BUILDING A TEACHING EXERCISE FOR GROUNDWATER MODELLING

Dissertation submitted as part requirement
for the Degree of Master of Science in
Contaminant Hydrogeology

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Caroline Hepburn certifies that all the material contained within this document is her own work except where it is clearly referenced to others.
1 Abstract

Groundwater is an important resource which must be managed prudently. However it is difficult to accurately characterise a groundwater system due to its inherent heterogeneity. Groundwater models are utilised by hydrogeologists to learn as much as possible from the available data. Groundwater modelling is not currently taught explicitly at Sheffield University, but the students on the Contaminant Hydrogeology course would find such a module beneficial.

The aim of this project is to design and produce a self-study exercise to teach groundwater modelling to students on the Contaminant Hydrogeology MSc at the University of Sheffield.

The Sherwood Sandstone aquifer beneath Nottingham was chosen as a case study the exercise. A simple model of the aquifer was created with the Interactive Ground Water (IGW) software and used to generate heads which are presented to the students as “field data”. Students undertaking the exercise recreate this model by building it up in stages – adding a new level of complexity and solving and calibrating the model each time. There is an opportunity, towards the end of the exercise, for students to experiment with different methods of representing the geology under Nottingham. Finally, the students are asked to write a report which will be marked as a piece of coursework. The different aspects of the exercise are designed to incorporate Kolb’s four learning methods so the exercise should be accessible to any student.

The students studying for the MSc in the current year (2010/11) were asked to test the exercise. Although all seven agreed to participate, only two submitted feedback. This feedback, along with notes taken by the author during the test session, was used to improve the exercise. The students’ experience was generally positive – they had enjoyed the exercise and felt it had increased their understanding of groundwater modelling. However they needed onsite supervision.

The volunteer students did not complete the exercise in the test session. It is therefore recommended that further testing takes place and/or a phased implementation is used to assess the later parts of the exercise. There is potential for extending the exercise to include additional aspects of modelling.
# Table of Contents

1. **Abstract** ................................................................................................................................. 3

2. **List of Figures** .......................................................................................................................... 6

3. **Introduction** .............................................................................................................................. 8
   3.1 Groundwater............................................................................................................................ 8
   3.2 Groundwater Modelling .......................................................................................................... 9
   3.3 This Project.............................................................................................................................. 10

4. **Literature Review** ....................................................................................................................... 11
   4.1 What is a model? .................................................................................................................... 11
   4.2 Why use a model? .................................................................................................................. 11
   4.3 Types of model...................................................................................................................... 12
   4.4 Numerical models ................................................................................................................ 14
   4.5 Published modelling software ............................................................................................. 15
   4.6 Building a model ................................................................................................................... 16
   4.7 Uncertainty in Modelling ..................................................................................................... 18
   4.8 Building a teaching exercise ............................................................................................... 18
   4.9 Teaching............................................................................................................................... 18

5. **Aims and Objectives** .................................................................................................................. 21
   5.1 Aim ......................................................................................................................................... 21
   5.2 Objectives................................................................................................................................ 21

6. **Methodology** ............................................................................................................................ 22
   6.1 Questionnaires ....................................................................................................................... 22
   6.2 Software Selection .................................................................................................................. 23
   6.3 Case Study Selection .............................................................................................................. 24
   6.4 Case Study Model .................................................................................................................. 26
   6.5 Exercise Format ...................................................................................................................... 29


2 List of Figures

Figure 3.1: Distribution of Earth's water (United States Geological Survey, 2011) .................. 8
Figure 3.2: Useable water on Earth (United States Geological Survey, 2011) ....................... 9
Figure 4.1: Finite difference grid laid over an aquifer (Fetter, 1988) .................................... 15
Figure 4.2: Finite element grid laid over an aquifer (Fetter, 1988) ....................................... 15
Figure 4.3: Steps in building a model (Anderson and Woessner, 2002) ............................... 16
Figure 4.4: Kolb's learning model and four learning styles (Loo, 2004) ............................... 19
Figure 6.1: Geology and groundwater of the Nottingham area (BGS, 1981; Charaley et al, 1990, cited in Yang et al, 1999) ................................................................. 26
Figure 6.2: Study area and boundaries of model (adapted from Yang et al, 1999 and Trowsdale, 2002) ........................................................................................................ 27
Figure 6.3: Zones used in model (Tait et al, 2008) ............................................................... 28
Figure 7.1: Geology and groundwater of the Nottingham area (BGS, 1981; Charaley et al, 1990, cited in Yang et al, 1999) ................................................................................... 34
Figure 7.2: Map showing the built-up areas in the study area (Tait et al, 2008) ....................... 35
Figure 7.3: Specified head flux type river .......................................................................... 37
Figure 7.4: Head-dependent flux type river ....................................................................... 37
Figure 7.5: Geological map of Nottingham area, showing boundaries to study area (adapted from Yang et al, 1999 and Trowsdale, 2002) .................................................... 38
Figure 7.6: Recharge zones ............................................................................................... 46
Figure 7.7: Hydraulic conductivity zones ........................................................................... 46
Figure 8.1: Example solution for exercise section 7.4.5: Your First Model ......................... 57
Figure 8.2: Example solution for exercise section 7.4.5: Your First Model ......................... 57
Figure 8.3: Solution for exercise section 7.4.6: The River Lean ......................................... 59
Figure 8.4: Model zones .................................................................................................... 60
Figure 8.5: Solution for exercise section 1.1.1: Recharge .................................................... 61
Figure 8.6: Solution for exercise section 1.1.1: Hydraulic Conductivity Zones .................... 62
Figure 8.7: Solution if River Trent is included as in exercise section 1.1.1: The River Trent. 63

Figure 8.8: Water balance for whole study area from exercise section 7.4.12: Water Balance ................................................................. 65

Figure 8.9: Water balance for zone three from exercise section 7.4.12: Water Balance...... 65

Figure 8.10: Solution with pumping well as in exercise section 7.4.13: Pumping Well, The pumping well is marked by a star. ................................................................. 66

Figure 8.11: Water balance for the whole study area as in exercise section 7.4.14: Pumping Well ........................................................................................................ 66

Figure 8.12: Result of backwards particle tracking from well for fifty years, exercise section 7.4.14: Contaminant Spill. The pumping well is marked by a star, The particle cloud is to the east of the well. ........................................................................................................ 67

Figure 8.13: Result of backwards particle tracking from well for one hundred years, exercise section 7.4.14: Contaminant Spill. The pumping well is marked by a star, The particle cloud is to the east of the well................................................................. 68

Figure 8.14: Geology as represented in model................................................................. 70

Figure 8.15: Geology with simple confining layer added.................................................. 70
3 Introduction

3.1 Groundwater
Water is an extremely important resource. Approximately two-thirds of the human body is made up of water. Humans can only survive without water for a few days. However, the vast majority of the Earth’s water is saline. The fresh water that we see in lakes and rivers is only a tiny fraction of the Earth’s water, as shown in Figure 3.1 below.

![Figure 3.1: Distribution of Earth’s water](United States Geological Survey, 2011).

Saline water from the oceans and frozen water locked in glaciers and ice-caps is unusable by humans. Therefore groundwater is a major component of the water available for public or private supply, as illustrated in Figure 3.2 overleaf.
Even in countries with frequent rainfall groundwater remains an important resource. About one third of public water supplies in England and Wales come from underground (Downing, 1998). 2400 million m$^3$/year is abstracted in the UK (Downing, 1998).

Using groundwater also has several advantages compared to surface water. Groundwater is filtered by the rocks it travels through (UK Groundwater Forum, 2011) and therefore needs minimal treatment before it can be used as potable water. Groundwater does not require storage infrastructure, such as reservoirs, which not only saves space but also reduces losses (substantial volumes are lost from reservoirs due to evaporation).

### 3.2 Groundwater Modelling

Groundwater is an important resource so it must be managed prudently. However there are several difficulties associated with understanding a groundwater system. Firstly, since groundwater is, by its very nature, underground, it cannot be directly observed, except via intrusive investigations, such as boreholes, or where it outcrops at a spring or wetland. Secondly, natural systems, especially the ground beneath our feet, are very heterogeneous. This makes it very difficult to accurately characterise the media in which the groundwater is stored. One way of improving our understanding of these highly complex systems is to build and experiment with models which replicate them.
3.3 This Project

This project aims to teach groundwater modelling to students studying hydrogeology. A self-study exercise is developed and tested on volunteer students. The feedback from the students is used to improve the exercise.
4 Literature Review

4.1 What is a model?
Fetter (1988) defines a model as “any representation of a real system”. Bedient et al (1997) are more utilitarian, stating that “a ground water model is a tool designed to represent a simplified version of a real field site”. Anderson and Woessner (2002) agree, defining a model as “any device that represents an approximation of a field situation”. The overriding concept is that a model enables the user to use limited field data to find the (approximate) answers to questions posed.

4.2 Why use a model?
There are two principle drivers behind most modelling exercises. First, to gain an understanding of why a system behaves as it does and, second, to predict future behaviour (Fetter, 1988; Anderson and Woessner, 2002). Anderson and Woessner (2002) add a third to this list: modelling generic settings to inform regulatory guidelines.

Models can help the designer to understand a system’s behaviour through the iterative process by which the model is modified until the results generated match field results (known as calibration, see later). For example, if a pumping test carried out in the field gives a greater drawdown than that predicted by the model, perhaps the aquitard separating the pumped aquifer from the aquifer below is leaky when it was assumed not to be.

Models are often used to predict future behaviour. A common use is to predict the impact of a development, such as a new well.

It is important to clearly establish the purpose of the model. Anderson and Woessner (2002) recommend that the following questions must be asked constructing a model:

- “What do you want to learn from the model?
- What questions do you want the model to answer?
- Is a modelling exercise the best way to answer the question(s)?”
Bedient et al (1997) add to this list:

- “What level of confidence can be associated with the available field data and the anticipated results from the modelling effort?”

Addressing these questions helps the modeller to decide if a model is needed, what type of model is appropriate, and what the data requirements might be.

4.3 Types of model
There are two main types of model: physical and mathematical. Physical models include scale models made up of the same materials as modelled system (for example sand tanks), electrical models (which use the analogous equations governing electrical current and groundwater flow), and viscous fluid models (Fetter, 1988). Mathematical models use equations to represent the processes occurring in a field situation and include analytical, numerical and stochastic models (Fetter, 1988). The different types of model are compared in Table 4.1 overleaf.
<table>
<thead>
<tr>
<th>Type of model</th>
<th>Description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>Scale models, electrical analogue models, viscous-flow models.</td>
<td>Good for visualisation of flow (not electrical models). Electrical models may be more accurate than computer models under some conditions (Fetter, 1988)</td>
<td>Construction time and materials cost is high. Large space requirement. Difficult to change model characteristics. (Fetter, 1988)</td>
</tr>
<tr>
<td>Analytical</td>
<td>Simple mathematical equations, e.g. Darcy’s Law; image well theory.</td>
<td>Can be solved on handheld calculator. Relatively small about of data required e.g. average values. Gives accurate solution. (Fetter, 1988)</td>
<td>Only suitable for simple cases (Bedient et al, 1997). Usually too many simplifying assumptions are required to properly represent the field situation.</td>
</tr>
<tr>
<td>Numerical</td>
<td>Algebraic approximation of partial differential equations.</td>
<td>Allows spatial and temporal variation of system properties.</td>
<td>Answer is only an approximation. Large data input required. More processing power required.</td>
</tr>
<tr>
<td>Stochastic</td>
<td>Mathematical model based on statistical theory.</td>
<td></td>
<td>Not in common use. Complex. (Fetter, 1988)</td>
</tr>
</tbody>
</table>

This project will focus on numerical modelling since this is the type most often used in industry. It allows heterogeneous systems to be modelled without the crippling assumptions required by analytical models. Numerical models are based on a computer program approximating the controlling partial differential equations as simultaneous
equations expressed in matrix form. The power of numerical modelling reflects the efficiency of computers in solving large numbers of simultaneous equations.

### 4.4 Numerical models

Numerical models all start with the equation of flow. At its most basic, this can be represented as the Laplace equation shown below (Fetter, 1988):

\[
\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0
\]

Where \( h \) represents head. This is a steady state equation. Anderson and Woessner (2002) give a more general form:

\[
\frac{\partial}{\partial x} \left( K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial h}{\partial z} \right) = S_i \frac{\partial h}{\partial t} - R^*
\]

Where \( K \) is the hydraulic conductivity, \( S_i \) is the specific storage and \( R^* \) is a source/sink term. This version of the governing equation allows for temporal variation of head. The governing equations can be chosen to suit the complexity of the model. For example, a modeller may only be interested in areal effects, in which case the \( z \)-term is not required. Kinzelbach (1986) presents the governing equation in a radial coordinate system which is convenient for examining head losses around a well:

\[
\frac{S}{r} \frac{\partial h}{\partial t} = \frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial h}{\partial r} \right)
\]

(This equation assumes radial symmetry.)

There are several different methods for approximating the governing equation, of which the finite difference method is the most commonly used. In this, the model is covered in a square grid of discrete points (nodes) and the equation is solved only at the nodes (Fetter, 1988). The finite element method is similar but the grid does not need to be made up of squares. The “elements” are usually triangular (Fetter, 1988). The finite element method is more accurate than the finite difference method because it has a more flexible configuration (see Figure 4.1 and Figure 4.2) and it solves higher order approximations.
(Zheng and Bennett, 2002). However this carries the penalty of requiring more computing power.

Other numerical modelling methods include the method of characteristics (Fetter, 1988), collocation methods and boundary element methods (Bedient et al, 1997). However these are much less commonly used so they will not be discussed further.

4.5 Published modelling software
It is uncommon for a groundwater modeller to write a new computer code for their model. Instead there are published codes which modellers can use to create their models. The most popular modelling programme is MODFLOW. This is a three-dimensional program which allows a wide variety of scenarios to be simulated (Fetter, 1988). It was published in 1984 by McDonald and Harbaugh and is endorsed by the United States Geological Society.
Its wide use is a testimony to its reliability, it has a very good user’s guide and it is possible to attend training courses in its use (Domenico and Schwartz, 1998).

### 4.6 Building a model

The steps involved in building a groundwater model are depicted in Figure 4.3 below.

![Figure 4.3: Steps in building a model (Anderson and Woessner, 2002)](image)

First of all the **purpose** of the model must be defined as discussed in section 4.2. This can consist of a list of questions for the model to answer.

A **conceptual model** is developed in any situation involving groundwater. It describes the best understanding of what is present under the ground from the available data. It can consist of text and/or diagrams, but usually includes a plan view and a cross-section.
The “mathematical model” box on the flowchart indicates choosing the relevant governing equation. The governing equation of flow in a porous media was discussed in section 4.4 but other governing equations may be required for other modelling purposes, e.g. solute transport for the migration of a contaminant plume.

A published computer code will usually have been used by other modellers (unless it is very new). Successful use of a computer code indicates that most bugs have been corrected and the code gives reasonable and reliable results. The more a code has been used by other modellers and shown to work, the greater the trust that will be put into new models built using the same code. It is therefore usual to use a well-established computer code.

The computer model is designed using information from the conceptual model. Usually a map is uploaded and features such as aquifers, aquitards and surface water bodies are added with their properties specified according to the conceptual model.

Calibration is the process by which the properties of features in the model are adjusted until the model produces heads and flows which match those measured in the field. A sensitivity analysis is carried out to assess the effect of uncertainties in the data. In some cases properties in the calibrated model (e.g. hydraulic conductivities) may be different to those measured in the field (Hill and Tiedeman, 2007) and it is necessary to make a professional judgment about whether this is appropriate. For example, hydraulic conductivity cannot be accurately measured so if the modelled hydraulic conductivity is within half an order of magnitude of the field value this is usually considered acceptable.

Verification can be confused with calibration but it is a separate stage. The calibrated model is run and should reproduce a set of field data which was not used in the calibration process. This is a “final check”. (Note: the term “verification” is also used to refer to the process of checking the computer code works correctly. To avoid confusion, the term “validation” is used elsewhere in this report to refer to the process of running a calibrated model with a new set of data.)

The model is then used to make the predictions required. A sensitivity analysis should also be performed at this stage to estimate the uncertainties associated with the answers generated by the model.
Models which are kept for a long time, such as those developed for aquifer management can undergo a process called “post audit”. The model was used to make predictions, for example ten years, into the future. In ten years’ time, the field data measured over the intervening period can be compared to the predictions made by the model and used to assess the model’s performance. Discrepancies can be used to inform changes to the model.

4.7 Uncertainty in Modelling
To the uninitiated, computer models can appear infallible. Unfortunately, this is not the case. As with any model (e.g. physical or analytical) the results of numerical models cannot have more certainty than the data set that was used to generate them. However a further issue arises with computer models: heads measured in boreholes are the usual data used to calibrate a model - but heads are insensitive to the parameters used to define a model (Evers & Lerner, 1998). This means that many different calibrations are possible for one model, potentially leading to a wide variation in “answers” to the questions posed. Evers & Lerner (1998) and Brookes et al (1994) recommend searching for different calibrations of a model in order to provide a range of answers.

4.8 Building a teaching exercise
The University of Sheffield offers an MSc in Contaminant Hydrogeology. As this is an advanced vocational course, it is assumed that many of the students attending this course hope to become professional hydrogeologists. During their careers they are likely to be exposed to groundwater models, and could be asked to create their own. It is therefore desirable that during the MSc course elements of groundwater modelling are taught. Currently groundwater modelling is only mentioned in passing where it is relevant in other modules. This project will develop a self-study exercise (or exercises) to provide an introduction to groundwater modelling and which students can complete in their own time.

4.9 Teaching
4.9.1 Learning Styles
An important concept in educational psychology is that students differ in their learning styles and will learn most effectively when the teaching method is tailored to their individual learning style (Cagiltay, 2008). A well-established model is Kolb’s experimental learning model. This is illustrated in Figure 4.4 overleaf.
Engineers are commonly “convergers” who are “strong in the practical application of ideas”, whilst scientists tend to be “assimilators” (Holvikivi, 2007). Assimilators specialise in “understanding a wide range of information and putting information into a concise and logical form” (Loo, 2004). However it is likely that students with all the learning styles will be present in a class due to the “increasing diversity of the student population” (Evans et al, 2010). Computer models are an effective method of catering for different learning styles (Egemen, 1998).

4.9.2 Non-Traditional Teaching Methods
Distance learning and non-traditional teaching methods are becoming much more common (Preston, 2005) due to technological advances beginning with the VCR (Desai et al, 2008). This is not limited to students working remotely from their institution but also applies to full-time residential students. Benefits of a self-study style education include flexibility in schedule for students (Baukal, 2010) and staff (Zigic & Lemckert, 2007). Students are able to learn at their own pace (Zigic & Lemckert, 2007) and in any location (McIntyre & Wolff, 1998). Desai et al (2008) even suggest that “face-to-face learning may even become a peripheral activity in the near future”.

4.9.3 Teaching Groundwater Modelling
The author has been unable to find any published exercises teaching groundwater modelling. As discussed above, this is an important skill and it seems likely that such
exercises exist, but have simply not been published. This may be in order to protect intellectual property (in the author’s experience at two universities, accessing online learning material almost always requires a password) or it may be that the authors of other exercises did not consider them to be of interest or use to the academic or general community.
5 Aims and Objectives

5.1 Aim
The aim of this project is to design and produce a self-study exercise to teach groundwater modelling to students on the Contaminant Hydrogeology MSc at the University of Sheffield.

5.2 Objectives
The objectives of this project are as follows:

- to evaluate different styles of exercise for self-study,
- to find and evaluate data sets for use in exercises,
- to decide what features of modelling need to be covered by the exercises, including techniques and pitfalls,
- to design self-study exercises covering the important basic principles of groundwater modelling,
- to test exercises on MSc student volunteers in order to detect problems and receive feedback,
- to improve exercises using the feedback,
- to present the exercises as a stand-alone self-study module.
6 Methodology

The exercises were developed in several stages. Firstly a questionnaire was given to the MSc students to gather their thoughts on the project. The modelling program (Interactive Ground Water) was selected for use in the exercise. The exercise model was constructed, based on a case study (Nottingham). This model was used as the basis of the exercise, i.e. the students are asked to create a replica of this model. Finally a second questionnaire was used to collect feedback from the test students, following which the teaching exercise was refined. This chapter describes these stages, ending with some comments on the format of the exercise.

6.1 Questionnaires

6.1.1 Preliminary Questionnaire

The initial questionnaire given to the students can be found in the appendices (sections 13.1). A very simple questionnaire was used because it was administered during a break in lectures - so it had to be quick to complete. There are three closed questions: two category questions and one rating questions (Saunders et al, 2009). Six students completed the questionnaire.

Five of the six students stated that they would probably complete the exercise if they were given it, which is positive, although they may not have been honest. Four felt that a long case study exercise was preferable to a series of short unlinked exercises and four thought that a coursework report was the best option for assessing the exercise. These results were taken into account when designing the exercise. Two students thought a multiple-choice exam would be the best way to assess the exercise but I suspect they chose this option because they thought a multiple-choice exam would be easier. It would be very difficult to test whether students understood the nature of uncertainty in modelling via a multiple-choice exam.

6.1.2 Feedback questionnaire

The feedback questionnaire combines rating-based questions for qualitative information about the exercise (Sanders et al 2009) and free-form answer sections for students to record their thoughts about the exercise, with particular emphasis on areas for improvement.
Firstly the students are asked how long they spent on the exercise and which sections they completed. They are then asked a series of questions about features of the exercise which they must rate. An example question is shown below:

On a scale of one to five, how did you feel about the complexity of the exercise?
(one = too complex, five = too simple)

The questionnaire may be found in full in the appendices (section 13.2).

6.2 Software Selection
Computer programming skills are not taught as part of this module since this would detract from the understanding of modelling processes, as found by Karssenberg et al (2001). Therefore, a published modelling program is required for the students to use in the exercises. Interactive Ground Water (IGW) was chosen for its simplicity and ease of use. MODFLOW is the most commonly used program in industry, but it is too complex for an introduction to modelling (D.N. Lerner, 2011, personal communication). IGW is much simpler, whilst remaining sufficiently complex to make the exercises worthwhile. The 2D version was selected for further simplicity, but a 3D version is also available should this be desired during further work.
IGW is user-friendly for the students attempting the exercises. It is freely downloadable from the IGW website (http://www.egr.msu.edu/igw/ - downloads). It can be run on an ordinary student laptop with no need for a high power computer. IGW 2D has the following specifications:

Table 6.1: Software specification for IGW (Li & Liu, 2006)

<table>
<thead>
<tr>
<th>Software Name</th>
<th>Interactive Groundwater (IGW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developers</td>
<td>Shu-Guang Li, Qun Liu</td>
</tr>
<tr>
<td>Contact</td>
<td>A133 Research Complex - Engineering, Department of Civil &amp; Environmental Engineering, Michigan State University, East Lansing, MI 48824. E-mail: <a href="mailto:lishug@egr.msu.edu">lishug@egr.msu.edu</a></td>
</tr>
<tr>
<td>Year first available</td>
<td>1997</td>
</tr>
<tr>
<td>Hardware required</td>
<td>IBM compatible PC</td>
</tr>
<tr>
<td>Programming language</td>
<td>Microsoft Visual Basic 6; Visual FORTRAN 5; Borland C++ Builder 6; Borland Delphi 5</td>
</tr>
<tr>
<td>Program size</td>
<td>150 MB</td>
</tr>
<tr>
<td>Availability</td>
<td>Downloadable with manual and supporting material from <a href="http://www.egr.msu.edu/igw/igw_download.html">http://www.egr.msu.edu/igw/igw_download.html</a></td>
</tr>
<tr>
<td>Available since</td>
<td>July 1997</td>
</tr>
<tr>
<td>Online documentation</td>
<td><a href="http://egr.msu.edu/igw/">http://egr.msu.edu/igw/</a></td>
</tr>
<tr>
<td>License</td>
<td>IGW version 3.x is free</td>
</tr>
</tbody>
</table>

Also available from the IGW website is a tutorial exercise which explains and demonstrates how to input data and run models. This exercise is included in the self-study module as it is effective and quick. This will allow the new exercises to concentrate on teaching modelling techniques.

6.3 Case Study Selection

A case study is used to bring some realism into the exercise. A completely artificial data set is not very interesting and is often unrealistic, particularly in terms of geometry.
Nottingham was selected as the case study as it is a well-studied aquifer and several published papers are available in the literature on which to base the model. However, like any aquifer system, there are some complexities which would have distracted from the purpose of this learning exercise so these were simplified.

Fetter (1988) lists the following data requirements for a groundwater model:

- Physical characteristics of aquifer
  - locations, areal extent (map-view) and thickness (for 3D models) of all aquifers and confining layers
  - locations of surface water bodies
  - boundary conditions

- Hydraulic properties
  - permeability/transmissivity of aquifers and confining layers
  - storage coefficients of aquifers and confining layers

- Hydraulic heads
  - maps of water table/potentiometric surface
  - natural recharge and discharge volumes/rates and locations

- System stresses
  - anthropogenic recharges/discharges
  - effects of the above on natural water bodies

Storage coefficients are not required for this model since it is a steady state model and storage coefficients are only needed for transient conditions.

The physical characteristics, permeability and natural recharges and discharges are all available in the literature for the Nottingham case study and are discussed in the section below. Real anthropogenic system stresses such as the network of pumping boreholes around Nottingham) have been ignored for simplicity with only one synthetic borehole used in the exercise.

Hydraulic heads calculated by other models were available for the Nottingham area but it was considered best to generate new heads via the case study model (described below in section 6.4) which take into account the simplifications made in the exercise.
6.4 Case Study Model

The exercise is based on a model created for this purpose. The model is based on a case study of the Sherwood Sandstone aquifer under Nottingham, albeit simplified.

The geology of the Nottingham area is summarised by Yang et al (1999) in Figure 6.1 below.

![Geology and groundwater of the Nottingham area](image)

**Figure 6.1: Geology and groundwater of the Nottingham area (BGS, 1981; Charaley et al, 1990, cited in Yang et al, 1999)**

The main features of interest for this exercise are the Sherwood Sandstone (aquifer), the Mercia Mudstone (confining layer) and the Rivers Trent and Lean. The study area and boundaries of the model are shown below in Figure 6.2.
Along the western edge of the study area (roughly co-incident with the River Lean) the aquifer pinches off and the Magnesian Limestone outcrops. Although the Magnesian Limestone is a minor aquifer (Tait et al, 2008), its hydraulic conductivity is considered negligible for the exercise model.

Another physical boundary is the Clifton Fault. Yang et al (1999) state that the fault “acts as a groundwater barrier”.

The hydraulic boundaries (the flow line to the north and the groundwater divide to the south) are taken from a detailed model of the area by Trowsdale (2002). A flowline is chosen since the aquifer extends approximately 200km to the north of Nottingham (Tait et al, 2008), which is much large than the desired study area.

Finally, since the aquifer has extends indefinitely to the east (Tait et al, 2008) the edge of the map has been taken as a no-flow boundary for convenience.

The thicknesses of the geological strata are given by Trowsdale et al (2002).
Table 6.2: Geology of Nottingham area (simplified from Trowsdale et al, 2002)

<table>
<thead>
<tr>
<th>System</th>
<th>Group</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jurassic</td>
<td>Penarth Group</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Triassic</td>
<td>Mercia Mudstone Group</td>
<td>0-200</td>
</tr>
<tr>
<td>Permo-Triassic</td>
<td>Sherwood Sandstone Group</td>
<td>65-150</td>
</tr>
<tr>
<td>Late Permian</td>
<td>Permian Marls</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Permian</td>
<td>Lower Magnesian Limestone</td>
<td>0-40</td>
</tr>
<tr>
<td>Upper Carboniferous</td>
<td>Lower/Middle/Upper Coal Measures</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

The model takes the very simplified version of the geology shown below (see section 1.1.1 for discussion).

Table 6.3: Model geology

<table>
<thead>
<tr>
<th>Ground surface</th>
<th>Top of aquifer</th>
<th>Bottom of aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td>80m</td>
<td>80m</td>
<td>-20m</td>
</tr>
</tbody>
</table>

Figure 6.3: Zones used in model (Tait et al, 2008)
The study area has been divided into zones (shown in the figure above) to approximate the variation in recharge rates and hydraulic conductivity. These zones are taken from the model made by Tait et al (2008). The values for the hydraulic conductivity and recharge rate within these zones are given in the table below. They are the means of the values used by Tait et al (1999) in their probabilistic model of the Nottingham area.

Table 6.4: Model parameter values

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
<th>Hydraulic Conductivity (m/d)</th>
<th>Recharge rate (mm/yr)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Confined</td>
<td>3.11</td>
<td>68</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>Confined, deeper and thinner than zone 1</td>
<td>2.59</td>
<td>68</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>Unconfined, rural</td>
<td>3.97</td>
<td>114</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>Unconfined, urban</td>
<td>3.97</td>
<td>211</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The River Lean is given a stage equal to the ground surface elevation (80m AOD) and the river sediments are given a leakance equal to the default value in IGW (0.1m/d) since no data was available. Gower et al (2008) provide some measurements of the stage of the River Lean at various locations over time. A value of 42.83m was chosen, this being the stage at the Day Brook logger in July 2004. This leads to a value for the river bottom of 37.17m AOD.

The River Trent is connected to the aquifer for only a short distance in the south-west corner of the study area before they are separated by the Mercia Mudstone. In the exercise model, the River Trent is considered not to be hydraulically connected to the aquifer at all. There will be local groundwater movement in the alluvium under the Trent but this is not included in the model as it is only two dimensional.

6.5 Exercise Format

The exercise takes the format of a long case study where the students build up a model of the Nottingham aquifer in stages. This allows them to grasp with the concepts of the modelling processes whilst their model is still simple yet maintains the realism of a (slightly) complex scenario. Four out of six students who completed the preliminary questionnaire felt that a longer case study would be preferable to a series of short, unlinked exercises.
After a short introduction followed by instructions to complete the IGW online tutorial, the students are given maps and data from the Nottingham case study model. They are then guided through the stages of building their model. They begin with a very simple model and add features, one at a time, to build up complexity. Finally, the students are asked to write a report.

The students are instructed to use an online tutorial in order to learn how to work with the program. This is important so they can focus on the learning objectives when they begin the exercise, otherwise they may spend “excessive amounts of time” experimenting with which button to click (Morgenroth et al, 2002).

Morgenroth et al (2002) also stress the need for “early rewards” i.e. the students should see the results of their efforts as soon as possible. For this reason the students are asked to solve their model every time they add a new feature. This also helps them observe the effects of changing the model.

A method of assessing the students work is very important to ensure the students complete the exercise. Desai et al (2008) point out that the flexibility of a self-study exercise also means students are able to “abandon it as other things begin taking up their time and attention”. The MSc course is very demanding so it is likely some students would fail to complete the module if it was optional.

Loo (2004) recommends that “educators use a variety of learning methods”. The exercise is designed to encompass all of Kolb’s proposed learning methods. **Concrete evidence** is provided as the students build models for themselves and observe the results; **abstract conceptualisation** occurs as part of the explanation of how models work; **active experimentation** is pertinent in a section towards the end of the exercise in which the students are encouraged to experiment with different methods of representing the geology in the model; and finally the report provides an opportunity for **reflective observation**. This means that all students should find a part of the exercise suited to them, whatever their learning style.
7 The Exercise

In this chapter the exercise is presented as it is in the handout given to the students.

7.1 Introduction

Modelling is a useful tool for hydrogeologists as it can help us understand the complex systems we study. Groundwater models can range in complexity from quick and simple to intricate models requiring a lot of computing power. Although this exercise concentrates on a simple model, the skills you will learn will apply to modelling at any level. Completing this exercise will also give you an appreciation of what can go wrong in modelling so you can treat the results of your own and other people’s models with appropriate caution and get the most out of them. This exercise will take approximately two days to complete (not including the report).

7.2 Getting Started

7.2.1 Downloading IGW 2D

1) Go to http://www.egr.msu.edu/igw/
2) On the left hand menu, click “Downloads”
3) Fill in the form. For “Your Name and Affiliation”, enter your name followed by “University of Sheffield”. For “Your Email”, enter your University of Sheffield email address. For “Your Comments”, enter “I am a student wishing to use IGW for a self-study exercise teaching groundwater modelling.”
4) Click “Submit Query”.
5) You will be redirected to the downloads page.
6) Click “2D version download (IGW 3.X)”.
7) Scroll down to “Stable Version Download” and click on IGW3.5.6 (10.1MB).
8) The programme will download.
9) When the download is complete, a zip folder will open.
10) Double-click on “setup.exe”.
11) Follow the instructions on the setup wizard.

7.2.2 The Online Tutorial

This tutorial is designed to teach you how to enter data into IGW and use the functions. You are advised to complete this tutorial before beginning the case study below. Working through the whole tutorial will take about two hours. At the very least, work through the
tutorial up to chapter six (these chapters teach you how to enter data into IGW and solve your model). You can come back to the tutorial later when you need use other functions.

Work through the tutorial using the embedded example (the instructions in the blue brackets). A printout of the instructions for the online tutorial has been given to you, but you may wish to look at the online version since it contains embedded videos. You do not need to watch these but some students may find them helpful.

1. Go to http://www.egr.msu.edu/igw/
2. On the left hand menu, click “Documentation”
3. Click on “Step-by-Step Tutorial for a Case Study”
4. Complete the following chapters:
   - Chapter one: Introduction
   - Chapter Two: Starting and exploring IGW
   - Chapter Three: Setting up a model
   - Chapter Four: Obtaining a solution
   - Chapter Five: Exploring the cursor activated table
   - Chapter Six: Exploring the attribute input and model explore window
   - Chapter Nineteen: Saving options
5. When you reach section 7.4.12 of this handout, you should complete chapter twelve of the online tutorial
   - Chapter Twelve: Utilising Mass Balances
6. When you reach section 7.4.14 of this handout, you will need to complete chapter eight of the tutorial
   - Chapter Eight: Particle Tracking
7. You may find chapter fourteen of the tutorial useful when you reach section 7.4.17 of this handout
   - Chapter Fourteen: Refining the model: stratigraphy

7.3 The Case Study

7.3.1 Introduction
There is thought to have been a settlement at Nottingham since Roman times (Trowsdale, 2002). It became a major industrial centre in the 18th and 19th centuries (Tait et al, 2008).
The population of the City of Nottingham in 2002 was 266,988 (Office for National Statistics, 2002) and that of the surrounding urban area is much greater.

Nottingham is situated on the Sherwood Sandstone aquifer from which most of the city’s water supply is drawn (Tait et al, 2008). The following case study presents a simplified conceptual model of the Nottingham area.

7.3.2 Tasks
You are a consultant undertaking a modelling exercise. Your client is considering drilling an industrial supply borehole but is worried it might be affected by contamination from industrial sites which could necessitate abandoning the borehole.

You will build a model of the Nottingham area and calibrate it using heads taken from observation boreholes. You will then use your model to evaluate the effect on the clients’ proposed borehole of contaminant spills in the study area.

7.3.3 Geology
A geological map is presented in Figure 7.1 below, along with two cross-sections. The basemap you will be provided with for your model is based on this geological map. Ignore the head contours shown on the map; these are taken from a different modelling scenario and are not related to your project.
Table 7.1 below shows the thicknesses of the geological strata present below Nottingham. You will be modelling the Sherwood Sandstone group as this is the major aquifer in the area.

**Table 7.1: Summary of geology of Nottingham (simplified from Trowsdale, 2002)**

<table>
<thead>
<tr>
<th>System</th>
<th>Group</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jurassic</td>
<td>Penarth Group</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Triassic</td>
<td>Mercia Mudstone Group</td>
<td>0-200</td>
</tr>
<tr>
<td>Permo-Triassic</td>
<td>Sherwood Sandstone Group</td>
<td>65-150</td>
</tr>
<tr>
<td>Late Permian</td>
<td>Permian Marls</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Permian</td>
<td>Lower Magnesian Limestone</td>
<td>0-40</td>
</tr>
<tr>
<td>Upper Carboniferous</td>
<td>Lower/Middle/Upper Coal Measures</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>
The shaded areas in Figure 7.2 below are the urban areas in the study area. This information will be useful when you add recharge to your model.

![Figure 7.2: Map showing the built-up areas in the study area (Tait et al, 2008).](image)

### 7.3.4 Field data

You are provided with the following heads measured in observation boreholes. You will need this data later to calibrate your model.

<table>
<thead>
<tr>
<th>OS Grid Reference</th>
<th>Head (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK 568 425</td>
<td>89.95</td>
</tr>
<tr>
<td>SK 564 410</td>
<td>86.76</td>
</tr>
<tr>
<td>SK 558 422</td>
<td>83.47</td>
</tr>
<tr>
<td>SK 559 516</td>
<td>85.68</td>
</tr>
<tr>
<td>SK 618 488</td>
<td>116.90</td>
</tr>
<tr>
<td>SK 630 434</td>
<td>120.62</td>
</tr>
</tbody>
</table>

Take this data to be true, i.e. there is no need to worry about fluctuations of the water table or variations in screened lengths. You will be building a 2D model so you can assume all these boreholes are screened at the same depth. Of course in a real modelling project you would need to worry about these factors, but for now let’s keep things simple!
7.4 Exercises

You will be guided through the modelling process in the sections below. You start with a simplistic model and add more features as you go along.

7.4.1 Defining the model purpose

Models can be designed for one of three purposes (Anderson and Woessener, 2002):

1) To understand why a system behaves as it does,
2) To predict future behaviour of a system,
3) To use a generic setting (i.e. not a case study) to inform regulatory guidelines.

Considering the problem stated above, what is the purpose of the model you will build during these exercises?

Answer: ........................................................................................................................................................................

Furthermore, it is useful to state at the beginning of the modelling exercise what questions you need the model to answer. State your questions below:

........................................................................................................................................................................
........................................................................................................................................................................
........................................................................................................................................................................
........................................................................................................................................................................

7.4.2 The basemap

You are provided with a copy of the geological map shown in Figure 7.1 as a BMP file. This can be found on MOLE. Upload this into IGW. The base of the map is 25km across in the real world and the OS National Grid reference of the bottom left hand corner is SK 450 340. Use this information to set X0, Y0 and Xlength for your basemap.

A six figure grid reference indicates a 100m x 100m square on the ground. You will therefore need to multiply the figures in your grid reference by 100 so you can enter them into IGW in metres. Hint: you should see the number 65840.00 near the bottom right hand corner of your map. If you don’t, try setting the co-ordinates again.
7.4.3 Identifying the boundaries of the study area

Real world boundaries can be physical or hydraulic. Physical boundaries are easiest to identify, for example surface water bodies or a change in rock type. Hydraulic boundaries are invisible and can move, e.g. groundwater divides or flowlines. Real world boundaries can be represented in a model in three different ways (Anderson & Woessener, 2002):

1) Dirichlet (specified head). Use this at a point or along a line where you know the head.

2) Neumann (specified flux). Use this along a line where you know the flow across (perpendicular to) the line. A no-flow boundary is a special case of a specified flux boundary where the flow across the line is zero.

3) Cauchy (head-dependant flux (also known as mixed)).

The figures below show rivers which act as a specified head boundary and head-dependant flux boundaries respectively. The specified head boundary occurs when the river is simply an outcrop of the groundwater. More usually there is a discontinuity between the water table and the river surface due to a change in hydraulic conductivity between the river sediment and the aquifer material. This makes the river a head-dependant flow boundary and the conductivity of the river sediment is required.

Figure 7.3: Specified head flux type river

Figure 7.4: Head-dependent flux type river

Figure 7.5 shows the boundaries of the study area.
The River Lean and the Clifton Fault are physical boundaries. The Clifton Fault can be modelled as non-transmissive (Yang et al, 1999). The groundwater divide and flowline are hydraulic boundaries.

Identify what type of boundaries will represent these real world features in the model. The edge of the map may be considered to be a no-flow boundary.

River Lean............................................................................................................................................................
Clifton Fault............................................................................................................................................................
Groundwater divide....................................................................................................................................................
Flowline........................................................................................................................................................................

A mixture of boundary types is required in a model. The model is solving a differential equation so it needs a reference head. If only flux boundaries are used there are an infinite number of possible solutions. Similarly if only head boundaries are used there are an infinite number of solutions to the governing equation. Remember this as it will help you answer the question in section 7.4.5.
Create the “whole study area” zone by tracing a zone around all the boundaries i.e. along the flowline, along the edge of the map, along the groundwater divide, along the Clifton Fault and along the left hand side of the River Lean. The elevations required for the aquifer are given in the next section. Use 5m/day as an initial estimate for hydraulic conductivity.

7.4.4 Aquifer elevations

Use the following elevations for the Sherwood Sandstone aquifer:

<table>
<thead>
<tr>
<th>Surface</th>
<th>Top</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>80m</td>
<td>80m</td>
<td>-20m</td>
</tr>
</tbody>
</table>

Take the aquifer porosity to be 0.2 (Tait et al, 2008).

Keep these parameters fixed when you calibrate your model in the following sections. Aquifer elevations are a particularly complex part of the modelling process and you will have a chance to make them more realistic towards the end of the exercise. You will find you have plenty of parameters to vary when calibrating your model before long!

7.4.5 Your first model

Congratulations! You have set up your first model of the Nottingham area.

Solve it now.

Are your results what you expected? Solve it again. Do the results change? Does this happen if you solve it again?

Can you explain why this is happening? Hint: look back at section 1.1.1.

7.4.6 The River Lean

Note: You may find you get an odd result after this section as well. This is due to a quirk in IGW and can be avoided by starting a new model now. Upload the basemap (remembering to set the coordinates) and create the “whole study area” zone as before but do not solve the model. Move straight on to adding the River Lean.
Create a zone around the River Lean. Model it as a river in the “sources and sinks” tab. Use the ground surface elevation (80m) for your initial estimate of stage, and 30m and 0.1m/d for your initial estimates for river bottom and sediment conductivity.

Solve your model. You should get more sensible looking head contours this time.

7.4.7 Calibration

Section 7.3.4 gave you a set of heads measured in boreholes. Use this field data to calibrate your model. You want your model to give you the closest match to the field heads you can get. One method of estimating “goodness of fit” is using the “root mean square” equation, shown below:

\[ \text{rms} = \sqrt{\frac{(h_{1m} - h_{1f})^2 + (h_{2m} - h_{2f})^2 + \cdots + (h_{nm} - h_{nf})^2}{n}} } \]

Where \( h_{nm} \) is the nth modelled head and \( h_{nf} \) is the nth field head.

This gives you an “average” difference between your modelled and field heads, which you want to be as small as possible.
Adjust the parameters of your model to try to get the best match you can for the field heads. Think about which parameters will have the greatest effect on your results. Record your attempts in the table below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Attempt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>Aquifer K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean bottom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean sediment conductance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 568 425</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 564 410</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 558 422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 559 516</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 618 488</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 630 434</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root Mean Square</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

You will notice that you cannot replicate the field heads you have been given. This is because your model is simple and does not represent the real world accurately enough. The next sections of the exercise will take you thorough refining your model and you will re-calibrate it at each stage in order to get closer to the field data.
7.4.8 Recharge

We have not yet considered the effect of recharge on the study area. Look at the maps and identify three zones which will have different recharge values. Add them to your model and re-calibrate. Hint: think about confined/unconfined areas and the effect of the urban area on recharge.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Attempt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>Aquifer K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone one</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone two</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone three</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean bottom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean sediment conductance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 568 425</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 564 410</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 558 422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 559 516</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 618 488</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 630 434</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root Mean Square</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.4.9 **Hydraulic Conductivity Zones**

Look at the geological information you have been given. Is it reasonable to assume a constant hydraulic conductivity across the whole aquifer? Try adding two or three zones with different hydraulic conductivities. Re-calibrate your model as before.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Attempt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>Aquifer zone one K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquifer zone two K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquifer zone three K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone one</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone two</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone three</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean bottom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean sediment conductance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 568 425</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 564 410</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 558 422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 559 516</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 618 488</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 630 434</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root Mean Square</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 7.4.10 The River Trent

The final item you will add to your model is the River Trent. Model the River Trent in the same way as you modelled the River Lean. Re-calibrate your model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Attempt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Aquifer zone one K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquifer zone two K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquifer zone three K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone one</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone two</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone three</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean bottom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean sediment conductance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Trent stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Trent bottom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Trent sediment conductance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 568 425</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 564 410</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 558 422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 559 516</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 618 488</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head at SK 630 434</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root Mean Square</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.4.11 Validation

Your model is now sufficiently complex to generate the heads given to you as field data. You have calibrated your model so that it gives the best match you can get to the field heads. The next step is called “validation”. This involves testing your model against a new set of data. It is normally only done with time-variant models, for example, you would use historical data from (say) 1850-1950 for calibration and then data from 1950-2010 for validation. Your model is a steady state model so instead you are given a new set of head data below:

<table>
<thead>
<tr>
<th>OS Grid Reference</th>
<th>Head (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK 562 403</td>
<td>85.98</td>
</tr>
<tr>
<td>SK 681 496</td>
<td>131.38</td>
</tr>
<tr>
<td>SK 558 472</td>
<td>86.82</td>
</tr>
</tbody>
</table>

Use the table below to record the heads at the given locations in your model. Calculate the Root Mean Square including this new field data.

<table>
<thead>
<tr>
<th>OS Grid Reference</th>
<th>Modelled head (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK 568 425</td>
<td></td>
</tr>
<tr>
<td>SK 564 410</td>
<td></td>
</tr>
<tr>
<td>SK 558 422</td>
<td></td>
</tr>
<tr>
<td>SK 559 516</td>
<td></td>
</tr>
<tr>
<td>SK 618 488</td>
<td></td>
</tr>
<tr>
<td>SK 630 434</td>
<td></td>
</tr>
<tr>
<td>SK 562 403</td>
<td></td>
</tr>
<tr>
<td>SK 681 496</td>
<td></td>
</tr>
<tr>
<td>SK 558 472</td>
<td></td>
</tr>
</tbody>
</table>

Root Mean Square

Are there any areas in your model where the match is less good?
Now you have built your model, email your values for each parameter to the SMR. This is for the uncertainty section later in the exercise. Sketch your recharge and hydraulic conductivity zones on the maps below and hand them in with your parameters.

Figure 7.6: Recharge zones

Figure 7.7: Hydraulic conductivity zones
7.4.12 Water balance

Complete chapter twelve of the online tutorial now. Perform a water balance for the whole of your model (i.e. the “whole study area” zone). You can also perform water balances on each individual zone. You will see outflows and inflows to and from the other zones. Do they add up?

<table>
<thead>
<tr>
<th>Zone</th>
<th>Inflow (m³/day)</th>
<th>Outflow (m³/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Trent</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.4.13 Pumping well

You are now in a position to make your prediction about the effect of the new pumping well. Add the well to your model. The OS grid reference for the well is SK 550 450. It is expected to pump at a rate of 5000m³ per day.

Perform a water balance again.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Inflow (m³/day)</th>
<th>Outflow (m³/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Trent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumping well</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 7.4.14 Contaminant spill

Complete chapter eight of the online tutorial now.

Use the particle tracking feature to investigate the effects of contaminant spills on the well. What is the area in which a contaminant plume would reach the well in fifty years? One hundred years?

You can calculate the catchment area of a well for a given period of time using the equation below (Bear & Jacobs, 1965, cited in Lerner, 2010):

$$ A_t = \frac{Q t}{b n} $$

Where $A_t$ is the catchment area for time $t$, $Q$ is the pumping rate of the well, $b$ is the thickness of the aquifer and $n$ is the porosity.

Use this equation to calculate the area in which a contaminant plume would reach the well in fifty and one hundred years. Compare your findings from the equation and the model.

<table>
<thead>
<tr>
<th>Time</th>
<th>Area (model) (km$^2$)</th>
<th>Area (equation) (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 years</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 7.4.15 Sensitivity analysis

You have chosen values for a large number of parameters whilst building your model. Further field investigations may show that some of these values are incorrect. A sensitivity analysis can be used to investigate which parameters are most “important”, i.e. which cause the largest changes to the results of your modelling exercise if they are changed.

Investigate how changing your parameters affects the capture area of your pumping well.

Try increasing and decreasing each parameter by fifty percent (one at a time).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original value</th>
<th>+ 50%</th>
<th>New capture area</th>
<th>- 50%</th>
<th>New capture area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquifer zone one K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquifer zone two K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquifer zone three K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone one</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone two</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge zone three</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean bottom</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Lean sediment conductance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Trent stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Trent bottom</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Trent sediment conductance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Does changing your parameters have a large effect on your capture area? Which of your parameters has the greatest effect?
You have probably found that varying your parameters has had only a very small effect on your capture area. This is because the heads calculated by your model are not very sensitive to the parameters of the model. This leads to the problem of uncertainty, as different sets of parameters can give the same heads.

7.4.16 Uncertainty
Once everyone has emailed their values for each parameter to the SMR, the SMR will put these together into a spreadsheet and email them back to everyone.

Take a look at other people’s parameters. Are they very similar to yours? Chose a few which are most different and try them out in a model for yourself. How do the head patterns generated by these alternative models compare to yours? Which model would you use when advising the client?

7.4.17 Geology
You may find chapter fourteen of the online tutorial useful for this section.

The geology has been represented very simply so far in your model. How would you improve this? Consider areas where the aquifer is confined/unconfined, variable thickness and the angle of slope of the aquifer. Does this have a big effect on your model results?
7.5 Report
You are required to write a report to the client informing them of the results of your modelling exercise.

Your report should include discussions about the following:

- The boundaries of your model (including rivers), why they were chosen and what effect they have on your results.
- The geology, how it was represented in your model and why. Could it have been done differently?
- Calibration and validation; how well does your model match the field data? Was calibrating your model an easy process?
- Sensitivity; which parameters affect your results the most? What effect does this have on your confidence in your results?
- Uncertainty; is there a variation in the models other students have developed from the same data? How does this affect your confidence in your results? Which model would you use when advising the client?

7.6 Conclusion
You have successfully built and utilised your first groundwater model. Although this exercise was simplified, the skills you have learnt and pitfalls you have observed apply to any modelling exercise. You will find them useful not only if you are required to build a model, but also in evaluating the results of other people’s models.

7.7 Recommended Reading
Anderson and Woessener 2002. “Applied Groundwater Modelling: Simulation of Flow and Advective Transport”. California: Academic Press. – This textbook gives a good overview of most of the areas covered in this exercise (with the exception of uncertainty). It focuses much more on the computer code behind the software than this exercise does, but the first section in each chapter are very helpful for students working through this exercise.

Brooks R.J., Lerner, D.N. & Tobias, A.M. 1994. “Determining the range of predictions of a groundwater model which arises from alternative calibrations”. Water Resources Research, vol. 30, no. 11, p2993-3000. – This paper gives an informative demonstration of how different modellers might get different values for parameters despite modelling the same problem with the same data.
8 Discussion

In this chapter the sections of the exercise are discussed in chronological order. An explanation of the intended learning outcomes is given for each section followed by my observations and feedback received. The resulting modifications are then described. The chapter ends with a discussion of the quantitative feedback received from the students. Note: the section numbers in chapter eight correspond to those in chapter seven, i.e. section 8.2.1 discusses section 7.2.1.

8.1 Introduction

A very short introduction is given since the students will be keen to begin the exercise. Emphasis is put on the benefits to the students of completing the exercise in order to motivate them.

8.2 Getting Started

8.2.1 Downloading IGW

All the test students found these instructions clear and had no problems downloading IGW. However, prior to the test session, it was discovered that, although it is possible to download IGW onto a CICS Managed Desktop (university intranet computer), the security settings prevent the program being installed. It had been intended that students would complete the exercise using the computers in a computer room, but instead they required their laptops. It may be possible to circumvent this problem when this exercise is part of the official MSc syllabus.

8.2.2 The Online Tutorial

Learning Objective: To enter data into IGW and use the functions.

An advantage of choosing the Interactive Ground Water (IGW) modelling program is that it is user-friendly and intuitive. However it is still necessary to teach the students how to enter data and use the functions of the program before they begin the exercise. The authors of IGW provide an online tutorial based on a case study to teach the novice user. The students are directed to use this tutorial in the section above.

A hard copy of the tutorial will be provided (as stated in the exercise) because when IGW is in use the internal program windows (in particular the AIME window) required for data
entry appear in front of all other open windows. This makes reading the tutorial on screen whilst following its instructions awkward. During the testing sessions this problem was resolved by using IGW on the student’s laptop and the tutorial on a university intranet computer, but for students at home a printout is more practical. However the students at the testing sessions found the videos provided in the tutorial useful so instructions to open the tutorial online were still included in the exercise handout.

There was confusion amongst the test students about whether the tutorial should be completed before or alongside the exercise. It is important that the students complete the tutorial before attempting the exercise since actions required in the exercise do not occur in the same order as in the tutorial. Also completing the tutorial first means the students are free to concentrate on modelling skills during the exercise, rather than which button they need to click. To make this clearer for the students, the sentences directing the student to complete the tutorial first and to use embedded example have been highlighted in bold.

Finally, when the test students opened the online tutorial they appeared daunted by its length and were unwilling to complete the whole tutorial. This is because the tutorial is broken down into many chapters so the contents page looks very long. In fact, some of the chapters are very short and the whole exercise takes around two hours to complete. I therefore incorporated a time estimate. To keep the students motivated, rather than ask them to complete the whole tutorial, the most relevant chapters have been selected. Also the students are able to start the exercise and return to the tutorial as other chapters become necessary.

8.3 The Case Study

**Learning Objective:** To read and assess a conceptual model and extract relevant data.

8.3.1 Introduction

As with the main introduction this has been kept short, but incorporates sufficient information to interest students.
8.3.2  Tasks
The task given to the students is very simple. This is in keeping with the intention to keep
the exercise simple. A task related to groundwater contamination was chosen since this is
the main focus of the MSc in Contaminant Hydrogeology, and although the hydrogeology is
the most important part of a modelling exercise, it was thought that bringing in an element
of contamination would give the students more interest in the exercise. Only basic particle
tracking is used (see later) so this does not distract from the groundwater modelling.

8.3.3  Geology
The students are given most of the maps and data used to develop model the exercise is
based on (see section 6.4).

8.3.4  Field Data
The “field heads” have been simply extracted from the model the exercise is based on. It is
therefore possible for the students to replicate these heads exactly if they choose identical
parameters to those used in the model. However the range of possibilities makes this
unlikely.

8.4  Exercises

8.4.1  Defining the Model Purpose

   **Learning Objective:** To understand the uses to which models can be put.

Defining the model purpose is the first stage of any modelling exercise and this is
highlighted by asking the students to explicitly do so.

The test students all correctly identified their model as a predictive model. The student
who returned his handout had written the following when asked for the questions for the
model to answer:

“The possible sources of contamination. Possible linkage (pathway) between source and
drilling BH? Is the supply BH is danger in terms of groundwater contamination.”

The last statement is the expected answer, showing that the student has understood the
task. The other issues the student has raised will not be covered in the modelling exercise
explicitly, but are relevant to the problem.
8.4.2 The Basemap

**Learning objective:** To manipulate co-ordinate systems.

The basemap provided is a geological map taken from the background geological information given to the students. A geological map was chosen for the basemap in preference to, for example, an OS map because the geological information is more relevant when the students are defining zones in their model.

It is important for students to learn to convert OS National Grid co-ordinates into whatever is needed for their modelling software. Understanding National Grid co-ordinates is a skill with much wider use than just for modelling exercises since almost all locations on any project in the UK will be given in this format. IGW requires a co-ordinate system to be given in metres, centimetres, feet or inches. Initially the second paragraph of the exercise excerpt above was not included and it was assumed that students, if they did not already have significant experience with National Grid co-ordinates, would look up (on the internet or elsewhere) how they related to real world distances. However the test session proved this was not the case. Most students converted the 25km base of the map to 25000m, but every student simply entered the co-ordinates of the bottom left hand corner as it was written, i.e. they entered X0 = 450m, Y0 = 340m and xlength = 25000m. (X0 and Y0 are the co-ordinates of the bottom left hand corner and xlength is the real world distance along the bottom edge of the basemap.) The correct values should be X0 = 45000m, Y0 = 34000m and xlength = 25000m. This was first noticed when one student observed that the “field heads” given for the purpose of calibration were off the edge of his map. Unfortunately if the co-ordinate system is entered incorrectly it cannot be corrected and the model must be started again from the beginning. For this reason a brief explanation of how to convert co-ordinates and a method of checking they are correct has been added to the exercise.

8.4.3 Identifying the Boundaries of the Study Area

**Learning Objective:** To understand the different types of mathematical boundary and identify which mathematical boundary appropriately represents a real-world boundary.

This section takes the students through defining the boundaries of model. The real-world boundaries are shown on the map (figure 4.3 of the exercise handout), which is also the map used as the basemap. The students are asked to identify which types of mathematical
boundaries are needed to model these real-world boundaries. The River Lean is a Cauchy boundary as the flow in the river is dependent upon the head difference across the river sediment (i.e. the groundwater head close to the river and the river stage). The Clifton Fault, groundwater divide and flowline are all no-flow (Neumann) boundaries.

The test students found this section a bit confusing so it has been rewritten to make it clearer. The student who returned his handout had given the following boundaries:

- River Lean – head dependent flux
- Clifton Fault – head dependent flux
- Groundwater divide – specified flux
- Flowline – specified flux

These are correct apart from the Clifton Fault, which should be a specified flux boundary. I believe the student understood the principles but missed the necessary fact that the Clifton Fault is non-transmissive. This has therefore been made more obvious in the text.

8.4.4 Aquifer elevations

The student is asked to keep the elevations of the aquifer the same throughout the exercise in order to prevent the exercise from becoming too complicated. At the end of the exercise the student is encouraged to experiment with different techniques to make the geology more realistic.

8.4.5 Your First Model

Learning Objectives: To identify strange results as incorrect and to understand the data requirements of a numerical model.

The student has created a model which contains no specified heads, leading to an infinite number of solutions. Some modelling programs might give an error message at this point, but IGW simply chooses a solution, apparently at random. If the model is solved repeatedly, a different solution is shown each time. Some examples of solutions from this model are shown overleaf.
Figure 8.1: Example solution for exercise section 7.4.5: Your First Model.

Figure 8.2: Example solution for exercise section 7.4.5: Your First Model.
The solutions shown by IGW tend to have strange angular head contours which do not resemble the sort of pattern expected as a solution. The test students were only told to solve the model once and it was hoped they would realise something was wrong when they saw the odd contours. They were then directed to look back at section 7.4.3: Identifying the Boundaries of the Study Area and provide an explanation for the failure of the model. However instead of realising this was intentional all the test students panicked and assumed they had made a mistake. It is hoped that by asking the students to solve the model multiple times and observe that the head contours change each the student will understand the problem is with the parameters of the model. The paragraph in section 7.4.3 which provides the information required to explain the problem has also been highlighted in the text to help students spot it.

It is considered that asking the students to solve a model which does not work at the beginning of the exercise is disheartening and confusing. However it is important to teach the students about the data requirements of models and the best way to do this is by showing what can go wrong. This part of the exercise cannot be put later in the exercise without asking students to delete some of their parameters from their model which will seem (rightly) counterintuitive. Therefore this section has been left in place.
8.4.6 The River Lean

Learning Objective: To recognise a sensible set of results.

Adding the River Lean to the model gives a reference head (the stage of the river) so a unique solution exists. The solution to the model in its current state is shown below.

![Figure 8.3: Solution for exercise section 7.4.6: The River Lean](image)

The smooth head contours and flow towards the river should make students feel comfortable that their model is now working sensibly.

8.4.7 Calibration

Learning Objective: To calibrate a model.

Calibration is a very important stage in modelling. The model is too simple to get a good match for the “field data” (taken from a more complex version of the model). However the
student is asked to calibrate this model so they understand the principles of how calibration is performed whilst they still have relatively few variables.

### 8.4.8 Recharge

**Learning Objectives:** To use information given in the conceptual model to enhance the model. To observe that adding new features to a model can have a large effect on the results.

The student can use the geological map given as the basemap to identify where the aquifer is confined and unconfined. Another map given in the case study background information shows the built up area (shaded in Figure 8.4).

The three zones are shown below (zones one and two have the same recharge). Zone one/two is confined and has the lowest recharge, zone three is unconfined and zone four is unconfined and urban, giving it the highest recharge.

![Figure 8.4: Model zones](image)

Adding the recharge has a larger effect than making zones of differing hydraulic conductivity, which is why the recharge section of the exercise occurs first. The head contours produced by this model (shown below) now have a very similar shape to those produced by the final model so students should begin to get a reasonable approximation for their “field heads”.

60
Figure 8.5: Solution for exercise section 1.1.1: Recharge
8.4.9 Hydraulic Conductivity Zones

**Learning Objectives:** To use information given in the conceptual model to enhance the model. To realise that calibrating a complex model is a time-consuming process.

The geological map can be used to identify two zones which could have a different hydraulic conductivity. Zone three/four (see Figure 8.4) is unconfined whilst zone one is confined and has a slightly lower hydraulic conductivity. The students may or may not add zone two which has a still lower hydraulic conductivity due to the aquifer getting deeper resulting in increased pressure and smaller pore sizes.

The solution to the model is now as shown below.
8.4.10 The River Trent

**Learning Objective:** To question the conceptual model and change it if required.

The River Trent is not hydraulically connected to the aquifer because it (mostly) runs over the Mercia Mudstone which acts as an aquiclude. Therefore it has not been included in the model, and students will find that adding the Trent to their models does not improve the match between their modelled heads and the “field heads”. This is intended to make the students think about their conceptual model. Rather than just adding the river because they have been instructed to do so, they can see the effect of the river on their heads and use the geological information to provide a justification for excluding the Trent from their model. Unfortunately none of the test students got this far with the exercise so I do not know whether they would have made this decision.

The figure below shows the solution if the River Trent in included in the model and given the same properties as the River Lean.

![Figure 8.7: Solution if River Trent is included as in exercise section 1.1.1: The River Trent](image)
The inclusion of the new surface water body has a large effect on the head contours, as expected, so it should have a large detrimental effect on the students’ “goodness of fit” between their modelled heads and the “field heads”.

8.4.11 Validation

Learning Objectives: To appreciate the difference between validation and calibration. To validate a model.

The process of validation would not normally be undertaken for a steady-state model, however it is included here so the students understand the principle, in particular how validation is separate from calibration.

The heads for calibration and validation have been simply read from the model as the basis for the exercise (described in section 6.4). The heads used for calibration are deliberately located mostly near the urban area and the River Lean. This is to simulate only having data in existing boreholes which may not be ideally placed. The heads for validation include one in the top right hand corner of the study area. The students may find that this head does not match their modelling heads as well as the heads in other parts of the study area. This is intended to show that insufficient data leads to uncertainties within the model.
8.4.12 Water Balance

**Learning Objective:** To examine the model in detail.

IGW can plot mass balances for water and contaminant particles. This section is included in the exercise to encourage the student to think about the model he or she has created by looking at it in depth. A water balance for the whole study area is shown below:

![Water Balance for Whole Study Area](image)

Figure 8.8: Water balance for whole study area from exercise section 7.4.12: Water Balance

As expected, the only input of water is from recharge and the only output is via the river. There is no change in storage since this is a steady state model.

Water balances can also be viewed for individual zones within the model. For example, a water balance for zone three is shown below (see Figure 8.4 for location of zones):

![Water Balance for Zone Three](image)

Figure 8.9: Water balance for zone three from exercise section 7.4.12: Water Balance

In this case there is an input of water from zone one ("bdy in") and a very small output to zone four ("bdy out"). The student is asked to perform mass balances for all the zones and will find that the input and outputs all add up to give the inputs and outputs for the whole study area.

8.4.13 Pumping Well

**Learning Objective:** To examine the effect of adding an anthropogenic feature to the model.

The pumping well only has a small effect on the heads contours as shown in Figure 8.10 below.
The student can check the water balance again; this time there is a second output to the well, as shown below.

The volume of water pumped by the well is small compared to the volume discharge to the river.
**8.4.14 Contaminant Spill**

**Learning Objectives:** To answer the question posed in the task. To compare an analytical solution to a numerical solution.

It is in this section of the exercise that the student finally answers the question posed in the task. They are encouraged to compare the modelled answer to an analytical answer since it is useful to have a “reality check” when modelling to help pick up gross errors.

The porosity of the aquifer is 0.2, the modelled thickness is 100m and the pumping rate of the well is $5000\text{m}^3/\text{day}$. This gives $A_{50} = 4562500\text{m}^2 \approx 4.6\text{km}^2$ and $A_{100} = 9125000\text{m}^2 \approx 9.1\text{km}^2$.

IGW allows the user to track particles forwards or backwards. The simplest way to complete this exercise is to put particles in the well and track them backwards for fifty and one hundred years. Figure 8.12 and Figure 8.13 show the results of this.

![Figure 8.12: Result of backwards particle tracking from well for fifty years, exercise section 7.4.14: Contaminant Spill. The pumping well is marked by a star, The particle cloud is to the east of the well.](image-url)
By drawing a shape around the particles and the well the area required by the exercise is shown.

8.4.15 Sensitivity Analysis

**Learning Objectives:** To perform a sensitivity analysis. To observe that heads are insensitive to model parameters.

A sensitivity analysis is an important part of any methodology since in hydrogeology most or all input data are uncertain. If the final result is heavily dependent on one or more parameters which are known to a low degree of certainty, then the result is only known to that same degree of certainty.
In a modelling exercise a sensitivity analysis is usually carried after calibration but this has been excluded from this exercise for simplicity. It is important for students to carry out a sensitivity analysis, however, so they analyse the sensitivity of the capture area of their well.

A problem with groundwater modelling is that heads are fairly insensitive to the alteration of many of the parameters in the model (Evers & Lerner, 1998). The students will find this is the case and their sensitivity analysis does not give any interesting results. This leads to the next part of the exercise on uncertainty.

8.4.16 Uncertainty

**Learning Objective:** To appreciate the problem of uncertainty in modelling in a non-mathematical way.

Uncertainty is a big problem in modelling. As heads tend to be insensitive to modelling parameters, it is possible for different modellers to replicate the same field data with different model parameters (Brooks et al, 1994). A class of students have all used the same field data, but deliberately little guidance has been given about the values of parameters to be used. Therefore all students will have different values and it is likely that some models have very different values. (Unfortunately the test students did not get this far so this theory has not been tested.) Collecting all the students’ values for parameters and allowing them to see the variation is intended to give the students a feel for the uncertainty inherent in modelling, without going into the complex mathematics, such as presented by Hill & Tiederman (2007).

Asking the students to think about which results they would present to a client should emphasise the fact that each student only produced one of these sets of results and therefore might not have the “best” set to present. The students are expected to choose either a worst-case (i.e. the largest capture area) or an envelope between the best- and worst-case.
8.4.17 Geology

**Learning Objective:** To develop a model without guidance.

The final section of the exercise is intended to give the student freedom to explore the modelling program and think for themselves. There are a number of different ways the geology could be made more accurate using the IGW program. Currently the aquifer is represented as completely flat, homogenous and unconfined as shown below:

![Aquifer representation](image1)

*Figure 8.14: Geology as represented in model*

A very simple method of adding the Mercia Mudstone would be to create two zones, one where the aquifer is confined and one where it is unconfined, e.g.

![Confined layer added](image2)

*Figure 8.15: Geology with simple confining layer added*
8.5 Report

**Learning Objectives:** To communicate the results of the modelling exercise. To consolidate students’ thoughts.

The students are asked to write a report in order to test their understanding of the project. This gives them an opportunity to discuss their experience of the exercise and ideas of how to improve their model (particularly the representation of the geology, see section 1.1.1). A report was the preferred method of assessment for four out of six students who completed the initial questionnaire.

A marking scheme for the report is shown overleaf. The criteria are based on the criteria for other coursework reports for the MSc.
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Threshold</th>
<th>Excellent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Presentation</strong></td>
<td>Sections numbered; figures labelled and referred to in text.</td>
<td>Sections numbered usefully; figures convey information effectively and are clearly labelled and referred to in text.</td>
</tr>
<tr>
<td><strong>Structure and coherence of argument</strong></td>
<td>Report has basic structure; argument is linked to student’s own data and model.</td>
<td>Report has useful structure; argument is linked to data and model, including other student’s models.</td>
</tr>
<tr>
<td><strong>Scope and accuracy of analysis</strong></td>
<td>All sections of exercise completed; brief discussion of sensitivity and uncertainty; discussion of how geology is not accurately represented (section 7.4.17).</td>
<td>All sections of exercise completed; discussion of sensitivity and uncertainty; discussion of one way of representing geology more accurately (section 7.4.17).</td>
</tr>
<tr>
<td><strong>Evidence of additional reading</strong></td>
<td>One source referenced correctly within text and in references list.</td>
<td>Multiple sources referenced correctly within text and in references list.</td>
</tr>
</tbody>
</table>
8.6 Quantitative Feedback

The two students who gave feedback seem to have worked at roughly the same rate which suggests that neither of them got “stuck”. Student A completed up to section 1.1.1: Recharge in four hours. Student B reached section 1.1.1: The River Lean in three hours.

Both students felt the exercise was a bit too long (giving a score of two for length where one = too long and five = too short). However they may have been expecting to complete the exercise in one day (since they were only asked to attend one test session). When the exercise is presented as a module students will expect it to take longer.

Student A felt the complexity of the exercise was about right (giving a score of three where one = too complex and five = too simple). However student B gave a score of one, indicating she felt the exercise was too complicated. This is a little worrying since the exercise cannot be simplified much more without losing its teaching value. Some of the text in the handout was modified after the test session so it is to be hoped that this might help student B.

Both students would have liked more guidance to be provided in the handout. Student A gave a score of two and student B a score of one where one = not enough guidance and five = too much. However they both seemed to be capable of progressing through the exercise. Some extra bits have been added to the guidance as a result of questions asked but increasing the amount of guidance substantially would result in the students simply putting numbers into the computer program without understanding why.

Both students felt they would have been worried about the report if they had been asked to write it. Again student A gave a score of two and student B a score of one where one = very worried about the report and five = very confident. However student B did note that she thought that writing the report would be straightforward if “we have done very well in previous questions”.

More positive results were gained when the students were asked how they thought the exercise had improved their understanding of groundwater modelling. Where one = not at all and five = a lot student A thought his understanding of groundwater modelling processes have been improved by a score of four, his understanding of groundwater modelling
uncertainty by a score of three and his overall understanding of groundwater modelling by four. Student B gave scores of four, four and five for the same questions. This is very promising, particularly as the students had not completed the exercise and so cannot have had the full benefit from it. It should be noted that neither student had reached section 7.4.16: Uncertainty so their scores for the improvement of the understanding of uncertainty are not related to this section.
9 Personal Reflection

This chapter contains some of my thoughts and feelings during the dissertation period, with particular emphasis on what I have learnt from completing this project. This chapter is included in this report because reflection on work at the end of a project is considered an important process for adult learning (Allan, 2009).

9.1 Skills

Most dissertation projects are based on original research carried out by the student; often this involves a substantial amount of lab or field work. This dissertation is unusual as it is not based on research, but instead on teaching. This worried me a little when I chose the project title. However, in the previous academic year (2009/2010) I had completed a Fourth Year (MEng) Project (equivalent to a dissertation) in the traditional sense (i.e. based around my own work in a laboratory and the results I obtained) so I was keen to use this opportunity to try something different and learn a new set of skills. The purpose of a dissertation project is to learn skills which may be useful in later life. Some careers (for example joining academia) have an obvious teaching element, but teaching may be required in any job, for example working in a consultancy. This could be formal, for example giving lectures to new staff, or informal, e.g. talking a colleague through how to use a new piece of equipment. I have had very little experience of teaching so I was keen to learn.

All dissertation projects involve presenting the work as a long report and often as a verbal presentation or poster. These elements are important to help students improve their communication skills. My project required a much higher level of communication since the exercises are intended to be completed without supervision. This was daunting, particularly as many of the students studying for the MSc speak English as a second language. I had to concentrate on using simple language when writing the exercise. I was relieved when the problems encountered by the students at the test sessions seemed to be easily solvable and did not relate to communication.

Time management is an important part of any large project, no less with this one. At the beginning of the project I felt I had plenty of time. I constructed a Gantt chart and this seemed to show that there would not be a large amount of time pressure. The first stages of the project (writing the exercise) went as planned although the exercise test sessions
occurred right at the end of their allocated period of time due to the availability of volunteers (see section 9.2 for more detail). However, I had not appreciated the amount of time required to write the report at the end of the dissertation. Two weeks now feels pitifully short! This was a useful lesson to learn since I am starting a PhD in October which will culminate in an even larger report (thesis). I had written some parts of my dissertation report as I went along which has saved some time now. This has been very useful and I intend to do this next year.

In addition to these transferrable skills, I have, of course, learnt a lot about groundwater modelling. Everything the exercises are intended to teach students, I have learnt by the process of reading textbooks and papers. I hope the exercises will provide a more rapid and stimulating method of transferring these skills!

9.2 Testing the Exercise

Testing the exercise on MSc students was a major part of this project. All of the students studying for the MSc Contaminant Hydrogeology course were asked at the beginning of a lecture if they would like to try the exercise. Emphasis was put on the benefits they would receive from taking part, i.e. improved understanding of modelling. All seven students stated that they were interested. An email list was compiled and an email sent around thanking them for their interest, describing how the test sessions would work and promising a bar of chocolate on handing in feedback. This positive reaction made me optimistic that the test sessions would run smoothly and I would receive lots of feedback. I had been a little anxious about obtaining volunteers.

Some flexibility was needed in arranging the test sessions since one (part time) student lives away from Sheffield and the other students were all working on their own projects at the time when the exercise needed to be tested. It was agreed that there would be test sessions in a computer room, during which I would be present so students could ask questions. The exercise handout and feedback questionnaire would also be emailed around so students could complete the exercise at home if they preferred.

Four dates in the fifth and sixth weeks of the dissertation work period were given initially. Nearer the time I received invitations to two interviews in the fifth week of the dissertation work period. I was worried about time so I cancelled the two sessions in the fifth week (Tuesday and Thursday) and replaced them with a third session (Friday) in the sixth week.
The sessions were now on the Monday, Wednesday and Friday of the sixth week. The students were asked to confirm which session they planned to attend but only four students did so. Three planned to attend the Friday session and one would attempt the exercise at home. Two of the students had previously said they intended to attend the Wednesday session so the later dates were clearly preferable. I was pleased that four students were still planning to test the exercise as I thought that four would give me a reasonable quantity of feedback.

The students who had not stated which session they wished to attend were each sent individual emails in an attempt to persuade them to participate. One student had been away and arranged to come to the Friday session. No replies were received from the remaining two, although I later learned that they were also away. It was disappointing that (as I thought) my emails were being ignored, but I had expected that some students would not wish to participate. I would have liked to contact the students by telephone but could not do so since I did not have their phone numbers.

As replies had not been received from all the potential test students, I needed to attend all the planned sessions in case somebody attended without informing me. (This may have been a case of misplaced optimism, but if someone had come and I had not been present an opportunity for feedback would have been missed.) It was frustrating to come into Sheffield on the Monday and Wednesday and sit on my own. The time was not wasted however, as on the Monday I attempted the exercise myself and discovered that if IGW was downloaded onto a CICS Managed Desktop (i.e. a university intranet computer) the security features would not allow it to be installed. Therefore the students attending the Friday session were instructed to bring their laptops. This discovery saved the Friday session from total disaster.

On Friday one student was ill but three attended. They did not get very far with the exercise (two had to leave early for meetings) so I asked for feedback on the exercise as far as they had got. One student had completed the feedback questionnaire hard copy. The other two wished to continue with the exercise at home. I asked them to send feedback by Sunday as this was the deadline I had set for the student completing the exercise remotely. On Sunday only one set of feedback was received. The students with outstanding feedback were emailed and both claimed to have not completed enough of the exercise. They were told that any feedback at all would be gratefully received but none arrived.
In summary, only two sets of feedback were received from an initial set of seven volunteers. This was disappointing after such a promising start but I have learnt a lot about working with volunteers. The main incentive for the students of helping me with my project (other than a bar of chocolate) was that they would learn about modelling from attempting the exercise. This was understandably a low priority compared to working on their own dissertation projects. It would have been better to conduct the tests at a time when the students were less busy, but this was not possible since, of course, my own dissertation also has to be completed in the dissertation period. Alternatively, a better incentive could have been offered, such as paying the volunteers. Clearly if the exercise is to become part of the MSc course it would be important to make it compulsory.

Only a small amount of feedback was received and most of the comments turned out to be very general. However I had also taken notes during the exercise session recording what students had asked me and noting problems they encountered. These notes turned out to be the most valuable source of information and most of the improvements to the exercise are derived from these. I felt relieved I had kept a project diary.
10 Further Work

10.1 Exercise Implementation

The exercise was intended to be an entirely self-study project whereby students are given
the handout and complete the exercise in their own time, subject to a deadline for the
report. However since the entire exercise has not yet been completed by a student, a
phased implementation is recommended.

The first year the exercise is used as part of the MSc there should be scheduled sessions in a
university computer room at which the SMR (Staff Member Responsible) or a
representative is present. These sessions will be similar to the test sessions run by the
author, except that the students will have a stake in the exercise and motivation for
completing it successfully. The presence of the SMR allows students to easily ask questions.
The SMR can record any areas of the exercise which commonly cause problems and need
refinement. A series of three or four afternoon sessions is suggested as this should give
most students enough time to work through the handout. Any students who do not finish
in the scheduled sessions will, of course, be able to complete the exercise on their own.
The students will subsequently write the report in their own time as usual for coursework.
There should be a coursework tutorial (as for other modules) during which students raise
questions about any remaining issues with the exercise or about the report.

The second year should be the same as the first, except that only one scheduled session
occurs. This will give students a chance to get started under supervision, but complete the
exercise on their own. Most problems are likely to occur towards the beginning, when the
students are less familiar with the exercise format.

In following years (or later is the SMR thinks it advisable) the students will be given the
handouts and complete the exercise on their own as intended, however one or more
coursework tutorials should still be held so students have a chance to ask questions. I
suspect that this may prove problematic and it could be best to keep the one scheduled
session to get the students started.
10.2 Exercise Extensions

The current exercise only comprises of a basic model in order to not overwhelm the students. However there is potential to expand it to cover other areas, either as extensions to the existing exercise, or as a separate follow up exercise. Some possibilities for further development are suggested below.

1) Different aquifers. As the exercise has been based on a case study, it has only looked at one aquifer. Different aquifers all have individual features so basing further exercises on alternative aquifers could be used to teach ideas about how to incorporate additional features into a computer model. For example the Chalk would provide a challenging exercise.

2) Different tasks. Models can be used to make a wide range of predictions. The model built in this exercise could be used to investigate (for example) the effects of multiple pumping wells on each other, or on the flow in the River Lean.

3) Transient behaviour. The exercise model is a steady state, but it would be relatively simple to add transient behaviour. For example, recharge rates could be given seasonal variation. IGW is capable of producing transient simulations and there is a relevant chapter in the online tutorial. This would be useful for teaching the process of validation more thoroughly since it is more appropriate for transient models.

4) Three dimensions. The 2D version of IGW had been used for this exercise but a similar exercise could be constructed using IGW 3D. This would teach greater awareness of vertical flows and the effects of confining layers, leaky confining layers and multiple aquifer systems.

10.3 E-Learning

The current format of the exercise involves hard copy handouts on which students are required to write answers and fill in tables etc. However this exercise lends itself to being completely computerised in a similar way to the Computer-Based Instructional (CBI) aid designed by Zigic & Lemckhert (2007). When students are asked, for example, what the purpose of their model is, they could select answers from drop down menus. A large number of tables are filled in by the students, particularly during model calibrations. These tables could be designed so they automatically calculate the root mean square for the student, which would save a lot of time spent repeating a simple (but long) calculation and
allow the students to focus on adjusting the parameters. Help functions could be incorporated which may reduce the need for supervision.

Presenting the exercise in this format would allow students to complete the exercise without physically visiting Sheffield as they could access the content via the internet. Professionals often attend modules from the Contaminant Hydrogeology MSc as part of their Continuous Professional Development (CPD). Remote modules could become an attractive feature and increase Sheffield’s share of the CPD market.
11 Conclusions

Groundwater modelling is an important skill in the hydrogeologist’s toolbox, but it is vital to recognise the limitations of models. The aim of this project was to design a self-study exercise to teach groundwater modelling to students studying for Sheffield University’s MSc in Contaminant Hydrogeology.

An exercise was created using the Interactive Ground Water (IGW) software and using the Nottingham area as a case study. This was tested on volunteers from the current cohort of MSc students.

Creating the exercise was feasible but not straightforward. Each of Kolb’s learning methods was incorporated into the exercise to make it accessible to all students. A staged approach adopted to allow students to solve the model at each stage, providing feedback and the opportunity to observe the effects of editing the model.

Students who tested the exercise found it useful and enjoyable, however they required onsite help. Further testing of the exercise is required to identify and rectify any remaining problems. It is envisaged that an initial supervised session will be required to launch the exercise for students.

Motivation of students remains an issue. Few students volunteered to attempt the exercise for the reward of learning (and a bar of chocolate). Only two students gave feedback. If the exercise is used as a part of the MSc course, the marks available to students for writing a report will provide motivation. This report should be equivalent to an ordinary piece of coursework.
12 References


13 Appendices

13.1 Preliminary Questionnaire

My dissertation project is to design self-study exercises for students to learn groundwater modelling techniques. Please take a few minutes to fill in this questionnaire to help me decide what format these exercises should take.

1) Which would you prefer (please tick one):
   - [ ] A series of short unlinked exercises each covering a particular aspect of modelling.
   - [ ] One long case-study exercise, building up a larger model.

2) If you were given a self-study exercise and told it was optional, how likely would you be to complete it?
   - [ ] I would definitely complete the exercise.
   - [ ] I would probably complete the exercise.
   - [ ] I would probably not complete the exercise.
   - [ ] I would definitely not complete the exercise.

3) What assessment method would you think was appropriate for these exercises?
   - [ ] A proper exam in the Mappin Building.
   - [ ] A multiple choice exam on MOLE.
   - [ ] A coursework exercise and report.
   - [ ] A fixed amount of marks for completing the exercises.
   - [ ] No assessment.
   - [ ] Other, please state: ............................................................................................................................................
13.2 Feedback Questionnaire

This questionnaire is in two sections. Firstly there are some general questions about your reaction to the exercises, and secondly there is space for any comments you have on the exercises.

13.2.1 Questions

How long did you spend on the exercise?

............... hours

What section did you get up to?

Section .............

On a scale of one to five, how did you feel about the length of the exercise?
(one = too long, five = too short)

......................

On a scale of one to five, how did you feel about the complexity of the exercise?
(one = too complex, five = too simple)

......................

On a scale of one to five, how did you feel about the amount of guidance provided?
(one = not enough, five = too much)

......................

On a scale of one to five, how confident would you feel about writing the report?
(one = very worried, five = very confident)

......................

On a scale of one to five, how much do you think the exercise has improved your understanding of the process of groundwater modelling? (I.e. the stages you have to go through to build a model.)
(one = not at all, five = a lot)

......................
On a scale of one to five, how much do you think the exercise has improved your understanding of the uncertainty associated with groundwater modelling?
(one = not at all, five = a lot)

……………………

On a scale of one to five, how much do you think the exercise has improved your understanding of groundwater modelling overall?
(one = not at all, five = a lot)

……………………

13.2.2 Comments

Use this space to make any comments about the exercises. Anything at all will be helpful, whether specific things like “this part is confusing / boring” and “more detail would be nice here” or more general things like how you think the exercise as a whole could be improved. Feel free also to write on the exercise handout if that is easier.

[A list of the exercise heading is then given with five lines by each for the students to record their comments. At the end was a further space for general comments.]