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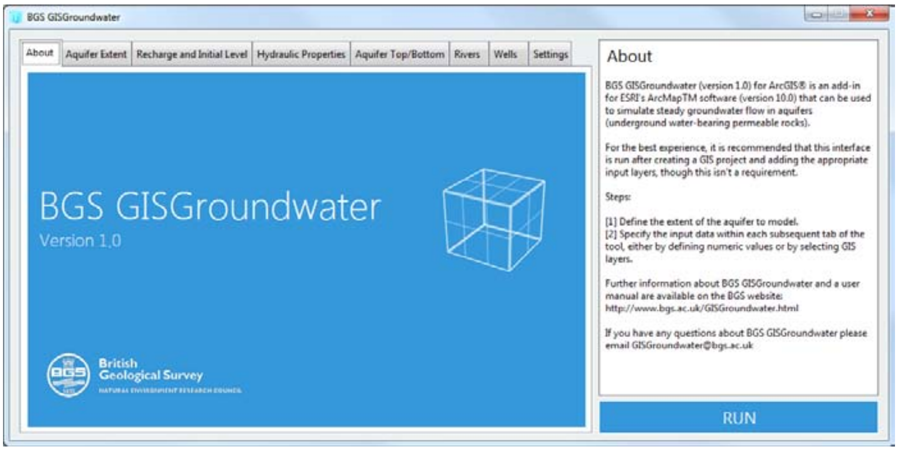
User's manual for BGS GISGroundwater: a numerical model to simulate groundwater levels for ArcGIS 10.0

Environmental Modelling Programme

Open Report OR/12/063



BRITISH GEOLOGICAL SURVEY

ENVIRONMENTAL MODELLING PROGRAMME

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User's manual for BGS GISGroundwater: a numerical model to simulate groundwater levels for ArcGIS 10.0

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Keywords

Groundwater flow model; finite difference; Arc GIS; GIS raster layer.

Front cover

The interface of BGS GISGroundwater Add-In for ArcGIS™

Bibliographical reference

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Summary

This is a user manual of BGS GISGroundwater that produces the depth to groundwater beneath the land surface. BGS GISGroundwater uses standard GIS datasets as inputs and implements data preparation, numerical modelling, post-processing and the visualisation of the modelled results all within the GIS environment. It allows non-modellers, such as scientists and students, to easily and efficiently build up groundwater flow models in ArcMap using GIS layers. For example, only few hours are needed to construct a numerical regional groundwater flow model using it with great flexibility. Therefore it is useful for carrying out preliminary groundwater flow modelling or evaluating hydrogeological conceptual models, before carrying out detailed costly groundwater modelling using one of traditional groundwater flow models.

This manual firstly introduces BGS GISGroundwater, and then explains its installation process and interface. The step-by-step tutorial materials are also provided to guide users to learn quickly how to use this tool.

1 What is BGS GISGroundwater

BGS GISGroundwater allows users to develop preliminary regional groundwater models quickly and visualise the modelled piezometric surfaces in the ArcMap. It represents variably unconfined, confined and heterogeneous aquifers, distributed recharge, river-aquifer interaction and groundwater abstraction; and these datasets can be flexibly entered into model using one of multiple options, such as a constant value, GIS raster layer, and automatically extracting river information using river shapefile and Digital Elevation Model (DEM) layer. BGS GISGroundwater allows end-users, who can use ArcMap, to easily and efficiently construct groundwater flow models to simulate the groundwater flow and produce the long term elevations of water table (groundwater levels) in porous medium.

BGS GISGroundwater solves the governing two-dimensional groundwater flow equation of the form:

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right)=Q^A+Q^R-R \qquad \textbf{Equation 1}$$

where h is the groundwater head [L], T_x and T_y are the aquifer transmissivity in the x and y direction respectively [L^2T^{-1}], Q^A is groundwater abstraction rate [$L^3\ T^{-1}$], Q^R is leakage to/from rivers [$L^3\ T^{-1}$], and R is the amount of groundwater recharge [$L^3\ T^{-1}$].

Wang et al. (2010) provided technical details of the tool.

1.1 ADVANTAGES OF BGS GISGROUNDWATER

- It is a seamless GIS groundwater flow model, which can be deemed as one of GIS spatial analysis functions

- All groundwater modelling processes of data preparation, running model and post-processing including visualisation of modelled groundwater levels can be carried out in the GIS environment

- It uses the standard GIS data formats; this means that there is no extra work for data exchanging and no extra costs for purchasing coupling interface programs

- It is a valuable tool for hydrogeologists or non-groundwater modellers to quickly build up preliminary groundwater flow models or evaluate hydrogeological conceptual models before constructing detailed and costly groundwater flow models.

1.2 DATA REQUIREMENTS

Table 1 lists the datasets and their formats required by BGS GISGroundwater. The extent of modelling area is defined by an aquifer layer in the format of GIS raster, and the optional non-aquifer layer can be used when modelling an aquifer overlain by an aquitard; the aquifer permeability can be entered into the model using transmissivity or hydraulic conductivity in conjunction with the GIS layers representing aquifer top and bottom; groundwater recharge with or without spatial distribution can be used in building up a groundwater flow model; the river data required can be a GIS raster layer or a shapefile that needs a DEM layer to derive river stage values; the fixed head boundary condition, such as lake, is represented in the model using the same format as the river dataset; abstraction data are optional and can be entered into the code in a GIS raster layer or a shapefile. Table 1 shows the different options by which input datasets can be input to the model.

Table 1. The formats options of the BGS GISGroundwater input datasets

Input datasets				Format options
Modelling extent	Option 1	Aquifer layer		A GIS raster layer
	Option 2	Extents of aquifer and non-aquifer		A GIS raster layer
Aquifer permeability	Option 1	Aquifer Top	Option 1	A GIS raster layer
			Option 2	A single value
		Aquifer Bottom	Option 1	A GIS raster layer
			Option 2	A single value
		Hydraulic conductivity	Option 1	A GIS raster layer
			Option 2	A single value
	Option 2	Transmissivity	Option 1	A GIS raster layer
			Option 2	A single value
Groundwater recharge	Option 1	Spatially distributed values		A GIS raster layer
	Option 2	Non-spatial distribution		A single value
Rivers / leaking points/ / fixed heads	Option 1	Having a raster layer containing information on river location and river stage		A GIS raster layer
	Option 2	Having vector data and DEM data.		A shapefile and DEM
Abstraction (optional)	Option 1	Having a raster layer representing abstraction locations and rates		A GIS raster layer
	Option 2	Having abstraction vector data		A shapefile

2 How to install BGS GISGroundwater

BGS GISGroundwater ('BGSGISGroundwater.esriAddIn') and its tutorial files ('BGS-GISGroundwater-tutorial-files.zip') can be downloaded using the following link:

http://www.bgs.ac.uk/GISGroundwater

An ArcMap 10.0 environment is needed to install and run BGS GISGroundwater. There are two ways to install BGS GISGroundwater, i.e., running Add-In directly, or installing through ArcMap 10.0 Add-In Manager:

Option 1: Running Add-In

- Locate the BGS GISGroundwater Add-In file and double click it to install.

Option 2: Through Add-In Manager

- Run ArcMap 10.0 and open a new blank map.
- Go to Customize -> Add-In Manager (Figure 1).
- In Add-In Manager select Customize (Figure 2).
- Select "Add from file…" (Figure 3 and 4).
- Confirm Add-In file installation by clicking "Install Add-In" (Figure 5) and OK in the next window (Figure 6).
- The available toolbars should be shown in the following window. Check the box next to BGS Groundwater Flow Model tools (Figure 7).
- Close the window.

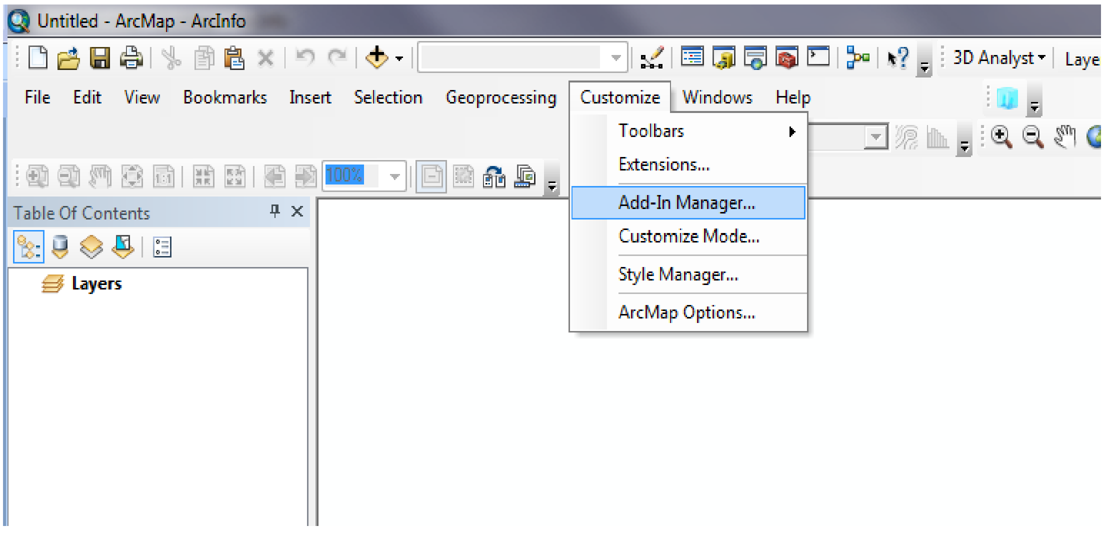


Figure 1. Loading the Add-In: step 1

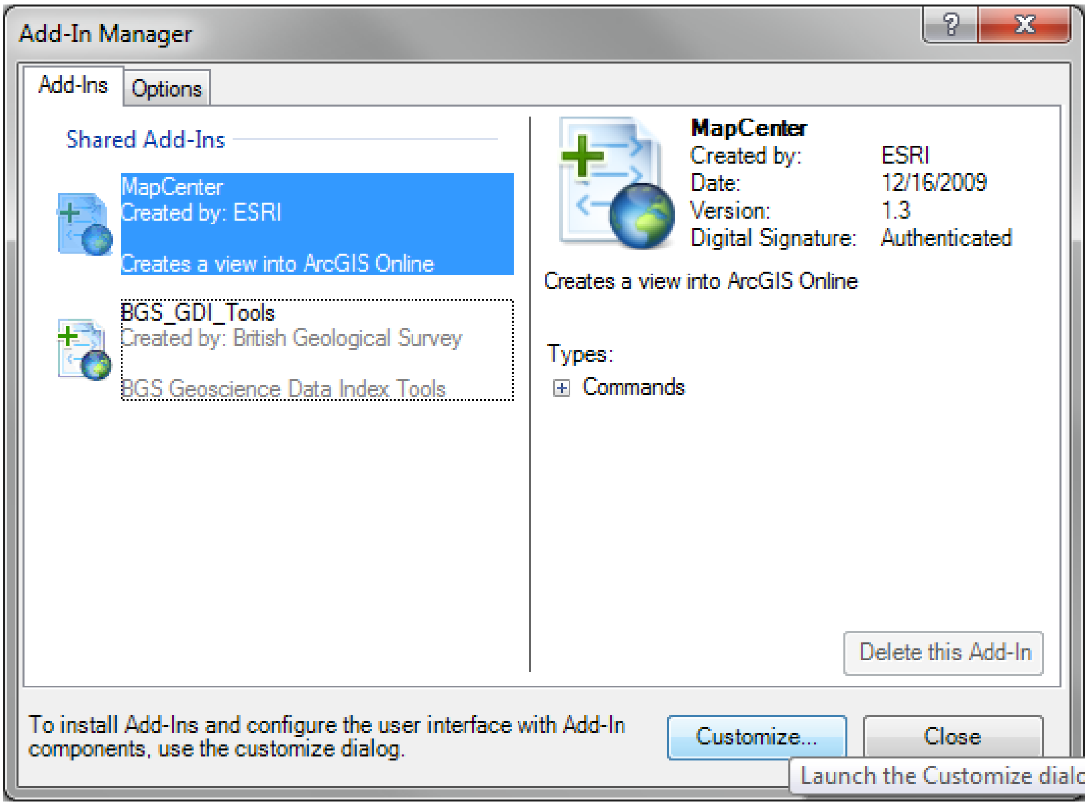


Figure 2. Loading the Add-In: step 2

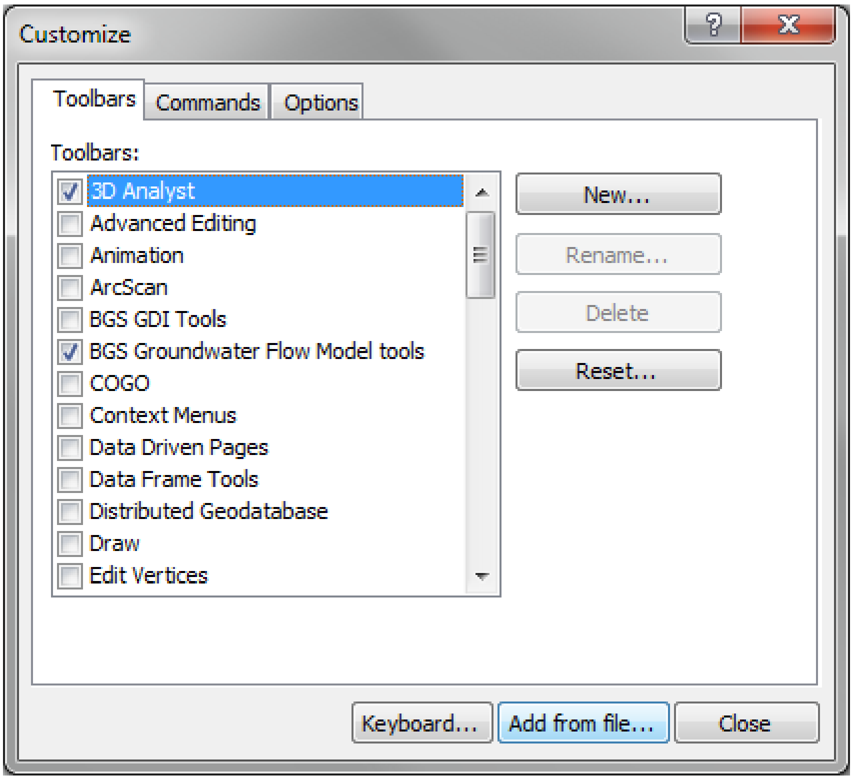


Figure 3. Loading the Add-In: step 3

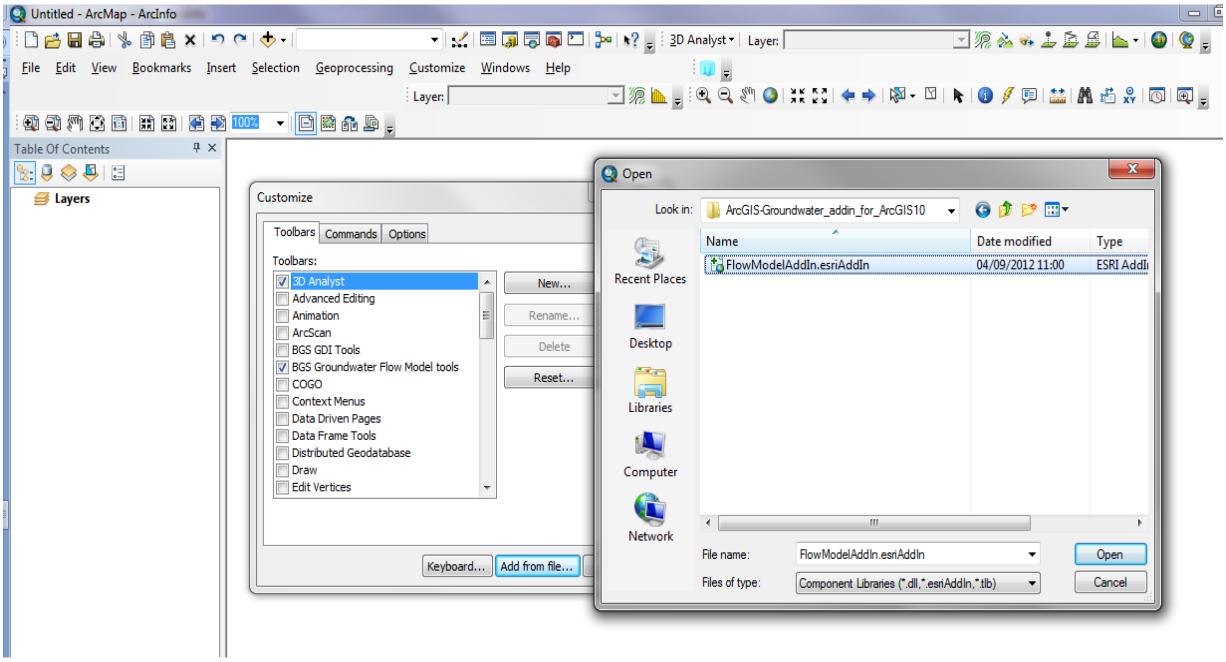


Figure 4. Loading the Add-In: step 4

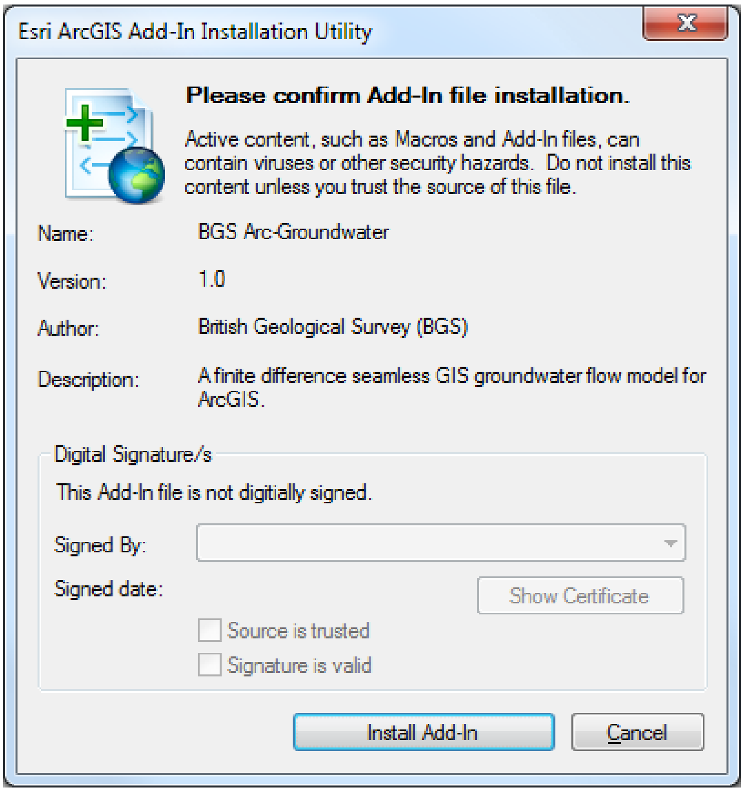


Figure 5. Loading the Add-In: step 5

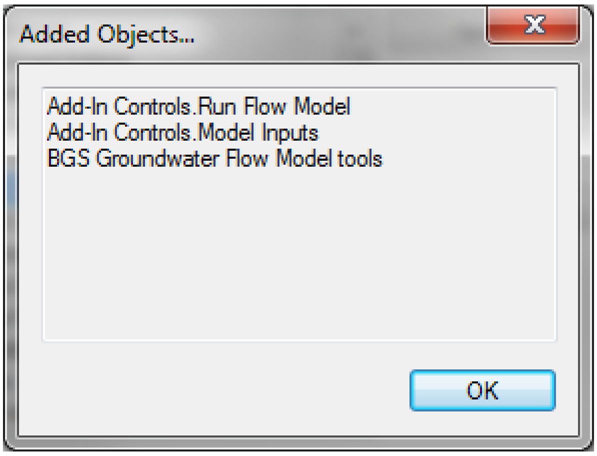


Figure 6. Loading the Add-In: step 6

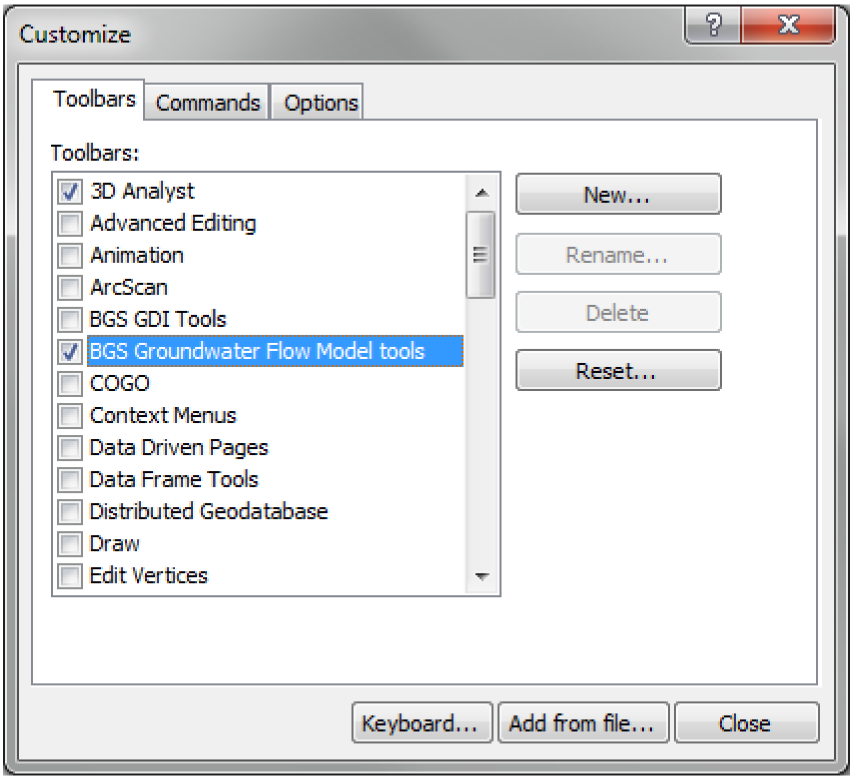


Figure 7. Loading the Add-In: step 7

BGS GISGroundwater Add-In is now installed. The BGS GISGroundwater interface can be opened by clicking on a slightly transparent blue cube  in the ArcMap toolbar menu. If the BGS GISGroundwater icon is not shown, it can be added to the toolbar by going to Customize -> Toolbars -> BGS Groundwater Flow Model tools (Figure 8).

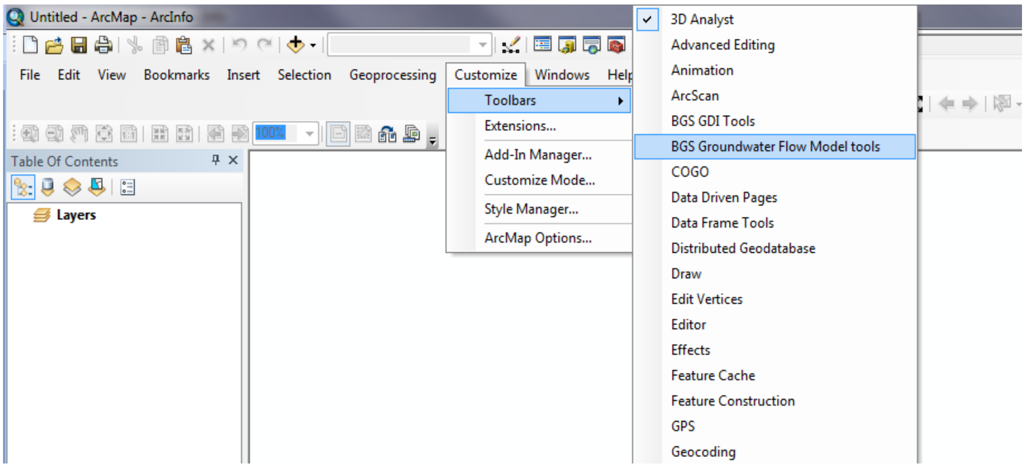


Figure 8. Enabling the tool via the toolbar menu

It is advisable that all relevant GIS layers are loaded into an ArcMap project before the BGS GISGroundwater tool is used. The layers can be added using the plus button in the ArcMap toolbar (Figure 9).

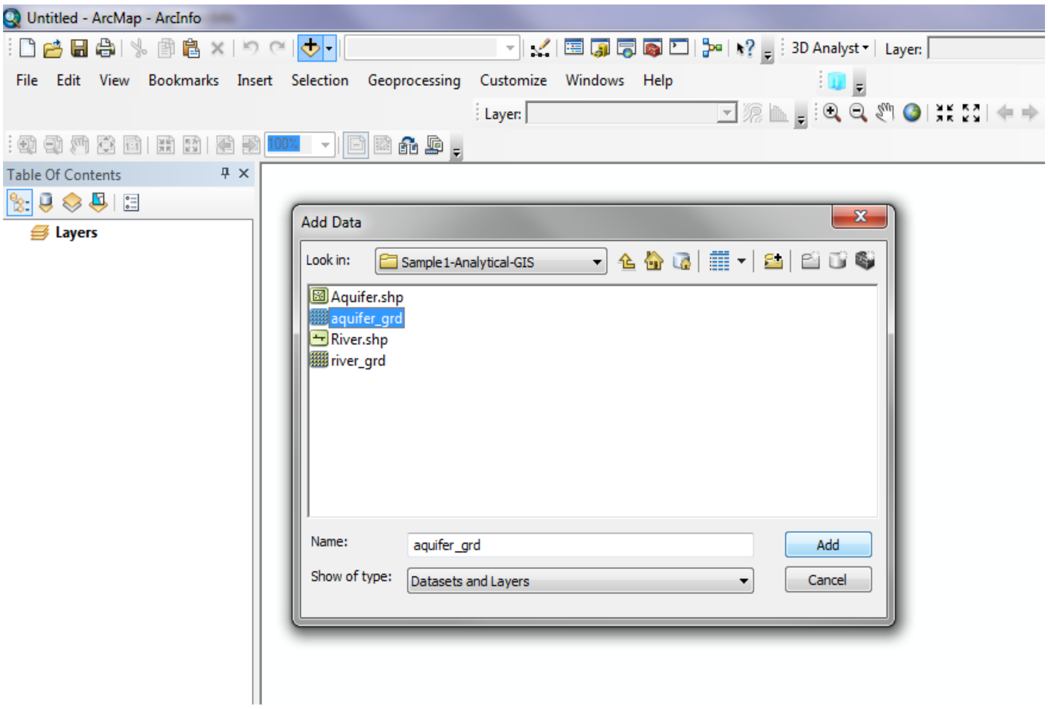


Figure 9. Interface of adding a GIS layer into an ArcGIS project

3 Workflow for building a model

Figure 10 shows the procedures of constructing a groundwater flow model using BGS GISGroundwater:

1) Define spatial extent and cell size at the first step by choosing an aquifer extent layer – an existing GIS layer representing the modelling area; and
2) Specify the input data within each subsequent tab of the tool, either by defining numeric values or by selecting GIS layers.

It is worth noting that the modelling nodes are located at the centres of GIS grids; therefore the actual modelling area is smaller (half cell size) than the aquifer extent layer. Other mandatory inputs include recharge, initial groundwater level, aquifer permeability and river. It is required that the extents of all GIS raster layers used in the construction a model to be equal or larger than that of the aquifer extent layer. It is permissible that the layer extent is larger than the aquifer extent, as it will be automatically clipped to the right size; but it can never be smaller. Additionally, it is important to make sure that the cell size of all the GIS layers is the same as the cell size of the aquifer layer.

It is required that the extents of all GIS raster layers used in the construction of a model to be equal or larger than that of the aquifer layer. It is permissible that the layer extent is larger than the aquifer extent, as it will be automatically clipped to the right size; but it can never be smaller. Additionally, it is important to make sure that the cell size of all the grids is the same as the cell size of the aquifer layer.

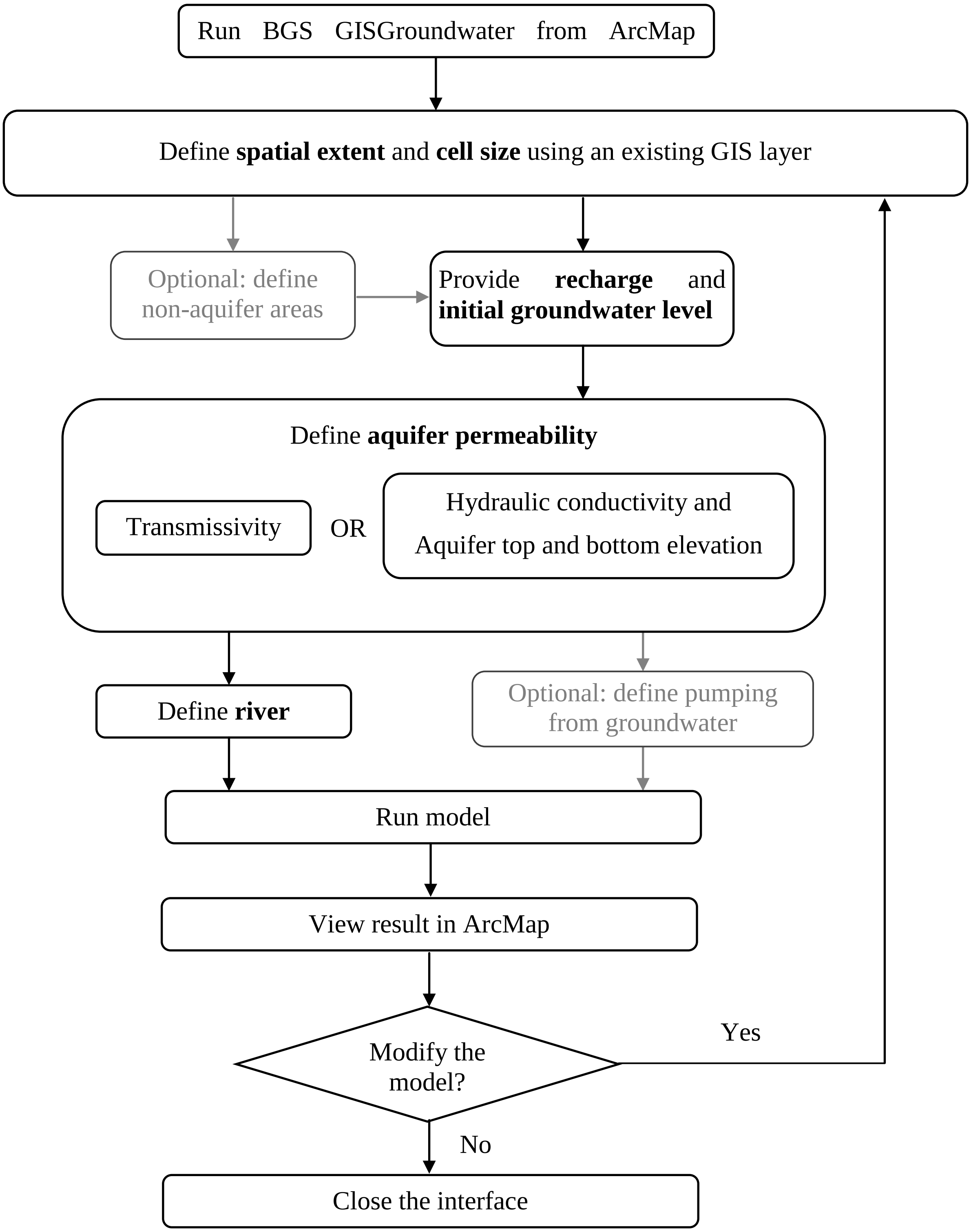


Figure 10. The workflow of using BGS GISGroundwater

4 The BGS GISGroundwater interface

The interface can be opened by clicking on the BGS GISGroundwater tool icon . It has several sections, in which model inputs are either entered directly as numeric values or loaded from raster layers. Each section has two parts. The left one is used to specify model input data and the right one provides help information.

4.1 ABOUT

This section provides information on the tool, the steps for constructing a groundwater flow model, and contact details (Figure 11).

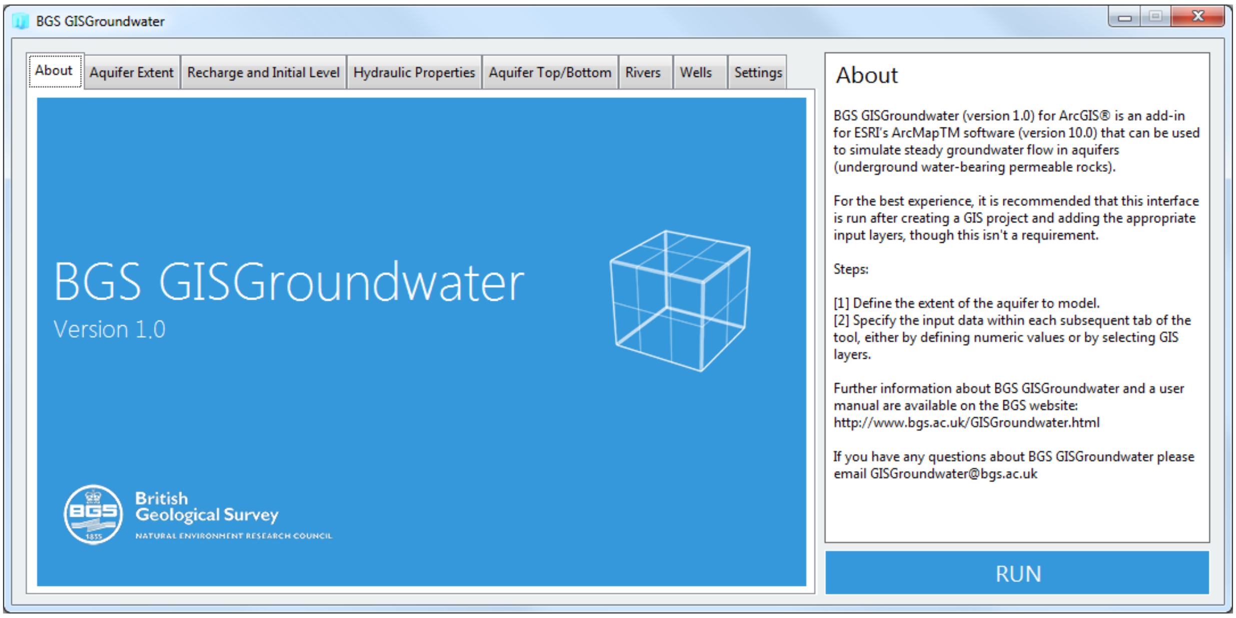


Figure 11. 'About' tab

4.2 AQUIFER EXTENT

In this section aquifer and optionally non-aquifer raster layers are selected. The area of the aquifer and the cell size of the model grid are defined by a raster layer defining the aquifer extent. An optional non-aquifer layer can be used to define sub-regions of the aquifer that are impermeable. The 'Model Cell Size', 'LEFT', 'TOP', 'RIGHT', and 'BOTTOM' (Figure 12) are updated automatically when the aquifer extent layer is chosen from the drop-down box. The calculation might take a few moments. The unit for both layers is metre. The 'Information' box shows successful or error messages when preparing data for groundwater flow modelling; and it is necessary to check these messages before moving to the next section.

It is necessary to check the 'Information' box each time before moving to the next section.

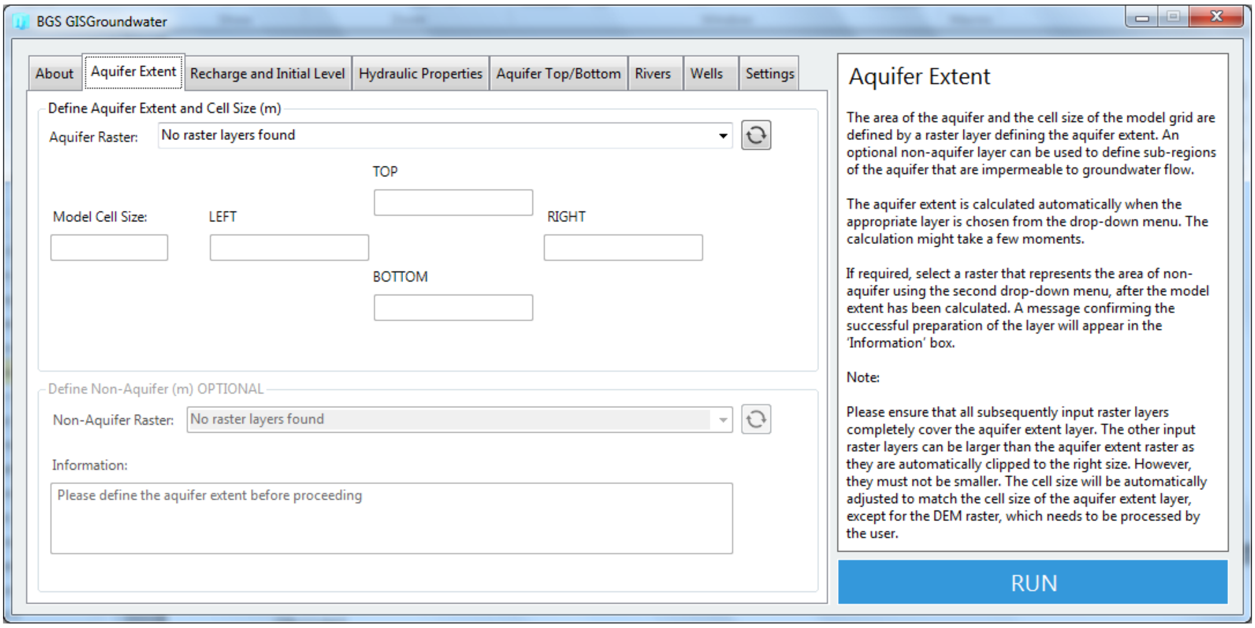


Figure 12. 'Aquifer Extent' tab

4.3 RECHARGE AND INITIAL GROUNDWATER LEVEL

Uniform or spatially distributed groundwater recharge is specified here. Groundwater recharge (**m/day**) can be entered into the model either as a single value across the whole aquifer or as a raster layer of spatially varying values. The radio buttons of "Layer values" and "Constant Value" change accordingly. A single value for the initial groundwater level is specified across the whole aquifer with the unit of **metres** (Figure 13).

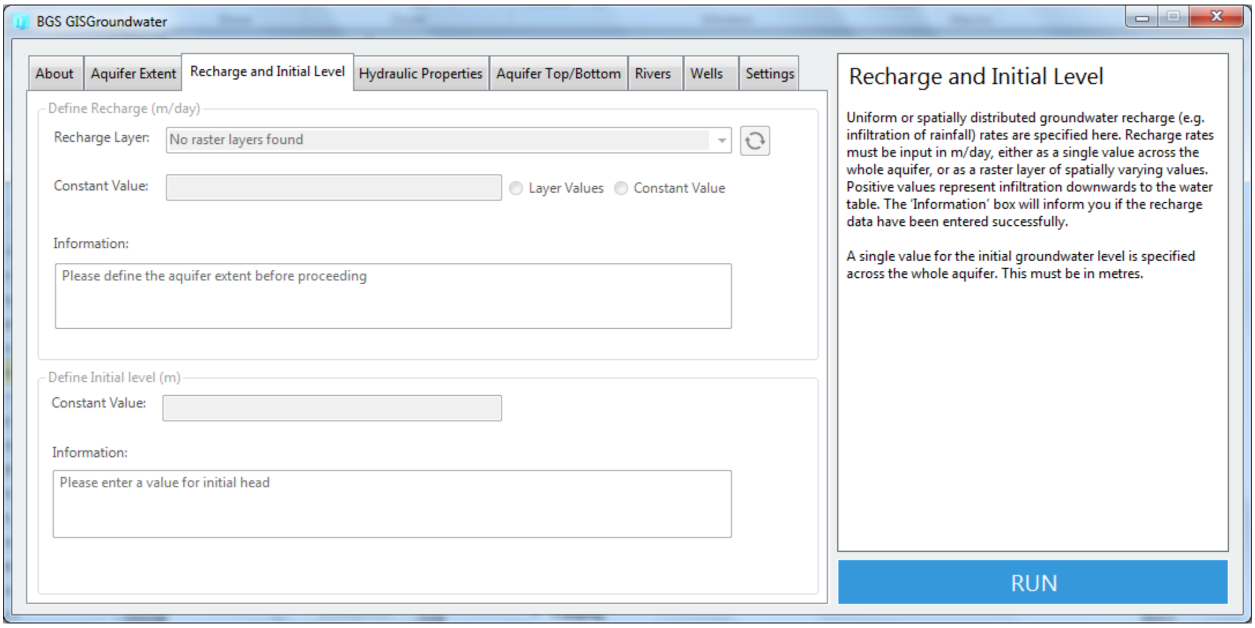


Figure 13. 'Recharge and Initial Groundwater Level' tab

4.4 HYDRAULIC PROPERTIES

Either transmissivity, T (m^2/day) or hydraulic conductivity, K (m/day) can be used here to describe the hydraulic properties of the aquifer. Transmissivity can be input either as a constant value, or as a raster layer of spatially varying values. Alternatively, the transmissivity can be calculated by inputting the hydraulic conductivity along with the elevation of the top and bottom of the aquifer. Hydraulic conductivity can be input either as a constant value, or as a raster layer of spatially varying values. The top and bottom elevations of the aquifer are entered on the next tab (Figure 14).

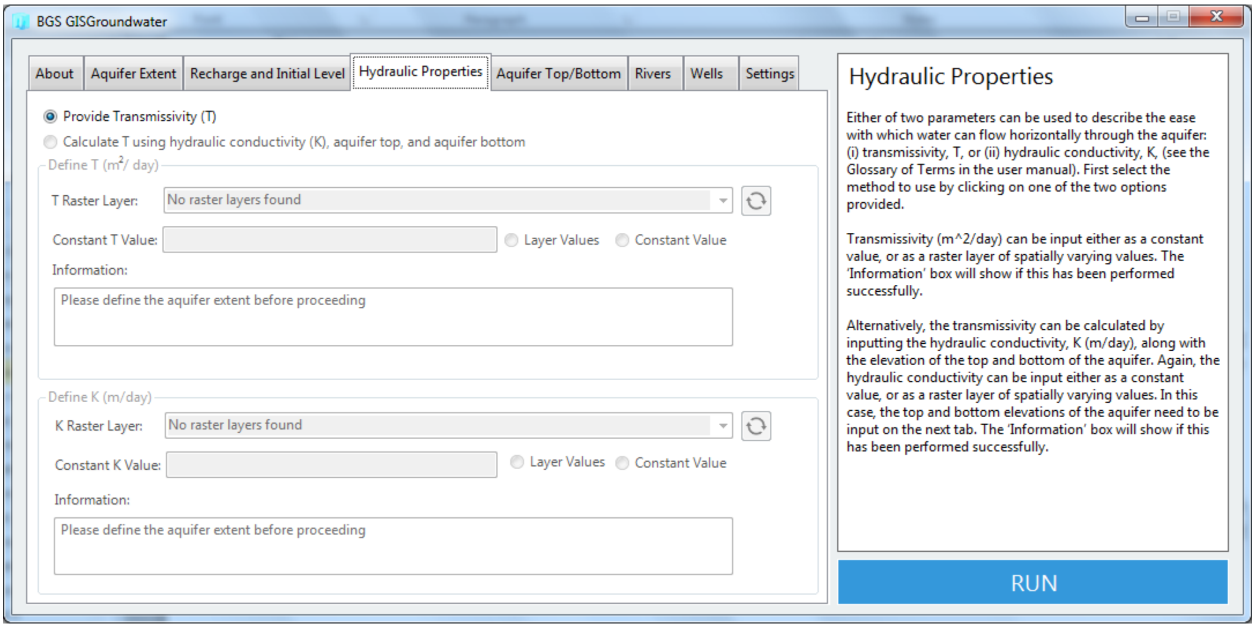


Figure 14. 'Hydraulic Properties' tab

4.5 AQUIFER TOP/BOTTOM

This section of the tool will only be active if the option to calculate transmissivity was selected on the previous tab. In this case the aquifer top and bottom elevations need to be provided to calculate the aquifer thickness, which will then be used to calculate the transmissivity. The top and bottom elevations can be input either as constant values or as raster layers of spatially varying values; both need to be provided in metres (Figure 15).

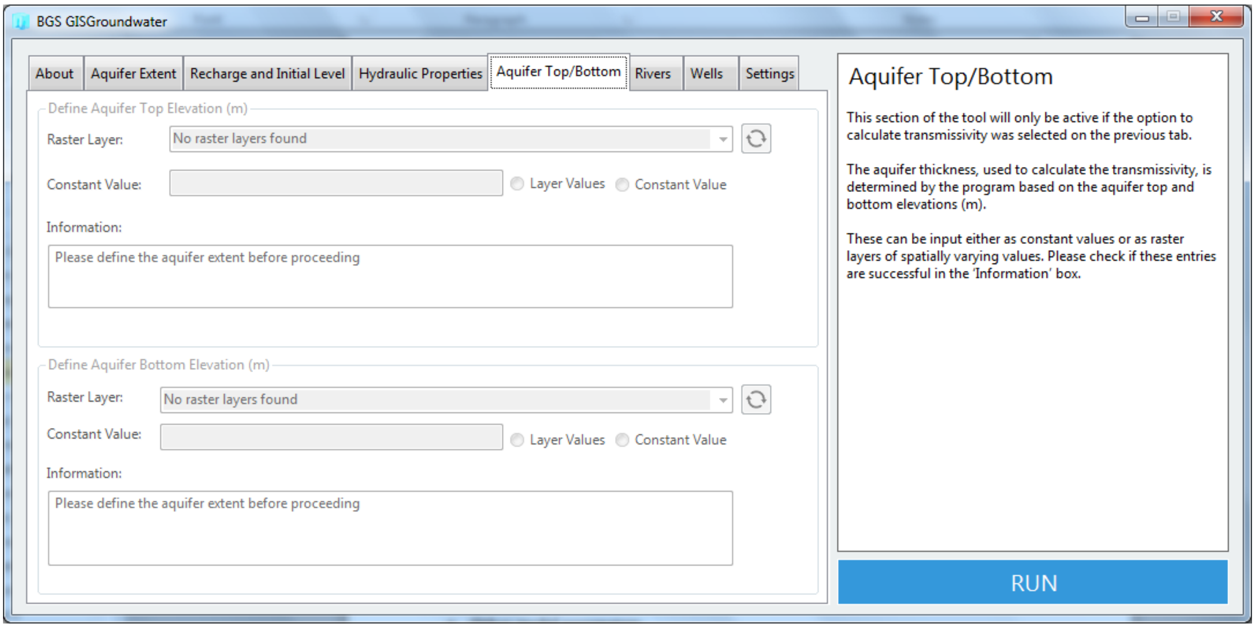


Figure 15. 'Aquifer Top/Bottom' tab

4.6 RIVERS

Rivers and other surface water features are represented by a grid, which can be defined either by a raster layer containing water surface elevation data, or a shapefile that specifies the locations of the surface water features and a DEM raster layer that specifies the associated water levels (Figure 16). Leaking points or fixed head boundary conditions can be represented as 'rivers' to provide the information on elevations of the specific locations (See tutorial 1 in section 5.1, and tutorial 2 in section 5.2).

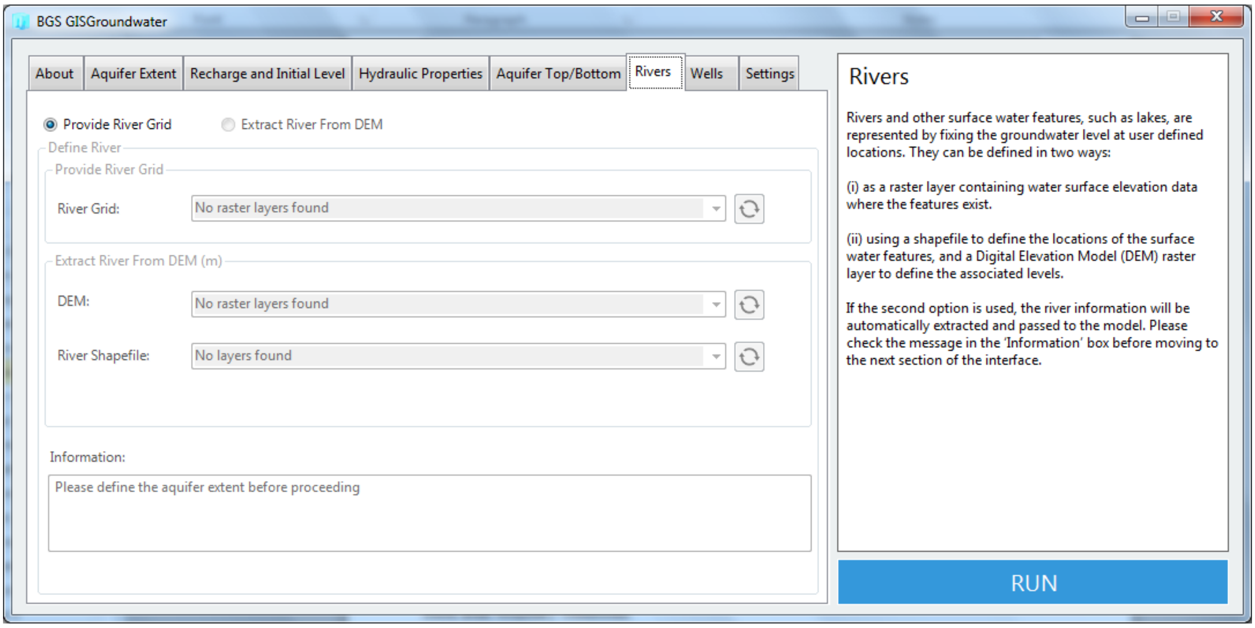


Figure 16. 'Rivers' tab

4.7 WELLS

The inclusion of rates of pumping from wells is optional. They can be input either as a raster layer, which contains pumping rates at specific locations, or can be extracted from a shapefile. If a point shapefile is used, its attribute table must contain a field that holds the pumping rates at the points (Figure 17).

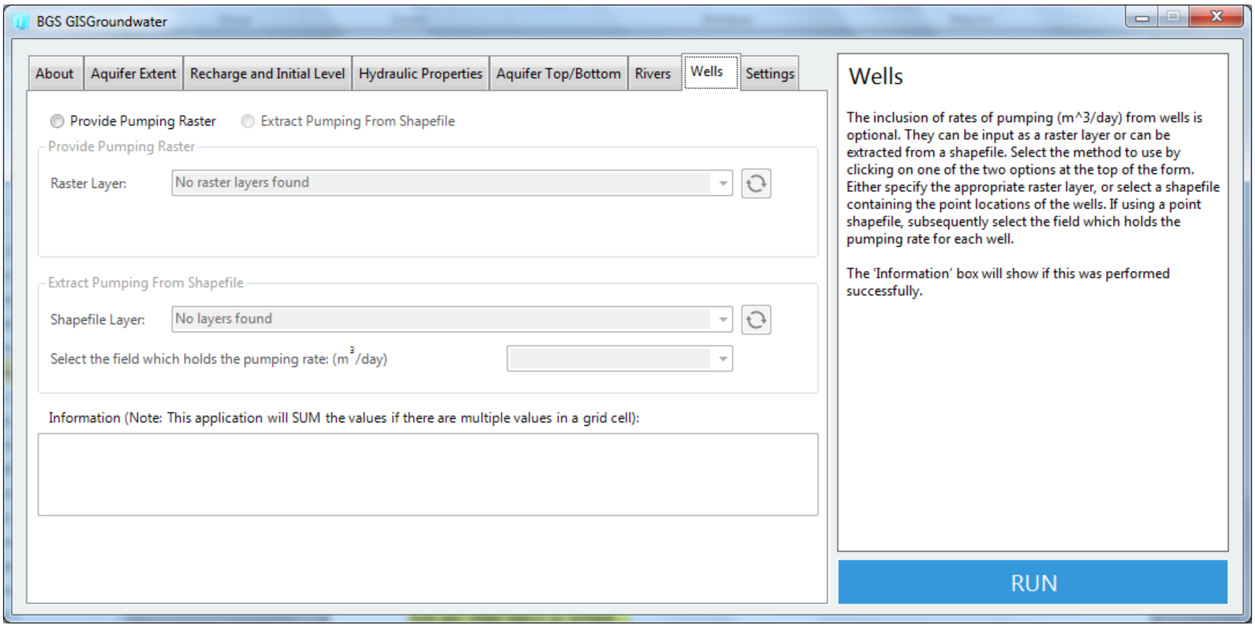


Figure 17. 'Wells' tab

4.8 SETTINGS

This tab allows the user to specify values for the parameters that determine when and how fast the model reaches a solution. The default values are provided but they can be overwritten by users (Figure 18).

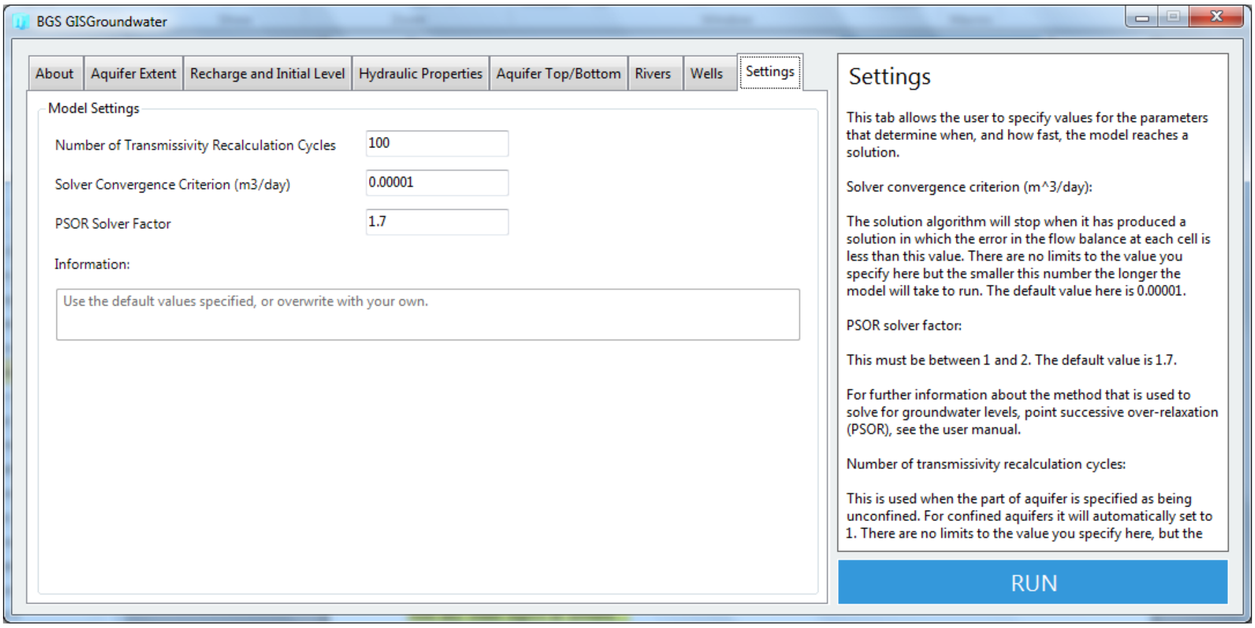


Figure 18. 'Settings' tab

The interface could be hidden behind the ArcMap window sometimes; and it can be found through the taskbar.

5 Tutorials for BGS GISGroundwater

5.1 TUTORIAL 1

Tutorial 1 shows how to use an analytical solution for a benchmark problem. After this you should be able to construct a simple groundwater flow model using GIS raster layers representing aquifer extent and river, and constant values for recharge, initial head and transmissivity.

5.1.1 Problem description

An aquifer (200m by 200m) has a homogenous hydraulic transmissivity value of 20 m^2/day; a 25m fixed piezometric head (a measurement of liquid pressure above a geodetic datum.) boundary is specified at the western side of the aquifer, and no-flow boundaries are specified at its north, east, and south sides. The groundwater recharge for the aquifer has a constant value 0.001 m/day (Figure 19). This problem can be solved using BGS GISGroundwater by discretising the aquifer domain into a raster of 10m square cells.

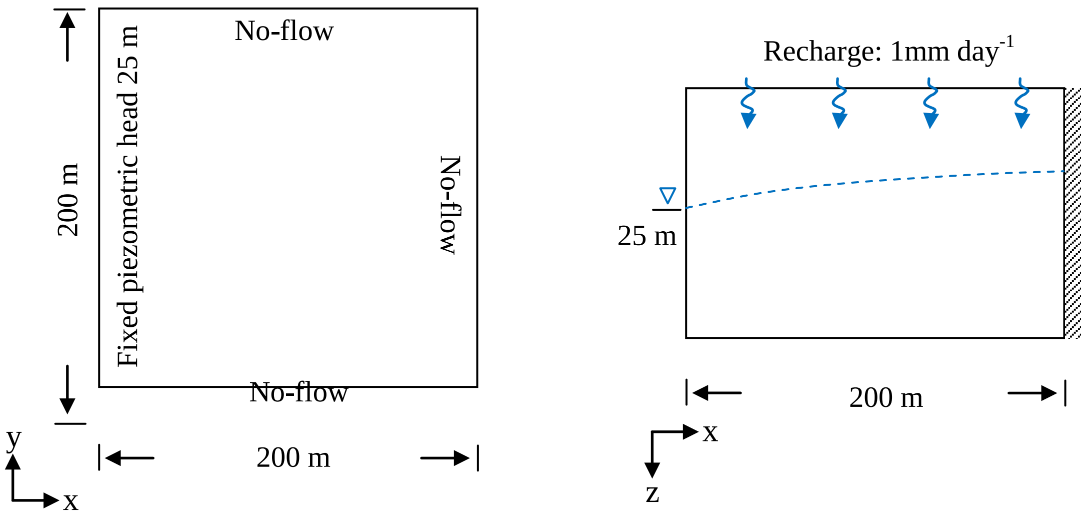


Figure 19. The sketch map of the problem in tutorial 1.

5.1.2 Data and parameters required

Data requirement:

- Aquifer extent (a GIS raster layer with the spatial resolution of 10m by 10m)
- Recharge (a constant value of 0.001 m/day)
- Initial piezometric head (a constant value of 25m)
- Transmissivity (a constant value of 20 m^2/day)
- A GIS raster layer representing a constant river level of 25m.

The GIS datasets or GIS project file "Sample1_ArcMAP10.0.mxd" needed for this tutorial can be found under the folder of "Sample1_Analytical_GIS". The tutorial materials can be downloaded from the BGS GISGroundwater link provided in section 2 and then extracted to a local drive.

Modelling nodes are located at the centres of GIS grids. In the aquifer extent section of this tutorial, the "LEFT" (-5m) and "BOTTOM" (-5m) are the left corner of the aquifer GIS layer, while the "TOP" (205m) and "RIGHT" (205m) are the top right corner of this aquifer layer. Therefore, the centres of the lower left grid and the top right grid of the aquifer are (0m, 0m) and (200m, 200m) respectively, representing an aquifer of 200m by 200m.

5.1.3 Using BGS GISGroundwater

- Before opening the interface, load aquifer and river grid layers into the project using the plus button in the ArcMap toolbar (Figure 20).

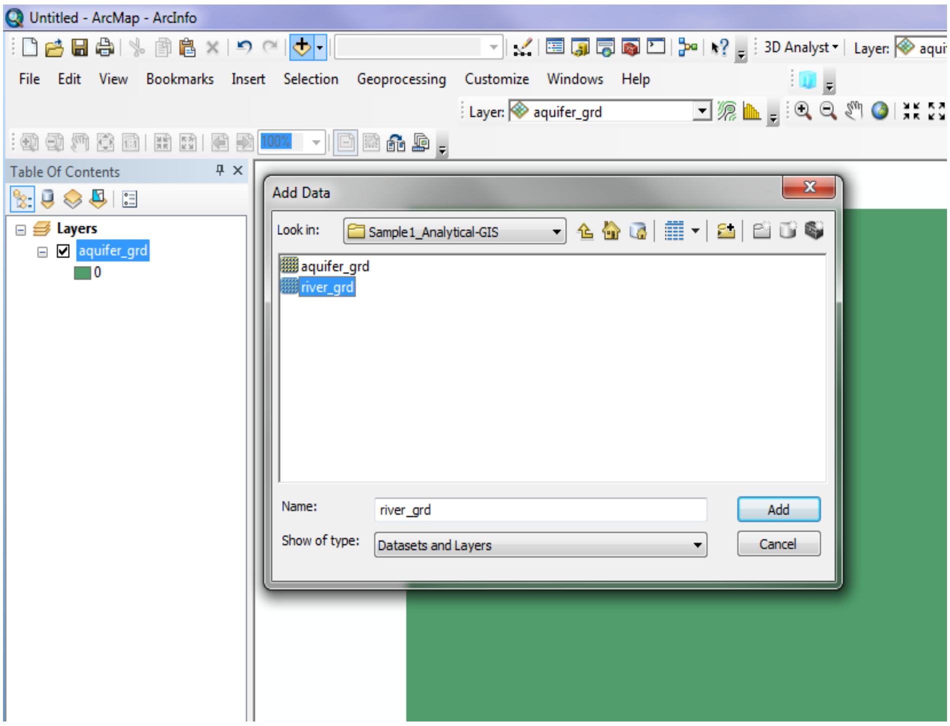


Figure 20. Loading layers to ArcMap project – Tutorial 1

Since ArcMap 10.0 has difficulties in handling very long file path names, it is a good practice to extract tutorial files to the root of one of your local drives to keep the file path names short, such as: "E:\BGS-GISGroundwater-tutorial-files\Sample1_Analytical_GIS".

Once the raster layers are loaded, the BGS GISGroundwater interface can be opened by clicking on the BGS GISGroundwater icon in the toolbar.

- Under 'Aquifer Extent' click on the drop-down menu next to 'Aquifer Raster' and select 'aquifer_grd'. If no raster layers appear in the list, click on the refresh button to the right of the drop-down menu (Figure 21).

- Wait until the model cell size and the modelling extent are calculated and proceed to the next tab

It is necessary to check the 'Information' box each time before moving to the next section.

- Under 'Recharge and Initial Level' select constant value option for the recharge and input 0.001. Input 25 for the initial head (Figure 22).
- Under 'Hydraulic Properties' select 'Provide Transmissivity' option; note that 'Define K' subsection is no longer active. Select constant value option for transmissivity and enter 20 (Figure 23).
- Since transmissivity is provided by a user 'Aquifer Top/Bottom' section is not active.
- Under 'Rivers' select 'Provide River Grid' option. Click on the drop-down menu and select 'river_grd' (Figure 24).
- Under 'Settings' input solver convergence criterion, PSOR solver factor, and the number of transmissivity recalculation cycles. The default values can be used if considered appropriate. Press 'Run' button to run the model (Figure 25).
- Two raster layers are produced: 'GWHEADS' and 'MODELAREA', which are added to the ArcMap project and plotted automatically. 'MODELAREA' raster define the modelling extend, and 'GWHEADS' raster contains steady state groundwater levels simulated by the model (Figure 26).

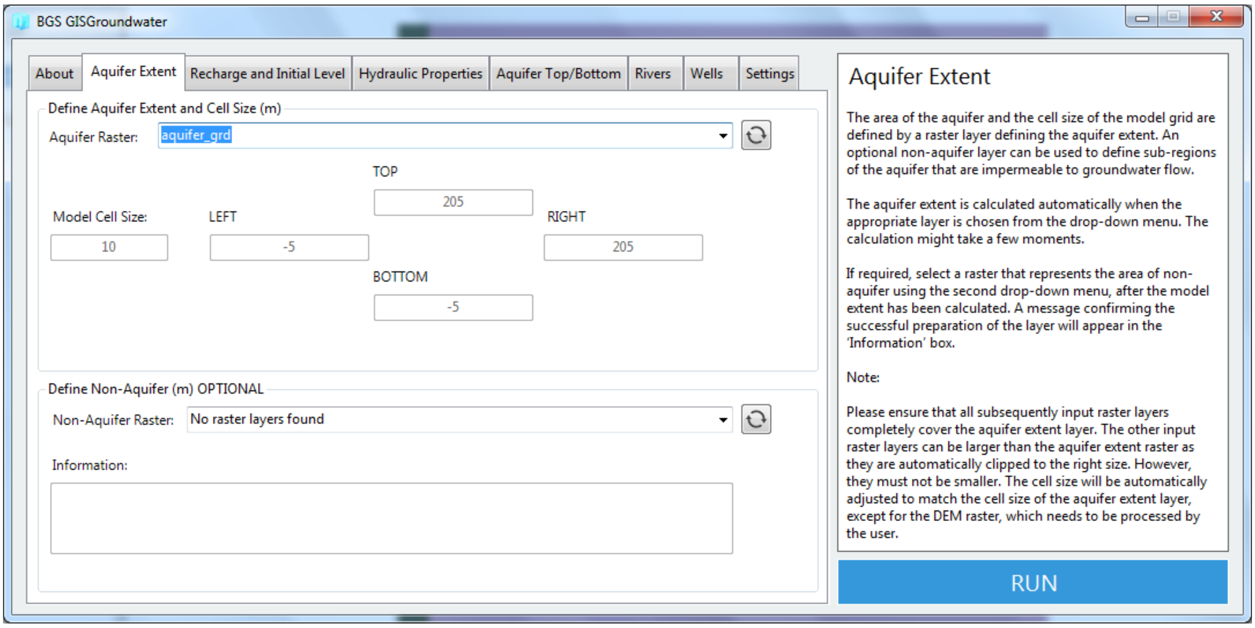


Figure 21. Aquifer Extent, Tutorial 1

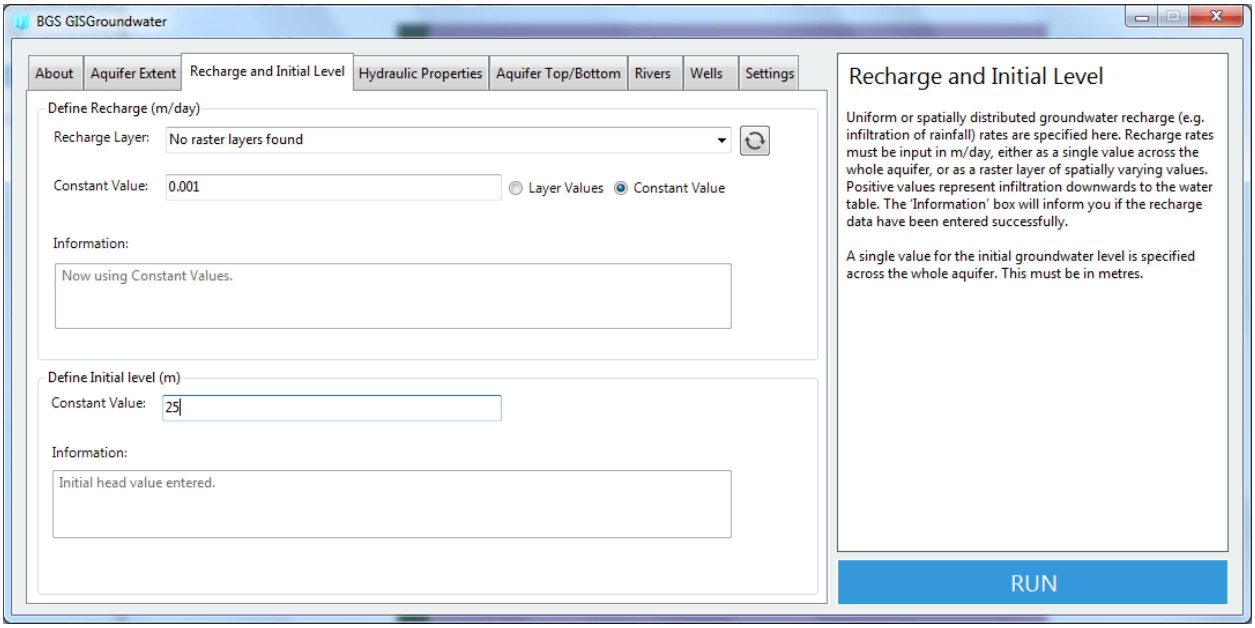


Figure 22. Recharge and Initial Level, Tutorial 1

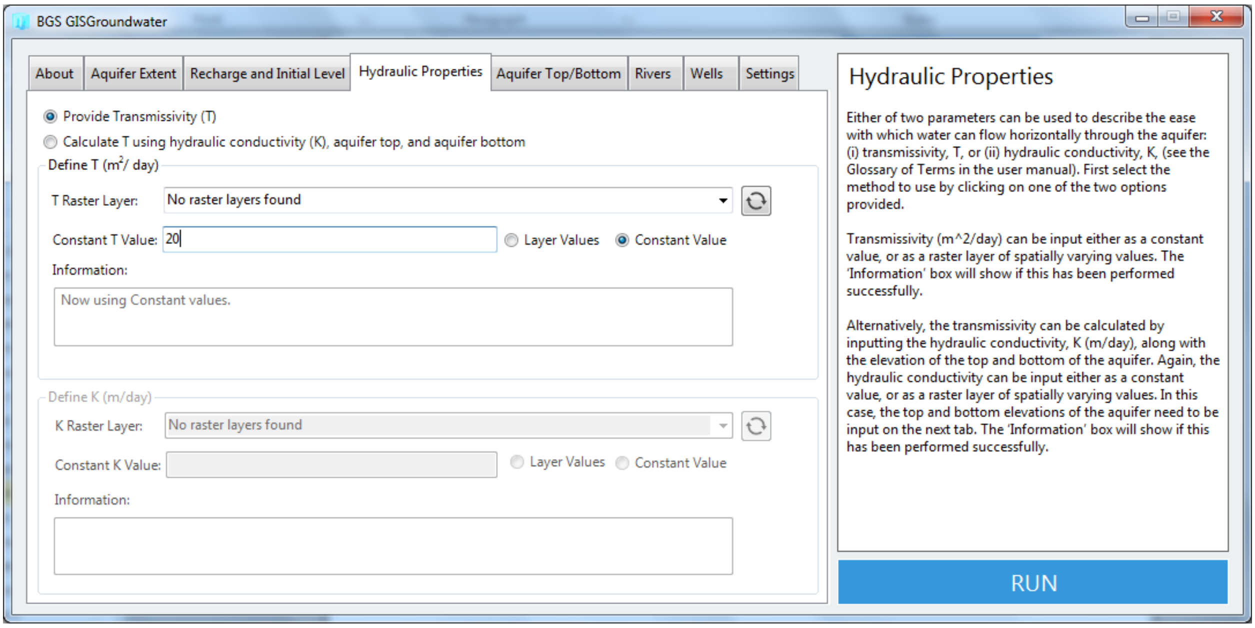


Figure 23. Using BGS GISGroundwater interface – Hydraulic Properties, Tutorial 1

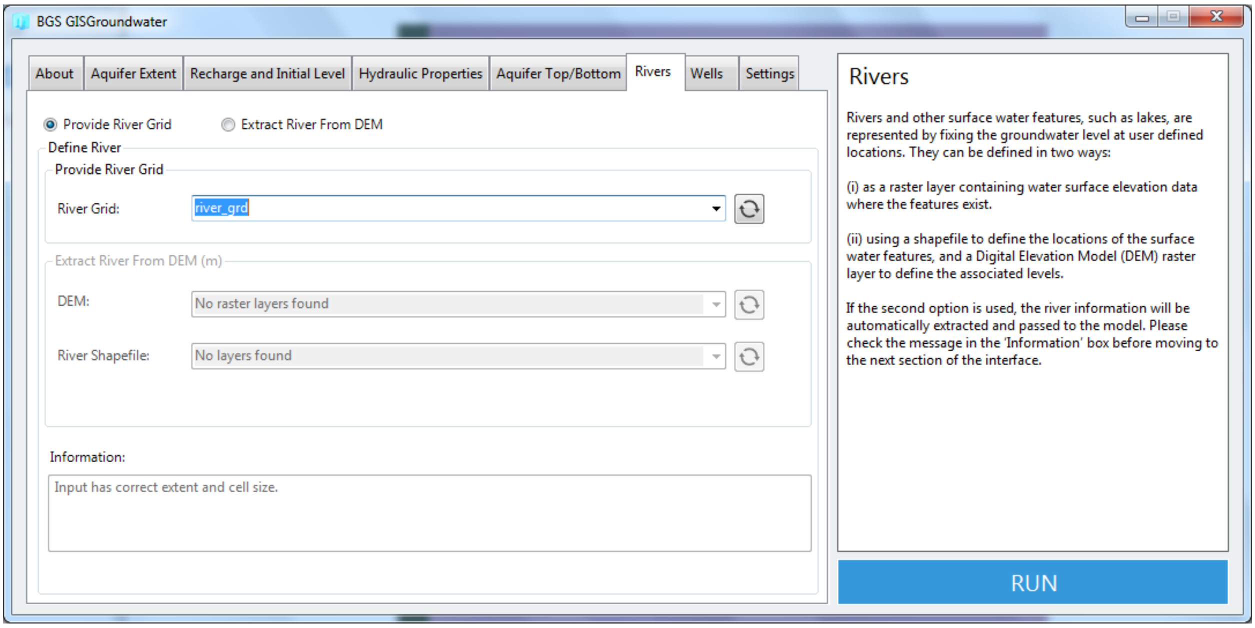


Figure 24. Rivers, Tutorial 1

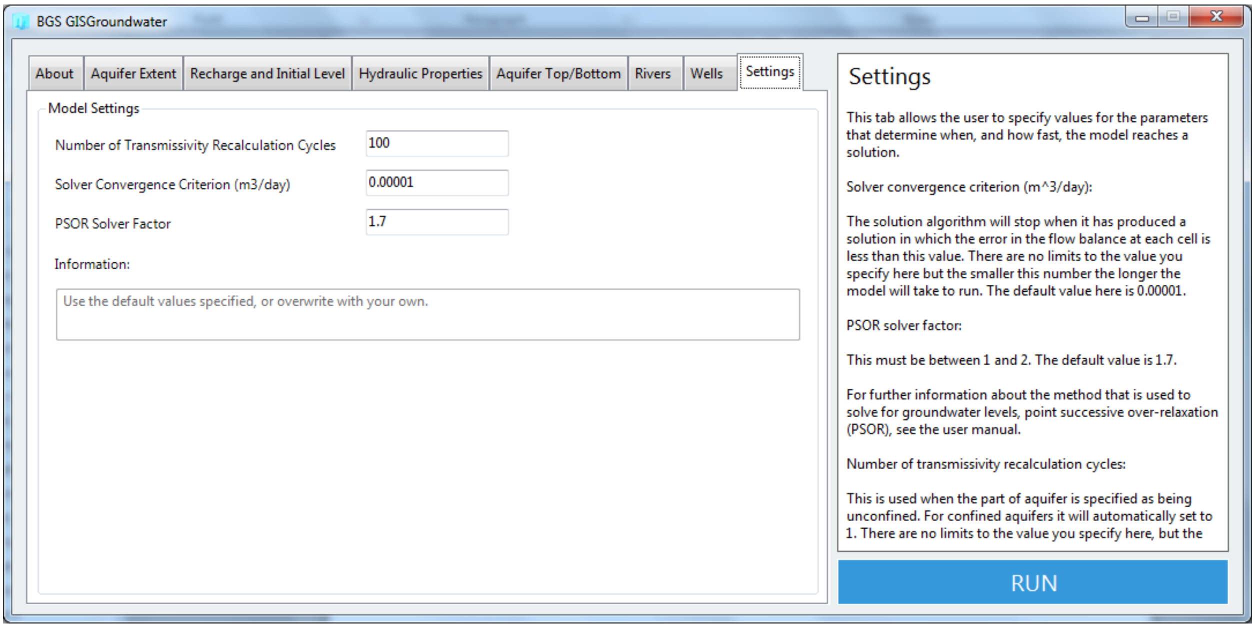


Figure 25. Settings, Tutorial 1

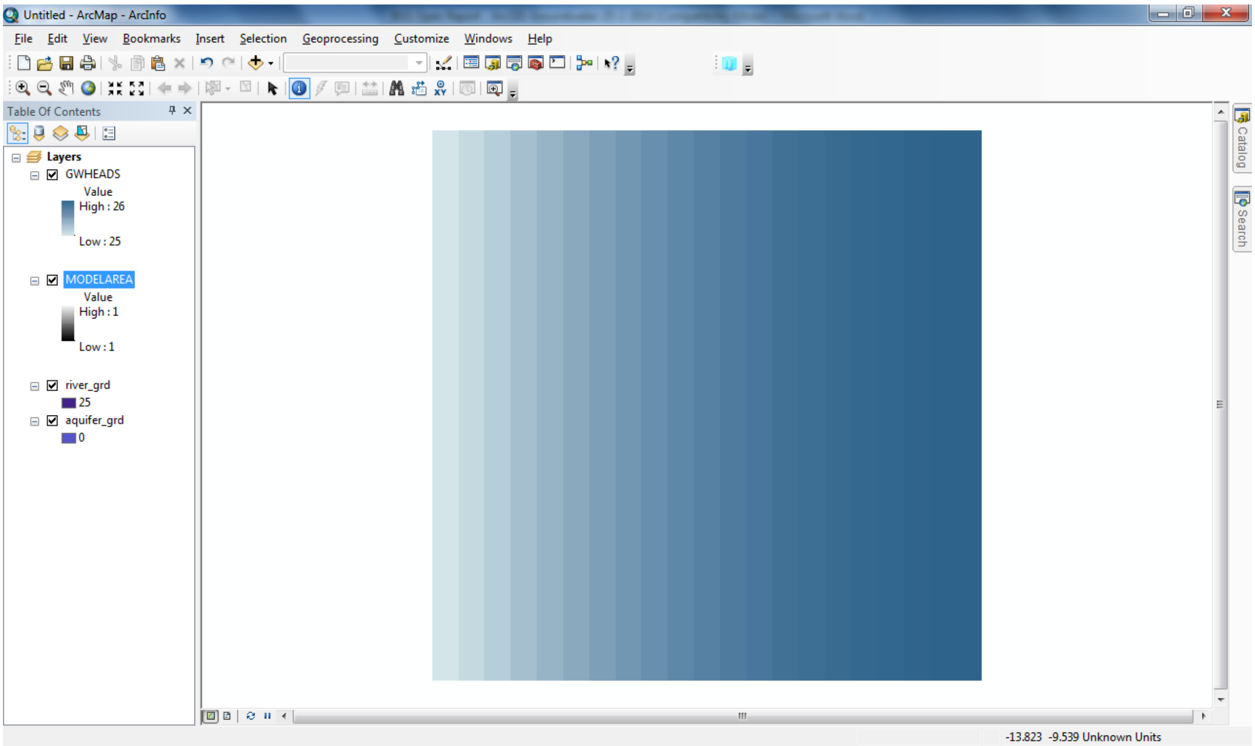


Figure 26. Groundwater levels produced by BGS GISGroundwater – Tutorial 1

After the simulation, the tool interface keeps open allowing users to change parameters and generate new results by re-running the model.

The problem in the tutorial 1 can also be solved using an analytical solution in the x direction. The analytical solution for this example can be expressed as:

$$H = H_o + R\frac{Lx}{T} - R\frac{x^2}{2T}$$ **Equation 2**

where H is the GWL (L); H_o is the fixed head (L); R is groundwater recharge (L T^{-1}); L is the length of aquifer (L) in the x direction; T is the transmissivity (L^2 T^{-1}); x is location in the x direction (L).

Substituting by H_o = 25 m, R = 0.001 m/day, T = 20 m^2/day, the results of Equation 2 should be the same as that simulated using GISGroundwater.

5.2 TUTORIAL 2

Tutorial 2 demonstrates how to construct a groundwater flow model for an aquifer with irregular boundary and the fixed groundwater head in the middle of the aquifer. After this you should be able to use a GIS point shapefile to represent fixed heads.

5.2.1 Problem description

An unconfined aquifer with an irregular shape has the extent of 10km by 10km. The aquifer has a homogenous hydraulic transmissivity value of 500 m^2/day; the recharge across the aquifer is 0.001 m/day; the aquifer has a 20m fixed head at its centre; there is no flow along the outside boundaries; this means that the aquifer centre is the only groundwater flow outlet for this system. The groundwater flow in this problem can be simulated using BGS GISGroundwater by discretising the aquifer domain by square grids (1km by 1km).

5.2.2 Data and parameters required

Data requirement:

- Aquifer extent (a GIS raster layer with the spatial resolution of 1km by 1km)
- Recharge (a constant value of 0.001 m/day)
- Initial head (a constant value of 40m)
- Transmissivity (a constant value of 500 m^2/day)
- A GIS shapefile containing a river point with a water level of 20m

The GIS datasets or GIS project file "Sample2_ArcMAP10.0.mxd" needed for this tutorial can be found under the folder of "Sample2_IrreqularShape_GIS". The tutorial materials can be downloaded from the BGS GISGroundwater link provided in section 2 and then extracted to a local drive.

5.2.3 Using BGS GISGroundwater

- Before opening the interface, load the aquifer grid layer and the point shapefile representing the surface water feature into the project using the plus button in the ArcMap toolbar (Figure 27).

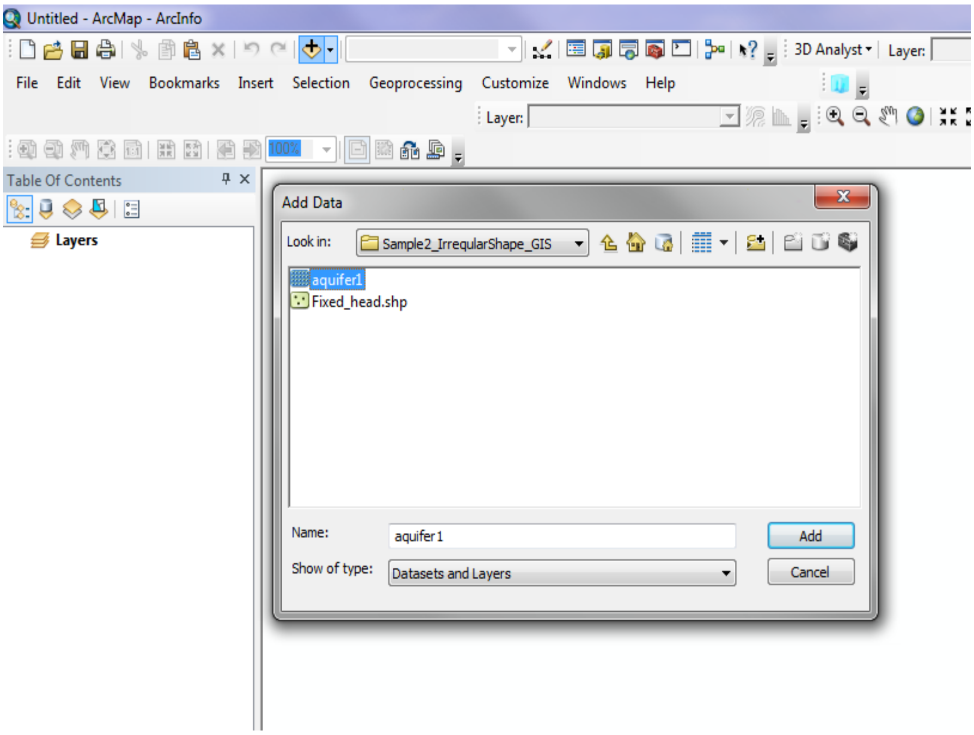


Figure 27. Loading layers to ArcMap project – Tutorial 2

The river point shapefile needs to be converted to a GIS raster layer and then entered as a river grid in the 'River' section of the interface. The conversion can be done using 'Point to Raster' tool from the ArcMap toolbox (Figure 28). In the tool's window select 'Fixed_head' layer from 'Input Feature' drop-down menu. To choose field holding elevation data select 'Fixed_head' from 'Value field' drop-down menu. To make sure the output layer has the same cell size of the aquifer grid, select 'aquifer1' from 'Cellsize' drop-down menu (Figure 28).

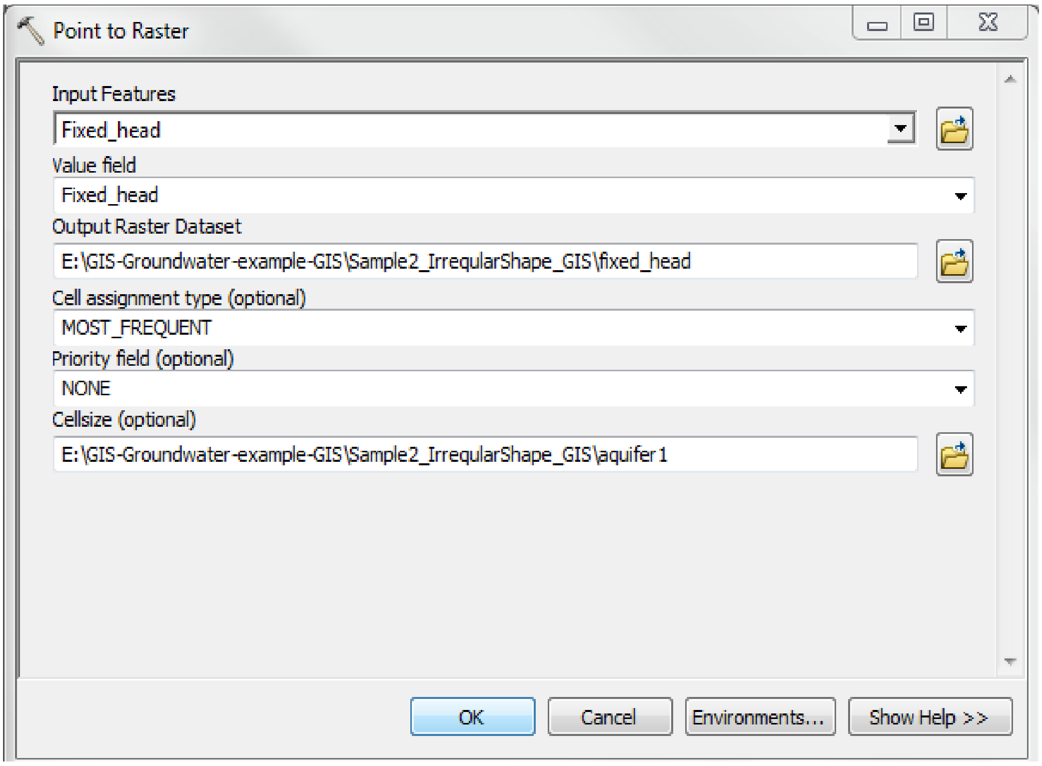


Figure 28. ArcMap 'Point to Raster' tool window

Since the extent of the river grid has to be the same as the extent of the aquifer grid, it is necessary to use the 'Environments' option (Figure 28) to define the extent of the output layer.

From the drop-down menu under 'Processing Extent' select 'Same as layer aquifer1' (Figure 29), and then click OK button.

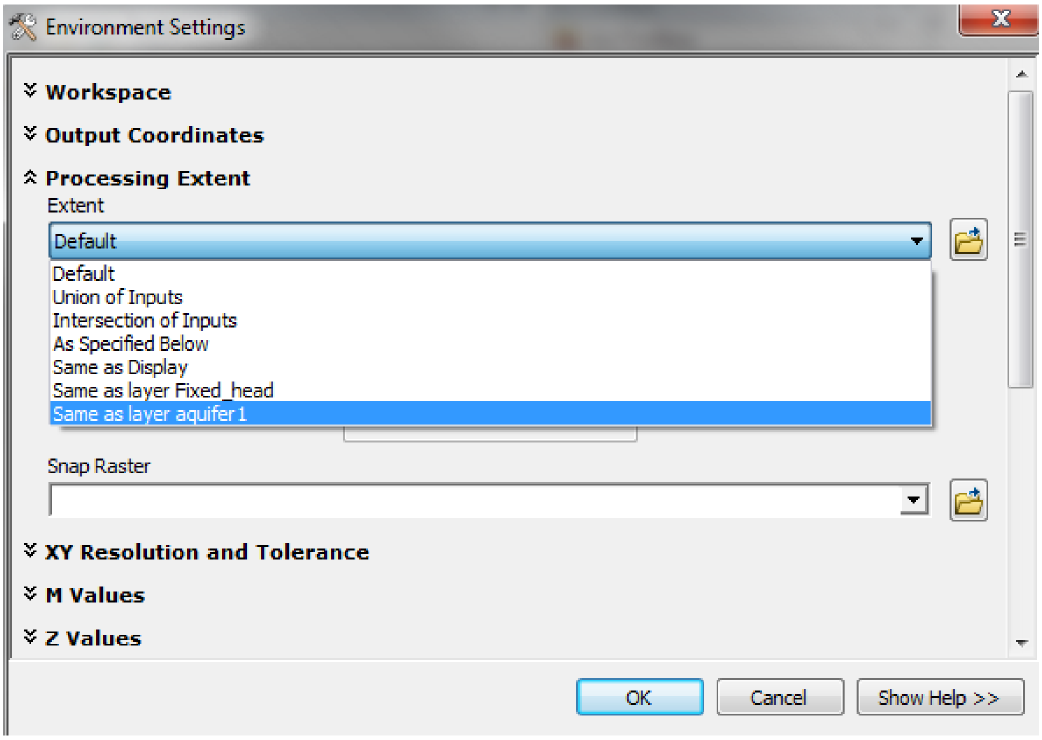


Figure 29. ArcMap ‘Point to Raster’ tool window – changing ‘Processing Extent’

Click on the folder icon next to ‘Output Raster Dataset' in Figure 28, specify the name of the new raster layer and save it in the project folder. Make sure to select ***different*** name for the raster layer than the name of the point shapefile.

The names of any layers used by the tool, either raster layer or shapefile must not be repeated! This will result in an error.

Once all the layers are loaded, the BGS GISGroundwater interface can be opened by clicking on the BGS GISGroundwater icon in the toolbar.

- Under ‘Aquifer Extent’ click on the drop-down menu next to ‘Aquifer Raster’ and select ‘aquifer1’. If no raster layers appear in the list, click on the refresh button to the right of the drop-down menu (Figure 30).
- Wait until the model cell size and the modelling extent are calculated and proceed to the next tab.

It is necessary to check the ‘Information’ box each time before moving to the next section.

- Under ‘Recharge and Initial Level’ (Figure 31), select constant value option for the recharge and input 0.001. Input 40 for the initial head.
- Under ‘Hydraulic Properties’ (Figure 32), select ‘Provide Transmissivity’ option. Note that ‘Define K’ subsection is no longer active. Select constant value option for transmissivity and enter 500.

- Since transmissivity is provided by a user ‘Aquifer Top/Bottom’ tab is not active.

- Under ‘Rivers’ select ‘Provide River Grid’ option. Click on the drop-down menu and select the river grid that was created when preparing the datasets at the beginning of this tutorial (Figure 33).

- Under ‘Settings’ input solver convergence criterion, PSOR solver factor, and the number of transmissivity recalculation cycles. The default values can be used or try different settings. Press ‘Run’ button to run the model (Figure 34).

Two raster layers are produced: ‘GWHEADS’ and ‘MODELAREA’, which are added to the ArcMap project and plotted automatically. ‘MODELAREA’ raster define the modelling extend, and ‘GWHEADS’ raster contains steady state groundwater levels simulated by the model (Figure 35).

After the simulation, the tool interface keeps open allowing users to change parameters and generate new results by re-running the model.

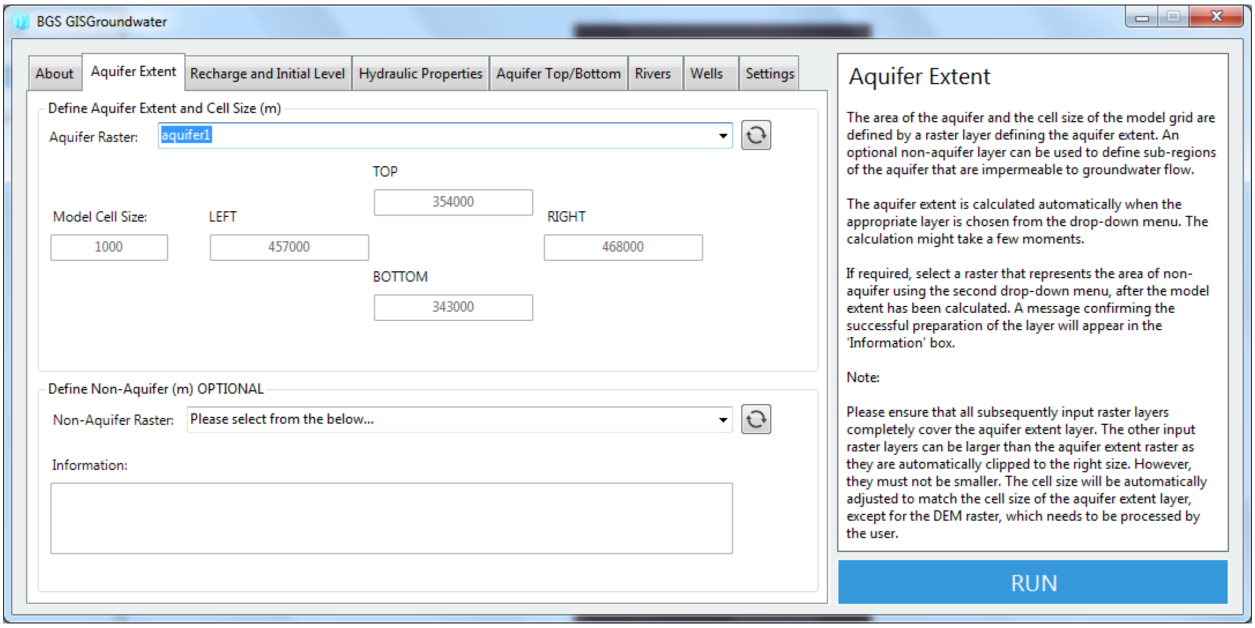


Figure 30. Aquifer Extent, Tutorial 2

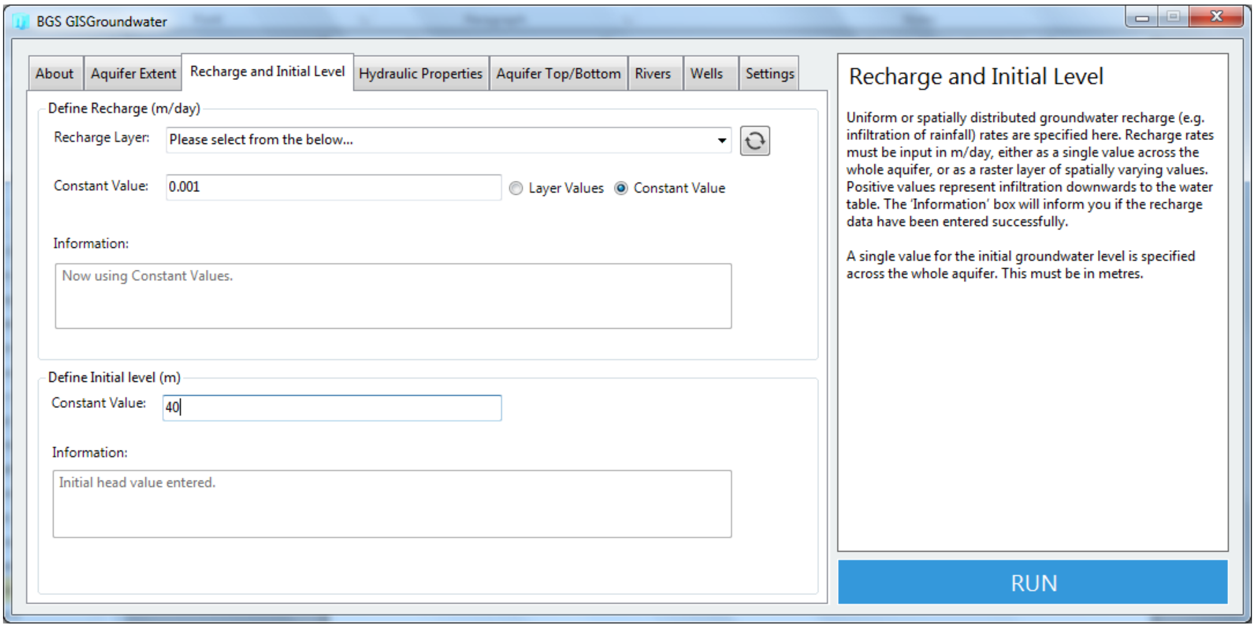


Figure 31. Recharge and Initial Level, Tutorial 2

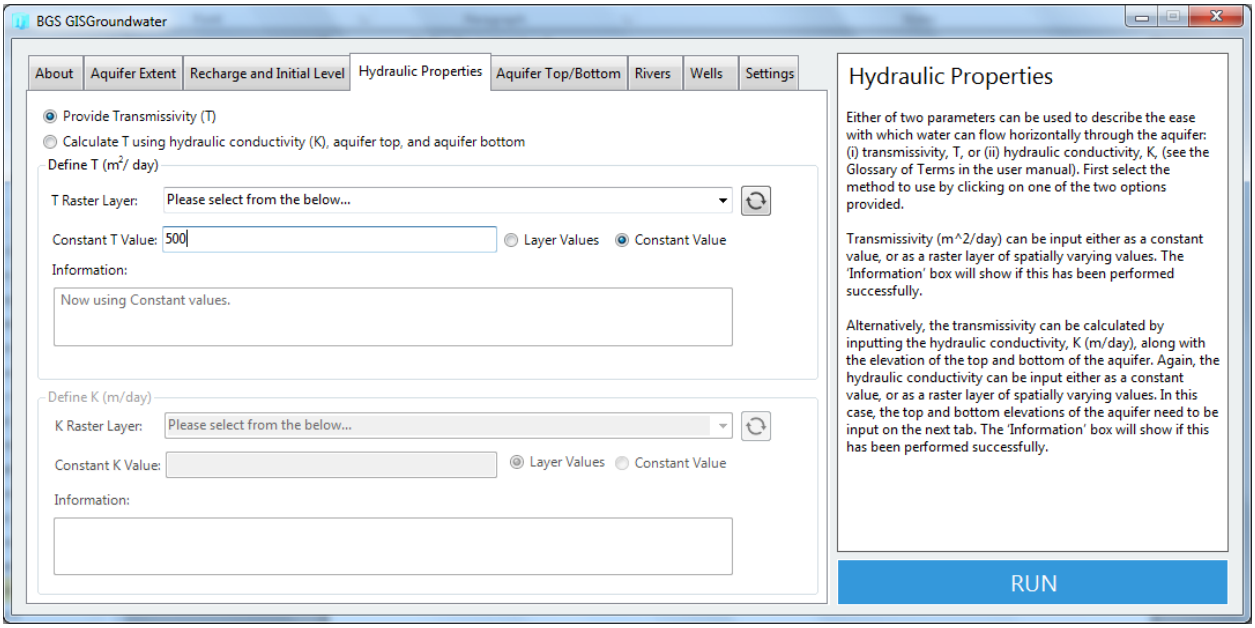


Figure 32. Hydraulic Properties, Tutorial 2

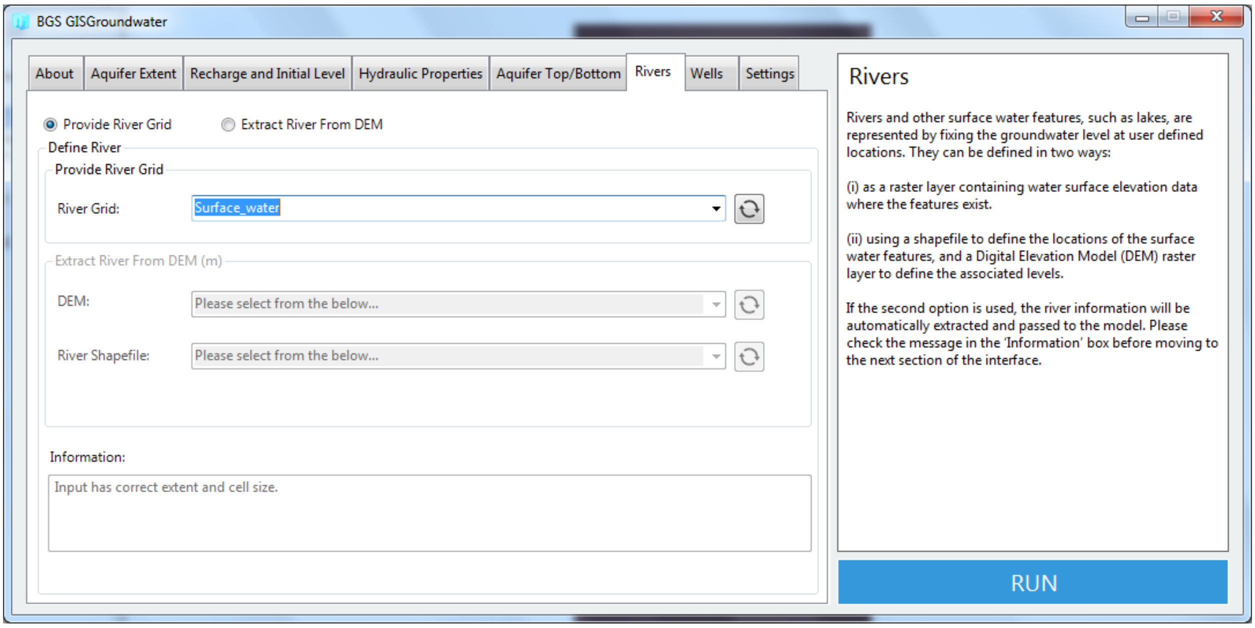


Figure 33. Rivers, Tutorial 2

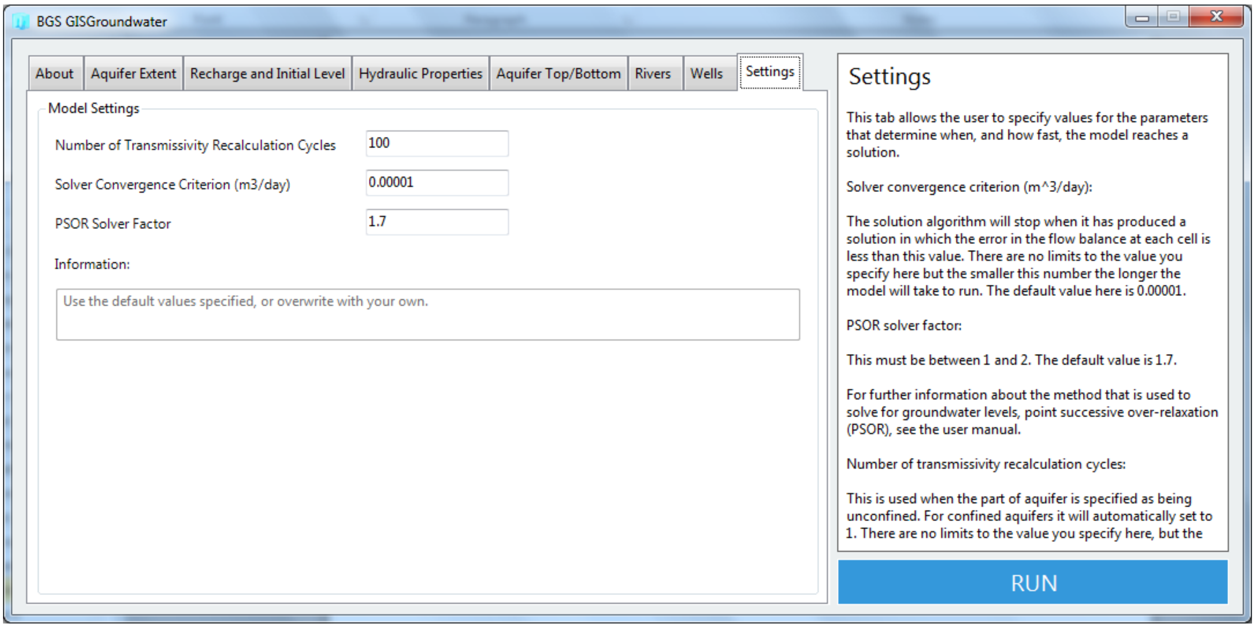


Figure 34. Settings, Tutorial 2

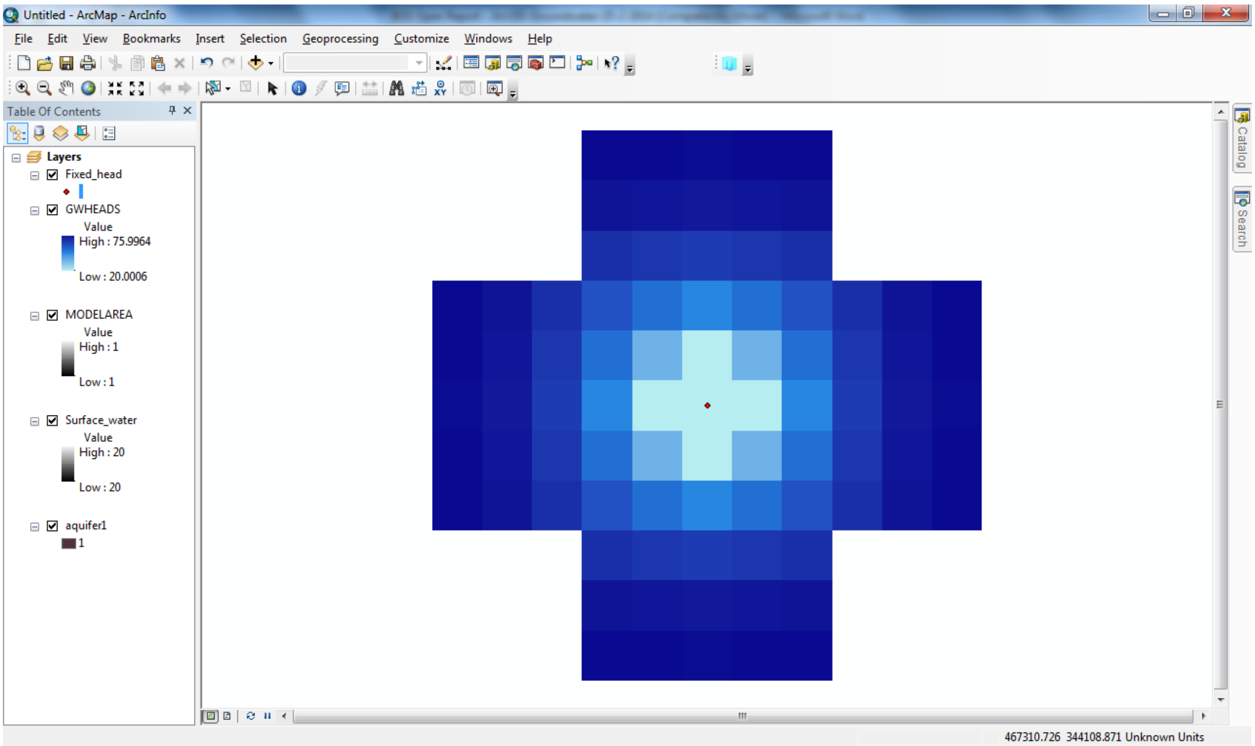


Figure 35. Groundwater levels produced by BGS GISGroundwater – Tutorial 2

5.3 TUTORIAL 3

This tutorial shows how to add more complexities into a groundwater flow model using a problem closer to reality. You will learn how to introduce distributed recharge into a groundwater flow model, and use hydraulic conductivity and aquifer geometry to calculate permeability, and how to represent pumping boreholes using a GIS point shapefile.

5.3.1 Problem description

An oval shape unconfined aquifer has spatial distributed recharge and hydraulic conductivity. Recharge decreases from (0.002 m/day) to (0.00125 m/day), while the hydraulic conductivity increases from 12.5 m/day to 15 m/day from west to east. The top and bottom elevations of this aquifer are 0m and 35m respectively. There are three pumping boreholes (ranges from 50 – 8000 m^3/day) in the area. There is no flow at the oval boundary of the aquifer; and groundwater flows out of the system through a river network, which has decreasing water levels eastwards.

5.3.2 Data and parameters required

Data requirement:

- Aquifer extent (a GIS raster layer with the spatial resolution of 100m by 100m)
- Recharge (a GIS raster layer with the same spatial resolution as the aquifer extent)
- Initial head (a constant value of 40m)
- Hydraulic conductivity (a GIS raster layer)
- Aquifer top and bottom elevations (constant values)
- River network (A GIS raster layer containing water level information)
- Pumping boreholes (A GIS shapefile contains the information on borehole locations and pumping rates).

The GIS datasets or GIS project file "Sample3_ArcMAP10.0.mxd" needed for this tutorial can be found under the folder of "Sample3_OvaleAquifer_GIS". The tutorial materials can be downloaded from the BGS GISGroundwater link provided in section 2 and then extracted to a local drive.

5.3.3 Using BGS GISGroundwater

- Before opening the interface, load aquifer ('aquifer_grd'), river ('river_grd.img'), recharge ('recharge_grd.img') and hydraulic conductivity ('K_GRD') raster grids, and abstraction point shapefile ('Abstraction.shp'), using the plus button in the ArcMap toolbar (Figure 36).

Once the raster layers are loaded, the BGS GISGroundwater interface can be opened by clicking on the BGS GISGroundwater icon in the toolbar.

- Under 'Aquifer Extent' click on the drop-down menu next to 'Aquifer Raster' and select 'aquifer_grd'. If no raster layers appear in the list, click on the refresh button to the right of the drop-down menu (Figure 37).

- Wait until the model cell size and the modelling extent are calculated and proceed to the next tab.

It is necessary to check the 'Information' box each time before moving to the next section.

- Under 'Recharge and Initial Level', select layer values option for the recharge, click on the drop-down menu and select 'recharge_grid'. Input 40 for the initial head (Figure 38).

- Under 'Hydraulic Properties', select 'Calculate T using hydraulic conductivity (K), aquifer top, and aquifer bottom' option.; note that 'Define T' subsection is no longer active. Select layer values option for hydraulic conductivity, click on the drop-down menu and select 'K_GRD.img' (Figure 39).

- Under 'Aquifer Top/Bottom' select constant value option for both elevations and enter 35 for the top of and 0 for the bottom of the aquifer (Figure 40).

- Under 'Rivers' select 'Provide River Grid' option, click on the drop-down menu and select 'river_grd.img' (Figure 41).

- Under 'Wells' select 'Extract Pumping From Shapefile' option, click on the drop-down menu and select 'Abstraction' shapefile. Select the field holding pumping rate information (Figure 42).

- Under 'Settings' input solver convergence criterion, PSOR solver factor, and the number of transmissivity recalculation cycles. The default values can be used or try different settings. Press 'Run' button to run the model (Figure 43).

Two raster layers are produced: 'GWHEADS' and 'MODELAREA', which are added to the ArcMap project and plotted automatically. 'MODELAREA' raster define the modelling extend, and 'GWHEADS' raster contains steady state groundwater levels simulated by the model (Figure 44).

After the simulation, the tool interface keeps open allowing users to change parameters and generate new results by re-running the model.

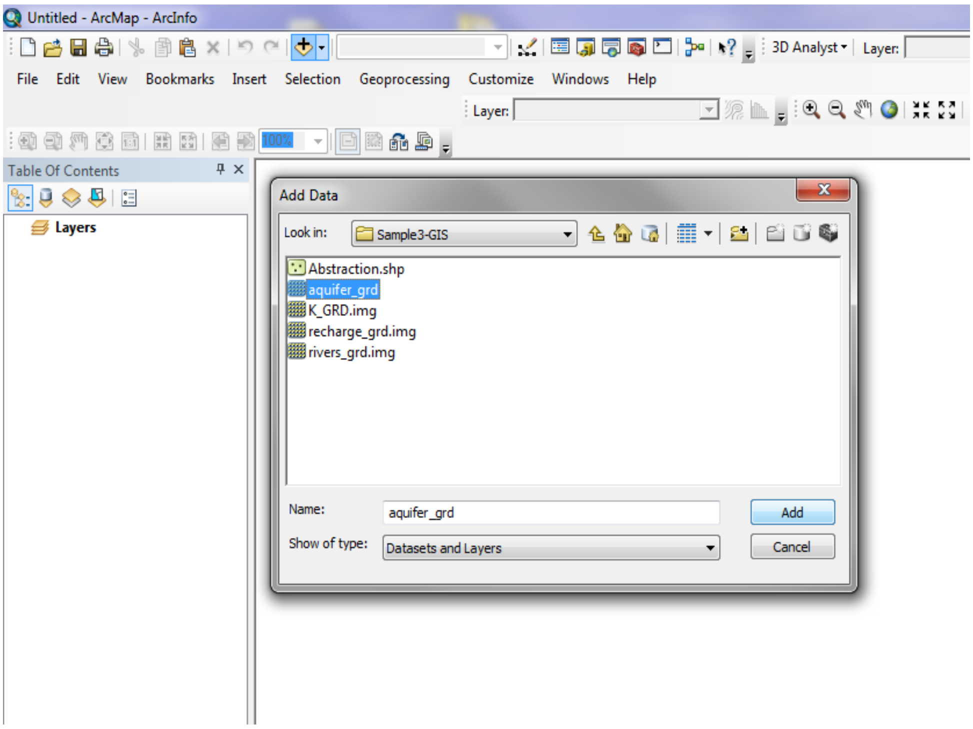


Figure 36. Loading layers to ArcMap project – Tutorial 3

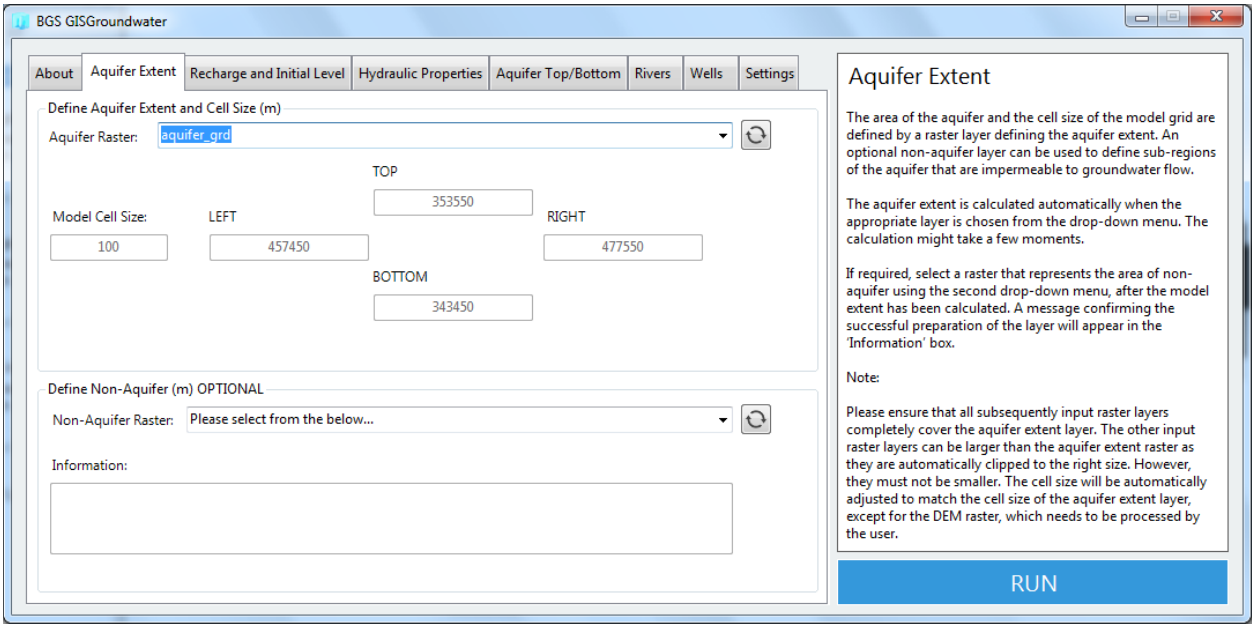


Figure 37. Aquifer Extent, Tutorial 3

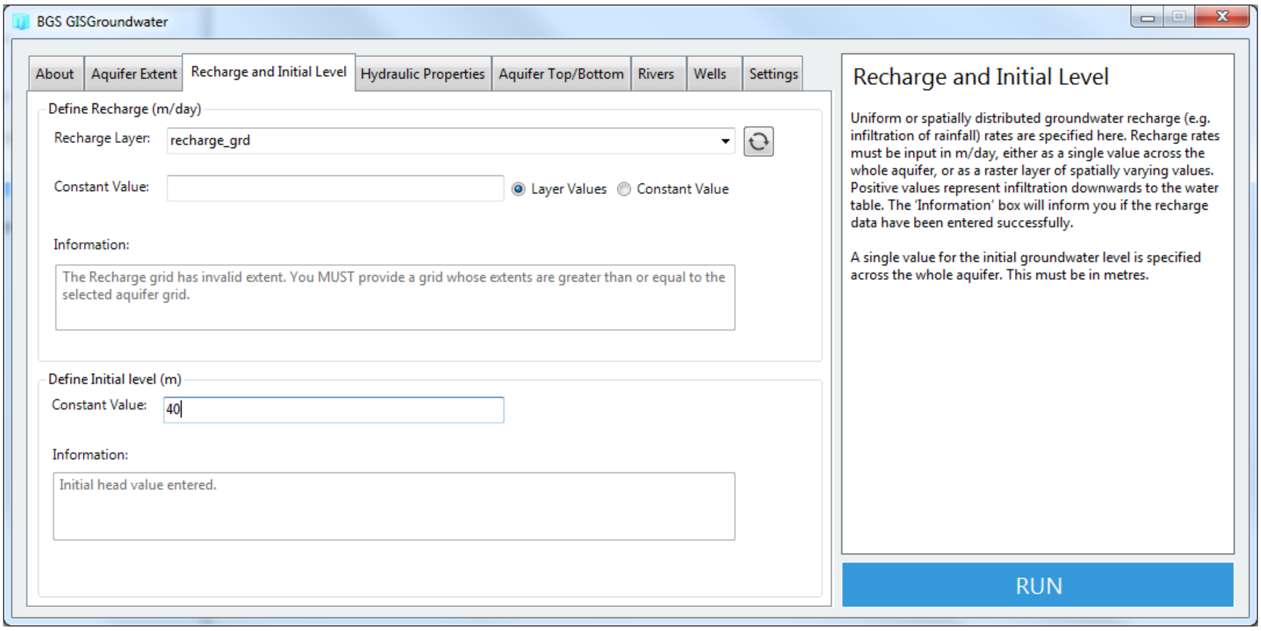


Figure 38. Recharge and Initial Level, Tutorial 3

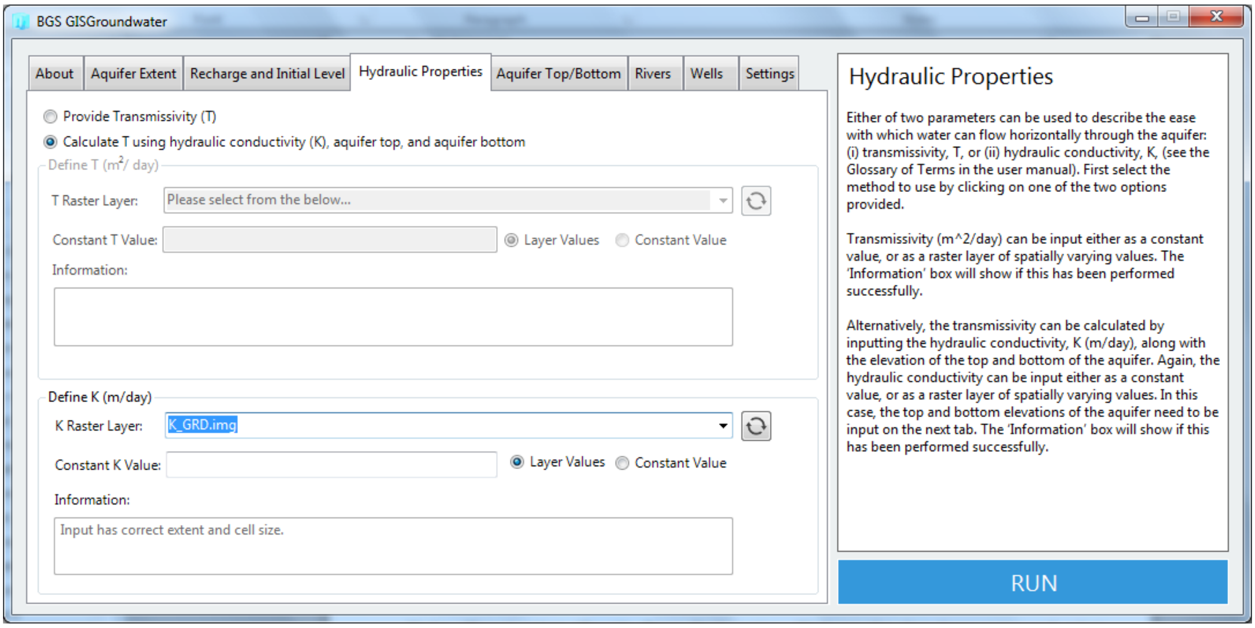


Figure 39. Hydraulic Properties, Tutorial 3

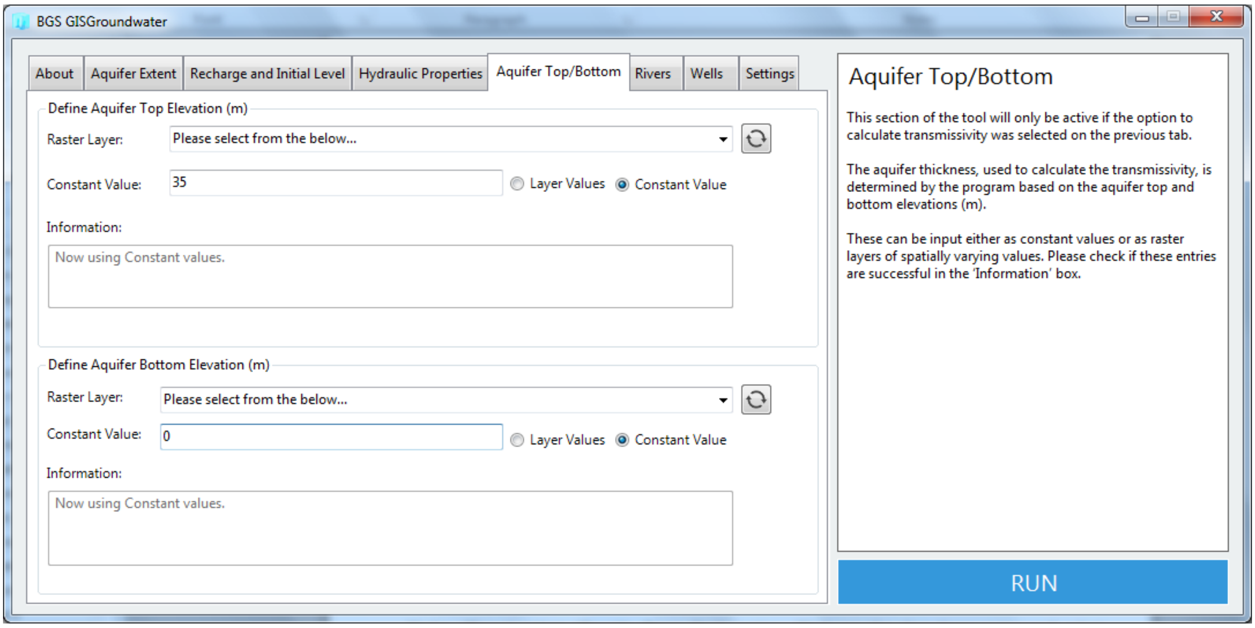


Figure 40. Aquifer Top/Bottom, Tutorial 3

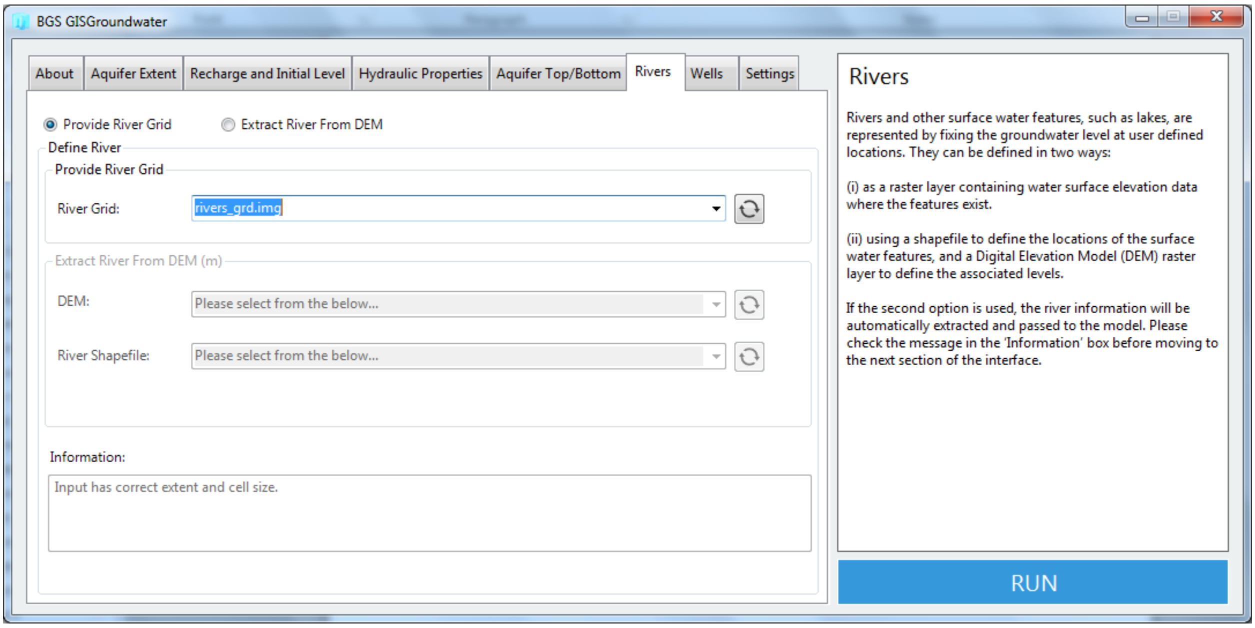


Figure 41. Rivers, Tutorial 3

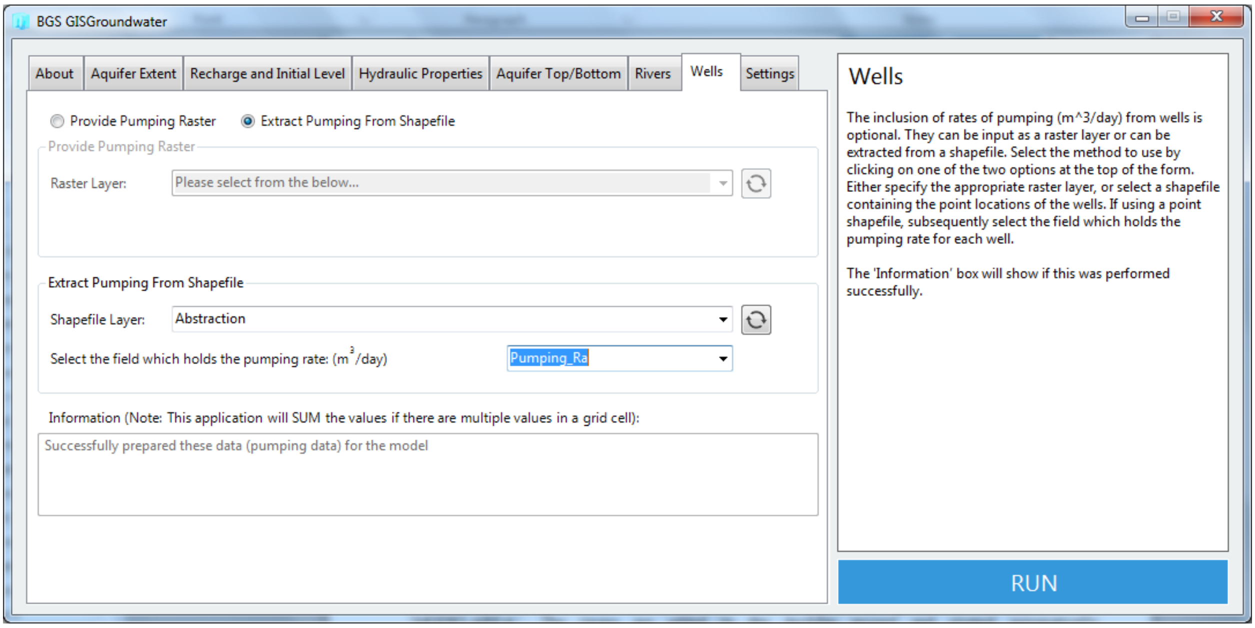


Figure 42. Wells, Tutorial 3

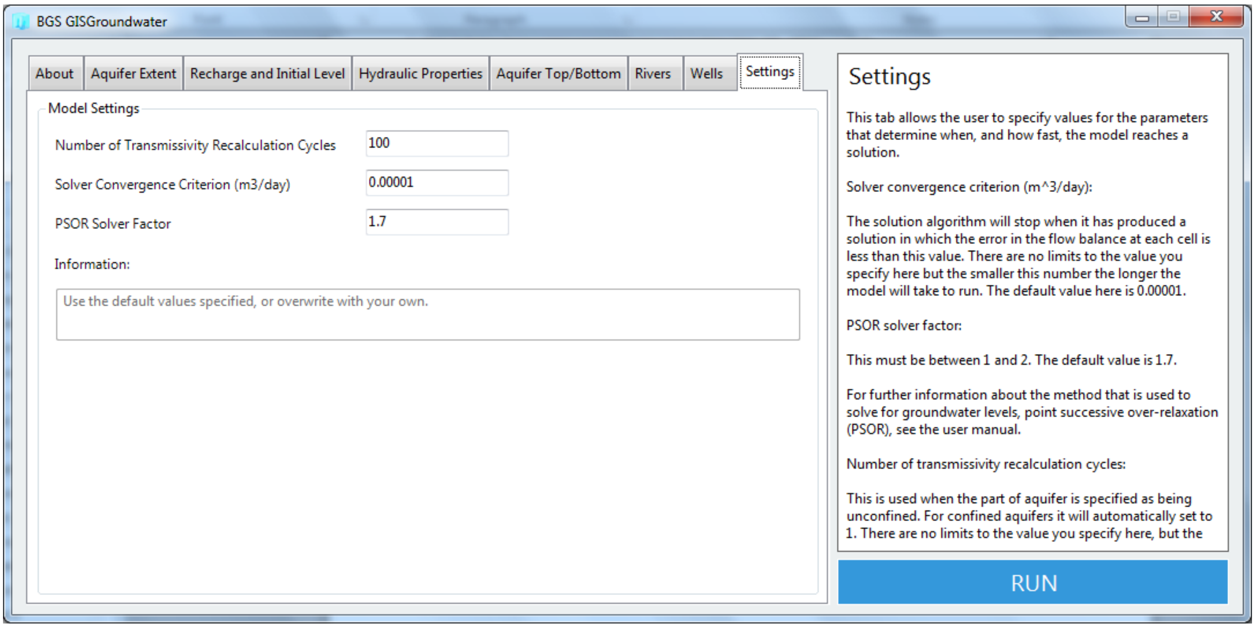


Figure 43. Settings, Tutorial 3

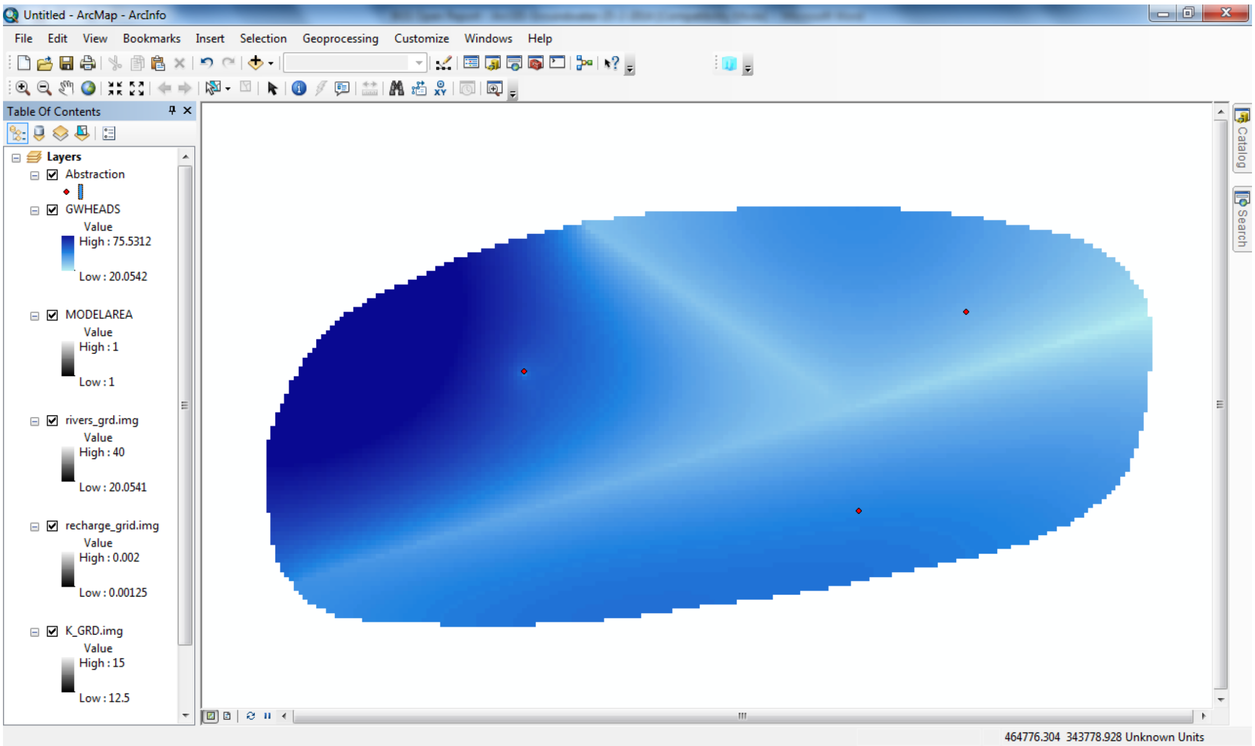


Figure 44. Groundwater levels produced by BGS GISGroundwater – Tutorial 3

5.4 TUTORIAL 4

This tutorial is an application of the tool to simulate groundwater flow in the Chalk, Thames Basin, UK. You will learn how to model groundwater flow in an aquifer that is partial overlain by low permeability formations (Non-aquifer represented using a GIS raster layer). This system consists of unconfined and confined aquifers; low permeable formations stop recharge reaching the aquifer beneath and make rivers disconnected from the aquifer. This tutorial also covers the usage of a river shapefile in constructing a groundwater flow model.

5.4.1 Problem description

The Chalk aquifer (a fractured microporous limestone) is isolated from other major aquifers by low permeability horizons within the Gault and Upper Greensand Formations in the Thames Basin, UK. It is, therefore, proper to model the groundwater flow in the Chalk separately. The Chalk is partially overlain by low permeability Palaeogene deposits; and the system consists of unconfined and confined aquifers. The groundwater system within the Chalk outcrops is unconfined whist the part underneath the Palaeogene deposits could be unconfined or confined depending on the groundwater heads and the top elevation of the Chalk. The Palaeogene deposits disconnect rivers from the Chalk (Figure 45). The spatial distributed recharge ranges from 3.14×10^{-6} – 0.0024 m/day; and the low permeability Palaeogene deposits stops recharge reaching water table. Three abstraction boreholes in the area are included in the model. Their pumping rates range from 3,550 m^3/day to 60,000 m^3/day.

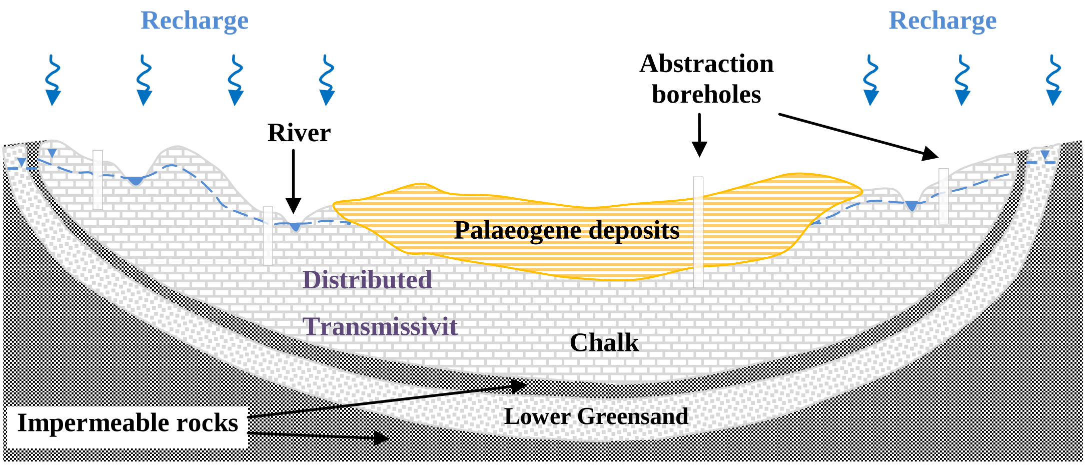


Figure 45. The sketch map of the conceptual hydrogeological model for tutorial 4

5.4.2 Data and parameters required

Data requirement:

- The Chalk aquifer layer (a GIS raster layer with the spatial resolution of 1km by 1km, representing the extent of the Chalk)
- Non-aquifer layer (A GIS raster layer representing the extent of the Palaeogene deposits)
- Recharge (a GIS raster layer with the same spatial resolution as the aquifer extent)
- Initial head (a constant value of 100m)
- Hydraulic conductivity (a GIS raster layer)
- Aquifer top and bottom elevations (constant values)
- River network (A GIS shape file without water level information)
- DEM (A GIS raster layer containing water level data)

- Pumping boreholes (A GIS shapefile contains the information on borehole locations and pumping rates).

The GIS datasets or GIS project file "Sample4_ArcMAP10.0.mxd" needed for this tutorial can be found under the folder of "Sample4_Chalk_TB_GIS". The tutorial materials can be downloaded from the BGS GISGroundwater link provided in section 2 and then extracted to a local drive.

5.4.3 Using BGS GISGroundwater

- Before opening the interface, load all the required layers using the plus button in the ArcMap toolbar, i.e.: aquifer grid ('chalk_grd'), aquifer top grid ('chalk_top_grd.img'), aquifer bottom grid ('chalk_bottom_grd.img'), hydraulic conductivity raster layer ('k_grd'), recharge raster layer ('Recharge_grd.m.img'), DEM raster layer ('DEM_1k_Large_TB.img'), non-aquifer grid ('non-aquifer.img'), river network shapefile ('TB_all_rivers.shp'), and point shapefile representing locations of the pumping wells ('Abstraction_Borehole.shp') (Figure 46).

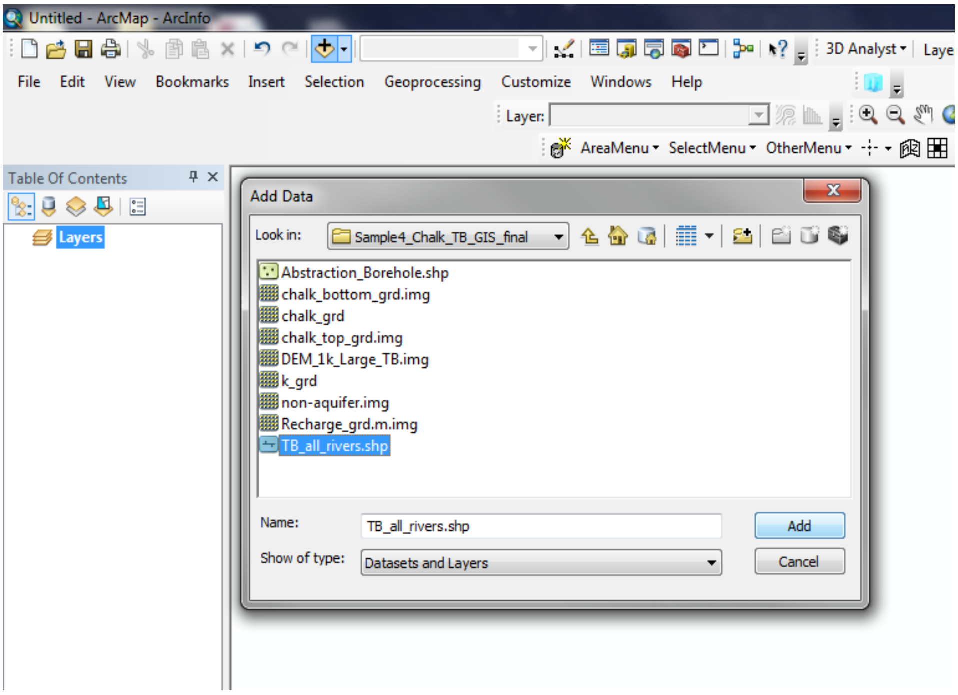


Figure 46. Loading layers to ArcMap project – Tutorial 4

Once the raster layers are loaded, the BGS GISGroundwater interface can be opened by clicking on the BGS GISGroundwater icon in the toolbar.

- Under 'Aquifer Extent', click on the drop-down menu next to 'Aquifer Raster' and select 'chalk_grd'. If no raster layers appear in the list, click on the refresh button to the right of the drop-down menu (Figure 47).

- Wait until the model cell size and the modelling extent are calculated and proceed to the next tab

It is necessary to check the 'Information' box each time before moving to the next section.

- Once the modelling extent and the cell size are calculated click on the drop-down menu next to 'Define Non-Aquifer' and select 'non-aquifer.img' (Figure 48).

- Under 'Recharge and Initial Level', select layer values option for the recharge, click on the drop-down menu and select 'Recharge_grd.m.img'; input 100 for the initial head (Figure 49).

- Under 'Hydraulic Properties', select 'Calculate T using hydraulic conductivity (K), aquifer top, and aquifer bottom' option.; note that 'Define T' subsection is no longer active. Select layer values option for hydraulic conductivity, click on the drop-down menu and select 'k_grd' (Figure 50).

- Under 'Aquifer Top/Bottom', select layer values option for both elevations. Click on the first drop-down menu and select 'chalk_top_grd.img'. Click on the second drop-down menu and select 'chalk_bottom_grd.img' (Figure 51).

River raster grid can be generated using the river network shapefile and the DEM raster layer supplied. If ArcMap package comes with the Spatial Analyst licence, the river grid will be created automatically by BGS GISGroundwater tool.

- In 'Rivers' select 'Extract River From DEM' option. Select 'DEM_1k_Large_TB.img' layer from the drop-down menu next to 'DEM' and wait until it is processed, then select 'TB_all_rivers' shapefile from the drop-down menu next to 'River Shapefile' (Figure 52).

Note that if the cell size of the Digital Elevation Model raster layer does not match the cell size of the aquifer grid, it needs to be resampled to match the cell size of the aquifer layer before it is loaded to BGS GISGroundwater.

If a Spatial Analyst license for ArcGIS™ does not exist, the steps in the Appendix 1 can be followed to manually create a river grid using a free GIS SAGA. Then in 'Rivers', select 'Provide River Grid' option, click on the drop-down menu and select the river grid that you have created.

- Under 'Wells' select 'Extract Pumping From Shapefile' option, click on the drop-down menu and select 'Abstraction' shapefile. Select the field holding pumping rate information (Figure 53).

- Under 'Settings' input solver convergence criterion, PSOR solver factor, and the number of transmissivity recalculation cycles. The default values can be used or try different settings. Press 'Run' button to run the model (Figure 54).

Two raster layers are produced: 'GWHEADS' and 'MODELAREA', which are added to the ArcMap project and plotted automatically (Figure 55). 'MODELAREA' raster define the modelling extend, and 'GWHEADS' raster contains steady state groundwater levels simulated by the model.

After the simulation, the tool interface keeps open allowing users to change parameters and generate new results by re-running the model.

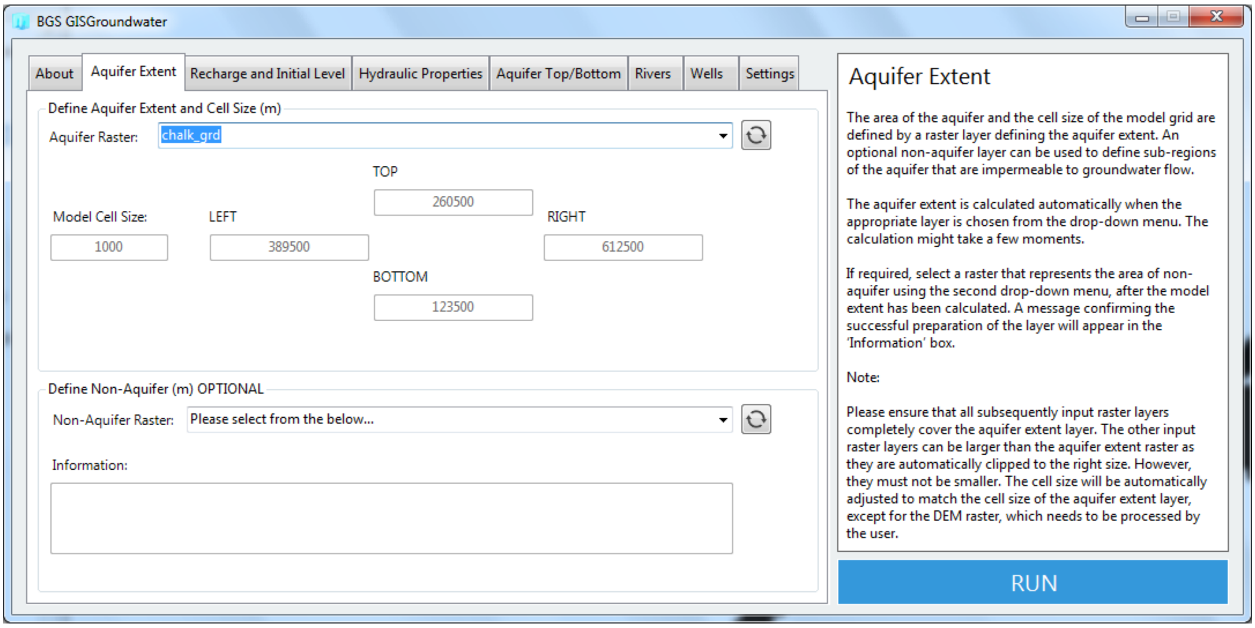


Figure 47. Aquifer Extent, Tutorial 4 (1)

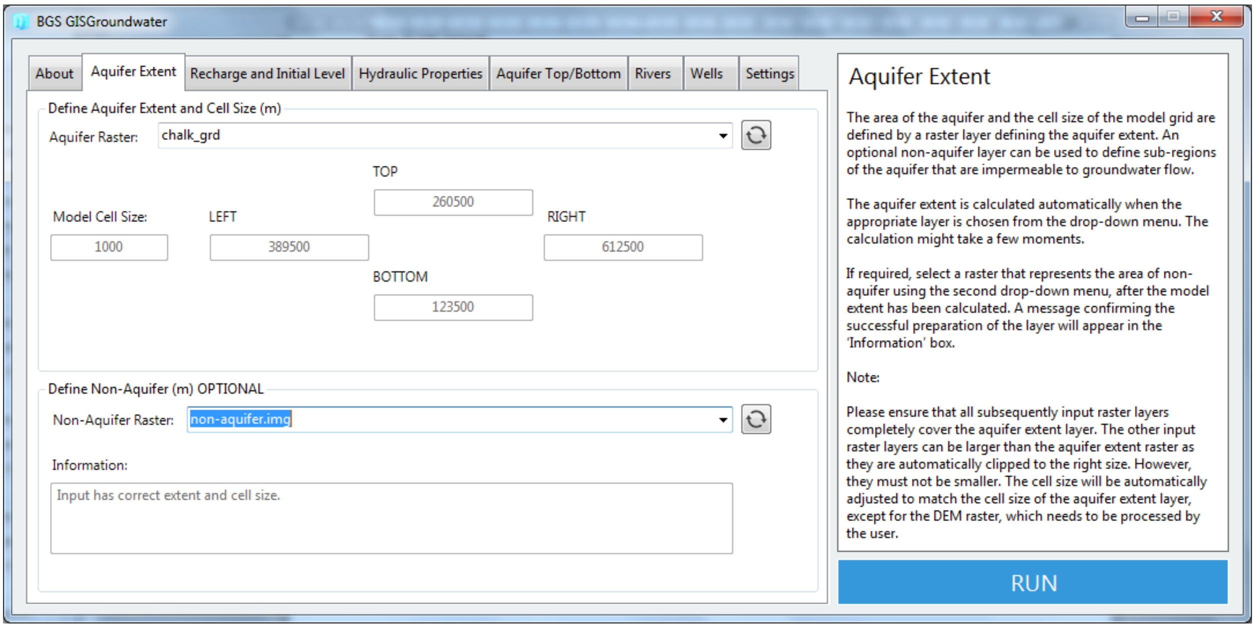


Figure 48. Aquifer Extent, Tutorial 4 (2)

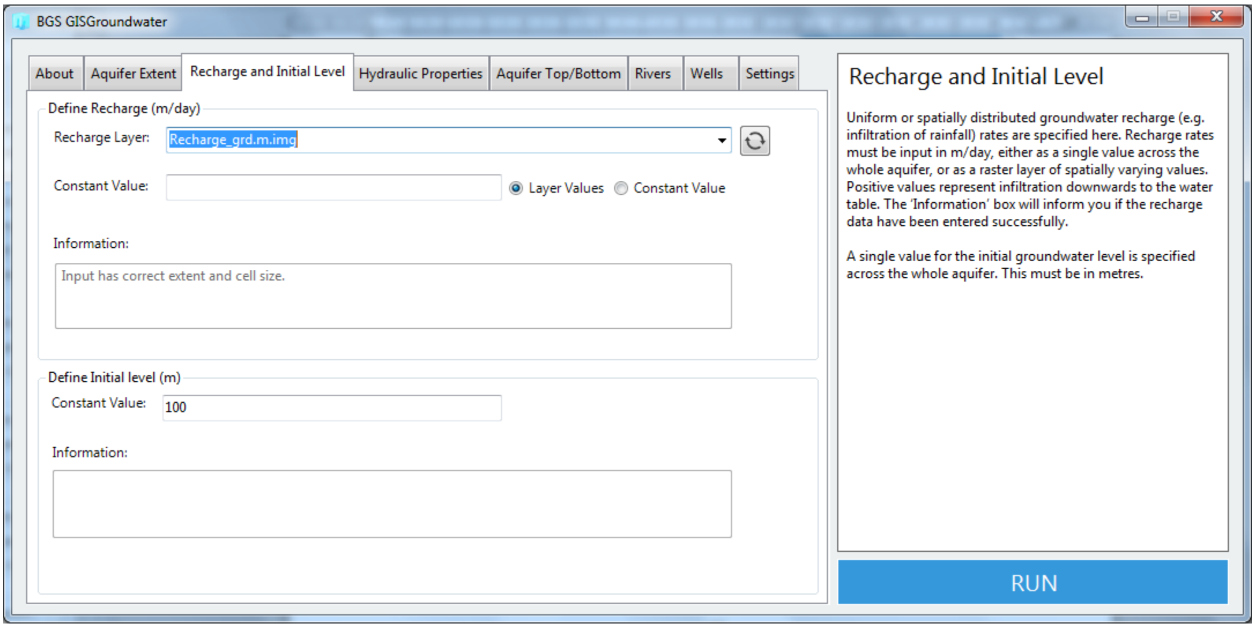


Figure 49. Recharge and Initial Level, Tutorial 4

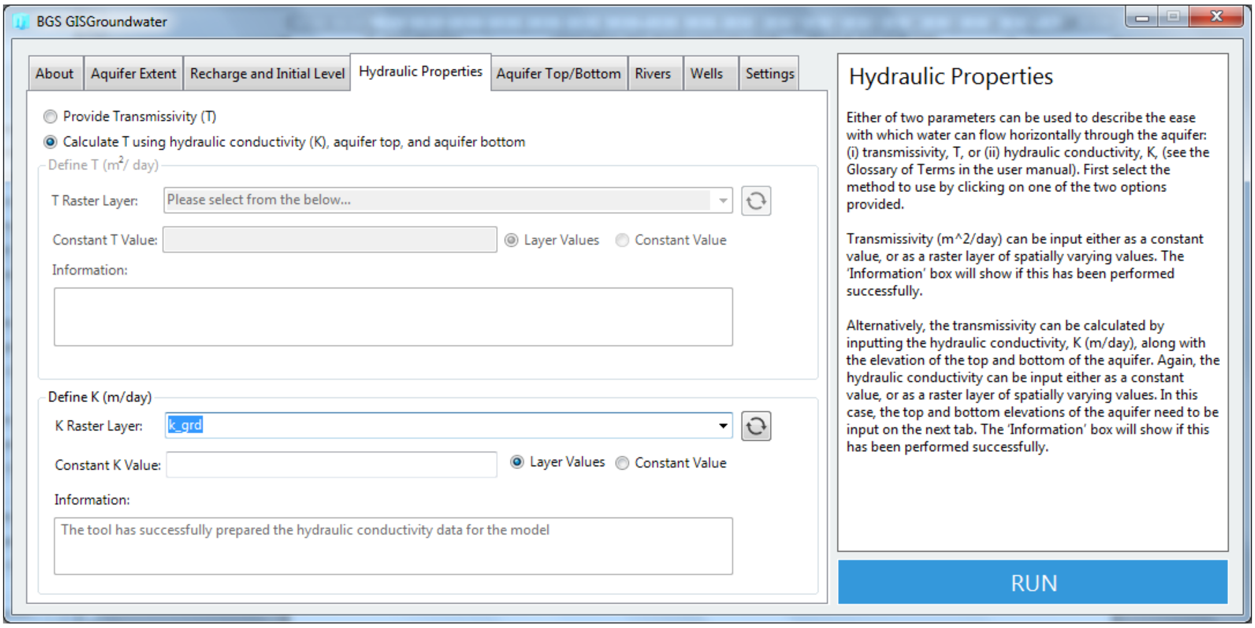


Figure 50. Hydraulic Properties, Tutorial 4

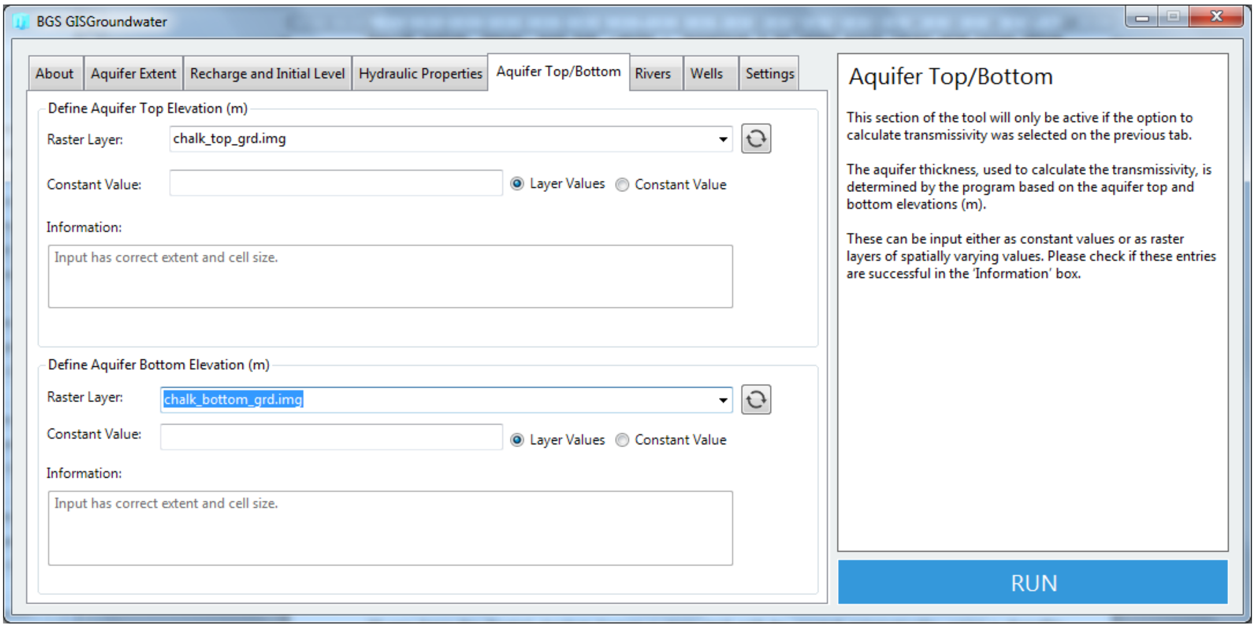


Figure 51. Aquifer Top/Bottom, Tutorial 4

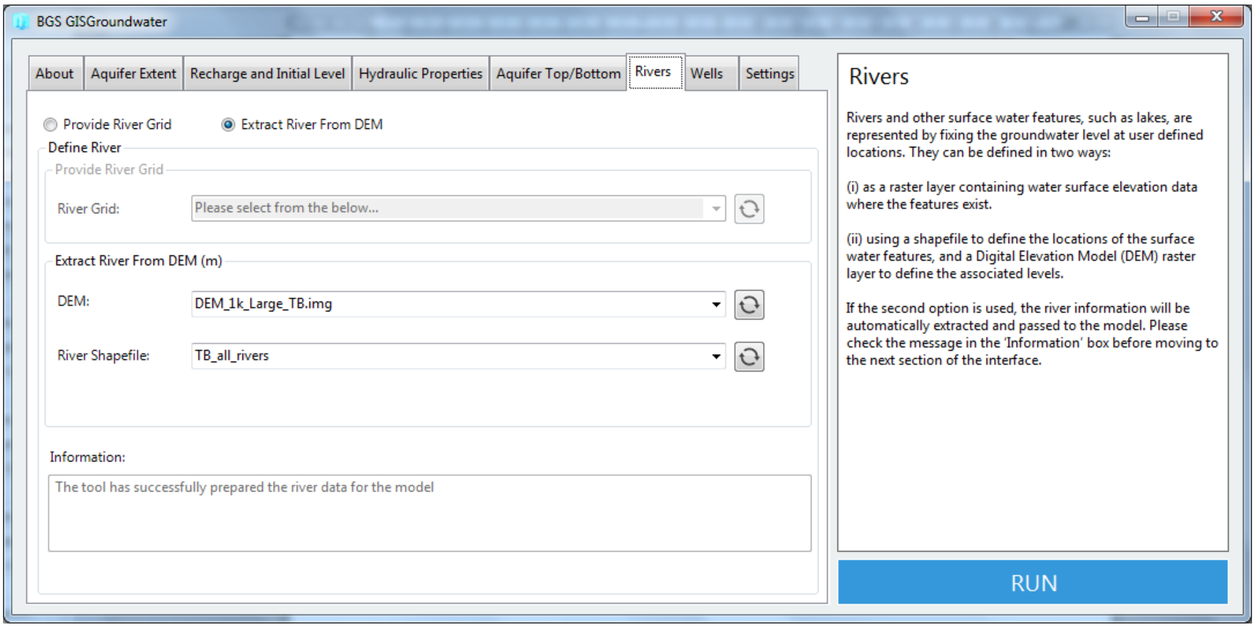


Figure 52. Rivers, Tutorial 4 (2)

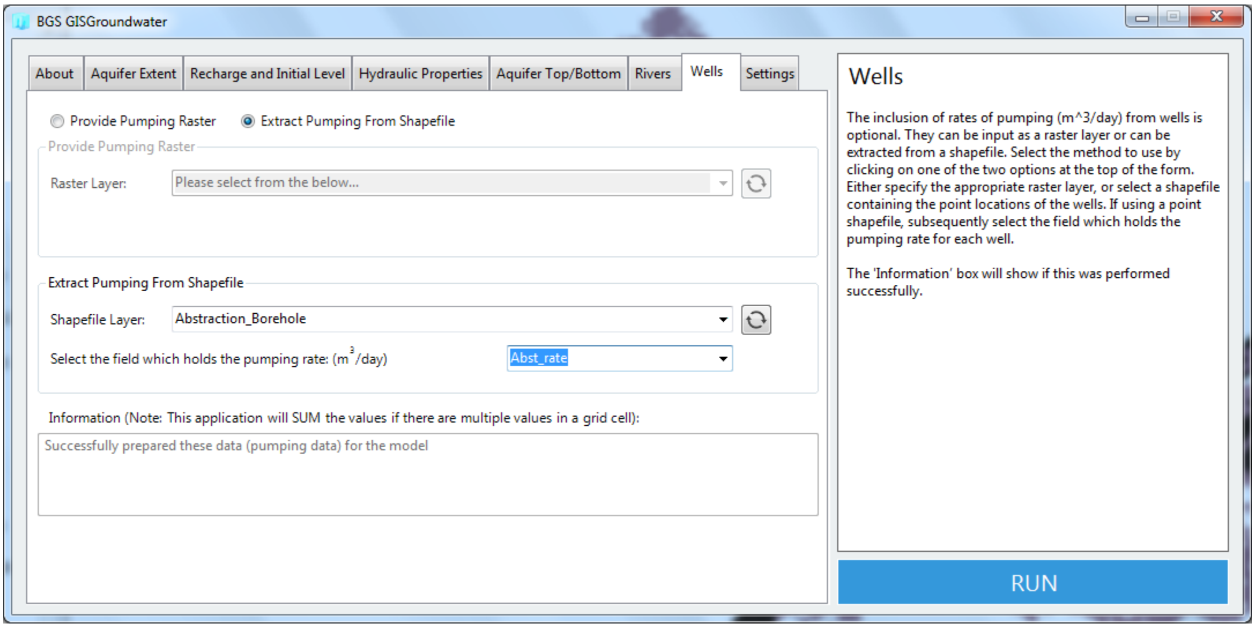


Figure 53. Wells, Tutorial 4

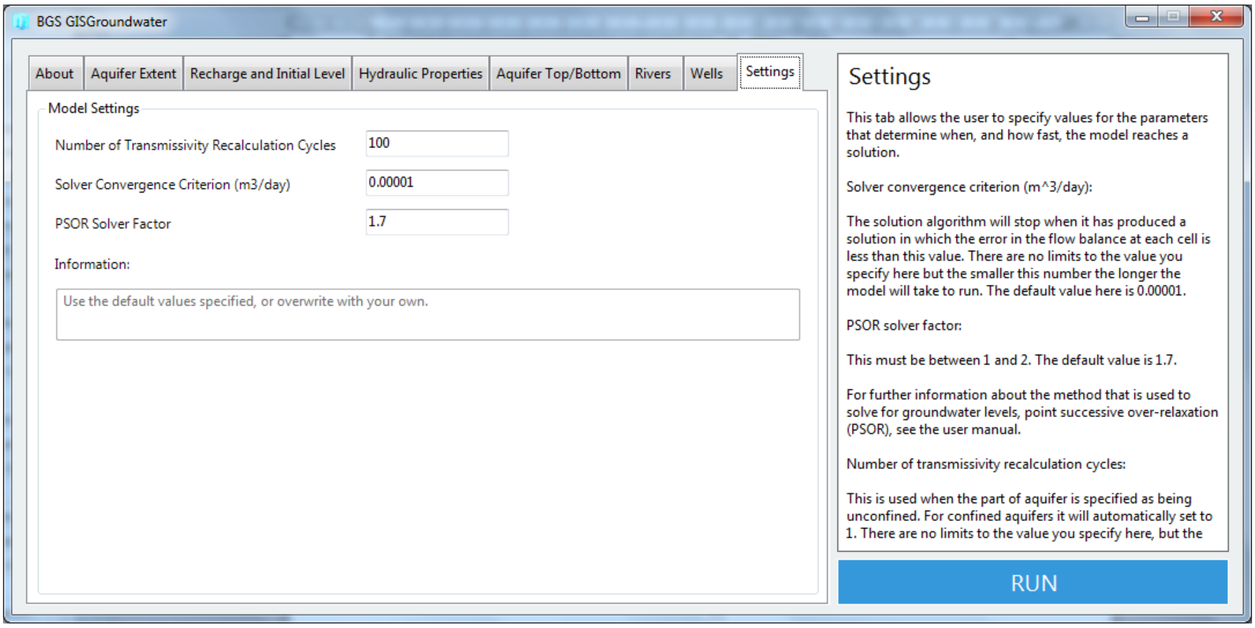


Figure 54. Settings, Tutorial 4

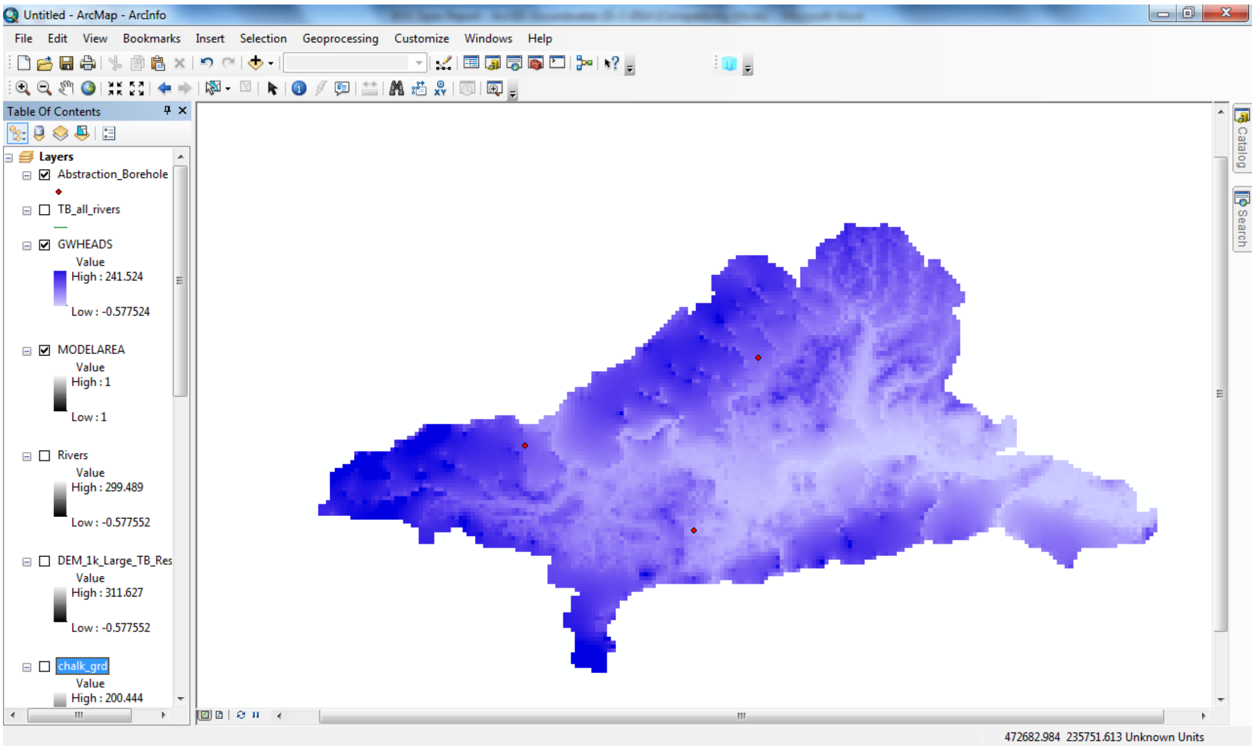


Figure 55. Groundwater levels produced by BGS GISGroundwater – Tutorial 4

Appendix 1: Extracting water levels using a free GIS

This section describes how to extract water level information from DEM data using free GISs when users do not have a Spatial Analyst licence for ArcGIS™. Otherwise, this can be automatically finished by BGS GISGroundwater (Tutorial 4).

In tutorial 4, a river grid is not provided but it can be generated using the river network shapefile ('TB_all_rivers.shp') and the DEM data ('DEM_1k_Large_TB.img') supplied. SAGA GIS software (System for Automated Geoscientific Analyses), which can be downloaded free of charge from http://www.saga-gis.org/ website, is used in this section.

- Open the river shapefile attribute table (Figure 56) and add a new field of type short integer (Figure 57 and 58).

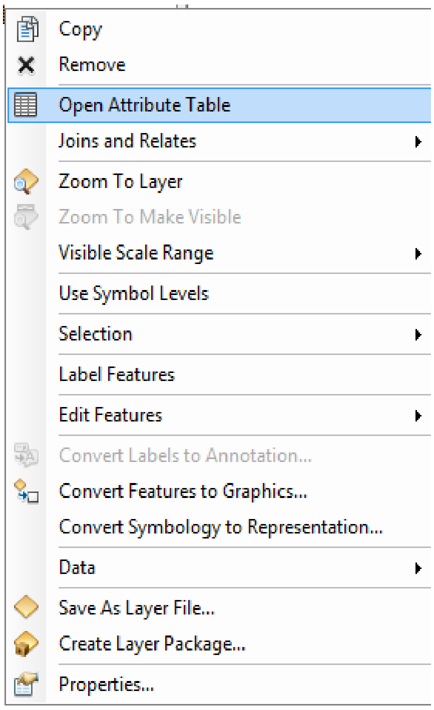


Figure 56. Opening river shapefile attribute table – App. 1

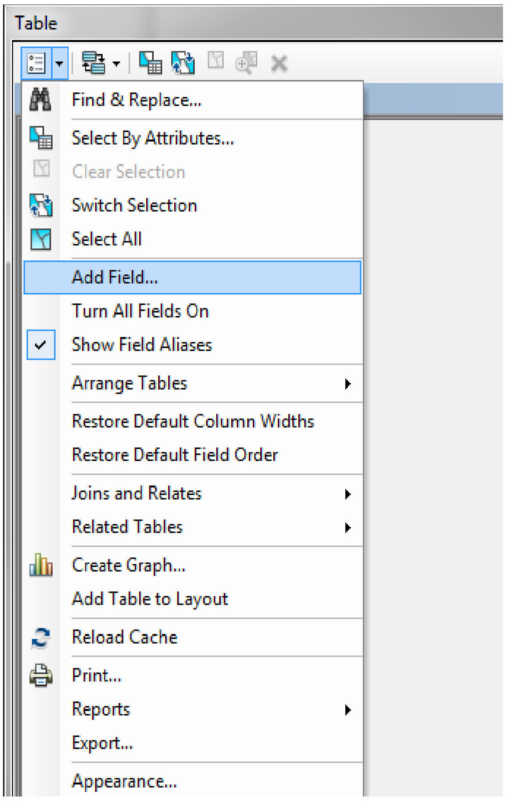


Figure 57. Adding new field in the attribute table – App. 1 (1)

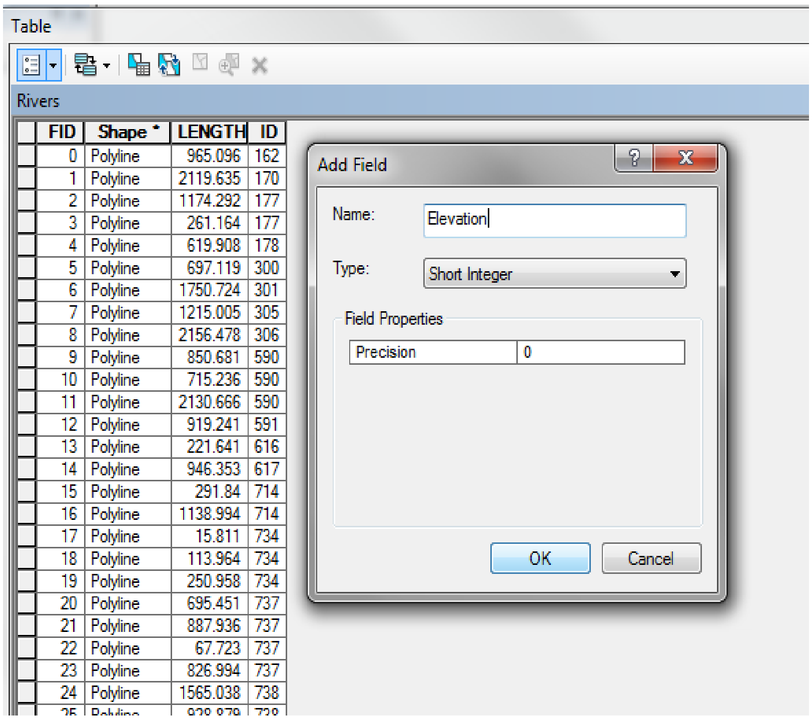


Figure 58. Adding new field in the attribute table – App. 1 (2)

- Highlight the newly created field and open 'Field Calculator' (Figure 59).

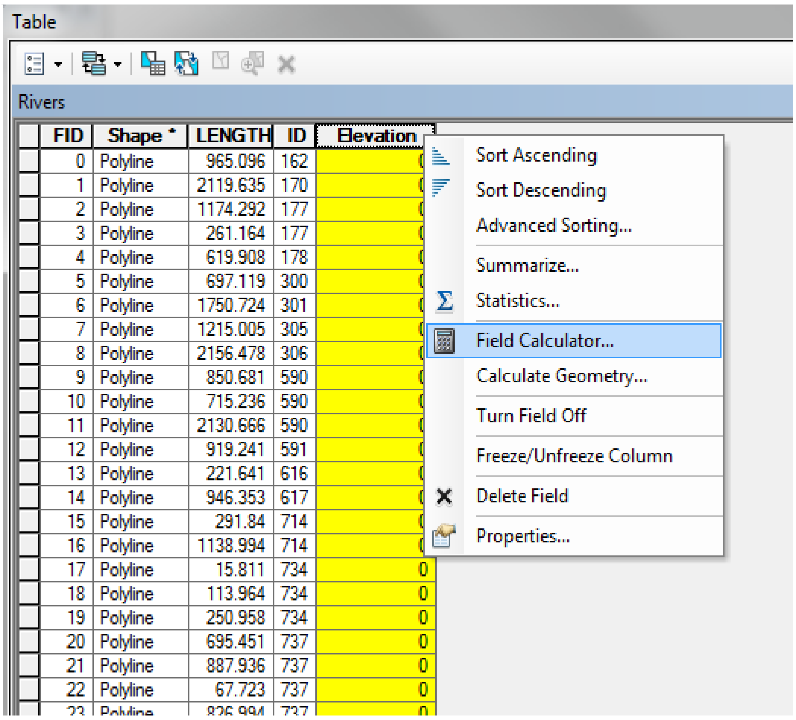


Figure 59. Opening Field Calculator – App. 1

- Using the calculator set values in the 'Elevation' field equal to 1 (Figure 60 and 61).

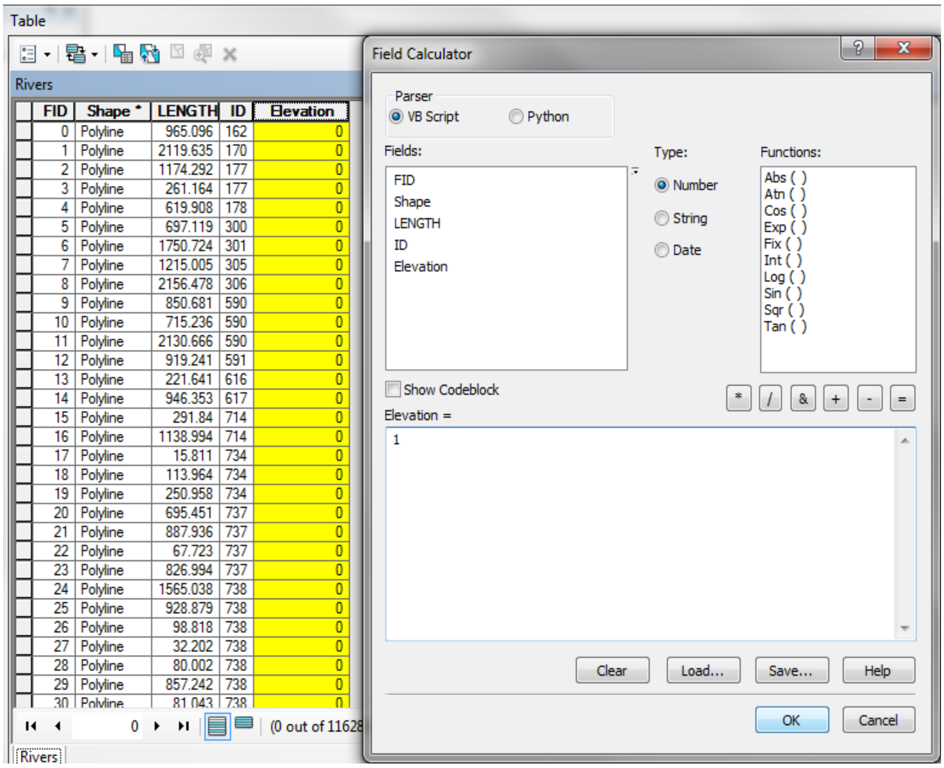
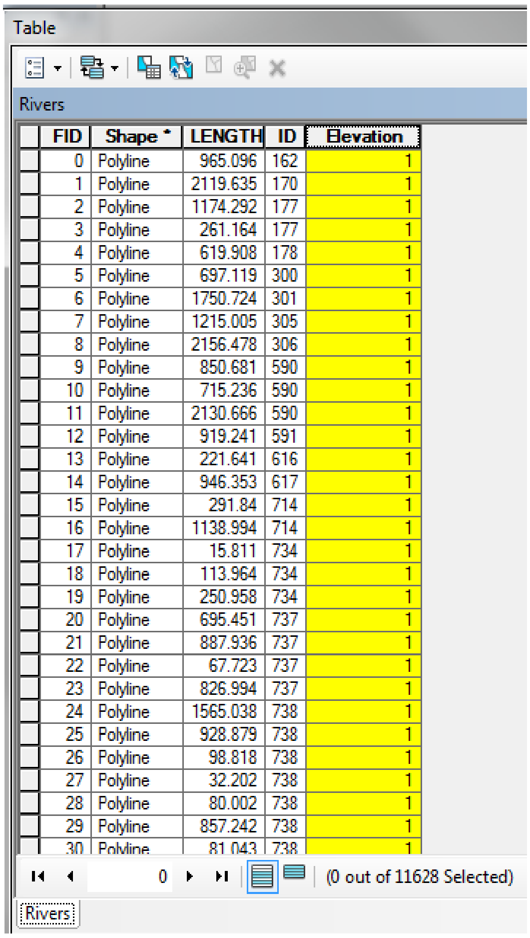


Figure 60. Using Field Calculator to set new values – App. 1 (1)



FID	Shape *	LENGTH	ID	Elevation
0	Polyline	965.096	162	1
1	Polyline	2119.635	170	1
2	Polyline	1174.292	177	1
3	Polyline	261.164	177	1
4	Polyline	619.908	178	1
5	Polyline	697.119	300	1
6	Polyline	1750.724	301	1
7	Polyline	1215.005	305	1
8	Polyline	2156.478	306	1
9	Polyline	850.681	590	1
10	Polyline	715.236	590	1
11	Polyline	2130.666	590	1
12	Polyline	919.241	591	1
13	Polyline	221.641	616	1
14	Polyline	946.353	617	1
15	Polyline	291.84	714	1
16	Polyline	1138.994	714	1
17	Polyline	15.811	734	1
18	Polyline	113.964	734	1
19	Polyline	250.958	734	1
20	Polyline	695.451	737	1
21	Polyline	887.936	737	1
22	Polyline	67.723	737	1
23	Polyline	826.994	737	1
24	Polyline	1565.038	738	1
25	Polyline	928.879	738	1
26	Polyline	98.818	738	1
27	Polyline	32.202	738	1
28	Polyline	80.002	738	1
29	Polyline	857.242	738	1
30	Polyline	81.043	738	1

Figure 61. Using Field Calculator to set new values – App. 1 (2)

- Use ‘Polyline to Raster’ tool from ArcMap toolbox to convert river shapefile to a grid (Figure 62).

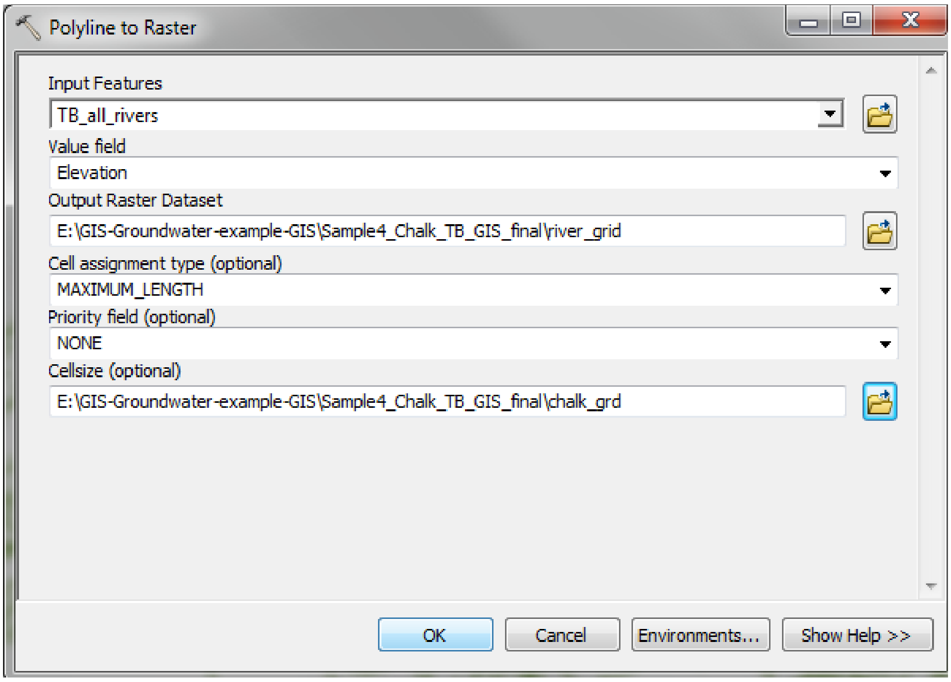


Figure 62. Using ‘Polyline to Raster’ tool from ArcMap toolbox – App. 1

- Select the field holding elevation data and the cellsize that matches the cellsize of the aquifer grid (Figure 62). From ‘Input Feature’ drop-down menu select ‘TB_all_rivers’, from ‘Value field’ drop-down menu select ‘Elevation’ and from ‘Cellsize’ drop-down menu select ‘chalk_grd’. Click on folder icon next to ‘Output Raster Dataset', specify the name of the raster layer and save it in the project folder.

- Convert river grid to ASCII file using ‘Raster to ASCII’ tool from ArcMap toolbox (Figure 63).

- Convert DEM raster to ASCII file using ‘Raster to ASCII’ tool from ArcMap toolbox (Figure 64).

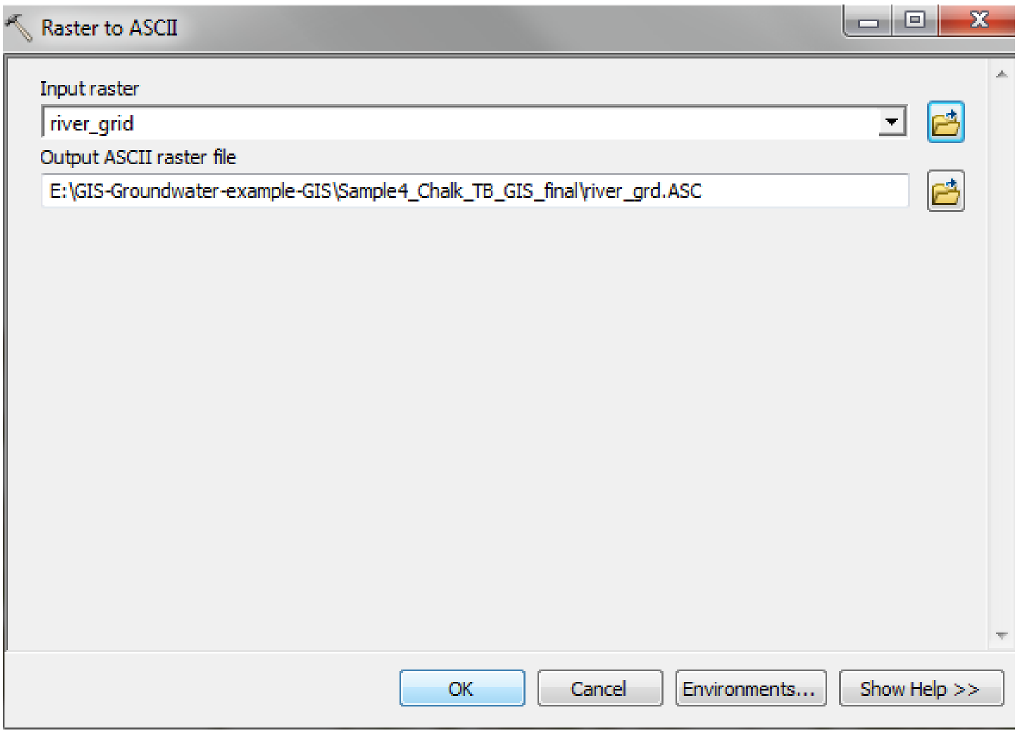


Figure 63. Using ‘Raster to ASCII’ tool from ArcMap toolbox – App. 1 (1)

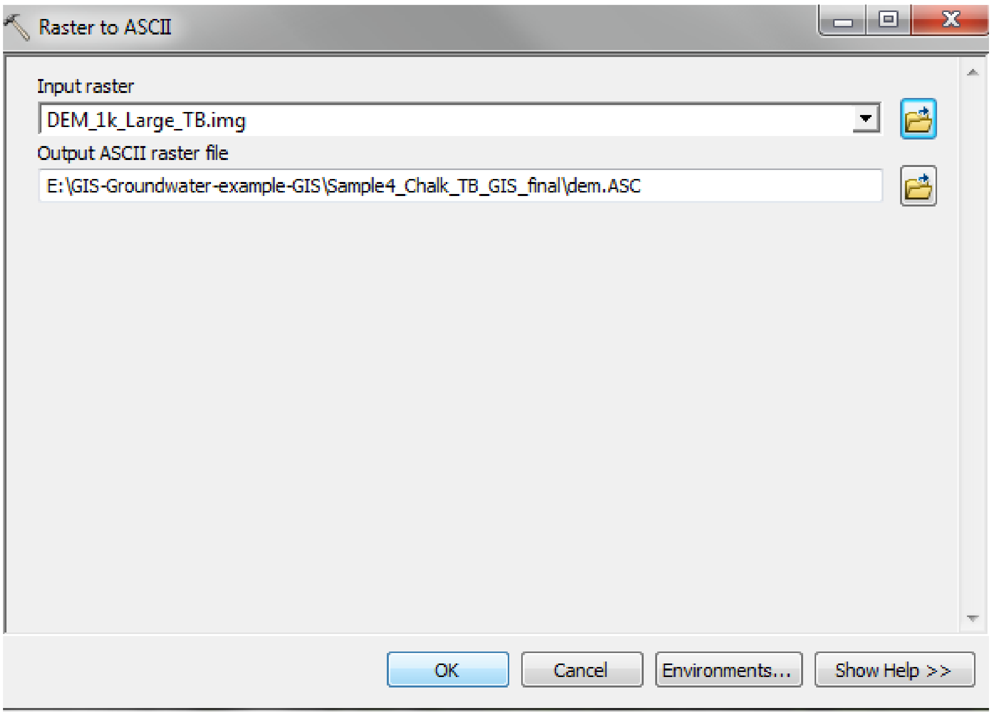


Figure 64. Using 'Raster to ASCII' tool from ArcMap toolbox – App. 1 (2)

Once the river grid and DEM ASCII files are created they can be processed in SAGA to extract elevations from DEM.

- Open SAGA and load river and DEM data by clicking on 'Modules' and selecting 'Import/Export – Grids' and 'Import ESRI Arc/Info Grid' (Figure 65, 66, 67, 68 and 69).

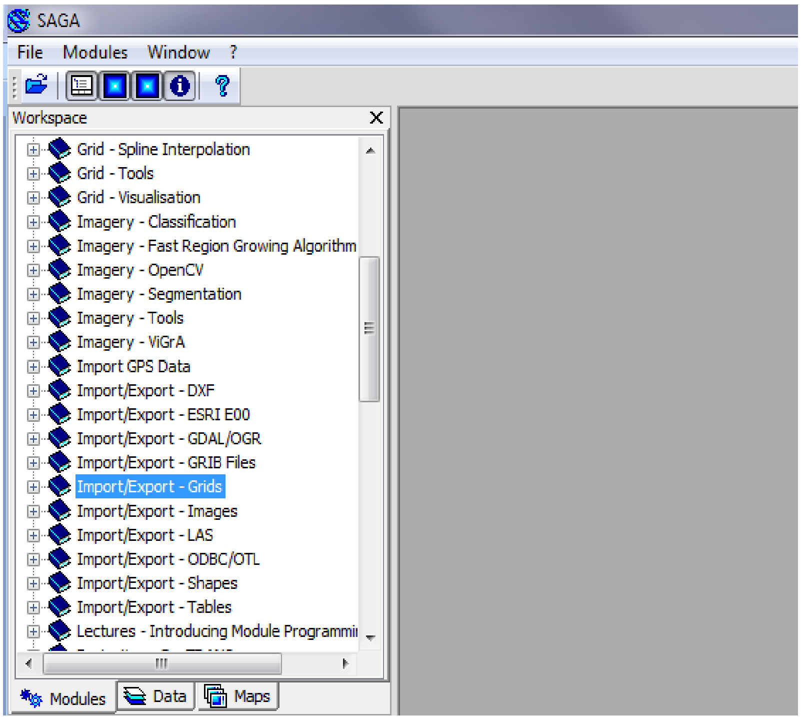


Figure 65. Loading grids to SAGA – App. 1 (1)

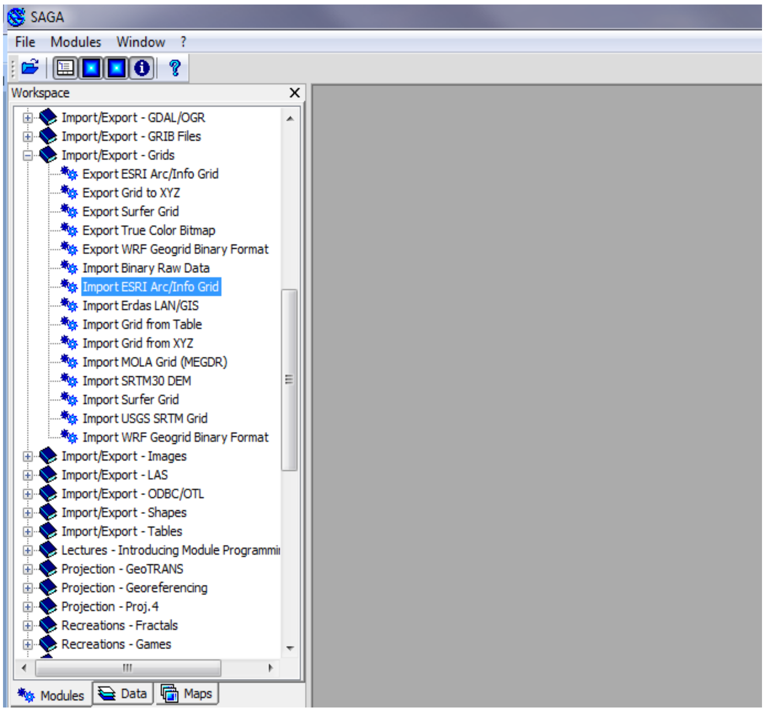


Figure 66. Loading ESRI Arc/Info grid to SAGA – App. 1 (2)

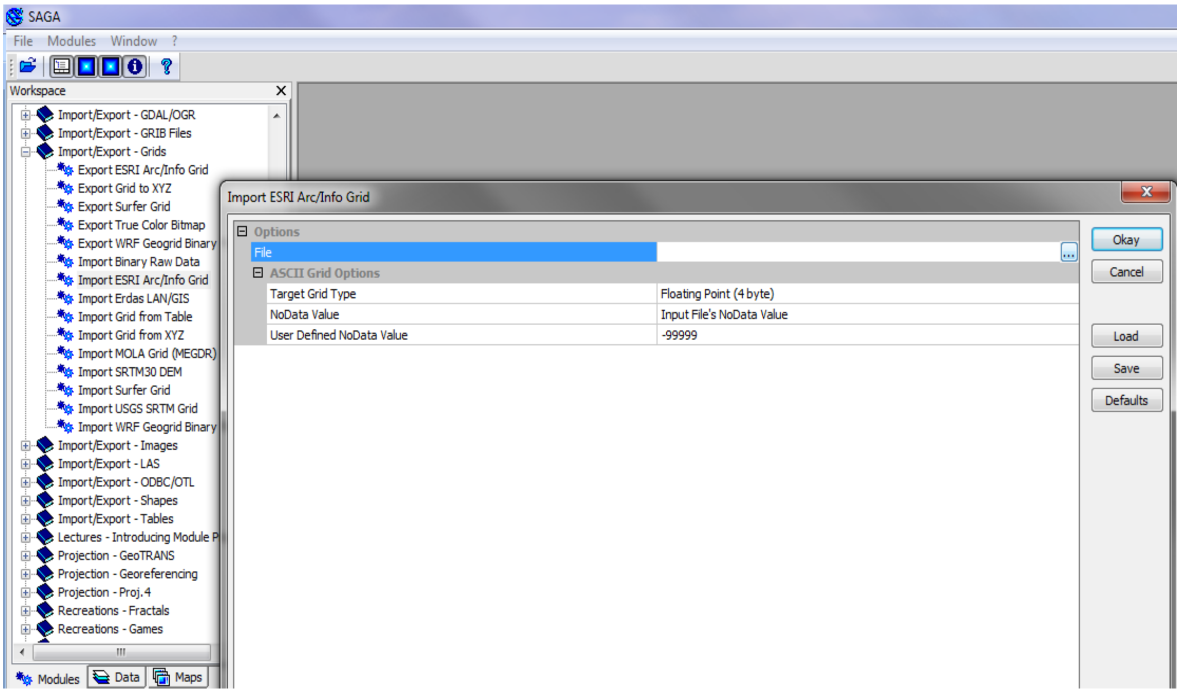


Figure 67. Loading ESRI Arc/Info grid to SAGA – App. 1 (3)

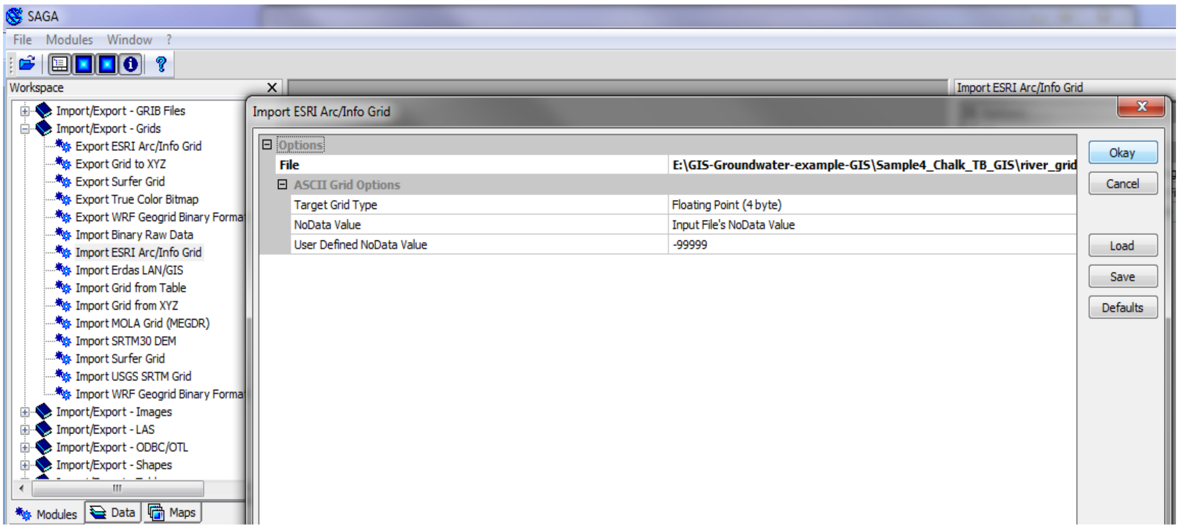


Figure 68. Loading river grid to SAGA – App. 1 (4)

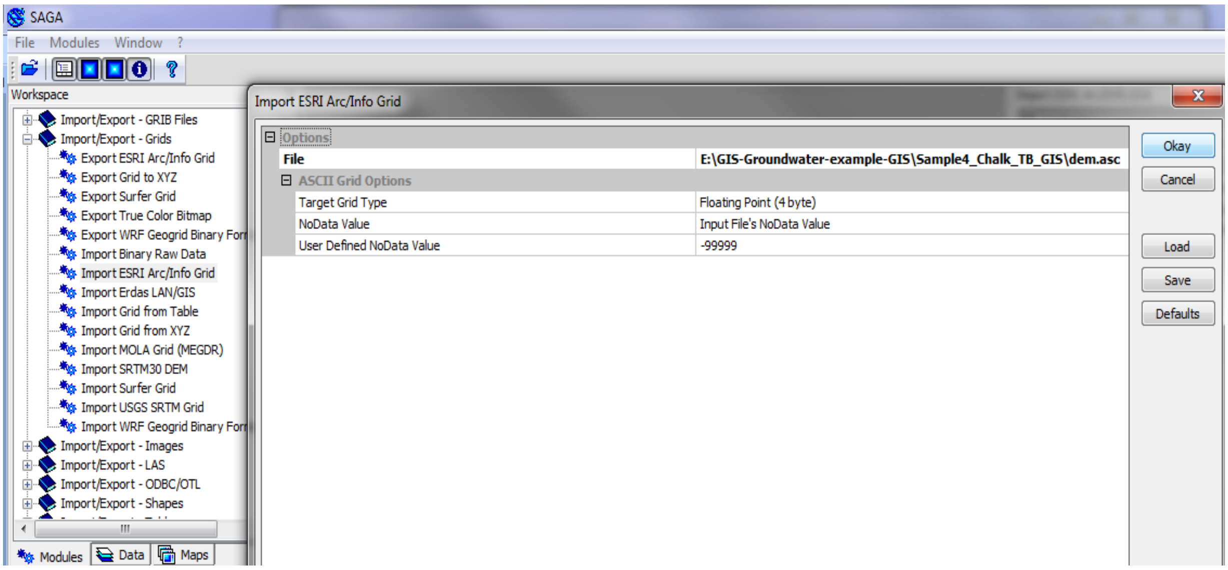


Figure 69. Loading DEM to SAGA – App. 1 (5)

The loaded grids are now in the 'Data' section of the SAGA interface. Note that they are in two different grid systems (Figure 70).

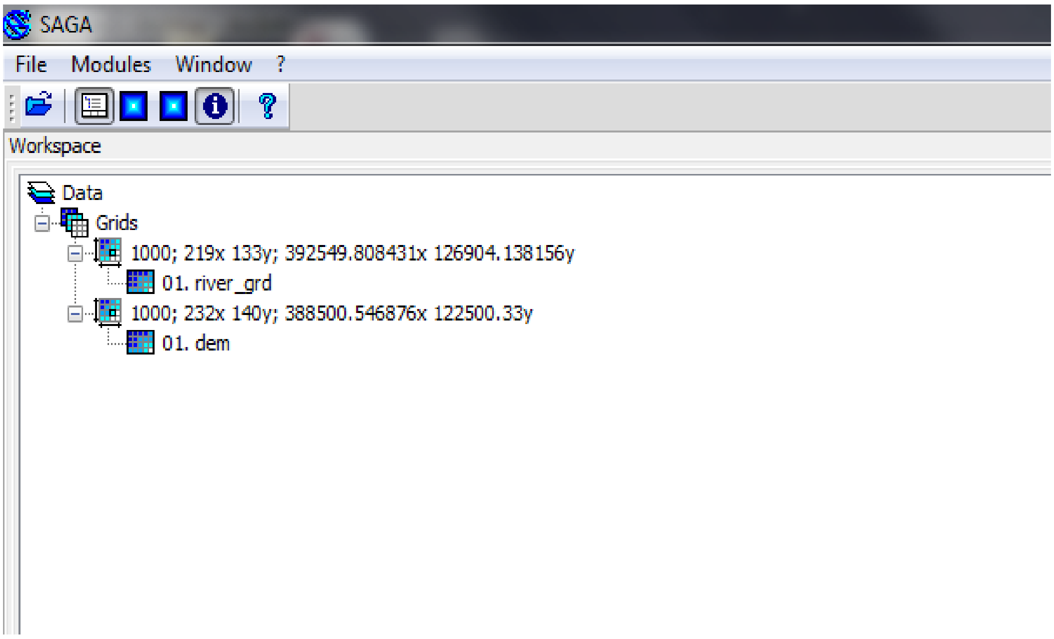


Figure 70. Comparing grid systems of the grids in SAGA – App. 1 (1)

Before producing the river grid with elevations extracted from DEM, the grid systems of both layers need to be changed to match the grid system of the aquifer (the cell size and the extents need to be the same).

- Load the aquifer grid asc file into SAGA (first convert the aquifer grid raster layer to asc file using ArcMap 'Raster to ASCII' tool) (Figure 71).

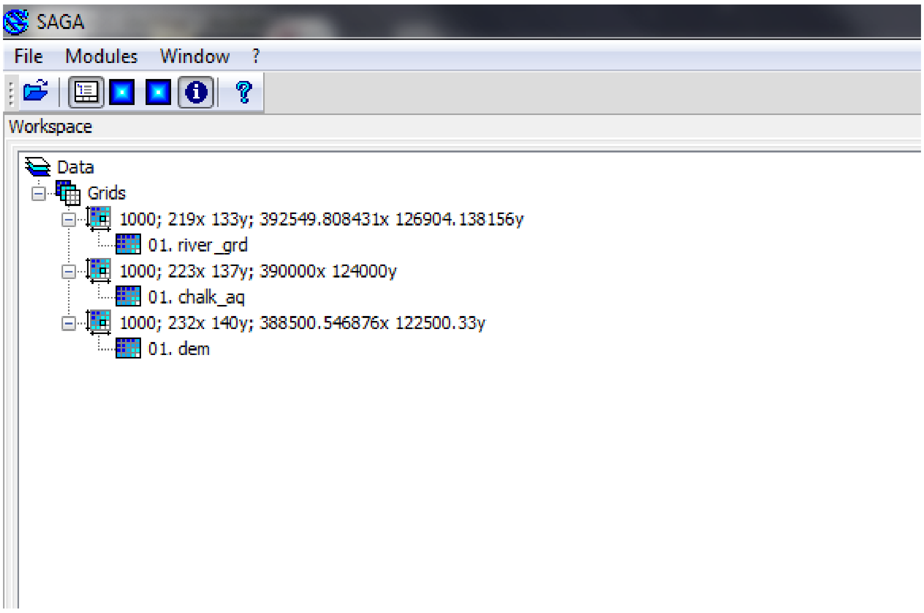


Figure 71. Comparing grid systems of the ASCII files in SAGA – App. 1 (2)

- To change the grid systems of river and dem layers go to 'Modules->Grid-Tools->Resampling' (Figure 72 and 73).

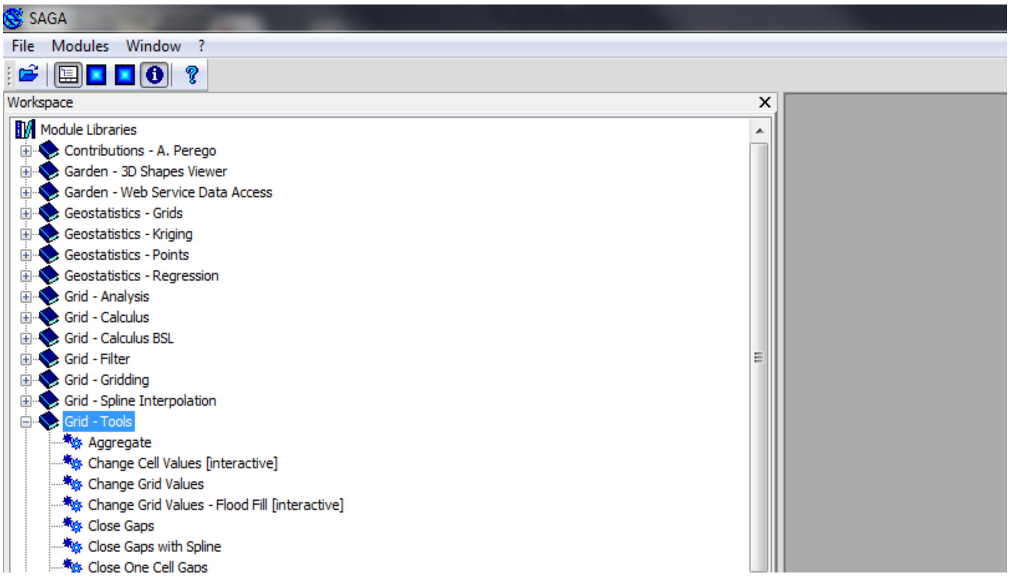


Figure 72. Accessing 'Resampling' tool from SAGA toolbox – App. 1 (1)

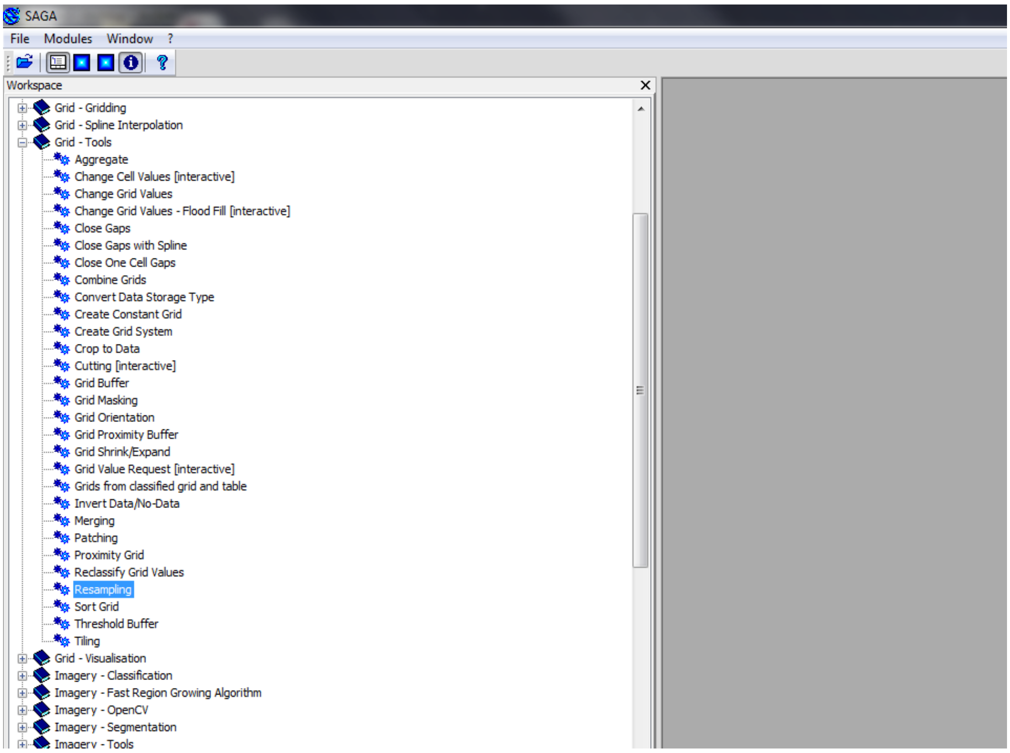


Figure 73. Accessing 'Resampling' tool from SAGA toolbox – App. 1 (2)

- Select the grid system of the river layer (1000, 219x 133y...) (Figure 74).

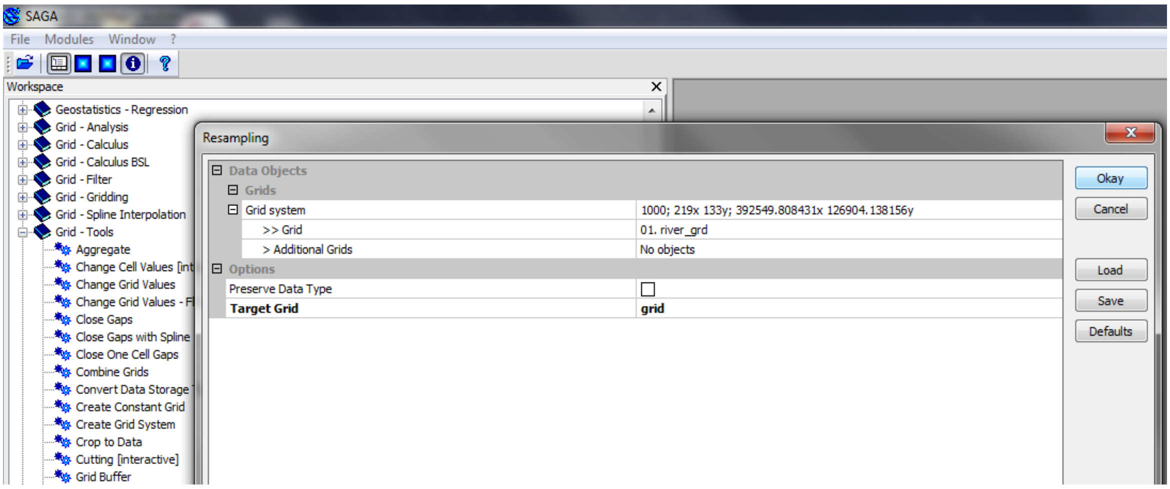


Figure 74. Selecting river grid system in the 'Resampling' tool – App. 1

- In the second window of the resampling tool select the aquifer grid system (1000, 223x 137y...) (Figure 75).

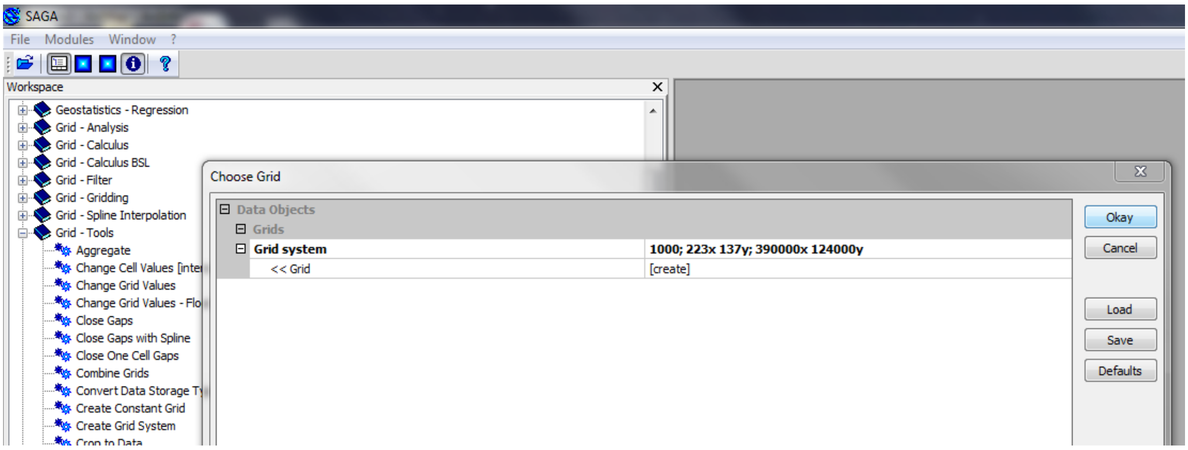


Figure 75. Selecting aquifer grid system in the 'Resampling' tool – App. 1

- In the third window select Nearest Neighbor interpolation method (Figure 76).

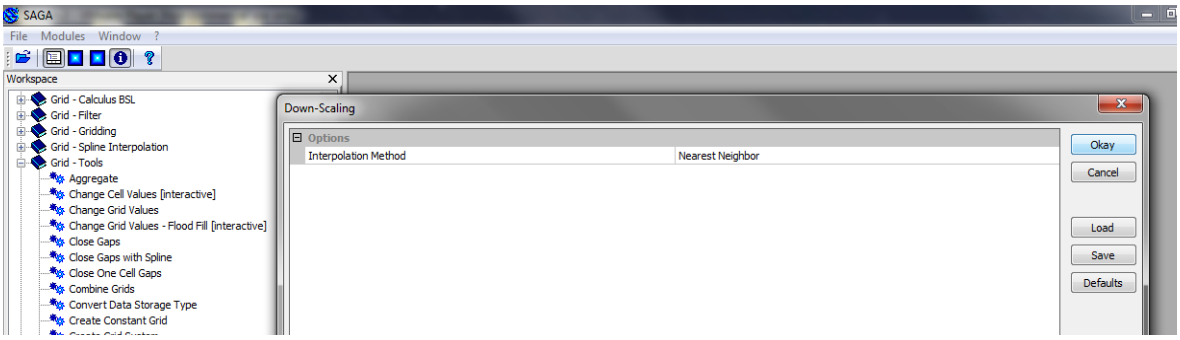


Figure 76. Selecting interpolation method in the 'Resampling' tool – App. 1

Note that the river grid system changed and is now the same as the aquifer grid system (Figure 77).

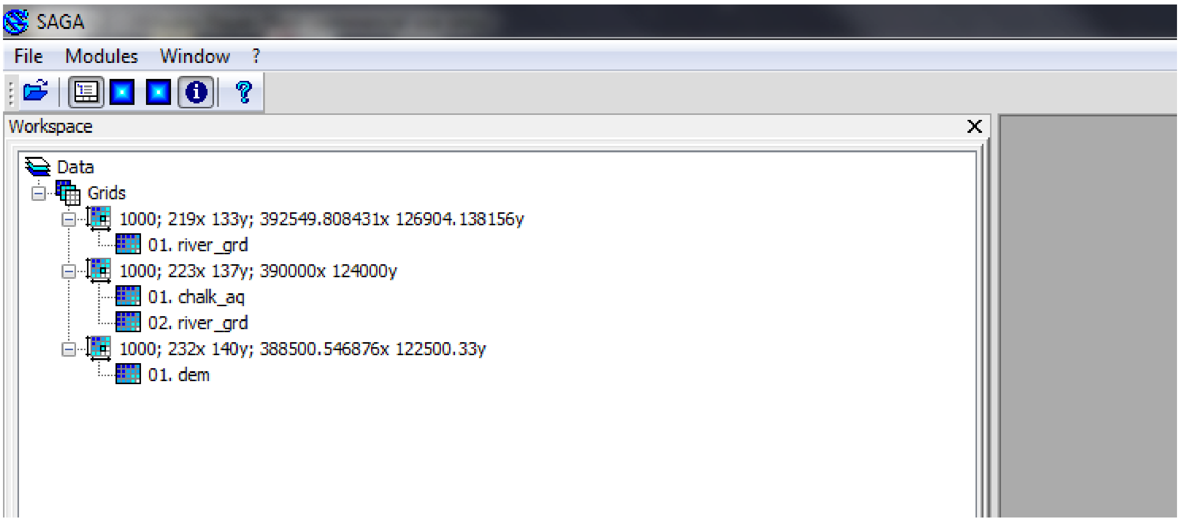


Figure 77. Comparing grid systems of the ASCII files in SAGA – App. 1 (3)

- Repeat the steps described above to change the grid systems of the DEM layer (Figure 78).

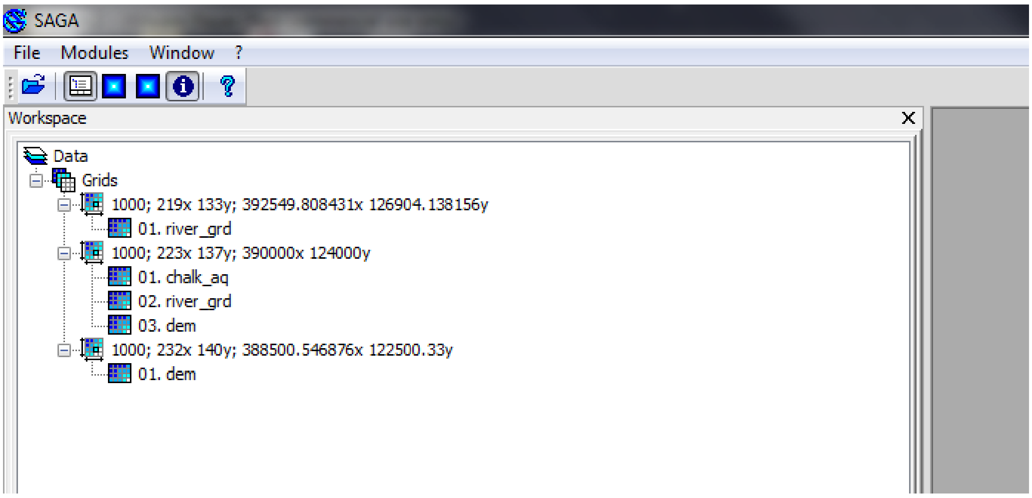


Figure 78. Comparing grid systems of the ASCII files in SAGA – App. 1 (4)

- Once the grid systems of the three layers (aquifer, chalk and dem) are the same, the river elevations can be extracted from DEM by going to ‘Modules->Grid-Calculus->Grid- Calculator’ (Figure 79).

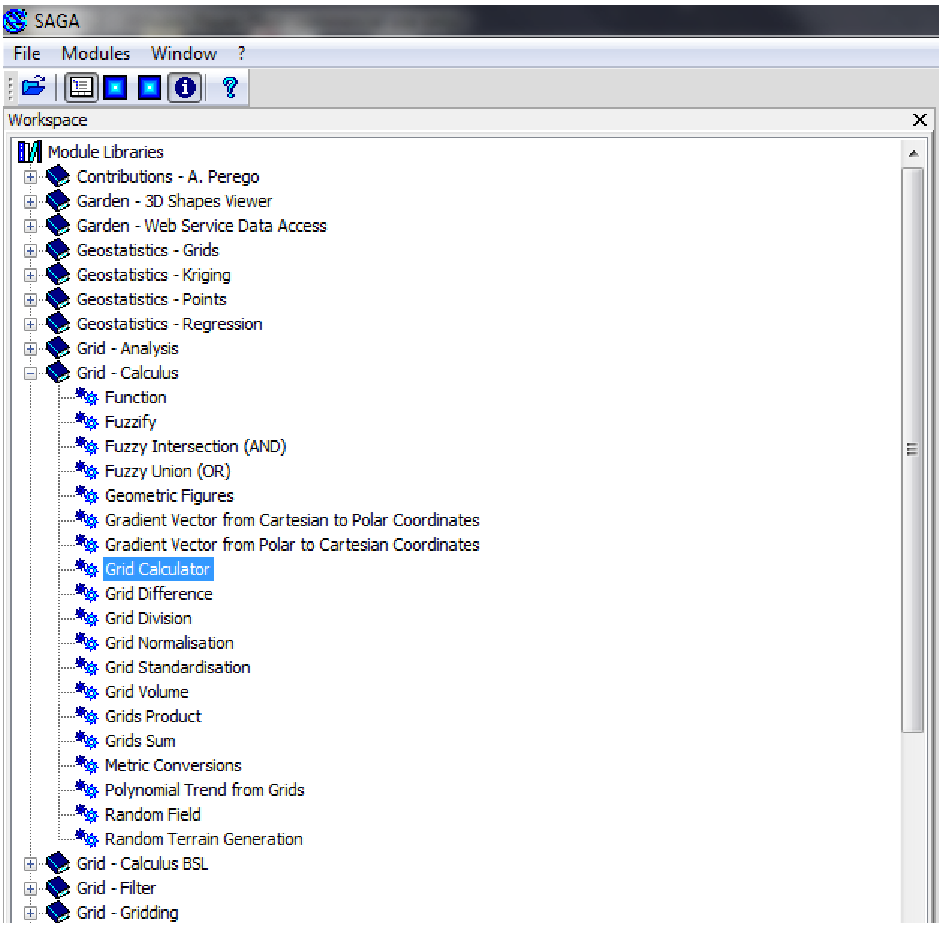


Figure 79. Accessing ‘Grid Calculator’ from SAGA toolbox – App. 1

- In ‘Grid Calculator’ select the adopted grid system from ‘Grid system’ drop-down menu (Figure 80).

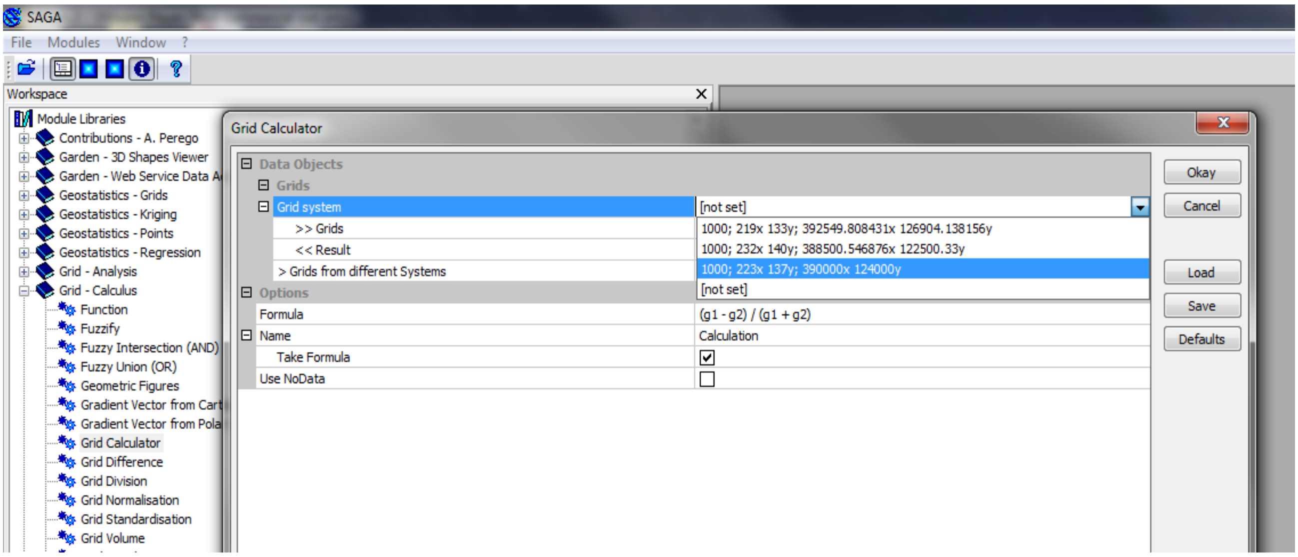


Figure 80. Selecting grid system in the ‘Grid Calculator’ – App. 1

- Select both grids (rivers and DEM) from ‘Grids’ drop-down menu (Figure 81).

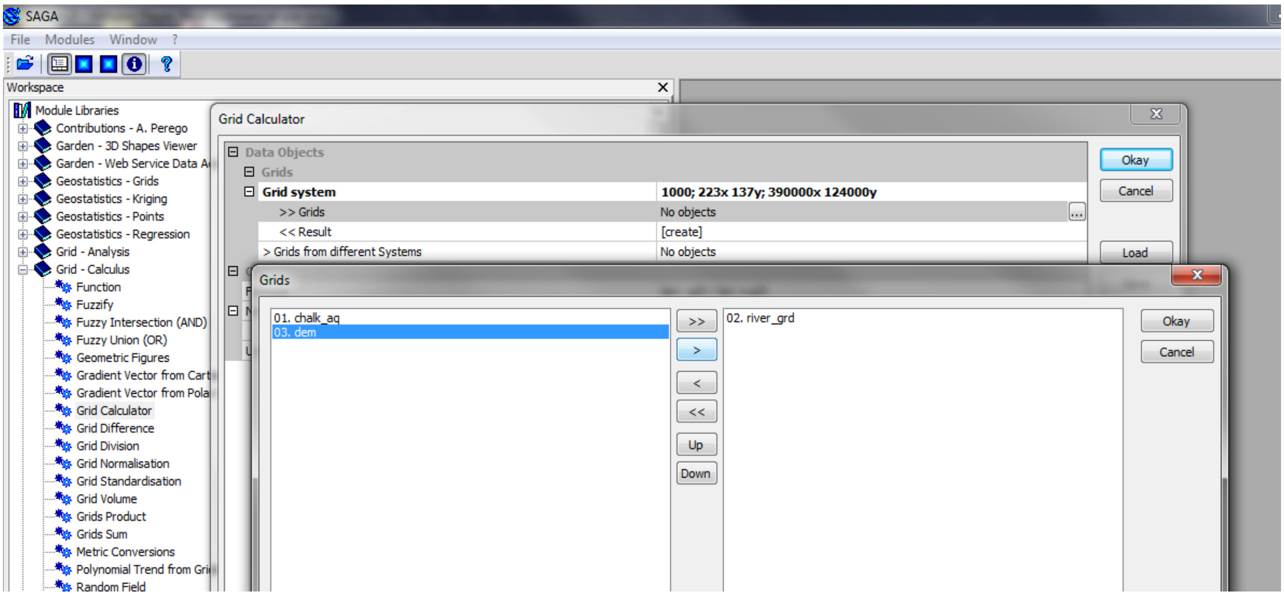


Figure 81. Selecting river and dem grids in the 'Grid Calculator' – App. 1

- In the 'Formula' cell enter 'a*b' (Figure 82).

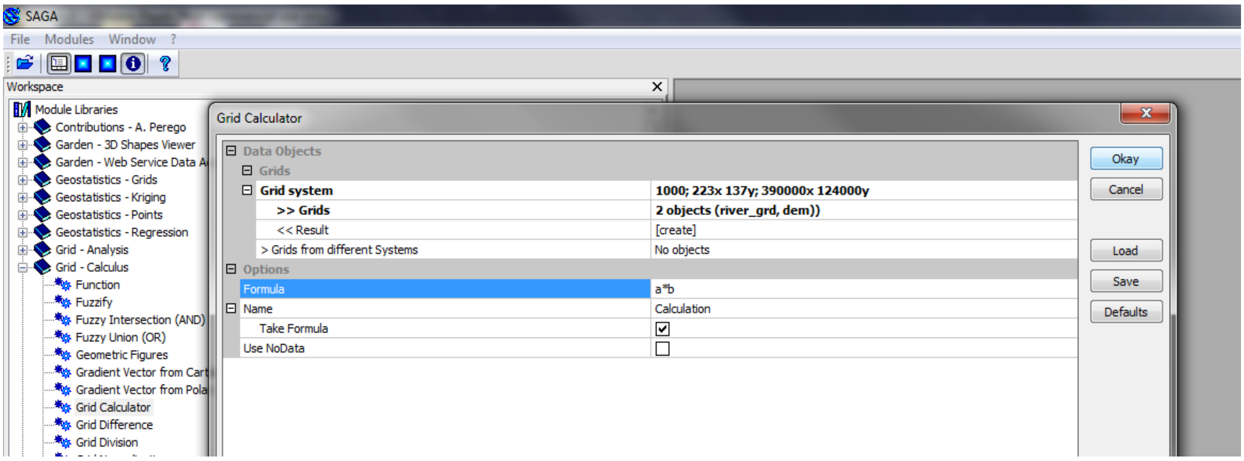


Figure 82. Entering formula in the 'Grid Calculator' – App. 1

Note that a new raster layer called 'Calculation [a*b]' was created in the 'Data' section of the SAGA interface (Figure 83).

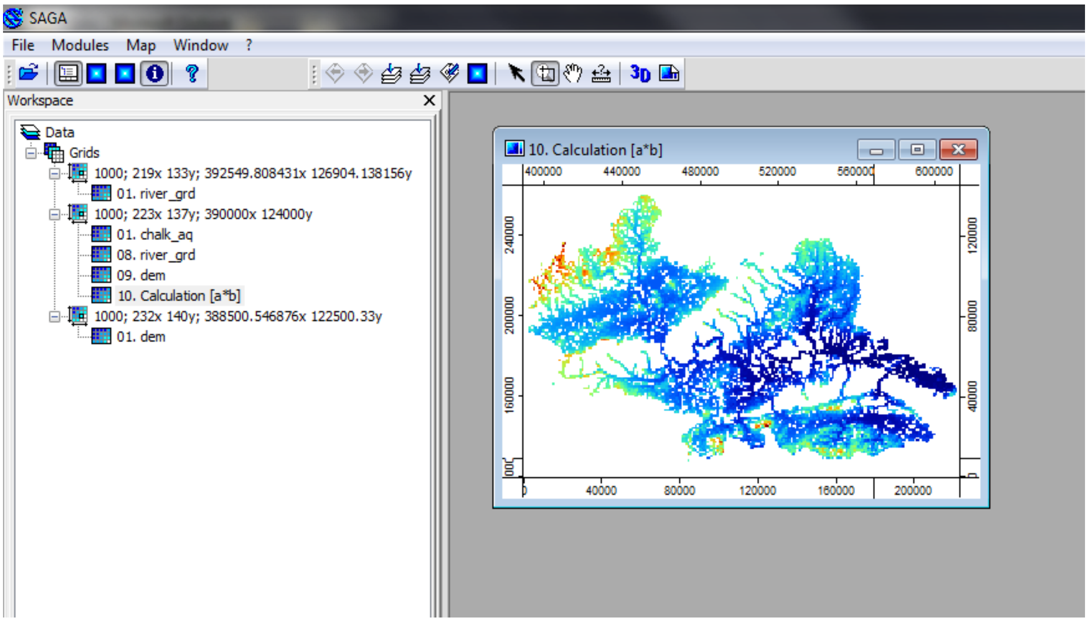


Figure 83. Viewing the newly created river network layer – App. 1

- To export the newly created layer to ArcMap go to 'Modules->Import/Export – Grids->Export ESRI Arc/Info Grid' (Figure 84).

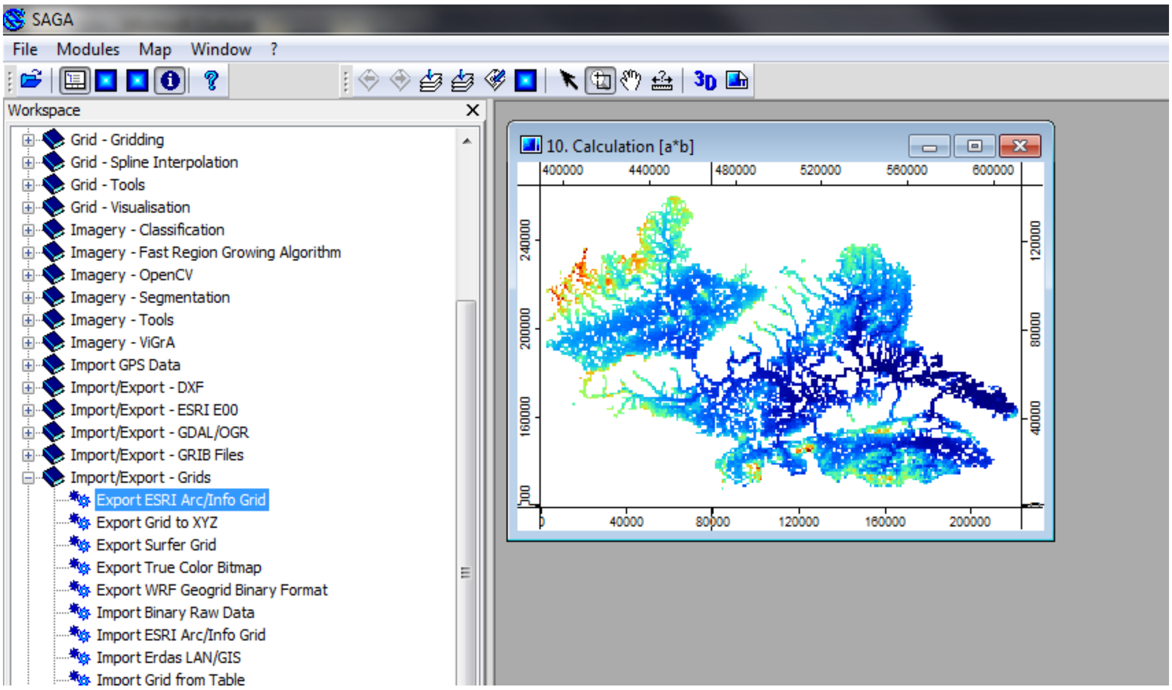


Figure 84. Exporting layers from SAGA – App. 1

- Select grid system from the drop-down menu (Figure 85).

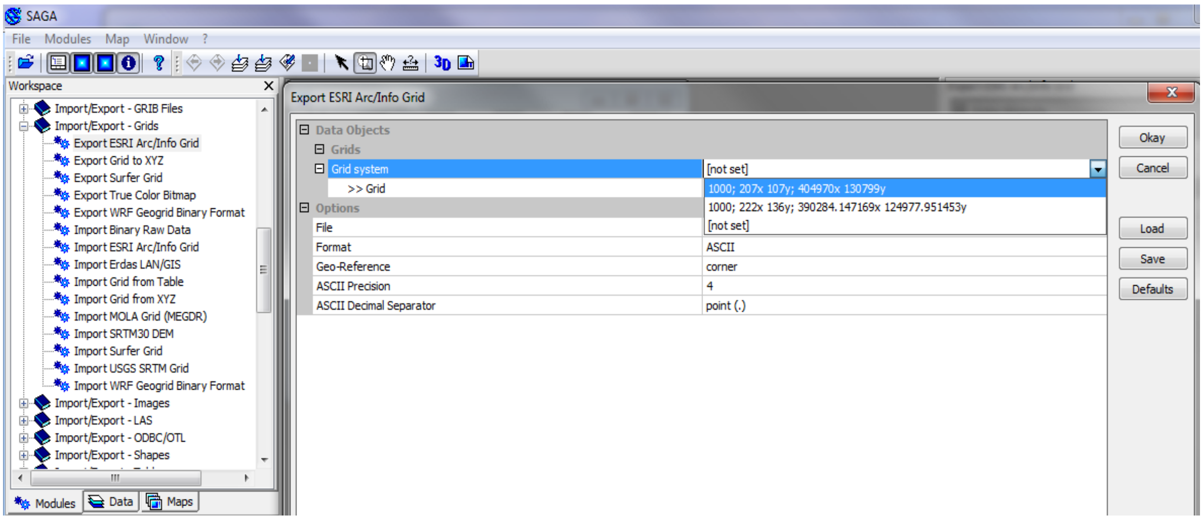


Figure 85. Exporting layers from SAGA (selecting a grid system) – App. 1

- Under ‘Grid’ select ‘Calculation [a*b]’ (Figure 86).

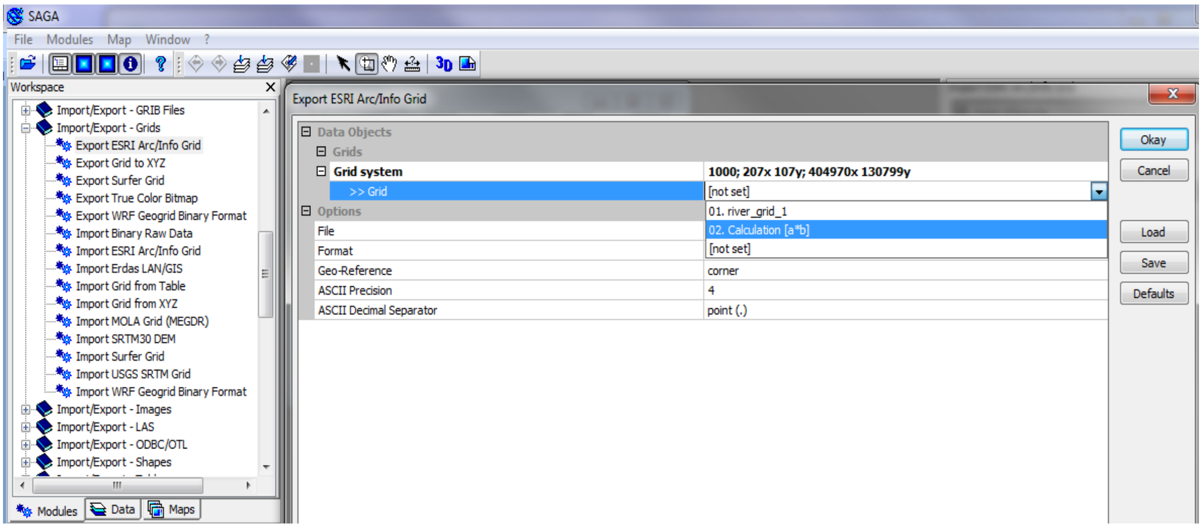


Figure 86. Exporting layers from SAGA (selecting a layer) – App. 1

- Select ASCII file format (Figure 87).

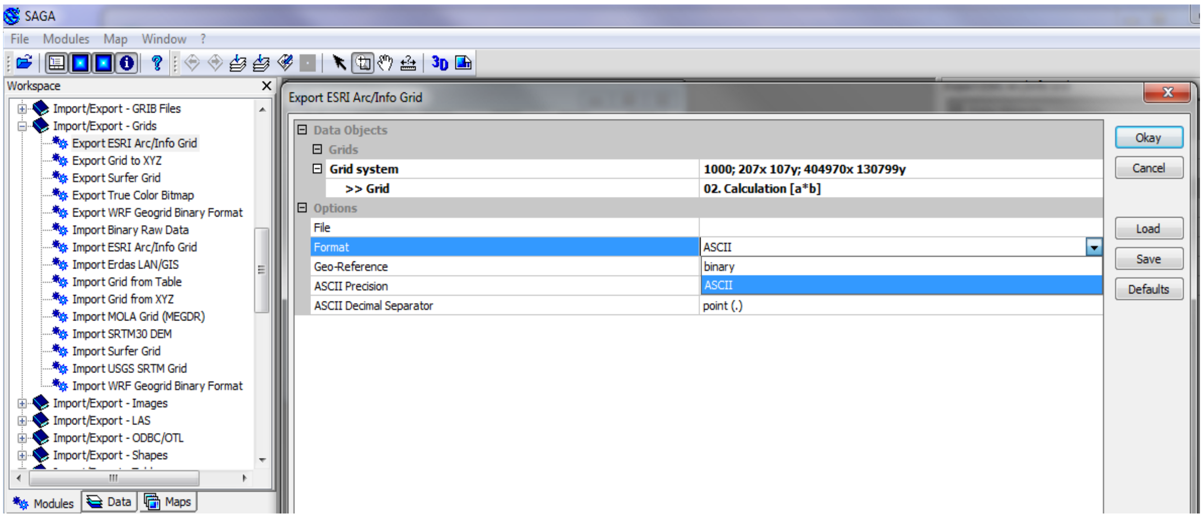


Figure 87. Exporting layers from SAGA (selecting a file format) – App. 1

- Save the file in the project folder (Figure 88 and 89).

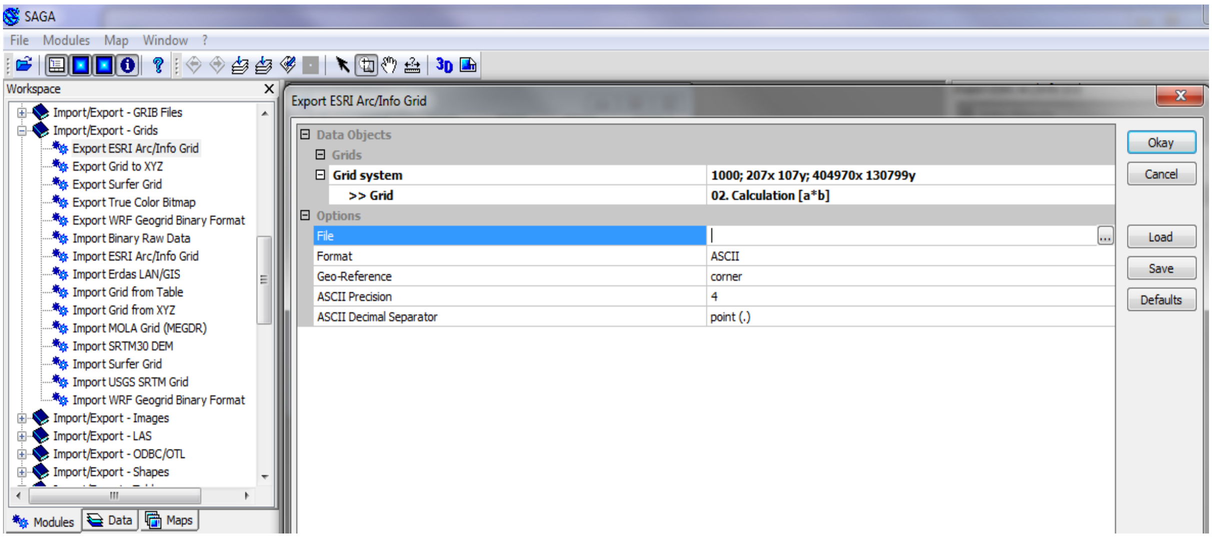


Figure 88. Exporting layers from SAGA (saving a file) – App. 1 (1)

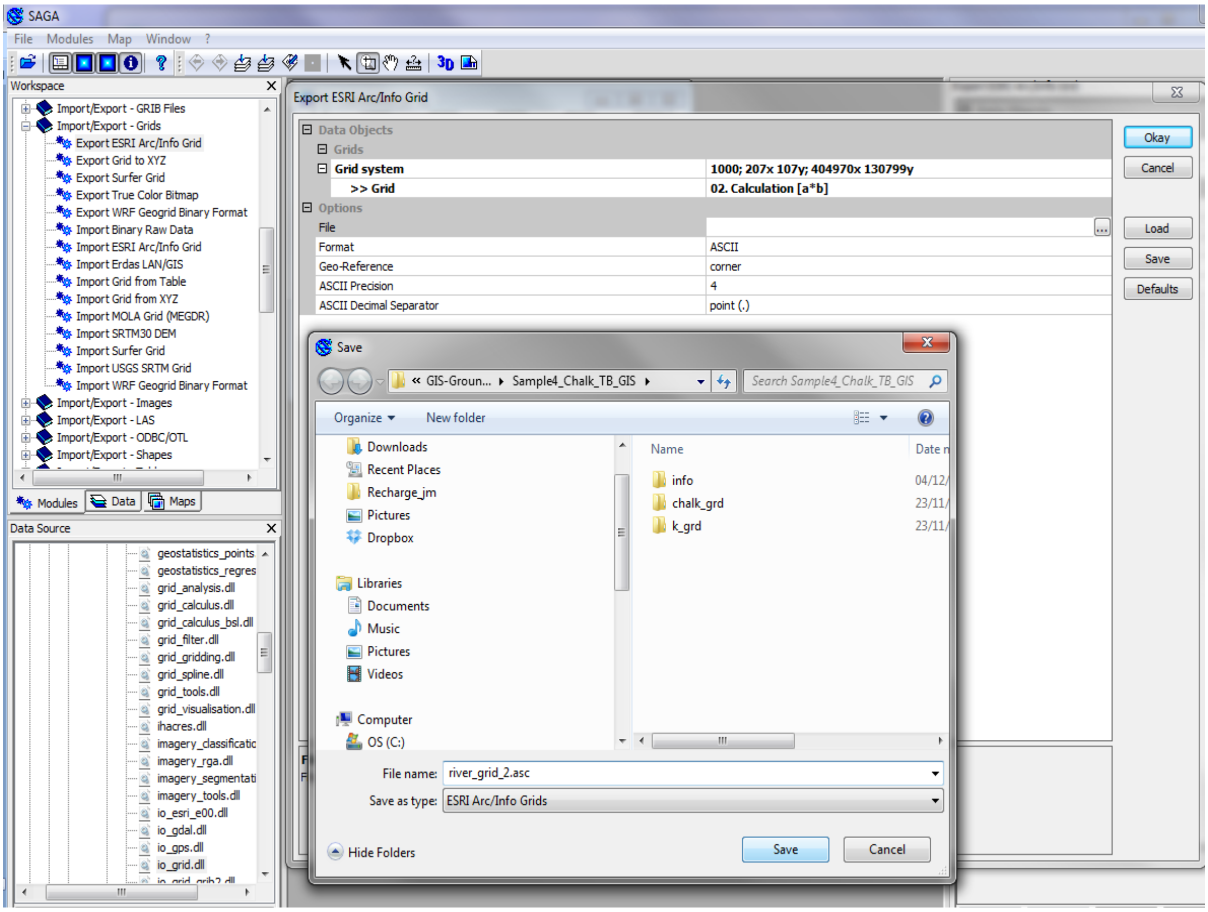


Figure 89. Exporting layers from SAGA (saving a file) – App. 1 (2)

- In ArcMap use 'ASCII to Raster' tool to convert the newly created asc file to river raster. Remember to change the 'Output data type' to float (Figure 90).

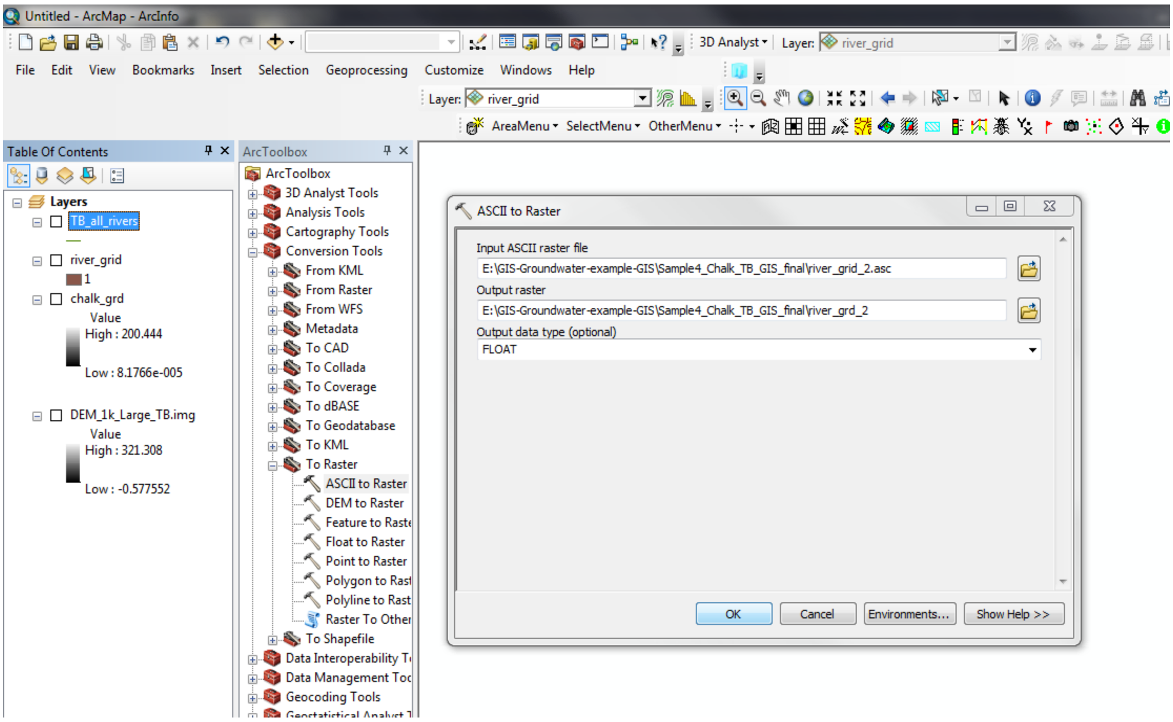


Figure 90. Converting a river network ASCII file to a raster – App. 1

6 Glossary

Aquifer An underground geological formation, such as rock and sand and gravel, is sufficiently porous and permeable to yield a significant quantity of water to a borehole, well or spring. The aquifer may be unconfined beneath a standing water table, or confined by an impermeable or weakly permeable horizon.

Confined Aquifer An aquifer whose upper and lower boundaries are low permeability layers which confine the groundwater under greater than atmospheric pressure. These aquifers are sometimes called artesian aquifers, the term first being used where the pressure surface was above ground level resulting in overflow under artesian pressure.

Head The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a ground water system. For a well, the hydraulic head is equal to the distance between the water level in the well and the datum plane.

Hydraulic conductivity For an isotropic porous medium and homogenous fluid, the volume of water that moves in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Commonly, though imprecisely taken to be synonymous with permeability.

Hydraulic gradient Slope of the water table or potentiometric surface. The change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Recharge The quantity of water per unit of time that is added to a groundwater reservoir from spatially distributed sources such as the direct infiltration of rainfall or leakage from an adjacent formation or from a watercourse crossing the aquifer.

Transmissivity A measure of the capability of the entire thickness of an aquifer to transmit water. It is the integral of the hydraulic conductivity of an aquifer over its saturated thickness.

Unconfined Aquifer A partially saturated aquifer which contains a water table which is free to fluctuate vertically under atmospheric pressure in response to discharge or recharge.

Water Table The top surface of an unconfined aquifer at which the pressure is equal to that of the atmosphere. The static water level in a well in an unconfined aquifer.

Well A bored, drilled or driven shaft, or a dug hole whose depth is greater than the largest surface dimension and whose purpose is to reach underground water supplies to inject, extract or monitor water.

7 References

Wang, L., Mansour, M., Hughes A., 2010. Developing a GIS based finite difference groundwater flow model GISGroundwater. Internal Report IR/10/070, British Geological Survey, Keyworth, Nottingham, UK.