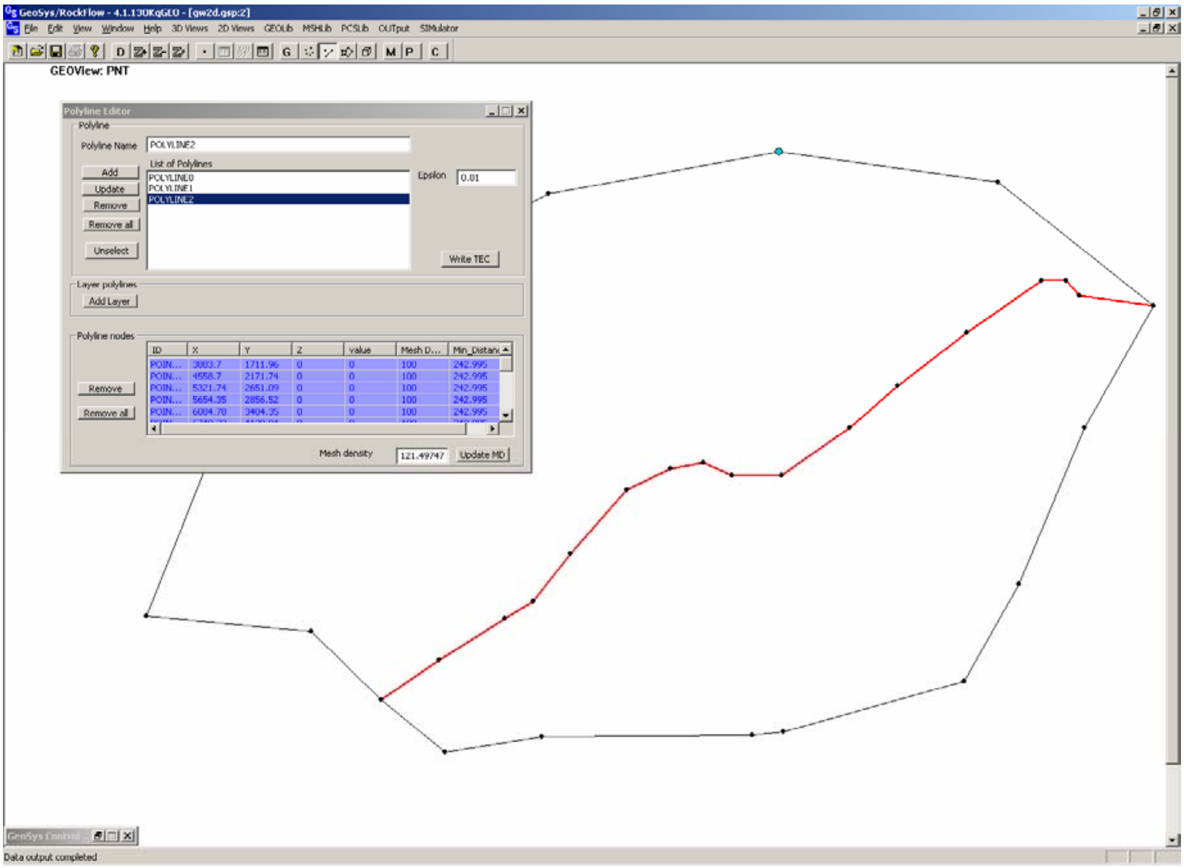


Figure 6.12: Draw polylines

Edit Polylines

Editing polyline includes:

- Remove selected polyline.
- Remove all polylines.
- Update the polyline name. Input the new name of the selected polyline, and click on Update button.
- Select polyline to highlight it (red color).
- Unselect polyline.

Editing the properties of one polyline includes: change the value of coordinates x, y, z, mesh density and includes also:

- Remove points from the polyline: put the mouse cursor on the list of points, and it will be highlighted, then click on Remove button. Alternatively, click on the first column, and then remove the selected item.
- Remove all the points.
- Change the every point mesh density by using the same method as in the point dialog, or using the button "Update all" to change the mesh density of the complete polyline. Here the mesh density field is the default value.

In the last column the minimum distance of two polyline points is given. As default mesh density the half minimum point distance is proposed.

6.5.4 Surfaces

Plane surfaces can be created from closed polylines, i.e. the last point of polyline is identical to the first one. Surfaces can be created by two ways:

- Using one closed polyline (polygon).
- Using several polylines, this has to form a polygon.

Surface can be used as 2-D domain boundaries. Surface can be used as:

- GEOLib: geometric basis of volumes,
- MSHLib: 2-D meshing purposes,
- PCSLib: assign boundary condition and source/sink terms at surfaces; assign material properties in surfaces.

Create Surfaces

Plane surfaces can be created from closed polylines (i.e. polygons). Open surface dialog, click on button "Add", and it assigns automatically the surface name starting with index as 0: surface0. Choose from the middle polyline list the polyline, and then click on button "Create surface", Then the created surface is displayed in the window. Plane surface can be created from polylines, and the steps are:

- Add a new surface,
- Select polyline from polyline list,
- Create surface.

Figure 6.13 shows the result of the created surfaces:

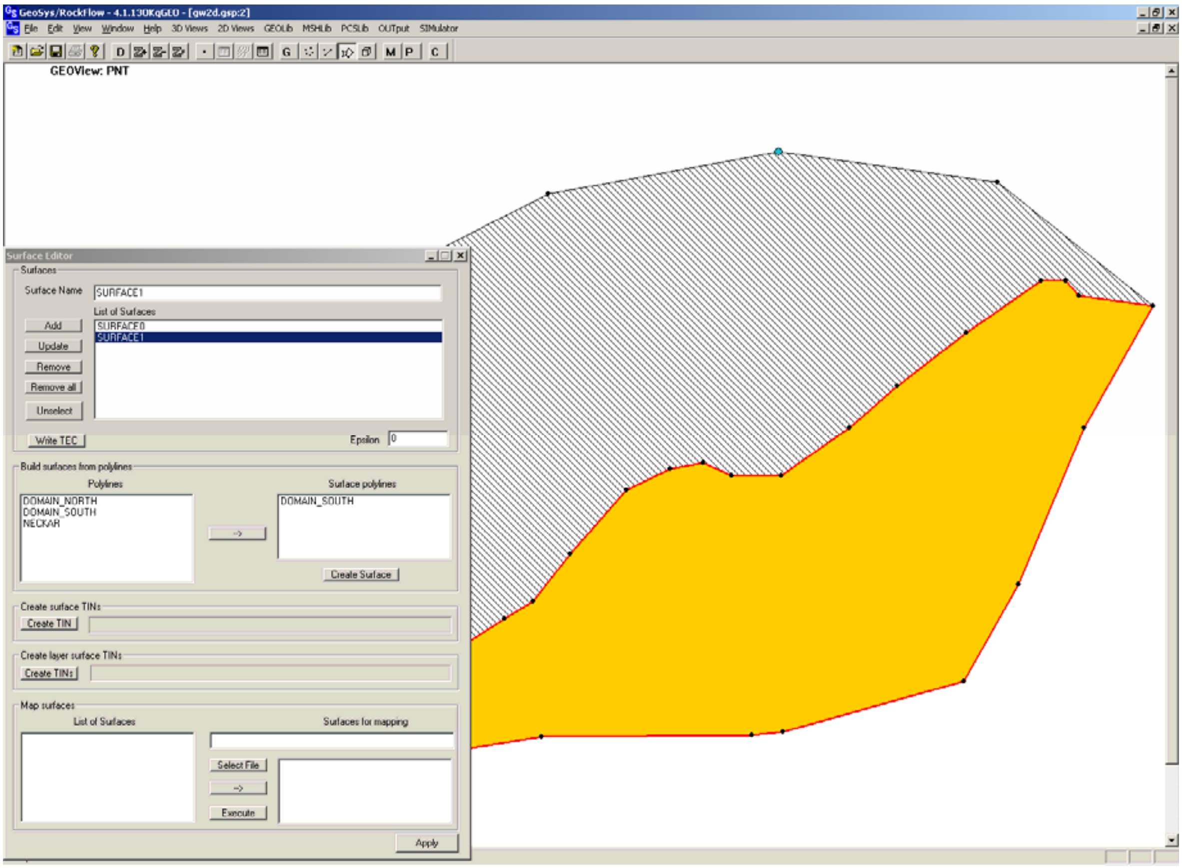


Figure 6.13: Create surfaces

Edit Surfaces

Editing surface includes:

- Edit the name of the surface using button "Update",
- Remove selected surface,
- Remove all surfaces,
- Select surface to highlight it (yellow color),
- Unselect surface.

6.5.5 Save Project

After the surface have been created, it is very important to save the result. Click on the save button, and the GLI (Fig 6.14) file is created with the information about points, polylines and surfaces.

```
gw2d.gli
#POINTS
 0     10823.016     6427.7778    0.00000000 $MD 25 $ID POINT0
 1     9894.4444     5829.3651    0.00000000 $MD 25 $ID POINT1
 2     9388.8889     5292.8571    0.00000000 $MD 25 $ID POINT2
 3     8862.6984     4807.9365    0.00000000 $MD 25 $ID POINT3
 4     8295.2381     4333.3333    0.00000000 $MD 25 $ID POINT4
 5     7738.0952     4323.0159    0.00000000 $MD 25 $ID POINT5
 6     7325.3968     4467.4603    0.00000000 $MD 25 $ID POINT6
......
#POLYLINE
 $ID
  0
 $NAME
  neckar
 $TYPE
  2
 $EPSILON
  2
 $MAT_GROUP
  -1
 $POINTS
 9
 8
 7
 3
 2
 1
 0
......
#SURFACE
 $ID
  1
 $NAME
  SURFACE1
 $TYPE
  -1
 $MAT_GROUP
  1
 $POLYLINES
  neckar
  POLYLINE_NORTH
#STOP
```

Figure 6.14: GLI file description

6.6 MSHLib Data – Spatial Discretization

The finite element library MSHLib consists of several 1D, 2D and 3D types:

- Lines – 1D,
- Triangles, quadrilaterals – 2D,
- Tetrahedral, triangle based prisms, hexahedra – 3D.

In order to approximate complex geometric structures, a very important feature of GeoSys/RockFlow is that multiple meshes can be used for modeling purposes.

6.6.1 MSH Density

A meshing distance defines mesh density for triangulations. This is the triangle edge length. For triangulation, the meshing distance has to be set in reasonable bounds. Finally, the meshing distance is a point property. The meshing distance can be defined for surfaces, polylines and points, as follows: polyline meshing distance overwrites surface data and point meshing distance overwrites polyine data. This way of local mesh refinements can be arranged.

6.6.2 Triangulation

The following files are required for meshing purposes, otherwise a warning comes:

- gmsh.exe (meshing tool),
- cygwin1.dll (meshing tool).

In this step, select the option Triangulation (Fig 6.15) from the menu MSHLib, and based on the selected mesh densities, a triangle mesh (Fig 6.16) is generated.

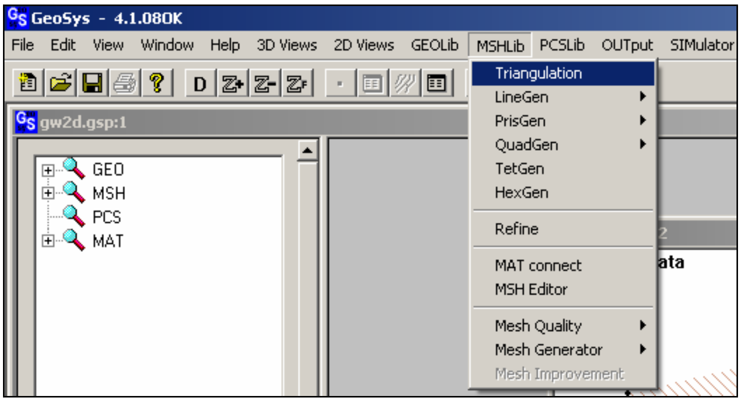


Figure 6.15: Triangulation in menu (Kalbacher 2003)

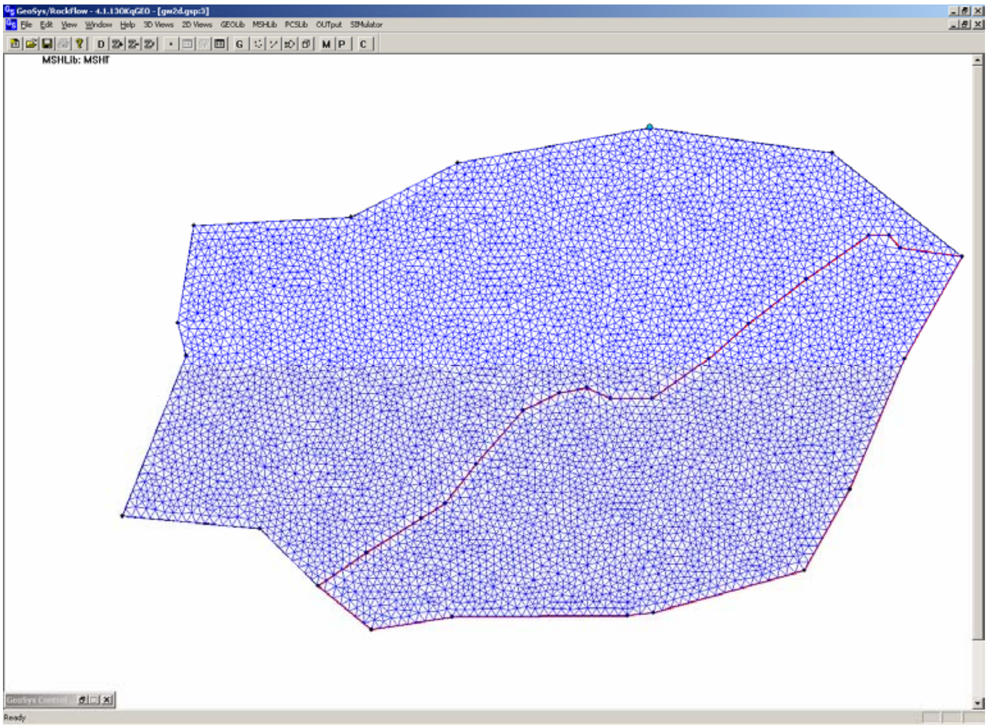


Figure 6.16: Triangle mesh

6.6.3 MSH Editor

The MSH editor (Fig 6.17) shows existing meshes and their data. In order to connect meshes with processes, the names of process and mesh have to be identical (i.e. GROUNDWATER_FLOW). The meshing tools create generic names (e.g. TRIANGLE0). These names can be edited as follows:

- Select the mesh from the MSH data list,
- The MSH name will be copied to the edit box at the bottom of MSH data,
- Rename the mesh to GROUNDWATER_FLOW,
- Confirm with the OK button,
- As a result, the changed name should appear in the MSH data list above as well as in the Control Panel.

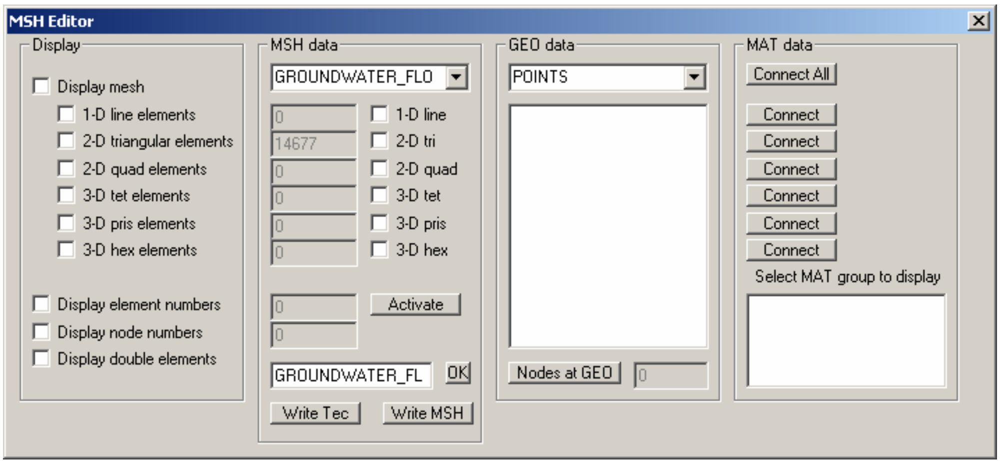


Figure 6.17: MSH Editor dialog

6.6.4 Re-Meshing

Usually re-meshing steps are necessary to produce appropriate meshes. In this study, it is essential to include the Neckar river explicitly in the geometric model. Use the Polyline Editor in order to change the mesh density along the neckar river. Figure 6.18 shows the result of the re-meshing. Along the neckar river, the mesh is refined.

6.6.5 Delete MSH data

Now a new triangulation is created, i.e. two meshes: TRIANGLES0 and TRIANGLES1.
Meshes can be deleted using the MSH editor. The steps are:

- Select mesh from MSH data list,
- Use the Delete function.

6.6.6 Rename MSH

Meshes and processes are linked by their names. Therefore, the MSH name must correspond to the PCS name accurately. MSH names can be changed with the MSH Editor (Fig 6.19).

- Select MSH name from ComboBox,
- Rename.

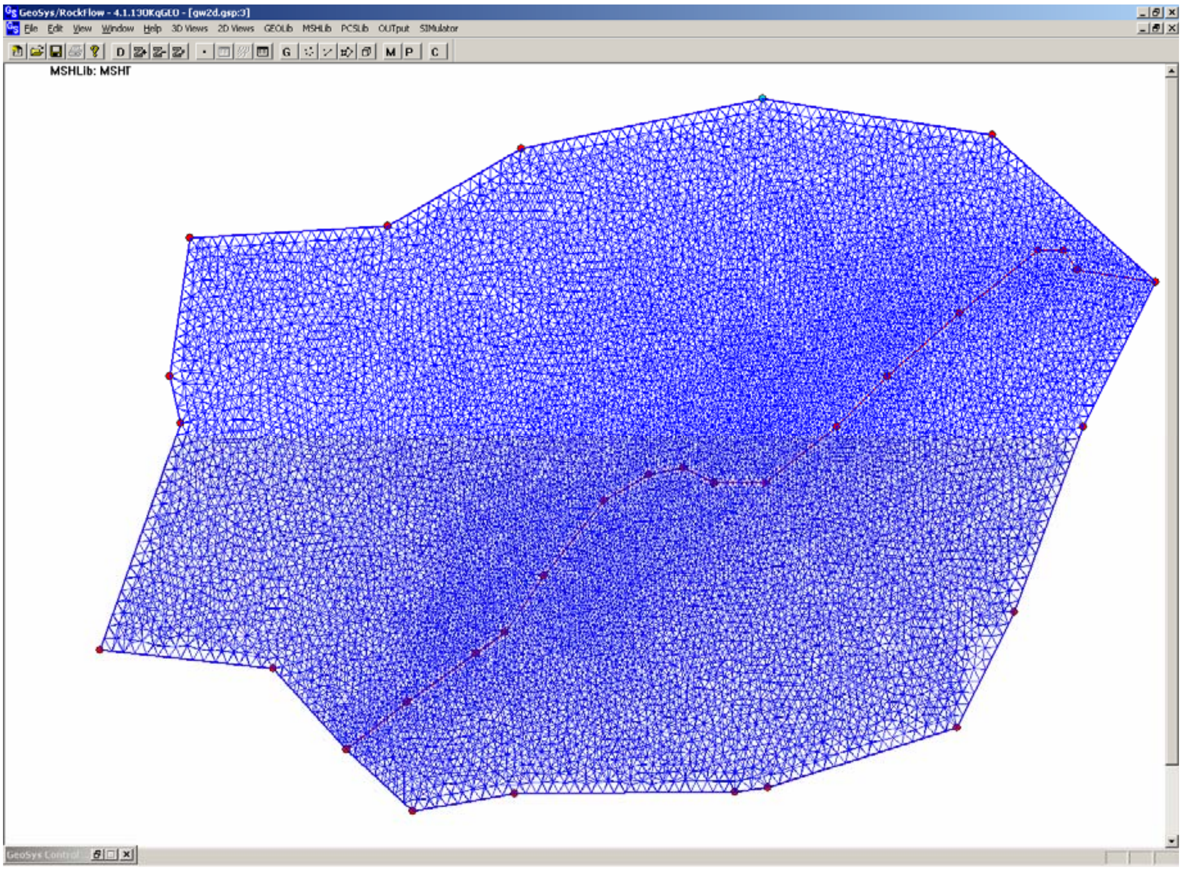


Figure 6.18: Re-Meshing result of the triangle mesh

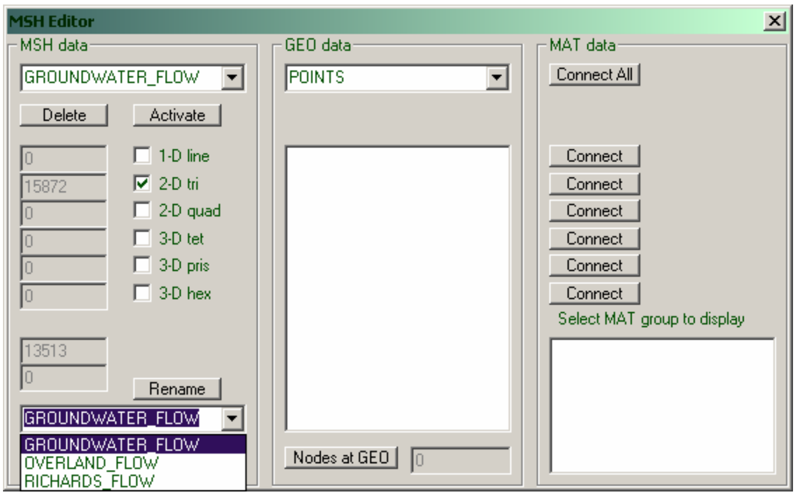


Figure 6.19: Rename the mesh

6.6.7 Save Project

After the triangle mesh has been created, a mesh file MSH (Fig 6.20) is created.

```
gw2d.msh
#FEM_MSH
 $PCS_TYPE
  GROUNDWATER_FLOW
 $NODES
  24429
0  5.14841000000000e+003  2.70317000000000e+003  0.00000000000000e+000
1  5.48889000000000e+003  2.91984000000000e+003  0.00000000000000e+000
2  6.38651000000000e+003  4.14762000000000e+003  0.00000000000000e+000
3  7.31508000000000e+003  4.47778000000000e+003  0.00000000000000e+000
4  7.63492000000000e+003  4.34365000000000e+003  0.00000000000000e+000
5  8.28492000000000e+003  4.35397000000000e+003  0.00000000000000e+000
6  1.00595000000000e+004  5.85000000000000e+003  0.00000000000000e+000
7  1.10913000000000e+004  6.61349000000000e+003  0.00000000000000e+000
8  1.16587000000000e+004  3.93095000000000e+003  0.00000000000000e+000
9  1.15349000000000e+004  2.79603000000000e+003  0.00000000000000e+000
10  9.56429000000000e+003  1.60952000000000e+003  0.00000000000000e+000
11  7.69683000000000e+003  1.60952000000000e+003  0.00000000000000e+000
12  4.51905000000000e+003  4.30238000000000e+003  0.00000000000000e+000
13  5.30317000000000e+003  6.13889000000000e+003  0.00000000000000e+000
14  7.61429000000000e+003  7.28413000000000e+003  0.00000000000000e+000
15  9.16190000000000e+003  7.50079000000000e+003  0.00000000000000e+000
……
$ELEMENTS
  48574
0  0  tri  450  451  2515
1  0  tri  1492  9637  9814
2  0  tri  9777  8521  1209
3  0  tri  8893  452  2664
4  0  tri  0  16  453
5  0  tri  8896  8894  8895
6  0  tri  2664  452  453
……
48571  1  tri  16783  24427  22106
48572  1  tri  17607  24428  24360
48573  1  tri  15047  24428  22661
$LAYER
  0
#STOP
```

Figure 6.20: MSH file description

6.7 PCSLib Data

After dealing with GEO and MSH data, it starts to create process (PCS) data. Typical process data are: the physical process itself, corresponding initial and boundary conditions, material properties for fluids, solids as well as the porous medium. Additionally numerical properties, time discretization schemes and output parameters have to be specified.

6.7.1 PCS View

As usual, at the beginning a corresponding view need to be created to deal with the data. All the functions will be activated when the PCSView is created.

6.7.2 PCS Editor

Four processes are now implemented in GeoSys/RockFlow: hydraulic process, thermal process, mechanical process and chemical process. In this step, the process is defined and added to the active process list for later simulation purposes. Figure 6.21 shows the process dialog; here the active process is defined.

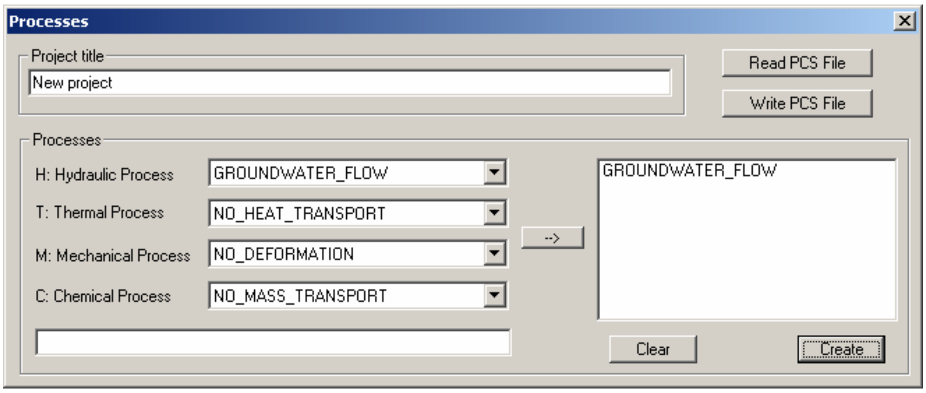


Figure 6.21: Process dialog

In the Control Panel the new process GROUNDWATER_FLOW will appear in the PCS data list. The field quantities of GROUNDWATER_FLOW (i.e. primary and secondary variables) are available in the Field quantities list.

6.7.3 Save Project

After the processes are defined, and a PCS (Fig 6.22) file is created by clicking on the save button.

```
gw2d.pcs
#PROCESS
 $PCS_TYPE
  GROUNDWATER_FLOW
 $NUM_TYPE
  NEW
 $CPL_TYPE
  PARTITIONED
 $TIM_TYPE
  TRANSIENT
#STOP
```

Figure 6.22: PCS file description

6.8 IC Data – Initial Conditions

Initial conditions have to be specified for each process. Using the IC dialog (Fig 6.23) the initial conditions can be created in a very compact way. Selecting the process (GROUNDWATER_FLOW) the primary variable (HEAD) is automatically pre-selected. Using the GEO type DOMAIN the value from the DIS type area will be assigned to the entire model domain.

6.8.1 Set Data

The following steps are necessary to create the initial condition:

- Select PCSType, GEOType and DISType,
- Click on button Create.

A new IC instance will appear in the OBJ list.

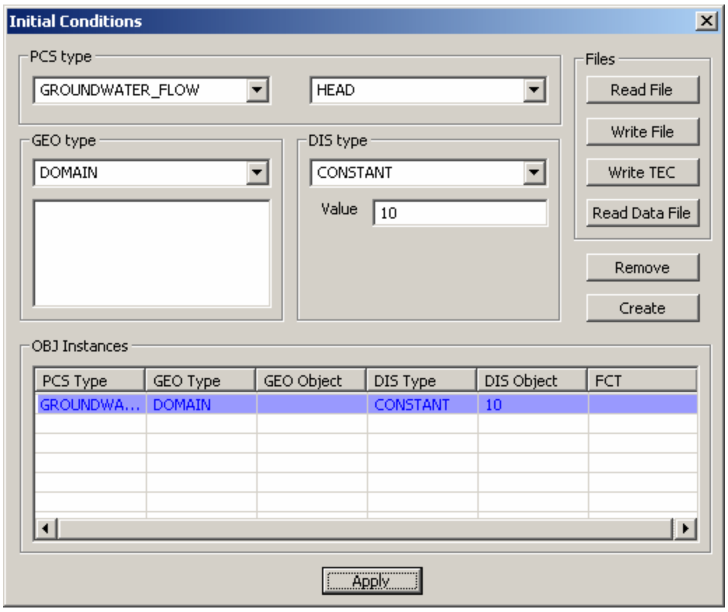


Figure 6.23: Initial condition dialog

6.8.2 Check Data

As result a marked check box Display initial conditions is shown in the Control Panel. Additionally, a distribution of initial conditions is displayed in the PCS View. See Figure 6.24.

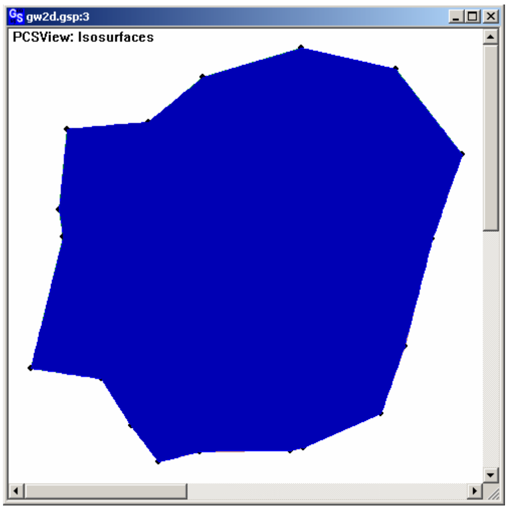


Figure 6.24: Display initial condition

6.8.3 Save Project

After creating the initial conditions, an IC (Fig 6.25) file is created by clicking on the save button.

```
gw2d.ic
#INITIAL_CONDITION
 $PCS_TYPE
  GROUNDWATER_FLOW
 $PRIMARY_VARIABLE
  HEAD
 $GEO_TYPE
  DOMAIN
 $DIS_TYPE
  CONSTANT 3.000000000000e+000
#STOP
```

Figure 6.25: IC file description

6.9 BC Data – Boundary Conditions

The BC dialog allows the creation of the boundary conditions in a very compact way. With help of the BC dialog, process (PCS data), geometric (GEO data) and distributions of BC values (DIS data) can be connected.

6.9.1 GEO Data

Boundary conditions can be connected to each type of geometric data. New polylines are cretated to define the boundary conditions at North and South. Figure 6.26 shows the result of new created polylines: polylines BC_NORTH and ST_SOUTH.

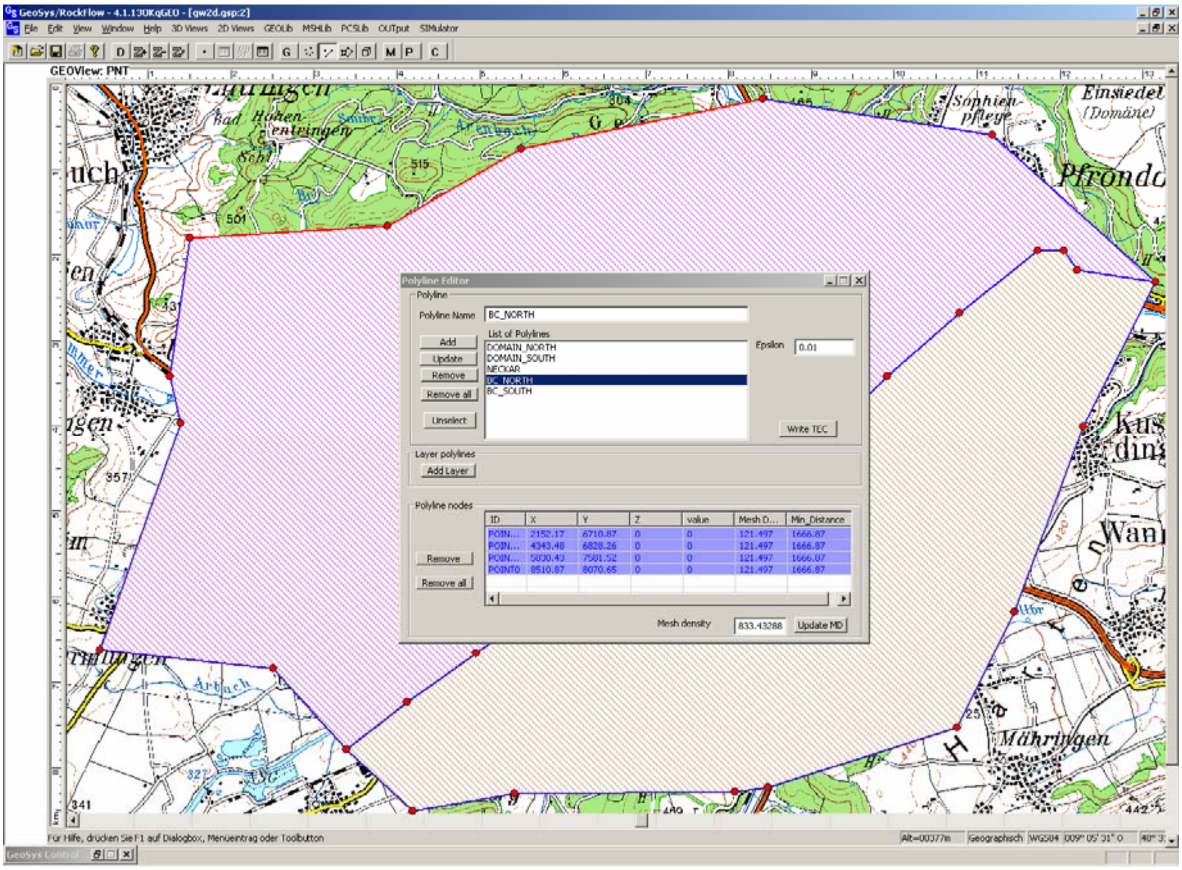


Figure 6.26: New polylines for boundary conditions

6.9.2 Set Data

After the required geometric data have been generated, boundary conditions will be created in the boundary condition dialog (Fig 6.27) as following steps:

- Select PCSType: GROUNDWATER_FLOW,
- Select GEOType: POLYLINE,
- Select GEOObj: BC_NORTH,
- Select DISType: CONSTANT,
- Set Value: 170,
- Create,
- Next BC,
- Create Group.

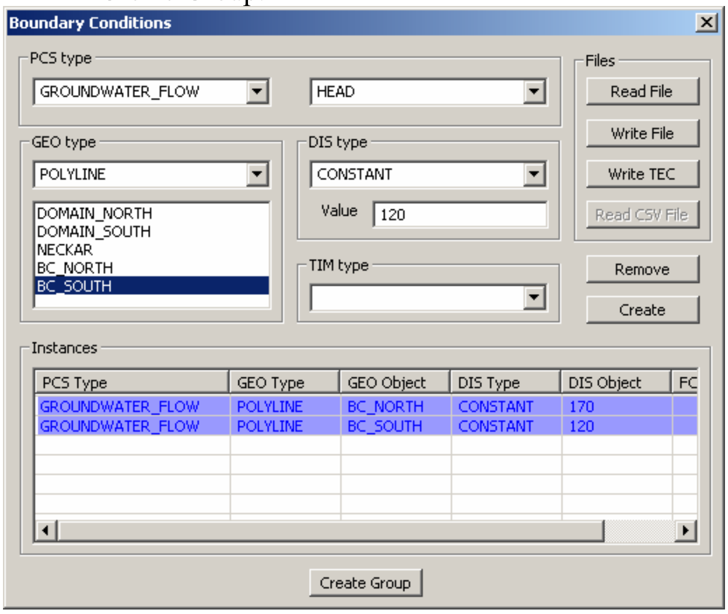


Figure 6.27: Boundary Condition dialog

6.9.3 Check Data

After the boundary conditions have been obtained, groups need to be created. During this operation, the boundary conditions are assigned to the finite element nodes of the selected MSH (GROUNDWATER_FLOW). As a result, the identified MSH nodes (Fig 6.28) are displayed in the PCSView. Additionally the check box Display boundary conditions are activated in the Control Panel. If not all mesh nodes are found, the property epsilon of the polyline need to be created, which is used to identify mesh nodes along polylines.

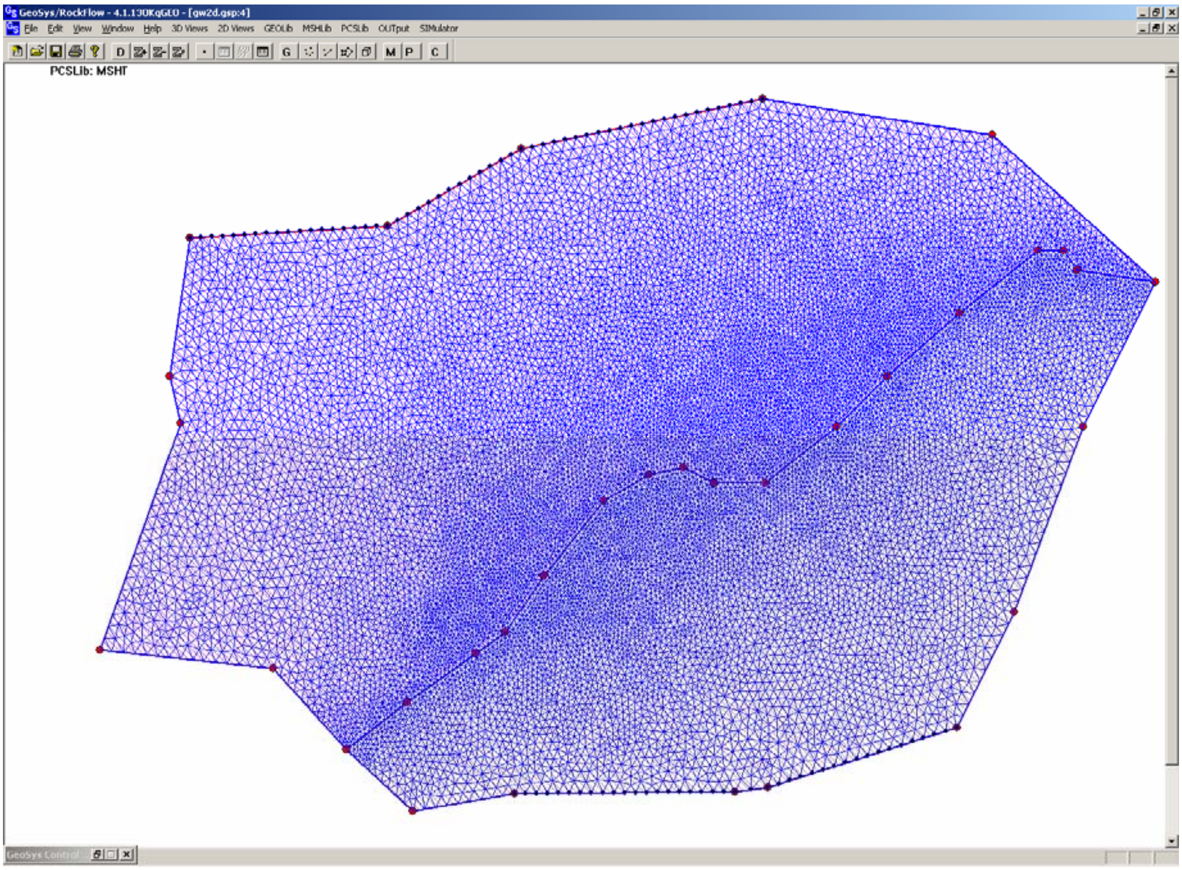


Figure 6.28: Check finite element nodes along the boundary condition

6.9.4 Save Project

After creating the boundary condition groups, the BC (Fig 6.29) file is created by clicking the save button.

```
gw2d.bc
#BOUNDARY_CONDITION
 $PCS_TYPE
  GROUNDWATER_FLOW
 $PRIMARY_VARIABLE
  HEAD
 $GEO_TYPE
  POLYLINE BC_NORTH
 $DIS_TYPE
  CONSTANT 5.000000000000e+001
#BOUNDARY_CONDITION
 $PCS_TYPE
  GROUNDWATER_FLOW
 $PRIMARY_VARIABLE
  HEAD
 $GEO_TYPE
  POLYLINE BC_SOUTH
 $DIS_TYPE
  CONSTANT 2.000000000000e+001
#STOP
```

Figure 6.29: BC file description

6.10 ST Data – Source Terms

The source term (ST) dialog (Fig 6.30) allows the creation of the boundary conditions in a very compact way. With the help of the ST dialog, process (PCS data), geometric (GEO data) and distributions of BC values (DIS data) can be connected.

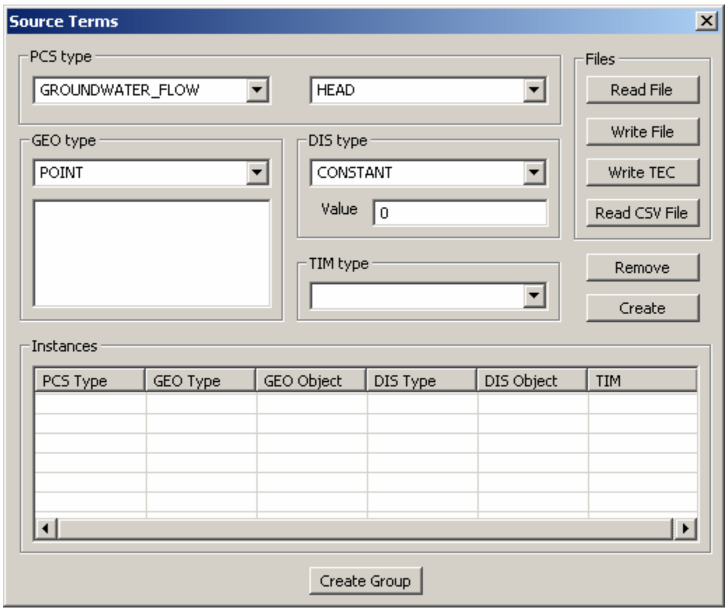


Figure 6.30: Source Term dialog

6.10.1 GEO Data

Pumping wells and Neckar river are used as source sink terms. Therefore, the related geometric objects need to be created. Figure 6.31 shows the results.

- Create polyline NECKAR,
- Create points WELL1 and WELL2.

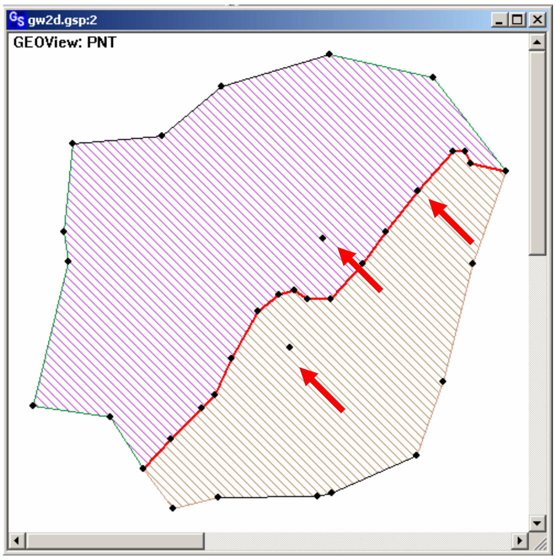


Figure 6.31: Create geo data for source terms

6.10.2 Set Data

River Condition

The following steps are necessary for setting the river as source term (Fig 6.32):

- Select PCSType: GROUNDWATER_FLOW,
- Select GEOType: POLYLINE,

- Select GEOObj: NECKAR,
- Select DISType: RIVER,
- Set Value: 3 (river water level),
- Create,
- Create Group.

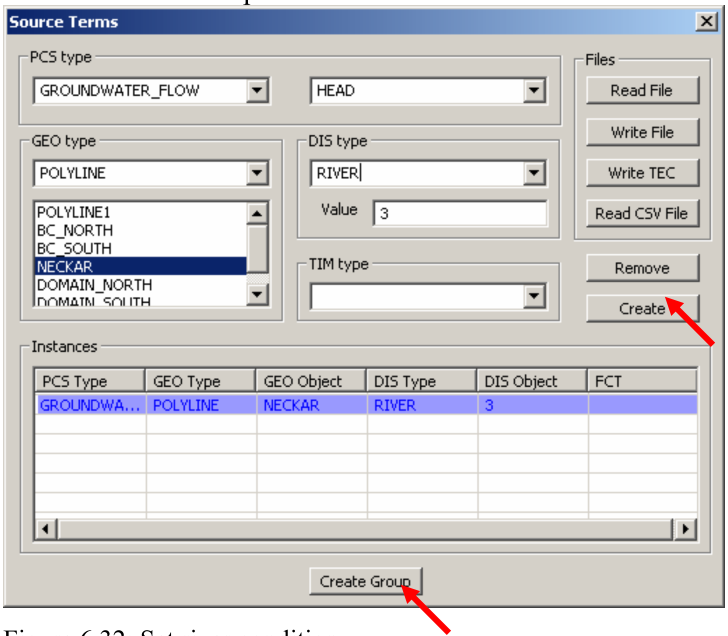


Figure 6.32: Set river condition

After the source terms have been obtained, groups need to be created. During this operation the source terms are assigned to the finite element nodes of the selected MSH (GROUNDWATER_FLOW). As a result, the identified MSH nodes (Fig 6.33) are displayed in the PCSView. Additionally the check box Display source terms is activated in the Control Panel.

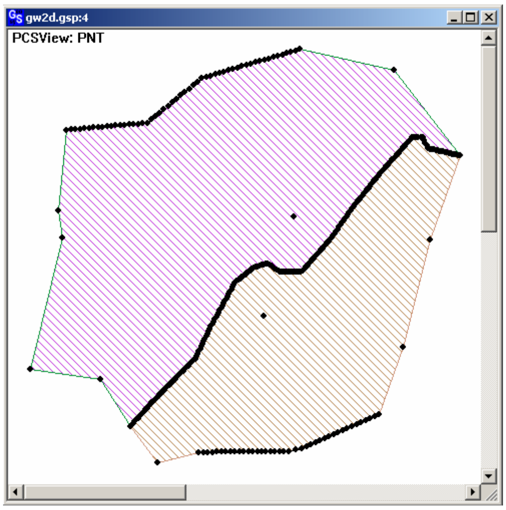


Figure 6.33: Identified mesh nodes along the river

Well Condition

The following steps are necessary for setting the wells as source term (Fig 6.34):

- Select PCSType: GROUNDWATER_FLOW,
- Select GEOType: POINT,
- Select GEOObj: WELL1,
- Select DISType: CONSTANT,
- Set Value: 1e-3 (pumping rate in m^3/s),

(positive sign + means injection rate, negative sign - means abstraction rate)

- Create,
- Create group.

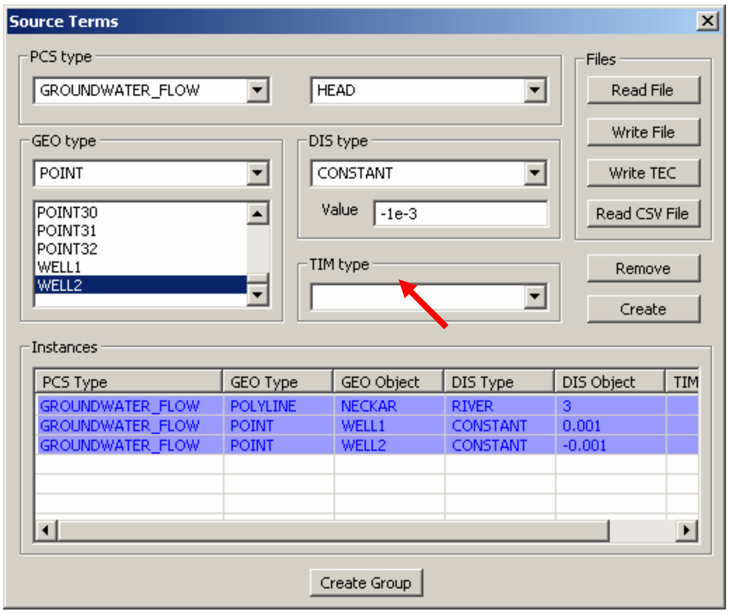


Figure 6.34: Set well condition

As a result, the MSH nodes for the well conditions are identified.

Time Dependencies

If it is not a steady-state simulation, source terms can be connected with so-called TIM types, i.e. time functions. See also Figure 6.34.

6.10.3 Save Project

After creating source terms, click on save button, and the ST (Fig 6.35) file is created.

```
gw2d.st
#SOURCE_TERM
 $PCS_TYPE
  GROUNDWATER_FLOW
 $PRIMARY_VARIABLE
  HEAD
 $GEO_TYPE
  POLYLINE neckar
 $DIS_TYPE
  RIVER 8
  0   3.000000000000e+000   1.000000000000e-006   6.000000000000e+001
1.300000000000e+000   1.000000000000e+000
  1   3.000000000000e+000   1.000000000000e-006   6.000000000000e+001
1.300000000000e+000   1.000000000000e+000
  2   3.000000000000e+000   1.000000000000e-006   6.000000000000e+001
1.300000000000e+000   1.000000000000e+000
  3   3.000000000000e+000   1.000000000000e-006   6.000000000000e+001
1.300000000000e+000   1.000000000000e+000
  4   3.000000000000e+000   1.000000000000e-006   6.000000000000e+001
1.300000000000e+000   1.000000000000e+000
  5   3.000000000000e+000   1.000000000000e-006   6.000000000000e+001
1.300000000000e+000   1.000000000000e+000
  6   3.000000000000e+000   1.000000000000e-006   6.000000000000e+001
1.300000000000e+000   1.000000000000e+000
  7   3.000000000000e+000   1.000000000000e-006   6.000000000000e+001
1.300000000000e+000   1.000000000000e+000
#SOURCE_TERM
 $PCS_TYPE
  GROUNDWATER_FLOW
 $PRIMARY_VARIABLE
  HEAD
 $GEO_TYPE
  POINT well1
 $DIS_TYPE
  CONSTANT 1.000000000000e-003
#SOURCE_TERM
 $PCS_TYPE
  GROUNDWATER_FLOW
 $PRIMARY_VARIABLE
  HEAD
 $GEO_TYPE
  POINT well2
 $DIS_TYPE
  CONSTANT -1.000000000000e-003
#STOP
```

Figure 6.35: ST file description

6.11 MFP Data – Fluid Properties

Parameters of typical fluids can be selected from a user-defined database or from standard fluids. Choose from the menu PCSLib – Materials – Fluid properties, the MAT-MFP Editor dialog (Fig 6.36) appears.

6.11.1 Set Data

The following steps are necessary to set the fluid properties.

- Select standard type WATER,

- Create MAT group.

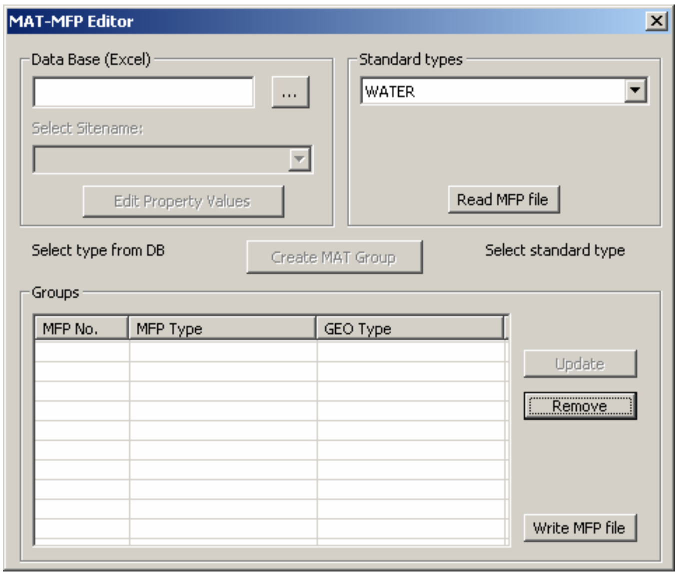


Figure 6.36: Fluid Properties dialog

6.11.2 Save Project

After defining the fluid properties, click on save button, and a MFP (Fig 6.37) file is created.

```
gw2d.mfp
#FLUID_PROPERTIES
 $FLUID_TYPE
  WATER
 $DAT_TYPE
  WATER
 $DENSITY
  1 1.000000000000e+003
 $VISCOSITY
  1 1.000000000000e-003
 $SPECIFIC_HEAT_CAPACITY
  1 4.680000000000e+003
 $SPECIFIC_HEAT_CONDUCTIVITY
  1 6.000000000000e-001
#STOP
```

Figure 6.37: MFP file description

6.12 MMP Data – Medium Properties

Properties of porous or fractured media can be selected from a user-defined database (e.g. Excel table). Select from the menu PCSLib – Materials – Medium properties, the MMP Group Editor dialog appears.

6.12.1 Set Data

The following steps are necessary for creating the medium properties data:

- Use file browser option in MAT Data Base (Excel), see figure 6.38.

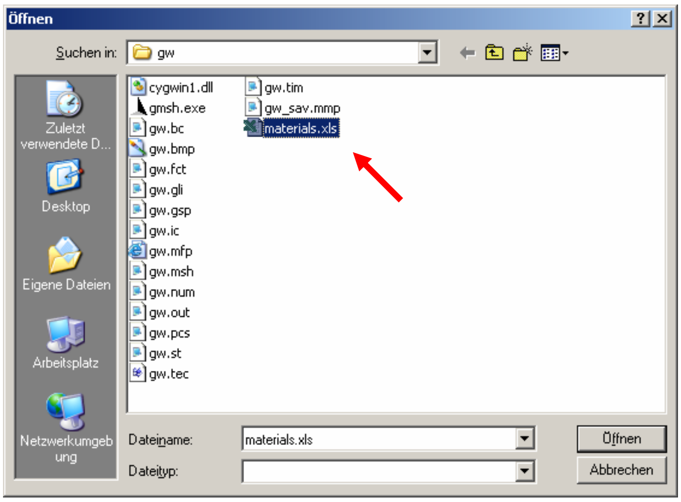


Figure 6.38: Select the excel file for MMP data

- Select EXCEL data base file: materials.xls,
- Select data base site name (AQUIFER1),
- Select GEO type (NORTH) (here only the geometric dimension (2-D) is important),
- Create MAT group.

As a result, a new material group is added in the MAT Groups list derived from AQUIFER1 and a 2-D geometric surface in the MAT group editor dialog (Fig 6.39). Geometric types can be also used for describing heterogeneous material behavior.

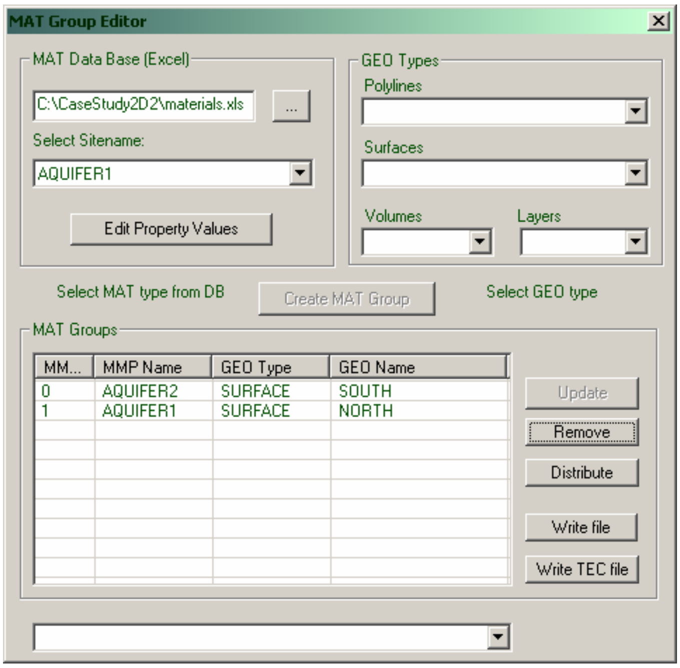


Figure 6.39: MAT Group Editor dialog (Gronewold etal 2005)

6.12.2 Save Project

After creating the MAT group data, the MMP (Fig 6.40) file is created by clicking the save button.

```
gw2d.mmp
#MEDIUM_PROPERTIES
 $NAME
  AQUIFER1
 $GEOMETRY_DIMENSION
  2
 $GEOMETRY_AREA
  1.000000000000e+000
 $POROSITY
  1 2.000000000000e-001
 $PERMEABILITY_TENSOR
   ISOTROPIC 1.000000000000e-005
#MEDIUM_PROPERTIES
 $NAME
  AQUIFER2
 $GEOMETRY_DIMENSION
  2
 $GEOMETRY_AREA
  1.000000000000e+000
 $POROSITY
  1 1.250000000000e-001
 $PERMEABILITY_TENSOR
   ISOTROPIC 1.246000000000e-005
#STOP
```

Figure 6.40: MMP file description

6.13 TIM Data – Time Discretization

If it is a transient simulation, TIM data need to be set. Time discretization data can be specified with the TIM editor (Fig 6.41).

6.13.1 Set Data

Time discretization data are connected with processes (PCS type). Each process can have different but only one time stepping scheme. Therefore, before editing TIM data, the existing TIM data set needs to be removed. As a result ten time steps a 3.2e+6 is displayed in the time step list.

- Select the TIM from the OBJ list (Instances) clicking the PCS type (first column)
- Remove
- Set dt in the Fixed stepping area: 3.2e+6
- Set End time: 3.2e7
- Create

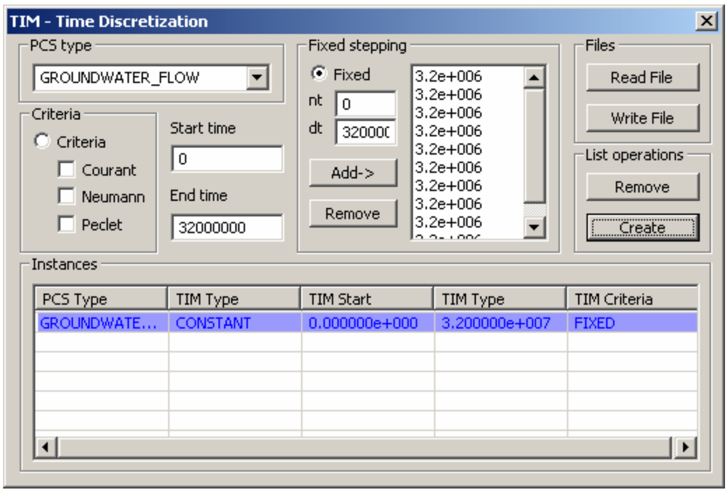


Figure 6.41: TIM editor dialog

6.13.2 Save Project

As a result, the TIM (Fig 6.42) file is created.

```
gw2d.tim
#TIME_STEPPING
 $PCS_TYPE
  GROUNDWATER_FLOW
 $TIME_START
  0.000000000000e+000
 $TIME_END
  1.000000000000e+000
 $TIME_STEPS
  1 1.000000000000e+000
#STOP
```

Figure 6.42: TIM file description

6.14 OUT Data – Output

Several output functionalities are currently available as follows:

- DOMAIN: output of node and element data in the entire model domain,
- PROFILES: output of node and element data along specified polylines,
- POINT: output of node and element data in specified e.g. points (temporal breakthrough curves).

6.14.1 Set Data

New output objects can be added using the OUT Editor (Fig 6.43) in the following steps:

- Select PCS type,
- Select node (NOD) or element (ELE) value,
- Use Clear to remove pre-selected variables,
- Select GEO type: DOMAIN, POLYLINE or POINT,
- Select GEO object,
- Select STEPS: number (then each number of time steps data are output),
- Create.

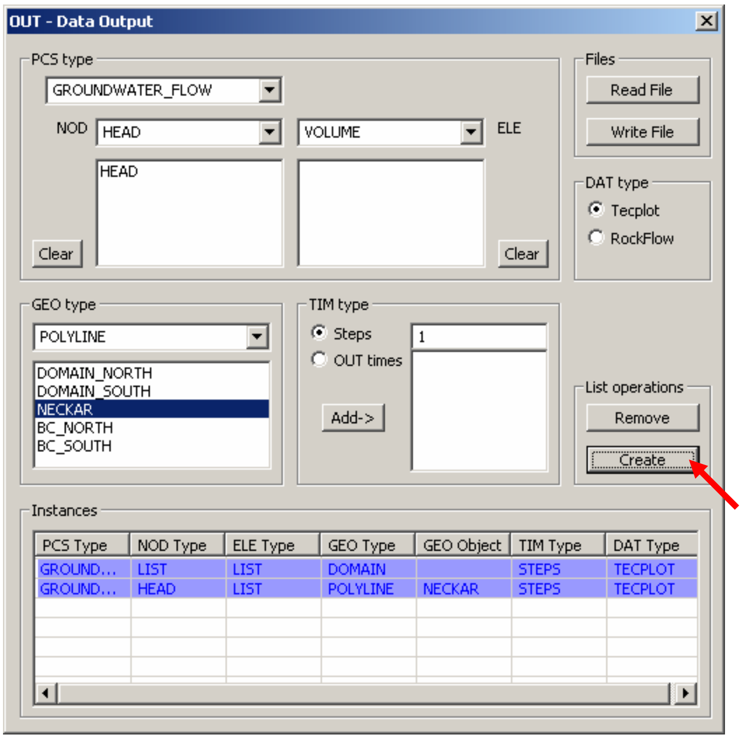


Figure 6.43: OUT data dialog

6.14.2 Display OUT Data

Contour Plots

Contour plots are displayed automatically in the PCSView during simulation. The quantities as well as plot ranges have to be selected in the Control Panel.

X-Y Plots

In order to display x-y plots (i.e. temporal breakthrough curves and profiles) a corresponding view for x-y plots is created. Figure 6.44a and 6.44b shows initial head distribution along the NECKAR polyline before and after simulation.

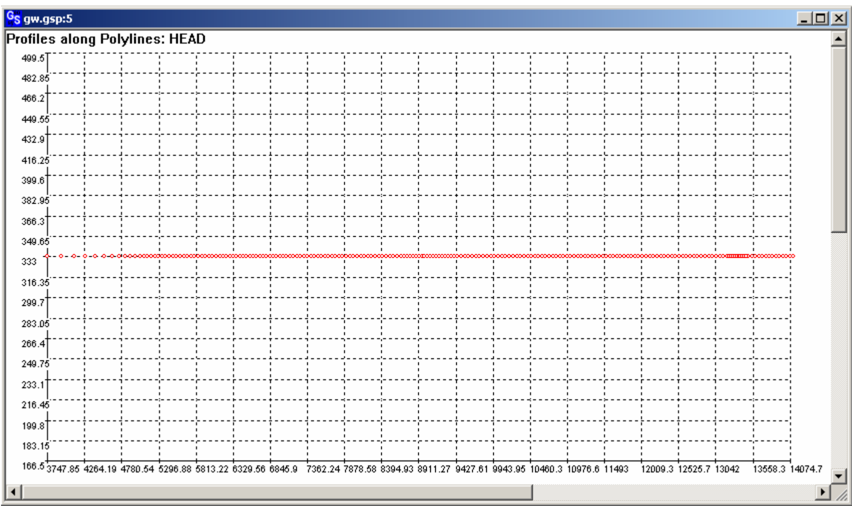


Figure 6.44a: Initial head distribution along Neckar river before simulation

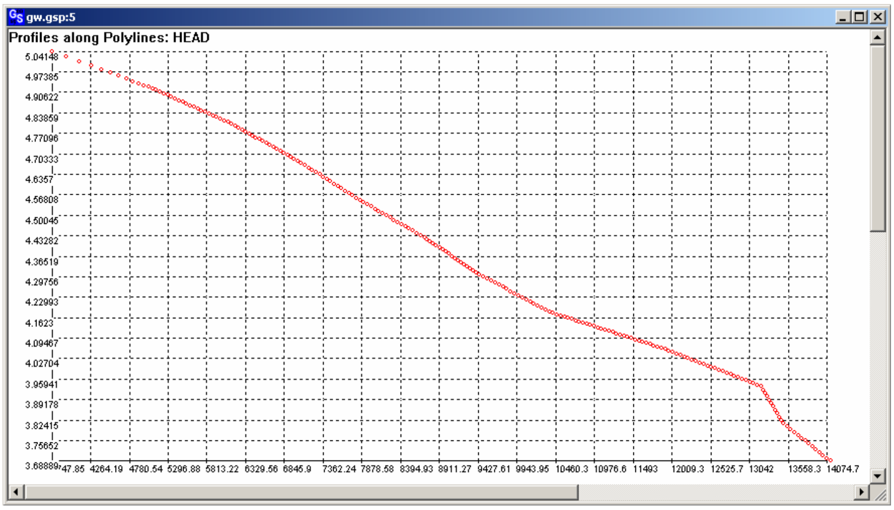


Figure 6.44b: Initial head distribution along Neckar river before simulation

Tecplot Interface

The default data type for output files is TECPLOT. These files can be directly imported using Tecplot. Figure 6.45 shows the result of the head distribution in the whole domain.

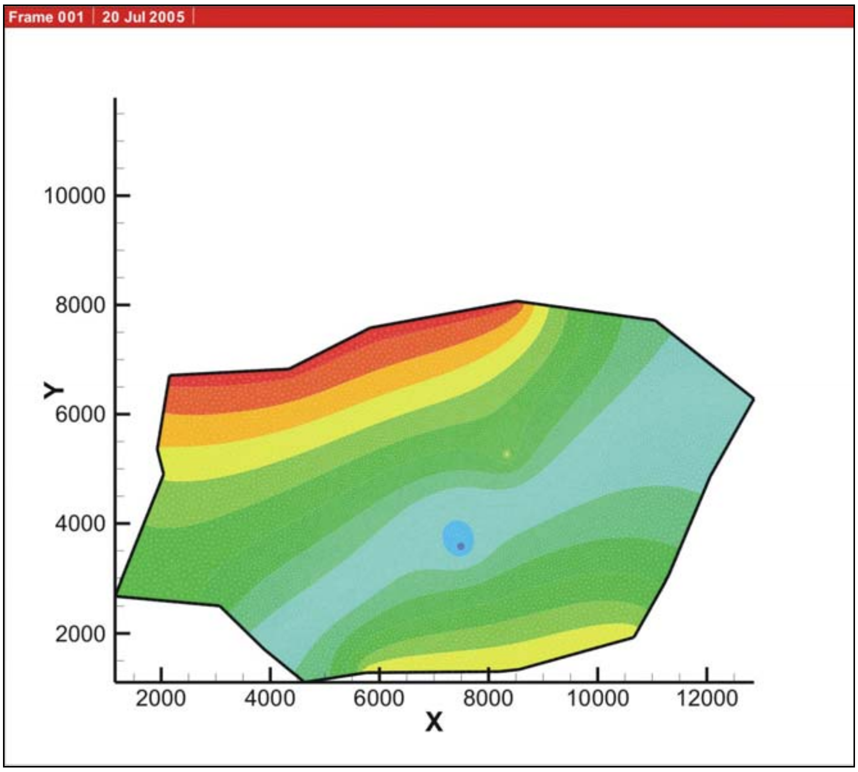


Figure 6.45: Head distribution in the domain in Tecplot

6.14.3 Save File

As a result, the OUT (Fig 6.46) file is created.

```
gw2d.out
#OUTPUT
 $PCS_TYPE
  GROUNDWATER_FLOW
 $NOD_VALUES
  HEAD
  FLUX
  WDEPTH
 $ELE_VALUES
 $GEO_TYPE
  DOMAIN
 $TIM_TYPE
  STEPS 1
#OUTPUT
 $PCS_TYPE
  GROUNDWATER_FLOW
 $NOD_VALUES
  HEAD
 $ELE_VALUES
 $GEO_TYPE
  POLYLINE neckar
 $TIM_TYPE
  STEPS 1
#STOP
```

Figure 6.46: OUT file description

6.15 FCT Data – Functions

Functions can be used to express functional dependencies of material properties or time dependencies of boundary conditions and source terms. Here functions are used to describe time dependencies of source terms (river condition and pumping wells). Functions can be displayed in a separate view - FCTView. After selecting the function (NECKAR) in the FCT data list, a plot of selected function, e.g. water level versus time is displayed in FCTView (Fig 6.47). During the simulation a blue ball will move along the function according the proceeding simulation time.

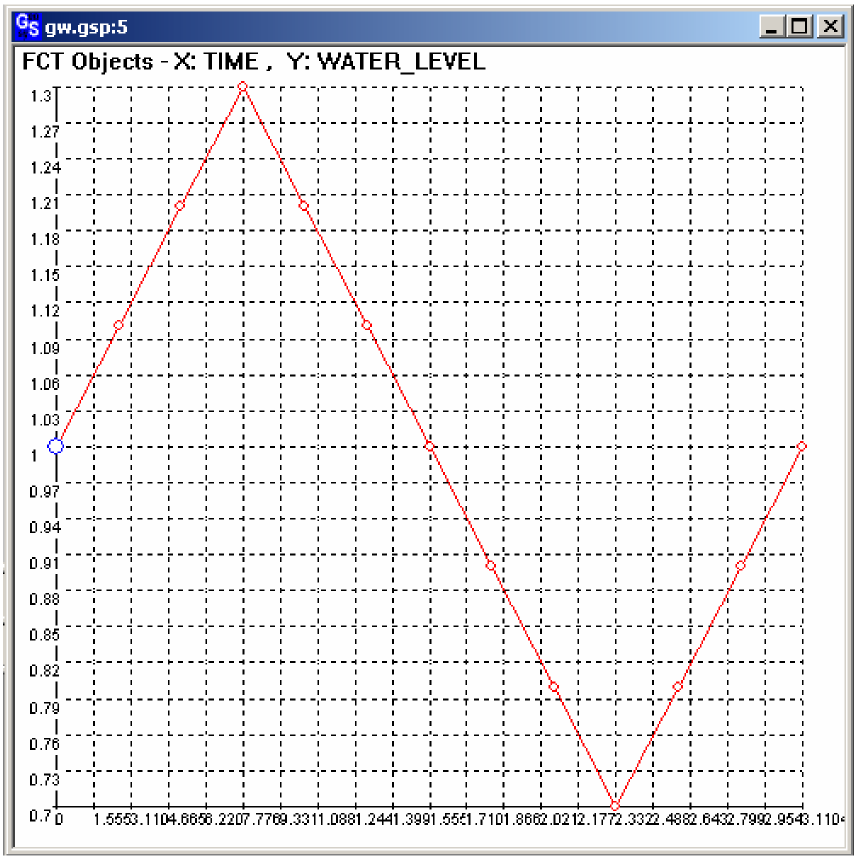


Figure 6.47: Function data in FCTView

6.16 Simulation

6.16.1 Check Status

Before the simulation is started, checking the problem status is necessary. A summary of specified data is obtained, and input files, which are used, for the simulation are listed in the simulation dialog (Fig 6.48).

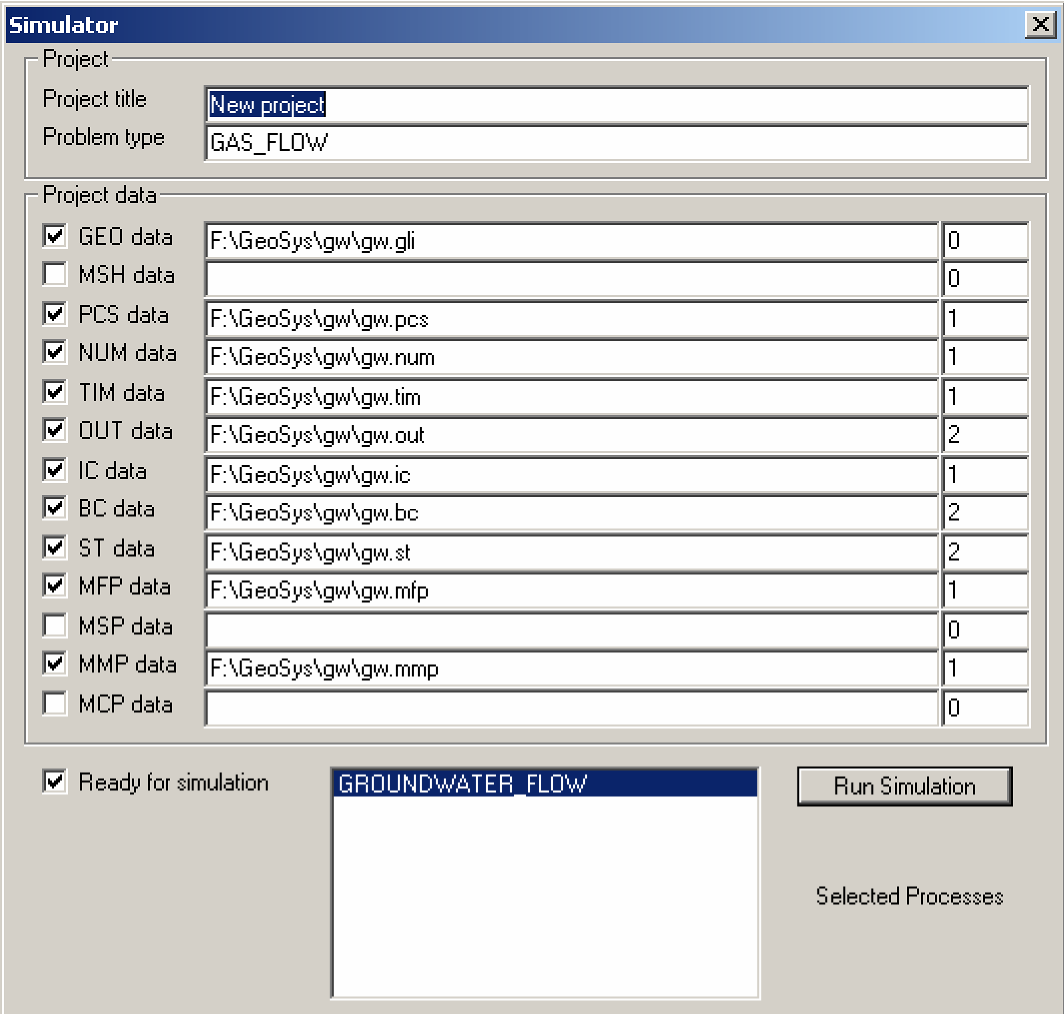


Figure 6.48: Checking simulation input files

6.16.2 Run

Now it is ready to run the simulation.

Draw Isolines and Isosurfaces

Contour plot results are automatically shown in the PCS View if the Display isolines / isosurfaces options are activated. Refresh the min-max values by selecting the quantity to be displayed in the Control Panel. The contour plot together with the x-y plot is displayed in Figure 6.49.

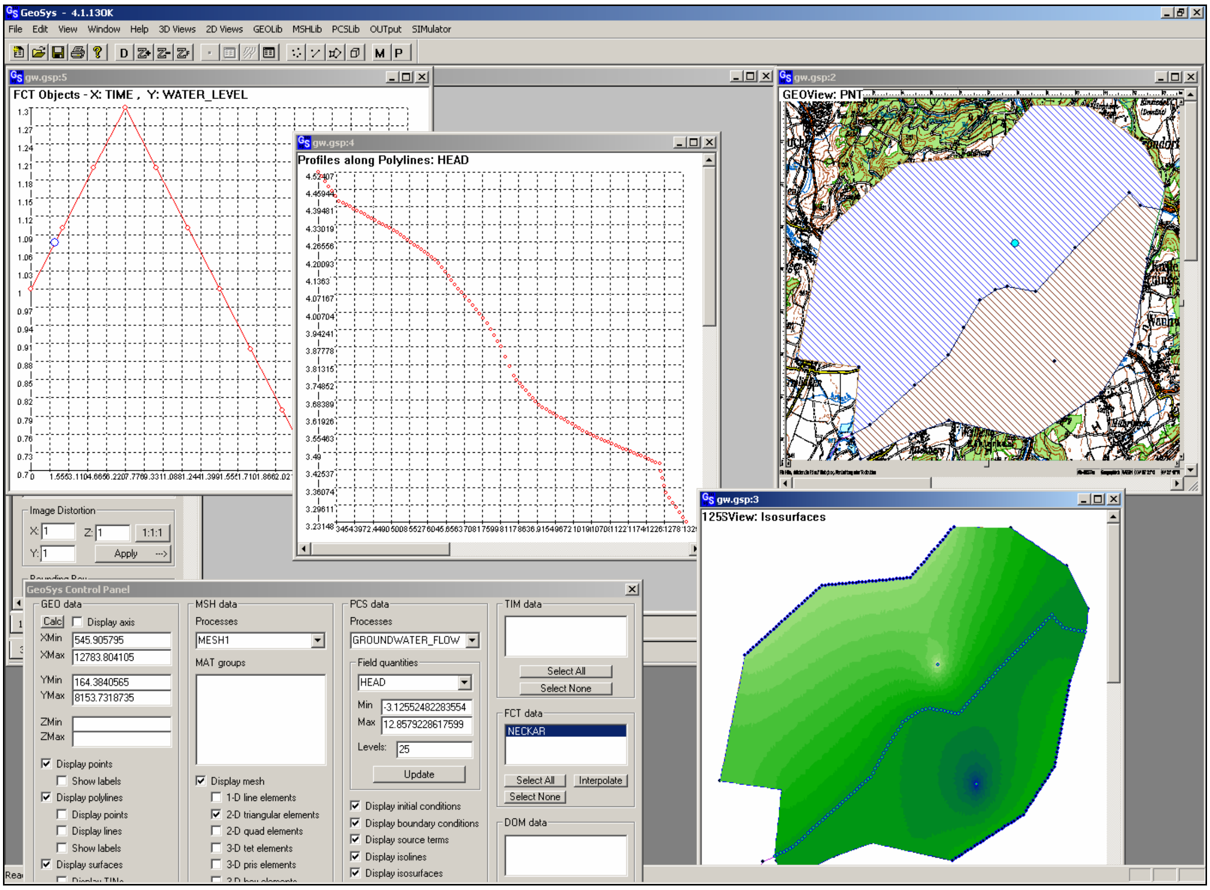


Figure 6.49: Display simulation result

Steady State flow and River Condition

As an example, results of different stages of the model set up are displayed in the following. Figure 6.50 shows the head distribution of the domain only when boundary conditions are activated. Figure 6.51 shows the result when the river condition is additionally activated.

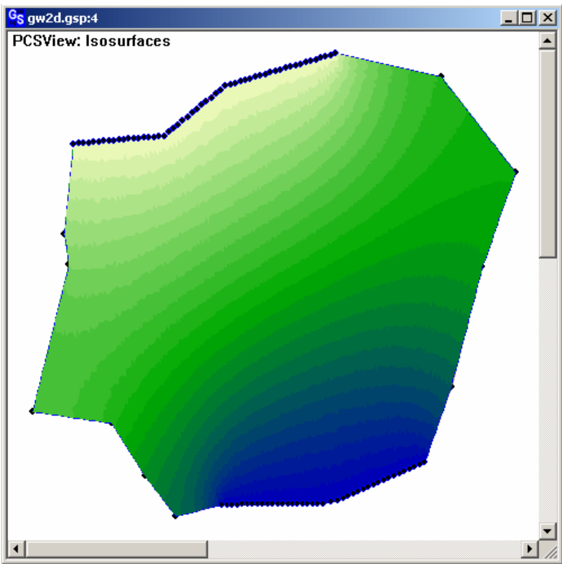


Figure 6.50: Only boundary conditions are activated

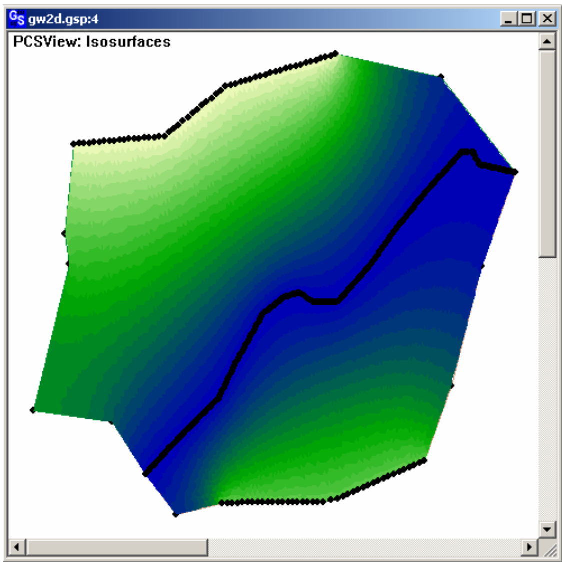


Figure 6.51: Additional river condition is activated

Pumping Wells and Injection Wells

Figure 6.52a and 6.52b shows separately when the first pumping well and the second injection well are activated.

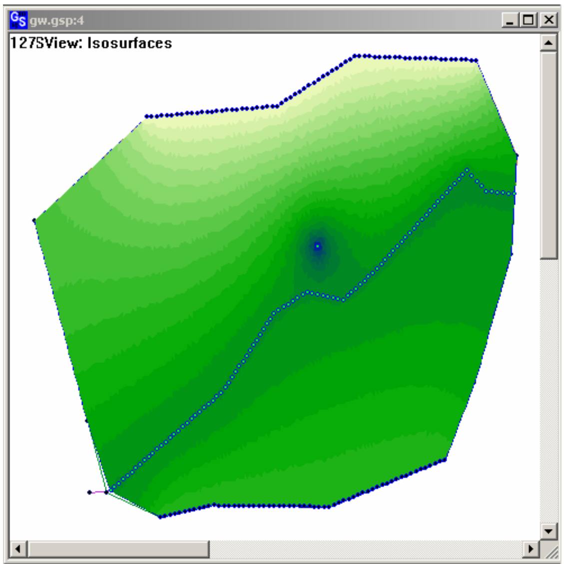


Figure 6.52a: The first pumping well is introduced

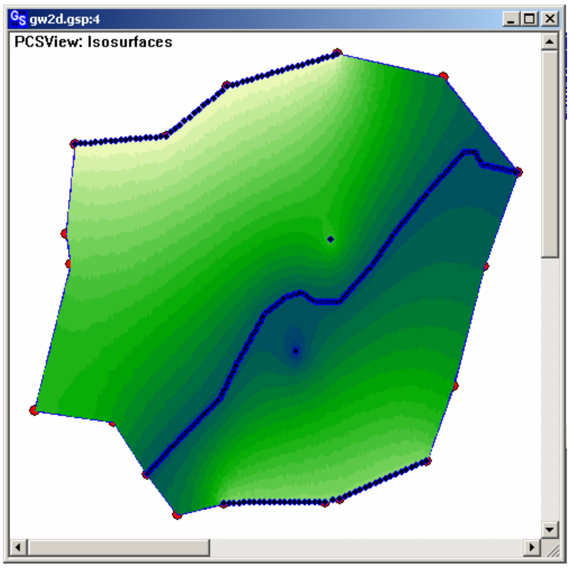


Figure 6.52b: The second injection well is introduced

7 FLOW AND HEAT TRANSPORT MODEL IN THE ZARQA MA'IN – JIZA AREAS IN CENTRAL JORDAN

Jordan locates in the arid and semi-arid region of the Middle East, and water resources are scarce there. Water is of vital importance to maintaining the socio-economic development of Jordan. Water resources consist mainly of surface water and groundwater. Managing groundwater resources in Jordan has been given great attention because of the water scarcity in the entire region (Al-Abed 2004). The study aims at exploring the groundwater flow and heat processes in the Zarqa Ma'in – Jiza area in central Jordan using GIS-based groundwater modeling concept. Shape files from ArcGIS, like points, polylines, polygons, are used not only for the basic geometric data of the model domain, but also for I-D line elements of finite element mesh, boundary conditions and source term. GeoSys/RockFlow scientific modeling software is applied to develop a numerical groundwater flow model to the study location in the Zarqa Ma'in – Jiza areas in Central Jordan to model a mixing process between water from upper and lower aquifers. Simulation results (steady state) are presented for the flow regime in the model domain based on recharge, discharge and springs data. Furthermore, a heat transport between the two aquifers in the study area is considered to certificate the thermal water from the lower aquifer to flow up via faults (conduits) to the upper aquifer. The proposed model and the appropriate result would be particularly helpful for the understanding of the water resources in this area.

7.1 Introduction – Study Area Description

The study area is located in the central part of Jordan, east of the Dead Sea and covers the northern third of the Wadi El Mujib groundwater basin and Wadi Zarqa Ma'in sub basin with total area of about 2300 km^2 (Fig 7.1).

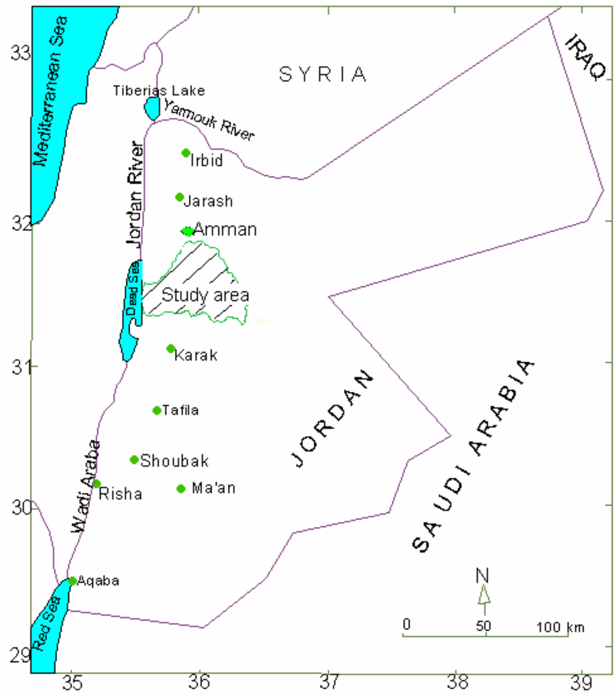


Figure 7.1: Location map of the study area (Sawarieh 2004)

The area consists of two major aquifer systems: the upper and the lower aquifers. The upper aquifer is considered as the main source for fresh water for domestic uses in Jordan. The aquifer is recharged mainly along the northern and western parts of the study area where it is outcropping and receiving the highest average rainfall (250– 400 mm/y). The groundwater within this aquifer mainly flows from north to south then to the west along the Wadi Waleh drainage pattern and from south to north then join the other flow to the west. Part of the water flows further to the east towards the Azraq groundwater basin. The main natural outlets from the aquifer are the Heidan springs and the Zarqa Ma'in spring with annual average discharge of about 15 MCM/Y and 0.7 MCM/Y respectively.

The lower aquifer consists mainly of sandstone of lower cretaceous and older ages. The major contribution to the lower aquifer recharge comes from the upper aquifer by infiltration, mainly in the eastern parts of Jordan. The infiltrated water receives heat under a normal to slightly elevated geothermal gradient and flows to the west towards the Dead Sea, where it inters the Dead Sea as subsurface flow or discharges to the ground surface as thermal springs, as in Zara and Zarqa Ma'in springs. The average discharge of the Zara-Zarqa Ma'in thermal springs amount to 20 MCM/Y (Salameh and Udluft, 1985).

In the last three decades, about 300 boreholes were drilled to the upper aquifer in the study area. Boreholes drilled mainly east and south east of Jiza town discharge thermal water ranging in temperatures from 30 to 46 C^{o}. The dense faults net which affecting the area, strongly suggested that the two-aquifer systems are hydraulically connected, especially in the eastern parts of the study area. This might allow the thermal water from the lower aquifer to flow up via faults (conduits) to the upper aquifer raising the water temperature (Sawarieh, 1990). The isotope content indicates that the thermal water from both aquifers is of meteoric origin. The chemical analysis and the isotope content of the thermal water from the upper aquifer indicate that it is a mixture of the two aquifers water (Sawarieh et al, 2004).

7.2 Model Settings

The Geological Formations

The sedimentary sequence, which covers the study area, is grouped into four main geological divisions. These are: the Kurnub sandstone formation of Lower Cretaceous and sandstone of older ages, the A1-6 marl and marly limestones formations, the B2/A7 limestone formations and the B3 and B4 chalk and marly limestone formations. The top and base elevation data was taken from the borehole records and the geological maps.

The Hydrological Units

The geological formations are subdivided into four hydrological units. These are: the confining beds (B3 & B4), the Upper aquifer (B2/A7), the lower Sandstone aquifer (Kurnub sandstone and the sandstone of older ages) and the main aquitard (A1-6), which separate the two aquifers, figure 7.2 shows these units and their hydrological properties.

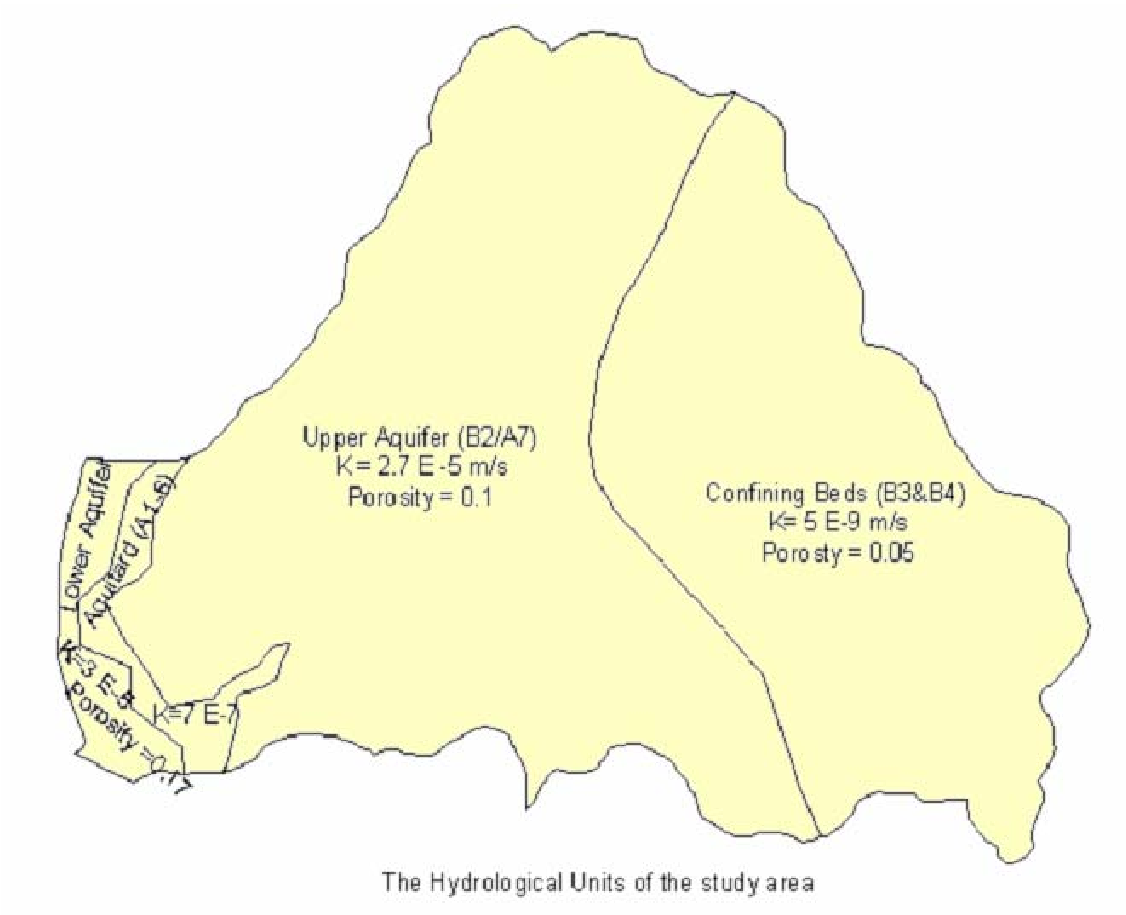


Figure 7.2: The hydrological units of the study area (Sawarieh 2004)

7.2.1 Data Acquisition in GIS Project

The conceptual model includes all the physical properties and stresses that affect the system, and they are geological formations, faults, wadis and the hydrogeological data like aquifers, aquitards, wells, springs, water table, top and base of aquifers and boundary conditions. All those data are created and organized in ArcGIS as thematic layers for later use as input data for modeling in GeoSys/RockFlow. The GIS thematic layers include the following features:

Study Domain

The study domain is subdivided into 29 sub-areas (Fig 7.3) based on the border of wadis and faults (blue polylines). 29 polygons are created in ArcGIS. 22 surfaces represent the upper aquifer system (0-21), three for the aquitard (22,23 and 28) and four representing the lower aquifer system (24-27). Each surface has an average value for hydraulic conductivity.

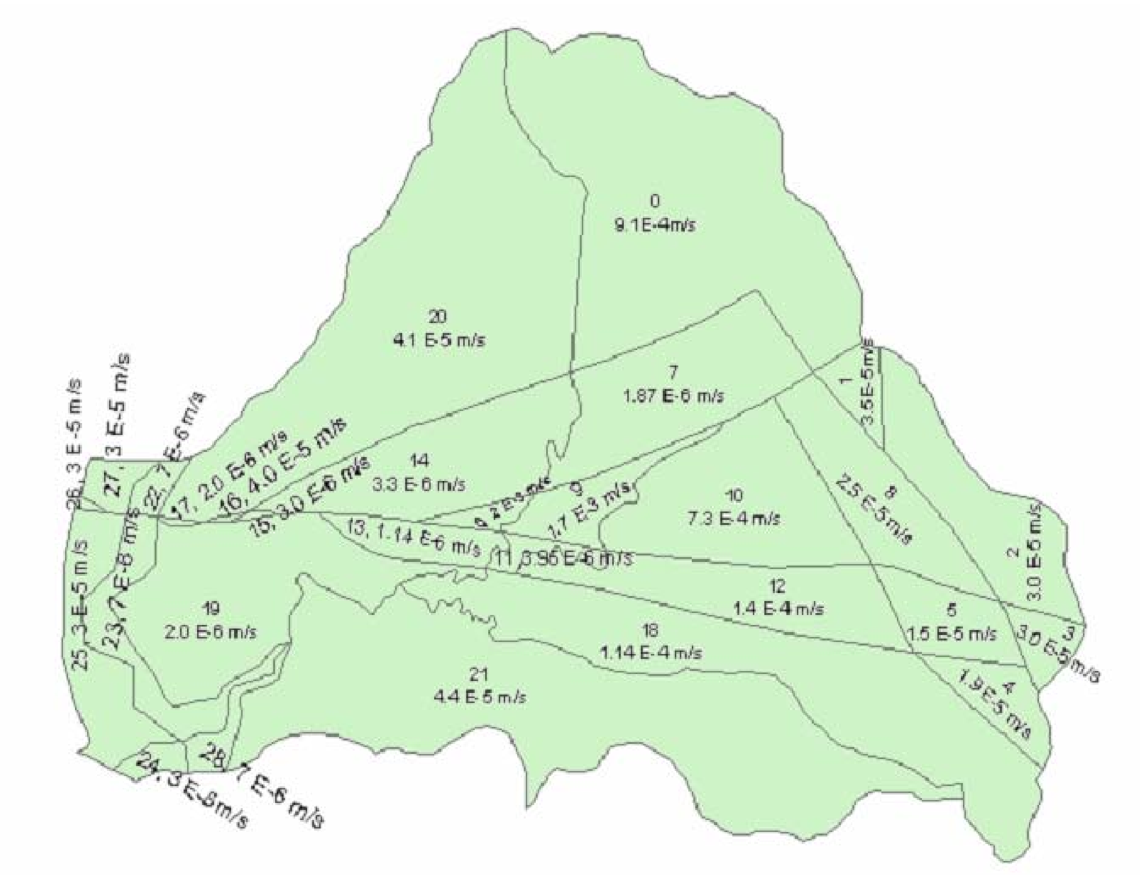


Figure 7.3: The study area domain

Wadis and Springs

The study area is drained westwards to the Dead Sea by two major wadis: Wadi Zarqa Ma'in and Wadi Waleh and their numerous tributaries. Perennial base flow is seen only on the lowest reaches down stream of Wadi Waleh between the elevations 450 and 250m where the biggest springs group is located at the location of 350m. Figure 7.4 shows these wadis and the main discharge outlets (springs) from the system.

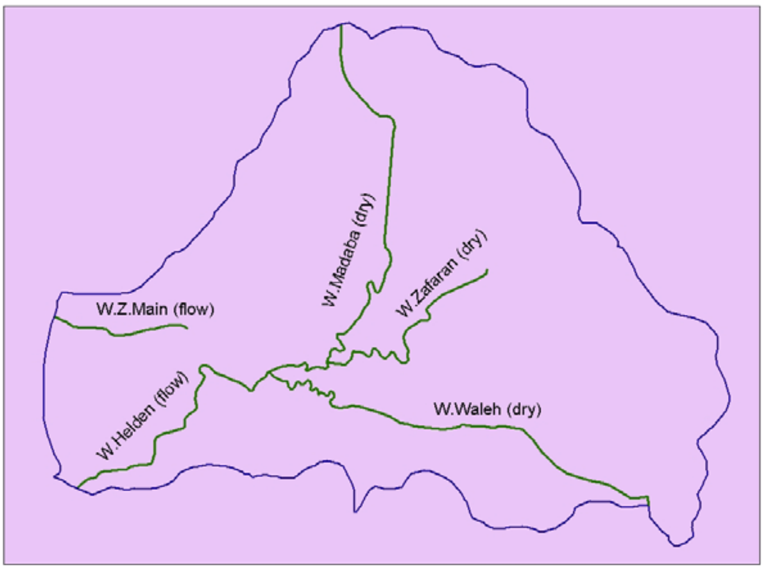


Figure 7.4: Wadis and major springs in the study area (Sawarieh 2004)

Faults

The study area is highly affected by faults especially in the eastern part. Some of these faults have tensional forces which allow them to act as conduit for the thermal water to flow up and mix with the upper aquifer water, raising the temperature of the water in the vicinity of these faults. See Figure 7.5.

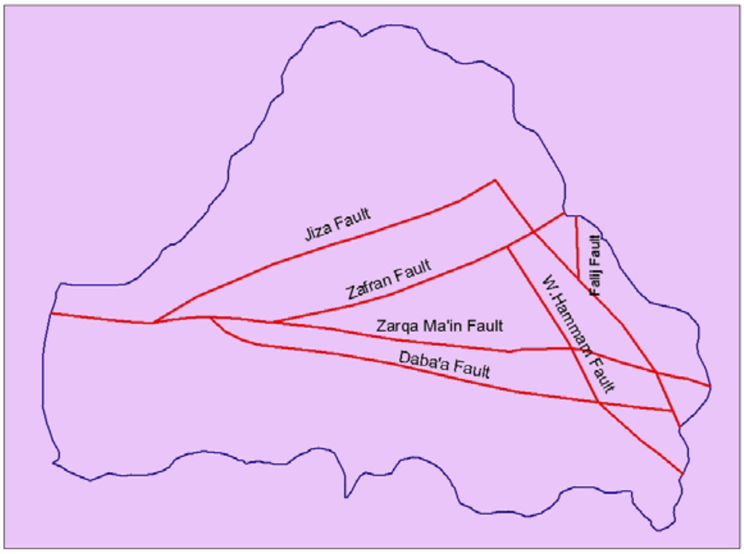


Figure 7.5: The main fault zones in the area (Sawarieh 2004)

Wells Location

During the last three decades, more than 200 wells were drilled in the study area. The majority of these wells are private wells, which have been drilled for agricultural purposes. The government drilled two well fields (Qastal and Waleh) for drinking purposes, mainly pumped to the capital. The location of these wells is shown in figure 7.6.

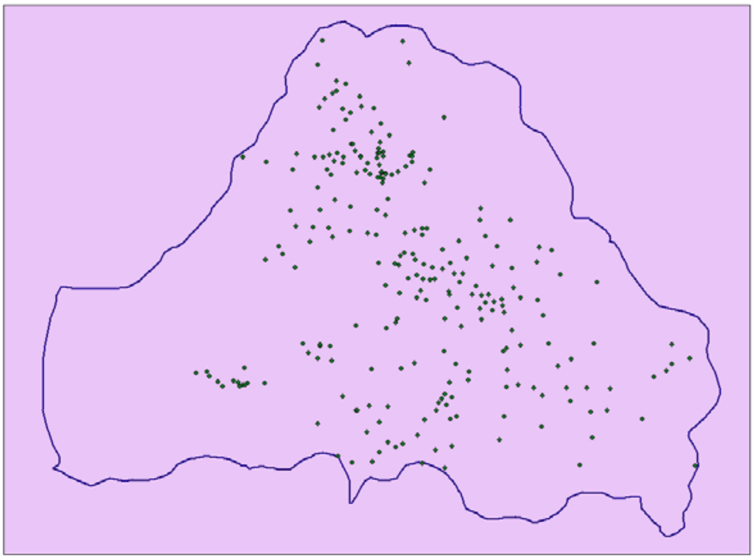


Figure 7.6: Wells distribution in the area (Sawarieh 2004)

Boundary Condition

The study area covers the northern part of Wadi El Mujib groundwater basin and Wadi Zarqa Ma'in sub-basin. The major recharging points to the upper aquifer are the northern and western highlands. Along the western border, there are the main discharge outlets from the aquifer through the base flow supported by the springs in the lower reaches of the wadis. There is also, some water leaving the aquifer along the eastern border towards the Azraq groundwater basin in the east. The southern border is set along the water divide between the northern and southern parts of the Mujib groundwater basin. Three types of boundary condition were set to the area, out flow, recharge and no flow. These are shown in figure 7.7. For the lower aquifer the boundary conditions are set as no-flow boundary condition at the northern and southern borders, in-flow boundary at the eastern border and out-flow boundary at the western border.

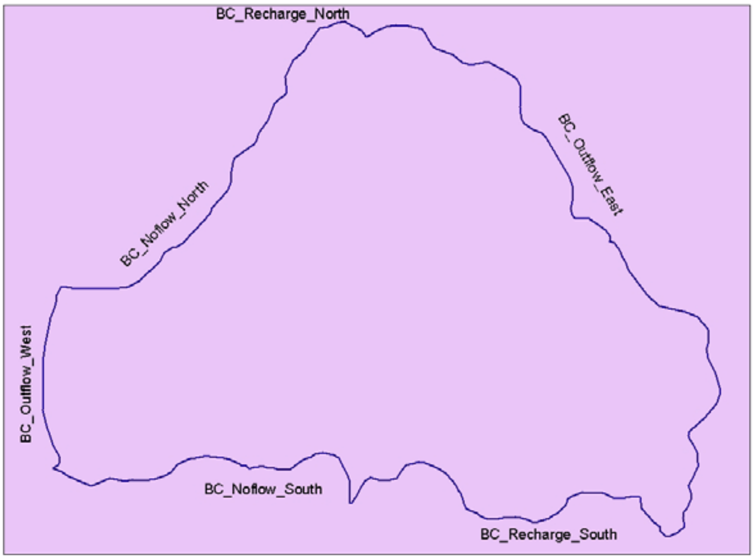


Figure 7.7: The boundary condition in the area

Water Level Contour Map

The water level measurements (Fig 7.8) in the study area before development are used in constructing a water level contour map in the upper aquifer system, and this could be served as initial condition in the modeling.

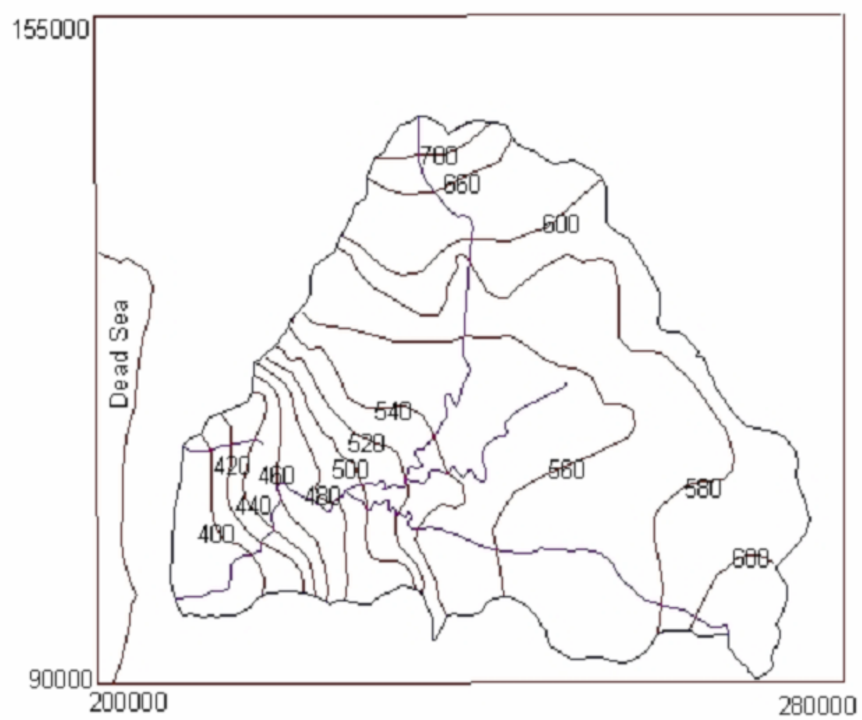


Figure 7.8: The water level contour map in the area (Sawarieh 2004)

7.3 Model Setup – GeoSys/RockFlow Project

Model setup includes the following steps:

Create a GeoSys/RockFlow Project

This is the first step when a new project is started in GeoSys/RockFlow. All the data reference needed for the model like geometry data, meshing data, processing data, are stored in one project file to keep the connection between the project and its data components. The file path and the name of this project need to be specified (Fig 7.9):

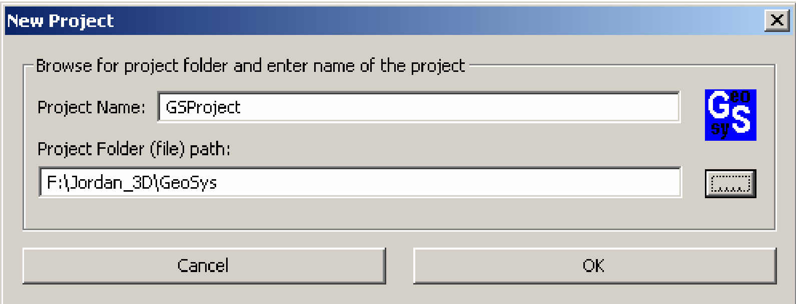


Figure 7.9: Create a new project

Import GIS Data (SHP files)

SHP file means ArcGIS data format. It is prepared by using the features of digitizing in ArcGIS. There are three major types for 2D model: point, polyline, and polygon. The GIS data is imported into GeoSys/RockFlow by using the implemented menu (Fig 7.10):

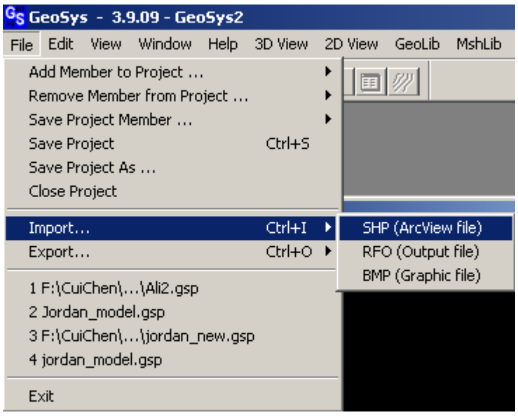


Figure 7.10: Import GIS data

7.3.1 Build Geometry Data (GEOLib)

The Shape files are important into GeoSys/RockFlow, which are converted into our own GEOLib data structure, and saved in file with extension as GLI. Points and polylines are automatically created, and surfaces need to be created from the closed polylines in this case.

Points

Figure 7.11 shows the point features in GeoSys/RockFlow.

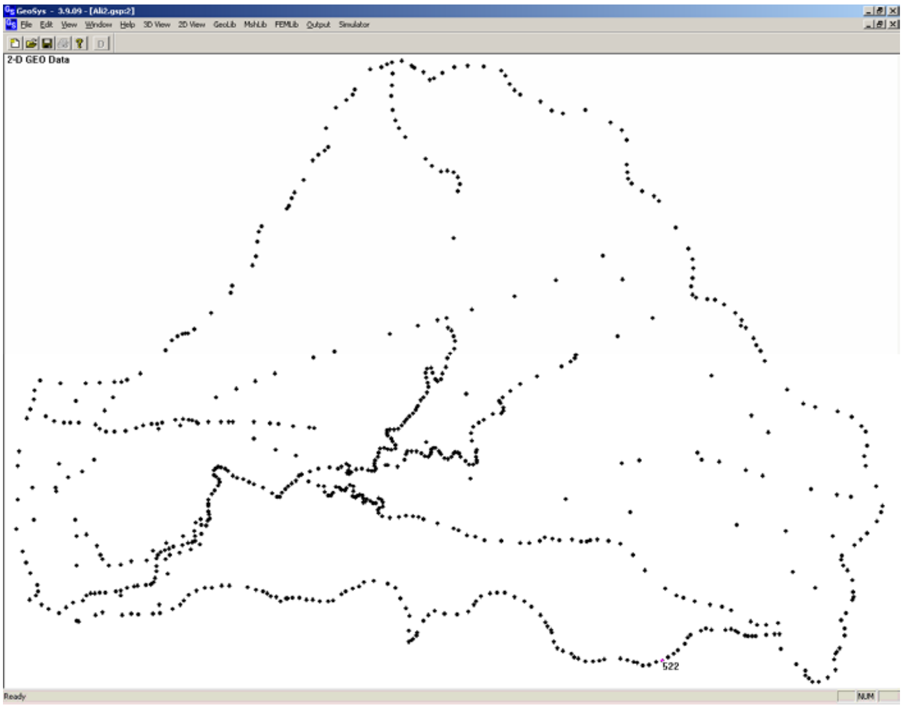


Figure 7.11: Points in GEOView

Polylines

Figure 7.12 shows the polylines in GeoSys/RockFlow.

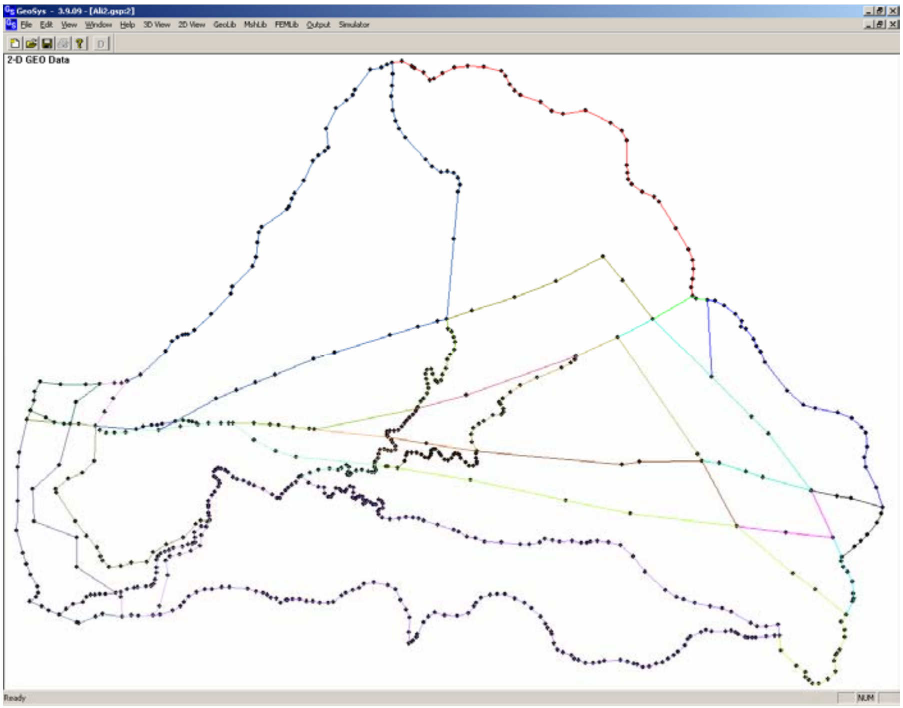


Figure 7.12: Polylines in GEOView

Layer Polylines

For 2.5-D vertically extended models, polylines can be copied to on so-called layer polylines. These layer polylines are copies to z-direction for each layer. Layer polylines can be used to define boundary conditions at vertical surfaces.

Surfaces

Surfaces need to be created. One surface could be created from one closed polyline (polygon) or from several polylines, which form a closed area. In our case, each surface is created from one closed polyline using the surface editor (Fig 7.13). Figure 7.14 shows the surfaces in GeoSys/RockFlow with different colors.

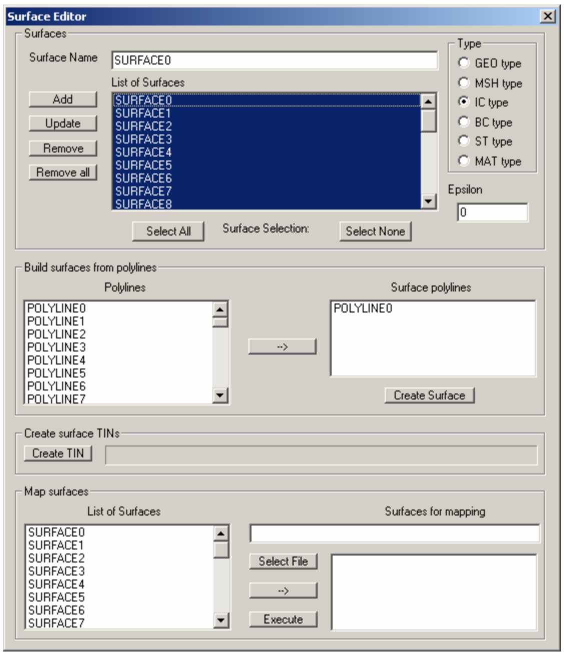


Figure 7.13: Create surfaces

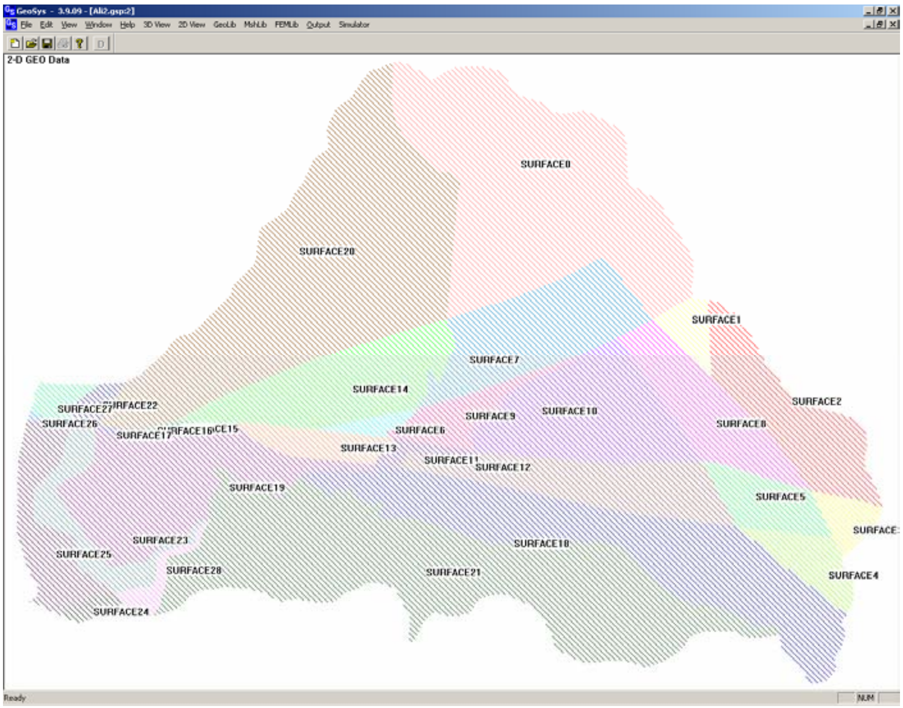


Figure 7.14: Surfaces in GEOView

TINs for Surfaces

TINs (triangulated irregular networks) can be used for a discrete geometric description of surfaces and then for volumes as well. The generation of TINs for surfaces requires an existing triangulation. The concept of TINs here is for the generation of volumes later. The number of TINs for each surface is equal to the number of the layers for this structural model. Figure 7.15 shows the dialog where the TINs are created. The following steps are necessary to generate TINs for the existing surfaces:

- Create GEO View
- Select the surface editor dialog from the GEOLib menu
- Deselect all marked surfaces (Select None)
- Select the surface for TIN generation
- Use the Create TIN push button to generate the TIN for the selected surface (a progress bar shows the status of TIN generation)
- A TIN file (surface_name.TIN) is generated automatically
- If the Create TIN push button is inactive, a TIN already exists.
- To see the results of TIN generation, select the graphics dialog from the 2D View – GEO View – Properties menu. Set the corresponding mark for displaying TINs and redraw.

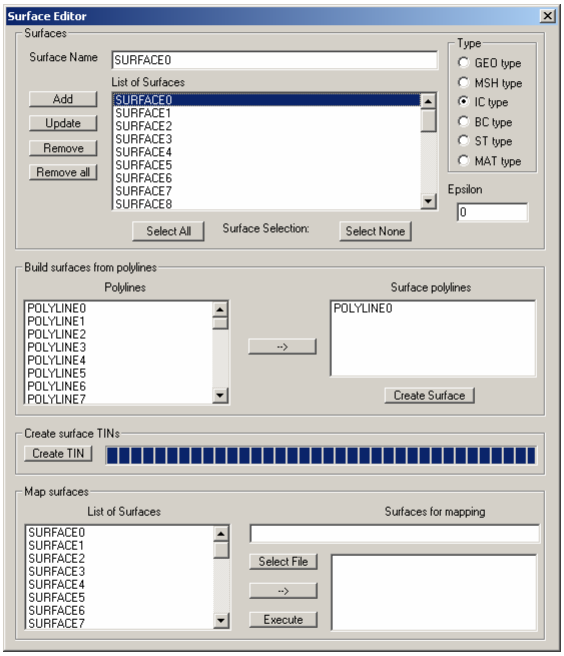


Figure 7.15: TINs generation

Figure 7.16 shows the result of the created TINs of the surfaces in Tecplot format.

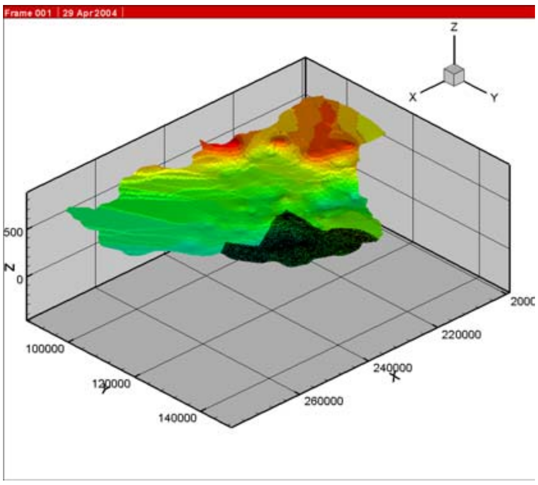


Figure 7.16: TINS for the surface

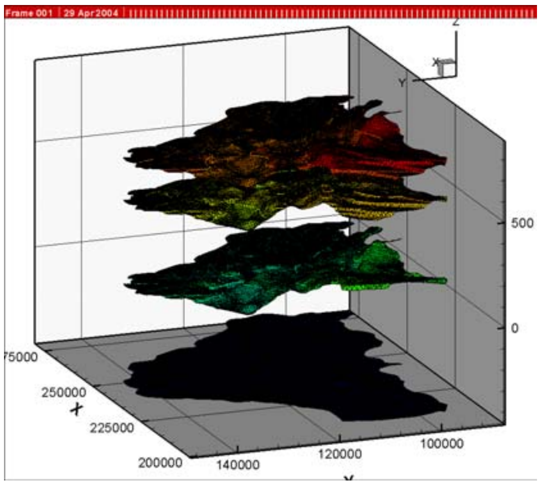


Figure 7.17: Layer 2.5D model

Layered 2.5-D Models
TINs for layer surfaces of an extended 2-D model are automatically created during prism element generation based on the TINs for the original 2-D model. Figure 7.17 shows the layer 2.5-D model.

Volumes
For a structural 3D model, the generation of a volume needs one upper and one bottom surface, and those two surfaces build the boundary of one volume. Figure 7.18 shows the result of volumes inside this modeling domain.

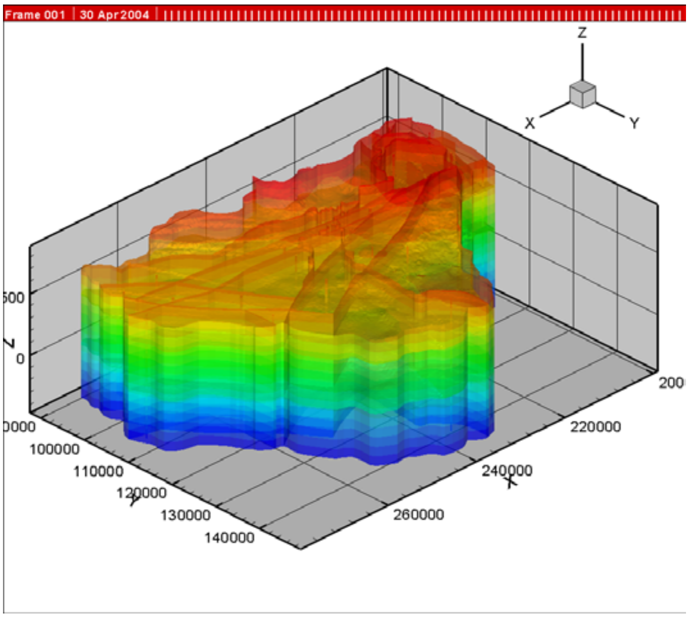


Figure 7.18: Volumes inside the modeling domain

7.3.2 Build Mesh Data (MshLib)

The second step is meshing. The general steps for the hybrid meshing procedure in this application are:

1. Create a triangulation based on surfaces for the 2-D surface water model.
2. Create line elements for the 1-D Wadis model based on the triangulation.
3. Create prismatic elements for the 3-D subsurface model.
4. Create quadrilateral elements for the 2-D fracture/faults model.

Triangulations
Use the option Triangulation from the MSHLib menu. For triangulation, an external program is used (gmsh). Gmsh uses a point wise parameter for adjusting the mesh density. This has to be set as one property of point (PNT) data. After meshing, the MSH file is generated automatically. In the following, it is a GLI example for PNT mesh density 500:

```
#POINTS
0   235397.44   146374.90   0.00000000   500.00000  0 0 0
```

Figure 7.19 shows the result of the triangulation.

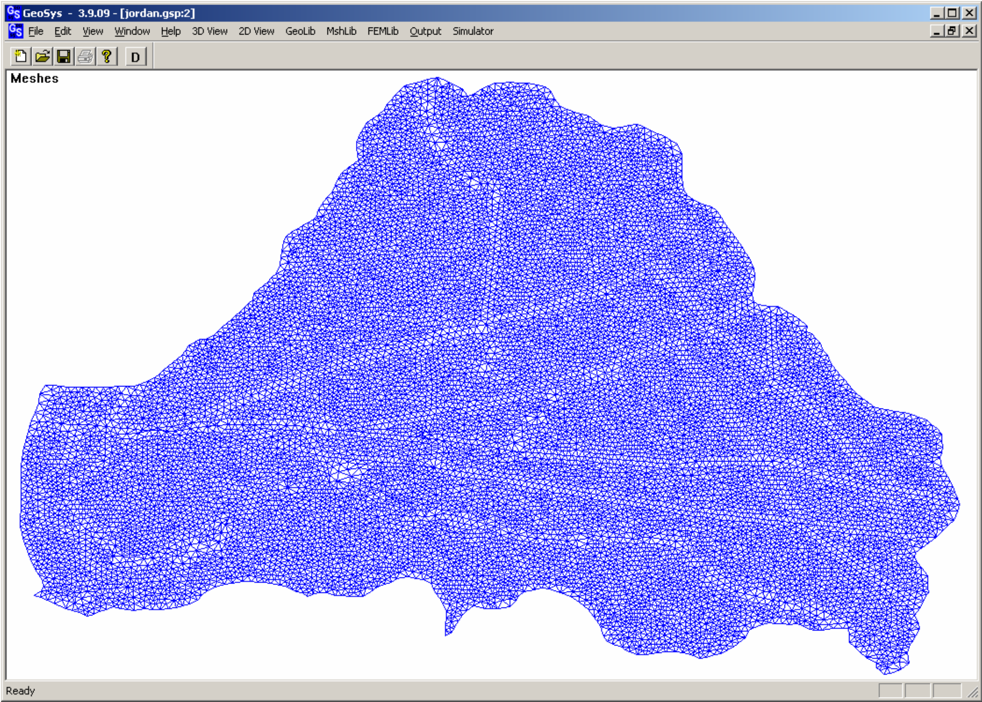


Figure 7.19: Triangulation

Lines: One-Dimensional Element

Line elements can be created along polylines, which are the shape file of wadis. To this purpose, the edges of triangles along these polylines are used. Therefore, the polylines intended for generating line elements must be part of the surfaces, which are used for the triangulation. Figure 7.20 is the line element generator, and the following steps are necessary for the generation of line elements:

- Create polylines for line elements by using our drawing tool in GeoSys/RockFlow or import shape file for Wadis.
- Select the LineGen option from the MSHLib menu.
- The Mesh Polylines dialog allows selecting existing polylines for line meshing.

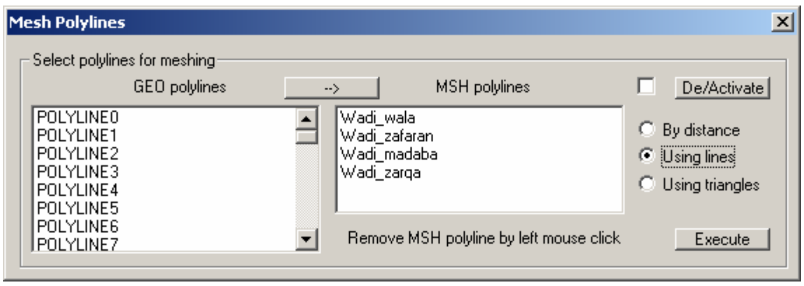


Figure 7.20: Dialog for line element generation from polylines

After executing the generation, the finite element nodes along the polylines are identified. In figure 7.21 the black color lines shows the line elements created along the wadis.

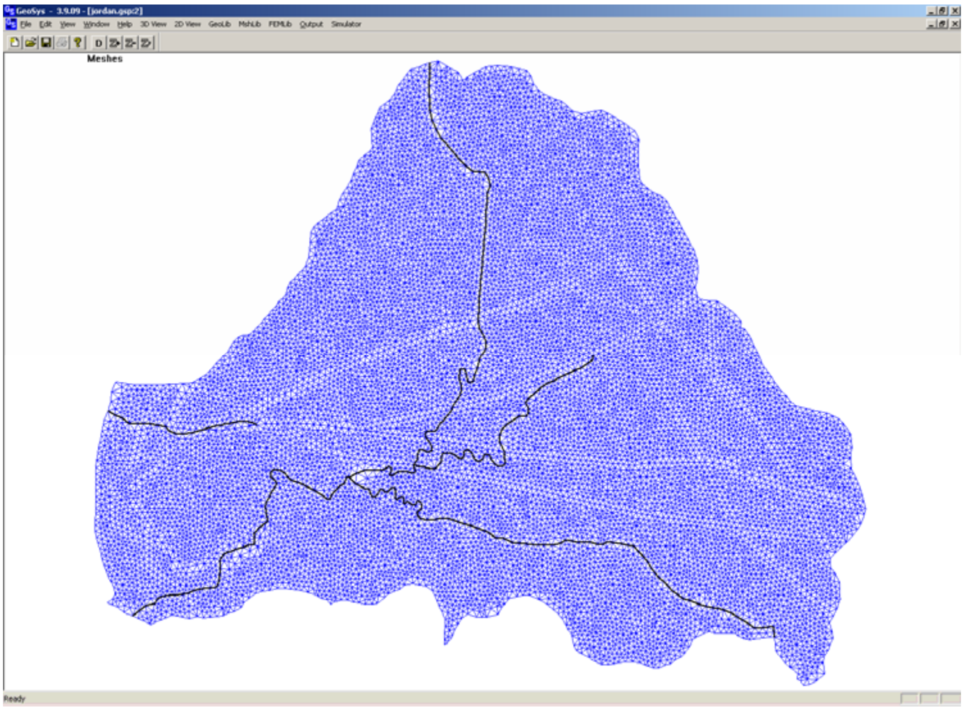


Figure 7.21: Line elements from Wadis

Prismatic Elements

Prism elements can be generated from triangles while extending these to the vertical direction. The PRISGEN dialog is used (Fig. 7.22) to generate the prisms. The following steps are necessary for the generation prisms:

- Select the Tri2Pri option from the MSHLib – PrisGen menu. The number of layers to be generated and layer thickness can be specified. Layer topography can be changed after using mapping techniques.

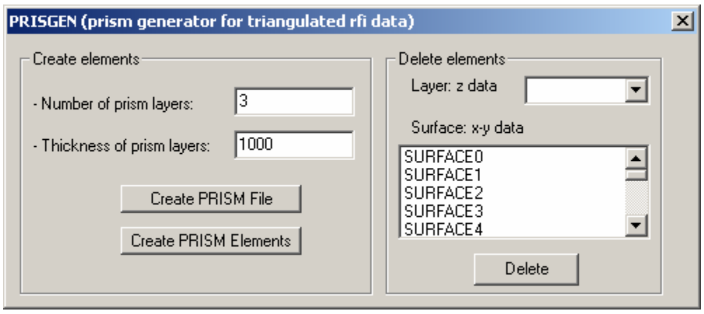


Figure 7.22: Dialog for creating prism elements (Beinhorn 2004)

- Use the option Create PRISM File to write elements to a file (without creating element data structures),
- Use the option Create PRISM Elements to generate the element data.

Figure 7.23 shows the prismatic element in a 3D view (Kalbacher, 2004).

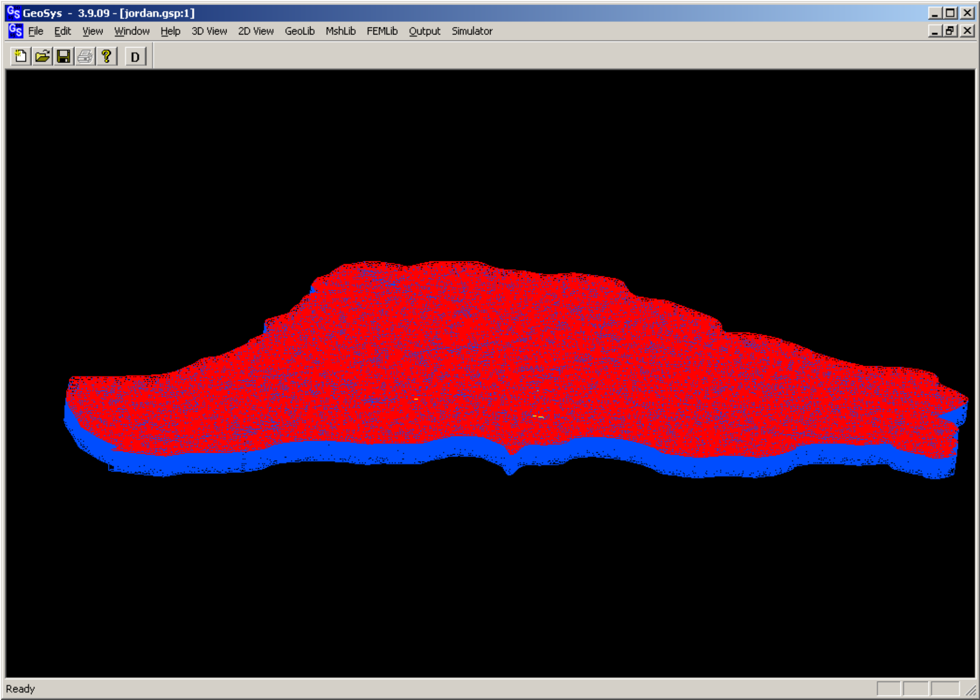


Figure 7.23: Prismatic elements in 3D view (Kalbacher 2004)

Quadrilateral Elements

Quadrilateral elements can be created along polylines, which are the shape file of faults. To this purpose, the faces of prism elements are used. Therefore, the polylines intended for generating quad elements must be parts of the surfaces which were used for the triangulation / prism generation. The elements are generated in the mesh polyline dialog (Fig 7.24). The following steps are necessary during the generation:

- Select the QuadGen option from the MSHLib menu,
- The Mesh Polylines dialog allows to select existing polylines for quad meshing,
- Applying the Execute option, the quad generation is conducted.

In figure 7.25, the red color lines shows quadrilateral elements for the faults.

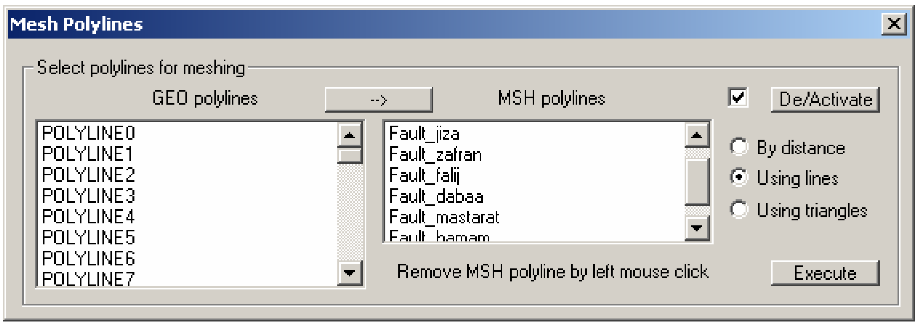


Figure 7.24: Generate quadrilateral elements using faults

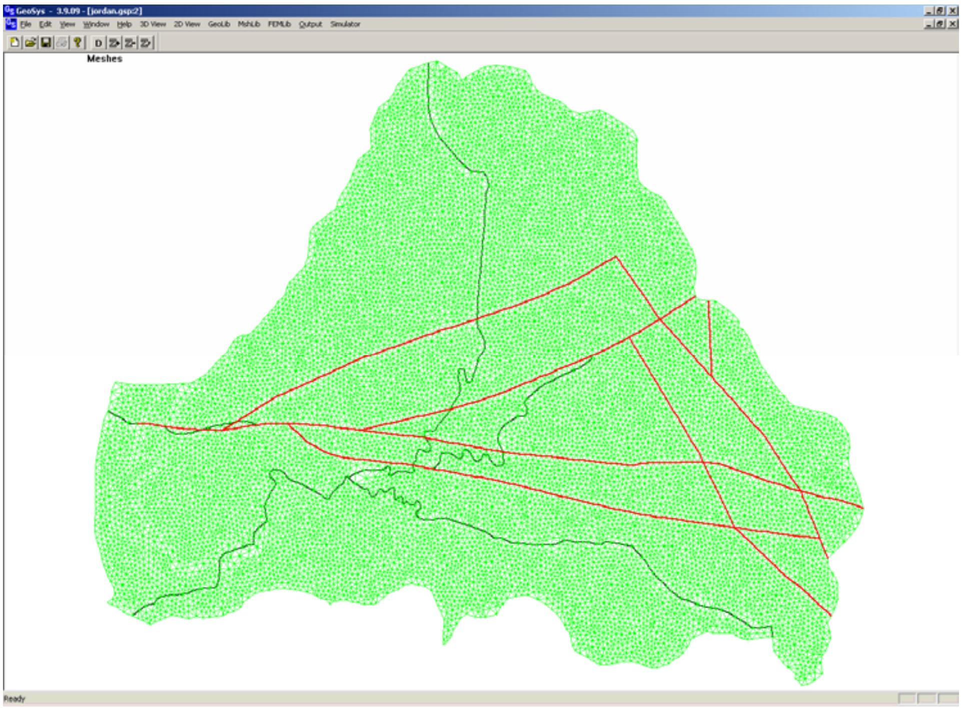


Figure 7.25: Quadrilateral elements (red color)

After all above steps, the 3D finite element mesh of the modeling domain has been finished. In the following, figure 7.26 displays the result with 1D line element, prismatic elements, and 2D triangles and quadrilateral elements to represent the Wadis, surface, faults as well as aquifers and aquitards.

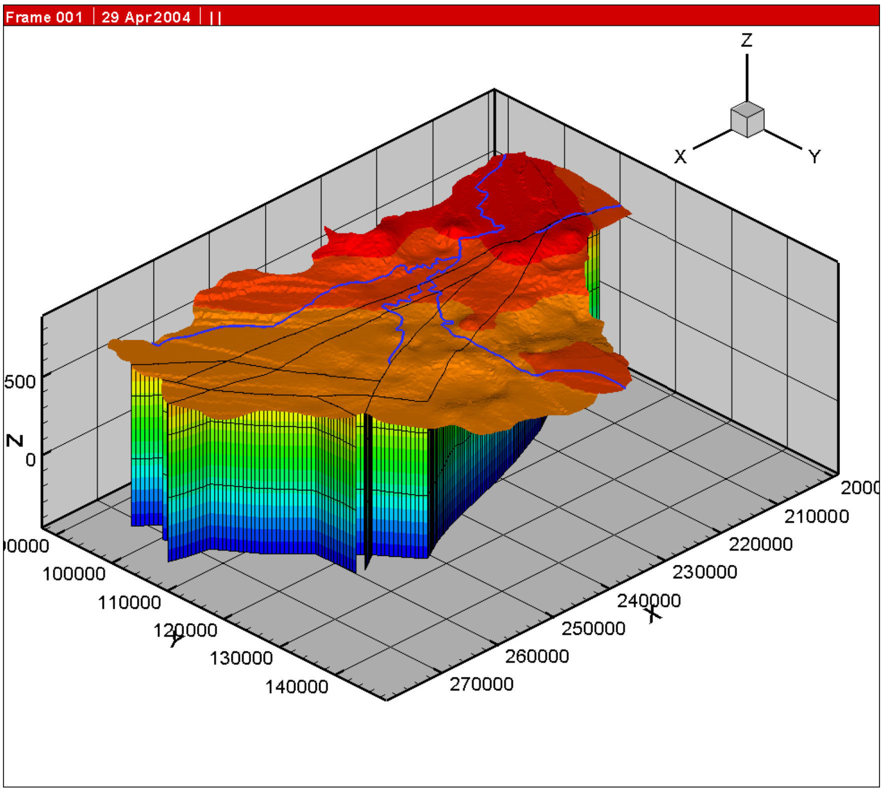


Figure 7.26: Inside the hybrid finite element mesh

Mapping

Surface mapping is the process of making the mesh conforms to stratigraphic irregularities, i.e. thickness and orientation of the mesh slices can be deformed. Different data types can be used; grid files created with Surfer or grid files created with ArcView, which uses a (.ASC) extension. There are four ASC files for four rows from uppermost to lowermost: top_b2a7.asc, base_b2a7.asc, top_ks.asc, base_ks.asc. For example, the nodes of prism elements with Z coordinates equals 0.0 will be mapped using the data given in top_b2a7.asc. If prism elements are to be mapped, prepare an rfi file, which stores element data. After mapping, based on the domain (created from volumes which are defined from surfaces), the three layers will be mapping into the corresponding vertical height (Fig 7.27). In figure 7.28, it shows the mapping result of the whole modeling domain.

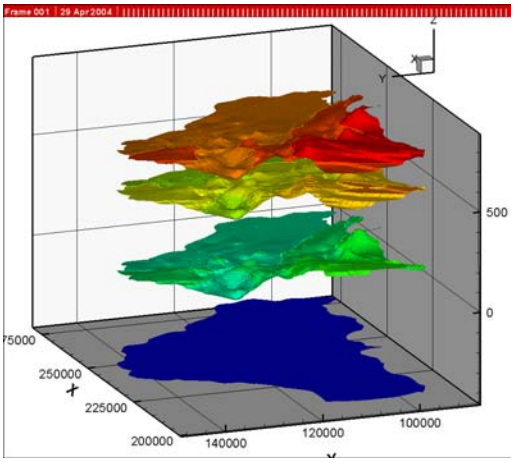


Figure 7.27: Mapping result for each layer

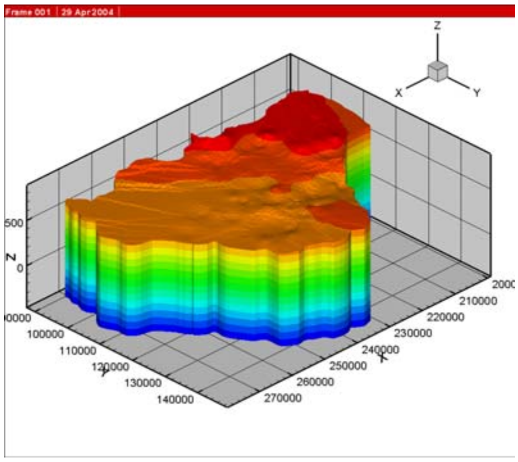


Figure 7.28: Mapping result of the whole domain

7.3.3 Build Process Data (FEMLib)

After having finished all geometric and meshing operations, it comes to specify data for the processes. At first, select flow process to be simulated. Then the boundary condition, source term, material properties need to be set for modeling purposes. Points, polylines and surfaces can be used to set boundary conditions and source term. Here three types of data: Process (PCS type: name of primary variable), Geometry (GEO type: GEOLib data) and the corresponding values for boundary conditions and source terms of the selected primary variable (DIS type) are to be connected. Boundary conditions data are stored in a *.bc file. Source terms data are stored in a *.st file. Material properties are element data, i.e. they are connected with the finite elements by a material group number.

Boundary Conditions

Points, polylines and surfaces (e.g. from GIS projects) can be used to set boundary conditions. In this case, polylines are used to create boundary conditions for the 2D case and surface for the 3D case. The Boundary Conditions dialog (Fig 7.29) combines three types of data: Process (PCS type: name of primary variable), Geometry (GEO type: GEOLib data) and the corresponding values for boundary conditions of the selected primary variable (DIS type). The created instances for boundary conditions are listed in a table and can be handled there (Update, Remove functions). Using the Create Group button a corresponding boundary conditions group for the selected primary variable is created, and the finite element nodes along the polylines are identified (Fig 7.30).

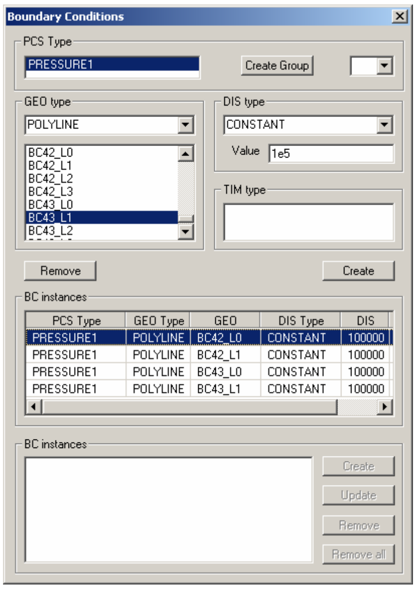


Figure 7.29: Boundary Condition dialog

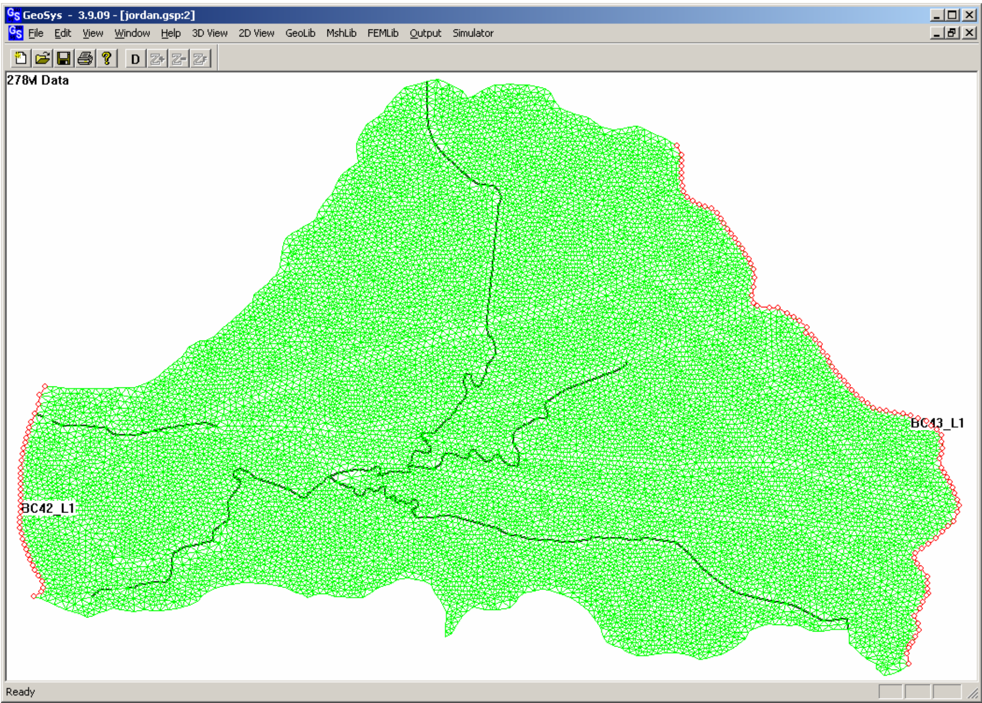


Figure 7.30: Identified finite element nodes for the boundary condition

The procedure to assign boundary conditions at surfaces is identical to that for polylines. As mentioned before, layer polylines are used to create vertical surface (Fig 7.31) for the 3D boundary condition. After creating the boundary condition groups, the mesh nodes of the surfaces are identified.

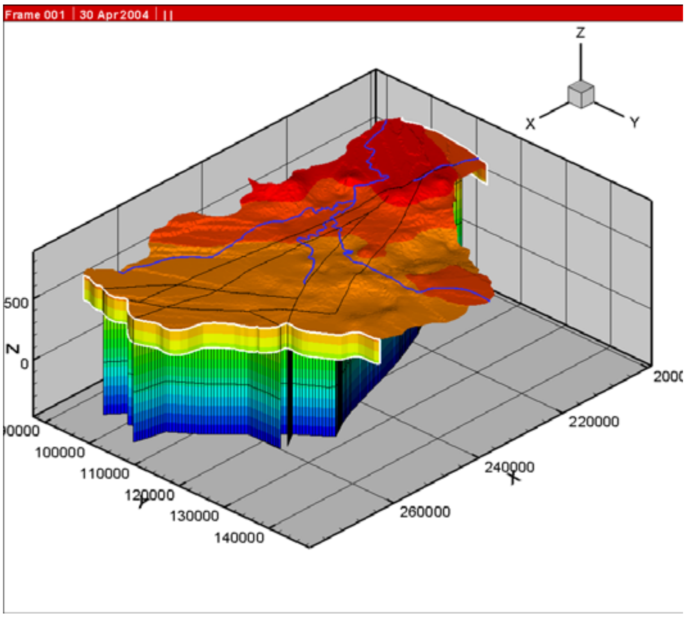


Figure 7.31: Vertical surfaces for the boundary condition

Source Terms

Points, polylines, surfaces and volumes (e.g. from GIS projects) can be used to specify source terms. The Source Terms dialog combines three types of data: Process (PCS type: name of primary variable), Geometry (GEO type: GEOLib data) and the corresponding values for boundary conditions of the selected primary variable (DIS type). In this case, wells are used to create source terms in the source terms dialog (Fig 7.32).

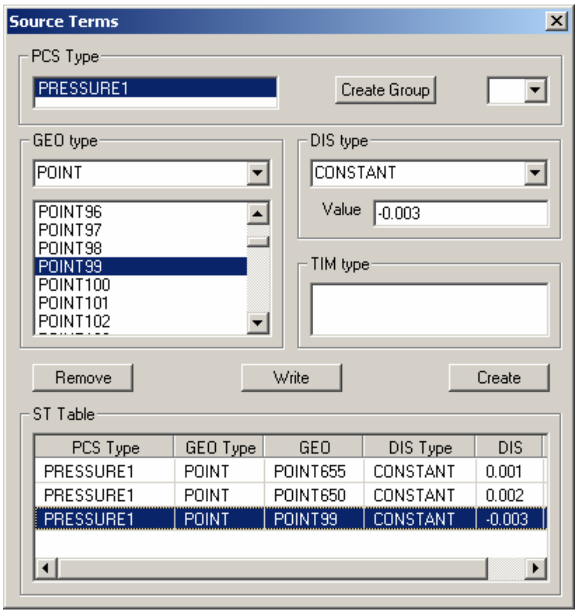


Figure 7.32: Source term dialog

Material Properties

Material properties (MAT) are element data, i.e. they are connected with the finite elements by a material group number.

The first step is to link MAT database with GEO data. The MAT group editor (Fig 7.33) allows combining material and geometric data. Material data can be imported from a database (button Load DB). In the below example the selected material (Upper Aquifer) is linked with the geometric object SURFACE1, i.e. all finite elements within this surface inherit the material data Upper Aquifer. The result for all the surfaces assigned with material properties are shown in Figure 7.34 with different displaying color.

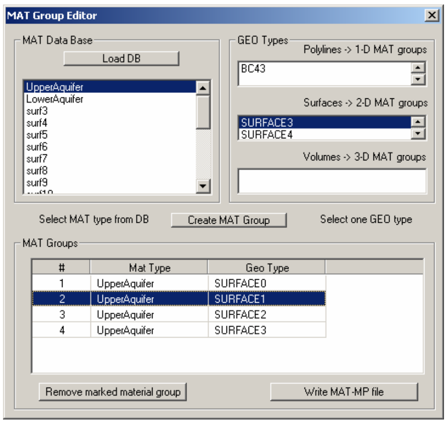


Figure 7.33: MAT Group Editor (Gronewold 2004)

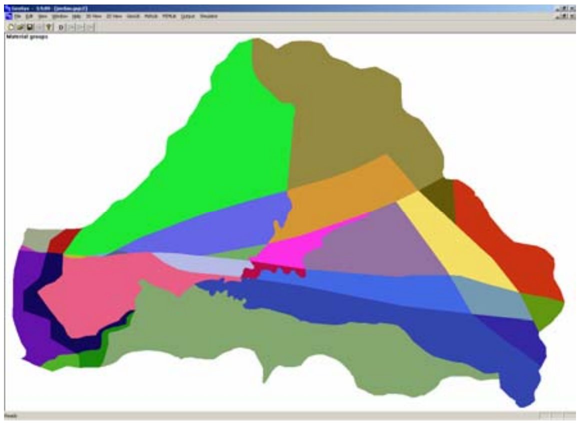


Figure 7.34: Link MAT data with DEO data

Now the second step is to link the MAT data with MSH data. The bold lines (Fig 7.35) shows the identified MAT groups for line elements, and figure 7.36 shows the identified MAT groups for 2D elements, e.g. triangulations.

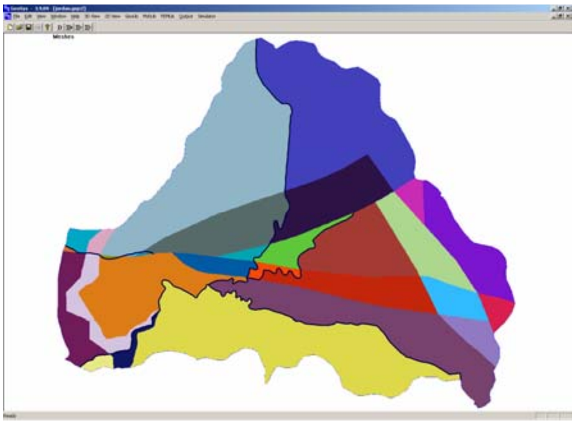


Figure 7.35: Link MAT data with 1D elements

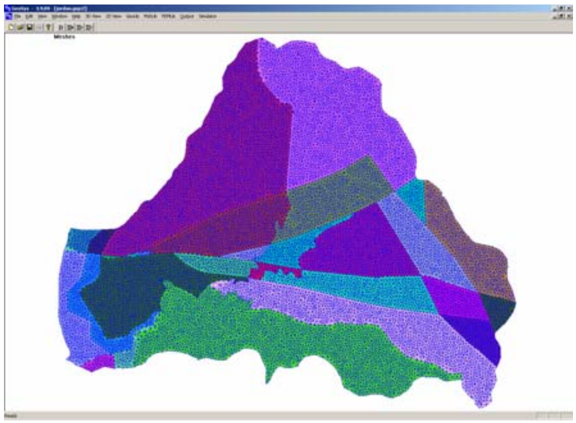


Figure 7.36: Link MAT data with 2D elements

Three layers (Fig 7.37) are shown to represent the two aquifers and the aquitard in between, which are modeled by prismatic elements.

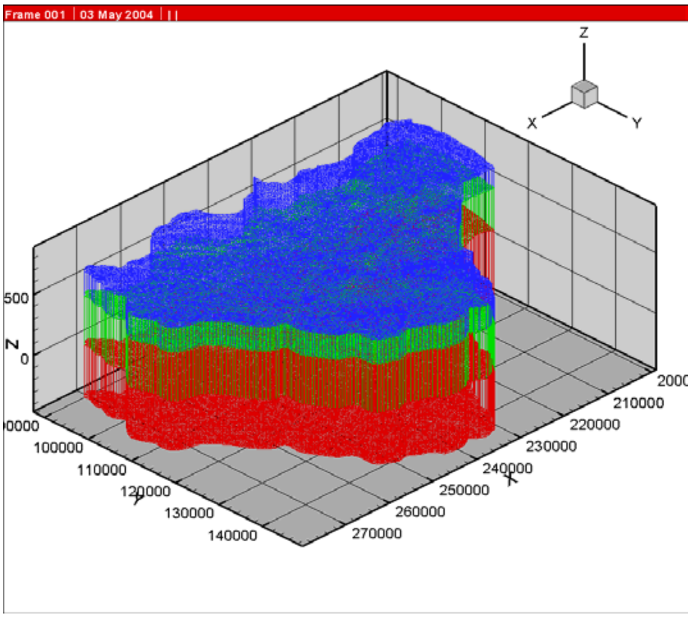


Figure 7.37: Link MAT data with 3D elements

7.4 Simulation Results

Flow Model

The simulation results (steady state) of a fully 3D flow and heat transport model are presented.
As mentioned in the above section, the hydraulic system is controlled by recharge and discharge conditions to or from the model area as well as by discharges from several springs. Figure 7.38 shows the distribution of the steady state hydraulic head in the model domain, where the highest values occur in the northern recharge area and the lowest values are in the western spring field. The model is now ready for flow simulations. Due to the multiple grid technology, different element types can be activated or deactivated in order to study different details of the complete model.

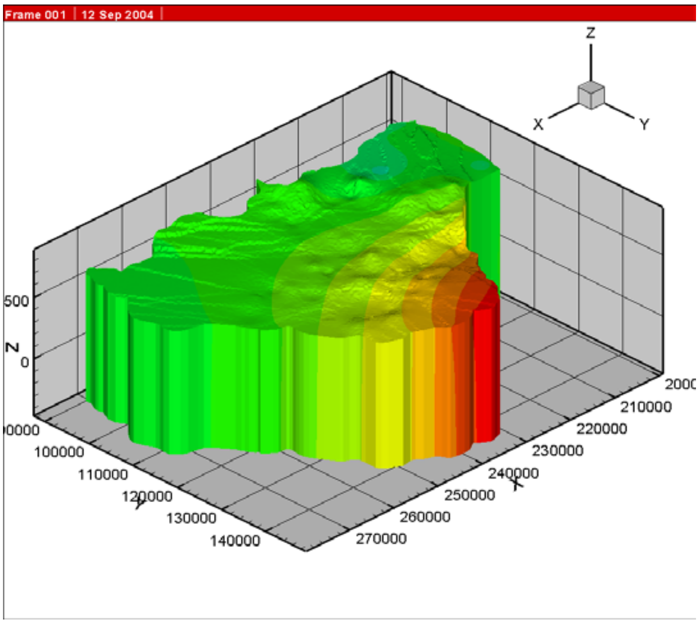


Figure 7.38: 3-D groundwater flow model, hydraulic head in the model area

Heat Transport Modeling

The thermal basic processes are illustrated in figure 7.39. There is a permanent heat flow from the base to the system. Through the North groundwater is entering the upper aquifer and through the East the lower aquifer. This groundwater has to cool the whole system; otherwise, the temperature will increase permanently.

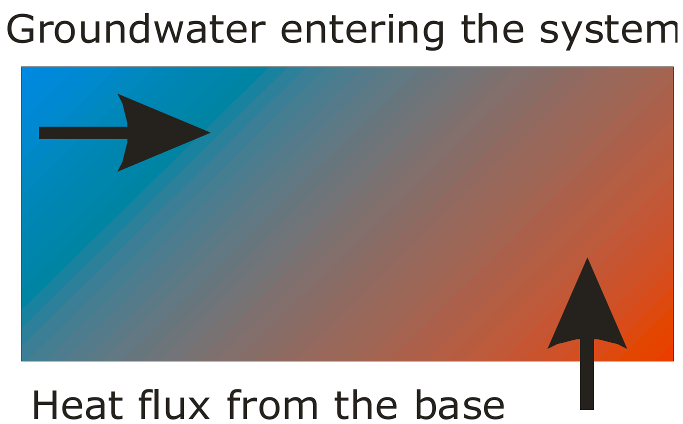


Figure 7.39: Thermal basic process in the area.

Figure 7.40 shows a first long-term simulation (30000 years) of the thermal system based on the hydraulic model. The simulation shows a permanent increase of temperatures. The groundwater entering the system is not equilibrating the base heat flux. This indicates to possible defects in the current model. Firstly, the outside groundwater recharged to the domain is underestimated. Secondly, the base heat flux is overestimated. This means, involving thermal data to the simulation, the hydraulic model can be improved.

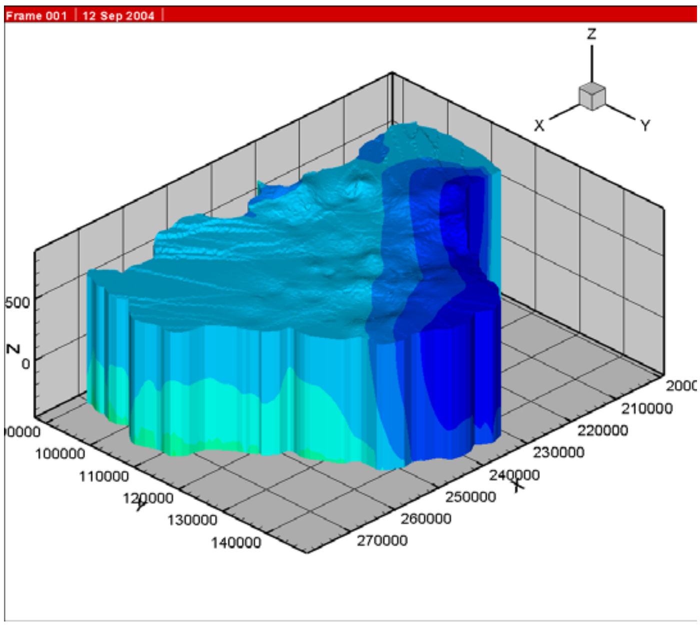


Figure 7.40: Temperature distribution in the model area

8 GROUNDWATER MODEL FOR THE JERICHO PLAIN AREA OF PALESTINE / LOWER JORDAN RIFT VALLEY

8.1 Introduction

This GIS based model using GeoSys/RockFlow program is set to visualize the effect of the well pumping on the water level. This effect is apparent during the dry season in October. The water level dropped in the first agricultural season, which come directly after the replenishment of the aquifer causes water level decreasing. The pumping process in the second agricultural season, which comes directly after the dry season, causes further decrement in the water head, as there was no replenishment after the first pumping time. The model concept and available data handling were new in this area, where the model was build based on the alternative marl and gravel layers that normally dominated in the alluvial environment. The model need to be improved and verified using skimming and scavenger pumping test, in order to show the over pumping effect on salinity more clearly.

8.2 Study Area

The study area is located in the eastern boundary of Palestine (Fig 8.1) to the north of the Dead-Sea basin. A previous study (Khayat et al, 2005) suggests two possible mechanisms of recharges. The first is the direct surface infiltration of the water run off through wadis and the second is the infiltration of irrigation network drained from Sultan spring that fed by the upper cretaceous aquifer system with $CaCO_3$ water to the west of the area. The data also indicates such a leakage from the water of upper cretaceous aquifer to the adjacent wells in the west, suggesting a mixing of two water sources. Moreover, the tritium units reflect a recent groundwater age in the west boreholes in relative to old water age (prior to 1956) in the eastern Arab Project wells. The ages of the water from the other sampled wells within the area range in between (Khayat, et al, 2005). However, this suggested mixing mode between the two possible recharge mechanisms is still not well studied.
A series of numerical simulations on the water level changes in relation with the possible recharge mechanisms, pumping rates and date were carried out, in order to better understand the mixing mode of the recharge mechanism as well as the effect of human activities on the ground water level variations. The model is therefore useful for maintaining a sustainable exploitation of the groundwater resources in the study area.

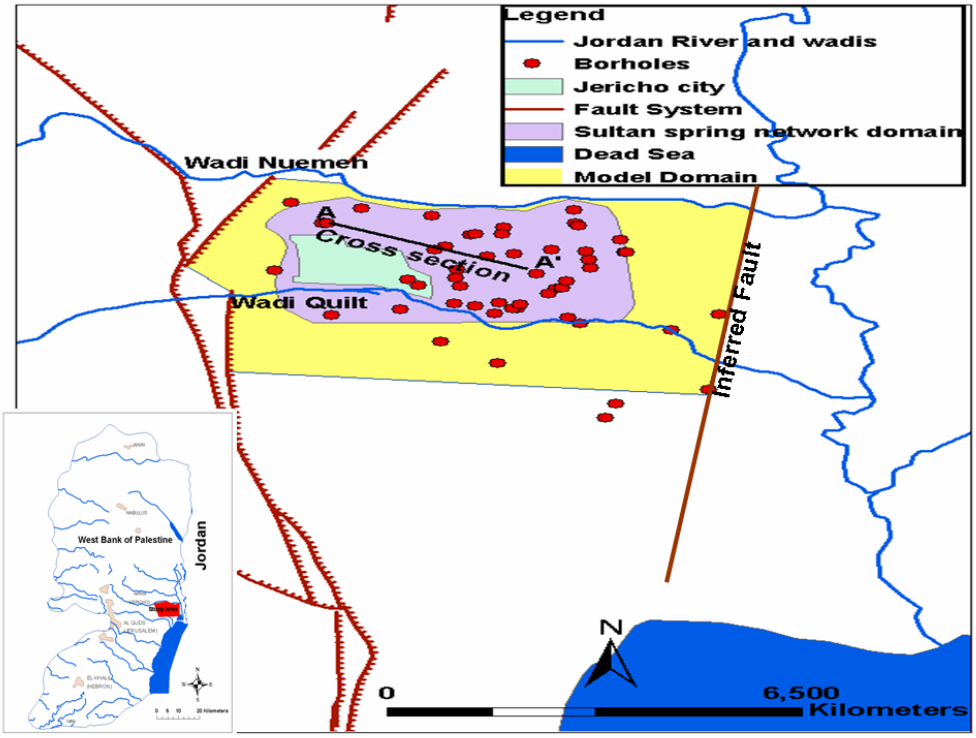


Figure 8.1: Location map of the study area (Khayat 2005)

Geological Background

The geology of the area is part of the Jordan rift valley geology. Two Dead Sea group aquifers are located in the Jericho area, the Holocene or sub-recent alluvial aquifer and the Pleistocene Samra aquifer. The Holocene of sub-recent Alluvial aquifer is distributed and used mainly in the Jordan Valley and neighboring areas. It is built up of sub-recent terrigenous deposits formed along the outlets of major wadis. These alluvial fans are still under accumulation after large floods and consist of debris from all neighboring lithology and are deposited according to their transport energy. The transport normally takes place along alternating channels. Thus, permeable horizons alternate with impermeable lithology within the deposits. The maximal thickness near the rift margins can reach up to high values, thinning out towards the center of the rift basin. The alluvial aquifer often directly overlies the Pleistocene gravel aquifer and by that is hydraulically interconnected with this aquifer (Fig 8.2). The three members (Samra coarse clastic, Samra silt and Lisan) of the Pleistocene Samra aquifer are a lateral facies succession from terrestrial/fluvial, to deltaic/limnic and limnic/brackish lake environments. They reflect the Plio-Pleistocene depositional conditions of the Lisan Lake. Lisan, the marl, gypsum and silt lacustrine unit is generally considered an aquiclude, void of exploitable water. It is distributed mainly towards the middle of the graben. Samra formation consists of two members: A silt member underlying or interfingering with Lisan and a coarse clastic member further to the West that predominantly consists of gravel, interbedded with clay, sand and marl horizons.

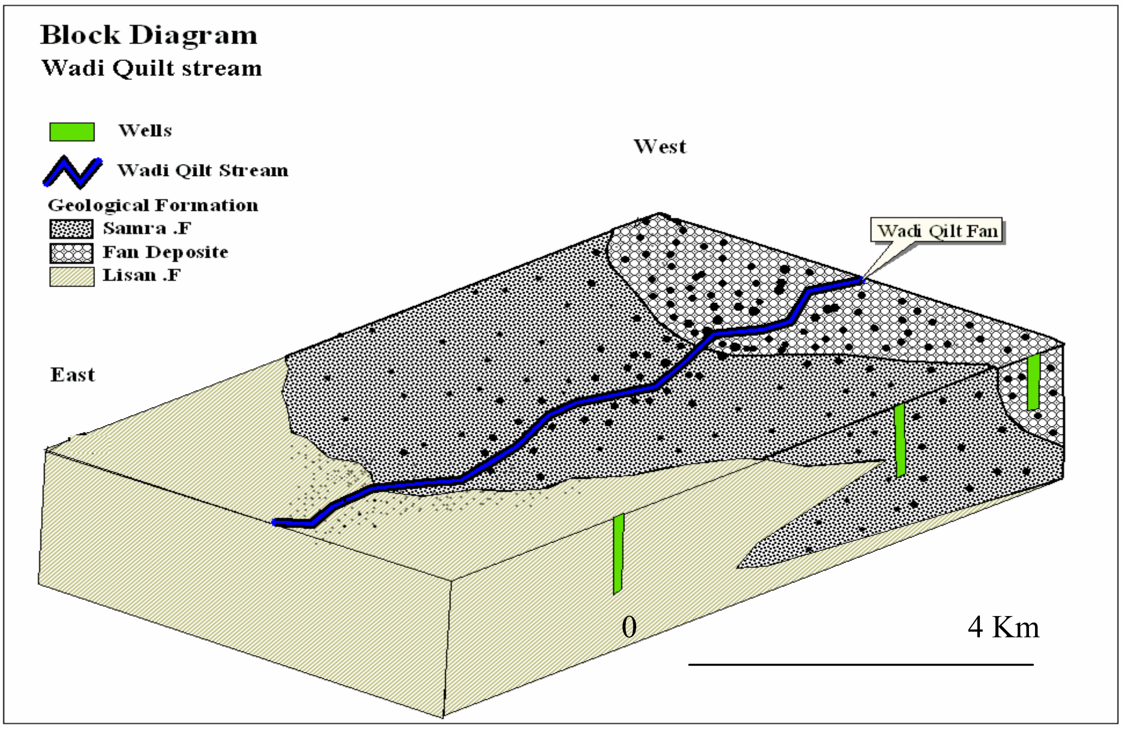


Figure 8.2: Interfingering between Lisan and Samara Formation surrounding Wadi Quilt stream (Khayat 2005)

8.3 Set up of a GIS Project

The first step of the whole modeling task is to prepare the input files for GeoSys/RockFlow. Those input files are shape files, which are created by using ArcGIS based on the hydrogeological conceptual model of Jericho area. The data from GIS could be imported directly into GeoSys/RockFlow for the modeling purpose. The whole GIS project are shown in Figure 8.3, and those thematic layers include:

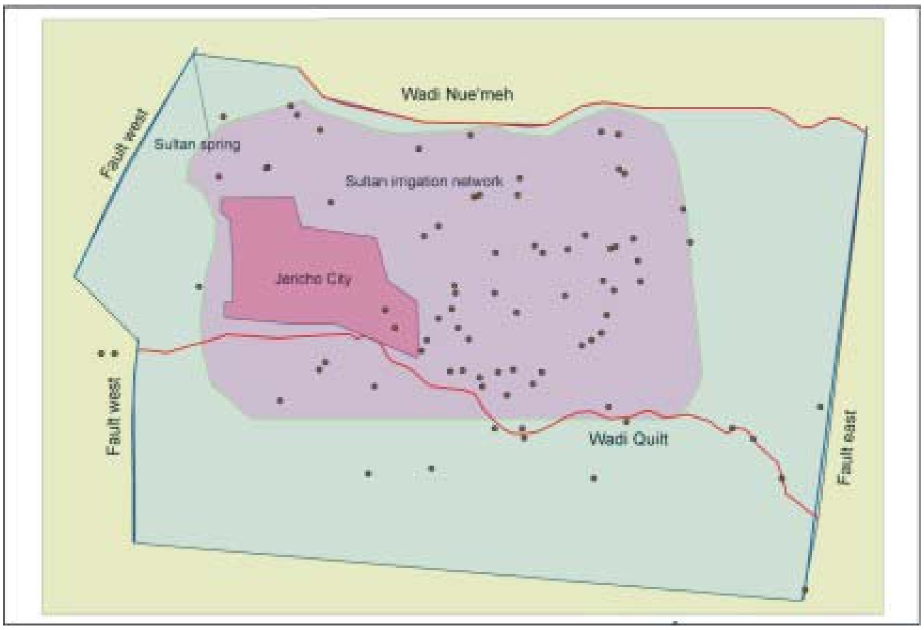


Figure 8.3: The GIS project in the area

The Study Area

The model domain is subdivided into four surfaces (Fig 8.4) based on the domain boundary, wadi, faults and the Jericho city.

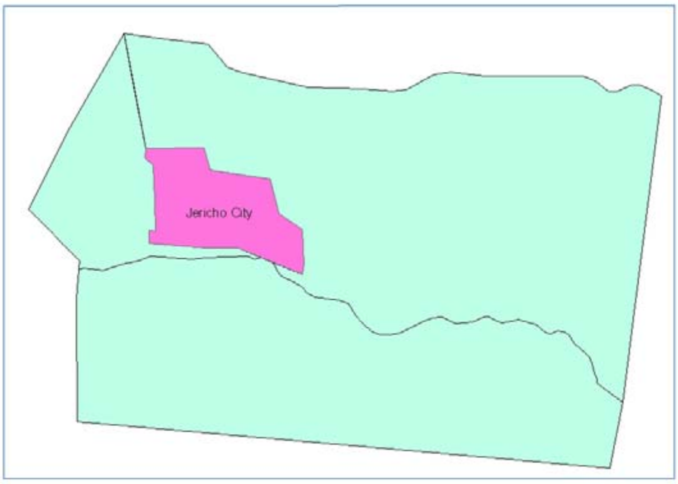


Figure 8.4: The surfaces area

Wadis

The study area is drained eastwards toward Jordan River by two major wadis (Fig 8.5): wadi Quilt in the South of the area and wadi Nue'meh in the north. A river model is built based on wadis.

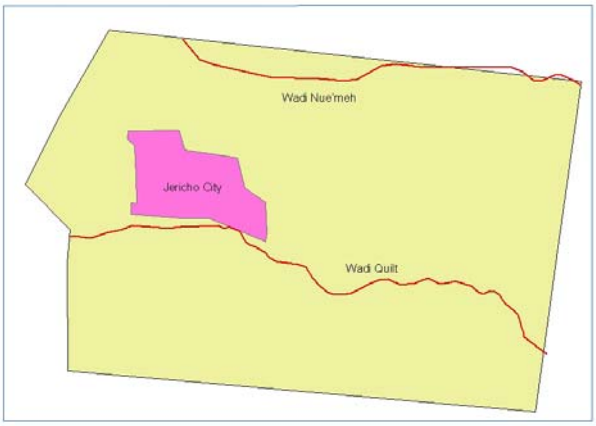


Figure 8.5: The major wadis in the area

Faults

The study area is highly affected by faults especially in the western part. These faults (Fig 8.6) to the west are responsible for the spring's system, mainly for Sultan spring, and act as a barrier between the upper cretaceous aquifer and the shallow Pleistocene aquifer.

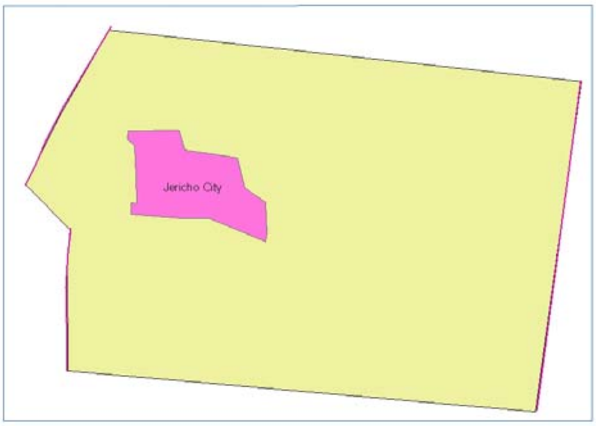


Figure 8.6: The major faults in the area

Borehole Locations

More than 60 wells were drilled in the Jericho plan area. The majority of these wells are private wells, which have been drilled for agricultural purposes, 12 of these wells are used to describe the lithological formation of the upper most 100-170 meter of the aquifer. Sultan spring in the west has relatively high water quality and is used for domestic as well as agricultural uses. Figure 8.7 shows the boreholes in 3D view.

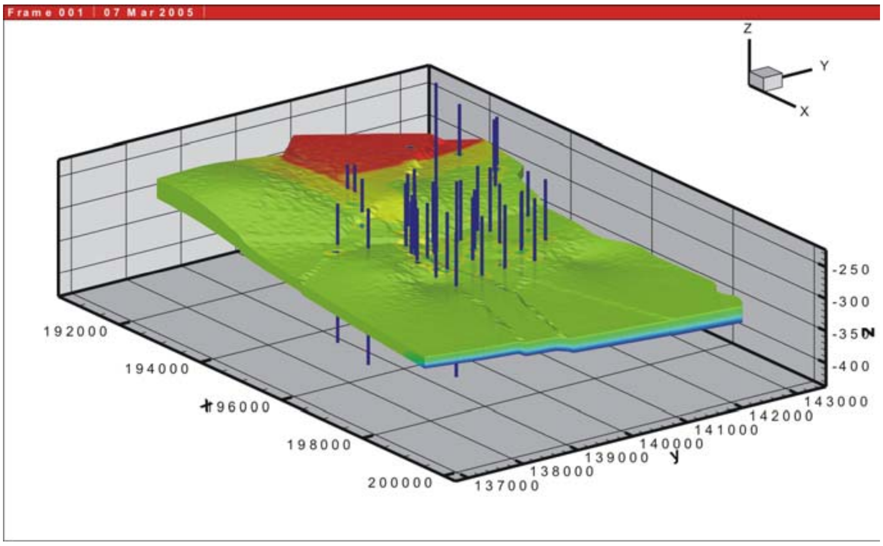


Figure 8.7: Borehole locations in 3D view

Water Level

Several water level measurements for many previous years are taken and are used in constructing a water level contour map in the shallow aquifer system.

Wells for Surface Topography

The wells used for constructing the surface topography are shown in figure 8.8. Applying interpolation tools processes the well data, and the derived data was managed and converted into ASCII file for the mapping purpose.

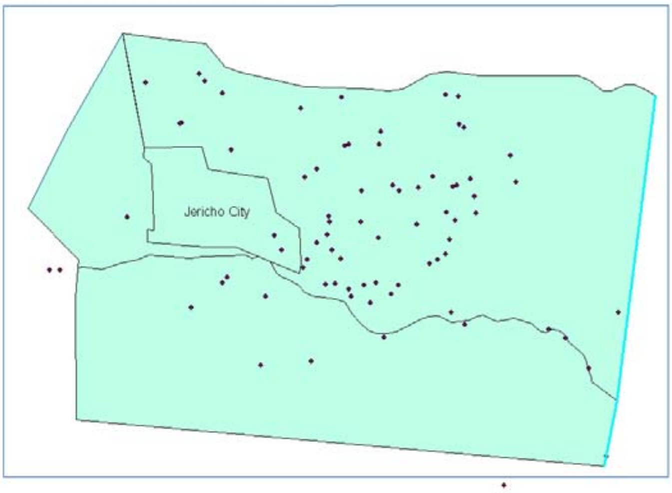


Figure 8.8: Wells for surface topography

Extraction Rates

Several extraction rate measurements were taken from the working wells in the area in m^3/hr, the average daily of wells operation is 8 hrs/day, and thus a long-term estimation for the system output in this aspect was calculated.

Sultan Irrigation Network

Depending on the irrigation network that is drained from the sultan spring, a shape file that covered the irrigation channel area is created. See figure 8.9.

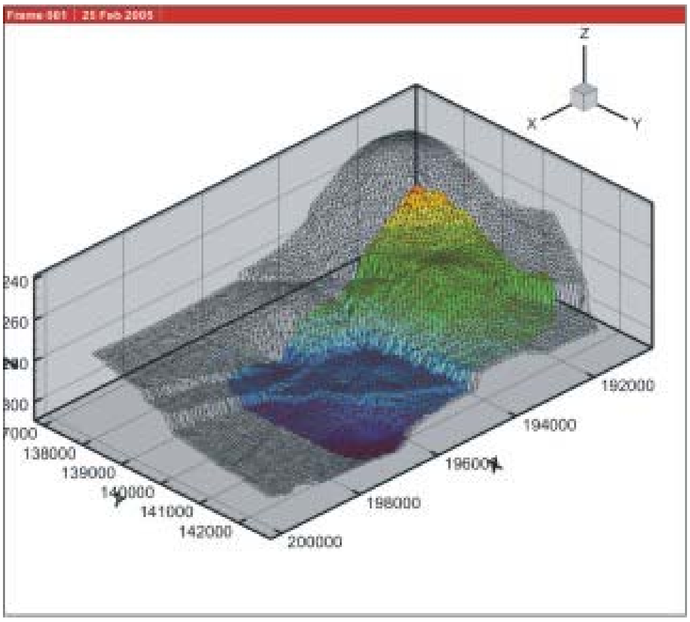


Figure 8.9: Top surface of the model domain with Sultan spring irrigation area

Interpolated Raster Maps for Layer Elevation

The interpolation capacity of spatial analyst is used to create raster map by processing on the observation well data, which describe the lithological information of the seven-layer model. There are altogether 7 layers including the surface layer for the 3D model, and are shown below (Fig 8.10):

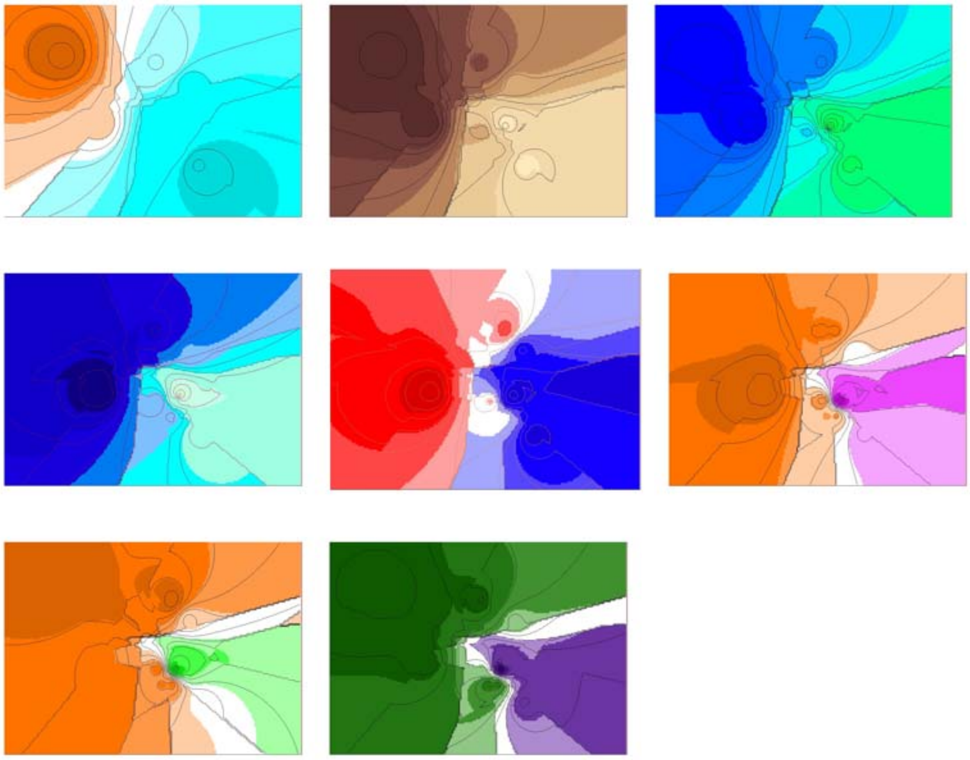


Figure 8.10: Interpolated raster layers

Boundary Conditions

Boundary conditions are given through Polylines defined in a shape file. It was assuming that there is no water movement from the north to the south or vice versa. Therefore, the only active model boundaries were assumed to flow the west and from the east.

8.4 Set up of a GeoSys/RockFlow Project

8.4.1 Set a 3D Structural Model

To build up a 3D structural model, the shape file of the model domain is imported into GeoSys/RockFlow and converted the shape file into GeoSys/RockFlow geometric data type GEOLib - GLI. Then create finite element mesh, e.g. triangles to build a 2D model. Based on this 2D model, a seven-layer 3D model is constructed by prismatic elements. The surface mapping is done which is the process of making the mesh conform to stratigraphic irregularities using raster grid files for those seven layers with one up most surface layer. The result is saved in a RFI file, which is the file format of MSHLib. In the last, build volumes for the whole model. Each volume consists of one top surface and one bottom surface and the prismatic elements inside it. Therefore, for this seven-layer model, each layer has four surfaces, and 28 volumes for the model are built. In the following, it introduces how to build a 3D structural model from 2D model.

2D Geometry

The imported GIS data are converted into points and polylines (Fig 8.11). Surfaces (Fig 8.12) are also created from the polylines.

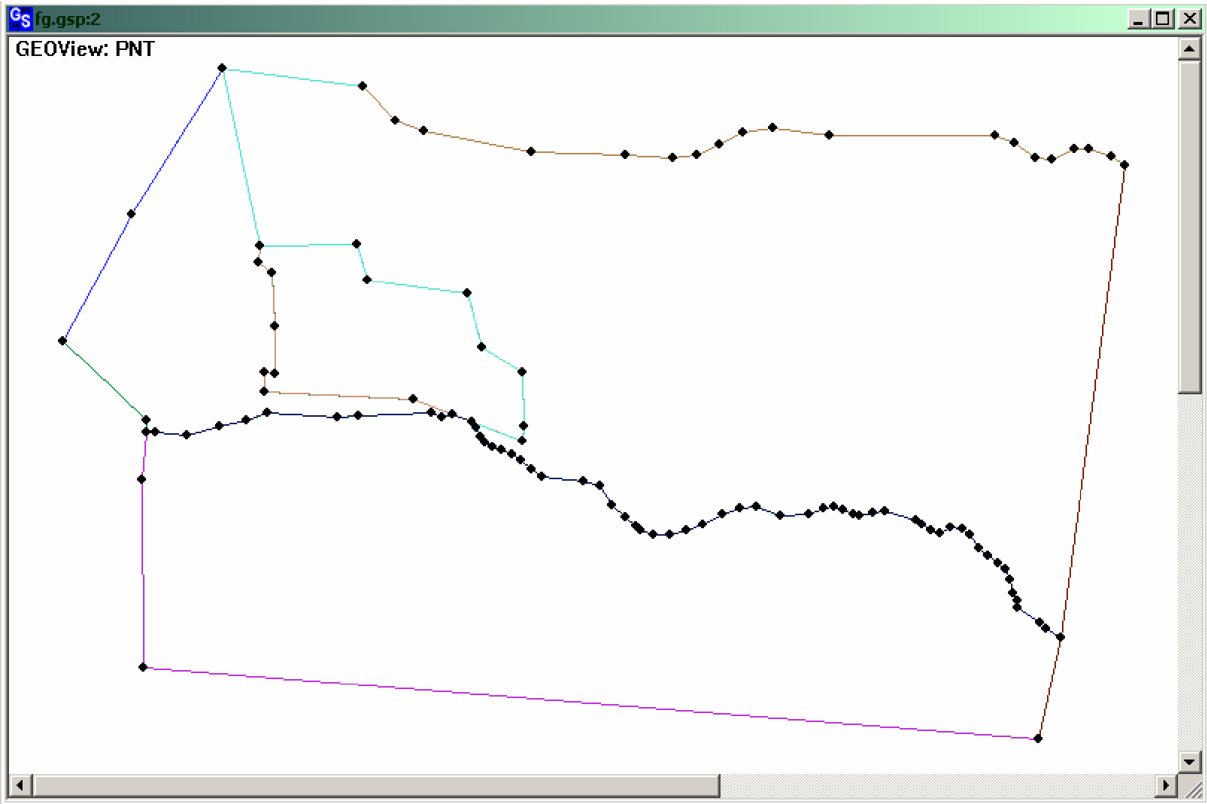


Figure 8.11: Polylines in GEOView

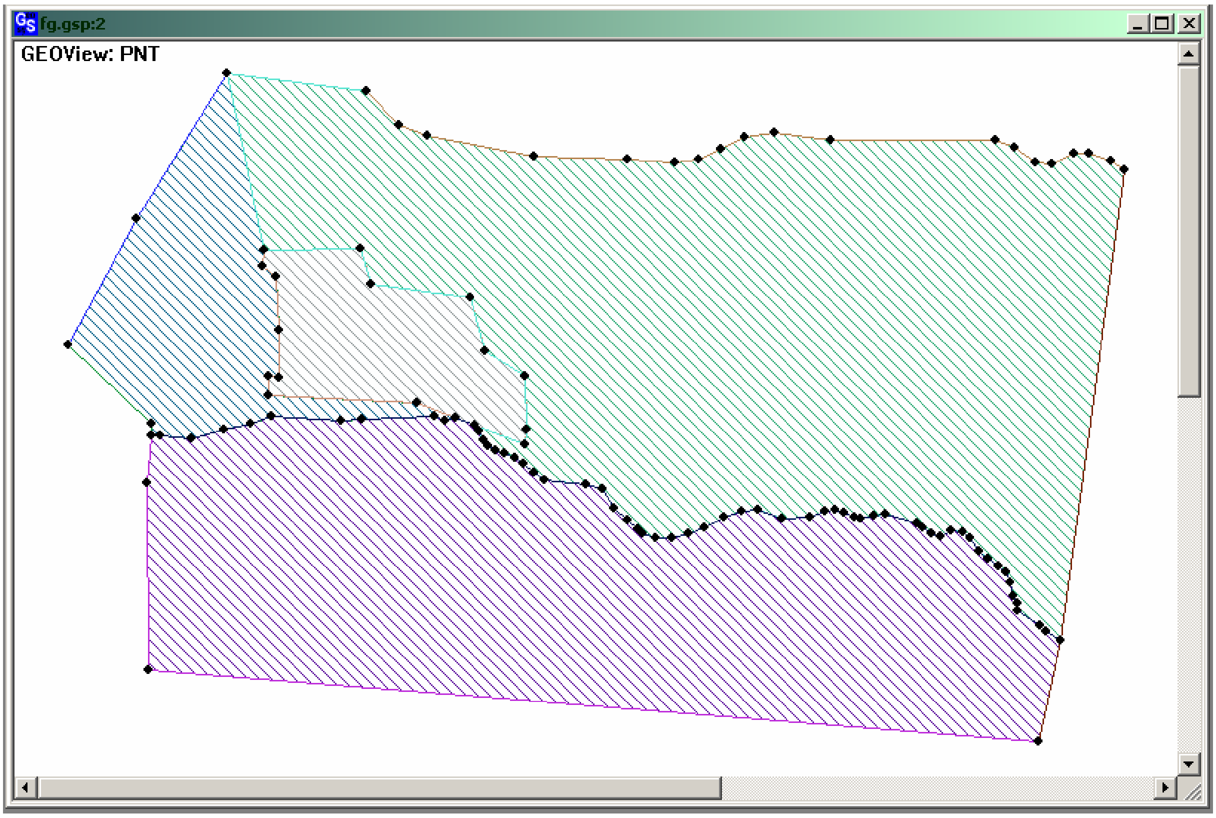


Figure 8.12: Surfaces in GEOView

Layer Polylines

The generation of layer polyline need the GLI file and mapped mesh file. As a result, files with extension.PLY are created depending on the layers of model and attached the new polylines in the GLI file. For example, BC_RIGHT_L0.ply, BC_RIGHT_L1.ply, BC_RIGHT_L7.ply. One .PLY file is an array of points (mapped nodes) with x, y, z coordinates. Figure 8.13 shows the Tecplot files for the layer polylines. Layer polylines are used as boundary conditions and to create layer surfaces for a 3D case.

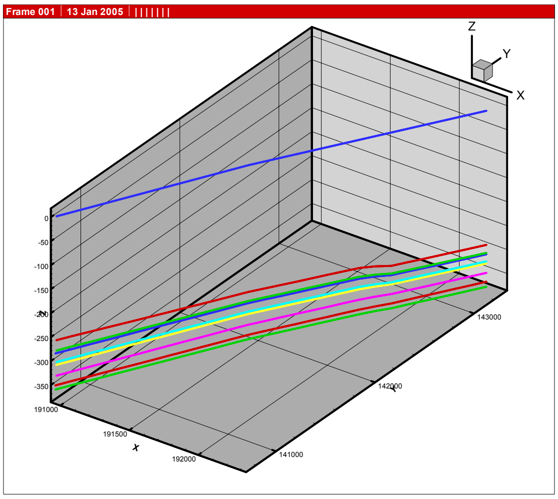


Figure 8.13: Layer polylines

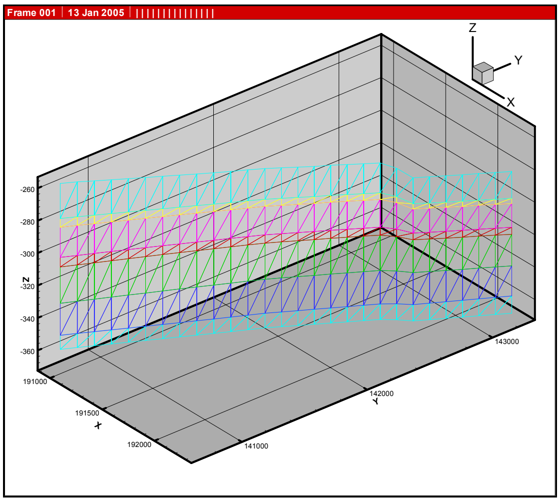


Figure 8.14: Layer surfaces

Layer Surfaces

Vertical surfaces can be created from two vertical layer polylines. Those surfaces are converted to TINs. Each layer surface is attached to the GLI file. Layer surfaces are used to create boundary condition. Figure 8.14 shows the TINs for the layer surfaces.

Volumes

To create the volumes, TINs for the surfaces need to be generated. Figure 8.15 shows the TINs for the surfaces. These surfaces are attached to the GLI file and the geometric information is saved in an extra TIN file. The result is shown in the Figure 8.16.

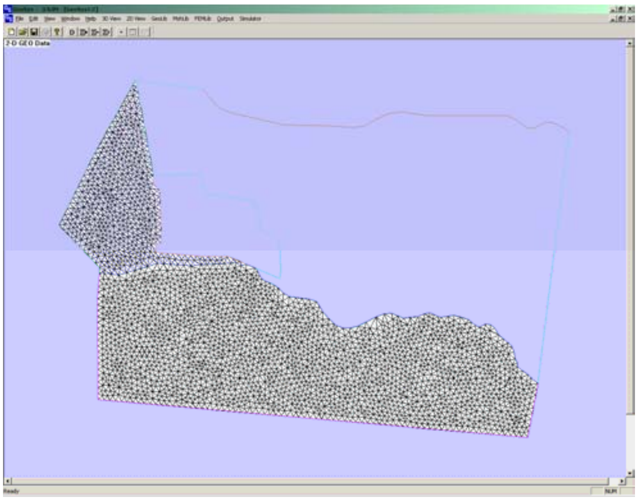


Figure 8.15: TINs for the surfaces

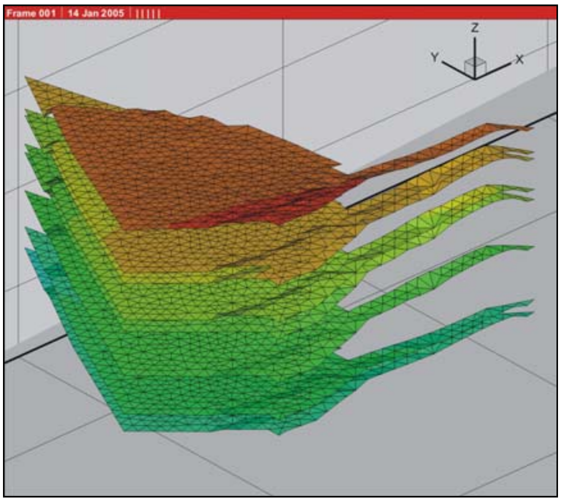


Figure 8.16: TINs for the layer surfaces

Layer Volumes

Select the surfaces from the surface list and add to the volume surface list in the volume editor (Fig 8.17). One volume consists of two layer surfaces. Figure 8.18 shows the layer volumes inside the modeling domain.

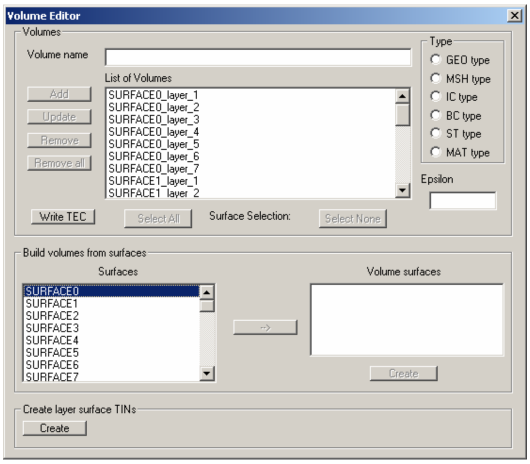


Figure 8.17: Volume editor

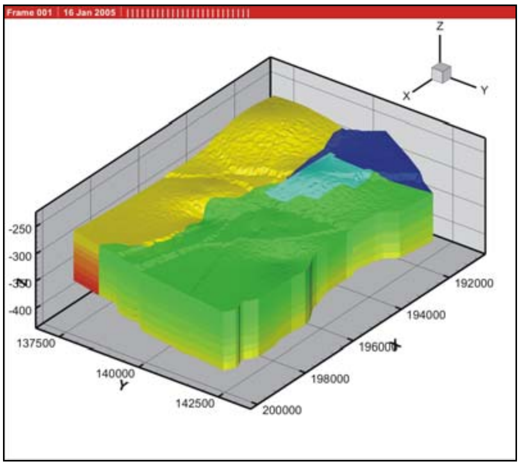


Figure 8.18: Layer volumes

8.4.2 Discretization

The general steps for the hybrid meshing procedure in this application are:

- Create a triangulation based on surfaces (SFC) for the 2-D surface water model. The surfaces must be topologically consistent,
- Create line elements for the 1-D Wadis model based on the triangulation,
- Create prismatic elements for the 3-D subsurface model.

Triangulation:

The triangle meshes for the 2D model domain are generated, and the result is shown in the figure 8.19.

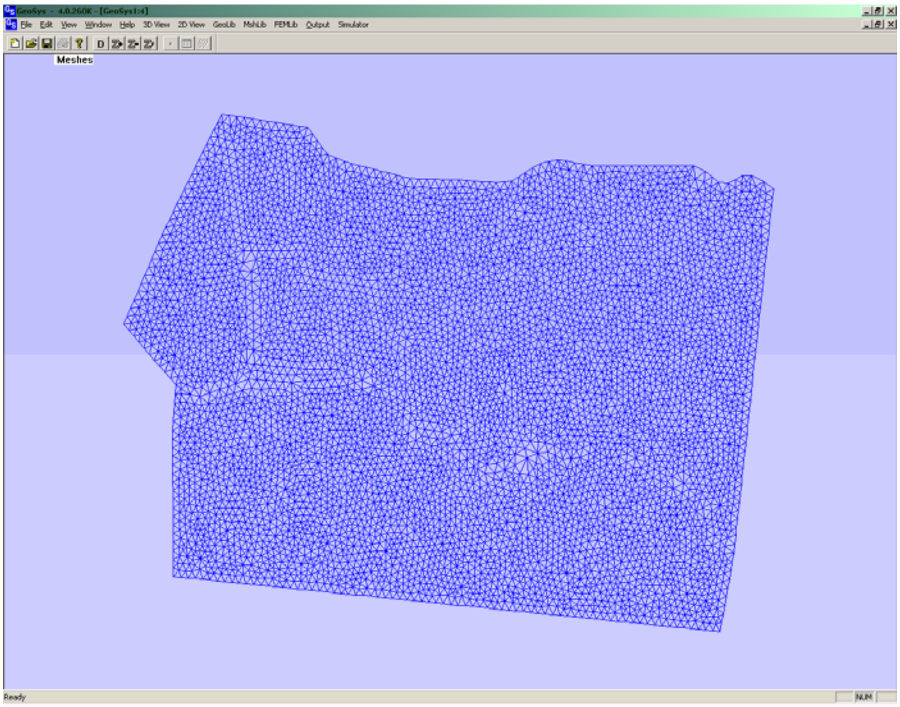


Figure 8.19: Triangulation

The irrigation area is refined by increasing the mesh density of the points along the boundary area, and the result is shown in Figure8.20.

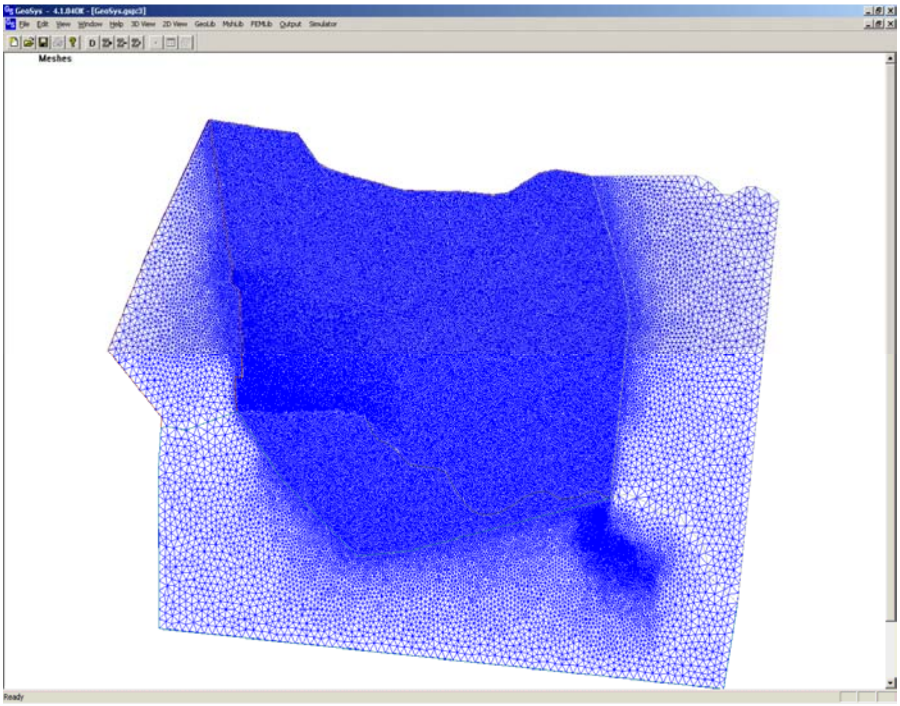


Figure 8.20: Triangulation with refinement in the well field and irrigation area

Prisms

The existing triangulation is used to create the prismatic elements in the PRISGEN dialog (Fig 8.21). The layer of this model is seven, and the thickness of prism layer is set to default value 1000. Figure 8.22 shows the prisms in 2D view.

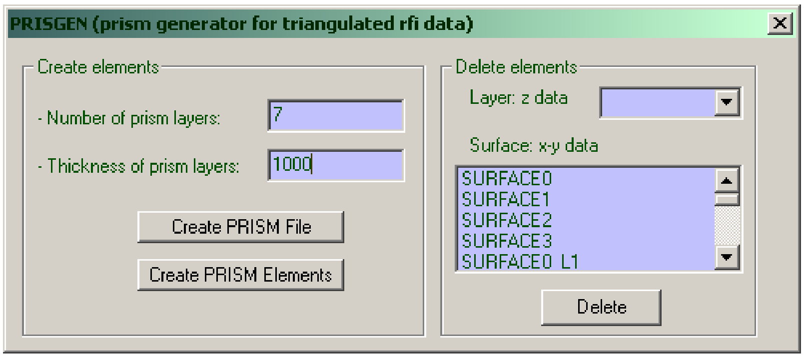


Figure 8.21: PRISGEN dialog (Beinhorn 2004)

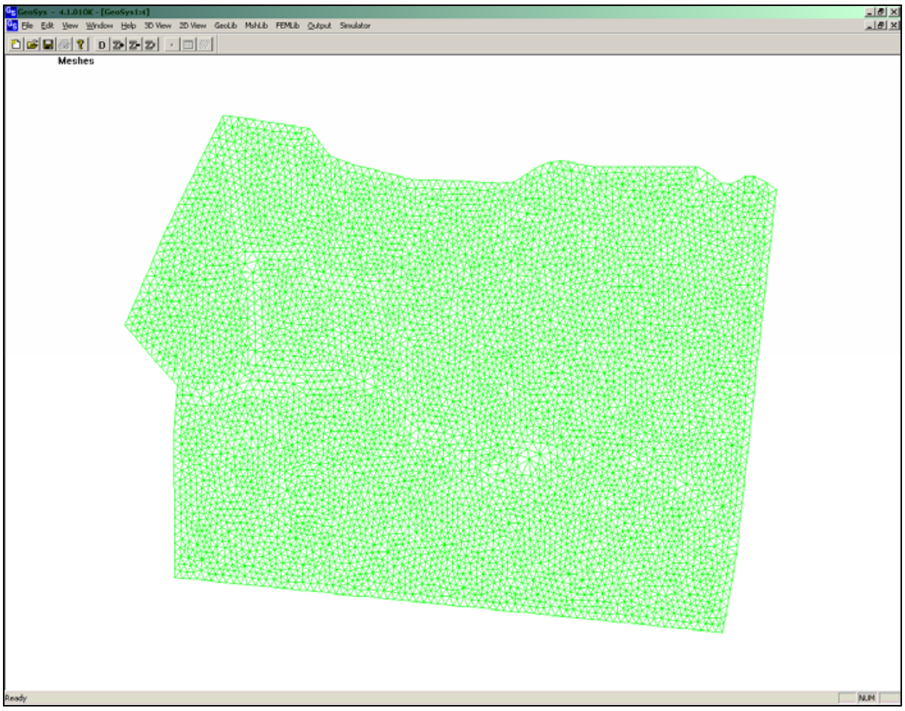


Figure 8.22: Prismatic elements in 2D view

Line elements

In this case, the line elements are generated along the wadis: WADI_North and WADI_South using the Mesh polyline dialog (Fig 8.23). The finite element nodes are identified and are used to generate the line elements and attached to the mesh file. The figure 8.24 shows the line elements.

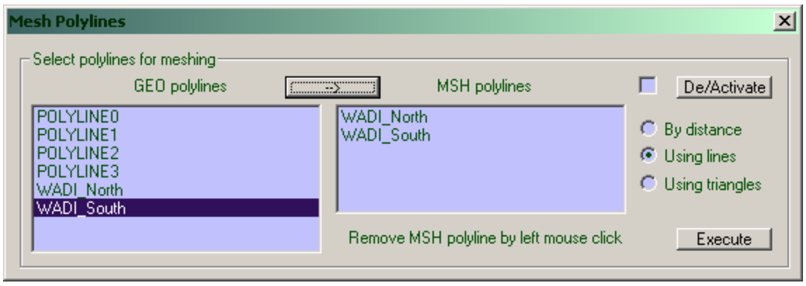


Figure 8.23: Create line elements

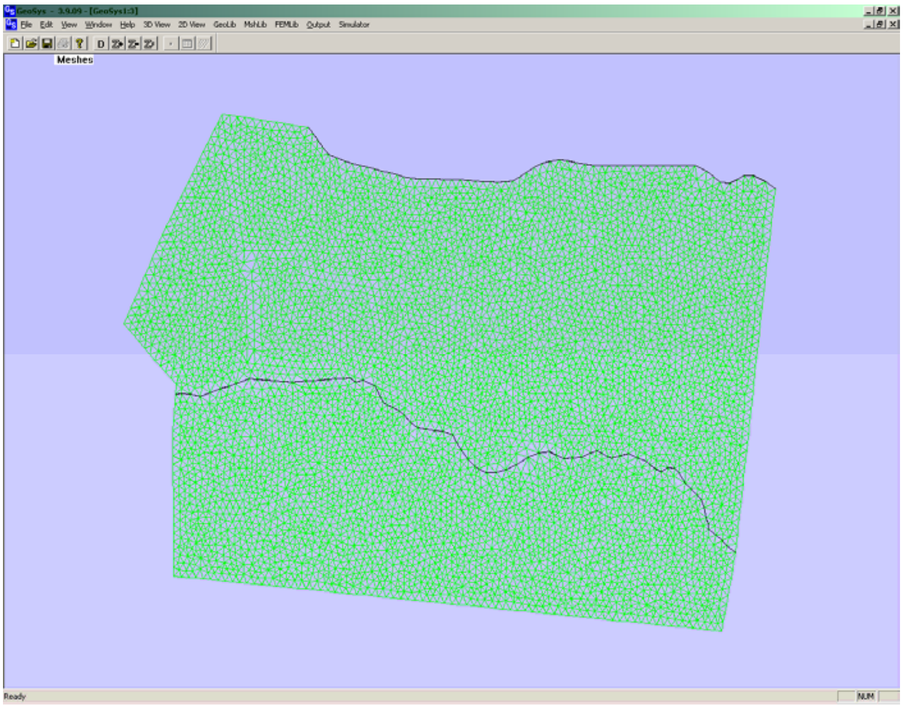


Figure 8.24: Line elements

Mapping

Surface mapping is the process of making the mesh conform to stratigraphic irregularities, i.e. thickness and orientation of the mesh slices can be deformed. Different data types can be used.

- Grid files created with Surfer, saved as asc file (use extension dat),
- Grid files created with ArcView (use extension asc).

Based on the Mapping dialog, the mapped result is shown in the figure 8.25.

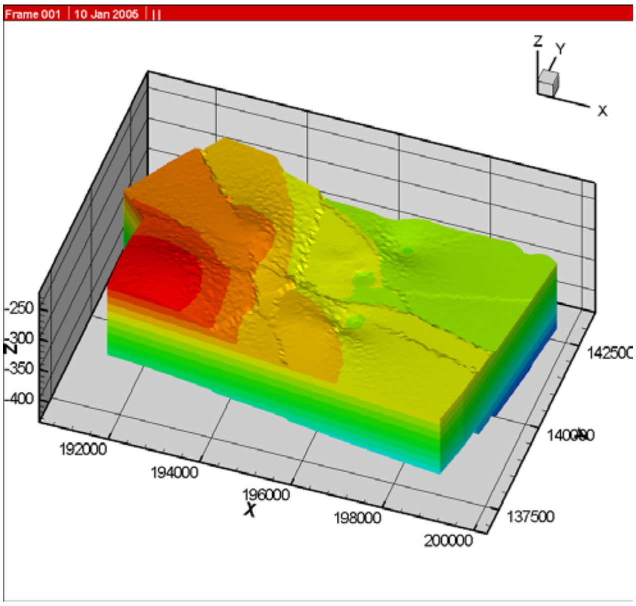


Figure 8.25: Mapping result of 3D model

8.4.3 Processing Data

After having finished all geometric and meshing operations it comes to specify data for the processes to be simulated.

Boundary Conditions

The geographical boundaries for the modeled area are set as: Wadi Nueima in the north, few kilometers from the Quillt to the south Jericho faults in the west and Hugla fault in the east.

It was assuming that there is no water movement from the north to the south or vice versa, depending on the fact that the water direction in this sub-basin is from west to the east and south east. Therefore, the only active model boundaries were assumed to be this from the west and from the east.

The polyline shape file for the boundary conditions is used to create layer polylines and use these to create surface of boundary condition in a 3D sense. In addition, the result is saved in an ASCII file with an extension as BC. Later assign the value on the finite element nodes on the surface inside a boundary condition Editor.

Material Groups

The material properties used for the different layers are stored in an Excel file. Connect the Material data with the mesh data, thus assign each volume a material property. The result is saved in an ASCII file with an extension as MMP. In Fig 8.26, different color means volumes have different material properties. The material properties used for the different layers are shown in Table 10. It was assumed that the hydraulic properties for the western surface near the spring have higher Kx and Ky values than the surfaces to the further to the east.

<table>
<tr><th colspan="2">Hydraulic Conductivities</th><th>For Sultan Surface in the west</th><th colspan="2">For the aquifer as a whole</th></tr>
<tr><td colspan="2">Marl</td><td>Marl</td><td>Sy(-)</td><td>0.1</td></tr>
<tr><td>Kx</td><td>4.6E-9 m/s</td><td>1.0E-6 m/s</td><td>Ss(1/m)</td><td>1.0E-5</td></tr>
<tr><td>Kz</td><td>1.0E-12 m/s</td><td>1.0E-9 m/s</td><td></td><td></td></tr>
<tr><td colspan="2">Gravel</td><td>Gravel</td><td></td><td></td></tr>
<tr><td>Kx</td><td>2.0E-4 m/s</td><td>1.0E-2 m/s</td><td></td><td></td></tr>
<tr><td>Kz</td><td>1.0E-6 m/s</td><td>1.0E-5 m/s</td><td></td><td></td></tr>
</table>

Table 10: Material properties (Khayat 2005)

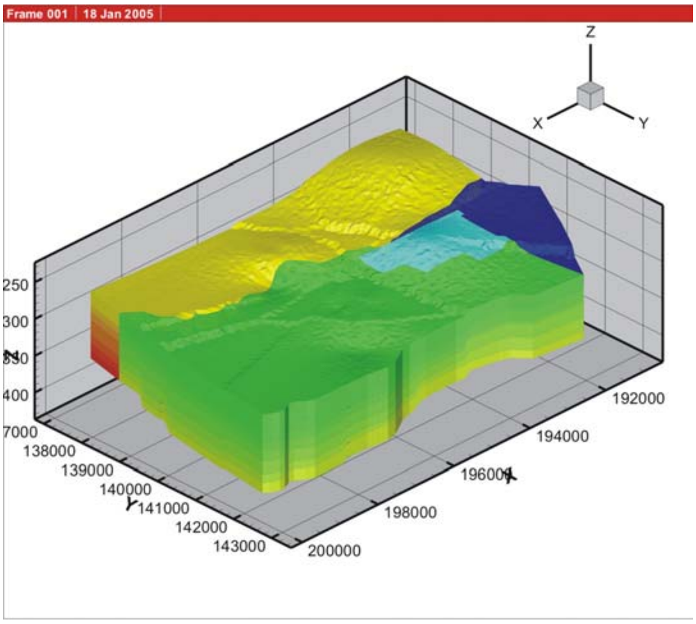


Figure 8.26: Connect material groups with finite elements

Source Sink Terms

In general, source terms are fluxes into or out of the model domain. Here, source terms are pumping wells, Sultan irrigation network, line recharge by wadis, area recharge by precipitation and area recharge by evaporation. Here, the well data can be imported directly from an Excel file. Using source term editor, connect the well data value with points and save the result in an ASCII file with an extension as ST.

The information about the pumping wells is stored in an Excel file (Fig 8.27).

Microsoft Excel - WellData.xls

Datei Bearbeiten Ansicht Einfügen Format Extras Daten Fenster ?

85%

K13 =

	A	B	C	D	E	F	G	H	I
1	Well ID	Xm	Ym	Zm	Depth	Q (m3/s)	Q (m3/hr)	Q(m3/day)	Q(m3/year)
2	19-13/005	195170	139650	-278,99	80	-0,00841	-30,2727	242,1818	87185,45455
3	19-13/006	195500	139580	-288	57	-0,01409	-50,7333	405,8667	146112
4	19-13/15	196100	139510	-292,686	45	-0,01	-36	288	103680
5	19-13/018	193770	139750	-260	94	-0,01049	-37,7692	302,1538	108775,3846
6	19-13/020	194320	139480	-270	120	-0,01865	-67,1538	537,2308	193403,0769
7	19-13/021	194960	138560	-279	138	-0,035	-126	1008	362880
8	19-13/024A	195390	138800	-306,852	137	-0,00778	-28	224	80640
9	19-13/042	193700	139670	-260	87	-0,00611	-22	176	63360
10	19-13/047	194850	139880	-278,3	90	-0,01189	-42,8	342,4	123264
11	19-13/048	195310	139660	-285	83	-0,0181	-65,1667	521,3333	187680
12	19-13/049	195530	139480	-290	72	-0,00433	-15,5833	124,6667	44880
13	19-13/050	195810	139380	-290	110	-0,01375	-49,5	396	142560
14	19-13/050A	195810	139380	-290	100	-0,0179	-64,4286	515,4286	185554,2857
15	19-13/051	195710	139640	-286	112	-0,00733	-26,4	211,2	76032
16	19-13/052	195880	139670	-289	120	-0,01464	-52,7143	421,7143	151817,1429
17	19-13/055	196200	139640	-295	98	-0,00667	-24	192	69120
18	19-13/061	196650	139940	-299,86	90	-0,00778	-28	224	80640
19	19-13/069	196950	139250	-315	112	-0,0251	-90,375	723	260280
20	19-14/005	194440	140340	-265,44	130	-0,01306	-47	376	135360
21	19-14/009	195230	140530	-277	74	-0,00898	-32,3333	14.9.00	93120
22	19-14/010	195220	140610	-277	86	-0,00993	-35,75	12.10.00	102960
23	19-14/012	195380	140010	-282	74	-0,01372	-49,3846	29.1.01	142227,6923
24	19-14/013	194910	140000	-275	70	-0,00472	-17	15.5.00	48960
25	19-14/014	194550	140140	-268,207	68	-0,01074	-38,6667	4.11.00	111360
26	19-14/015	195670	140530	-285	93	-0,01393	-50,1429	4.2.01	144411,4286
27	19-14/017A	195920	140310	-290	74	-0,01083	-39	7.11.00	112320
28	19-14/019	196460	140500	-291,85	57	-0,01236	-44,5	21.12.00	128160
29	19-14/020	196490	141020	-295	70	-0,00694	-25	18.7.00	72000
30	19-14/021	196210	140980	-288	120	-0,00611	-22	24.6.00	63360
31	19-14/023	195040	140240	-270	100	-0,01452	-52,2857	21.2.01	150582,8571
32	19-14/024	195260	140140	-280	75	-0,01164	-41,8889	335,1111	120640
33	19-14/037	196120	141060	-287,38	120	-0,00762	-27,4286	6.8.00	78994,28571
34	19-14/038	193450	142530	-244	110	-0,0105	-37,8	302,4	108864
35	19-14/040	193710	142360	-244,005	54	-0,00528	-19	152	54720
36	19-14/049	195930	141630	-275	90	-0,00389	-14	112	40320
37	19-14/052	195680	140980	-282	87	-0,01377	-49,5556	396,4444	142720
38	19-14/054	195500	141630	-274	132	-0,00972	-35	280	100800
39	19-14/058	194880	141170	-270	55	-0,00639	-23	184	66240
40	19-14/058A	195040	141280	-270	59	-0,00361	-13	104	37440
41	19-14/062	193380	142630	-240	150	-0,02289	-82,4167	659,3333	237360

Figure 8.27: Well information in excel file (Khayat 2005)

- Wells as geometric data:

Figure 8.28 shows the wells after import the wells from the excel file into ArcView and converted into GLI file.

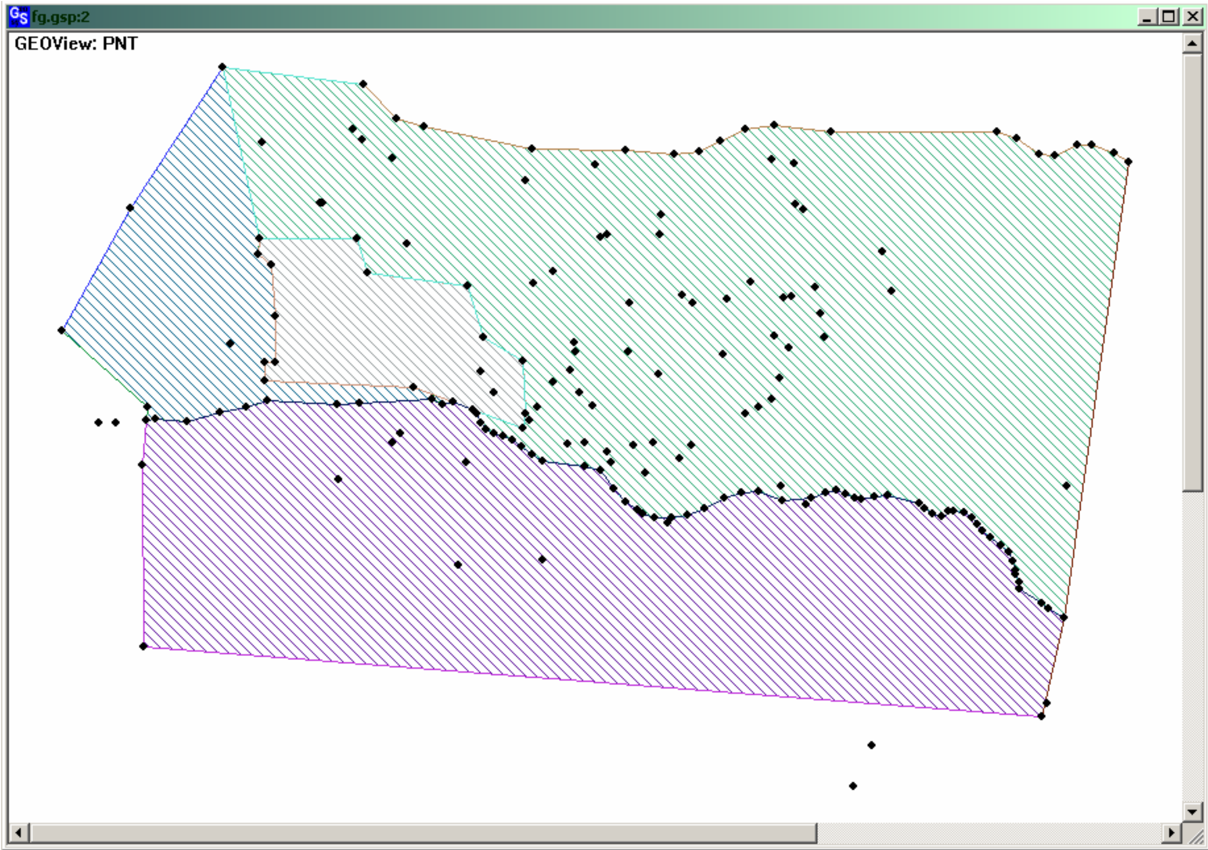


Figure 8.28: Wells as geometric data

Initial Condition

Water levels measurements from the years 2002-2003 (Fig 8.29) are used as an initial reference head data.

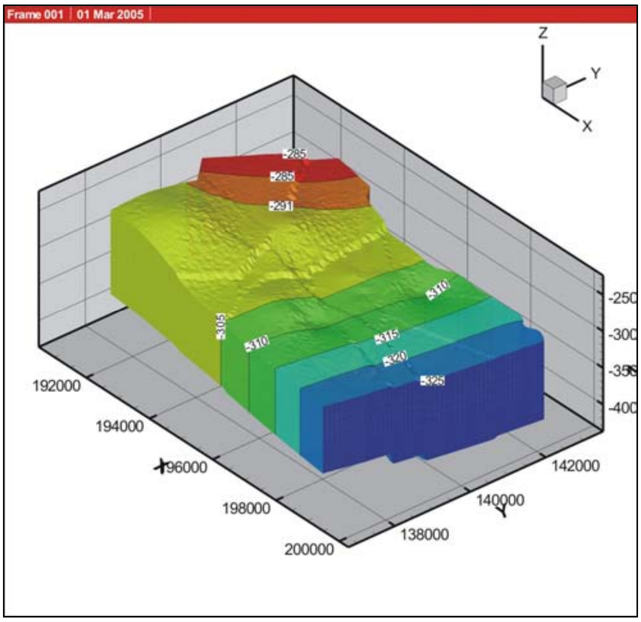


Figure 8.29: 3D volumetric model and initial head conditions

8.5 Simulation Results and Discussion

The first simulation result in the Jericho area is the regional groundwater flow model about the hydraulic distribution of the first aquifer layer (Fig 8.30) without the effect from pumping wells and irrigation network.

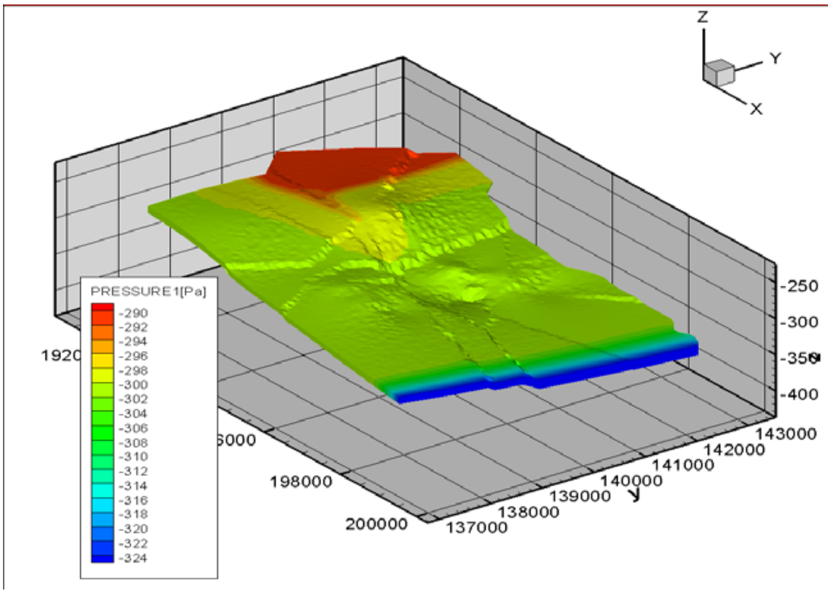


Figure 8.30: 3D view for the hydraulic distribution of the first aquifer layer (undisturbed situation without pumping and irrigation)

Then successively data of all pumping wells and irrigation from Sultan spring are included in the simulation. The overall irrigation from Sultan spring is calculated to 3.024 MCM/year. Irrigation modeled as a homogeneous infiltration rate. Figure 8.31 shows simulation results to highlight the hydraulic functioning of each contributor. Figure 8.31a depicts the groundwater level if pumping only is taken into account. Local hydraulic head lowering is observed. Figure 8.31b depicts the groundwater level if homogeneous irrigation only is taken into account. A rise of groundwater is resulting from this area water source. Figure 8.31c, d illustrates the hydraulic head distribution for different assumption of infiltration rates (2 and 10% of irrigation rate). Qualitatively, these modeling results fit very well to the measured data. There is a groundwater lowering in the central northern part and a rising in the central southern part of the investigated Jericho area. However, the absolute distribution of hydraulic head from the undisturbed situation overestimated.

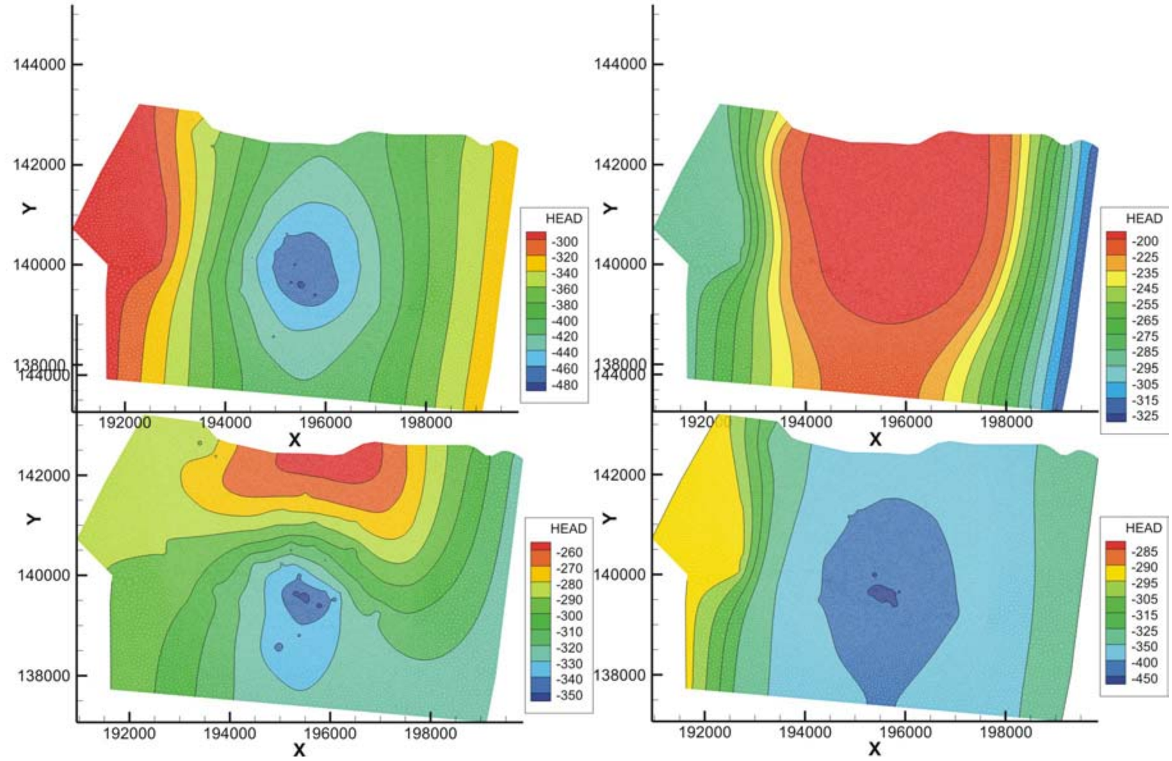


Figure 8.31: Hydraulic head distribution in the upper aquifer taking into account: (a) pumping wells only, (b) irrigation from Sultan spring only, (c) pumping and irrigation (10% infiltration rate) and (d) pumping and irrigation (2% infiltration rate)

These results assumed a high contribution from the spring irrigation network to the water level, which show the suggested recharge mixing from the spring water with the Wadis flood recharge. The water level as expected have its higher values to the west near the spring recharge and begin to decrease under the heavy abstraction from the wells further to the east.

In the last, the effect of pumping rate in a specific season of a year is considered. The ground water level in Jericho is highly affected by the seasonal pumping rate from the agricultural boreholes. This effect can be located more sharply during the dry season by the end of October (Fig 8.32) after a long period of summer time (Fig 8.33). The effect of the seasonal water pumping on the water head of the shallow aquifer in Jericho is quite clear, the water level dropped in the first agricultural season which come directly after the replenishment of the aquifer causes water level decreasing. The pumping process In the second agricultural season which come directly after the dry season cause further decrement in the water head, as there was no replenishment after the first pumping time.

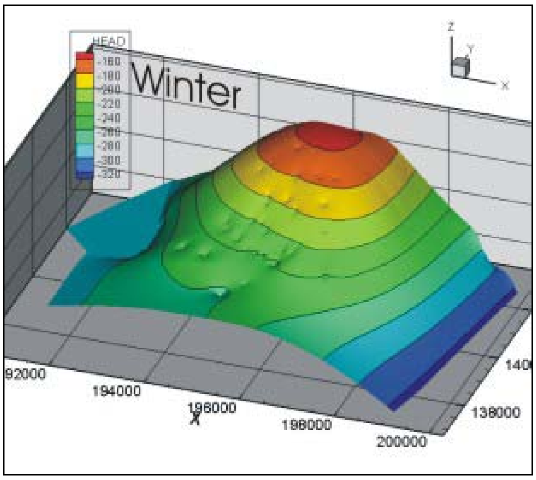


Figure 8.32: Water level after the pumping in the dry season of February

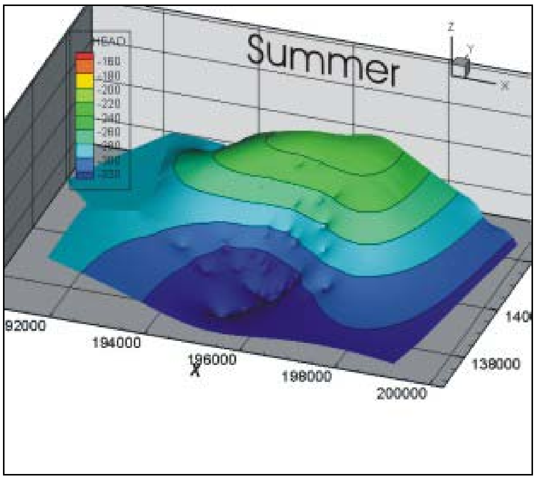


Figure 8.33: Water level after the pumping in the dry season of October

The model visualized for a certain extend the effect of the major extensive pumping at different time from the aquifer. However, this model still subjected to further refining process to have clearer picture about the mixing rate from different sources. Moreover, different expectation scenarios should also considered after refining this model to see the expected fluctuation values depending on the assuming future surrounding conditions.

9 3D GROUNDWATER MODEL IN BRAND AREA

This chapter introduces how to build a steady-state 3D groundwater model with complicated aquifer systems in GeoSys/RockFlow. There are several new features implemented in the new version of GeoSys/RockFlow, for example, the concept of layer volumes has solved the problem of assigning material groups to complicated aquifer systems. Here, the material property has been connected to each model layer using GIS data. The creation of the 3D groundwater mode includes a GIS project and a GeoSys/RockFlow project.

9.1 GIS Project

The GIS data is used to prepare the geometry model and for the process data. These GIS shape file layers are:

Model Domain
The model domain (Fig 9.1) is one polygon feature in GIS, and it covers the modeling area of interest.

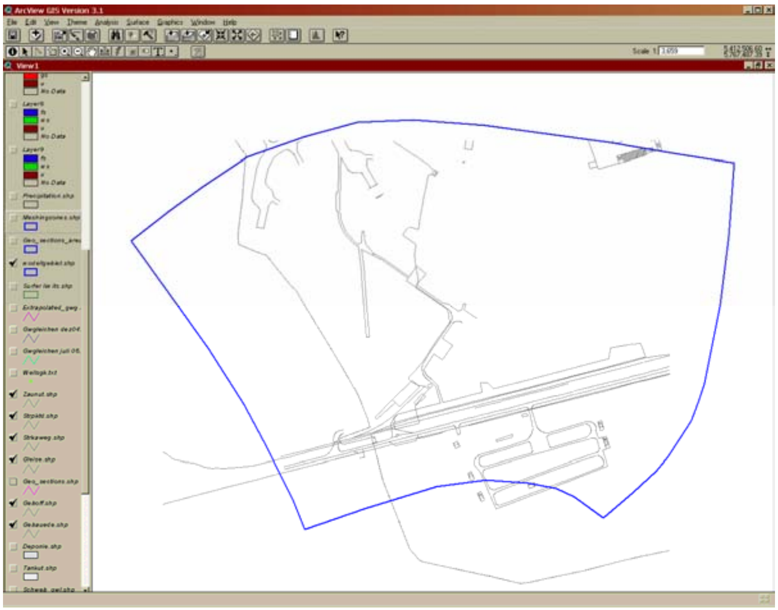


Figure 9.1: Model domain (Miles 2006)

Zonation for Different Mesh Densities
The whole model domain is subdivided into several zones (Fig 9.2). For each zone, it has a different mesh density.

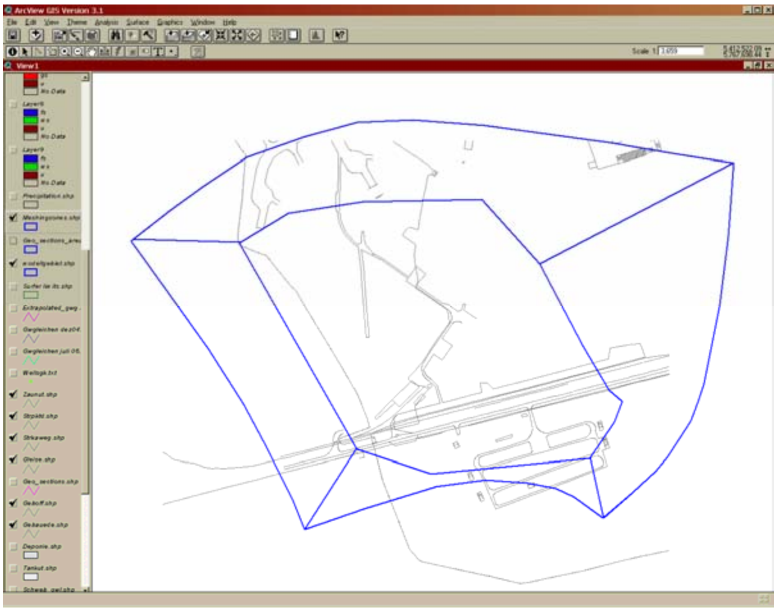


Figure 9.2: Zonation with different mesh densities (Miles 2006)

Material Property Zones for nine Model Layers

From the geological formation of the modeling domain, a nine-layer subsurface conceptual model is build. For each layer, they have different material group distribution. The following nine GIS thematic maps (from Fig 9.3a to Fig 9.3i) are prepared for the material properties for those nine layers. In general, there are five material groups: fine sand, medium sand, coarse sand, silt and clay. Each color means one material group:

fs = fine sand (blue)
ms = medium sand (green)
gs = coarse sand (red)
u = silt (brown)
t = clay (purple)

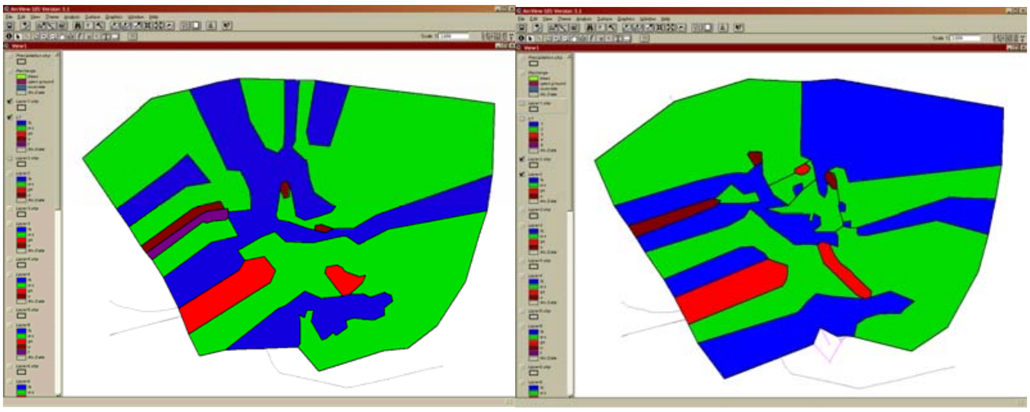


Figure 9.3 (a, b): Layer one and Layer two (Miles 2006)

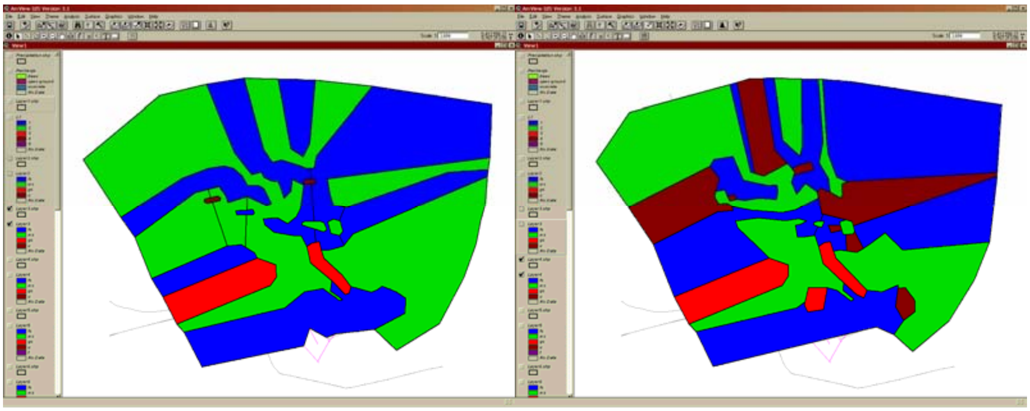


Figure 9.3 (c, d): Layer three and Layer four (Miles 2006)

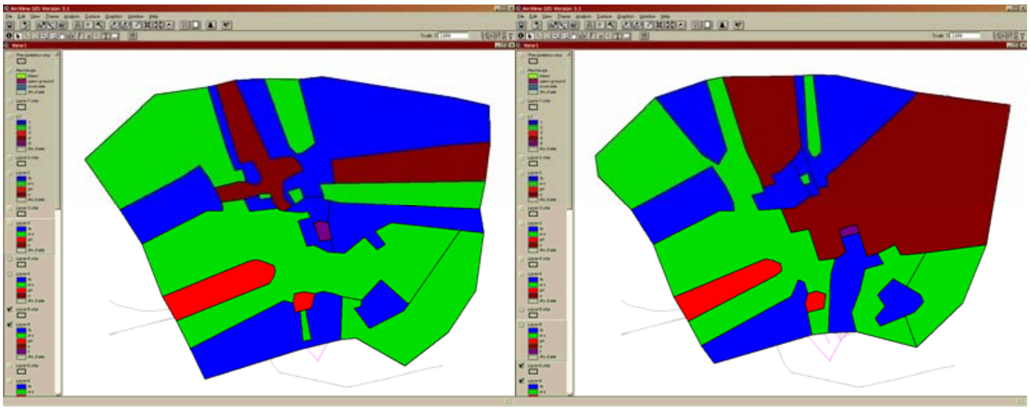


Figure 9.3 (e, f): Layer five and Layer six (Miles 2006)

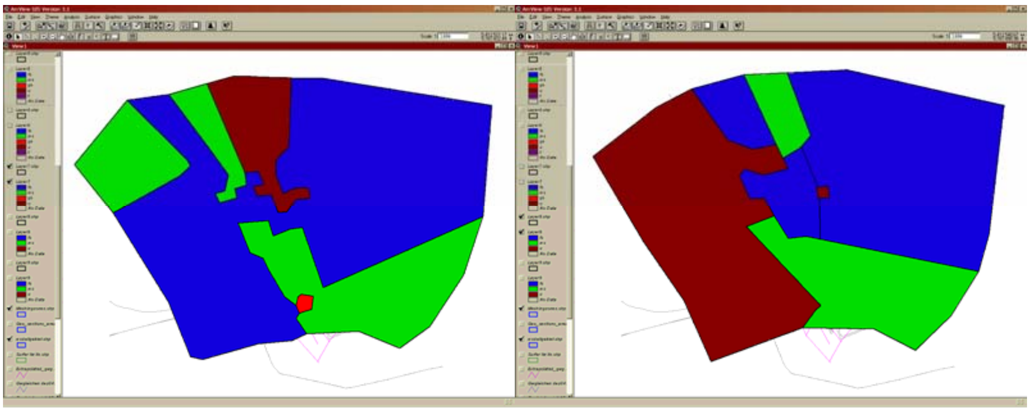


Figure 9.3 (g, h): Layer seven and Layer eight (Miles 2006)

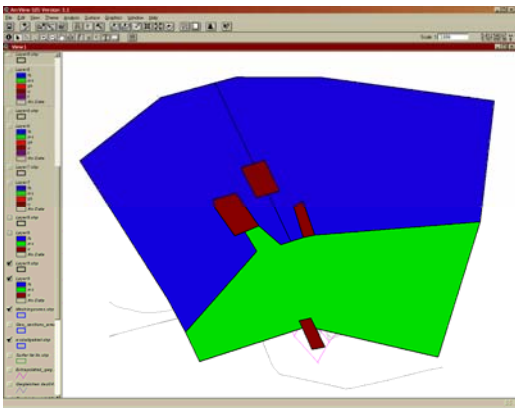


Figure 9.3i: Layer nine (Miles 2006)

9.2 GeoSys/RockFlow Project

The first step is to create a new GeoSys/RockFlow project and then prepare the geometric data by importing from GIS.

9.2.1 Import GIS Data

The information in the files is imported as polylines made up of points. The imported data (points and polylines) can be viewed in the main graphical window. Figure 9.4 shows the 3D view by integrating OpenGL with GeoSys/RockFlow (T.Kalbacher, 2004).

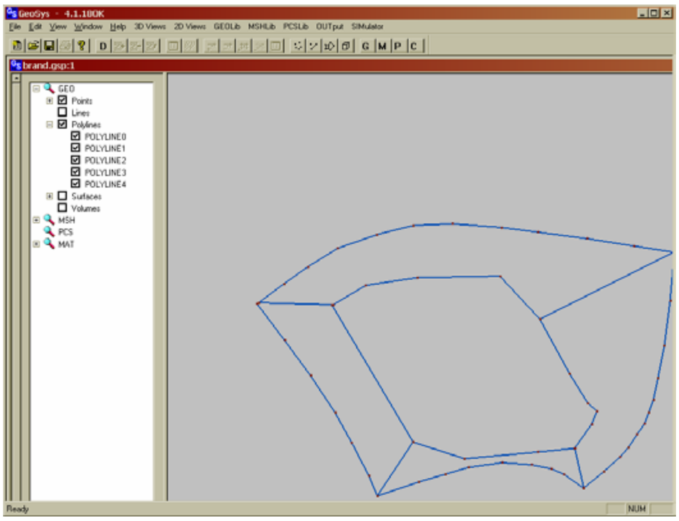


Figure 9.4: Import GIS data

9.2.2 GEOLib Data – Geometry

The imported GIS data are converted into GEOLib data structure: GLI. One 2D GLI file consists of points, polylines, and surfaces created from existing polylines.

Points

Figure 9.5 shows the relationship between the point editor and GEOView under the GeoSys/RockFlow framework. Points can be created using the drawing tool, and edited by changing the point properties like name, x, y, z coordinates, mesh density, type, etc. One selected point or all the point objects could be removed. Another function is to check the double points. Based on the tolerance defined by your own, two points closer to the tolerance are taken as double points, and after the cleaning process, one is removed and the point array building the polyline is rearranged.

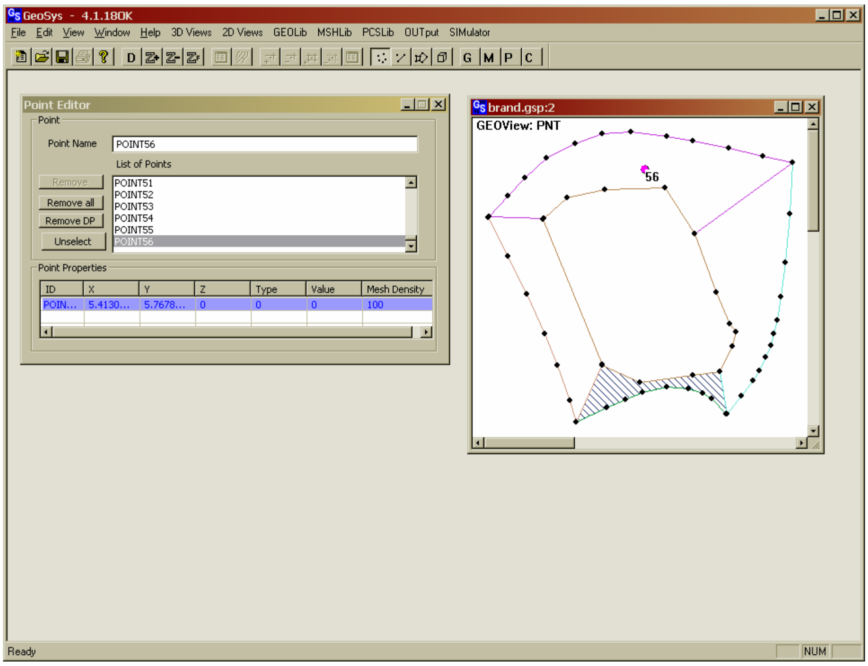


Figure 9.5: Point editor and GEOView

Polylines

Figure 9.6 shows the relationship between the polyline editor and GEOView under the GeoSys/RockFlow framework. Polylines can be created using existing points, and edited by changing the point properties like name, x, y, z coordinates, mesh density, type, etc. One selected polyline or all the polyline objects could be removed. The polyline meshing density could be changed simply by the updating function.

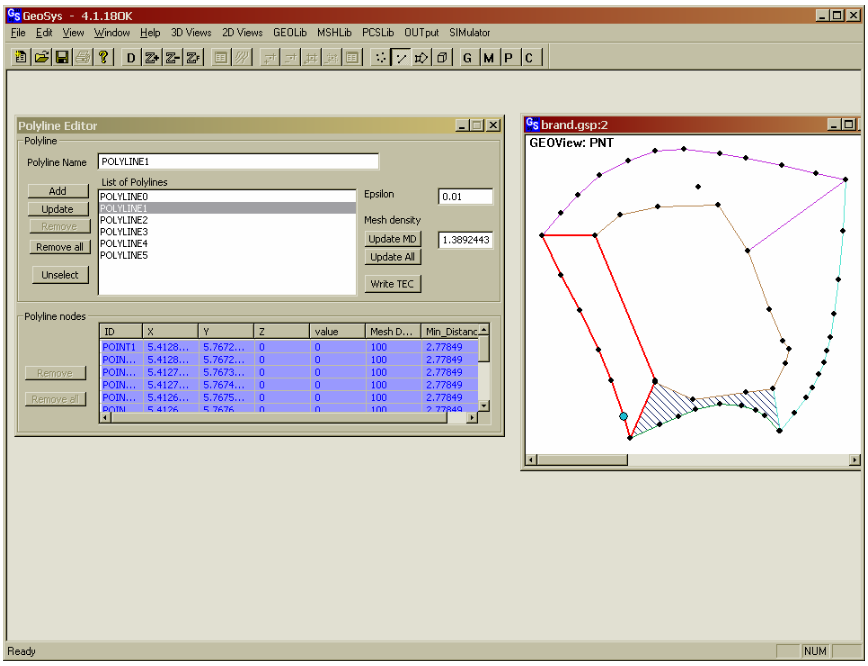


Figure 9.6: Polyline editor and GEOView

Layer Polylines

Layer polylines are necessary to (for example) assign boundary conditions to the vertical faces of a 3D model domain. A standard polyline has elevation z = zero. In creating layer polylines, for each interface between layers of the model a line is created with elevations according to the nearest nodes in the existing 3D mesh. Layer polylines are created using the mesh editor. Under GEO data, select polylines, then from the polyline list, choose the line for which layer polylines are to be created. Click "Layer polylines". PLY and TEC files are automatically generated. Figure 9.7 shows the created layer polyline for polyline BC_NORTH in the list.

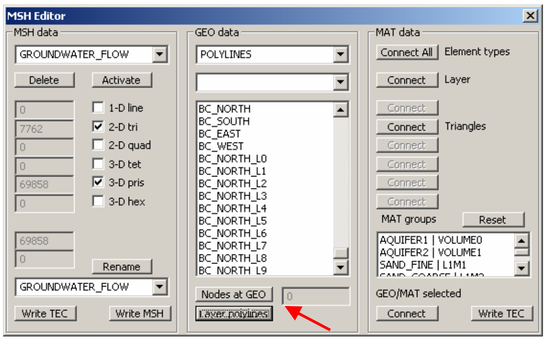


Figure 9.7: Created layer polyline list

Figure 9.8 shows the Tecplot interface of the layer polylines for the whole model boundary.

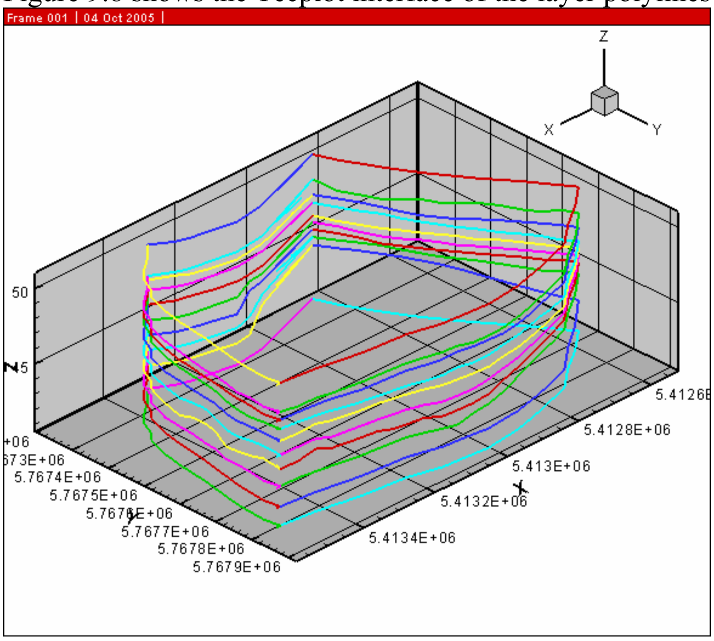


Figure 9.8: Layer polylines in Tecplot interface

Surfaces

Figure 9.9 shows the relationship between the surface editor and GEOView under the GeoSys/RockFlow framework. Surfaces can be created from polylines. One selected surface or all the surfaces objects could be removed.

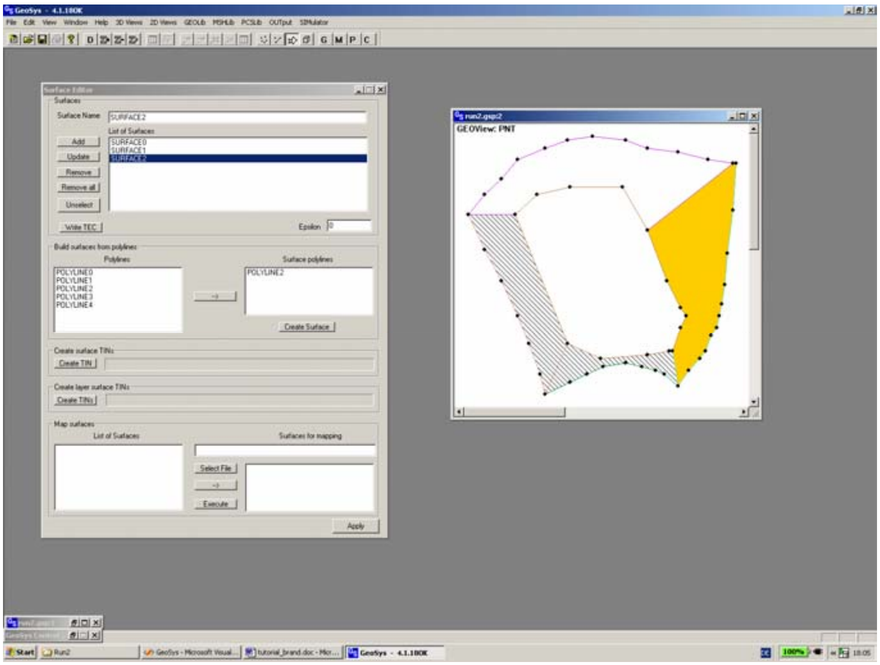


Figure 9.9: Surface editor and GEOView

Layer Surfaces

Layer surfaces (Fig 9.10) are vertical surfaces in a 3D model domain, necessary for assigning boundary conditions etc. They are created from existing layer polylines.

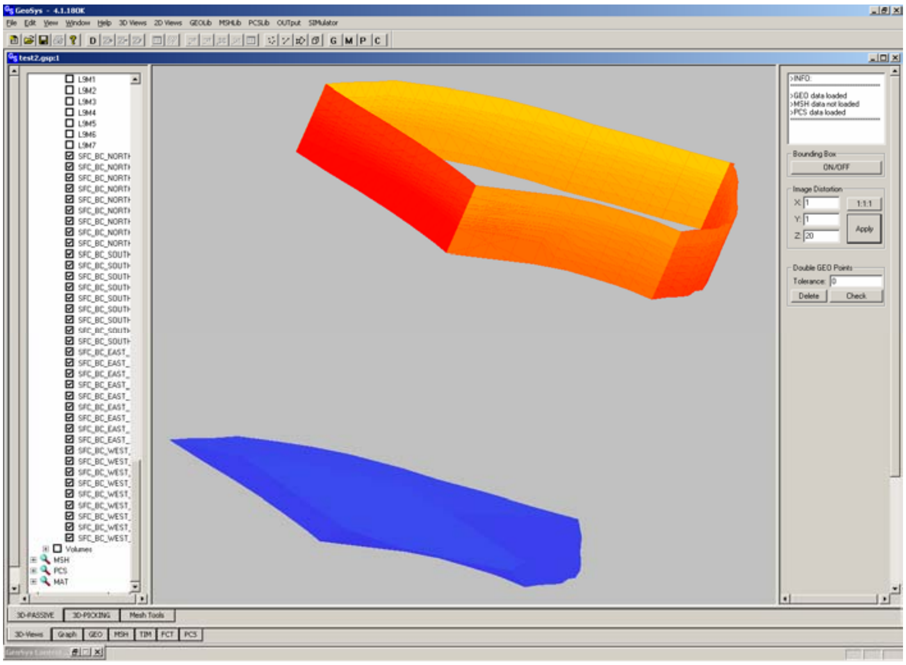


Figure 9.10: Layer surfaces and the model domain

Volumes

For a 3D model, volumes within the model layers are created from existing surfaces using the GEO volume dialog (Fig 9.11). Select the appropriate mesh in the MSH list, the appropriate layer and surface. The surface here means the surface with a single material group. Click “Create” to generate the volume in the lower window. The number of volumes for each layer is the same as the number of polylines for the corresponding thematic material group layer mentioned before.

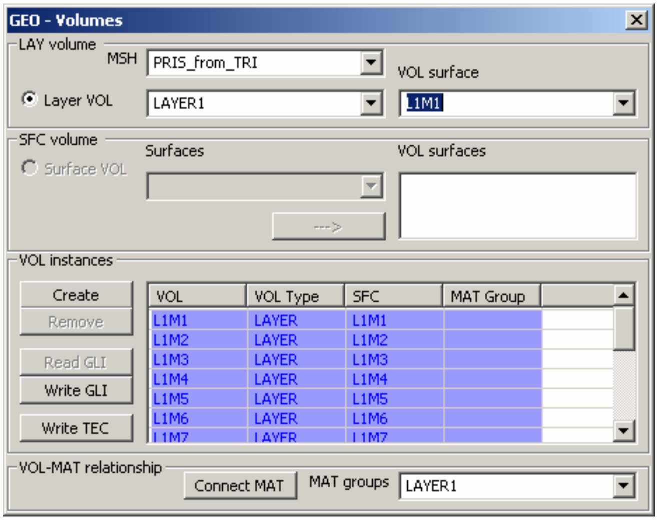


Figure 9.11: Volume editor

Figure 9.12 and figure 9.13 show the volume for one layer and for all the layers in Tecplot interface

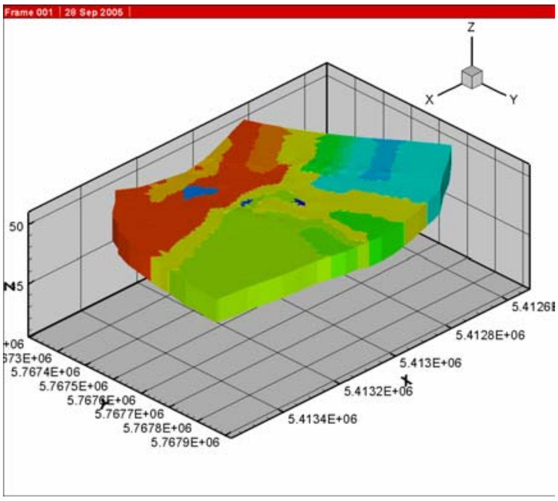


Figure 9.12: One layer volume

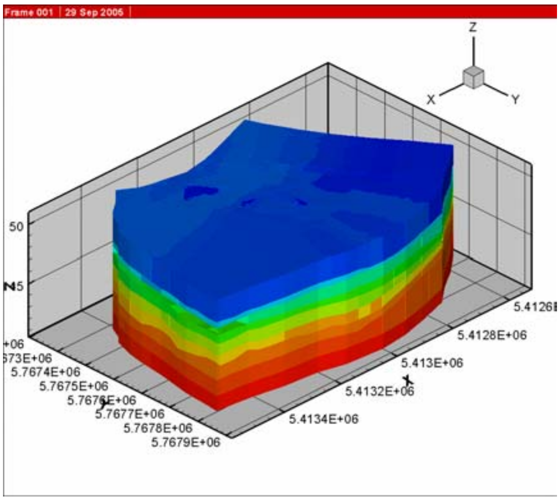


Figure 9.13: Volumes for all layers

Assign Material Groups to Volumes

Material groups are assigned to volumes by selecting the volume from the list in the lower window (Fig 9.14), choosing the appropriate material group from the MAT groups dropdown list (material properties must be imported), and clicking “Connect MAT”. The material group for the volume will then appear in the MAT Group column in the volume list.

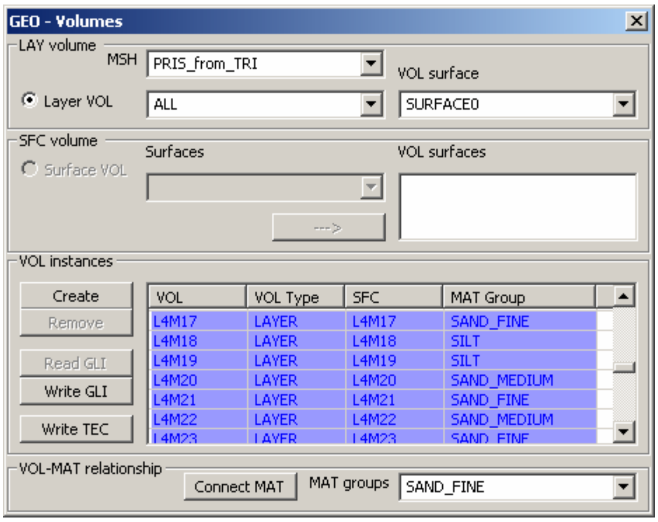


Figure 9.14: Connect MAT data with volumes

9.2.3 MSHLib Data – Spatial Discretization

The finite element library consists of 1D, 2D and 3D types, and they are Lines for 1D, Triangles, quadrilaterals for 2D, and Tetrahedra, triangle based prisms, hexahedra for 3D.

Mesh Density

A meshing distance defines mesh density for triangulations. This is the favored triangle edge length. Hence, a higher value for mesh density will result in a mesh with larger triangles, and vice-versa. For triangulation, the meshing distance has to be set within reasonable bounds. The meshing distance is a point property that can be defined for surfaces, polylines and points according to the hierarchy: polyline meshing distance overwrites surface data and point meshing distance overwrites polyine data. Thus, local mesh refinements can be arranged.

Triangulation

Based on the selected mesh densities, a triangle mesh (Fig 9.15) is generated using the interface with an external program gmsh.exe. Usually re-meshing steps are necessary to produce appropriate meshes. In this way, the mesh density needs to be changed and execute the triangulation again.

Prisms

The 3D prismatic mesh is generated from the 2D triangular mesh using the Tri2Pris function. In the prism generation editor (Fig 9.16), select the triangle mesh from the MSH list, input the number of the model layers 10 and the thickness of each layer, and create the prismatic elements by clicking on the "Create elements" button. Figure 9.17 shows the nine layer prisms in Tecplot interface.

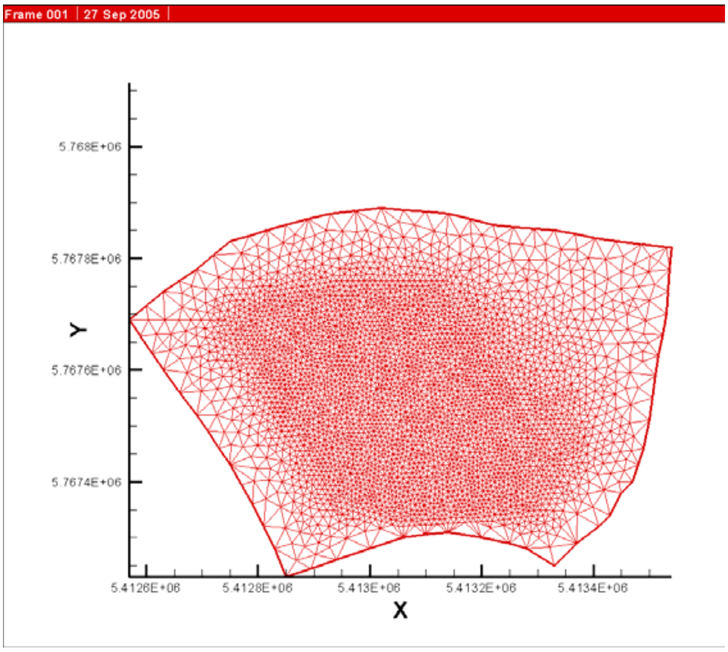


Figure 9.15: Triangulation

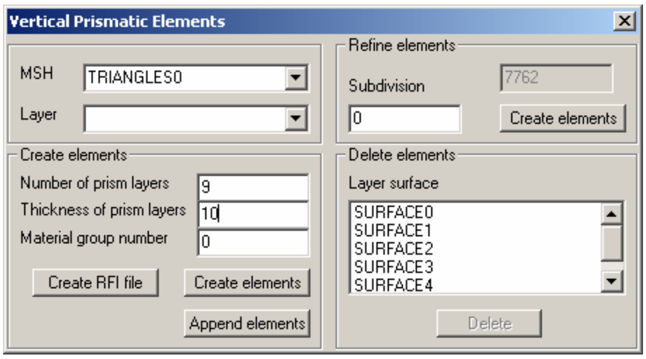


Figure 9.16: Prism generation editor

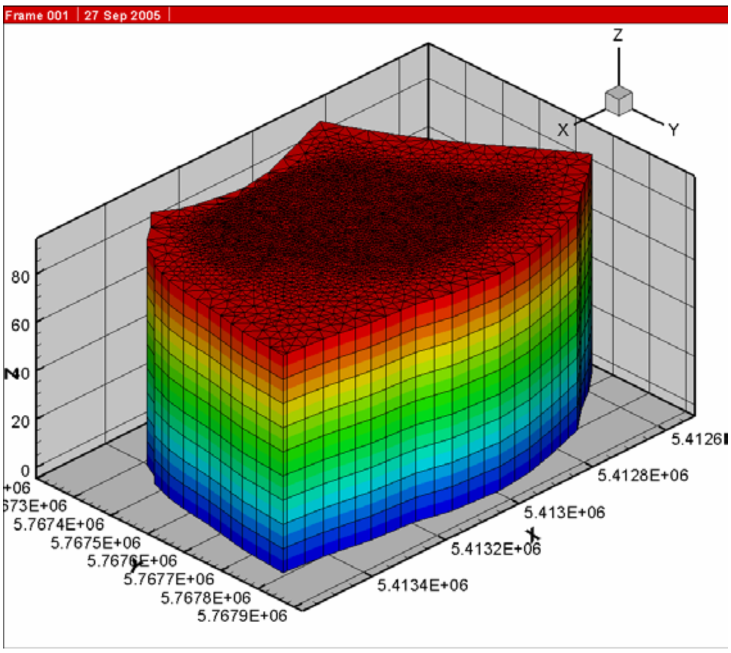


Figure 9.17: Prism layers

Editing Meshing

Two functions are important. They are deleting mesh data and rename the mesh data. Both could be done in the MSH editor. The meshing tools create generic names (e.g. TRIANGLE0). In order to connect meshes with processes, the names of process and mesh must be identical (e.g. GROUNDWATER_FLOW).

Assign Material Groups to Mesh Data

Material group is a finite element property, and the material groups and mesh data are connected. Material groups for a layer are assigned by link the appropriate selected mesh (e.g. PRIS_FRM_TRI), the layer and the GEO data.

Mapping

To map elevations for the interfaces between model layers to the 3D prismatic mesh, the mapping tool is used. The elevations are imported as Surfer .dat files as follows (Fig 9.18):

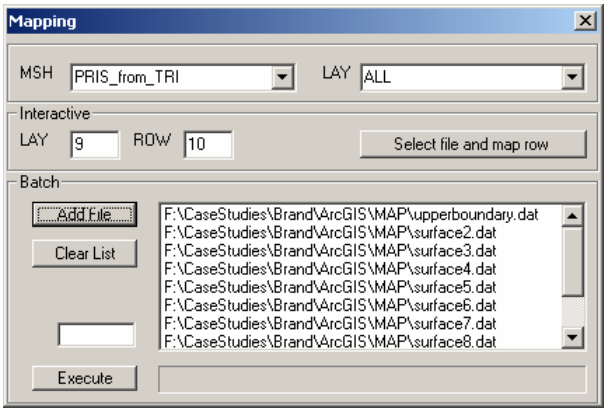


Figure 9.18: Mapping editor

The process is done by selecting the appropriate mesh, choosing the layer to map and importing the elevation raster data (.dat) and then clicking on the button "Execute". A Tecplot interface for the mapping result is shown in Figure 9.19.

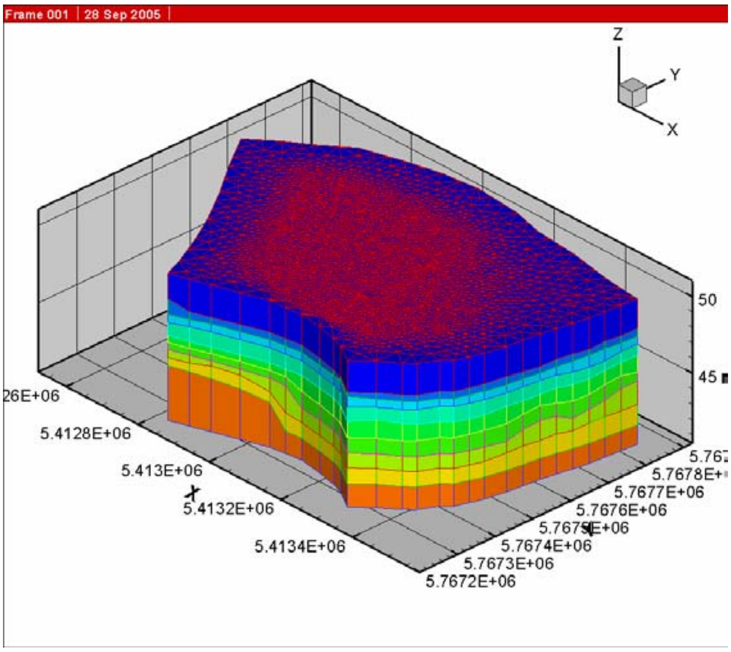


Figure 9.19: Mapping result for the prisms

9.2.4 PCSLib Data – Processing

PCSLib deals with process (PCS) data. Typical process data are: the physical process itself, corresponding initial and boundary conditions, material properties for fluids, solids as well as the porous medium. Additionally numerical properties, time discretization schemes and output parameters have to be specified.

IC Data – Initial Conditions

Initial conditions are assigned to the process (PCS type) and geometrical units (points, polylines, surfaces or whole domain) by selecting as desired and clicking "Create" in the dialog (Fig 9.20). The initial condition is then displayed in the lower window (Fig 9.21).

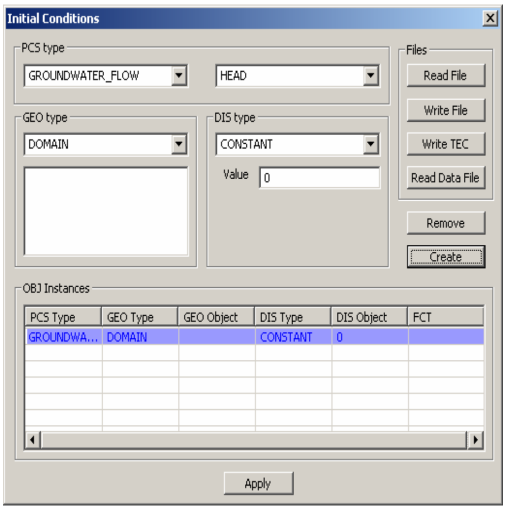


Figure 9.20: IC editor

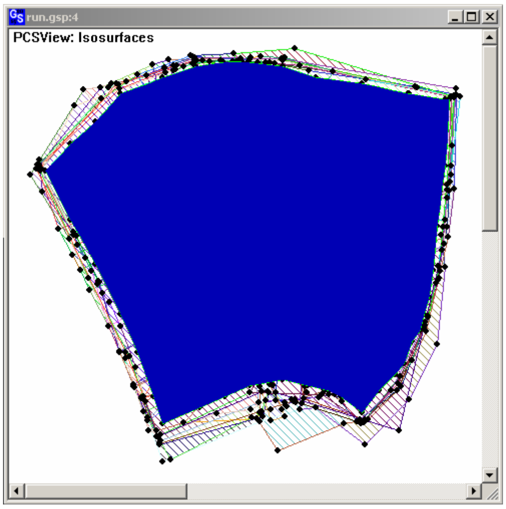


Figure 9.21: IC for the whole domain

BC Data – Boundary Conditions

For a 3D model, the boundary condition is to be set for layer surfaces. Here two layer surface from the south and the north are set for boundary condition. The function of creating groups is the identification of the finite element nodes on the layer surfaces. Figure 9.22 shows the result of the identified nodes.

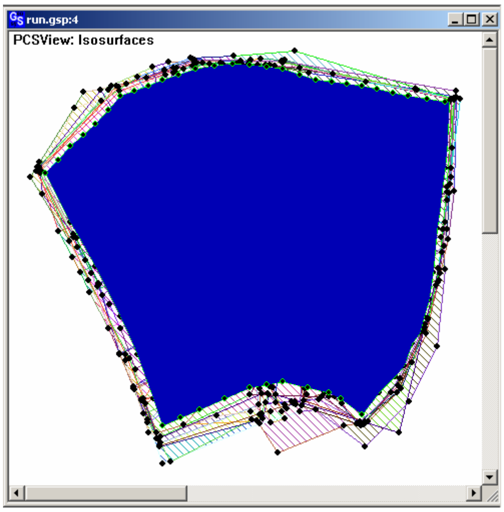


Figure 9.22: BC on the layer surfaces

MFP Data – Fluid Properties

Parameters of typical fluids can be selected from a user-defined database or from standard fluids. Here the standard fluid is water.

9.3 Result and Analysis

Steady State Flow

Figure 9.23 shows the head distribution of the 3D groundwater model when only boundary conditions are activated.

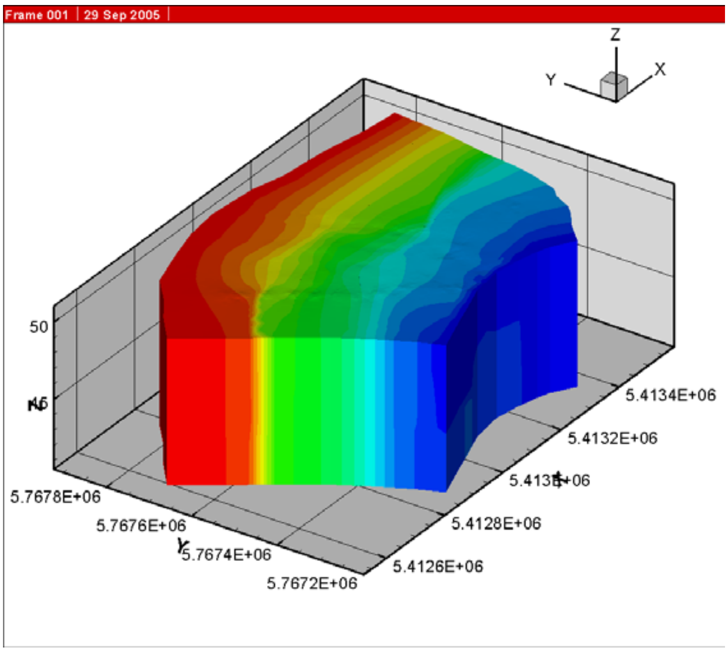


Figure 9.23: Hydraulic head in the 3D model

10 MULTIPLE RESOLUTION CONCEPT FOR RIVER NETWORK EXTRACTION IN THE GALLEGO CATCHMENT

This chapter concentrates on the use of digital elevation model (DEM) to extract river network and water catchment boundary in the Gallego catchement area and later use this to create the river model as line elements based on the multiple resolution concept. The functionality of Geographic Information Systems (GIS) and digital data sets make it possible to automate the river network extraction process using DEMs. Furthermore, the DEMs provide adequate information for the topography of the surface of the model area, which can be used to conform 2D finite element mesh to stratigraphic irregularities using the mapping funtion. The river model is built in the finite element program GeoSys/RockFlow, and can be used for the surface water modeling. As a result, a one-layer 3D model of the Gallego catchment is also created.

10.1 Methodology

Acquisition and processing of DEM data

World wide DEM data in 90m resolution is available from site SRTM (shuttle Radar Topography Mission) and can be downloaded for example from the following source: http://glcf.umiacs.umd.edu/data/srtm/desc.shtml. The SRTM data must of course cover the Gallego catchment area. The data is in binary format with (.HGT) extension. DEM with good quality are needed to support the water-resource related activities, but the DEM obtained contains still missing data holes and uses geodetic (latitude-longitude) projection, which leads to an east-west distortion at high latitudes. The latest 3DEM software package, developed by Horne (2005) was used to convert any terrain using Geodetic (latitude-longitude) projection into a Universal Transverse Mercator (UTM) projection. The UTM projection corrects this distortion, providing a more realistic map view and 3D scene.

The next step is to convert the SRTM file into USGS DEM file format, while the ArcGIS hydrologic processing function handles the USGS DEM file format. Because of the computer limitation and the memory problem, the DEM file need to be cut in order to reduce the size, but should also big enough for mapping. This step was done also in 3DEM.

ArcGIS has three level of licensing: ArcView, ArcEditor, and ArcInfo. All licenses have the same common applications: ArcCatalog, ArcMap and ArcToolbox. Since the GeoSys/RockFlow use ASC file for the mapping, USGS DEM file need to be converted into ASC format by using the tools from ArcToolbox. Figure 10.1 shows the DEM for the Gallego catchement area after the above processing.

In this example, the ArcInfo command FILL in the grid module is used to exact the river network from the DEM and the command is an implementation of the approach outlined by Jenson and Domingue (1988). Figure 10.2 shows the extracted river network with watershed boundary for the Gallego catchment area, which are shape files.

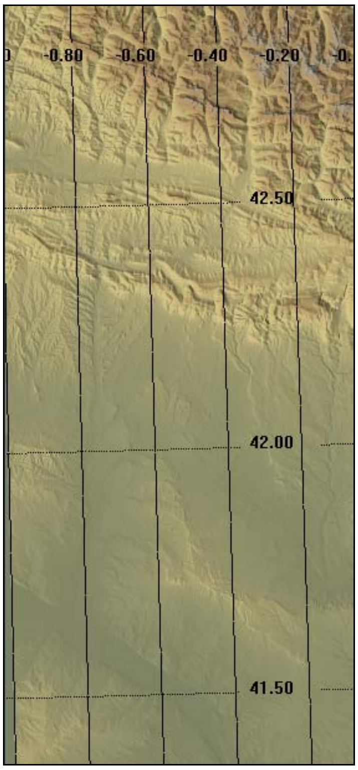


Figure 10.1: DEM for the gallego catchment

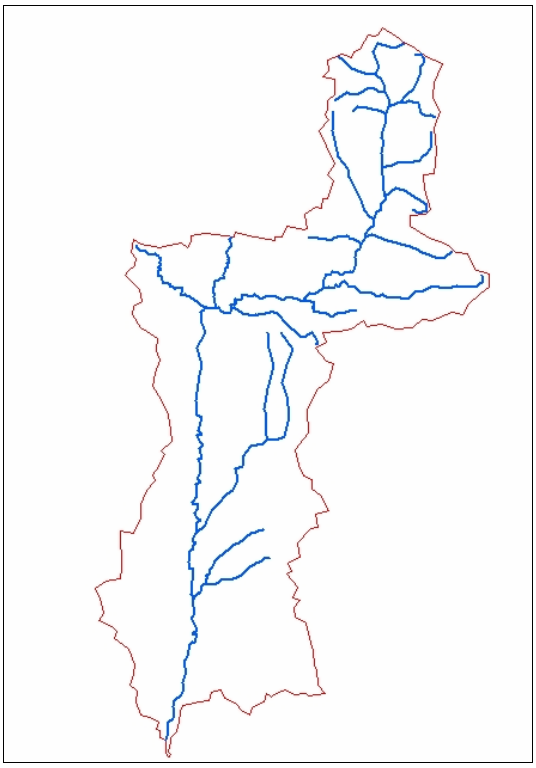


Figure 10.2: Extracted river network with Catchment boundary

Create GIS Project

The shape files for the gallego catchment boundary and river network are used to create surfaces for the modeling purpose in GeoSys/RockFlow. The model domain is subdivided into several surfaces based on those two shape files. The river network, in this way, matches exactly for the boundary of the surfaces. See Figure 10.3.

Generate 3D Model using Finite Element Method

After preparing the GIS data, the shape files are imported into GeoSys/RockFlow. 2D triangle meshes are generated for the domain. The shape file of the river network is also imported to generate the river model, and they belong to the line elements group. The river polylines match topologically the meshing surfaces on the edge, so changing the mesh density of the points on the river network leads to the change of the mesh density of the surfaces too. The procedures are:

- Import Stream network inside the basin in Shape file format into GeoSys,
- Delete the double points based on the pre-defined tolerance,
- Assigning for each polylines (river network) the mesh density based on the minimal distance between the points on this polyline,
- Meshing- triangulation. See Figure 10.4,
- Prismatic element – one layer,
- Mapping using DEM file. The ASC file which was created in the above is used here for surface mapping,
- Create Line elements based on the river network using meshing polyline editor, and this part will identify the finite element nodes on the river network.

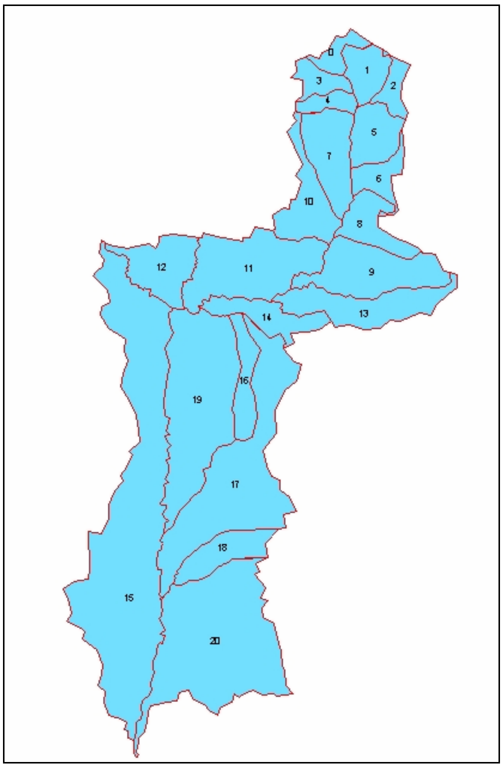


Figure 10.3: Model surfaces in GIS

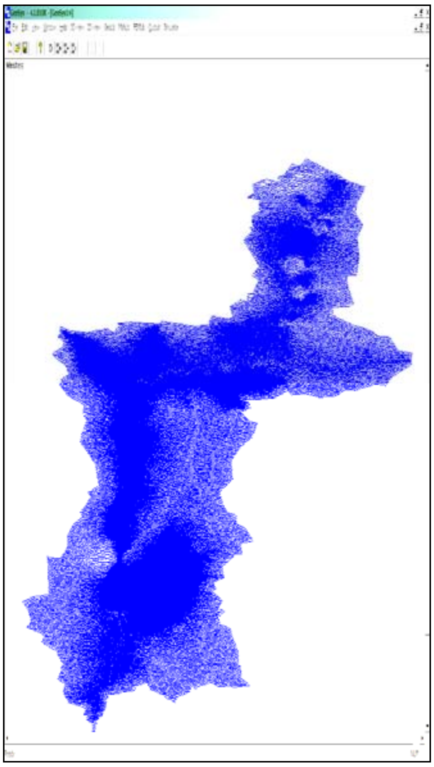


Figure 10.4: Multiple resolution triangulations

10.2 Result and Conclusion

Figure 10.5 shows one layer 3D model of Gallego catchment with river network. From the demonstration above, we found some problems. For line element generation, if the result is not good, that means, the finite element nodes on the polylines are not completely identified, which can lead to the inconsistency of the modeling system, there are two possible reasons: Firstly, rivers and surfaces are not topologically in consistency, and we can edit those shape files inside ArcGIS using its topological checking function to obtain the relationship between rivers and surfaces. Secondly, the mesh density of the points along the river network is not well defined. It can be too small or too big. So by defining the mesh density based on the half of the minimal distance between the points of each polyline, a better result can be achieved.

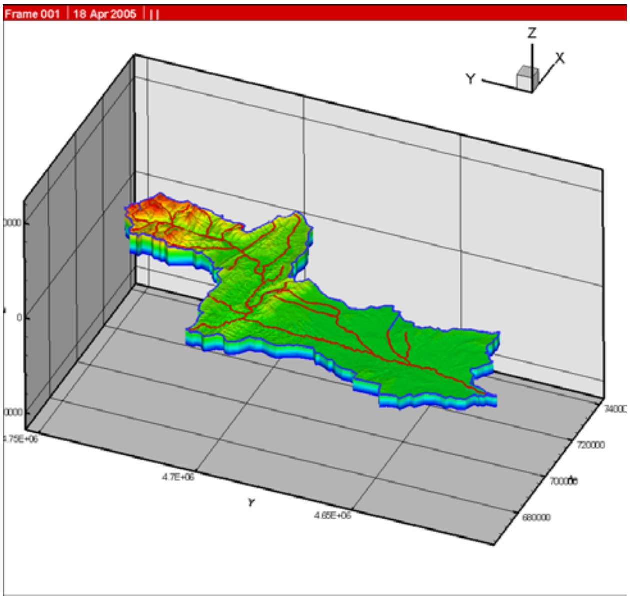


Figure 10.5: One layer 3D model of Gallego catchment with river network

11 INTERACTIVE VISUAL FRAMEWORK TO DEMONSTRATE THE UNCERTAINTY OF CONTAMINATED PLUME INVESTIGATION

11.1 Introduction

This chapter aims at the visual framework implementation of an investigation model under the numerical modeling software GeoSys/RockFlow. This contributes to the applications of Virtual Aquifer (VA) approach to demonstrate the uncertainty of a contaminated plume investigation. Due to the limited accessibility of the subsurface, observation wells and thus measurements of piezometric heads and contaminant concentrations at contaminated sites may not be representative of the heterogeneous hydrogeologic condition (Bauer et al., 2006). Therefore, the conclusions deduced are subject to uncertainty, reflecting the limited knowledge on the aquifer properties. The Virtual Aquifer approach can be used to study this kind of uncertainty (Schäfer et al., 2002; Schäfer et al., 2004b; Bauer et al., 2004). In this approach, synthetic aquifer models are generated and used as test sites to evaluate investigation or monitoring strategies. A reactive transport model is then used to simulate typical contamination scenarios like the spreading of a plume from a contaminant source, resulting in a realistic concentration distribution in the virtual aquifer. In comparison to the "real world", the unique advantage of the virtual aquifer is that the spatial distribution of all physical and geochemical properties and parameters as well as the contaminant concentrations are exactly known. The resulting (virtual) contamination can then be investigated virtually by standard monitoring and investigation techniques. By comparing the results with the true parameter distributions, the investigation methods can be tested and evaluated with respect to their performance (Bauer et al., 2005).
The investigation model deals with the problem of a reliable spatial mapping of contaminant plumes. An as exact as possible survey of the contaminated domains of an aquifer is one of the most important prerequisites for the remediation measures. However, in “real world” field applications, the density of monitoring networks is most often severely limited by financial budgets. As a consequence investigation results are always tainted by significant uncertainty. This problem is illustrated in an interactive plume mapping task using this model. This application is primarily addressed to persons involved in the investigation of contaminated sites, i.e. in regulation authorities and companies. Confronted with the scenario of a contaminant migration downstream from a source zone in the virtual aquifer, task of the user is the investigation of the site and the characterization of the contaminated domains as exact as possible. By placing observation wells into the virtual aquifer the user can “measure” local contaminant concentrations. For the regionalisation of these measurements, the user can choose between different interpolation schemes like kriging or inverse distance weighting. The implementation of these methods in GeoSys/RockFlow was realized by programming of an interface to the well-known mapping software Surfer (Golden Software, Inc. 2002). The steps “drilling of observation well” and “interpolation” can be repeated as often as desired, until the user is satisfied with his investigation results. Based on the result, statistical methods are used to analyze the uncertainty of the contaminant plume investigation in our groundwater contamination study.

11.2 The workflow of the investigation model

Figure 11.1 shows the workflow for this investigation model. This interface is to compare the virtual contaminant plume to investigation results of that plume to give people some information for decision making based on almost zero-cost program in the virtual labor. Based on this flexibility, we get to know the uncertainty of contaminant plume investigation. Moreover the investigation results are evaluated to get ideas of how to set well locations for our interpolation to get a better contaminated plume estimation in the study area. It offers also possibilities for hydrogeologist to innovate methodology for improving existing groundwater monitoring plans. The input file is the "virtual reality" – a GeoSys/RockFlow file, generated by using virtual aquifer method, which contains nodes and elements with their properties, like pressure, concentration, etc. The output file is the interpolated result. Wells are located and can be edited for a new sampling. Then users can execute the interpolation by choosing different methods and parameter settings. The interpolation result is displayed directly after the interpolation. This step is repeatable. That means you may go back to edit the wells, e.g. deleting wells or adding new wells and start a new interpolation until a satisfactory plume is generated. After that, the last interpolation result and the virtual plume are compared to visualize the difference.

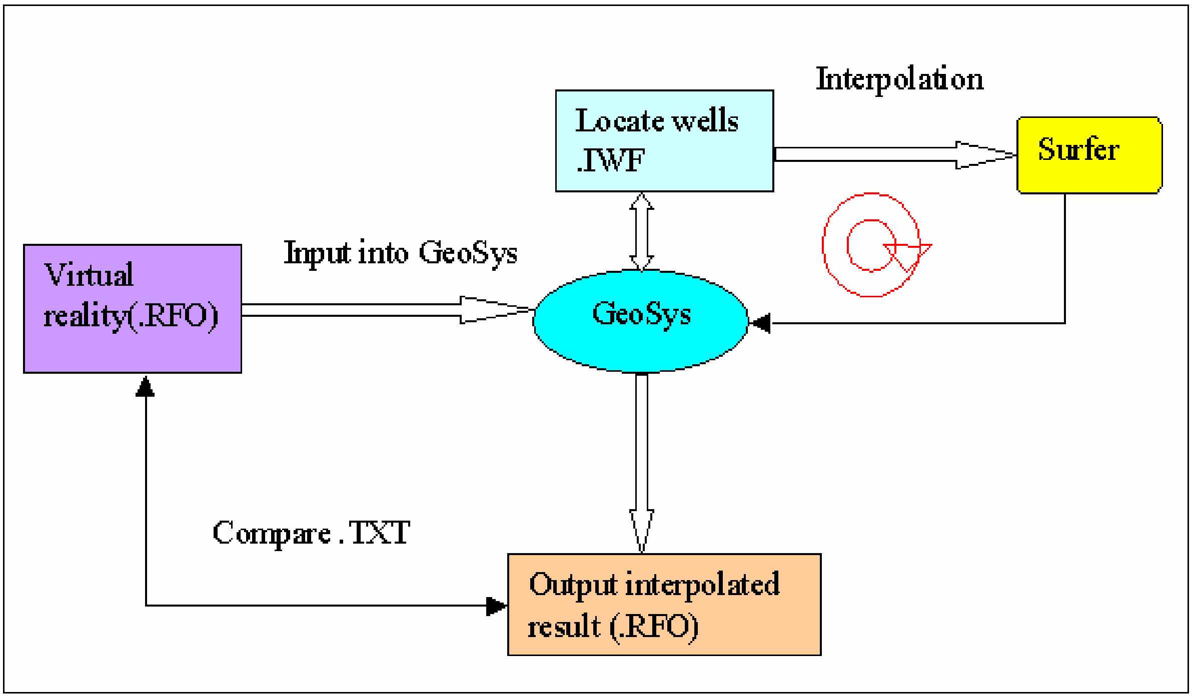


Figure 11.1: The workflow of the investigation model

11.3 Example

The implementation of the graphical user interface (GUI) for this investigation model is described as follows using an example. The investigator interpolates contaminant concentrations and hydraulic heads measured at the observation well to get an impression of the spatial distribution of the contaminant.

Graphical User Interface - Toolbar

The following buttons on the toolbar (Fig 11.2) are implemented under the GeoSys/RockFlow framework for this demonstration. These functions include: Draw points, well editor, interpolate, display and compare.

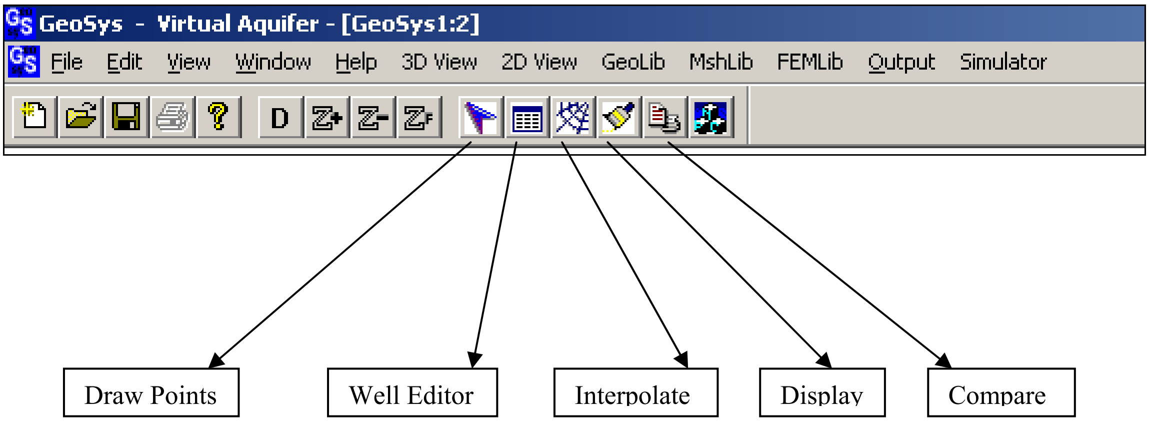


Figure 11.2: Toolbar of the investigation model

Input Data

The first step is to open a GeoSys/RockFlow project: plume.gsp, This file includes the references to geometry file- plume.gli, mesh file- plume.rfi, and processing file - plume.rfo file, which contains the head, concentration and mass distribution of the mesh nodes. The second step is to create an output view to display the data. In this dialog (Fig 11.3), the minimum and maximum value for selected variables, the levels of contour lines and the time steps can be changed. In this example, flow is at steady state.

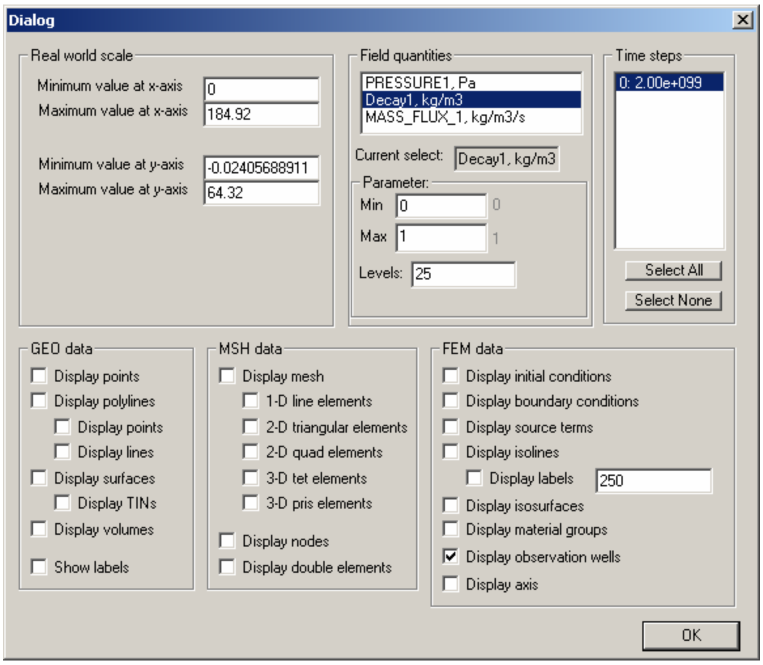


Figure 11.3: Set properties for displaying

Locate Well for Interpolation

Confronted with the scenario of a contaminant migration downstream from a source zone in the virtual aquifer, observation wells are created by using the drawing tool from the toolbar. Here four wells are shown in the figure 11.4:

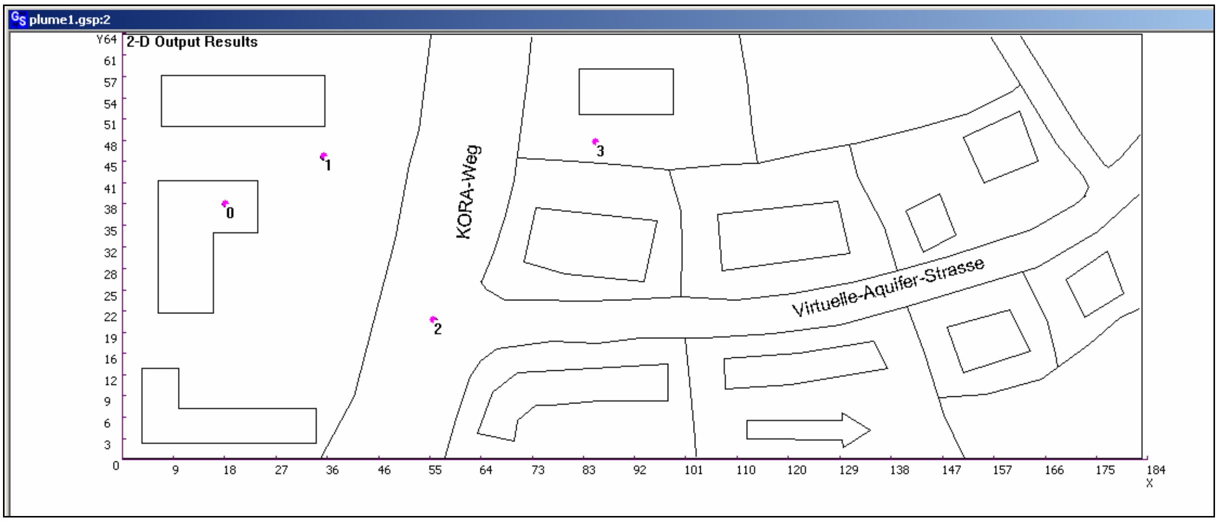
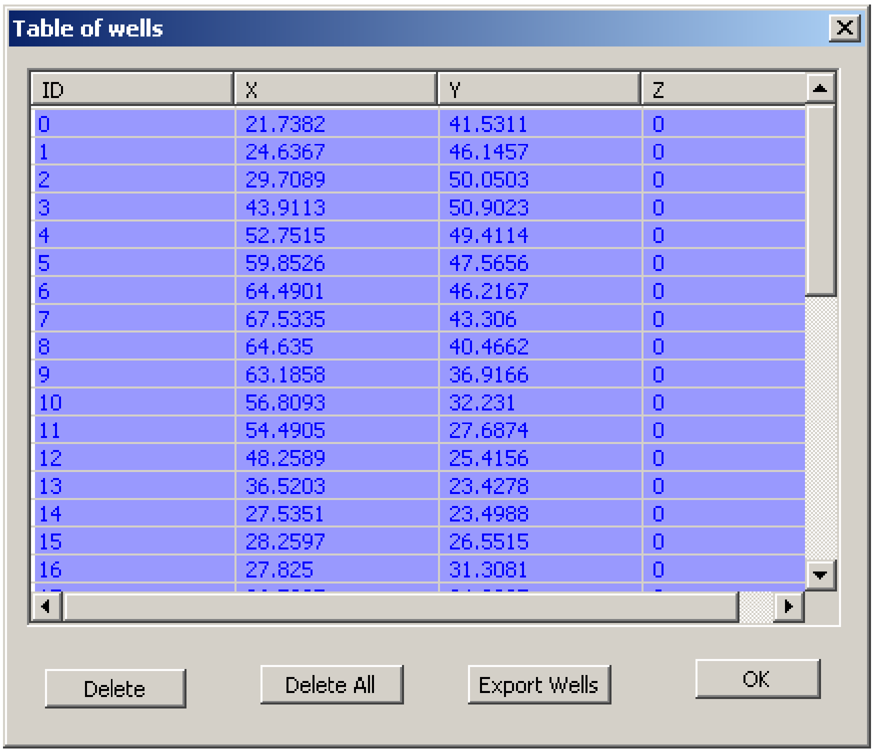


Figure 11.4: Locating wells

Wells can be edited using the well editor (Fig 11.5). The editing functions includes:

- Delete well,
- Delete all the wells,
- Export well data into an ASCII file used for the input file of interpolation.



ID	X	Y	Z
0	21.7382	41.5311	0
1	24.6367	46.1457	0
2	29.7089	50.0503	0
3	43.9113	50.9023	0
4	52.7515	49.4114	0
5	59.8526	47.5656	0
6	64.4901	46.2167	0
7	67.5335	43.306	0
8	64.635	40.4662	0
9	63.1858	36.9166	0
10	56.8093	32.231	0
11	54.4905	27.6874	0
12	48.2589	25.4156	0
13	36.5203	23.4278	0
14	27.5351	23.4988	0
15	28.2597	26.5515	0
16	27.825	31.3081	0

Figure 11.5: Well table

Interpolate

In this step, interpolation parameters are created for the variables of pressure and concentration using the interpolate dialog (Fig 11.6). The file will be saved with the name: interpolmethod0.txt, interpolmethod1.txt.

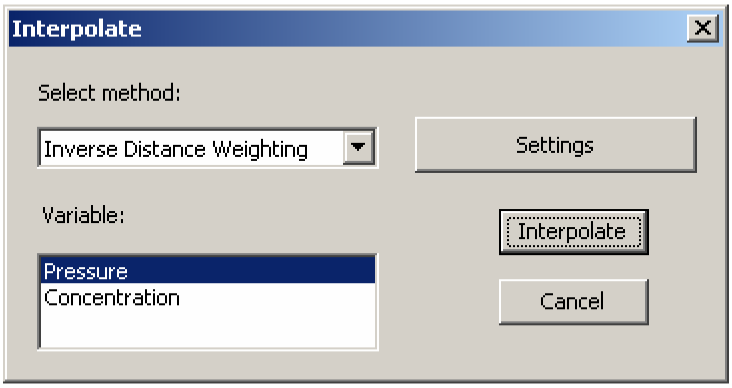


Figure 11.6: Interpolation editor

After the method is chosen, a corresponding dialog for the interpolation schemes: Inverse Distance Weighting, Kriging, and Radial Basic Functions (Fig 11.7) are opened. For each method, the respective parameters can be set to default or user defined value.

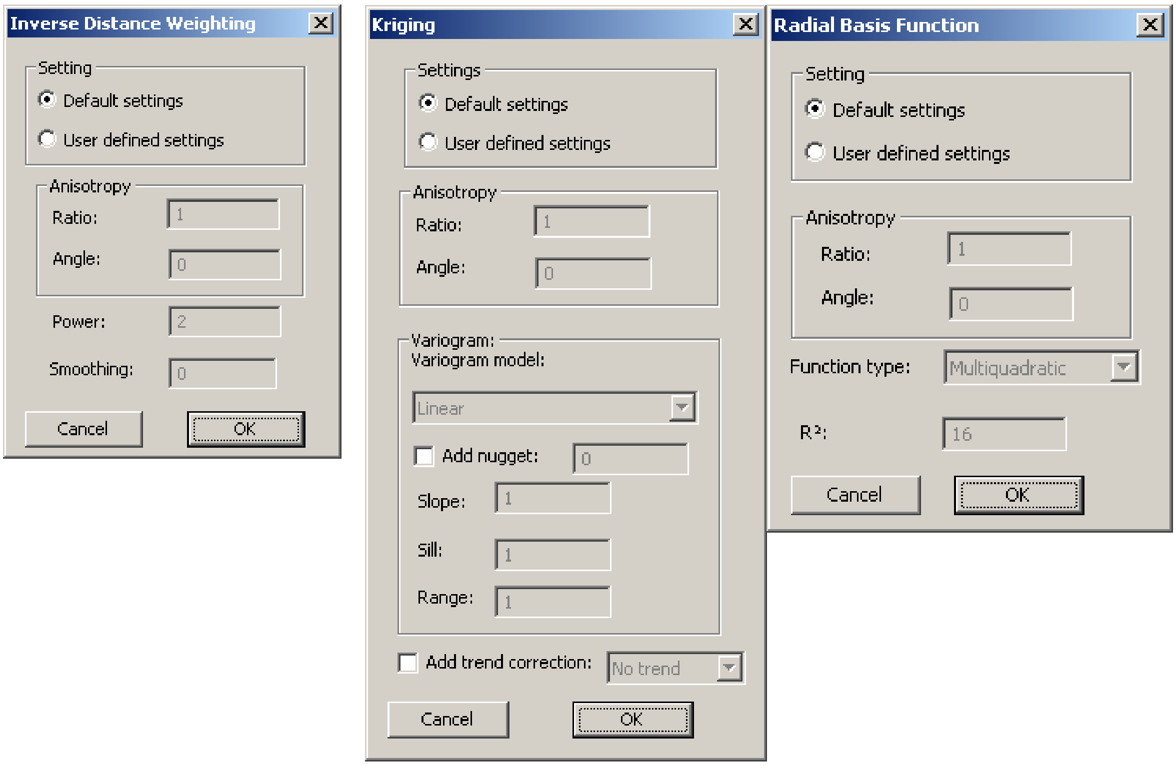


Figure 11.7: Interpolation schemes

After the interpolation, the results are displayed immediately in a 2D view. The following three examples use the same interpolation settings: Inverse Distance Weighting with default settings. The number of sample wells for the examples are respectively 10, 14 and 20 as shown in Figure 11.8.

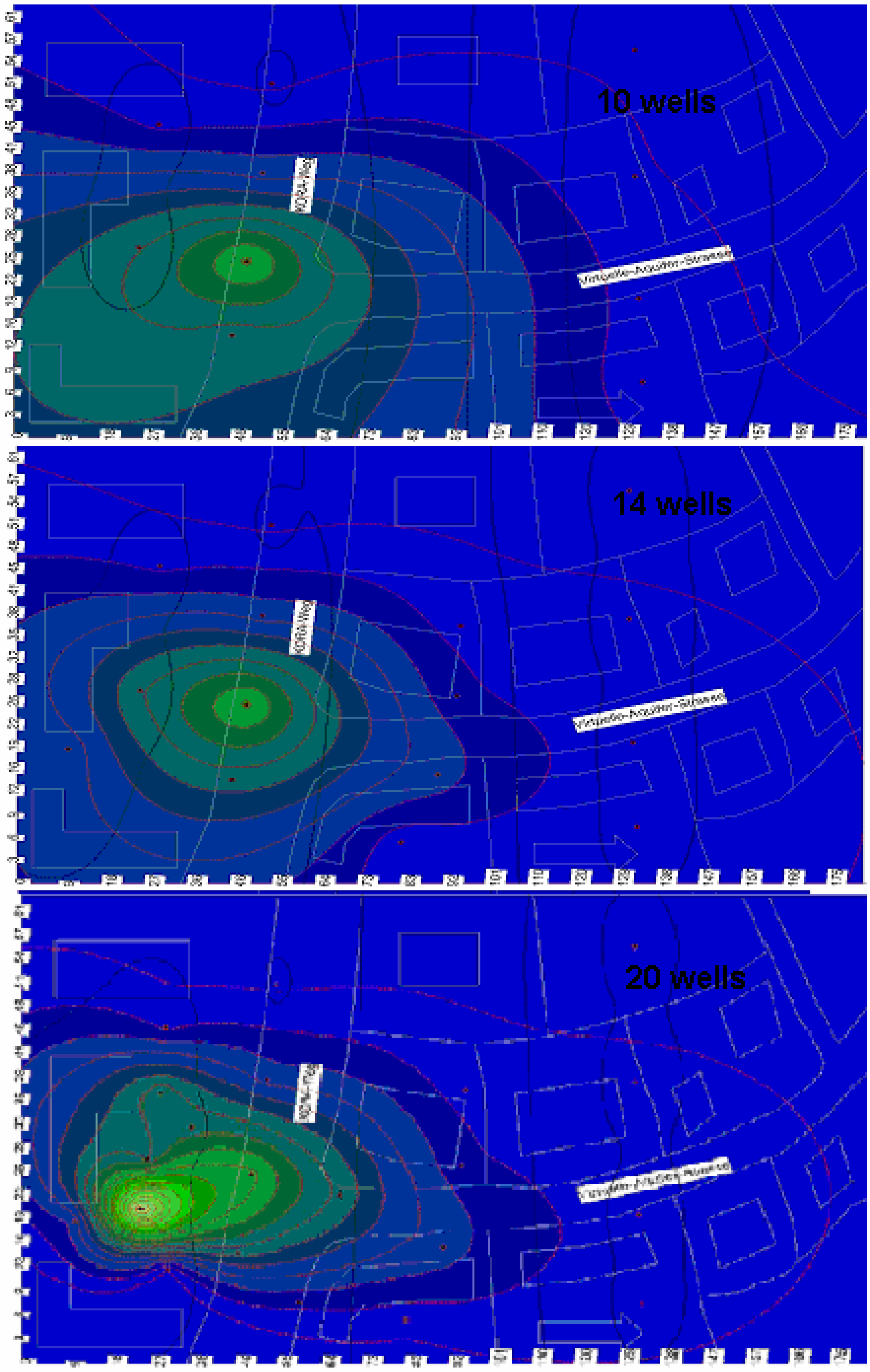


Figure 11.8: Interpolated plumes and hydraulic head with 10, 14 and 20 wells.

This step can be repeated as often as desired by the investigator until the interpolated contaminant plume was deemed accurate enough to properly characterize the contaminant distribution. Thus, the interactive site investigation is an iterative procedure.

Compare results

In this step, virtual contaminant plume and the investigation result of the plume are compared. The comparing result in a text file is shown in Figure 11.9. The result describes the following information: the length, width, mass, maximal concentration and x, y coordinate of the center of the mass of real and investigated plume.

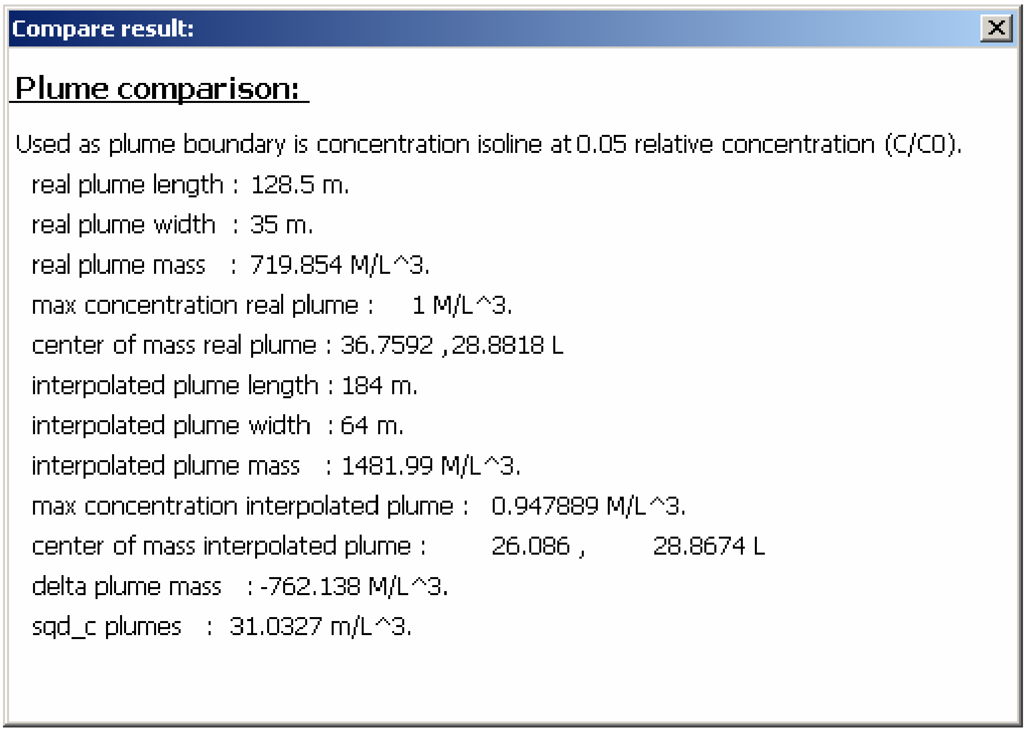


Figure 11.9: Comparison of some plume characteristics

Display data

The Real plume, investigated plumes and the plume describing the difference between them can be chosen for the purpose of displaying as shown in Figure 11.10.

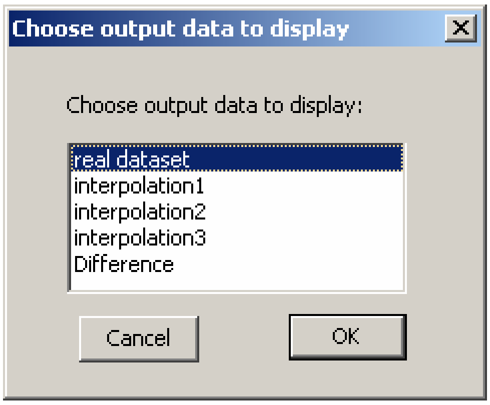


Figure 11.10: Choose dataset to display

Figure 11.11 (a, b) shows the real plume and difference. By comparison of the true plume with the investigation result the uncertainty involved in the investigation strategy can be quantified. The difference plot highlights the regions of largest deviations from the true contaminant distribution, i.e. the interpolation error.

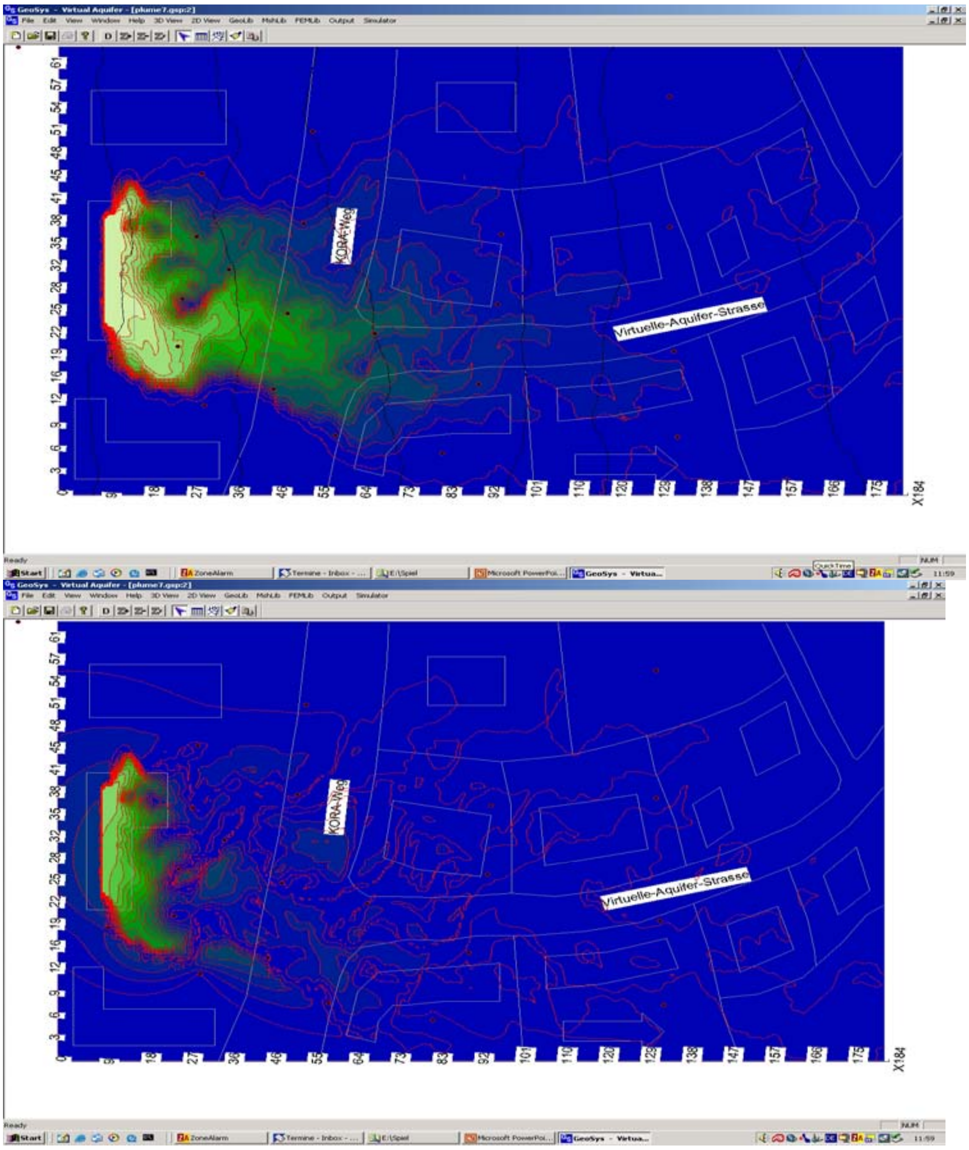


Figure 11.11(a, b): True virtual plume and the difference plot

11.4 Conclusion

To assess the uncertainty involved in an interpolation of contaminant concentration in groundwater, 20 different real plumes were created and the plumes thus generated were independently investigated by different test persons, engaged in hydrogeological and environmental research, consulting or administration. These investigators were confronted with the scenario of contaminant migration downstream from a source zone in the virtual aquifer. A two-dimensional top view of the site, the mean ground water flow direction and the approximate location of the contaminant source were given as the only prior information for the site investigation. After some testing on those plumes, an overview of the result is shown in the following Figure 11.12. This graph shows the correspondence of the interpolated results and the real value. They are: length, width, mass, area, x and y coordinates of the center of mass of the interpolated and real plume. The interpolation results are shown on the x-axis, and the respective true values are shown on the y-axis. The gray line gives the 1:1 line, where interpolated values are equal to the real values. From the graph, it shows he area of the interpolated plume is underestimated. Most of the length of the interpolated plume is underestimated, and most of the width of the interpolated plume is overestimated. Figure 11.13 shows the result of one single plume – plume 10. Here an index - interpolation quality – is used to show the relationship between the number of wells, number of interpolation steps and the interpolation quality. When the number of wells or the number of interpolation step is increased, it will not definitely lead to a better result. When the number of wells is less than 20, the interpolation quality can be low or high. When the number is more than 30, the quality is mostly high. But it still shows the uncertainty of contaminant plume investigation and demonstrates in a striking way for a simple scenario, which kinds of problems and uncertainties have to be faced when interpolating and interpreting data in heterogeneous aquifers.

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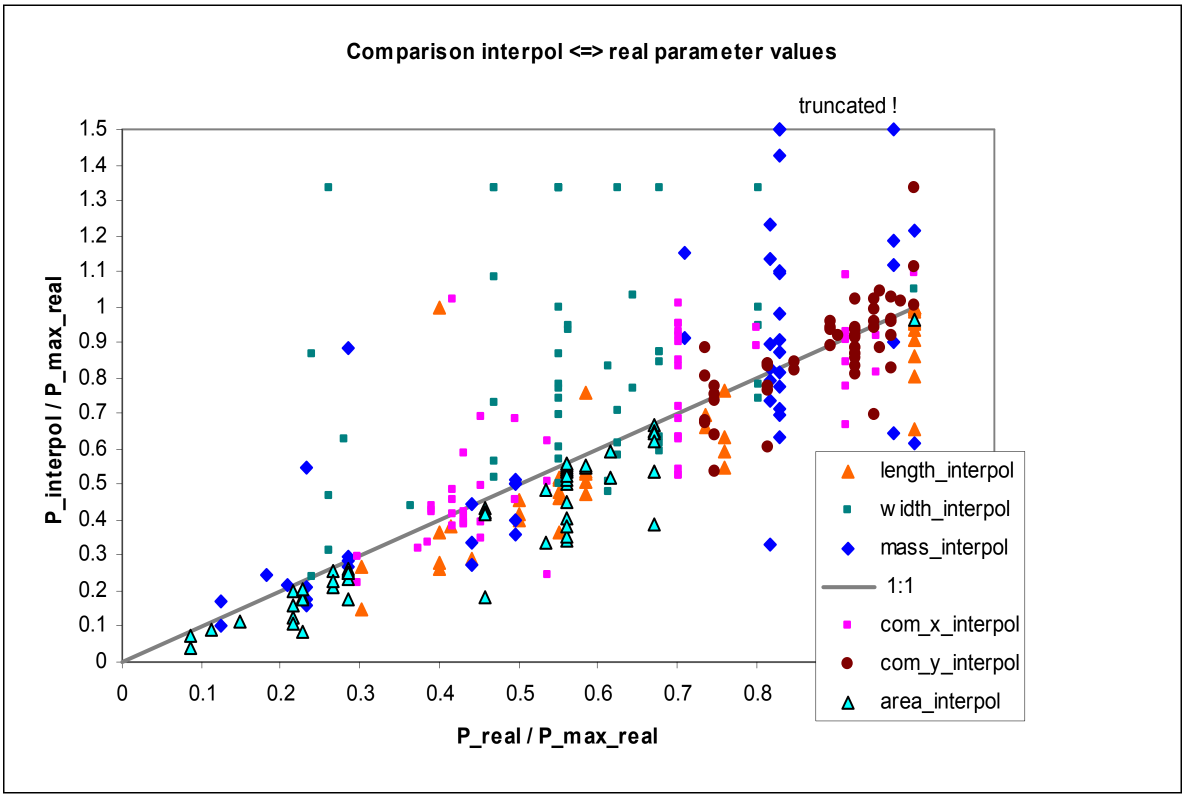

Figure 11.12: Result of all interpolations (Bauer 2005)

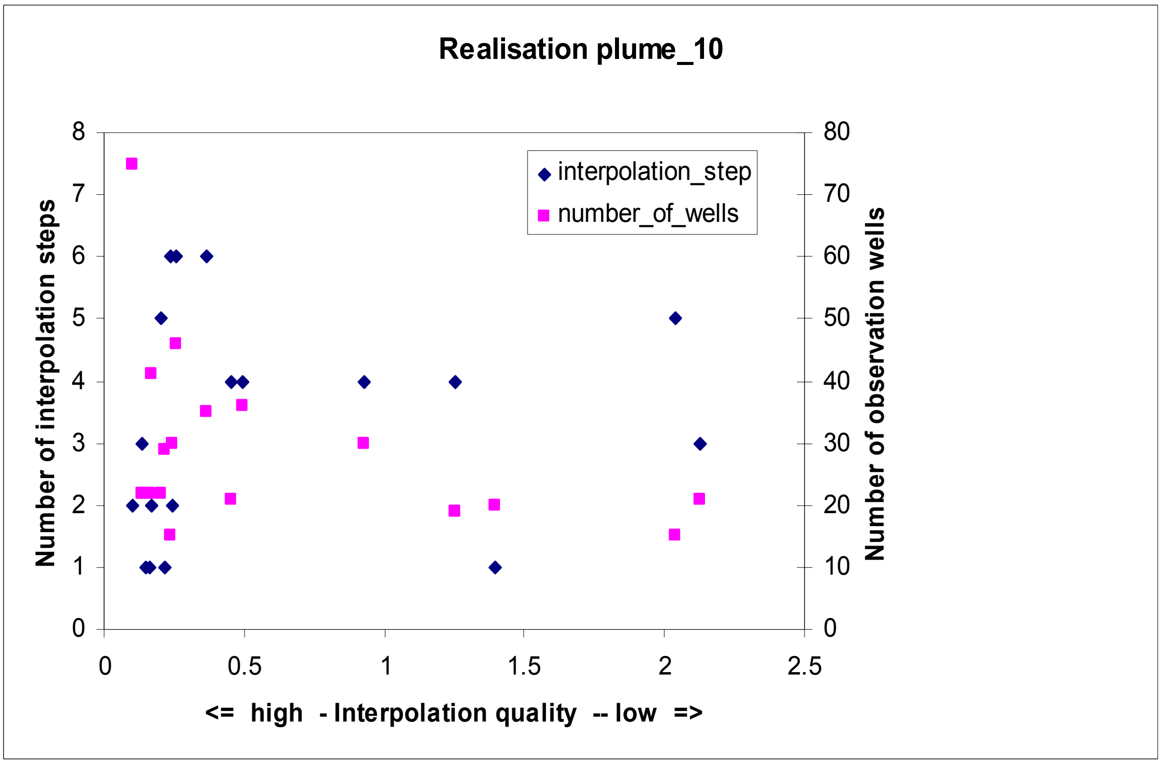

Figure 11.13: Result of plume 10 (Bauer 2005)

12 SUMMARY AND CONCLUSIONS

In summary, the research presented in this dissertation aims to develop a GIS based model for the analysis of GeoSystems. The ability to store hydrogeological information in a common understandable structure combined with the capabilities of GIS software will facilitate the integration of applications and models. The data model will provide a description of the groundwater system to which applications can interface directly or through a data model interface, thus providing a platform for model integration and data assimilation. GIS integrated within numerical modeling software GeoSys/RockFlow provides the ability to model GeoSystems in two or three dimensions. Two-dimensional models are generally applicable for larger studies while site-specific studies require a 3D description of the subsurface. Now focus on the 3D thing, traditionally, GIS applications focus on 2-D problems and many models used 2 or 2.5 dimensions to represent the subsurface and characterize groundwater system. The integration of numerical modeling software GeoSys/RockFlow and GIS can solve the 3D problem. GIS technology allows for quantification and interpretation of large quantities of geohydrological data with computer accuracy and minimum risk of human error. GeoSys/RockFlow can import data directly from ArcGIS shape file, and the shape date (.SHP) will be converted into .GLI - our input file format of GEOLib and served as the input geometric data of modeling area.

In ArcGIS environment, thematic data will be prepared as different kind of shape files (point, polyline or polygon) based on the hydrogeological properties, for example, study area domain, well and springs, wadi or faults, boundary condition, source term, initial condition etc. Then all these data is imported from our graphical user interface into GeoSys/RockFlow, and fill in the list or vector from the geometric data structure in GEOLib and served as the input data for meshing and modeling purposes. In principle, one GEOLib library is composed of point, polyline, surface, volume and domain. The hierarchical relationship between them is: point is the basic element of all other geometry types. It can be used to define 1-D element as source term or boundary condition. Polyline is composed of points, which could be used as 2-D element as: boundary of domain, boundary condition or line element. Surface is closed polyline, which is used as 2-D domain boundaries. Surface could also be created by several polylines. Volume consists of two surfaces with closed boundary. Domain includes every geometric object mentioned above. Editing both spatial data and its attribute could be done from its corresponding dialog: point editor, polyline editor, and surface editor and volume editor.

The layer models are built in the model, like layer polylines, layer surfaces and layer volumes, which are the key for the construction of a 3D structural model. Furthermore, the Digital Elevation Model (DEM) is used for the 3D topographical surface model with higher accuracy, which is very important for the surface water modeling in the case that the topographical parameters play an important role in the surface modeling. The concept of GIS integrated modeling system is illustrated in Figure 12.1.

Another contribution of the work is the implementation of the Graphical User Interface (GUI) for the above functions inside GeoSys/RockFlow software based on the understanding of the finite element program and object-oriented programming language. The GUI and the GIS integrated concept are demonstrated in several case studies in Middle East, Europe, and in local area Tübingen, which are also served as an education example for the students.

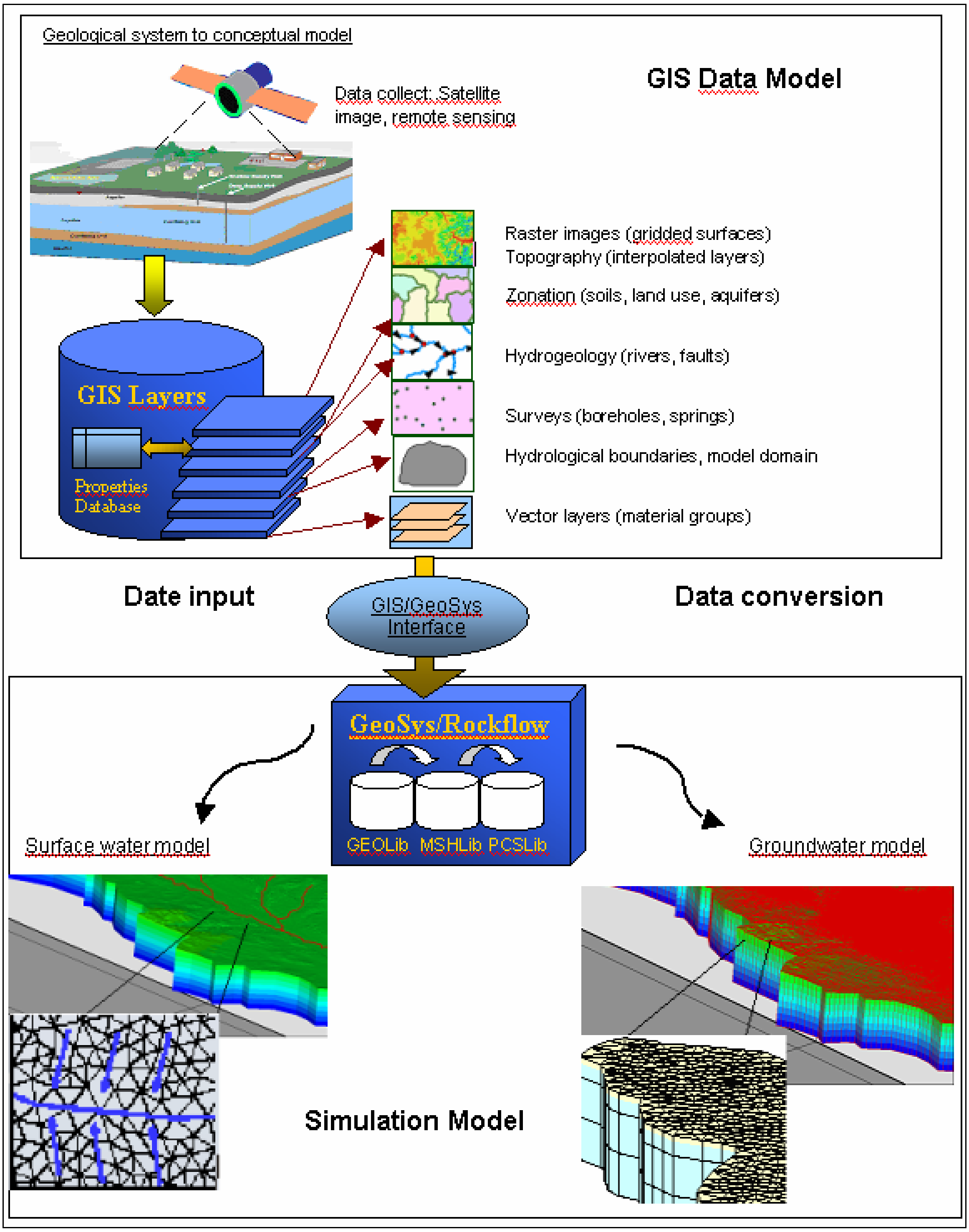

Figure 12.1: The concept of GIS integrated modeling system

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