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## A GIS BASED 3-D HYDROSYSTEM MODEL OF THE ZARQA MA'IN-JIZA AREAS IN CENTRAL JORDAN

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*A GIS based hydrosystem is used for groundwater modeling. The system takes advantage of GIS capabilities, such as image georeferencing, feature creation, data modification, and data thematic organization to assemble hydrogeological data with computer accuracy and a minimal risk of human error. Shape files from ArcGIS, like points, polylines and polygons, are used not only for the basic geometric data of the modeling domain, but also for 1-D line elements of the finite element mesh, boundary conditions and source term. The GeoSys/RockFlow scientific modeling software uses this concept to develop a numerical groundwater flow model at 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, heat transport between the two aquifers in the study area confirms that the thermal water from the lower aquifer flows up via fault conduits to the upper aquifer. The integration of GIS and GeoSys is based on open data formats and standards and may be used for many other application areas, especially where 3-D modeling is involved.*

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## INTRODUCTION

### GeoSys Structure and Concept

GeoSys is an object-oriented program to simulate flow, mass, heat transport and deformation as well as chemical reaction processes in porous and fractured media (Kolditz et al., 2003). The main concept of GeoSys is the separation of geometrical, topological and physical data. They are:

**GeoLib** contains the basic geometric entities such as points, lines, polylines, surfaces, volumes, and domains.

**MshLib** contains the basic topological entities such as finite elements (triangles, tetrahedra, hexahedra, etc.).

**FEMLib** contains the numerical methods for solving partial differential equations (PDEs) such as the finite element methods.

Figure 1 shows the multiple document interface (MDI) of GeoSys with a focus on the above three parts. Their relationship is shown in Figure 2.

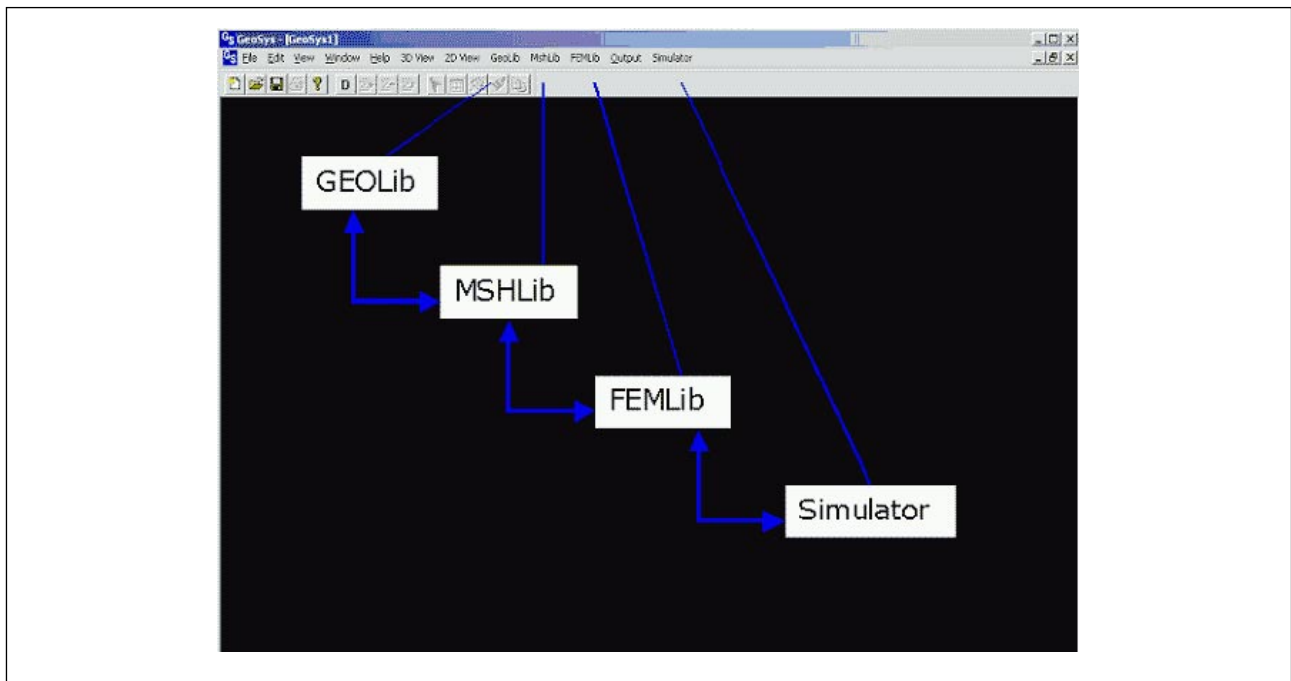


Figure 1. GeoSys user interface.

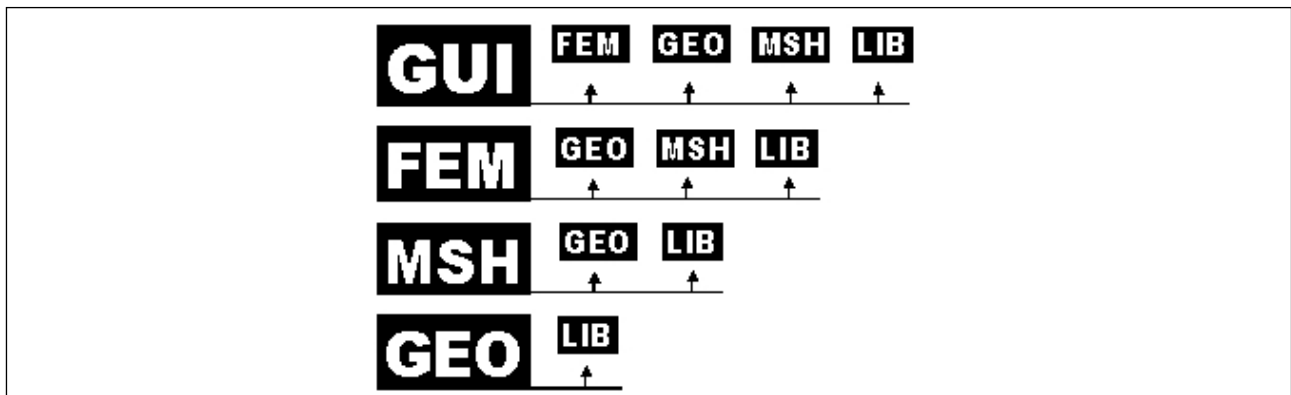


Figure 2. Hierarchical relationship between GeoSys components.

Data are displayed in different views based on the multiple view concept of the Windows® programs GEOView, MSHView and FEMView.

### Process of a GeoSys Project and its Interface

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

- Create geological features as layers for the study domain in ArcGIS by using feature creation tools and save as shape files. Import shape files into GLI, the input file format of GeoLib, and save as the input geometric data of the modeling area.

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

- Create and edit the process data. The concept of GeoSys is based on a multi-phase/multicomponent approach. We have to specify the physical and chemical properties of fluid and solid phases as well as material properties representing the geologic formations. Moreover, we have to specify initial and boundary conditions for the unknown field functions (e.g. pressure, temperature, concentrations) related to the selected process. Finally, we have to manage the numerical method. As a result, output data of each process is saved in a RFO file.

In addition, GeoSys has also implemented interfaces with different software packages including GINA, GoCAD, Excel, Surfer, ArcGIS, and GMSH to make the program more powerful and user friendly.

### APPLICATION TO THE ZARQA MA'IN-JIZA AREAS IN CENTRAL JORDAN

The study area is located in the central part of Jordan east of the Dead Sea. It covers the northern third of the Wadi El Mujib groundwater basin and Wadi Zarqa Ma'in sub basin and has a total area of about 2300 km<sup>2</sup> (Figure 3).

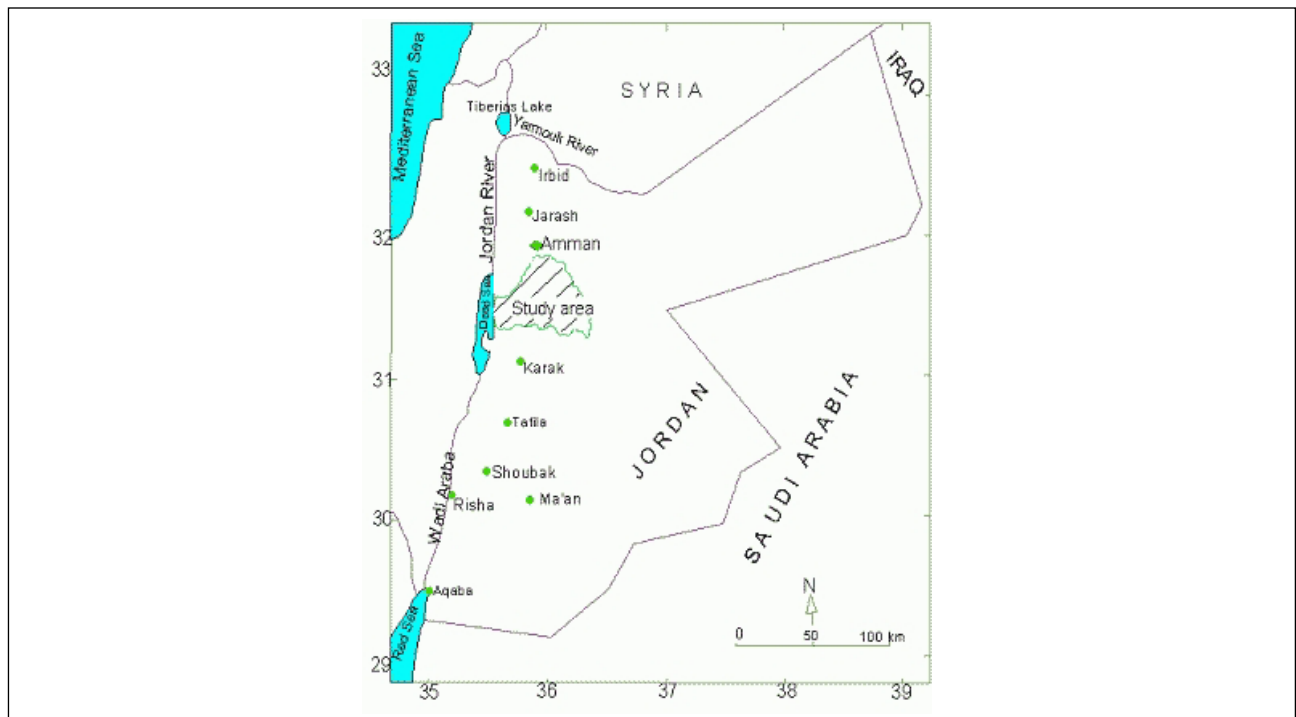


Figure 3. Location map of the study area.

The area consists of two major aquifer systems: an upper and a lower aquifer. The upper aquifer is 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 outcrops and receives the highest average rainfall (250-400 mm/y). The groundwater within this aquifer flows mainly from north to south then to the west along the Wadi Waleh drainage. Flow is also from south to north joining the flow to the west. Part of the water flows further to the east towards the Azraq groundwater basin. The main natural outlets of the aquifer are the Heidan springs and the Zarqa Ma'in spring with annual average discharges of about 15 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 is heated under a normal to slightly elevated geothermal gradient and flows to the west towards the Dead Sea, where it enters the Dead Sea as subsurface flow or discharges to the ground surface as thermal springs, as at the 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 temperature from 30°C to 46°C. The dense network of faults in the area, strongly suggests that the two-aquifer systems are hydraulically connected, especially in the eastern parts of the study area. This could allow the thermal water from the lower aquifer to flow up via fault 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 water from the two aquifers (Sawarieh et al., 2004).

## MODEL SETTING

### Data Acquisition for the GIS Project

The conceptual model includes all the physical properties and stresses that affect the system, including geological formations, faults, wadis, aquifers, aquitards, wells, springs, the water table, top and base of aquifers, and boundary conditions. All these data are created and organized in ArcGIS as thematic layers for later use as input data for modeling in GeoSys.

The GIS thematic layers include the following features:

*The hydrological units:* The geological formations are subdivided into four hydrological units. These are the confining beds (B3 and B4), the upper aquifer (B2/A7), the lower aquifer and the main aquitard (A1-6), which separates the two aquifers.

*Study domain:* The study domain shown in Figure 4 is subdivided into 29 subareas based on the border of wadis (red polylines) and faults (blue polylines). Twenty nine polygons are created in ArcGIS (see Figure 5). Twenty two surfaces represent the upper aquifer system (0-21), three the aquitard (22,23 and 28) and four the lower aquifer system (24-27). Each surface has an average value for hydraulic conductivity.

*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 downstream of Wadi Waleh between the elevations of 450 and 250m. The largest spring group is located at an elevation of 350m.

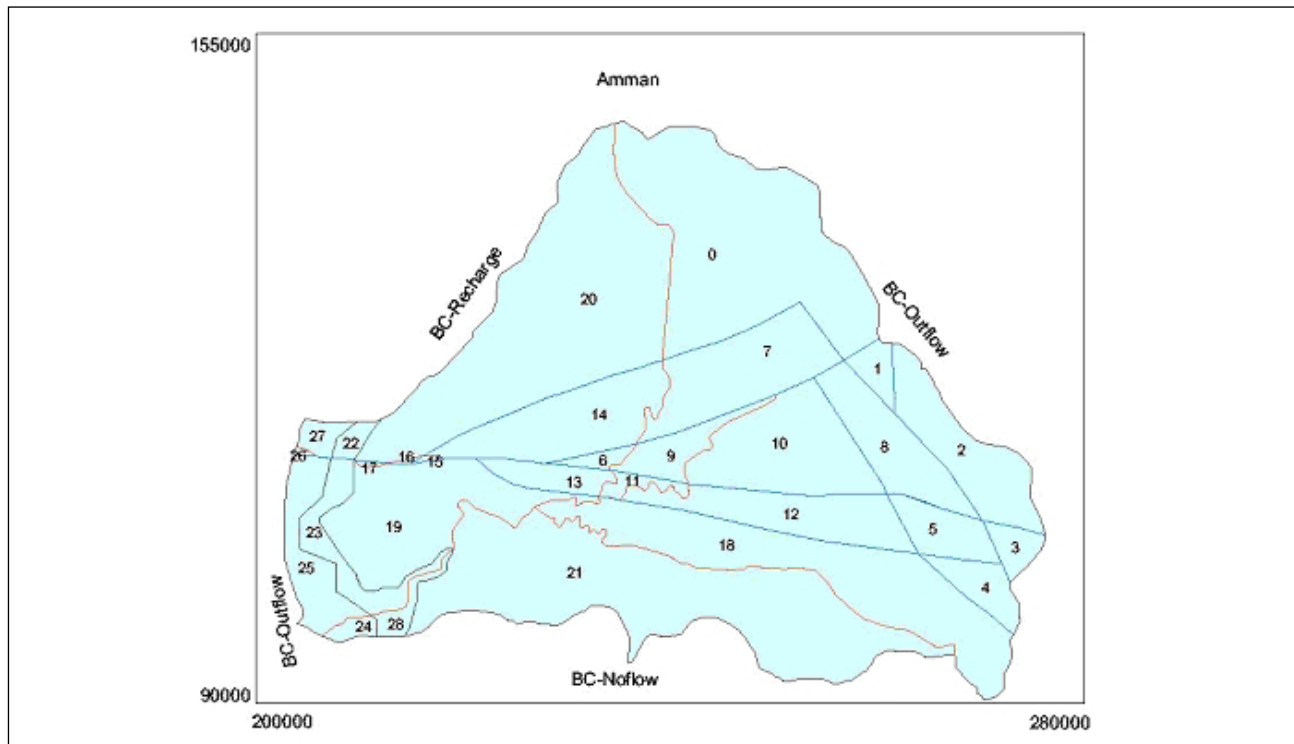


Figure 4. The study area domain and boundary conditions in the upper aquifer.

*Faults:* The study area is highly impacted by faults, especially in the eastern part. Some of the faults are tensional which allow them to act as conduits for the thermal water to flow upward and mix with the upper aquifer water, raising the temperature of the water in the vicinity of these faults.

*Well locations:* During the last three decades more than 200 wells were drilled in the study area for agricultural and drinking purposes.

*Boundary Conditions:* The study area covers the northern part of the Wadi El Mujib groundwater basin and Wadi Zarqa Ma'in sub-basin. The major recharge points to the upper aquifer are the northern and western highlands. Along the western border the main discharge outlets from the aquifer through 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 conditions were set for the area, outflow, recharge and no flow. These are shown in Figure 4. For the lower aquifer the boundary conditions are set as no flow at the northern and southern borders, inflow at the eastern border and outflow at the western border.

## Model Setup

### Import of GIS data (SHP files)

The first step is to import the shape files into GeoSys, which are converted into our own GeoLib data structure (Chen et al., 2003), and saved a file with extension GLI.

### Geometry (GeoLib)

There are three major types for a 2-D model: point, polyline and polygon. The hierarchical relationship between them is as follows (see Figure 5):

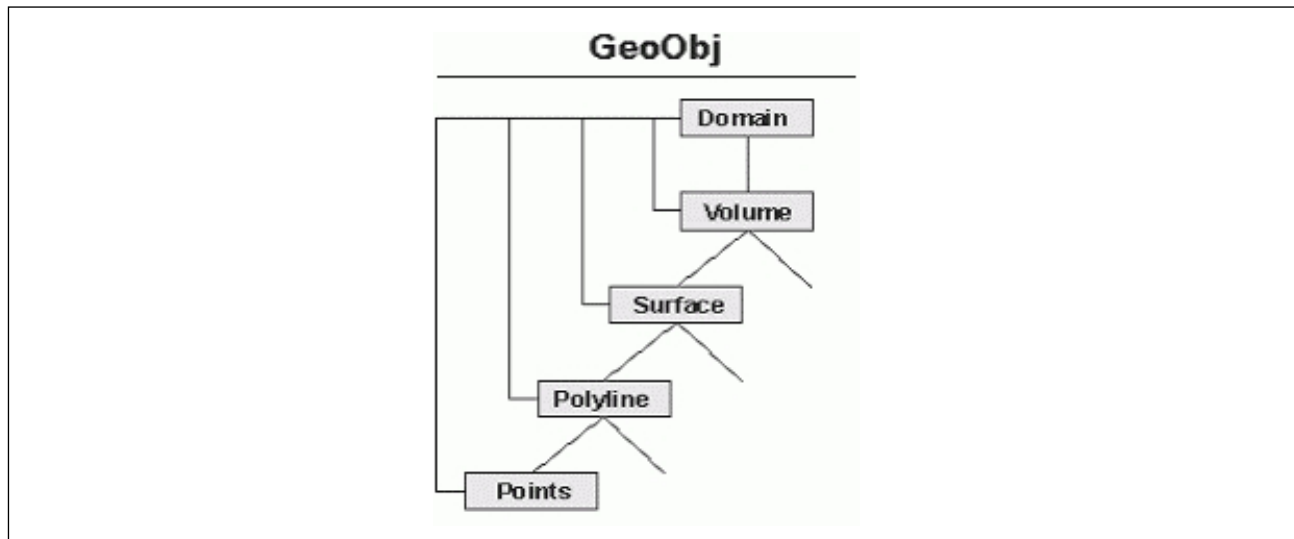


Figure 5. Hierarchical relationship between geometric objects.

Points are basic elements of all other geometry types. We can use point to define the 1-D geometry elements, source terms, and boundary conditions. Polylines are important geometry objects, and we can use polylines to define the following 2-D geometric elements:

- Boundary of a model domain,
- Boundary to assign a boundary condition, and
- Line structures.

For 2.5-D (quasi 3-D) vertically extended models, polylines can be copied on to so-called layer polylines. These layer polylines are copied in the z-direction for each layer. Layer polylines can be used to define boundary conditions at vertical surfaces. Surfaces are closed polylines, i.e. the last point of polyline is connected to the first one. Surfaces can be used as 2-D domain boundaries. One surface could be created from one closed polyline (polygon) or from several polylines. In our case, each surface is created from one polygon.

#### TINs for surfaces

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 then for volumes as well. The generation of TINs for surfaces requires an existing triangulation.

#### **Meshing (MshLib)**

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, and
4. Create quadrilateral elements for the 2-D fracture/faults model.

In the following, Figure 6 shows the geometrical representation of those elements inside one 3-D finite element:



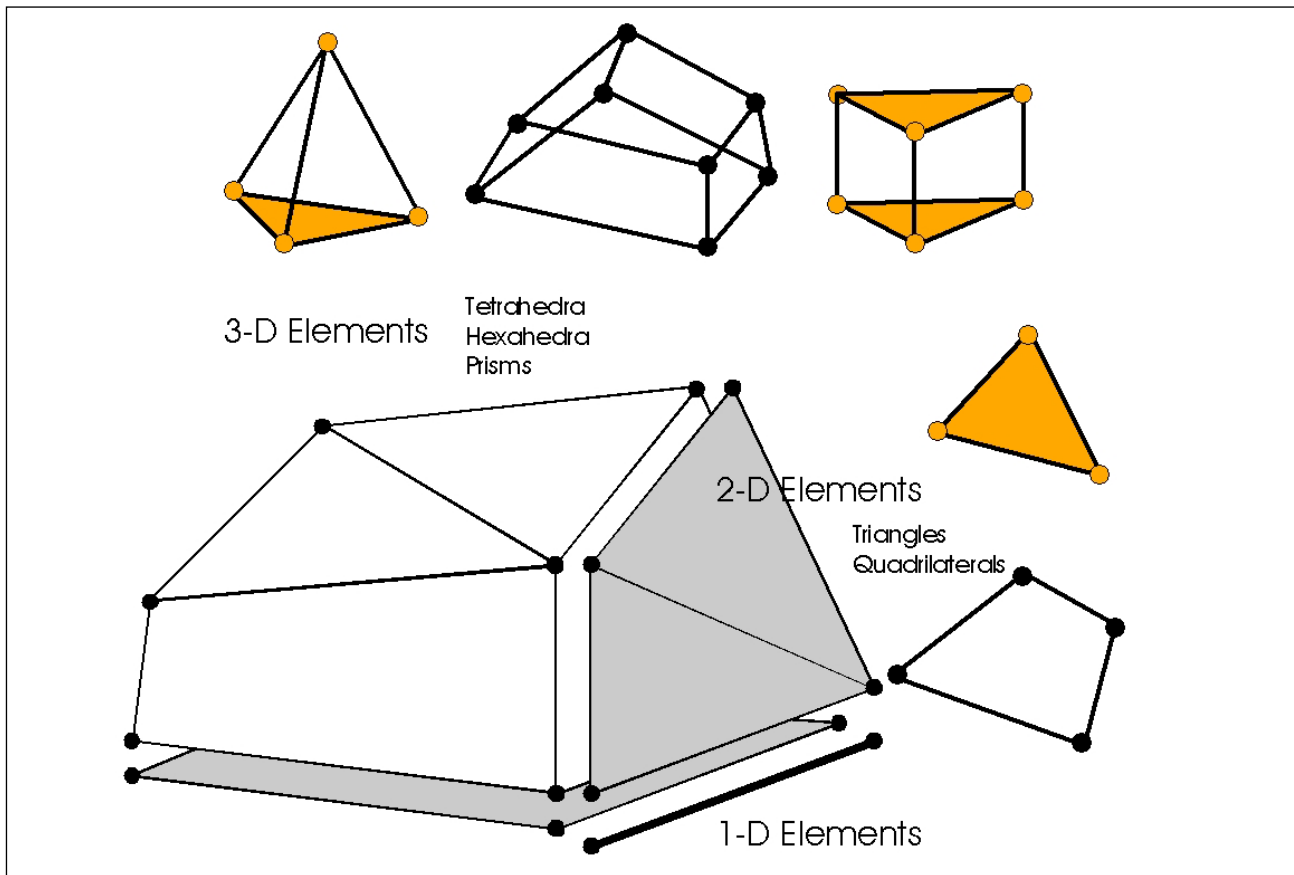


Figure 6. Geometrical presentation of one 3-D finite element

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 RFI file is generated automatically.

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 were used for the triangulation. Figure 7 shows the line element generator which:

- Creates polylines for line elements by using our drawing tool in GeoSys or import the shape file for wadis,

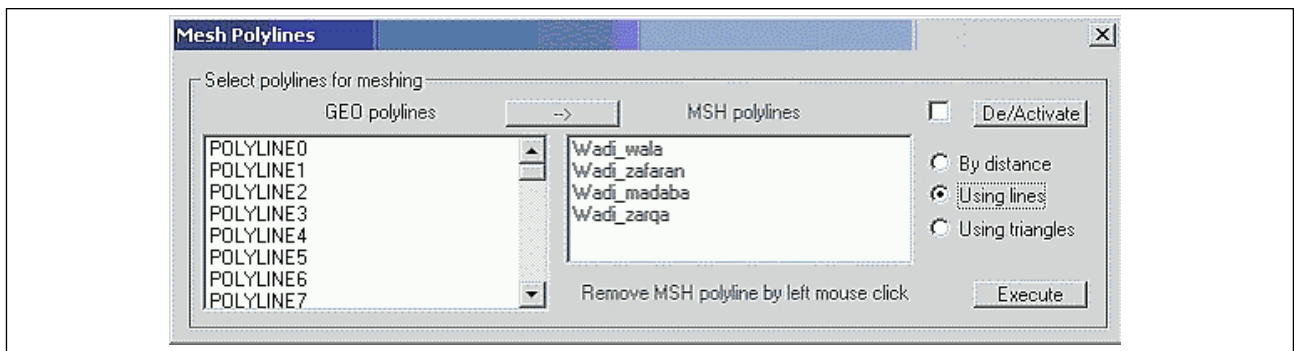


Figure 7. Dialog for line element generation from polylines

- Selects the LineGen option from the MSHLib menu, and
- Uses the Mesh Polylines dialog to select existing polylines for line meshing.

### Prisms

Prism elements can be generated from triangles while extending these in the vertical direction as follows:

- 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 (see Figure 8),
- Use the option Create PRISM File to write elements to a file (without creating element data structures), and
- Use the option Create PRISM Elements to generate the element data.

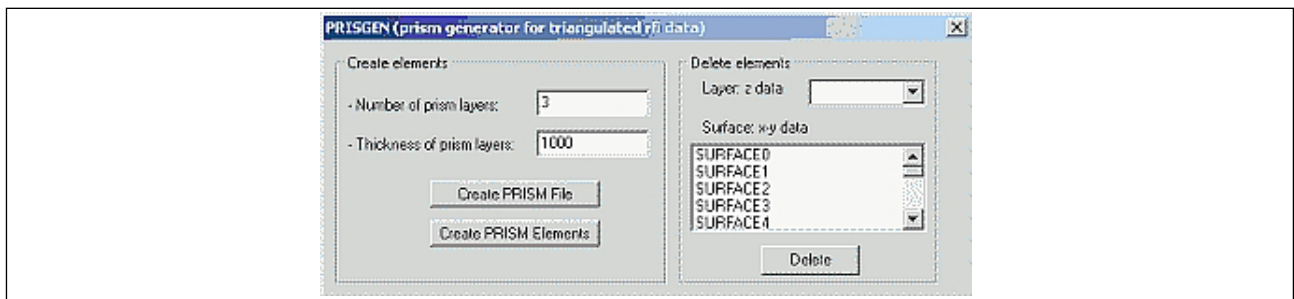


Figure 8. Dialog for creating prism elements.

### 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. After these steps, the 3-D finite element mesh of the modeling domain is finished. Figure 9 displays the

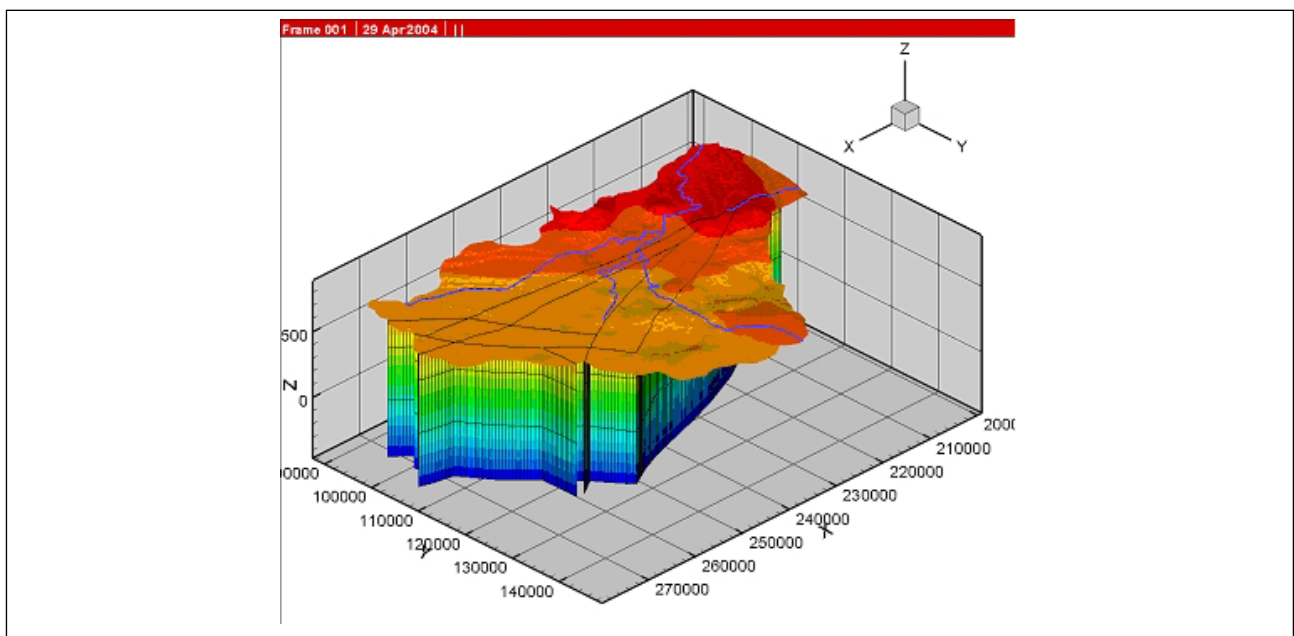


Figure 9. Inside the hybrid finite element mesh.



result with 1-D line elements, prismatic elements, and 2-D triangles and quadrilateral elements to represent the wadis, surface, faults, and aquifers and aquitards.

### 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 or grid files created with ArcView, which uses the extension ASC. There are four ASC files for four rows from uppermost to lowermost: top\_b2a7.asc, base\_b2a7.asc, top\_ks.asc, and base\_ks.asc. For example, the nodes of prism elements with Z coordinates equal to 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 mapped to the corresponding vertical height (elevation). Figure 10 shows the mapping result of the domain.

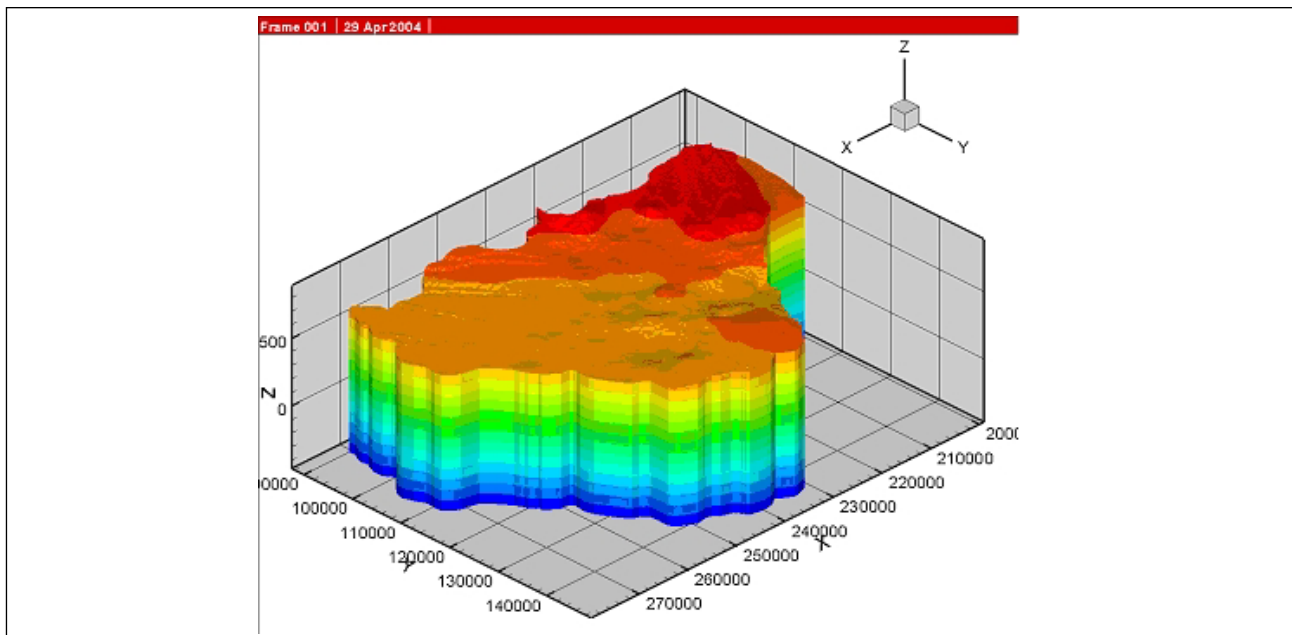


Figure 10. Mapping result of the study domain.

### **Process (FEMLib)**

After having finished all geometric and meshing operations, it is necessary to specify data for the processes. At first, select flow process to be simulated. And then the boundary condition, source term, and material properties need to be set for modelling purposes.

#### Boundary Conditions and Source Terms

Points, polylines and surfaces can be used to set boundary conditions and the source term. Here three types of data are to be connected: 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). Boundary condition data are stored in a \*.bc file. Source term data are stored in a \*.st file.

#### Material Properties

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

*Link Material Database with Geometric Data:*

The MAT group editor (see Figure 11) allows combining material data with geometric data. Material data can be imported from a database (e.g. Excel). In the example shown below the selected material (upper aquifer) is linked with the geometric object SURFACE3. All finite elements within this surface inherit the material data (MAT) of the upper aquifer. MAT can be saved to a \*.mp file.

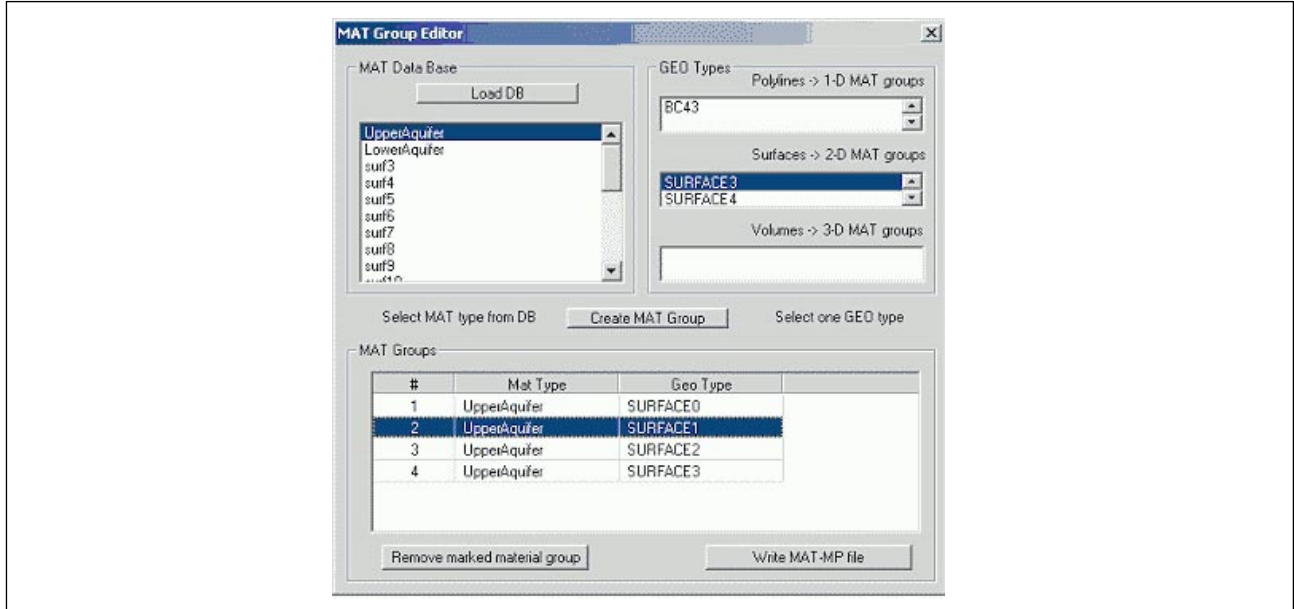


Figure 11. Material group dialog.

*Link Material Data with Meshing Data:*

Material groups have to be connected with the finite elements. This is done using the MAT Connect function from the MSHLib menu (see Figure 12). 1-D, 2-D and 3-D elements are needed to connect with MAT data.

Three layers are shown to represent the two aquifers and the aquitard in between, which are modelled by prismatic elements. In the following Figure 13a different color shows each layer is connected to corresponding MAT data. The method PointInVolume () is used.

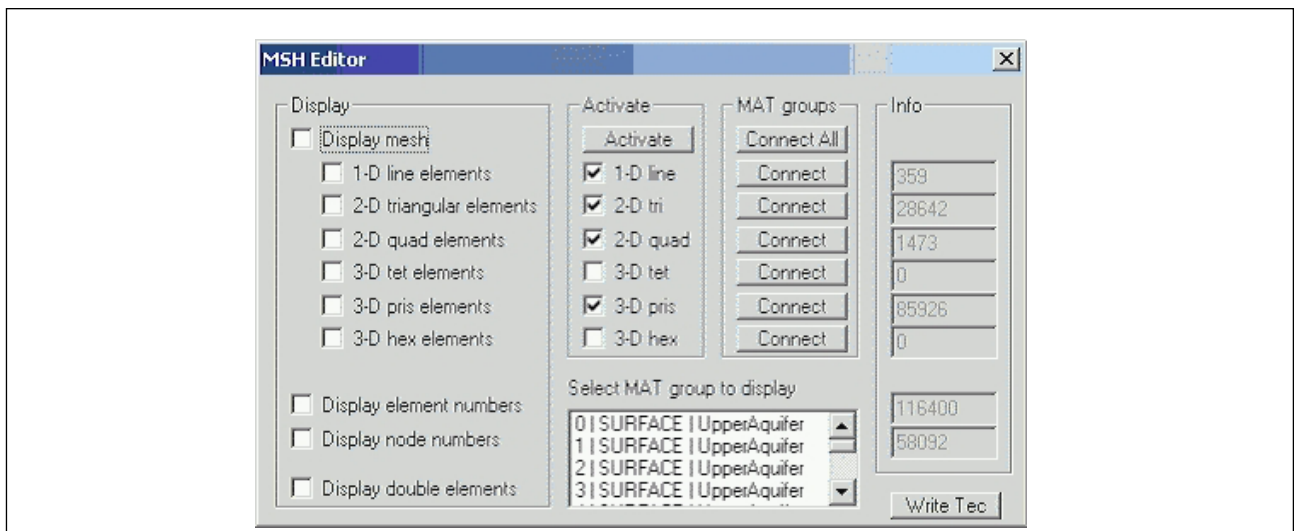


Figure 12. Menu of MSH editor.

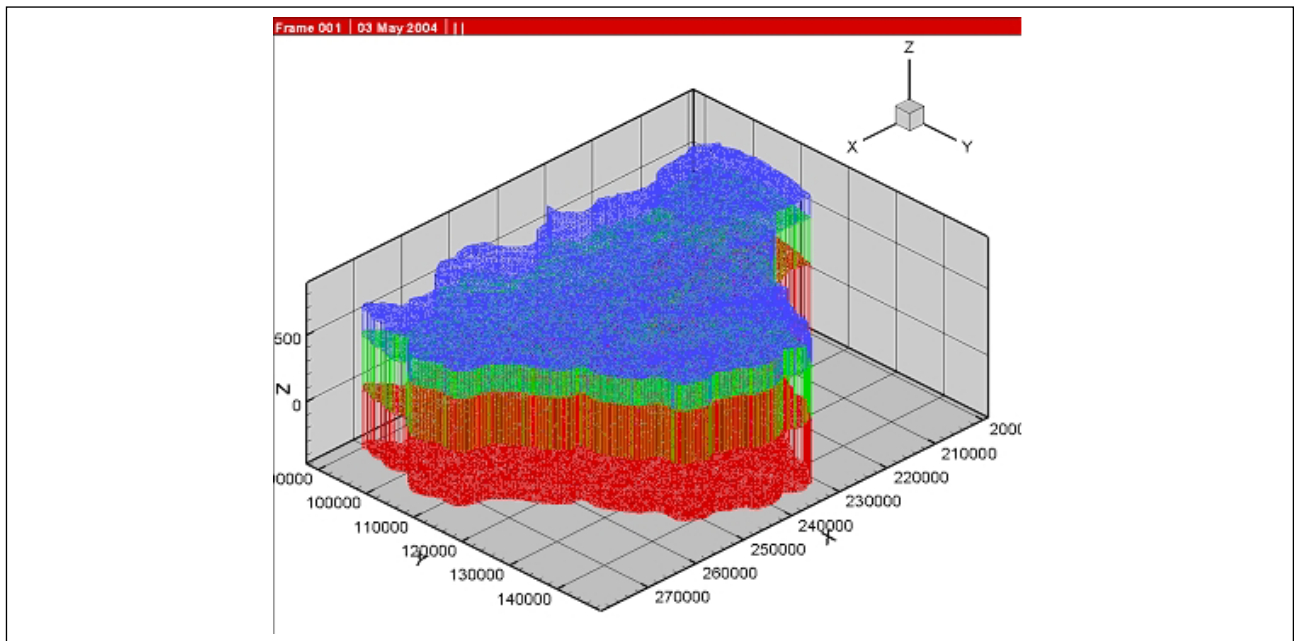


Figure 13. Connect 3-D elements with MAT data.

### Simulation Results

We present the first simulation results (steady state) of a fully 3-D flow and heat transport model.

#### Flow model

As mentioned in section above, 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 14 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.

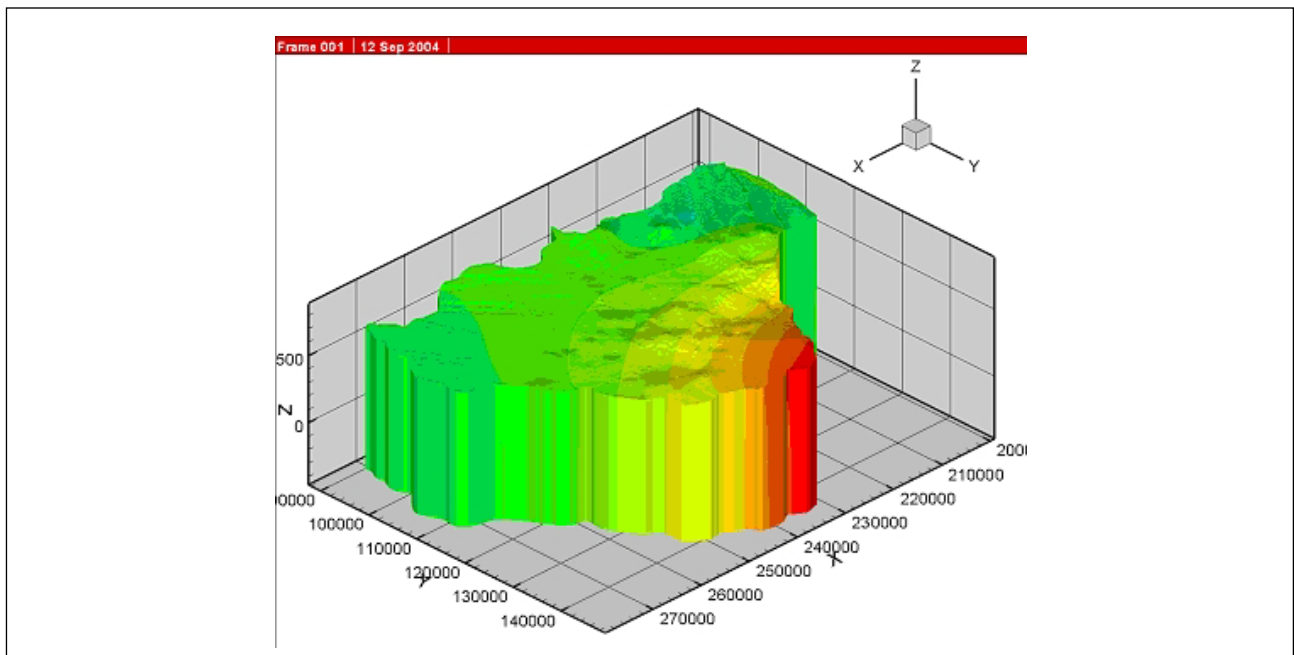


Figure 14. 3-D groundwater flow model hydraulic head in the model area.

### Heat transport modeling

The basic thermal processes are illustrated in Figure 15. There is a permanent heat flow from the base to the system. Groundwater is entering the upper aquifer from the North and the lower aquifer from the East. This groundwater has to cool the whole system, otherwise the temperature will increase continuously.

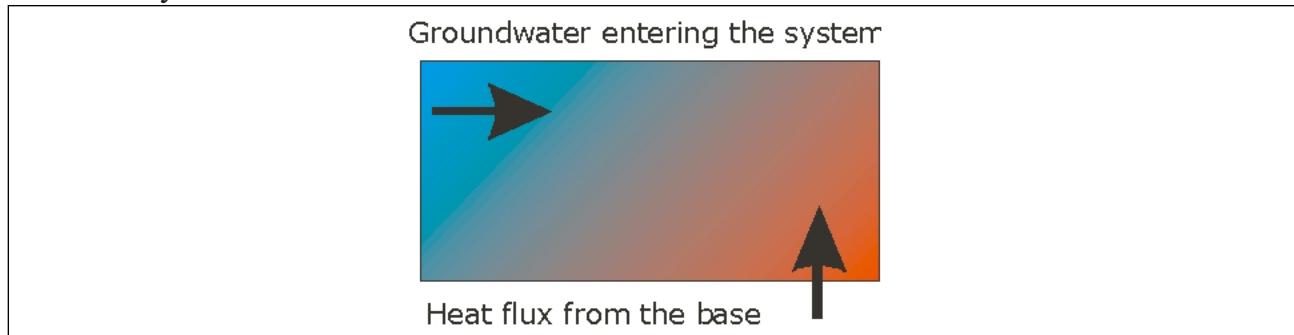


Figure 15. Basic thermal processes in the area.

Figure 16 shows a first long-term simulation (30,000 years) of the thermal system based on the hydraulic model. The simulation shows a permanent increase of temperature. The groundwater entering the system is not in equilibrium with the base heat flux. This indicates a possible defect in the current model. First, the groundwater recharged to the domain may be underestimated. Second, the base heat flux may be overestimated. Based on the thermal data from the simulation, it is concluded the hydraulic model may have errors and can be improved.

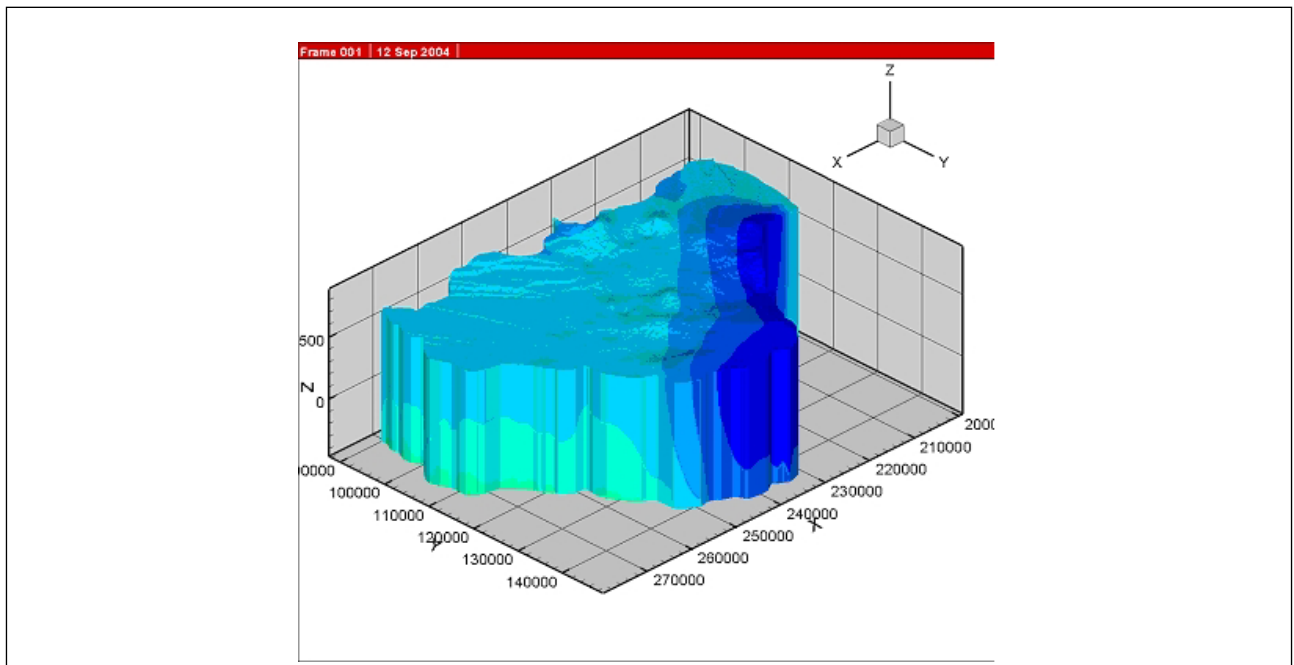


Figure 16. Temperature distribution in the model area.

### ACKNOWLEDGMENTS

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## REFERENCES

- Chen C., T. Kalbacher, S. Bauer, and O. Kolditz; (2003). Integration of GIS in GeoSys and Geometric Unit-GeoLib. ZAG-GHI Annual Report, GeoSys–Preprint [2003-49], Center of Applied Geosciences, Geohydrology/HydroInformatics, University of Tübingen.
- Abu Ajamieh, M.; (1980). The geothermal resources of Zarqa Ma'in and Zara. Report of phase-1 of the geothermal energy project in Jordan, Natural Resources Authority, Amman, Jordan.
- Kalbacher T., W. Wang, Ch. McDermott, O. Kolditz, and T. Taniguchi; (2003), Development and Application of a CAD Interface for Fractured Rock. ROCKFLOW-Preprint [2003-5], Submitted to 12th International Meshing Roundtable New Mexico, USA, 2003.
- Kolditz, O., J. De Jonge, M. Beinhorn, M. Xie, T. Kalbacher, W. Wang, S. Bauer, Ch. McDermott, C.I. Kaiser, R. Kohlmeier; (2003). ROCKFLOW – Theory and User Manual, release 3.9. Technical Report, Groundwater Modeling Group, Center for Applied Geosciences, University of Tübingen & Institute of Fluid Mechanics, University of Hannover, 2003. GeoSys–Preprint, [2003-37], Center of Applied Geosciences, Geohydrology/HydroInformatics, University of Tübingen.
- Salameh, E., and P. Udluft; (1985). The hydrodynamic pattern of the Central part of Jordan. *Geol. Jahrb*, 38, pp. 39-53.
- Sawarieh, A.; (1990). Hydrogeology of Wadi Wala Sub-basin and Zarqa Ma'in Hot Springs. MSc. thesis, Department of Geology, University of London, UK.
- Sawarieh A., H. Hoetzi, and E. Salameh; (2004). Hydrochemistry and Origin of Thermal Water from Zara-Zarqa Ma'in and Jiza Areas, Central Jordan. 5<sup>th</sup> International Symposium on Eastern Mediterranean Geology, 14-18, April 2004, Thessalonica–Greece.

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