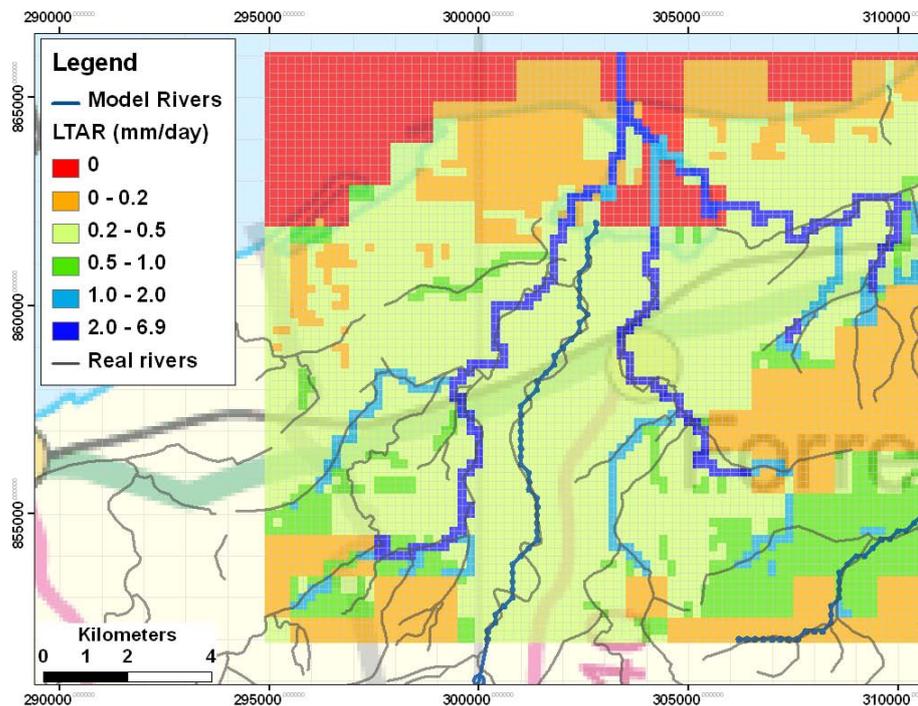




Regional and catchment scale groundwater models of the superficial deposits underlying the Moray Ness area: Initial results

Geology and Landscape: Scotland Programme
Internal Report OR/11/024



Regional and catchment scale groundwater models of the superficial deposits underlying the Moray Ness area: Initial results

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Long-term average recharge for the catchment model

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T Vounaki, A Hughes, A MacDonald

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Contents

Acknowledgements	i
Contents	ii
Summary	iv
1 Introduction	5
2 Recharge Model	5
2.1 Introduction	5
2.2 Model setup	5
3 Regional Groundwater Model	9
3.1 Model construction	9
3.2 Initial model results	11
4 Refined Groundwater Model	14
4.1 Model construction	14
4.2 Model results	14
5 Summary and recommendations	16
References	18
Appendix 1 Linking GSI3D to ZOOMQ3D	19
Appendix 2 Refined groundwater model: adding in k distribution	22

FIGURES

Figure 1 Recharge Model boundary	6
Figure 2 Run-off coefficients	7
Figure 3 Long-term average recharge for 1975 to 1995	8
Figure 4 Thickness of the superficial deposits	10
Figure 5 Thickness of the sedimentary deposits	10
Figure 6 Thickness of the crystalline and igneous rocks	11
Figure 7 Groundwater levels in the superficial deposits	12
Figure 8 Groundwater levels in the sedimentary deposits	12
Figure 9 Groundwater levels in the crystalline and igneous rocks	13
Figure 10 Transmissivity of the superficial deposits	13
Figure 11 long-term average recharge used in the refined model.....	14
Figure 12 Steady-state groundwater heads in layer 1.	15
Figure 13 Steady-state groundwater heads in layer 2.	15

Figure 14 Steady-state groundwater heads in layer 3. 16

Figure 15 The export ZOOM function window in GSI3D..... 19

Figure 16 Extract of GSI3D output file with extension “.G2ZE” containing XY coordinates of ZOOM grid, followed by ground elevation, layer number and layer base elevation. 20

TABLES

Table 1 Geological units and corresponding run-off values 7

Summary

This report describes the groundwater modelling work that was carried out as part of a BGS research programme on Quaternary Mapping and Modelling in the north of Scotland. The report describes the recharge model, the regional groundwater model and the catchment groundwater model. The work involved using GSI3D models at two scales (regional scale along the coastal strip of the Moray Firth and catchment scale where the River Findhorn flows over superficial deposits) as the basis for the geometry of the model layering and hydraulic conductivity distribution. This is novel and shows that geological models can be used to parameterise groundwater flow models. The project produced a preliminary model which showed potential and requires improvements to the steady-state groundwater flow model and the introduction of time variant behaviour to complete. Any future development of the model should be informed by a particular question or issue. This should be developed in conjunction with the appropriate stakeholders.

1 Introduction

BGS has undertaken a number of hydrogeological investigations and groundwater modelling in the Moray-Ness area (e.g. MacDonald et al., 2008). The work, predominantly funded by The Moray Council has examined groundwater flooding. This work has raised a number of issues which could not be examined during the lifetime of the project, such as geological understanding, bedrock topography and boundary conditions. As part of the Quaternary Mapping and Modelling project, work has been undertaken to examine those shortcomings. This report describes the use of GSI3D in constraining the geological understanding of the study area.

The ZOOM family of models were used to undertake this work. Using the recharge model, ZOODRM (Mansour and Hughes, 2004) and the groundwater flow model, ZOOMQ3D (Jackson and Spink, 2004), a recharge model and two groundwater flow models were built. The groundwater models were constructed at two different scales: Regional model covering the north coast and a smaller, refined model covering the River Findhorn and its tributaries. The geometry for both these models has been provided from the GSI3D model (Kessler et al., 2009) at the appropriate scale. This work can be seen as a “test bed” for the ZOOM-GSI3D linkage.

The report describes the development of the recharge model, the construction of the regional groundwater flow model and also the refined groundwater model. Finally recommendations for further work are made.

2 Recharge Model

2.1 INTRODUCTION

The long-term average recharge (LTAR) values are estimated using the distributed recharge model ZOODRM (Mansour and Hughes, 2004), which is part of the ZOOM suite of models. The model applies the soil moisture deficit (SMD) method, which is based on the work of Penman (1948) and Grindley (1967), to calculate the actual evaporation, changes in soil moisture and recharge. The model uses daily rainfall and potential evaporation in combination with land-use type, topography and run-off coefficients from data files and calculates surface run-off and recharge values. The average recharge values calculated over the simulation period are used in combination with the groundwater flow model to produce input for the steady-state simulation.

2.2 MODEL SETUP

A model base grid with 1000 m square cells is used to cover the catchment area and the regional groundwater model. This grid is refined over the area of the Forres groundwater flow model using 200 m square cells.

The extent of the recharge model is normally based on the surface water catchment, which is often not the identical with the groundwater catchment. When the surface catchment goes far beyond the area of interest, such as in this site, the boundaries can be set to be coincident with river gauging stations to provide inflow to the area (Figure 1).

The rainfall data came from a national gridded dataset containing average daily values per 1 km² for the period from 1975 to 1995. The potential evaporation data have been obtained from the Meteorological Office’s 40 km by 40 km MORECS data set for Squares 19, 20, 21, 22, 28, 29, 30 and 31. These data are available on monthly basis and cover the period from 1961 to 2009.

To calculate the overland flow to rivers both run-off coefficient values and aspect directions (north, south, east and west) must be specified at all model nodes. An aspect direction map is produced in ArcGIS environment using the digital terrain model (DTM) map. The run-off value

at a model node is specified according to the surface geology (Table 1). The surface geological units were derived from the 625k DigMap. The northern side of the model going towards the coast has a lower run-off than the southern part of the model, which is mainly covered by till (Figure 2). The model area that is covered by the sea was assigned a 100% run-off coefficient to reduce recharge to zero.

The land use over the catchment area is extracted from LCM2000, national gridded dataset that contains the percentage cover for each of the ten land-use classes per 1 km². The rivers are derived from a simplified river network created for the national recharge model for the UK, based on simplified maps from the Centre of Ecology and Hydrology (NERC, 2003).

The LTAR produced by the recharge model is shown in Figure 3. The LTAR varies from 0 to 5 mm/day, with higher values occurring in the south-west. Some areas in the eastern part of the site appear to have no recharge while adjacent nodes often have elevated recharge. This is thought due to run-off recharging the river valleys.

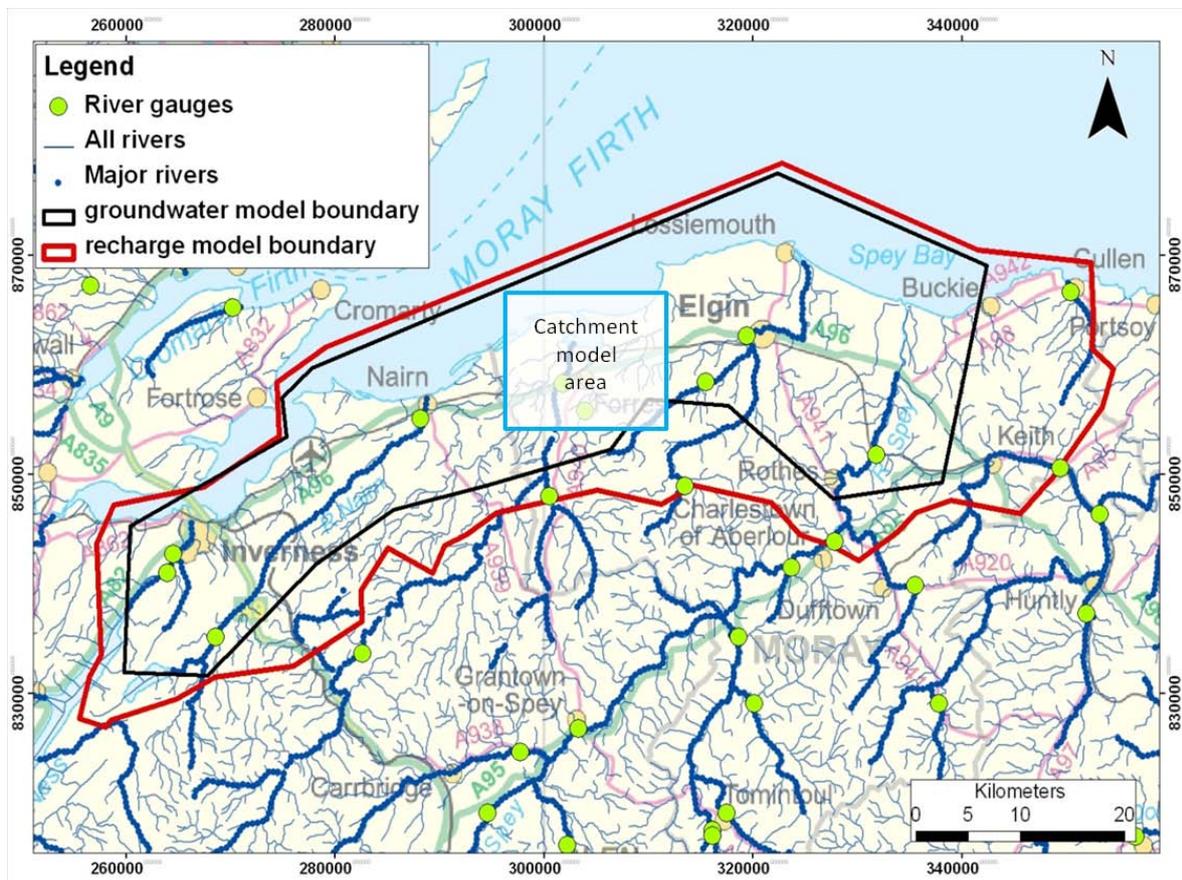


Figure 1 Recharge Model boundary

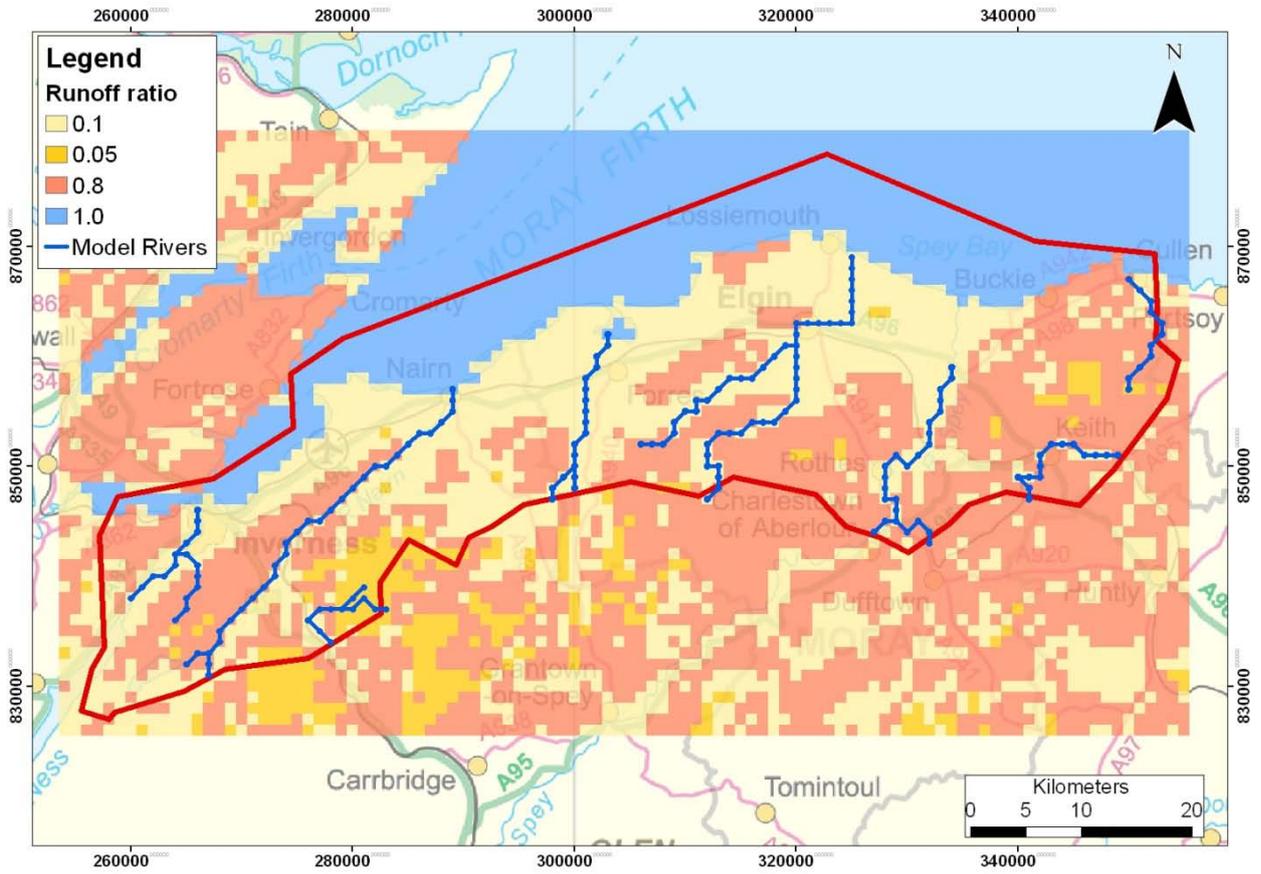


Figure 2 Run-off coefficients

Table 1 Geological units and corresponding run-off values

Geology	Crystal-line & Igneous	Sedimentary	Raised Marine Deposits	Blown Sand	Peat	Till	Unknown	Gravel & Sand	Alluvium	sea
Code	UISD	UORS	RMD	BSA	PEAT	TILL	UNKN	GSG	ALV	NA
Type	bedrock	bedrock	drift	drift	drift	drift	Drift	drift	Drift	sea
Zone id	1	2	3	4	5	6	7	8	9	10
Run-off value	0.1	0.1	0.1	0.1	0.05	0.8	0.1	0.1	0.1	1

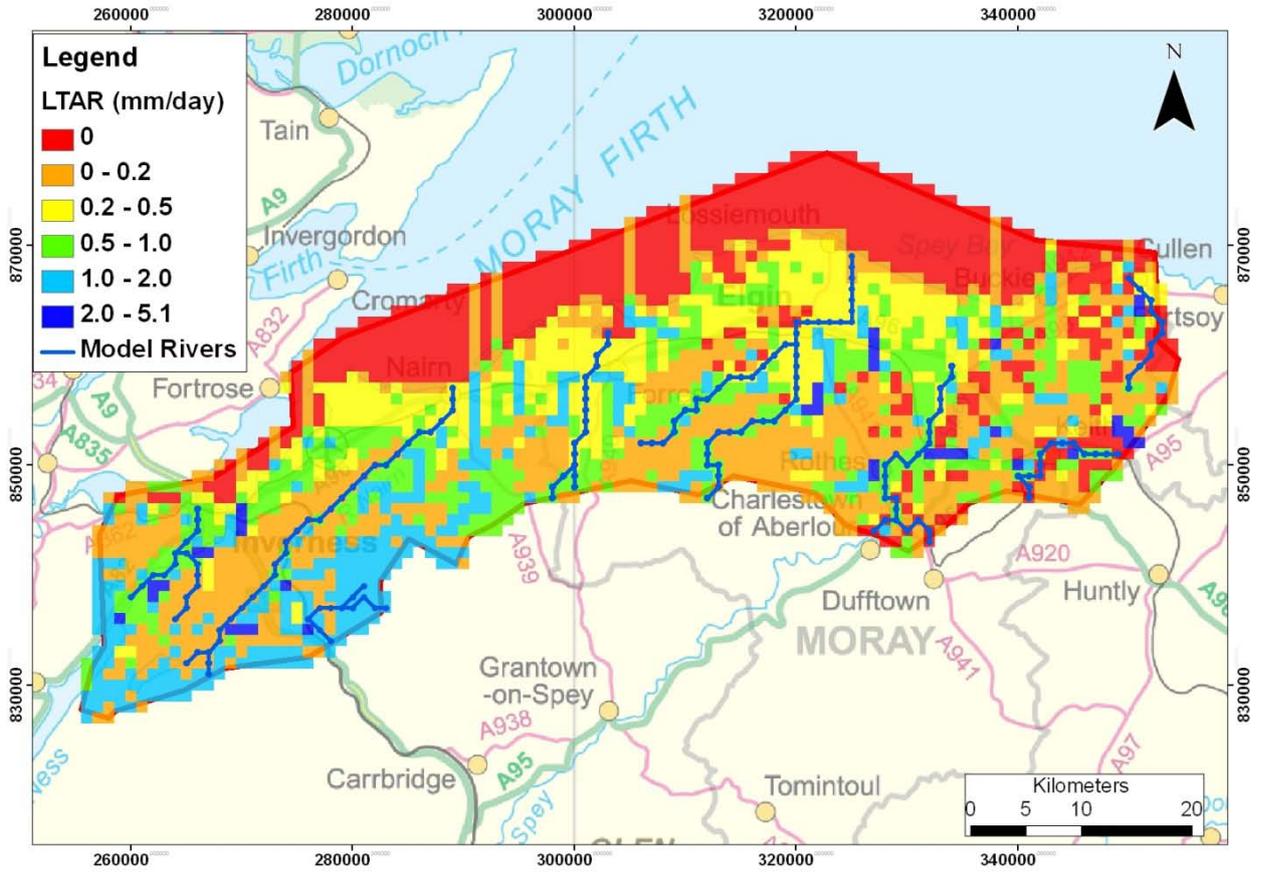


Figure 3 Long-term average recharge for 1975 to 1995

3 Regional Groundwater Model

3.1 MODEL CONSTRUCTION

The ZOOMQ3D groundwater flow model (Jackson and Spink, 2004) has been used to produce a groundwater flow model of the site. The model extends over an area of 1200 km² and matches the dimensions of the GSI3D model. The groundwater flow model has a 1000 m cell size and comprises three layers with a combined saturated thickness varying from 500 to 800 m. The model has three layers derived from the regional GSI3D model. The six geological formations of the GSI3D model were combined into superficial, sedimentary (Old Red Sandstone, Permo-Triassic and Jurassic) and crystalline rocks (igneous intrusions and crystalline rock). Where the layers did not exist at a node, a minimum thickness of 1 m was introduced as the groundwater model requires that each layer is continuous throughout the domain.

The thickness of the superficial deposits increases towards the sea (Figure 4), where it reaches 50 m and in some areas is as high as 120 m. Where in reality there are no superficial deposits, the thickness is 1 m as shown in red. The thickness of the middle layer shows a clear increasing pattern from a minimal 1m along the southern boundary covering one fifth of the model, to 500 m close to the sea (Figure 5). The base of the model is taken directly from the base of the GSI3D model.

The layers were assigned the following horizontal hydraulic conductivity from top to bottom: 10 m/day, 0.5 m/day and 0.0001 m/day based on hydrogeological data from investigations in the Forres area (MacDonald et al. 2008, MacDonald et al. In press). The vertical conductance between the layers was calculated for each node based on the thickness of the layers at that node. For the top layer that is unconfined, the thickness was calculated using the DTM as the top elevation instead of the groundwater levels for simplicity. The vertical hydraulic conductivity in a layer was set to be equal to a third of the horizontal hydraulic conductivity (see for example Freeze and Cherry, 1979).

The rivers included in the groundwater flow model are the same as those in the recharge model. The river stage relative to Ordnance Datum (OD) is taken from a Digital Terrain Model (DTM) of the area, produced by the Centre for Ecology and Hydrology (CEH). No flow was added at the top of the rivers.

With the exception of the boundary nodes to the north that are fixed to 0 m to represent the sea, the south, west and east sides of the groundwater model are assumed to be impermeable.

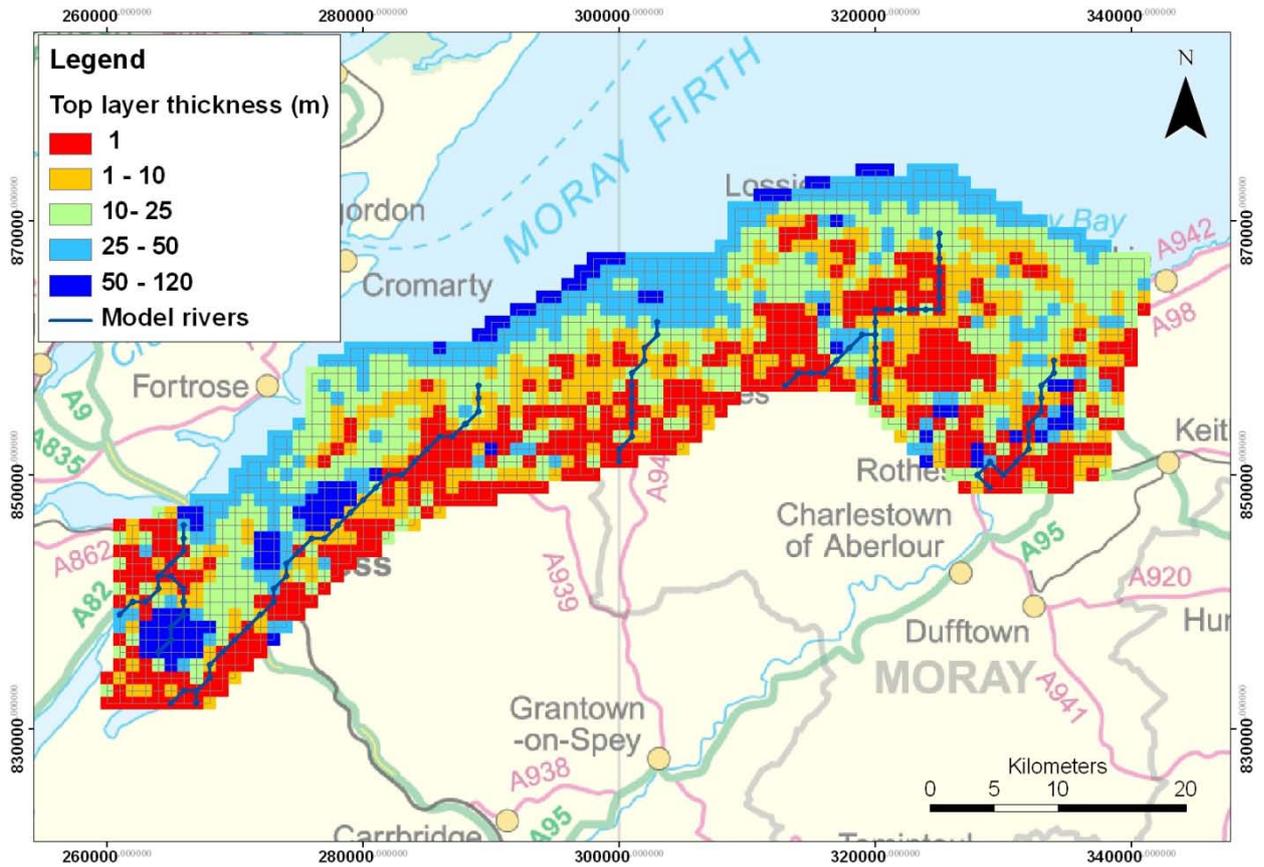


Figure 4 Thickness of the superficial deposits

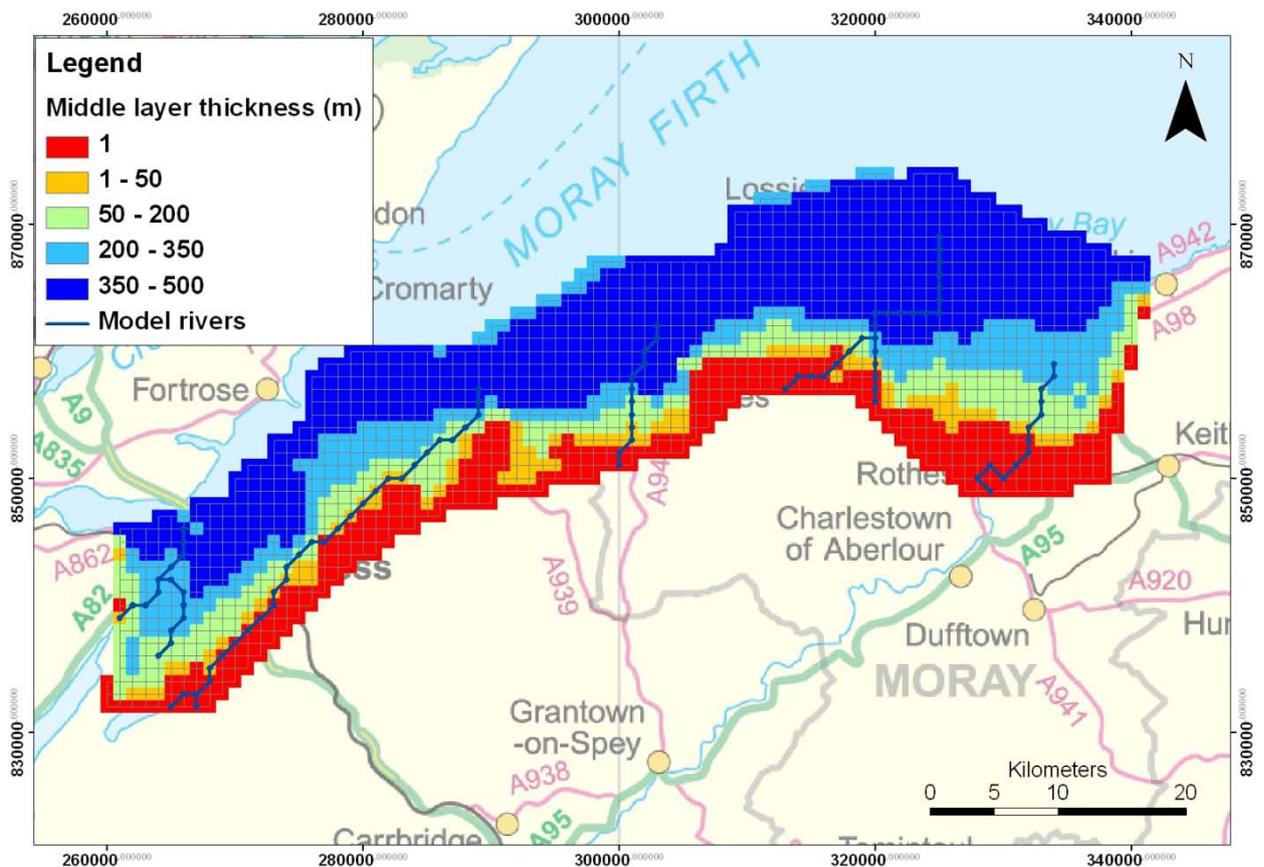


Figure 5 Thickness of the sedimentary deposits

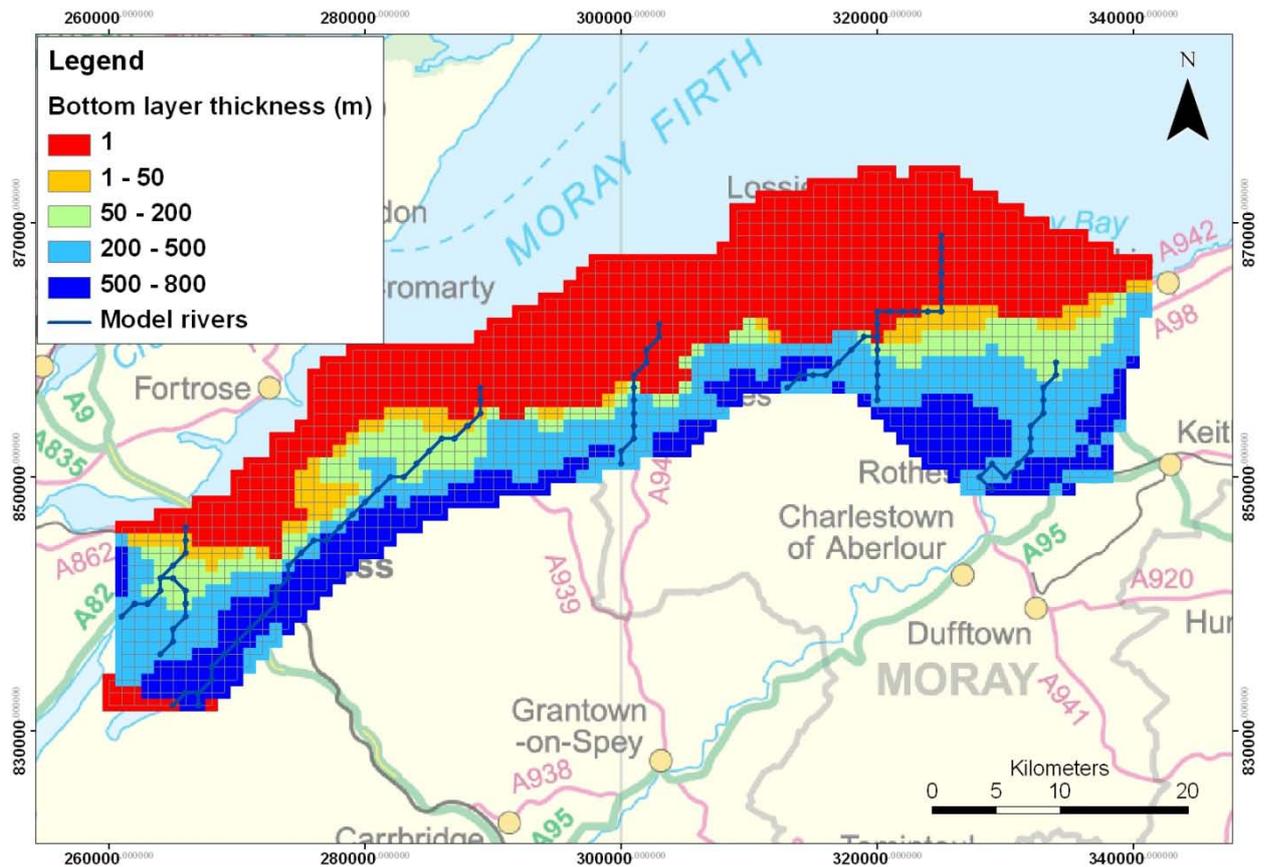


Figure 6 Thickness of the crystalline and igneous rocks

3.2 INITIAL MODEL RESULTS

The groundwater levels in the top layer vary from 500 m AOD inland to 0 m AOD at the coast where the heads are controlled by the fixed head boundary conditions (Figure 7). In the southern part of the model the groundwater levels drop below the base of the layer shown in the figures by no colour. This is justified by the presence of dry boreholes in the south, and the minimal thickness of the superficial deposits in that area. In the middle layer the groundwater levels have the same range as the top layer and the same overall pattern (Figure 8). Dewatering also happens in this layer although on fewer nodes. The dewatered zone matches the one from the top layer and corresponds to areas where the thickness of the middle layer is also very thin. The groundwater heads of the bottom layer are very similar to the top layer except for some nodes having values exceeding 2000 m (Figure 9). Dewatering is restricted to nodes in the south-west that coincides with a sharp contrast in the thickness of the layer.

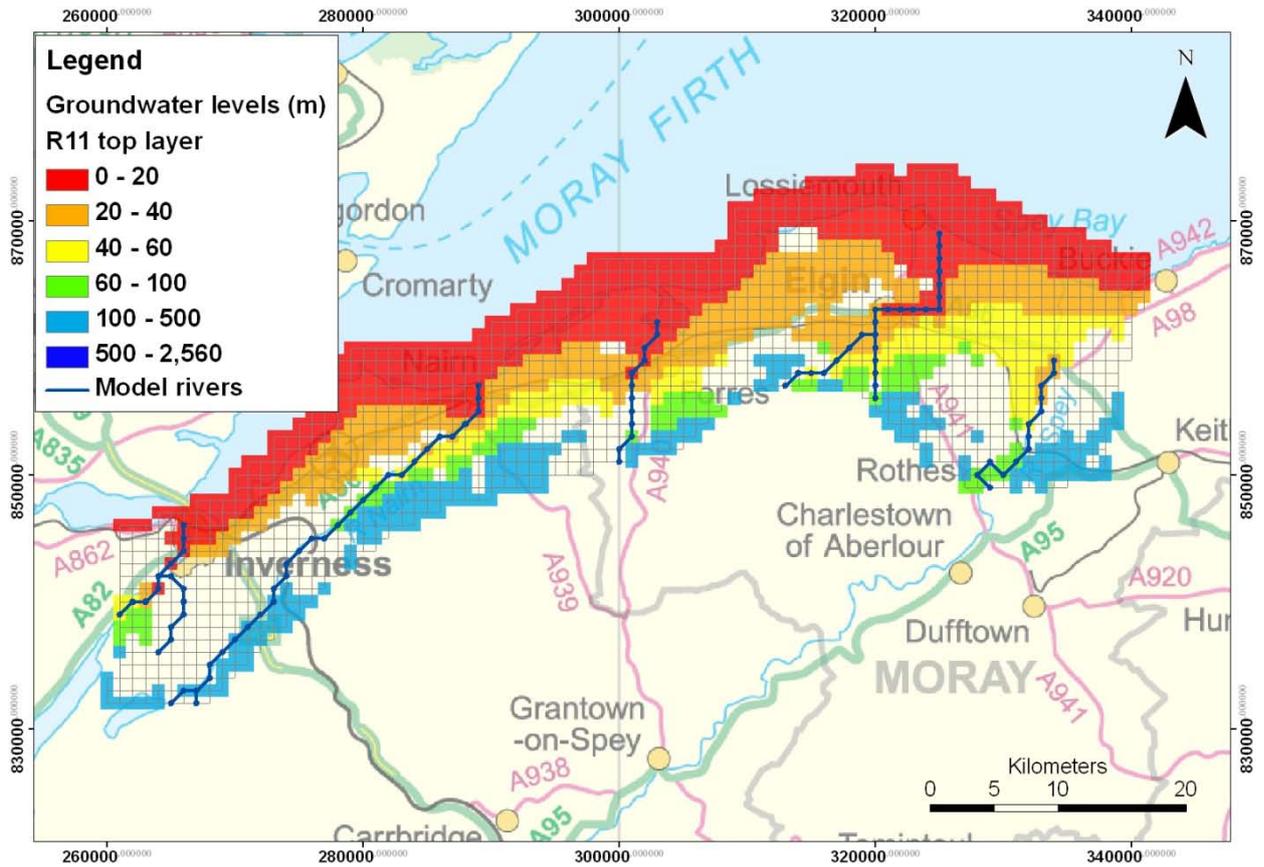


Figure 7 Groundwater levels in the superficial deposits

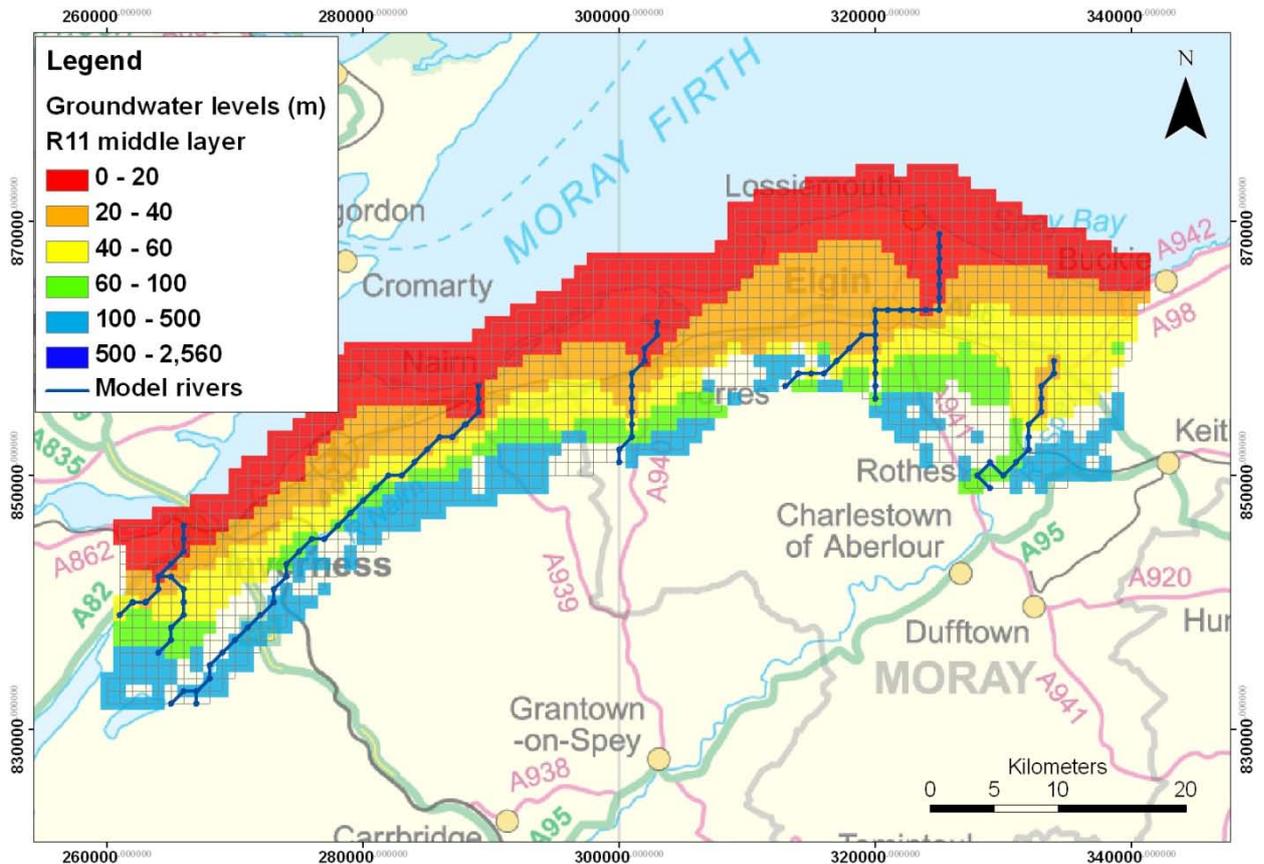


Figure 8 Groundwater levels in the sedimentary deposits

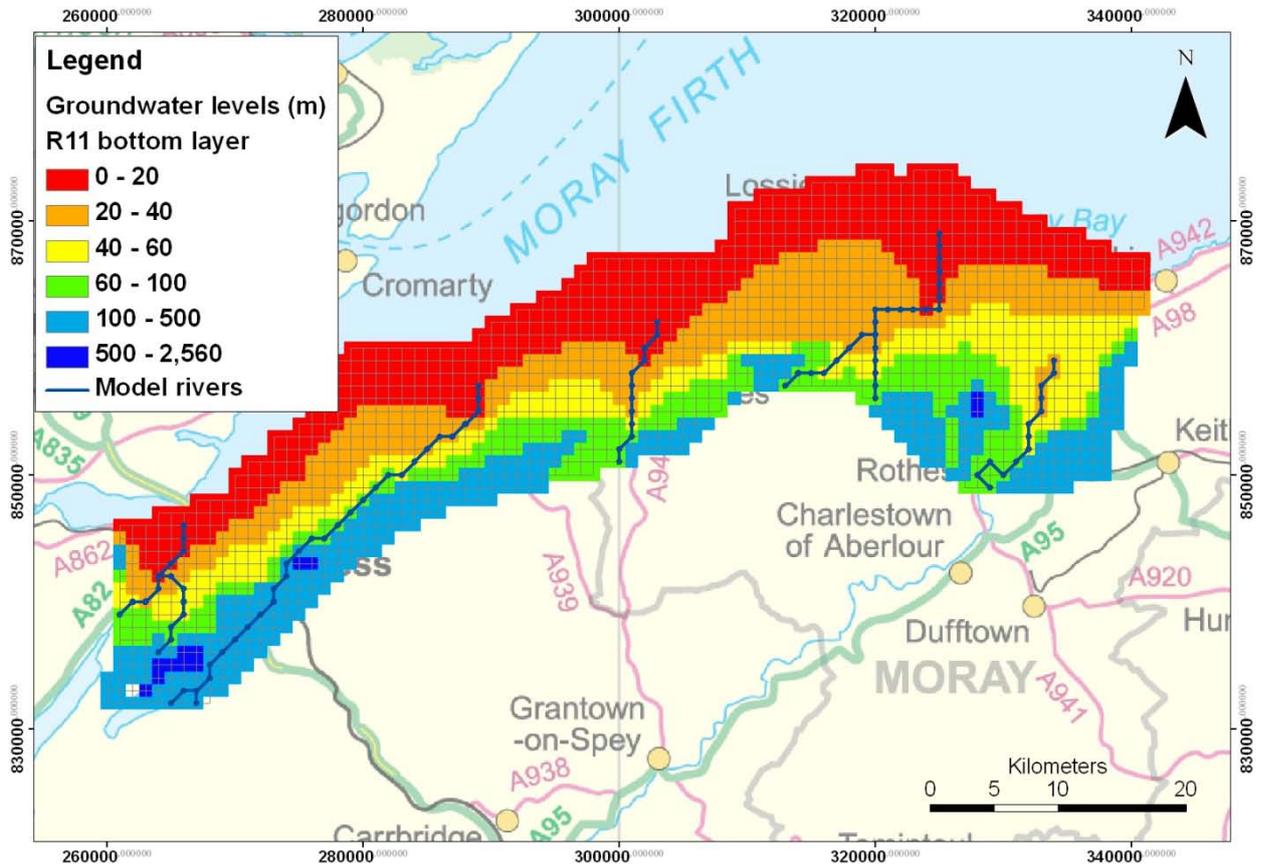


Figure 9 Groundwater levels in the crystalline and igneous rocks

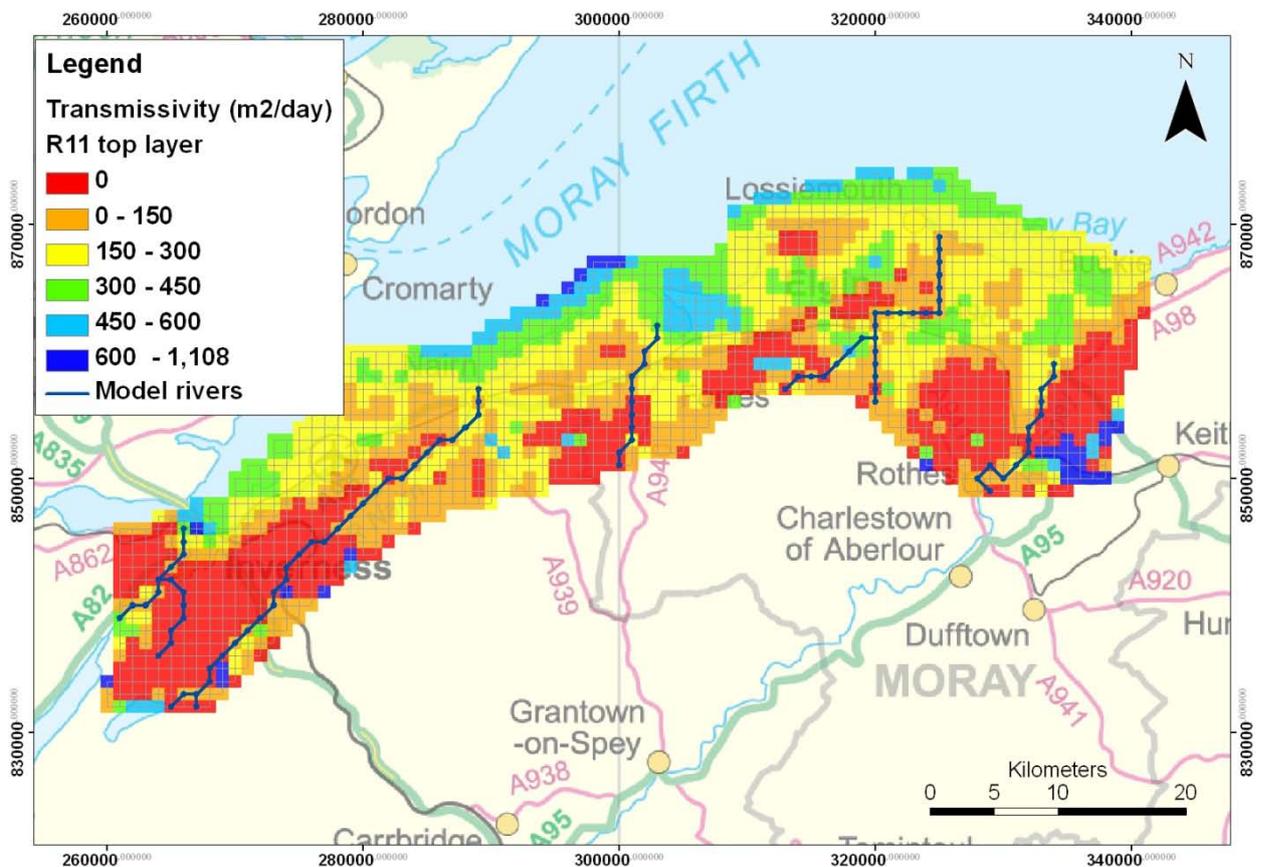


Figure 10 Transmissivity of the superficial deposits

4 Refined Groundwater Model

4.1 MODEL CONSTRUCTION

The refined model was built within the regional model. The model extends over an area of 145 km² and matches the dimensions of the GSI3D model. The groundwater flow model has a 200 m cell size and comprises three layers derived from the regional GSI3D model. The superficial deposits are split into two layers with the lower layer representing the bedrock. Where the layers did not exist at a node, a minimum thickness of 1 m was introduced as the groundwater model requires that each layer is continuous throughout the domain. The hydraulic conductivity for the ZOOMQ3D model was derived from the GSI3D model (see Appendix 2). The process works in a similar way to the layer geometry in which the value of hydraulic conductivity is taken as an average of the value assigned to the geological unit which is combined to produce the model layer.

Long-term average recharge (Figure 11) was used to provide input to the model, which was run until steady-state was reached.

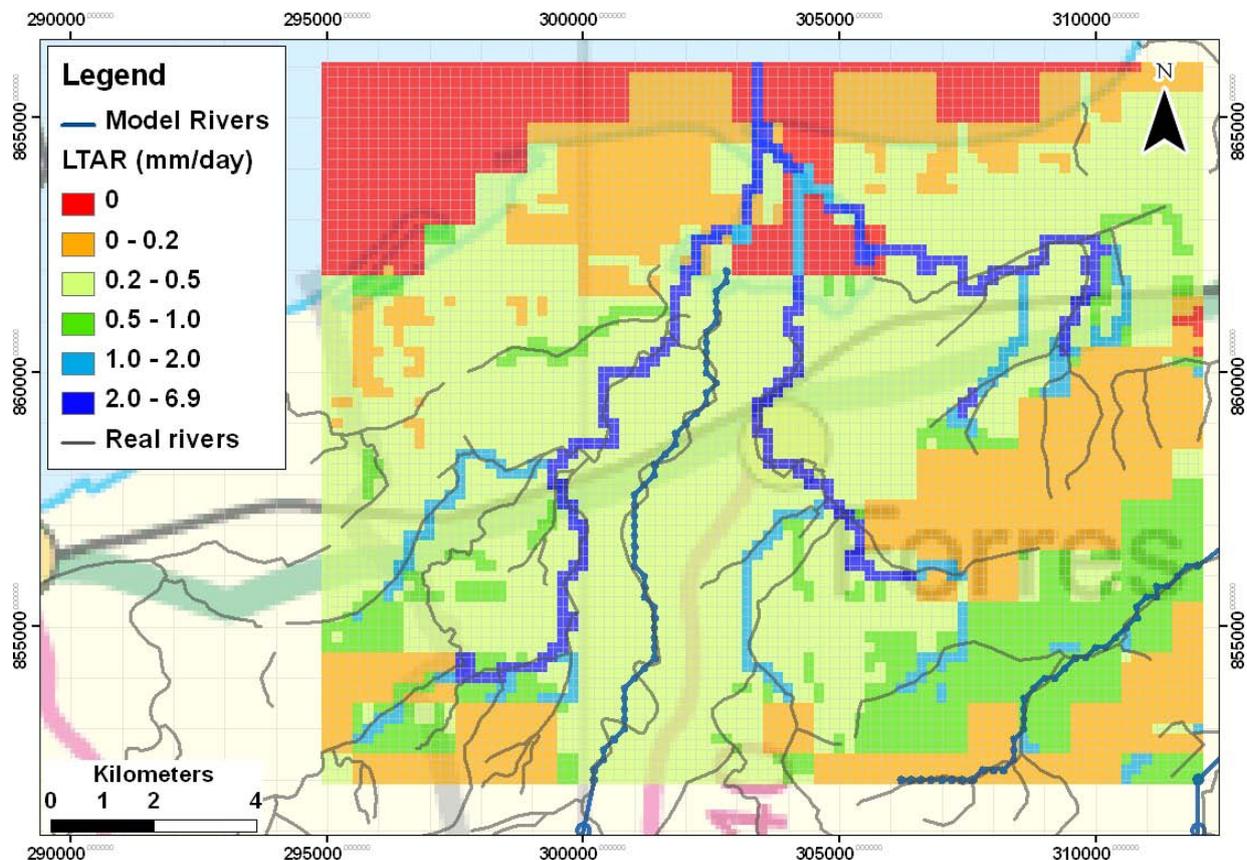


Figure 11 long-term average recharge used in the refined model.

4.2 MODEL RESULTS

The steady-state groundwater heads for the refined model are presented in Figures 12 to 14. In general they show that groundwater flows towards the main outflows of the system, namely the rivers and the sea. There are dry nodes in layer 1 which represents the superficial deposits and these are where the deposits are thin or non-existent.

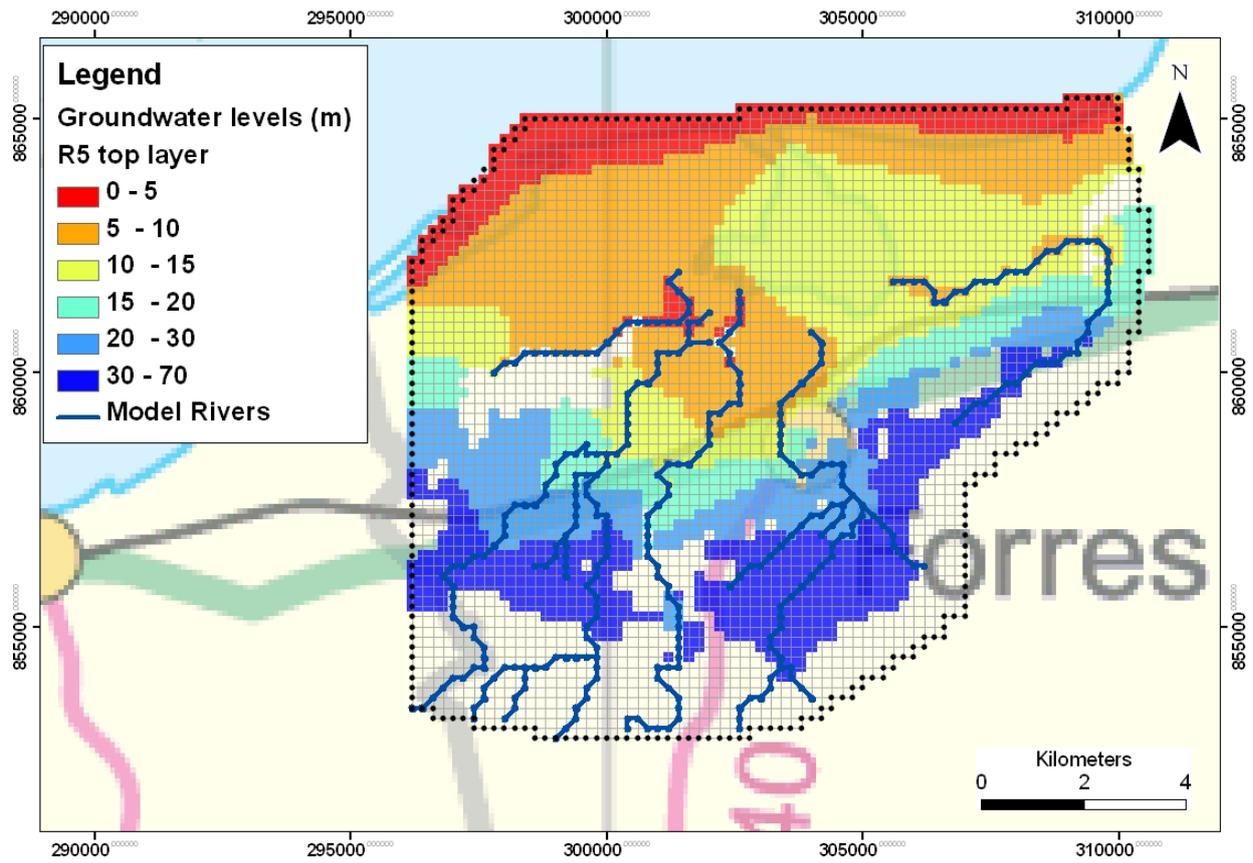


Figure 12 Steady-state groundwater heads in layer 1.

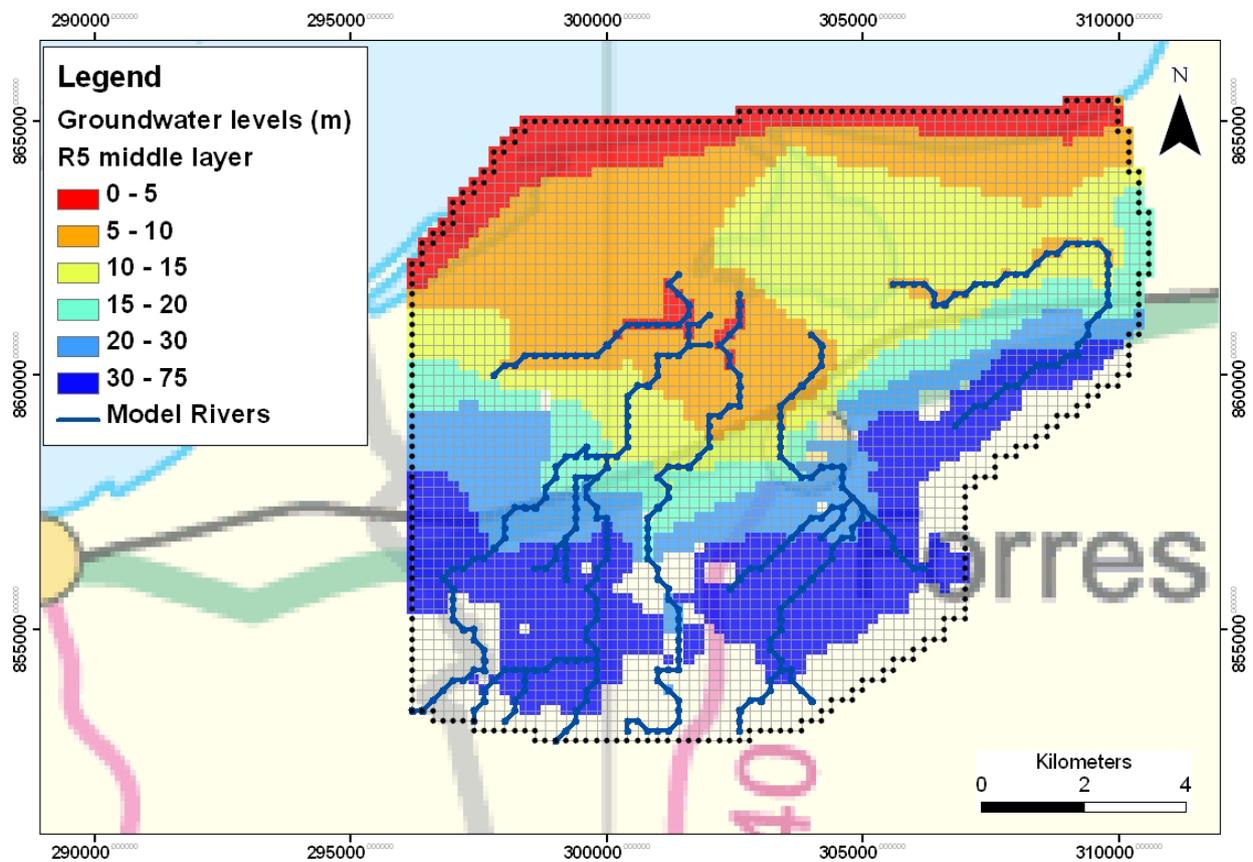


Figure 13 Steady-state groundwater heads in layer 2.

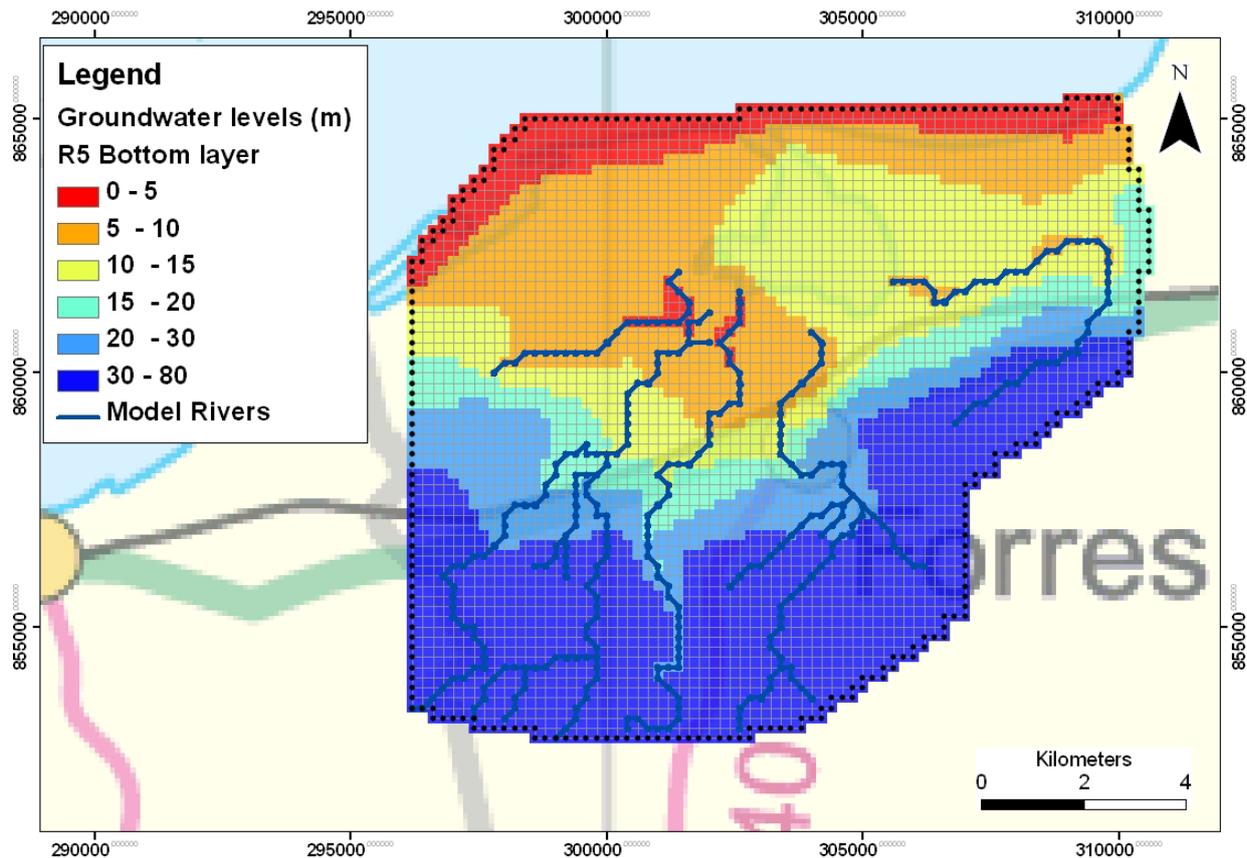


Figure 14 Steady-state groundwater heads in layer 3.

5 Summary and recommendations

The groundwater model reported here was constructed based on the lessons learnt from the work undertaken for The Moray Council (MacDonald et al. 2008). This work showed the potential importance of bedrock topography and the impact of positioning lateral boundaries on groundwater flow. The work reported here was designed to address these issues and to advance the use of geological models to parameterise groundwater flow models.

The work presented in this report has shown that linking the groundwater flow model, ZOOMQ3D, to GSI3D is possible and brings benefits. The project has developed a workflow whereby 3D geological models can be developed and the layer geometry and parameterisation of hydraulic conductivity can be used to develop a groundwater model.

However, the work reported here is in an early stage and requires development for the model to be a suitable tool for use in answering scientific questions. The following recommendations are made for further work:

1. Consideration to be given to the model's purpose as this will guide the detail of its development, e.g. the influence of bedrock topography on groundwater flooding.
2. Improve the current steady-state modelling:
 - Determine why the heads are so large in the regional model (~1000m)

- Include hydraulic conductivity distribution in refined model based on GSI3D model (see Appendix 2).
 - Improve recharge model by considering more sophisticated run-off coefficient distribution based on superficial deposit permeability
 - Consider aquifer-sea interaction based on enhanced understanding of offshore quaternary deposits
 - Create water balances for the whole model and for particular catchments, e.g. River Findhorn
 - Compare model results with observed heads, where available
3. Undertake time variant runs:
- Collect and collate data for groundwater and river baseflow hydrographs
 - Extend recharge model run to as near to the present day as possible
 - Undertake a dynamic balance run then a full time variant simulation using updated recharge model
 - Compare model results with the available time variant data
 - Prepare water balances as appropriate
4. Engage with stakeholders to obtain data and to provide resources for further model development (e.g. SEPA, The Moray Council and The Highland Council).

References

- Freeze A.R. and Cherry J.A., 1979. Groundwater. PrenticeHall, Englewood Cliffs, USA.
- Grindley J., 1967. The estimation of soil moisture deficits. *Meteorol. Mag.*, 96 (1137), pp 97-108.
- Jackson C.R. and Spink A.E.F., 2004. User's manual for the groundwater flow model ZOOMQ3D, British Geological Survey Internal Report, CR/04/140N, Wallingford, U.K.
- Kessler, H., Mathers, S.J. & H.-G. Sobsich. 2009. The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology. *Computers & Geosciences*, 35, 1311–1321.
- MacDonald A M, Hughes A G, Vounaki T, Graham M T, Lilly A, Mansour M, Stephens C A. 2008. Groundwater and the Forres (River Findhorn & Pilmuir) Flood Alleviation Scheme, Morayshire. British Geological Survey Commissioned Report, CR/08/023. 94 pp.
- MacDonald A.M., Maurice L., Dobbs M.R., Reeves H.J., Auton C.A., 2012. Relating in situ hydraulic conductivity, particle size and relative density of superficial deposits in a heterogeneous catchment. *Journal of Hydrology*. In press. 10.1016/j.jhydrol.2012.01.018
- Mansour M.M. & Hughes AG., 2004. User's manual for the recharge model ZOODRM. British Geological Survey Internal Report no. CR/04/151N, Wallingford, U.K.
- NERC, 2003. Hydrological data United Kingdom: Hydrometric Register and statistics 1996-2000, *CEH: Wallingford*
- Penman H.L., 1948. Natural evaporation from open water, bare soil and grass. *Proc. R. Soc. London, Ser. A*, 193, pp 120-145.

Appendix 1 Linking GSI3D to ZOOMQ3D

The following describes step-by-step how to link GSI3D model with a ZOOMQ3D model.

Step 1: Calculate the volumes within GSI3D

Step 2: modify the gvs file

In excel open the gvs file, rename it and then do the following changes:

- Remove the row containing dtm information
- Add one column and name it ZOOM_layer. This column is where you assign to the different geological units a ZOOM layer. Several geological units can have the same ZOOM layer; this is how the GSI3D model is simplified into ZOOM. The numbering of the ZOOM layers start from the top to the bottom. If the geology is complex in the GSI3D which it is likely to be, it is recommended that the user spends some time interrogating the model to decide how to amalgamate the layers prior to assigning layer values in the GVS.
- Add one column and name it ZOOM_K value. In this column the hydraulic conductivity for the geological unit and not for the ZOOM layer is assigned. Even if this is not used, a value needs to be attributed to all geological units
- Go to file>properties in the GSI3D model and set the gvs file to the modified one

Step 3: Export units to ZOOM

In the ZOOM grid file > browse to the location where the ZOOM file grids.out or grids.dat exists (Figure 15)

In ZOOM grid Elevations and Grid Conductivity browse to the folder location and type the name of the run to create the files where the output data will be stored. The files will be automatically saved with the right extensions.

In ZOOM layer and conductivity definition choose the names that correspond to ZOOM_layer and ZOOM _ conductivity respectively which are the two columns added in the GVS file.

In the final tab specify the minimum thickness of the zoom layer when there is no geological unit.

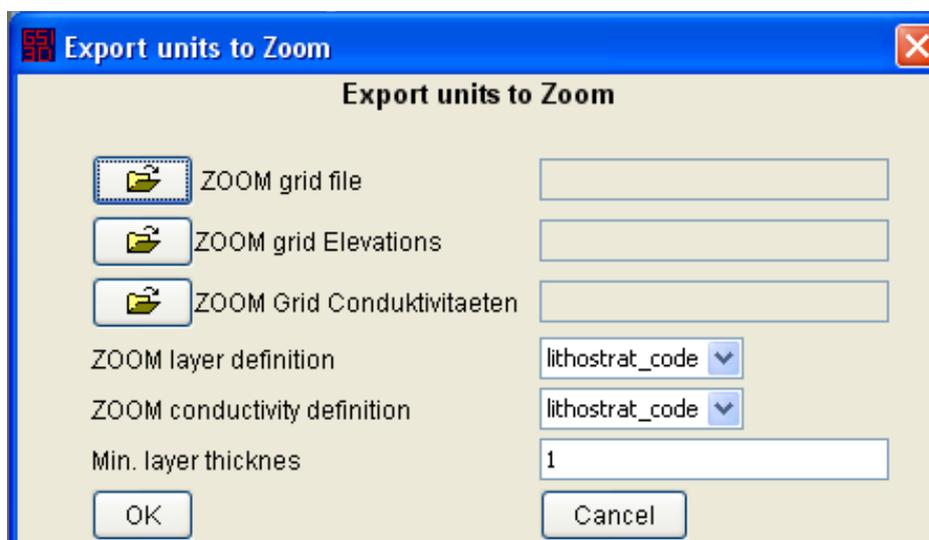


Figure 15 The export ZOOM function window in GSI3D.

	0	10	20	30	40	50	60	70	
1	260000.0	832000.0	235.99	1	234.99	2	233.99	3	232.99
2	261000.0	832000.0	221.85	1	220.85	2	219.85	3	218.85
3	262000.0	832000.0	214.65	1	213.65	2	212.65	3	211.65
4	263000.0	832000.0	213.0	1	212.0	2	211.0	3	210.0
5	264000.0	832000.0	213.0	1	212.0	2	211.0	3	210.0
6	265000.0	832000.0	222.9	1	221.9	2	220.9	3	219.9
7	266000.0	832000.0	255.02	1	254.02	2	253.02	3	-401.37
8	267000.0	832000.0	212.89	1	211.89	2	210.89	3	-400.75
9	268000.0	832000.0	225.24	1	217.1	2	216.1	3	215.1

Figure 16 Extract of GSI3D output file with extension “.G2ZE” containing XY coordinates of ZOOM grid, followed by ground elevation, layer number and layer base elevation.

How to use the output from GSI3D into ZOOM

The export function from GSI3D to ZOOM produces a txt file containing the surface and base elevation of each layer for each ZOOM grid node in column format (Figure 16). The output then needs to be modified before using it in ZOOM for the elevation of the top and bottom of each layer (ztop and zbase files). The changes involve:

- transforming the column base information to gridded data (like in GIS ascii data).
- Extending the extent to the basegrid extent. The number of columns and rows missing will be equal to the number of rows and columns of inactive cells surrounding the active nodes.

QUICK FIX

Currently the file “grids.dat” is used to create the output files with extension “.G2ZC” and “.G2ZE”. Another file needs to be loaded in order to get the full extension of the model. This can be done using any of the following files:

Aquifer.map

This file is probably the best to read. In the first line it contains the XY coordinates of the lower left and upper right of the model. This info is within a comment line, so the code needs to pick up the numbers.

It then contains in gridded format the boundary (so ascii GIS format, but without the first 5 columns necessary in GIS to convert to raster files). Nodes that are outside the “active” model are assigned a “o” value, while those within are assigned an “a”.

LTARecharge.asc

This file contains the Long Term Average Recharge in gridded format. It is produced by ZOODRM (recharge model) and is a key input in ZOOM (groundwater model). It is the ideal file if the user has created a recharge model. This should be always the case, and even if the user has not created himself the recharge model, he will use that file as input within ZOOM. This file is like aquifer.map, only it contains 6 rows before the gridded data with information on number of

columns, rows, cell size etc. In the gridded data, the nodes that are outside the model but within the basegrid are assigned a -999 value.

Basegrid.dxf

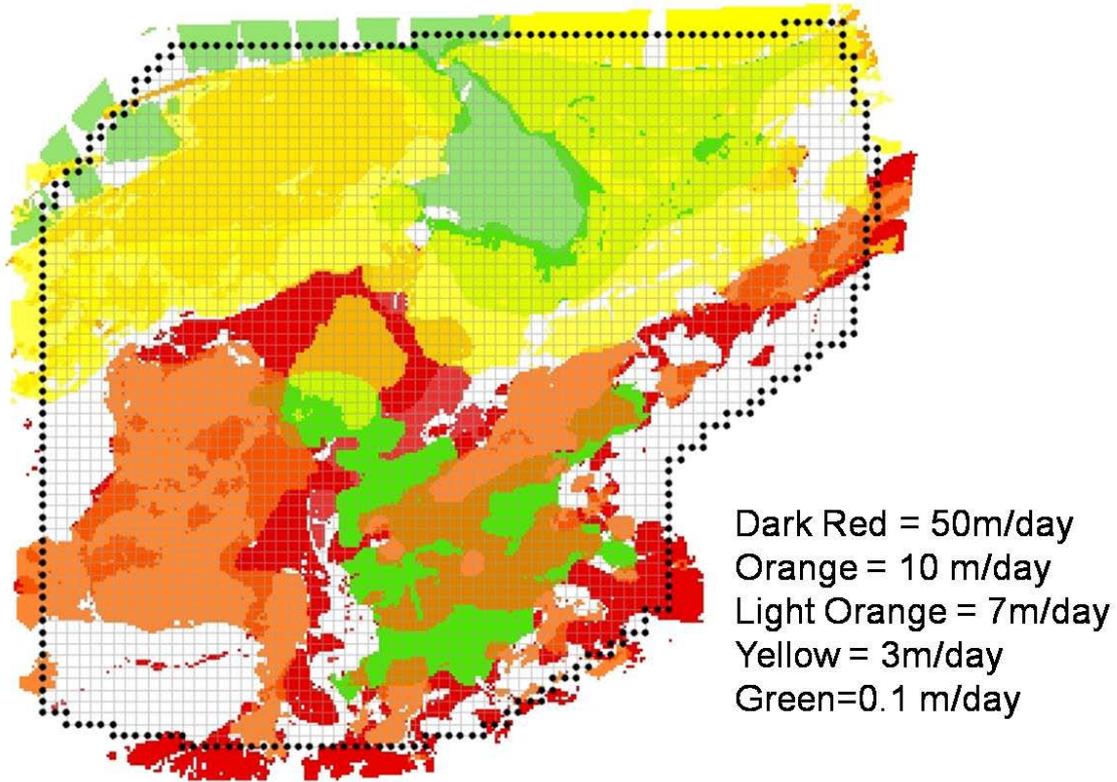
This is a dxf file, it's not straightforward to understand it, but could be used in conjunction with grids.dat.

Boundary.bln or boundary.dat

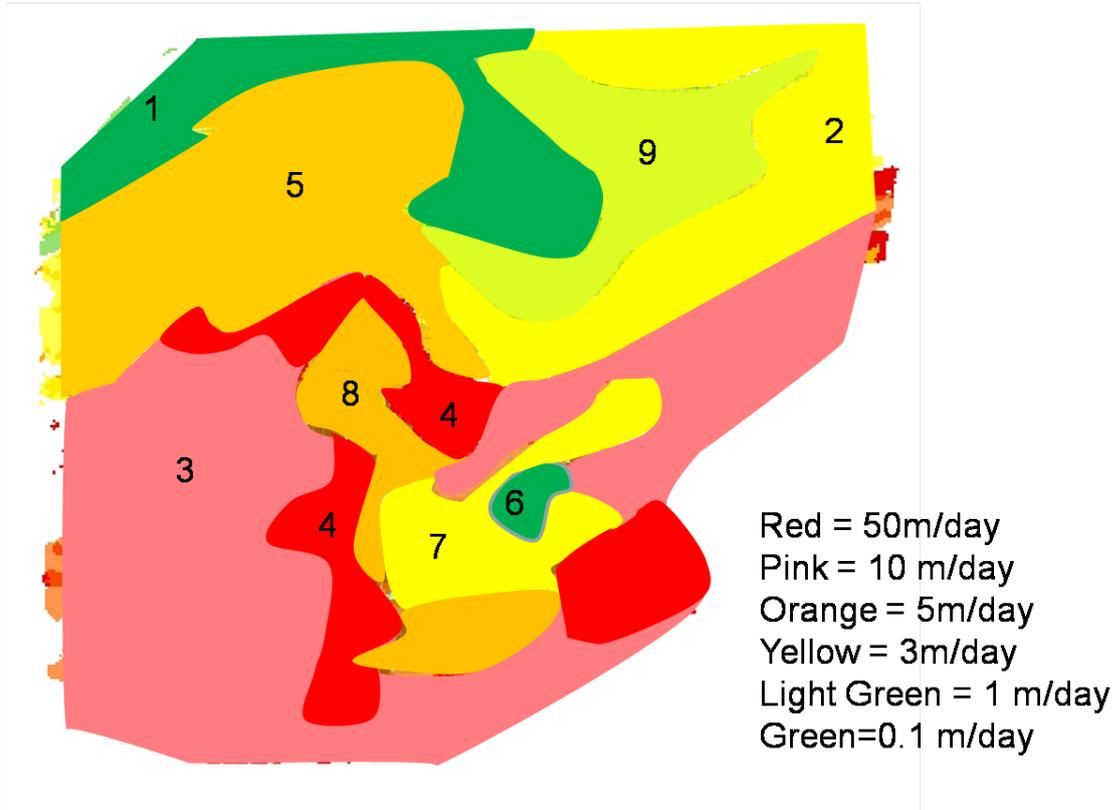
These files contain XY coordinate of all the nodes that form the model grid. If you use one of these files you will need also something like basegrid.dxf or aquifer.map or LTAR recharge.asc, so I guess it probably is not useful.

Appendix 2 Refined groundwater model: adding in distribution of hydraulic conductivity

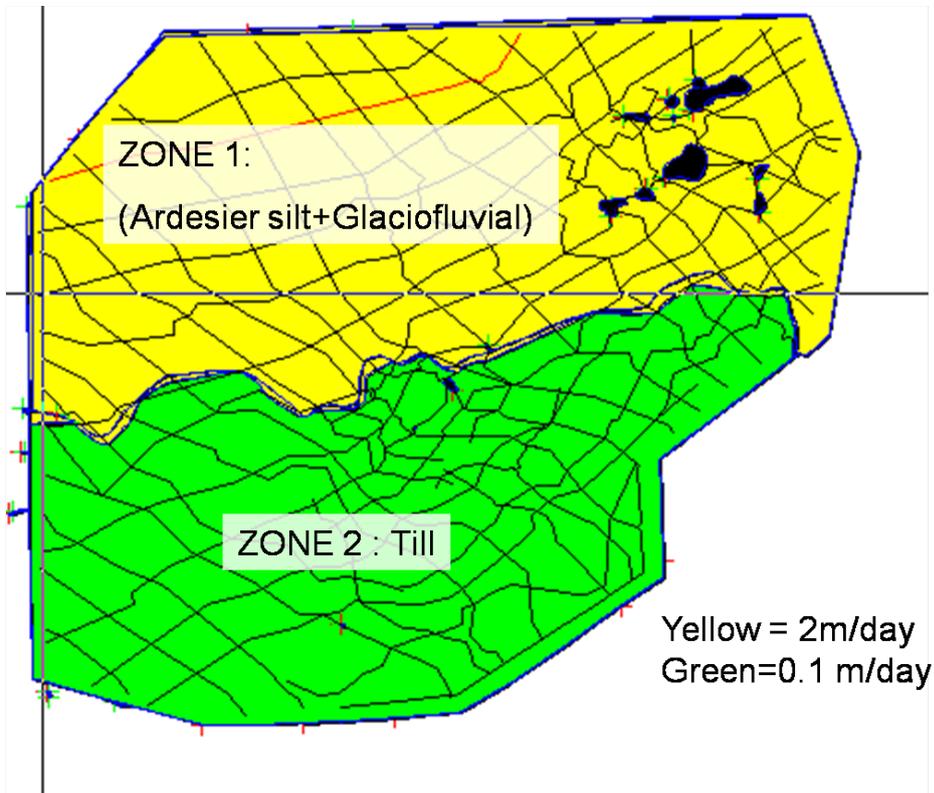
Original K values for the major geological units



LAYER 1 :K distribution zones



LAYER 2



LAYER 3

