Protection of Adit Systems in UK Aquifers

Project Record
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This report provides a guide to defining groundwater protection zones for sources with adit systems.

Keywords
Adit; Pipe flow; Open channel flow; Water exchange; Preissmann slot; Protection of inflow zone; 50 day time-of-travel zone.

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R&D PROJECT RECORD W6/014/1

CONTENTS

List of Figures

Inception Report

First Progress Report

Second Progress Report

Third Progress Report

Fourth Progress Report

Fifth Progress Report

Sixth Progress Report

List of Tables

Inception Report

Fourth Progress Report

Fifth Progress Report

Sixth Progress Report

EXECUTIVE SUMMARY

The Chalk forms the most important aquifer of southern England and in many parts of north-west Europe (Price et al. 1993). Many Chalk groundwater sources in England have adits, which are horizontal tunnels below the groundwater table. The adits are connected to pumped wells from which groundwater is pumped to surface. Adits in the UK are typically 1.2 m wide and 1.8 m high. The flow in an adit may be pipe or open channel flow. Darcy's formula is not applicable to the adit, and conventional groundwater models are inappropriate to model aquifer-adit systems. Adits are often close to the water table and probably place the source at greater risk of pollution. Adits will cause a distinct three dimensional pattern of groundwater flow and influence the shape and position of source protection zones - these effects have not previously been quantified. In summary, there is a need for analysis and prediction of the hydraulic behaviour of adit systems.

The project was initially proposed as a two years project, However is extended for another six months to study stepped adits (adits located at different levels but connected by boreholes). The project started from July 1997 at the University of Bradford, and moved to the University of Sheffield in January 1998, and finished in January 2000.

Three objectives have been achieved in this project, (1) providing a suitable computer code for modelling groundwater to adit systems, (2) drawing up guidelines for modelling adit systems, and (3) developing guidelines for delineation of adit source protection zones.

The research consisted of five parts, which were: development of the method, Wilmington case study • steady state, Cottingham case study • transient condition, delineation of protection zones and modelling of stepped adits.

The U.S.Geological Survey (USGS) model BRANCH simulates one-dimensional unsteady, non-uniform, multiple-branch interconnected open channel flow. MODBRNCH incorporates BRANCH into MODFLOW simulating open channel and aquifer interaction using deterministic responses of both systems. An aquifer-adit model can be created by two steps. First, an integrated surface water and groundwater model (MODBRNCH) enables open channel flow to be simulated. Second, introducing a fictitious narrow slot (Preissmann slot) above the adit allows pipe flow to be simulated by open channel flow equations. The slot does not affect the adit cross-section area, and the water level in the slot represents the pressurized adit head, which can be used by MODBRNCH to calculate the water exchange between aquifer and adit according to their head differences. A small modification has been made to handle the slot.

The method was initially applied to Wilmington case study. Wilmington pumping station is one of the largest groundwater source owned by Thames Water Utilities Ltd and is located in southeast London. A steady state and multi-layer model was calibrated against multi-level piezometer data.

The second case study was Cottingham case study. Cottingham pumping station is one the largest groundwater source that Yorkshire Water Services has in Hull area. Cottingham groundwater source is very complex comprising of two operational pumping shafts, 17 other shafts and 1000 m of adit in use. Model calibration was against multiple targets including steady state and transient conditions, aquifer heads and adit heads, and temporal changes of adit head during a pumping test. Three alternative conceptual models were tested, each with different hydraulic assumptions about the interrelation between aquifer, adit and shafts.

Regarding delineation of protection zones, several artificial aquifers were studied, and the particle tracking program MODPATH was employed using the head distribution generated from following three methods: (1) specifying a high value of hydraulic conductivity for adit cells in MODFLOW, (2) replacing the adit by multiple abstraction boreholes using MODFLOW, and (3) a Combination of MODBRNCH and the slot approach. In addition, the differences between two-dimensional and three-dimensional models were examined to decide when a two-dimensional model is sufficient to delineate adit protection zones.

Finally the modelling of stepped adits was studied, which indicates that the step has little effect on the simulation results when the adit is saturated.

The study indicates that:

- The combination of the Preissmann slot approach and the modified MODBRNCH is able of simulating aquifer-adits interaction for both steady state and transient conditions.

- For calibration purposes, several multi-level piezometers and head measurements in the adit will be very valuable.

- A transient model simulating a pumping test is a necessary approach for modelling in order to understand the hydraulics and hydrogeology of adit systems.

- 2D models are sufficient for most adit sources in the UK. MODBRNCH and High K method derive similar 50-day time-of-travel zones and projection of inflow zones. However, MODBRNCH can simulate flow in the adits more accurately and indicate the interaction between aquifer, adit and shafts more precisely.

The project produced an Inception Report, six Progress Reports and a Final Report. The publications include two international conference papers and a GROUND WATER journal paper. Besides, a manuscript has been submitted to Journal of Hydrology.

Key words: Adit; Pipe flow; Open channel flow; Water exchange; Preissmann slot; Projection of inflow zone; 50 day time-of-travel zone

OPERATION AND PROTECTION OF ADIT SYSTEMS IN UK AQUIFERS

INCEPTION REPORT

August 1997

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SUMMARY

A literature survey on simulation of adit systems has been carried out and there is no existing computer code available for simulation of adit systems. A plan of code development for modelling adit systems is proposed herewith. The code development will be based on MODFLOW, which will be extended to incorporate adit flow and its simulation into aquifer simulation. The aquifer will be simulated as laminar flow by MODFLOW, whereas the adit flow will be formulated as turbulent flow. The water exchanges between these two flows will be computed iteratively.

The extended packages will be set up for two adit sites to test the computer code and to explore modelling techniques for adit systems. A Telescopic Mesh Refinement (TMR) modelling approach is proposed to be used, i.e. extracting a local model from its regional model, using the head values derived from the regional model to initialize the local model. This approach provides a mean of accurately incorporating regional controlling factors and characteristics into local model domain, and allows investigations to be focused on the pertinent area of interest for the adit system.

The primary criterion for site selection is the availability of field data including local groundwater levels, multiple piezometric levels, pumping test data and regional context information. These data can be either existing or planned to carry out, using existing data is preferred. The available data for five possible sites are introduced, each of them has both advantages and disadvantages.

1. INTRODUCTION TO THE PROJECT

A number of major groundwater sources in the UK have adits, horizontal tunnels up to 7km long, often with a number of vertical boreholes and shafts penetrating them. The hydraulics of these systems are not understood well enough to predict their behavior and reliable yield, nor are there well defined techniques for field testing systems to estimate yield. Adits are often close to the water table and probably place the source at greater risk of pollution. Adits will cause a distinct three dimensional pattern of groundwater flow and influence the shape and position of source protection zones - these effects cannot be quantified at present. In summary, there is a need for analysis and prediction of the hydraulic behaviour of the adit system.

1.1 Objectives

The objectives of this project are :

1. Providing a suitable computer code for modelling groundwater flow to adit systems.

2. Preparing guidelines for determining the yield of adit systems.

3. Demonstrating the effects of adits on source protection zones and develop guidelines for revising protection zones.

1.2 Methodology

Work will start with a literature review, which comprises: (1) the nature and behaviour of adit systems in the UK, available data from field sites; (2) published literature providing some ideas and methods related to the project; (3) literature introducing available computer codes to choose the most suitable code for modification.

Code development will include writing additional subroutines for a selected existing groundwater model code and testing the modified program.

Calibrated models will be developed for two field sites with different characteristics. Both will be in the chalk aquifer with adits, probably one confined and one unconfined. This will test the codes, as well as providing detailed understanding of the two sites, exploring techniques of adit field tests, estimating their reliable yield and revising protection zones.

The yield and source protection studies will attempt to generalize the results of the site specific studies, to draw up guidelines for modelling of adit systems.

2. LITERATURE REVIEW

2.1Characteristics of adits in the UK

The chalk forms most important aquifer of southern England. The total outcrop covers an area of some 21,000km^2. The chalk has a high primary porosity but low primary permeability. Boholes can however yield large quantities of groundwater, up to 20,000m^3/d. Approximately 15% of chalk groundwater supply sources have adits in England, to induce water into wells. Most of them are 6 feet high and 4 feet wide with arched roofs. The length of adits varies from tens of meters up to 7000m. The depth of adit varies between 10m-100m below ground surface, with a few of them even deeper. All adits are horizontal to authors' knowledge except one example called raker borehole (the profile diagram showing it is attached in appendix 1). The plan views of adit have patterns of straight lines, radial lines, T shape, loop and dendrite, etc. A group of adits can either be located at same depth, or varied depths but connected together by boreholes and shafts. Table 1 gives examples of chalk adits and Figure 1 shows a pattern of adit distribution.

Table 1. Example of Chalk Adit System

Site Name	Adit Length (m)	Depth (m)	Pattern	Number of Adits
Springhead	**1500**	**12**	**Straight Line**	**1**
Wilmington	**180**	**28**	**T shape**	**2**
Bricketwood	**1050**	**37**	**Radial Line**	**6**
Wall hall	**1201**	**34**	**Radial Line**	**3**
Eastbury	**Not clear**	**Varied**	**Dendrite & loop**	**> 10**
Lord of Manor	**7000**	**Not available**	**Curve**	**Not available**

Pumping tests show that groundwater levels observed in the boreholes connected with same adit drawdown at similar rates during pumping test (An example is shown in Table 2). This indicates that the groundwater in adits flows just like in pipes. The basic groundwater formula - Darcy's formulae is not applicable to the adit themselves. Consequently, most of computer programs for groundwater modelling, like FLOWPATH, MODFLOW and MODPATH which are based on Darcy's formula are not ideally applicable to adit systems.

Table 2. Example Taken from a Constant Yield Test at Springhead Pumping Station

Name of Sites	Pumping Time (minute)	Water Depth (meter)	Drawdown Rates
Springhead	270	4.60	0.8 mm/minute
	510	4.80	
Davis Corner	330	20.46	0.8 mm/minute
	520	20.62	

Notes: This constant yield test was taken palace at Springhead pumping station by Yorkshire Water on 17 July, 1997. The abstraction rate was 23000m^3/d. Davis Corner is connected with Springhead by an adit of 1.5 km long.

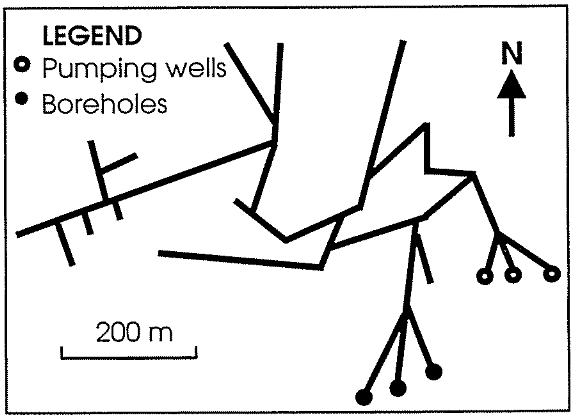

Figure 1. Example of Adit with Patterns of Loop and Dendrite.(Thames Water)

2.2 Published Literature Related to the Project

Published literature has been searched on the subject of adit groundwater modelling. The review found no research on modelling adits in aquifers, which indicates that this research area is a completely new development of groundwater modelling. There is some literature presenting researches having some similarities with modelling adits, which can be divided into two categories: modelling of Karst systems and modelling of abandoned mineworkings.

2.2.1 Modelling of Karst Groundwater

In general, the effective porosity of Karst terrain is a result of combinations of secondary porosity fissures and tertiary porosity in areas where the fissure system has been enlarged to conduits by chemical dissolution. Karst needs special computer programs to model it because groundwater flow within well developed channels and conduits may represent a significant departure from the assumptions of groundwater within the analytical and numerical techniques conventionally used. There are a few researchers working on the subject. The methodologies of modelling Karst systems can be described briefly as follows:

The characteristics of Karst water movement depend on the pattern of void media. Up to now, there is no standard method to formulate and simulate Karst terrain. A classification of Karst media into four categories according to their geometry is proposed by Chen Y.and Bian J. (1988), and is summarized by Table 3.

Table 3. Classification of Karst Media

Void Type	Void Width (cm)	Hydraulic Characteristics	Media Type
Cavern	**1-----10**	**Turbulent Flow**	**Control Media**
Fracture	**0.1-----1**	**Laminar---Turbulent**	**Transport Media**
Crack	**0.001-----0.1**	**Laminar Flow**	**Transport Media**
Matrix porosity	**< 0.001**	**Laminar Flow**	**Storage Media**

A scale hierarchy concept developed by Haldorsen (1986) has provided a useful method for analysis and simulation of groundwater in heterogeneous formations (It is showed in Figure 2). Employing the terminology introduced by Dagan (1986), three different scales are considered:

a) L, the length scale of flow domain
b) I, the length scale of flow dominating heterogeneities
c) D, the length scale of the detection method used.

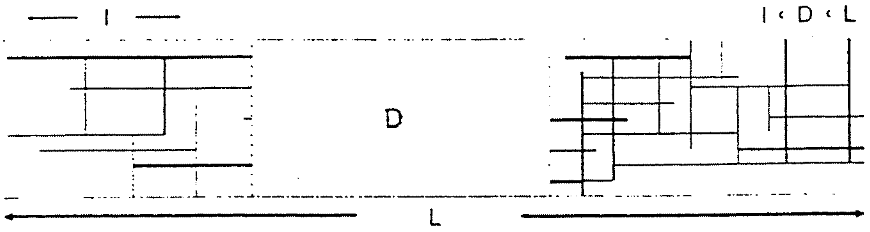

Figure 2: Schematic example of length scale hierarchy (I: heterogeneity-, D: detection-, L: domain-scale) (Haldorsen, 1986)

Figure 3 Shows a schematic example of heterogeneous system with I, L and D length scales.

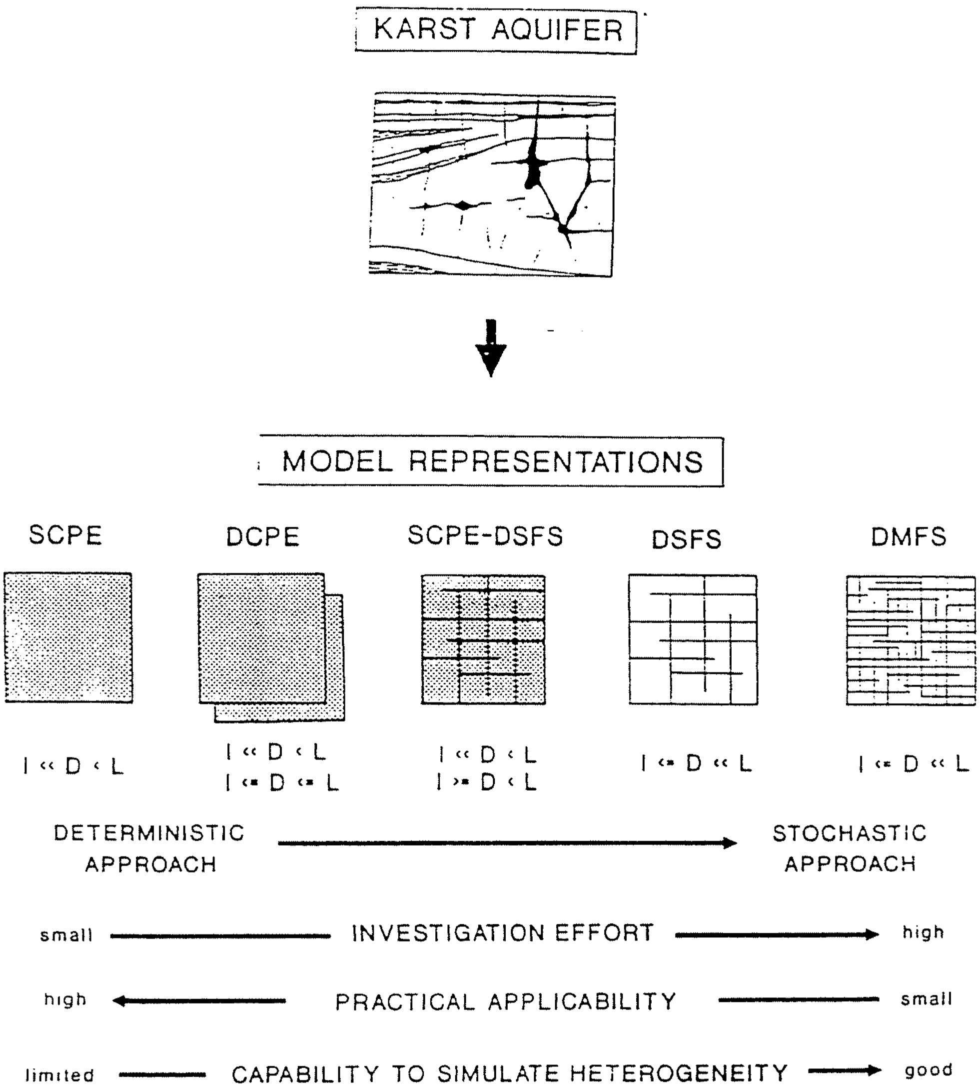

Figure 3 Karst aquifer prototype and five possible model representations (SCPE: single-continuum porous equivalent, DCPE: double-continuum porous equivalent, DSFS: discrete singular fracture set, DMFS: discrete multiple fracture set)

(Teutsch and Sauter, 1991)

The simplest approach to Karst flow is the single-continuum porous equivalent (SCPE). It is certainly a crude approximation to the complex variability of the prototype system. Obviously, using this approach individual fractures or conduits cannot be adequately represented except that the investigation at a scale D is much larger than the size of the heterogeneities.

For the double-continuum porous equivalent (DCPE) approach, one continuum is represented by conduit flow, and the other continuum is represented by fissure flow. Typically, the model of DCPE is applicable for medium size of modelling areas.

A much better representation of the real Karst system would be achieved by the model of discrete single fracture set (DSFS) and discrete multiple fracture set (DMFS). Only one set of fissured or conduit is represented by DSFS, whereas DMFS comprises multiple sets of discontinuities representing the whole range of flow systems with small scale fissures and large scale conduits. However, it should be noted that for the discrete fracture approach, the location and geometry of all individual discontinuities must be known. Still, DSFS and DMFS are becoming more and more widely used for Karst water modelling.

A program CAVE (Carbonate Aquifer Void Evolution) was applied in the EU GRACE project 'Modelling of Changes in Hydraulic Parameters of Carbonate Aquifers as a Result of Change in Climate' (Liedl et.al.,1996). The approaches used are briefly introduced as follows:

Karst water is divided into two components. A fissured system is modeled by a continuum approach, and a conduit network is simulated by flow through a discrete pipe network. Both components are coupled hydraulically by a linear exchange term. The conceptual model is illustrated in Figure 4 and the simulation of groundwater contour lines is shown in Figure 5.

The flow in the fissured system is simulated using the well known and widely accepted computer code MODFLOW which is based on Darcy's law and continuity equations. MODFLOW is primarily developed for a porous medium, although, MODFLOW has been successfully applied to some evenly fissured aquifers as well.

For well developed channels and conduits, MODFLOW is, however, not applicable, due to its fast flow pattern. The fast flow system of the Karst aquifer is represented in CAVE by a pipe network model. The conduits are assumed to be cylindrical and permanently saturated. The hydraulic formulae for turbulent flow in pipes or conduits are employed to calculate heads and velocities of flow.

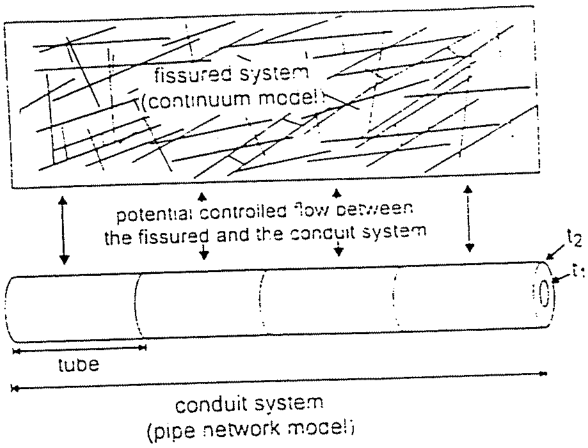

Figure 4 Conceptual model illustrating the fissured and the conduit system as well as the dissolutional enlargement of the tube diameter for two different times $t_1 < t_2$ (Liedl 1996)

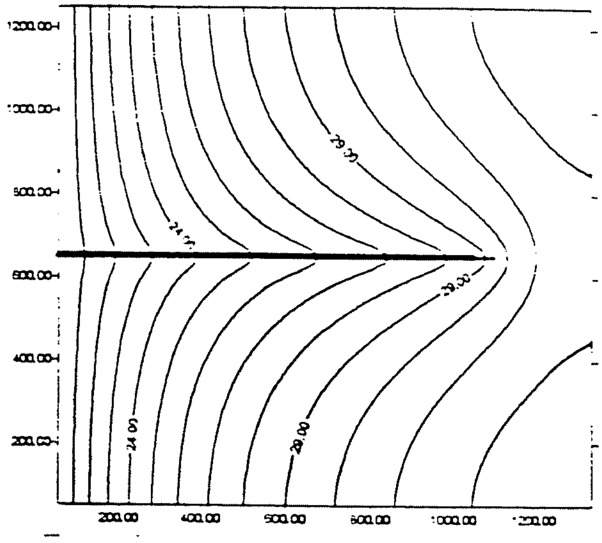

Figure 5 Simulation of Continuum and Conduit systems

2.2.2 Groundwater Modelling of Abandoned Mineworkings

The hydrogeology of abandoned mineworkings often includes a complex mixture of unsaturated zones, saturated aquifers and fast flow regions. Applications of two - dimensional groundwater model codes to abandoned mineworkings have had varying success (Toran and Bradbury 1988). Finite element groundwater codes had been modified to predict inflows into mineworking system (Fawcett et.al.1984, Girrens et.al. 1981). MODFLOW was also used to assess pumping requirement at mineworkings (Perry 1993). The unusual characteristics of mined strata and data limitation appear to have restricted the success of this models.

A lumped parameter model GRAM (Groundwater Rebound in Abandoned Mineworkings) has been developed (Sherwood & Younger,1994). This is a simple transient model which conceptualizes a minefield as a group of 'ponds'. Each pond is an area of mineworking which has been extensively worked and can be considered as a single hydraulic unit. The ponds can form any shape in plan, however they must be bounded by vertical walls of intact mine through which there is assumed to be no flow. The hydraulic gradient within ponds is assumed to be flat. This means that all flow to and from the pond is applied over its entirety. The ponds are connected by roadways along which flow is assumed to be turbulent.

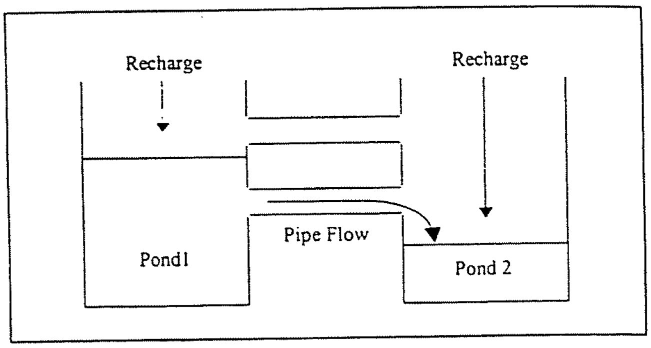

Figure 6 Ponds are Connected by Pipe Flow

There is a study (Adams &Younger, 1997) which divides an abandoned mineworking into two components, with one being called Variably Saturated Subsurface (VSS), which represents variably saturated porous media simulated by a program SHETRAN and the other referring to turbulent flow in abandoned mineworkings.

The governing equation for groundwater flow in variably saturated subsurface is:

$$\eta\frac{\partial\psi}{\partial t}=\frac{\partial}{\partial x}\left[K_x k_r\frac{\partial\psi}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y k_r\frac{\partial\psi}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_Z k_r\frac{\partial\psi}{\partial z}\right]+\frac{\partial(k_r K_z)}{\partial z}-q \qquad (1)$$

where x,y,and z are Cartesian co-ordinates,

q is a specific volumetric flow rate out of the medium representing sources or sinks,

ψ is pressure potential,

K_X, K_Y, K_Z are the saturated hydraulic conductivity tensors,

K_r is the relative conductivity which defines the unsaturated hydraulic conductivities ($K_r < 1.0$ in unsaturated media).

η is the storage coefficient defined as

$$\eta=\frac{\theta S_s}{n}+\frac{d\theta}{d\psi} \qquad (2)$$

where θ is the volumetric moisture content,

S_s is the specific storage

n is the porosity.

The model solves for a new value of the pressure potential ψ at each iteration.

In regions where the flow regime is likely to be turbulent, groundwater flow cannot be directly simulated by SHETRAN. In order to simulate turbulent flow, a pipe network model is adopted which will allow the large flow pathways to be discretised by a series of interconnected conduits, which are joined together at nodes where sources and sinks are added to the network.

The connections between the pipes in the network and VSS component are calculated by water exchange at each model iteration.

2.3 Available Computer Codes and Modification

No research into the groundwater modelling of adit systems has been carried out to authors' knowledge, so that no computer modelling code is available for modelling of adits. One has to either develop a complete new code or modify an existing computer code. Perhaps the latter approach is more efficient.

2.3.1 Finite Difference and Finite Element

Most commonly used numerical methods for groundwater modelling include the finite difference method and the finite element method.

For the finite difference method, the continuous system described by governing equation is replaced by a finite set of discrete points in space and time, and the partial derivatives are replaced by terms calculated from the differences in head values at these points. The process leads to systems of simultaneous linear algebraic difference equations and their solution yield values of head at specific points and times. These values constitute an approximation of head distribution that would be given by an analytical solution of the partial differential equation flow.

In the authors' opinion, the finite difference method has a very clear philosophy, is easily understood and used. Particularly, boundary conditions for adits are usually not too complicated comparing with Karst conduits. On the contrary, the finite element method is more complicated and will need much more computer memory and computation time if it is used, although it has an advantage in following the boundary geometries more closely.

2.3.2 MODFLOW

MODFLOW is recommended as the code for modification. The arguments are as follows:

1. MODFLOW has been extensively used for simulation of groundwater flow and is accepted world wide. As every one knows, MODFLOW is able to simulate both steady and unsteady states, single and multiple layers, confined and unconfined aquifers.

2. Although MODFLOW is based on Darcy's formula and is primarily developed for porous media, it has been successfully used in fissured limestone and chalk aquifers .

3. The specific computational and hydrological options of MODFLOW are constructed in such a manner that each option is independent of main program and other options. This means that new options or subroutines can be added without changing the existing program.

4. MODFLOW is able to be used in conjunction with MODPATH. In other words, the flow velocities calculated by MODFLOW can be used by MODPATH. Also, FLOWPATH file can be imported into MODFLOW.

5. MODFLOW, MODPATH and FLOWPATH are adopted by Environmental Agency of UK for determination of Groundwater Protection Zones.

6. The popularity and wide acceptance of MODFLOW has spurred the development of a large number of MODFLOW compatible programs for particle tracking, contaminant transport modelling, parameter estimation, uncertainty analysis, management optimization, graphical interfaces and visualization packages. Also, more and more extended packages of MODFLOW have been developed for specific groundwater transport media, including modelling Karst water, modelling abandoned mineworking, and perhaps modelling adit systems in the near future. This makes MODFLOW more and more convenient to be used and to play a key role in leading the future direction of groundwater modelling.

7. The authors of some of the MODFLOW interfaces have indicated that there should be no difficulty in using an adopted version of MODFLOW with their software, particularly Visual MODFLOW and Groundwater Vistas.

2.3.3 MODBRNCH

A program called MODBRNCH developed by USGS, is a combination of BRANCH and MODFLOW programs (Swain & Wexler). It simulates surface and groundwater interaction. Comparing with the River package for MODFLOW, MODBRNCH simulates not only river leakage, but also spatial and temporal distribution of water levels, flow discharges, flow velocities and water volumes within the open-channel network. It can be used to simulate steady and unsteady flows in a single open-channel branch or throughout a system of branches (network). MODBRNCH is particularly suitable for simulation of flow in complex geometric configurations involving regular or irregular cross sections of channels having multiple interconnections.

Flow equations are formulated by using water level and discharge as dependent variables. Subdivision of a branch into segments of unequal lengths is accommodated by the finite difference technique and the implicit solution scheme permit computations at large time steps. This produces a significant saving of execution time and computer memory.

Besides the input data for MODFLOW, MODBRNCH input data consist of channel geometry and initial flow conditions defined at all cross-section locations and boundary conditions defined at channel extremities.

Additional output data include spatial and temporal distribution of river stages, flow velocities and discharges.

MODBRNCH is written in FORTRAN 77 with extensions of MODFLOW and BRANCH. To the authors' knowledge, visualized preprocessors and postprocessors supporting it have not been developed yet up to now, so it will not be that convenient to use. Besides, MODBRNCH simulates only open-channel at the top layer, adits under top layer and conduit systems can not be simulated. However, MODBRNCH could help the project in some ways although it is not fully suitable.

2.3.4 CAVE (Carbonate Aquifer Void Evolution)

The model CAVE is capable of simulating the process of karstification in limestone aquifers(see Section 2.2.1.above). It simulates both types of flow: including slow flow within fissured systems and fast flow within conduit systems. The latter flow regime has a laminar flow pattern during initial phase because the conduits are small. Flow becomes turbulent after the conduits have been widened sufficiently by the dissolution of limestone. In order to take into account of the dynamics of the Karst system, i.e. the changes in the state of saturation or high fluctuations in groundwater levels, CAVE allows the examination of conduit development during recharge events, and quantification of influences of geological, hydrochemical and climatic factors on the change of conduit geometries.

Simulating enlargement processes of Karst conduits is a major advantage of CAVE. It can only simulate two dimensional model. For the project, a three dimensional model is necessary.

A plan of extending MODFLOW or adding additional subroutines to MODFLOW to simulate adit systems is therefore proposed, and some preliminary design is introduced in Chapter 3. The program will be gradually improved during the period of modelling of two sites for yield estimation and source protection zone studies.

3. PROGAM DESIGN AND OPTIONS

3.1 Principle of Program Design

Basic principle of programming modification to the MODFLOW will be similar to programs for modelling of Karst water and modelling of mineworkings. The flows in adits will be treated as turbulent flow while surrounding aquifer is still simulated as Darcy flow by MODFLOW. The adit systems will be connected with aquifer by water exchange through the interface at every iteration. The subroutines required to incorporate adit flow and its solution algorithm into aquifer simulation will be grouped by a package, say ADIT package. The ADIT package will be parallel to all other packages such as River package, Well package etc., which could be called by the main program if appropriate. The data input is proposed through Visual MODFLOW interface except for the data related to adits such as adit geometry, initial adit flow conditions etc. The output data could be represented by Visual MODFLOW unless extra information is required, for instance, the amount of water exchanged between adits and aquifers.

The ADIT package will consist of two models, one simulates conduit flow and the other one simulates open channel flow. The selection of one of these two models depends on whether the adit is full of water. The program will make decision according to the elevations of adit roof and adit water level.

3.2 Adits Full of Water------Conduit System

The adits are assumed to be cylindrical to be easy to formulate when adit system is full of water. This assumption is usually acceptable although it is not always true. Adit flow is assumed incompressible i.e. the density of water remains constant, and storage effects do not need to be considered

3.2.1 Steady State of Conduit flow

For steady flow, the solution procedure can greatly reduced.

In the first step the hydraulic relationship for a section of adit needs to be considered. Flow in the adits can be calculated using the Colebrook - White pipe resistance formula in conjunction with Darcy - Weisbach flow formula. The absolute value of head loss Δh due to adit flow friction is given by the Darcy - Weisbach relation and can be expressed as

$$\Delta h = f\frac{LV^2}{2dg} \tag{1}$$

where d is the adit diameter,

V is the average flow velocity in the adit,

g is the gravitational acceleration,

L is the length of the adit section,

f is the friction factor, which can be expressed by implicit Colebrook-White formula:

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{2.51}{\mathrm{Re}\sqrt{f}} + \frac{k}{3.71d}\right] \tag{2}$$

where k is the adit roughness and the Reynolds number is given as:

$$\mathrm{Re} = \frac{Vd}{v} \tag{3}$$

where v is kinematic viscosity depends on temperature.

Discharge Q is given by

$$Q = -2Y\log\left[\frac{2.51\pi v d}{4Y} + \frac{k}{3.71d}\right] \tag{4}$$

where $$Y^2 = \frac{\Delta h g d^5 \pi^2}{8L} \tag{5}$$

In the second step, a system of network connected adits with n nodes is considered. For steady state, the sum of inflow and outflow at any node i of the network is zero, i.e.

$$\sum_{j=1}^{n_i} Q_{ij} + R_i + \sum_{l=1}^{m_i} \Gamma_{il} = 0 \tag{6}$$

where n_i denotes the number of adit nodes connected to adit node i,

Q_{ij} is the flow through the adits connecting nodes i and j,

j is counted from 1 to n,

R_i stands for the sources and sinks in the adit node i,

Γ_{il} is the flow exchange rate between the aquifer node l and the adit node i.

For every node in the adit network system with an unknown head an equation of the form (6) can be obtained. Thus, a system with n unknown heads of n nodes can be expressed as a system of n nonlinear equations with n unknowns.

The water exchange between adit system and aquifer can be expressed as:

$$\Gamma_{il} = \alpha_{il}(h_{c,l} - h_{a,i}) \tag{7}$$

where α_{il} is the exchange coefficient between adit node i and aquifer node l, which depends on the characteristics of water exchange as well as on the characteristics of the adit itself and permeability of the immediate environment.

$h_{c,l}$ is the hydraulic head in the continuum aquifer at node l,

$h_{a,i}$ is the hydraulic head at the adit node i.

The water exchange will be calculated at every iteration.

3.2.2 Unsteady State of Conduit Flow

For the unsteady flow in the adit, the equation of motion is expressed as:

$$V\frac{\partial V}{\partial x} + \frac{\partial V}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial x} - gS_a + \frac{2fV\,|V\,|}{d} = 0 \tag{8}$$

where

S_a is longitudinal slop of the adit
f is Darcy-Weisbach friction factor
d is adit diameter
p is pressure inside the adit
V is flow velocity in the adit
ν is kinematic viscosity.
ρ is water density.

The governing equations for unsteady flow in the adit may be obtain from conservation of mass and momentum, and expressed as:

$$\frac{\partial V}{\partial x}+\frac{1}{\rho}\frac{\partial p}{\partial t}+\frac{1}{A}\frac{\partial A}{\partial t}=\frac{q}{A} \qquad (9)$$

where A is area of cross section for adit
q is water from aquifer to adit in unit length.

For incompressible fluid and pipes with unchanged cross section area, the equation may be simplified as:

$$\frac{\partial Q}{\partial x}=q \qquad (10)$$

3.3 Adit is Partially Full of Water ------ Open Channel Flow

3.3.1 Steady State of Open Channel Flow

When adit is partially full, the water has a free surface, and water is not under pressure. In this situation, the adit flow is proposed to be treated as open channel flow. For steady state, the well known Manning equation is employed and expressed as:

$$V=\frac{1}{n}R^{2/3}\left[\frac{\Delta h}{L}\right]^{1/2} \qquad \text{(SI units)} \qquad (11)$$

where n is Manning roughness coefficient.
R is hydraulic Radius

$$R=\frac{A}{P} \qquad (12)$$

The continuity equation and water exchange formula are the same as that for conduit system.

3.3.2 Unsteady State of Open Channel Flow

For unsteady state, the momentum equation:

$$V\frac{\partial V}{\partial x}+\frac{\partial V}{\partial t}+g\frac{\partial h}{\partial x}+g(S-S_a)=0 \qquad (13)$$

where S is energy slop or frictional slop, and defined as

$$S=\frac{fV|V|}{2gR} \qquad (14)$$

The continuity equation is:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \qquad (15)$$

The equation indicates that the changing of cross section area of adit flow needs to be taken into account i.e. storage change should be considered.

4. SITE SELECTION AND MODEL DESIGN

As mentioned in part of methodology, two calibrated models will be build to test computer code, develop methods for modelling and delineation of Groundwater Protection Zone for adit system, as well as providing detailed understanding of two sites.

4.1 Site Selection Criteria

The most important criterion is that selected sites have to have good hydrogeological data, such as local groundwater levels including adit water level and surrounding aquifer water level, multiple piezometric levels and various pumping tests, in particular, yield test is useful. This provides an understanding of adit hydraulics and its relationship to the aquifer to formulate and simulate adit system. Regional context including regional geology, hydrology and hydrogeology are necessary information to enable the total situation to be modeled.

The another important criterion is that geometry of adit has to be clear, otherwise it is impossible to build a right model. Adits in chalk aquifer preferred because most of adits in the UK exist in chalk aquifer (see adit list). If possible, one confined and one unconfined site will be chosen to represent different conditions, but the primary criterion is availability of good data.

4.2 Alternatives for Site Selection

Up to now, the author has visited EA Thames Region, Southern Region, Anglian Region, Thames Water, Yorkshire Water and Mott MacDonald Consultants Limited. Available information include provisional list of adits and some diagrams of water source construction, Darent Catchment flow modelling report, Yorkshire Chalk groundwater modelling report, pizometric water levels and water source construction diagram for Wilmington, some pumping test data and local groundwater levels from Cottingham, Wall Hall Report, Hydrogeological Survey of the clay Lane Group of Resources, Colne Valley, from the GU PROJECT. Other simple reports from GU PROJECT for Eastbury, Bushey, Bushey Hall, Berrygrove, Bricket Wood and Netherwilde are also available. Besides, some MODFLOW, MODPATH and FLOWPATH data files from Southern Region, Thames Region and North East Region are available.

4.2.1 Alternative 1 ------ Wilmington

Wilmington is situated in the Darent Valley approximately 500m from the River. The chalk outcrop dips gently to the north with Gault clay to the south of the Escarpment. Variable alluvial deposits flank the Darent and some clay caps occur on higher parts of the chalk in the south.

There are two wells and two abstraction boreholes existing at Wilmington, and 8 observation boreholes were drilled around the pumping station (figures are attached in Appendix 2). Piezometric levels were measured in observation boreholes at 3 elevations in February 1993. The figures attached in Appendix 2 show the site lay out and multiple piezometric water levels.

The historical groundwater levels and some pumping tests data are believed to be available and need to be collected.

The Darent Catchment regional model in which Wilmington is included was built by Mott MacDonald consultant using ICMM code and has be calibrated with many years of data so that the regional background should be very clear and the conceptual model and calibrated parameter distribution can be used for the project.

The total length of Wilmington adit is 180 meters so it may not be long enough to show influences of adit. Still, Wilmington could be a possible site for the study.

4.2.2 Alternative 2 ------ Cottingham

Cottingham is situated to the west of River Hull and north of the Humber Estuary. The Cottingham groundwater source is located within the Yorkshire Chalk where the Chalk is covered by a thick sequence of Boulder Clay.

There are 10 shafts, 3 wells and 2 boreholes connected by a 950m adit at Cottingham pumping station. Monthly groundwater levels was recorded from January 1975 to December 1977. A 14-hour constant pumping test and a 5-step step pumping test were taken place in September 1996. Furthermore, a 7-day constant yield pumping test is planned for middle of September 1997.

The regional model 'Yorkshire Chalk Groundwater Modelling' developed by Aspinwall Consultants. The Geraghty & Miller model code was used. The conceptual model, calibrated parameter distribution and other regional information are available.

Cottingham can be considered as one of the sites although the data of multiple piezometrical groundwater levels do not exist.

2.2.3 Alternative 3 ------ Netherwild

Netherwild is located to the northeast of Watford and sited toward the down-dip edge of Upper Chalk outcrop, which is directly overlain by Alluvium and River Gravels.

The abstraction system at Netherwild comprises two similarly constructed boreholes, one shaft and a system of adits, the locations are shown in figures attached in Appendix 4. Constant rate and step yield pumping tests were carried out during March 1993. Piezometers were installed at three different levels during the pumping tests.

The regional and local groundwater modelling seem to be not available yet. Still, Netherwild has some possibilities as a study site.

2.2.4 Alternative 4 ------ Bricket Wood

Bricket Wood is located on Drop Lane to the north of Watford and sited toward the down-dip edge of the Upper Chalk outcrop, which is overlain by fluvial deposits.

The abstraction system at Bricked Wood consists of two boreholes, a main shaft, an access shaft and a adit system. The location and layout are shown in figures attached in Appendix 5.

Constant rate and step pumping tests were carried out using both borehole pumps during May and June 1993. Four observation boreholes were drilled on the site, three in a line perpendicular to an adit and one closer to the abstraction boreholes and main shaft. Piezometers were installed at three differing levels in each observation borehole. The piezometers were monitored for level variation during the pumping tests.

Historical pumping and groundwater level daily recorded are reviewed by GU PROJECT for years 1973, 1976, 1982 to 1992.

The hydrogeology of the site is complex and is influenced by a two layer system and overlying river. This may increases the difficulties for the project. In addition, construction details for the two boreholes are some what uncertain as discrepancies exist between various sources. However, it is still could be considered.

4.2.5 Alternative 5 ------ Wall Hall

Wall Hall pumping station is located northeast of Watford, and lies within the relatively flat, low-lying Colne River Valley. The location of the site is shown in Appendix 6. Wall Hall is sited toward the down dip edge of the Upper Chalk outcrop. The chalk outcrops along the valley flanks and is directly by fluvial deposits within the Colne Valley.

The abstraction system at Wall Hall comprises two wells, a shaft and a system of adits (see Figure of Site Layout enclosed in Appendix 6). Four observation boreholes were drilled and sunk to varying depths: 26m, 34m, 15m, 25m, 34.2m, and 15m to monitor water levels within different elevations of the upper and middle Chalk. Two observation boreholes, one shallow and one deep, were drilled within 5m of the north-south trending adit. A further two observation boreholes were positioned approximately equidistant from the two branching adits (see Figure of layout in Appendix 6). This was done to monitor groundwater levels at different elevations within chalk, and determine the effect of adits.

The pumping test at Wall Hall comprised a recovery period, a 3-day constant rate test at the maximum discharge rate 30.85Ml/day, a further recovery period followed by 3 consecutive 24-hour steps and 30 minute fourth step increasing the discharge rates to 15Ml/day, 20.8Ml/day, 27Ml/day and 36Ml/day. A final recovery period of four days was monitored prior to the station returning to operational running. Upon installation the instruments were confirmed to be operating accurately and reliable. The logger readings were checked with the know water levels as recorded by a conventional dip meter.

There are six hydrographs from observation boreholes, pumping stations and other abstractors, within 10 km of Wall Hall. One dates from 1961, one 1974 and the rest post-date 1986.

Due to the extensive adit system at Wall Hall, the validity of classical pumping test analyses is doubtful. Numerical models were therefore used to provide better estimation of aquifer parameters. A 2-dimensional finite element program 'Aqua' was initially used in horizontal, followed by a vertical 'Aqua' model. The 'Aqua' models clearly show that the groundwater flow to Wall Hall could not be modeled fully by a 2-dimensional model: a horizontal model greatly over simplified any vertical flow and could not include vertical changes in permeability; a vertical model could not adequately include either the radial flow to the shaft and wells, and effects of well storage. A 3-dimensional model was therefore required to simulate the groundwater flow at Wall Hall. A 3-dimensional program $R\theta Z$ model (developed by Birmingham University) was used for Wall Hall source which includes six layers. It does not allow for adit dewatering or development of a seepage face the shaft and boreholes, and not include components to account for traditional well losses. However, the model simulates the drawdown with reasonable agreement to all piezometers and high permeability zones represent adit system.

The regional groundwater modelling seems to be not available to authors' knowledge.

Summarizing above evidences, Wall Hall meets most of the criteria as one of the study sites.

4.3Telescopic Mesh Refinement

The model size needs to be considered. It needs to be big enough to see the impacts of adits on the surrounding aquifer, on modelling and on delineation of GPZ. Fixing boundary conditions requires a large model area as well. On the other hand, the model size needs to be small enough to reduce the influences from other factors, for instance, other groundwater sources, so that one can focus on the adit issue. To accomplish this, a Telescope Mesh Refinement (TMR) modelling approach is proposed to apply. That is withdrawing a local model from a regional model. Figure 7 illustrates the conceptual of TMR. This approach provides the means of accurately incorporating regional controlling factors and characteristics into smaller model domain, and allows investigators to focus on the pertinent area of interest for a particular problem.

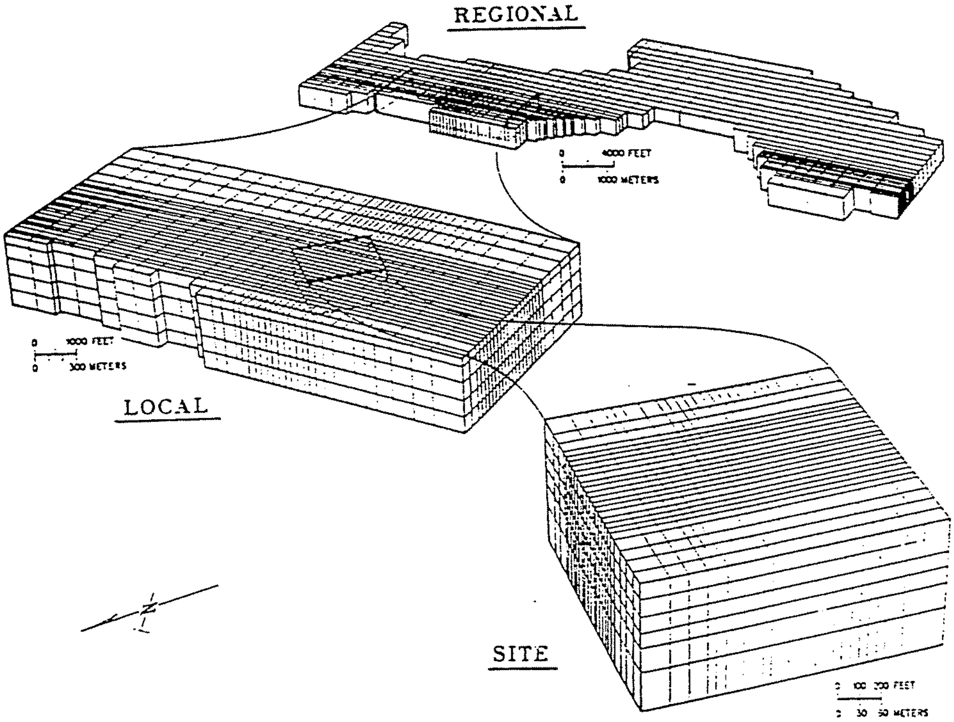

Figure 7 Conceptual diagram of Telescope Mesh Refinement modelling approach

The example presented here is a application of Telescope Mesh Refinement Modelling Approach at Chem-Dyne hazardous waste site, which is located in southwestern Ohio (D.S.Ward et.al.1987). Data are localized because investigation conducted at the site are specially for the purpose of defining contaminant plumes. The grids for contaminant site are required sufficient fine to design exact positions of wells for remedial purpose. However, the finer the grids, the more the computer time. To simulate groundwater flow and contaminant transport in this setting, a TMR approach is appropriate. A finite difference model was applied at three scales: regional scale, local scale, and site scale.

The regional model was built in two-dimensions to provide an understanding of regional groundwater context and determine boundary conditions for local model. The local model was built in three-dimensions to incorporate the three dimensional flow system in the site-scale model and to determine the potential impact of contaminant on the local scale. At the site-scale, both flow and transport simulations were performed to assess proposed remedial actions. The grids were gradually refined from regional to local and to site scale.

For the Chem-Dyne site, TMR was found useful. It permits effective model construction at spatial concentrated data. The approach allows site phenomena to be simulated with a smaller model domain but still maintaining consistency with the regional flow system.

For Modelling adit systems, the 2-dimensional regional models are proposed to build by using conceptual models and calibrated parameters which are existing. The computer code MODFLOW will be used as mentioned previously. This provides an overall understanding of regional groundwater flow system. In particular, it is used to test conceptual ideas and determine boundary conditions for local model.

The local models concerning adits will be developed in three-dimensions from corresponding regional models. The results from regional model will be used to initialize boundary conditions and model parameters in the local model. The grids will be refined sufficiently.

A software MTMR developed by Geraghty & Miller can be used to execute this process. MODFLOW and its compatible programs are supported by MTMR, such as MODELCAD and Visual MODFLOW et.al. The procedure is quite simple. For instance, one can using MTMR withdraw a smaller model from a larger model which is built by Visual MODFLOW, then import it into Visual MODFLOW again, the head values derived in the larger model will be initial head values of new model, and refined grids will get data by the interpolation.

5. DATA REQUIREMENT

Understanding, formulating and modelling of a adit system absolutely depend on a substantial and accurate data set. So that a collection, assessment and interpretation of data are important fundamental jobs. The following data will be needed for the research:

1 Adit and well/shaft/borehole construction details include diagrams and description.

2 Geological Succession presenting at the source location.

3 Abstraction details of individual wells specifying seasonal, annual and maximum abstraction rates.

4 Various pumping test data.

5 Historical groundwater level data.

6 Hydrogeological and hydraulic features such as aquifer layering and aquifer properties.

7 Aquifer recharge including precipitation data, infiltration coefficient, and surface water /groundwater interaction.
8 Groundwater balance result and regional model file and output if they are available.

6. Progress and Work Plan

A progress schedule is illustrated in Table 4. Addition to it, perhaps some field tests need to be carried out according to the situation of available data for selected sites.

The main work for next four months will be code development. Therefore the next report will introduce the situation of code development, and the selection of the first study site will be fixed by that time.

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GPRG

OPERATION AND PROTECTION OF ADIT SYSTEMS IN UK AQUIFERS

FIRST PROGRESS REPORT

January 1998

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Summary

After the stage of literature review, the project has moved on to the code development stage. This stage started from a further literature review focusing on detailed numerical methods and numerical solutions for conduit flow and open channel flow, and computer program of MODFLOW and MODBRNCH.

Through further literature review, the author found that both open channel flow and conduit flow are non-linear. For a general non-linear system it is not usually possible to prove the existence of a solution a prior, and if a solution does exists, it may not be unique and non-linear iterations are not usually global convergent. The model stability, numerical reliability and accuracy largely depend on the selected numerical computation scheme and transformation into a computer program.

MODBRANCH interface incorporates BRANCH model into MODFLOW. It simulates surface and groundwater interaction through leakage term. The coupling of BRANCH and MODFLOW expands the simulation capability to include routing of stream velocities and discharge with abilities of generating of accurate results by means of a stable, convergent and numerically reliable computational scheme.

The further literature review followed by a program writing period including formulation of conduit flow, approximation of finite difference, formulation of coefficient matrix, equation transformation and specification of boundary conditions.

The code test and case studies will be carried out during next stage. Calibrated models will be developed for field sites. This will test the code, as well as providing detailed understanding of the two sites, exploring techniques of adit field tests, estimating their reliable yield and drawing up guidelines for modelling adit systems.

1. INTRODUCTION

1.1 Objectives

The objectives of this study are still the same as mentioned in the Inception Report, they are:

1. Providing a suitable computer code for modelling groundwater flow to adit systems.
2. Preparing guidelines for determining the yield of adit systems.
3. Demonstrating the effects of adits on source protection zones and developing guidelines for revising protection zones.

1.2 Progress against Plan

After the stage for literature review, within which an inception report was submitted, the project has moved on to the code development stage. The second stage started from a further literature review focusing on detailed numerical methods and computer program, followed by a program writing period. There have been some delays. It has been very difficult to obtain the manual for MODBRNCH, but this arrived in mid-December. Thames Water have been slow in providing information on Wilmington site. This will only be a problem if the site turns out unsuitable for study, or if there are any further delays.

1.3 Further Literature Review

Further literature review was carried out focusing on following topics:

- Principles of steady and unsteady groundwater flow.
- numerical method (finite difference) for steady and unsteady groundwater flow.
- MODFLOW code (programme structure).
- Principles of steady and unsteady open channel flow.
- Numerical method (finite difference) for open channel flow.
- Principles of steady and unsteady conduit flow.
- Numerical method (finite difference) for conduit flow.
- MODBRNCH code
  BRANCH code
  interface between MODFLOW and BRANCH

Through above literature review, the author realises that unlike the linear governing equation for groundwater seepage flow, which is obtained by substituting Darcy's law into continuity equation, both open channel flow and conduit flow are non-linear. For a general non-linear system it is not usually possible to prove the existence of a solution a prior, and if a solution does exist, it may not be unique and non-linear iterations are not usually global convergent (Baker and Phillips 1981). The model stability, numerical reliability and accuracy largely depend on the selected numerical computation scheme and transformation into a computer program. The numerical modelling and programming for non-linear equations are much more complicated than those for linear equations. It happens very often that one has spent a long period of time writing a computer program to model a system governed by non-linear equations however the program might not be convergent at all. Therefore it is decided that use the structure of an existing and tested computer code and modify it to simulate adit systems.

2. MODBRNCH CHOICE

2.1 River package and Stream Package

MODFLOW was originally written with River package, which calculates leakage between the aquifer and river. Rivers contribute water to the aquifer or drain water from it depending on the head gradient between the river and groundwater regime by assuming that the river stage remains constant during one stress period. River package does not calculate the river velocity and river discharge so it will regardless pumping rate if we use River package to simulate adit flow.

A simple stream flow routing package has been added to MODFLOW, but is limited to steady and uniform flow.

2.2 Drain Package

Drain package is similar to River package except that drains will only remove water from the model. Drain package remove water from the aquifer at a rate proportional to the difference between the head in the aquifer and fixed drain elevation, as long as the head in the aquifer is above that elevation. If the head in the aquifer cell drops below the drain elevation, the drain will not inject water into the aquifer.

Also, Drain package has no relation with pumping rate so what one can do is either set the drain at very low position or increase the values of conductance if we use Drain package to simulate adit flow. However, changing the adit elevation is not reasonable, and the values of conductance is not sensitive enough for us to use Drain package simulating adit.

2.3 MODBRNCH Interface

BRANCH is a numerical model widely used to simulate unsteady, non-uniform flow by solving the non-linear momentum equation and continuity equation for open channel flow. The program is both general and flexible in that it can be used to simulate a wider range of flow conditions for various channel configurations. It is based on a four point(box), implicit, finite difference approximation of the governing equations with the abilities of generating of accurate results by means of a stable, convergent and numerically reliable computational scheme; providing of a high degree of computational efficiency whether used for short-term special study or long-term routine operations.

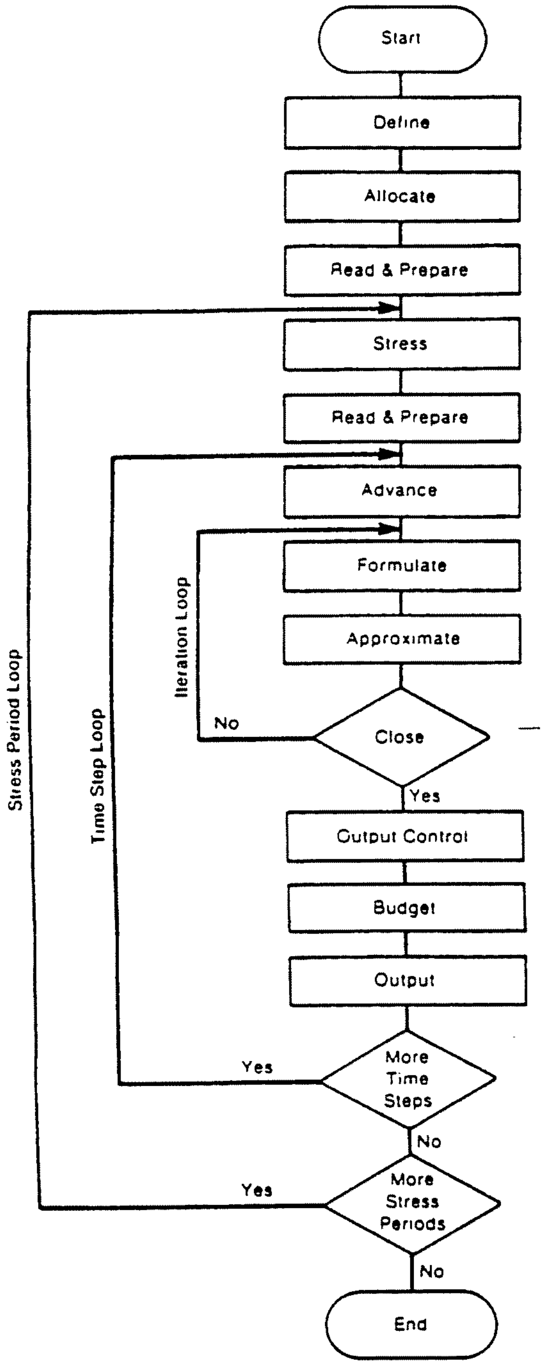
MODBRNCH interface incorporates BRANCH model into MODFLOW. The coupling of BRANCH with MODFLOW expands the simulation capability to include routing of stream in a network of interconnected open channels while accounting for the effects of transient stream velocities and discharge. Terms that describe leakage between stream and aquifer as function of streambed conductance and difference between aquifer head and stream stage were added to the continuity equations in BRANCH and MODFLOW separately. Thus, leakage between the aquifer and stream can be calculated separately in each model, or leakage calculated in BRANCH can be used in MODFLOW. This makes it possible that we account the influence of pumping rate from wells connected with adits by modifying MODBRNCH.

3. PROGRAM STRUCTURE AND FEATURES OF MODBRNCH

3.1 Overall Structure of MODFLOW

MODFLOW program consists of a main program (MAIN) and a large number of highly independent subroutines called modules. The functions of MAIN and how the modules can be grouped into "packages" and "procedures" are explained as follows:

The functions which must be performed for a typical simulation are shown in Figure 1. The period of simulation is divided into a series of "stress periods" within which specified stress parameters are constant. Each stress period, in turn, is divided into a series of time steps. The governing equation is solved at the end of each time step. Iterative solution methods are used to solve for the heads for each time step. Therefore, within a simulation, there are three nested loops: a stress period loop, within which there is a time step loop, which in turn contains an iteration loop.



DEFINE — Read data specifying number of rows, columns, layers, stress periods, and major program options.

ALLOCATE — Allocate space in the computer to store data.

READ AND PREPARE — Read data which is constant throughout the simulation. Prepare the data by performing whatever calculations can be made at this stage.

STRESS — Determine the length of a stress period and calculate terms to divide stress periods into time steps.

READ AND PREPARE — Read data which changes from one stress period to the next. Prepare the data by performing whatever calculations can be made at this stage.

ADVANCE — Calculate length of time step and set heads at beginning of a new time step equal to heads calculated for the end of the previous time step.

FORMULATE — Calculate the coefficients of the finite difference equations for each cell.

APROXIMATE — Make one cut at approximating a solution to the system of finite difference equations.

OUTPUT CONTROL — Determine whether results should be written or saved on disk for this time step. Send signals to the BUDGET and OUTPUT procedures to indicate exactly what information should be put out.

BUDGET — Calculate terms for the overall volumetric budget and calculate and save cell-by-cell flow terms for each component of flow.

OUTPUT — Print and save heads, drawdown and overall volumetric budgets in accordance with signals from OUTPUT CONTROL procedure

Figure 1 Overall Structure of MODFLOW

Figure 1 provides a flow chart for the overall structure of MODFLOW, a list of the various procedures, and an indication of sequence in which those procedures are implemented; it also provides a flow chart for the MAIN program. Each rectangle in Figure 1 is termed a "procedure" and performed by individual subroutines, or modules, called by MAIN program. The MAIN program itself is simply an organised sequence call statements and calls the various modules in the proper sequence. Modules which are called directly by the main program are termed " primary" modules; those that are called by other modules are termed "secondary" modules.

Thus the various procedures indicated in Figure 1 are implemented through individual modules; and the modules can accordingly be grouped by "packages", where a packages includes those modules required to incorporate a particular hydrological process or solution algorithm into the simulation, for example, the River package, Well package or SIP package etc.

		Flow Component Packages							Solver Packages	
			Stress Packages							
Procedures	BAS	BCF	WEL	RCH	RIV	DRN	EVT	GHB	SIP	SOR
Define (DF)	X									
Allocate (AL)	X	X	X	X	X	X	X	X	X	X
Read & Prepare (RP)	X_U	X_{US}							X	X
Stress (ST)	X									
Read & Prepare (RP)			X	X_U	X	X	X_U	X		
Advance (AD)	X									
Formulate (FM)	X	X_S	X	X	X	X	X	X		
Approximate (AP)									X_S	X_S
Output Control (OC)	X									
Budget (BD)		X_{US}	X_U	X_U	X_U	X_U	X_U	X_U		
Output (OT)	X_U									

Figure 2 Organisation of modules by procedures and packages.

Figure 2 illustrates the classification of modules by procedure and by package in terms of a matrix of primary modules. The rows correspond to procedures, while the columns correspond to packages. Entries marked with a subscript "S" indicates primary modules which utilise submodules; submodules are secondary modules which are utilised only in a single package. Entries marked with the subscript "U" indicates primary modules which utilise utility modules; utility modules are secondary modules which are available to many packages.

Figure 3 shows the names of the primary modules arranged in the same matrix format that was used in Figure 2.

PROCEDURES	Packages									
	BAS	BCF	WEL	RCH	RIV	DRN	EVT	GHB	SIP	SOR
Define (DF)	BAS1DF									
Allocate (AL)	BAS1AL	BCF1AL	WEL1AL	RCH1AL	RIV1AL	DRN1AL	EVT1AL	GHB1AL	SIP1AL	SOR1AL
Read & Prepare (RP)	BAS1RP$_U$	BCF1RP$_{US}$							SIP1RP	SOR1RP
Stress (ST)	BAS1ST									
Read & Prepare (RP)			WEL1RP	RCH1RP$_U$	RIV1RP	DRN1RP	EVT1RP$_U$	GHB1RP		
Advance (AD)	BAS1AD									
Formulate (FM)	BAS1FM	BCF1FM$_S$	WEL1FM	RCH1FM	RIV1FM	DRN1FM	EVT1FM	GHB1FM		
Approximate (AP)									SIP1AP$_S$	SOR1AP$_S$
Output Control (OC)	BAS1OC									
Budget (BD)		BCF1BD$_{US}$	WEL1BD$_U$	RCH1BD$_U$	RIV1BD$_U$	DRN1BD$_U$	EVT1BD$_U$	GHB1BD$_U$		
Output (OT)	BAS1OT$_U$									

Figure 3 Primary Modules organised by Procedures and Packages

3.2 Program Structure of MODBRNCH

The method used integrating the BRANCH and MODFLOW was to create an interface code MODBRNCH called by MODFLOW that passes information between MODFLOW and BRANCH and calls BRANCH. This makes BRANCH similar with other MODFLOW packages, and performs step by step according to MODFLOW procedures.

Figure 4 shows the structure of MODBRNCH, from which, one can see that: BRC1AL allocates space for data arrays used by BRANCH; BRC1RP reads input data for BRANCH; BRC1FM calls BRANCH and adds leakage to MODFLOW; BRC1BD calls BRANCH to calculates and accumulated volumes over a MODFLOW time step.

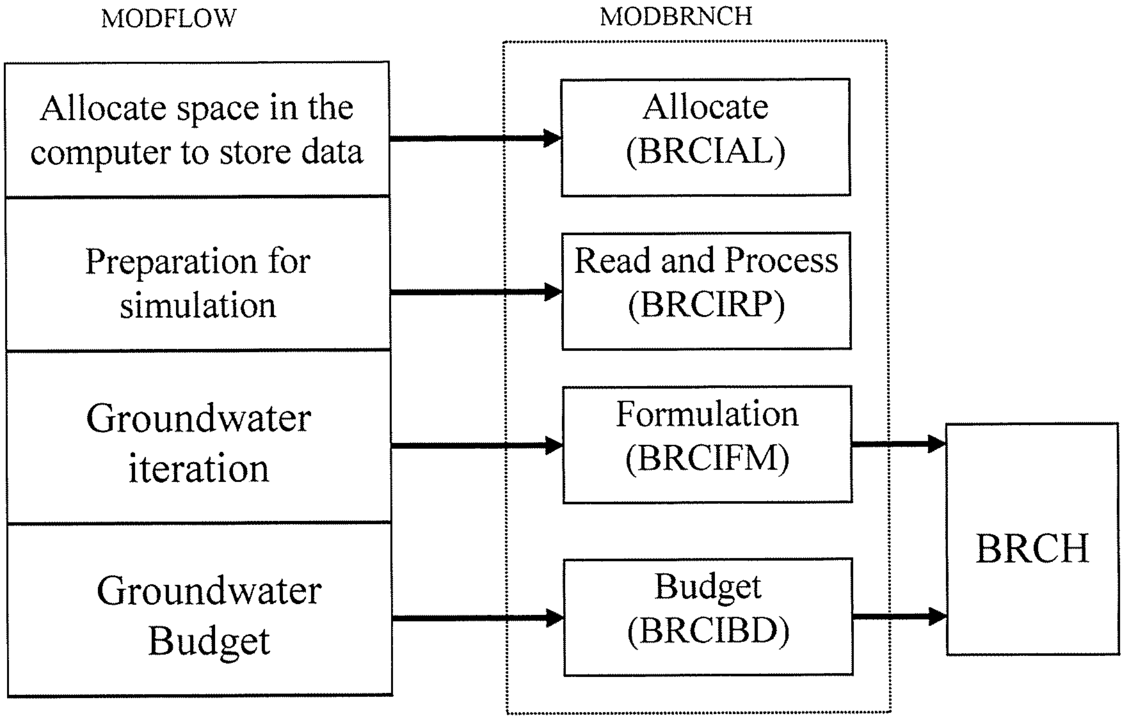


Figure 4 Schematic of Module calling Sequence

3.3 Features of MODBRNCH

3.3.1 Coordination of Time Steps between BRANCH and MODFLOW

The time scale of variations in open channel flow is on the order of minutes and hours. While groundwater flow generally varies in days or months. Thus, it is necessary to allow multiple time intervals in BRANCH to pass within one time step in MODFLOW. For each time step of MODFLOW, BRANCH is called from MODFLOW to simulate the number of open channel flow time intervals that correspond to one MODFLOW time step. This scheme requires that the BRANCH time interval size must be less than or equal to the MODFLOW time step, and the MODFLOW time step must be an integral multiple of BRANCH time interval.

3.3.2 Incorporation of Leakage

The term for leakage or other inflow or outflow in MODFLOW had already been incorporated in Well, River, Stream, Drain and Recharge packages. Leakage from BRANCH is incorporated in the same pattern into MODFLOW. Average leakage flow rates calculated by BRANCH during a MODFLOW time step are computed and applied to MODFLOW during the entire MODFLOW time step. The aquifer head at each BRANCH time interval is linearly interpolated from the heads calculated by MODFLOW at the beginning and end of this time step. This scheme maintains mass balance between the two models.

The scheme necessitates multiple iterations between the two models for each MODFLOW time step. Figure 5 shows how MODFLOW and BRANCH interface and pass variables. Groundwater heads at the beginning and end of each new time step are initialised using heads computed at the end of previous time step. BRANCH is then called with the interpolated groundwater heads. The stream flow is calculated for number of BRANCH time intervals in the MODFLOW time step. The total leakage per BRANCH time interval is calculated simultaneously. After returning to MODFLOW, the single MODFLOW time step is simulated using leakage calculated by BRANCH, and a new estimate of groundwater heads is made. BRANCH is called again, and stages and discharges in the channel are reset to their values at the beginning of MODFLOW time step, and stream flow is recalculated with leakage based on the new estimate of aquifer heads at time step end. This process is repeated until the difference in successive estimates of heads and stages drops below a user specified criteria. The model then advances to the next MODFLOW time step.

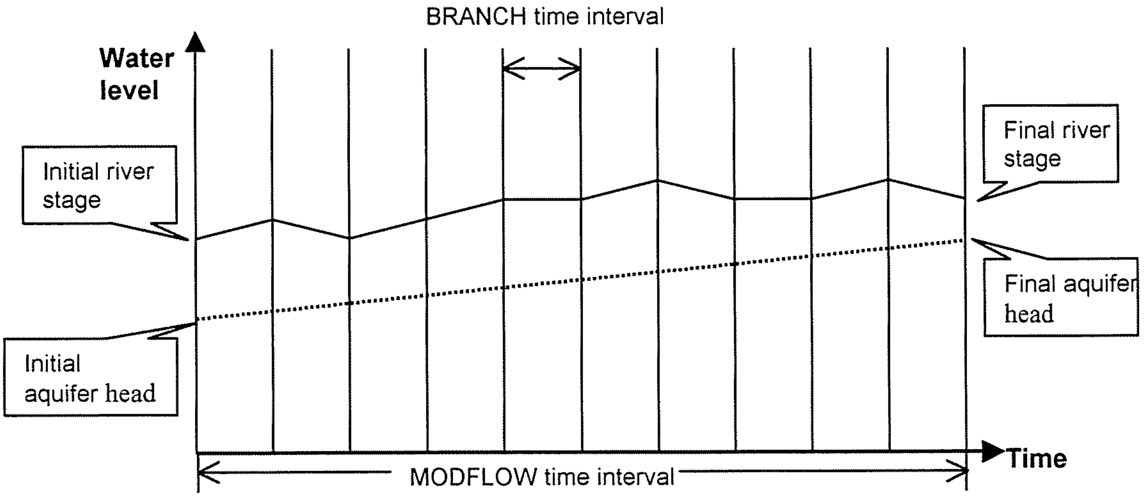


Figure 5 Computation of head difference in the BRANCH and MODFLOW models

3.3.3 Arrangement of MODFLOW Cells and BRANCH Stream Segments

The location in the aquifer corresponding to stream reaches are specified in the BRANCH input. The head in each model aquifer cell is assumed to be the same throughout the entire cell. Each stream segment is assigned to an aquifer model cell; thus, no segment can span more than one cell, and channel cross section is defined at each point where a river enters or leaves an aquifer model cell. Multiple river segments can occur within a cell, but inflow and outflow from each reach is considered to occur at the centre of the cell. A typical arrangement of aquifer model cells and river segments is shown in Figure 6. All leakage to and from a river segment is considered to occur only with the corresponding aquifer model cell.

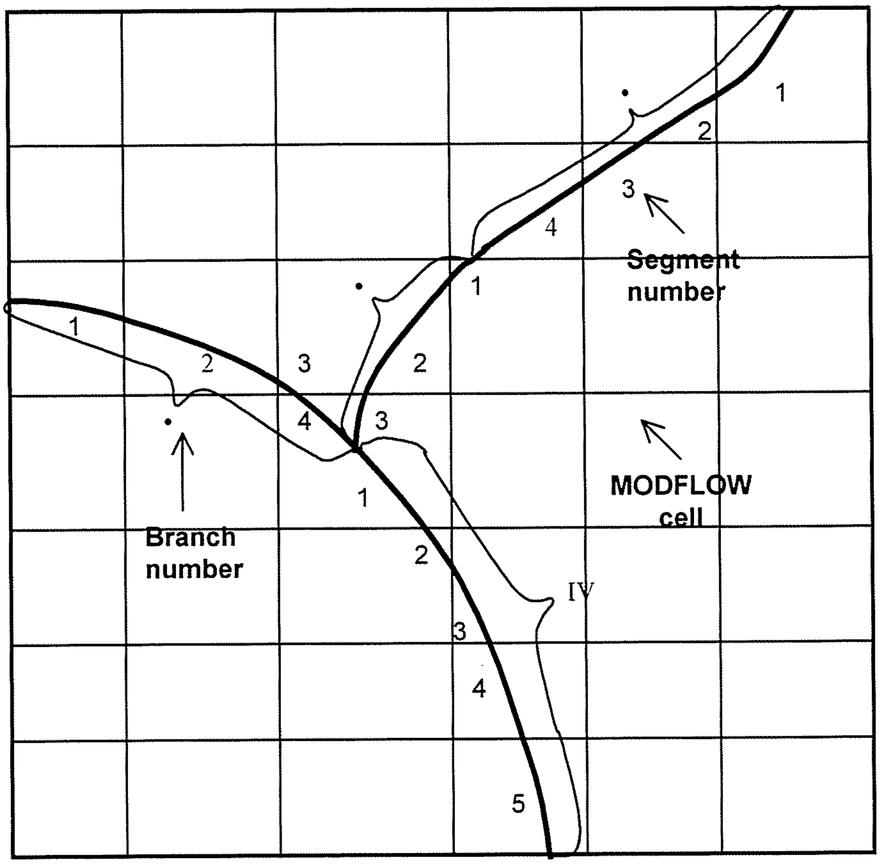


Figure 6 Arrangement of MODFLOW cells and BRANCH segments

4.CODE DEVELOPMENT
----- MODIFICATION OF MODBRNCH TO SIMULATE ADITS

4.1 Adits are Partially Full of Water-----Open Channel Flow

The original partial differential equation of continuity used in BRANCH is (Schaffranek, etc.1981)

$$B\frac{\partial Z}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad (1)$$

where B is Channel topwidth,
Z is stage in the channel,
t is time,
Q is flow rate in the channel,
x is longitudinal distance down the channel.

When lateral inflows and outflows are included, the equation is (Schaffranek, 1987)

$$B\frac{\partial Z}{\partial t}+\frac{\partial Q}{\partial x}-q=0 \tag{2}$$

where q is lateral inflow per unit length of channel.

If the inflow is the result of leakage from aquifer, Darcy's law gives the leakage as

$$q=\frac{K`}{b`}B(h-Z) \tag{3a}$$

where K` is vertical hydraulic conductivity,
b` is thickness of river bed,
h is head in the aquifer.

The Equation (3a) is used for leakage in the River package and Stream package in MODFLOW. However it is possible that adit is partially full of water while aquifer head is higher than the elevation of adit top. In this circumstance, the Equation (3a) should be changed to

$$q=\frac{K`}{b`}B(h-Z_{top}) \tag{3b}$$

where Z_{top} is the elevation of adit top.

4.2 Adit Full of Water------ Conduit Flow

Most of adits in the UK is perhaps full of water, so the Adit Conduit Package is probably more important than Adit Open Channel Package is. Therefore one have to do following works to model adit flow as conduit flow:

- Formulation of conduit flow.
- Approximation of finite difference for conduit flow.
- Formulation of coefficient matrix .
- Equation Transformation.
- Specifying boundary conditions.

4.2.1 Formulation of Conduit Flow

one dimensional, unsteady non uniform flow in conduits can be described by two partial differential equations expressing mass and momentum conservation. The continuity equation and momentum equation for conduit flow can be expressed as:

$$\frac{\partial Q}{\partial x}+\frac{1}{\rho}\frac{\partial p}{\partial t}-q=0 \tag{4}$$

$$\frac{\partial Q}{\partial t}+\frac{Q}{A}\frac{\partial Q}{\partial x}+\frac{A}{\rho}\frac{\partial P}{\partial x}+\frac{f}{2Ad}Q|Q|=0 \tag{5}$$

where A is the cross section area of adits,
P is water pressure within adits,
ρ is water density,
f is friction coefficient,
d is adit diameter.
Q is discharge of adit flow.

4.2.2 Approximation of finite difference

The space-time grid system shown in Figure 7 depicts the region in which solution of the flow equations is sought. The symbols θ and ψ represent weighting factors used to specify the time and location, respectively, within the Δt_j time increment and Δx_i distance increment at which derivative and functional quantities are to be evaluated. The temporal and spatial derivatives of the variables are discretized respectively as follows:

$$\frac{\partial f(I)}{\partial t} \approx \frac{f_{i+1}^{j+1} + f_i^{j+1} - f_{i+1}^{j} - f_i^{j}}{2\Delta t} \tag{6}$$

$$\frac{\partial f(I)}{\partial x} \approx \theta \frac{f_{i+1}^{j+1} - f_i^{j+1}}{\Delta x_i} + (1-\theta)\frac{f_{i+1}^{j} - f_i^{j}}{\Delta x_i} \tag{7}$$

Usually θ is assigned in the range of $0.5 \le \theta \le 1$. A value of 0.5 yields the fully centered scheme, whereas value of 1.0 yields the fully forward scheme.

In a manner similar to treatment of the spatial derivatives, the nonderivative form of variables in the momentum equation (5), denoted f(I), are discretized as follows:

$$f(I) \approx \chi \frac{f_{i+1}^{j+1} + f_i^{j+1}}{2} + (1-\chi)\frac{f_{i+1}^{j} + f_i^{j}}{2} \tag{8}$$

Therefore, these dependent variables can be represented on the same time level as the spatial derivatives or at any other different level within the time increment. The weighting factor χ may be assigned in the range $0 \le \chi \le 1$.

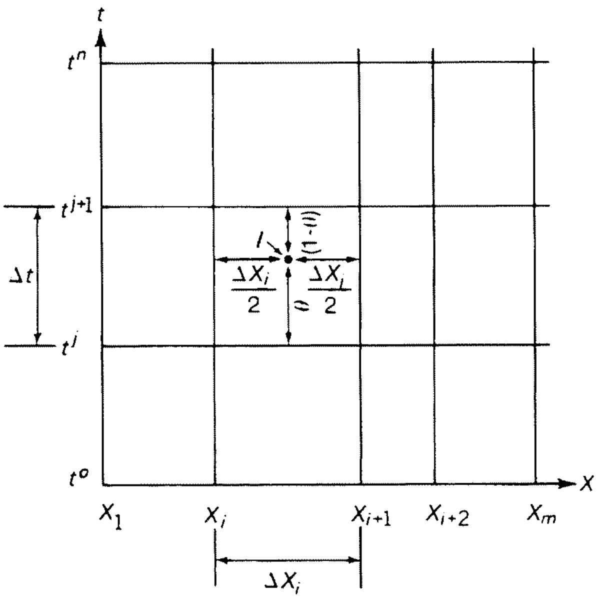


Figure 7 Space-time System for Finite difference Approximation

4.2.3 Formulation of coefficient matrix

The governing equation (4) and (5) can be transformed into finite difference expressions by application of the operators defined in equations 6-8 (Schaffranek etc.1981). using tilde (~) notation to signify quantities taken as local constants, updated through iteration in the computation process, the equation of continuity can be reduced to

$$\gamma P_{i+1}^{j+1} + Q_{i+1}^{j+1} + \gamma P_i^{j+1} - Q_i^{j+1} = \delta \qquad (9)$$

in which

$$\gamma = \frac{1}{\rho}\frac{\Delta x_i}{2\Delta t\theta}$$

and

$$\delta = \gamma(P_{i+1}^j + P_i^j) - \frac{1-\theta}{\theta}(Q_{i+1}^j - Q_i^j) + \frac{q\Delta xi}{\theta}$$

and the momentum equation can be reduced to

$$P_{i+1}^{j+1} + \zeta Q_{i+1}^{j+1} - P_i^{j+1} + \omega Q_i^{j+1} = \varepsilon \qquad (10)$$

in which

$$\zeta = \lambda + \sigma + \mu$$

$$\omega = \lambda + \sigma - \mu$$

$$\lambda = \frac{\Delta x_i \rho}{2\Delta t A\theta}$$

$$\sigma = \frac{\chi f \Delta x_i \tilde{Q}}{4A^2 d\theta}$$

$$\mu = \frac{2\rho\tilde{Q}}{A^2}$$

and

$$\varepsilon = -\frac{(1-\theta)}{\theta}(P_{i+1}^j - P_i^j) + (\lambda - \sigma\frac{(1-\chi)}{\chi})(Q_{i+1}^j + Q_i^j) - \mu\frac{(1-\theta)}{\theta}(Q_{i+1}^j - Q_i^j) + \frac{\tilde{Q}^2\rho}{A^3\theta}(\tilde{Z}_{i+1} - \tilde{Z}_i)$$

Equation (9) and (10), which define the flow in the Δx_i segment, can then be expressed in the following matrix form:

$$\begin{bmatrix} \gamma & 1 \\ 1 & \zeta \end{bmatrix} \begin{bmatrix} Z_{i+1}^{j+1} \\ Q_{i+1}^{j+1} \end{bmatrix} + \begin{bmatrix} \gamma & -1 \\ -1 & \omega \end{bmatrix} \begin{bmatrix} Z_i^{j+1} \\ Q_i^{j+1} \end{bmatrix} = \begin{bmatrix} \delta \\ \varepsilon \end{bmatrix} \qquad (11)$$

4.2.4 Equation of Transformation

Equation (11) can be applied to all Δx_i segments within the conduit network and the resultant equation set can be solved directly using appropriate boundary conditions and initial values. However, in the

conduit network model, transformation equations are developed from the segment flow equations to correlated the unknowns at the end of the branches, that is, at the junctions.
From a two component vector of state for *i*th cross section

$$S_i^{j+1} = \begin{bmatrix} Z_i^{j+1} \\ Q_i^{j+1} \end{bmatrix}$$

the following transformation equation for *i*th segment can be written as

$$S_{i+1}^{j+1} = U_{(i)} S_i^{j+1} + u_{(i)} \qquad (12)$$

in which S_{i+1}^{j+1} is the vector of state for (*i*+1)th cross section. The transformation matrices of *i*th segment, $U_{(i)}$ and $u_{(i)}$, in which the subscript (*i*) denotes the segment, follow from the previously defined coefficient matrices:

$$U_{(i)} = \begin{bmatrix} \gamma_{(i)} & 1 \\ 1 & \zeta_{(\mathrm{i})} \end{bmatrix}^{-1} \begin{bmatrix} -\gamma_{(i)} & 1 \\ 1 & -\omega_{(\mathrm{i})} \end{bmatrix}$$

and

$$u_{(i)} = \begin{bmatrix} \gamma_{(i)} & 1 \\ 1 & \zeta_{(\mathrm{i})} \end{bmatrix}^{-1} \begin{bmatrix} \delta_{(i)} \\ \varepsilon_{(i)} \end{bmatrix}$$

Successive application of the segment-transformation equation (12) to all segments contained in a branch results in an expression that relates the unknowns at the end cross section 1 and *m* of the *n*th branch,

$$S_m^{j+1} = U_n S_1^{j+1} + u_n \qquad (13)$$

The transformation matrices of the *n*th branch, U_n and u_n in which the subscript *n* denotes the branch, are obtained through successive substitution of the segment-transformation equation from the (*m*-1)th segment down to the first segment. These branch-transformation matrices

$$U_n = U_{(m-1)} U_{(m-2)} \cdots\cdots\cdots U_1 \qquad (14)$$

and

$$\begin{aligned} u_n = u_{(m-1)} &+ U_{(m-1)}(u_{(m-2)} + U_{(m-2)}(u_{(m-3)}\cdots\cdots \\ &+ U_{(3)}(u_{(2)} + U_{(2)}u_{(1)}).....) \end{aligned} \qquad (15)$$

describe the relationship between the vectors of state, S_1^{j+1} and S_m^{j+1}, at the end cross sections of the branch, that is, at the junctions.

After applicable boundary condition equations are formulated, the resultant equations are solved simultaneously, yielding values of pressure and discharges at the termini of the branches (at the junction cross section). Intermediate values of the unknowns at the internal segment ends (at cross sections between junctions) are subsequently determined through successive solution of the segment transformation equation (12). This transformation procedure effects significant reductions in the model's requirements for computer memory and execution time. For example, if segment flow equations are used, a network consisting of N sequentially connected branch, each composed of M_i segments, would form a coefficient matrix of minimum order 2M+2, where M is the total number of segments in the network, that is, the sum of M_i's for the N branch system. By combing segments into branches and using branch transformation equations instead of segment flow equations, the size of the coefficient matrix can be reduced to the order of 4N.

4.2.5 Specifying boundary conditions

To solve the branch transformation equations implicitly, boundary conditions must be specified at internal junctions located at branch confluences within the network as well as at external junctions located at the extremities of branches, for example, where branches physically terminate or are delimited for modelling purpose. Equations describing the boundary conditions at internal junctions are automatically generated by the model, where as boundary conditions for external junctions are formulated by the model from user supplied time series data or from user specified functions.

Discharge and flow pressure compatibility conditions can be expressed for internal junctions by neglecting velocity head differences and turbulent energy losses. At a junction of *n* branches, discharge continuity requires that

$$\sum_{m=1}^{n} Q_m = W_k \tag{16}$$

where W_k is zero or some user-specified external flow (inflow or outflow) at junction *k*, and flow pressure compatibility requires that

$$P_m = P_{m+1}, \quad m=1, 2, \ldots\ldots.(n-1) \tag{17}$$

Various combinations of boundary conditions can be specified for external junctions. Known flow pressure or discharge as a function of time, or a known, unique pressure-discharge relationship can be prescribed.

Together, the internal and external boundary conditions provide a sufficient number of additional equations to satisfy requirement of the solution technique.

5. CODE TEST AND CASE STUDYAND SPZ

Code test and case studies will be carried out during next stage. Calibrated models will be developed for field sites. This will test the code, as well as proving detailed understanding of the two sites, exploring techniques of adit field tests, estimating their reliable yield and drawing up guidelines for modelling adit systems. Code improvement will be carried out through out of the study.

Cottingham is selected as one of two sites. A detailed adit geometry examination was carried out recently by Yorkshire Water and multiple level piezometers were built there recently.

Influences of adit on Source Protection Zone will be studied. The study will attempt to generalise the results of the site specific studies, to draw up guidelines for revising protection zones.

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OPERATION AND PROTECTION OF ADIT SYSTEMS IN UK AQUIFERS

SECOND PROGRESS REPORT

JUNE 1998

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SUMMARY

MODBRNCH, which couples the USGS surface water model – BRANCH – and the groundwater model – MODFLOW –, has been adapted for the project. To simulate the relation between pressurized adit flow and groundwater in the aquifer, a slot approach (Preissmann slot) is proposed. This introduces a fictitious slot above the adit, so the adit cross-section area remains similar. The water level in the slot represents the pressurized adit head which can be used by MODBRNCH to calculate the water exchange between aquifer and adit according to their head differences.

The modified computer code and the approach were tested in several hypothetical cases with the characteristics of straight adit, multiple interconnected adits, steady and unsteady states respectively. Some simple sensitivity tests of parameters were carried out.

The Wilmington case study has been carried out to test the code and the approach, and to demonstrate the application. Wilmington modelling was carried out by both MODFLOW and MODBRNCH independently. The study indicates that MODBRNCH can predict the effect of the adit on groundwater heads in the three layers. The adits affect groundwater heads in the layer above, and the layer containing adit, but have little effect on the layer below. The area of drawdown predicted by MODBRNCH is much larger than MODFLOW suggests. Although Wilmington adit is a small adit, still the study shows that the 50 – day protection zone predicted by MODBRNCH is moved south eastern direction compared with the one of MODFLOW because of adit's south eastern extension.

The effect of adit on protection zone is not significant for Wilmington because of the small adit, a further study was carried using the Wilmington model. The Wilmington main adit was extended to 1250m long, and all other conditions were kept the same. The further study indicates that a long adit affect all three layers and has a smaller drawdown, so long adits increase yield. As expected, the protection zone of the long adit is much bigger than the one can be expected a well of the same yield..

The Cottingham case study is supposed to be main work for the next stage. We are uncertain whether sufficient data will be available in time. In addition, more sophisticate study such as detailed pumping test simulation, sensitivity analyses of parameters, the influences of vertical distribution of permeability and anisotropy of Chalk on adit modelling etc, are proposed for later study to achieve the project objectives.

1. INTRODUCTION

1.1 Objectives

The objectives of this study have been kept the same from the proposal, to the inception report and the progress reports, up to present:

1. Providing a suitable computer code for modelling groundwater to adit systems.
2. Preparing guidelines for determining the yield of adit systems.
3. Demonstrating the effects of adit on source protection zones and developing guidelines for revising protection zones.

1.2 Progress against Plan

This research has been proceeding as the proposal and the inception report. A computer code has been provided, and first site — Wilmington — has been studied. The code has been tested, and Wilmington adit has been understood better in some respectes. The project objectives appear to be achievable.

A brief plan for sensitivity tests of parameters was proposed in last steering group meeting. However, we have spent quite a lot of time modifying the program, and making the program simulating multiple interconnected adits, unsteady state, and sorting out compatibility with Visual MODFLOW. The parameter tests have been carried out very roughly, the influences of parameters have not been understood well enough yet, therefore we have more work to do on this issure to prepare the guideling for modelling aquifer – adit systems.

One of this main objectives of this study is to demonstrate the effects of adits on source protection zones. However, the Wilmington adits are small adits, and the influences of the adits are not significant. A normal size of adit (more than 1000 m long) should be studied in next stage, to demonstrate the impacts of adits on source protection zones.

1. MODBRNCH ADAPTION

2.1 MODBRNCH Choice

As introduced in the first progress report, BRANCH (Schaffranek, et al,1981) is an USGS model widely used to simulate one-dimensional unsteady, non-uniform, multiple branch interconnected open channel flow by solving the following non-linear momentum and continuity equations for open channel flow

$$\frac{\partial Q}{\partial t}+\frac{\partial(\beta Q^2/A)}{\partial x}+gA\frac{\partial Z}{\partial x}+\frac{gk}{AR^{4/3}}Q|Q|=0 \qquad (1)$$

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad (2)$$

where Q is the channel discharge, Z is the river stage, x is the distance in the longitudinal direction, t is the elapsed time, A is the channel water cross section area, g is the acceleration of gravity, R is the hydraulic radius, k is a function of the flow resistance coefficient, with $k=\eta^2$ in metric system, where η is similar to Manning's n.

The MODBRNCH (Swain and Wexler,1996) interface incorporates BRANCH into MODFLOW(Harbaugh and McDonald, 1988). The coupling of BRANCH with MODFLOW expands the simulation capability of stream-aquifer interactions including routing of surface flows in a network of interconnected open channels while accounting for the effects of stream velocity and discharge

2.2 SLOT Approach

MODBRNCH simulates relations between open channel flow and groundwater successfully. However, adits in the UK are normally full of water, so that the adit flow becomes pressurised, a situation which is not normally handled in MODBRNCH. To overcome the problem, we introduce a fictitious slot (Preissmann Slot; Preissmann and Cunge,1961) above the adit, as schematized in Fig.1.

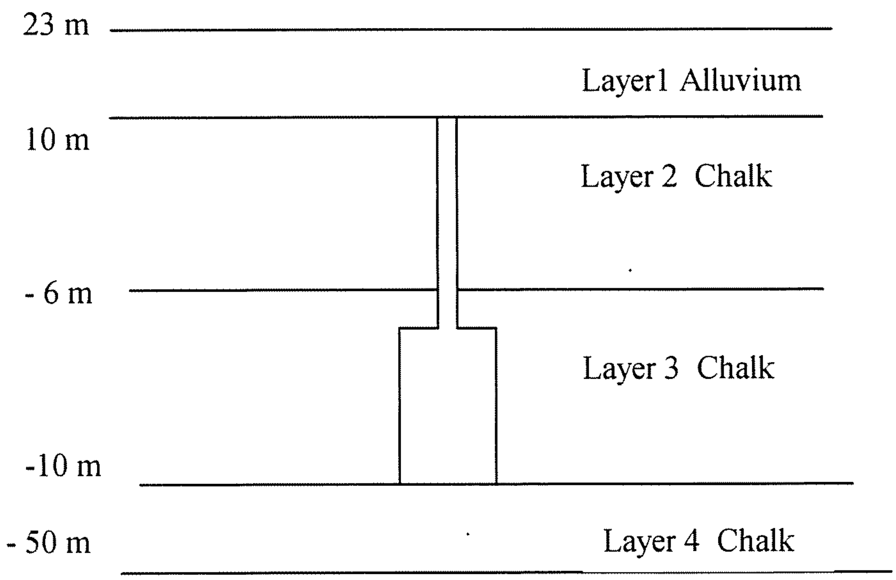

Fig.1. Profile of slot illustration and Wilmington model layers (not to scale)

This approach makes the calculated adit cross sectional area remain similar to the actual adit water conveyance area, while the pressurized adit head can be accounted and represented by the water level in the slot, and used by MODBRNCH to calculate the water exchange between aquifer and adit according to their head differences. MODBRNCH allows users to construct a slot above the adit as the actual channel geometry is assigned by defining the channel cross section.

2.3 Modification of MODBRNCH

A small modification is needed to handle Preissmann slot in MODBRNCH. MODFLOW and BRANCH are linked by water exchange as mentioned previously, for which the leakage term to be added to the continuity equation (2) for the BRANCH model is

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}+q=0 \qquad (3)$$

where q is outflow per unit length of channel and is calculated as

$$q=\frac{\mathrm{k}'}{\mathrm{b}'}B(Z-h) \qquad (4)$$

where k'/b' is the leakage coefficient of the river bed, B is the channel top width, and h is the head in the corresponding aquifer cell.

Equation (4) is only a good approximation for streams whose top width is much larger than the flow depth. However, when the slot is introduced, the top width would become the narrow slot width. A better approximation is to use the adit perimeter, instead of the top width, replacing Equation (4) by

$$q=\frac{\mathrm{k}'}{\mathrm{b}'}W_p(Z-h) \qquad (5)$$

where W_p is the adit perimeter.

The leakage term – q, is also added to the continuity equation in MODFLOW.

2. CODE TEST

The modified computer code and the approach were initially tested in several hypothetical cases with the characteristics of straight adit, multiple interconnected adits, steady and unsteady states respectively. Some simple sensitivity tests of parameters were carried out.

3.1Straight Adit

The most simple adit is a straight adit, which was put in a 2 km by 2 km auifer with a thickness of 50 m. The western and eastern boundaries are specified as constant head boundaries with the heads of 45 m and 40 m, respectively, so that groundwater flow from west to the east. No flow boundaries are defined to the north and south. The aquifer is discretised into 40 columns and 39 rows with three layers. A 1.2 km adit was set in layer 2 with a pumping rate of 20 ml/day. A 2m high and 2m wide adit was set in the middle layer.

Fig.2 illustrates the simulation results of straight adit, and is the expected flow pattern.

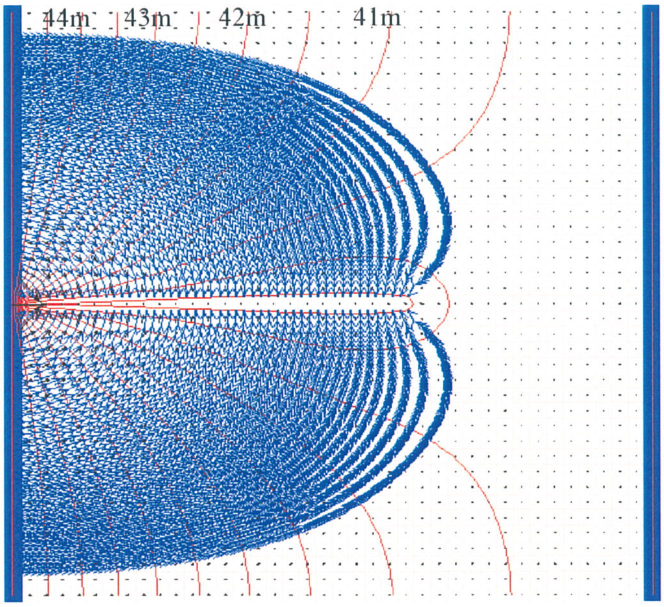

Fig. 2 Simulation result of a straight adit

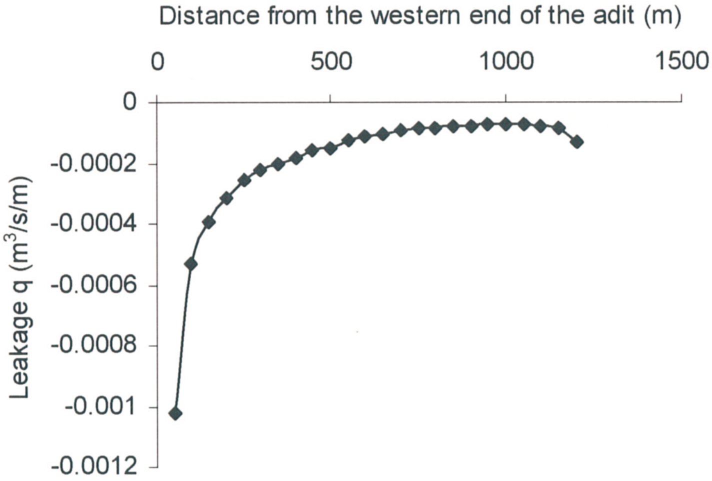

Fig.3 Leakage against the distance from the western end of the adit

Fig.3 shows the distribution of leakage along the adit. The negative values refer to groundwater flows from the aquifer to the adit. One can see that an enormous amount of water flows to the adit from the western end of the adit due to it's constant head boundary.

3.2 Multiple Interconnected Adits

The test for multiple interconnected adits was carried out in a 4 km by 4 km aquifer with a thickness of 50 m. 45 m and 40 m constant boundaries were assigned along the western and the eastern boundaries, and no flow boundaries to the north and south. Groundwater flows from west to the east. The aquifer was discretized into 80 columns and 79 rows. Again, the aquifer is divided into three layers, and adits were set in the middle layer. The adits consist of three branches as illustrated in Fig. 4, which also the resulting groundwater contours.

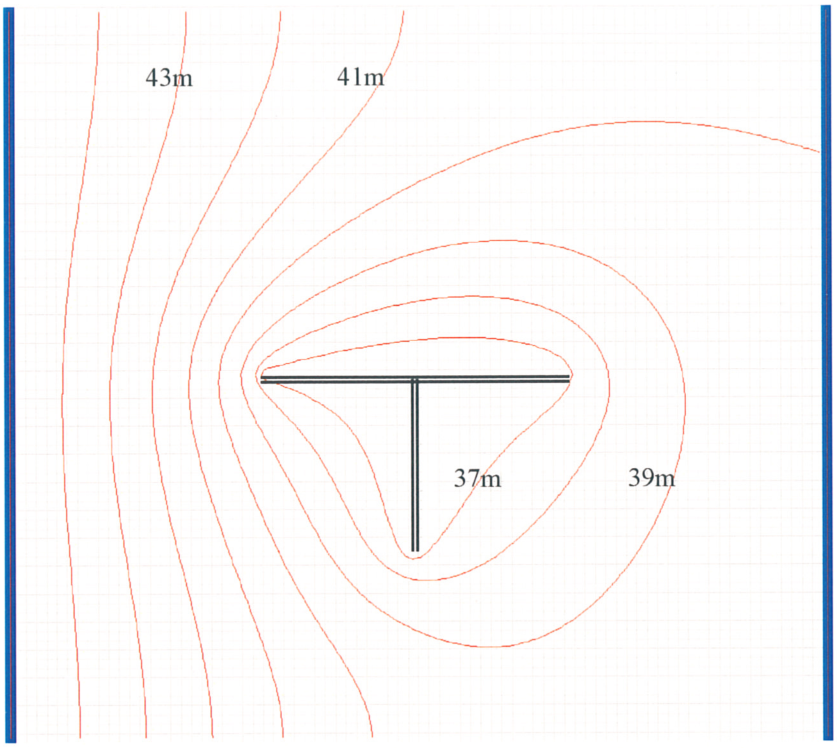

Fig.4 Groundwater contour map for interconnected three adit branches

3.3 Steady and Unsteady States

The simulations shown in both of Fig.2 and Fig.4 are steady state. An unsteady state was tested with a straight adit, the all aquifer and adit conditions are the same as introduced in Section 3.1 and Fig.2. Fig.5 shows the groundwater heads at the western end of the adit against pumping time, which is a 60 hour pumping test. One can see that the groundwater heads decreases quickly at the beginning of the pumping, then turns to a stable value. The unsteady state has been tested very briefly, just to prove the code can simulate unsteady state, therefore, pumping test can be simulated. More sophisticated tests need to be done later to understand the hydraulics of aquifer-adit system.

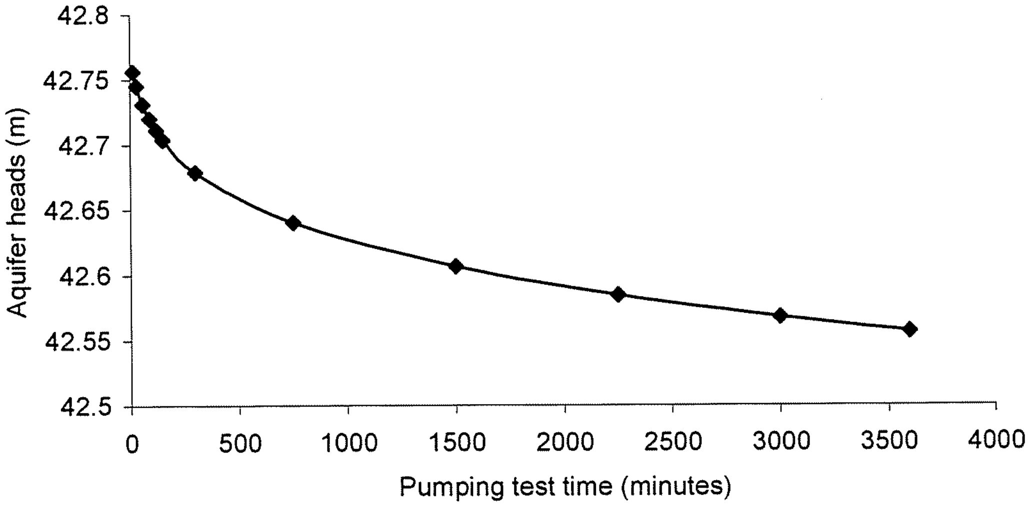

Fig. 5 Groundwater heads against the pumping time

3.4 Sensitivity Test of the Parameters

Besides common groundwater parameters, there are several additional parameters for MODBRNCH such as slot width and resistance coefficient. Sensitivity tests were carried out with respect to these parameters. All the parameter tests were carried out with the straight adit, as illustrated in Fig.2, and all the aquifer conditions have remained the same.

3.4.1 Test of Slot Width

The slots were set as 0.01m and 0.001m separately for the test. The contour maps of these two simulations are exactly the same as shown in Fig.2. The comparison of leakage is shown in Fig.6. It is hard to see any difference between the two simulations. This is an expected result. The test indicates that the simulation is not sensitive to slot widths under a certain value. This is because the slot width is not related to the water exchange area any more after the program has been modified. It affects the model only through the adit cross section area. The slot only contributes 0.35 % – 3.5% of cross-section area if the slot width is set as 0.001m – 0.01 m for 2m wide and 2m high adit, and the adit head is 14m higher than the top of the adit in this test.

3.4.3 Test of Resistance Coefficient

The resistance coefficient used in Equation (1) was tested in both steady and unsteady states. Fig. 7 shows a strong impact of the resistance coefficient. A larger value of resistance coefficient generates larger hydraulic slope in the adit flow, consequently causes a larger gradient of groundwater head.

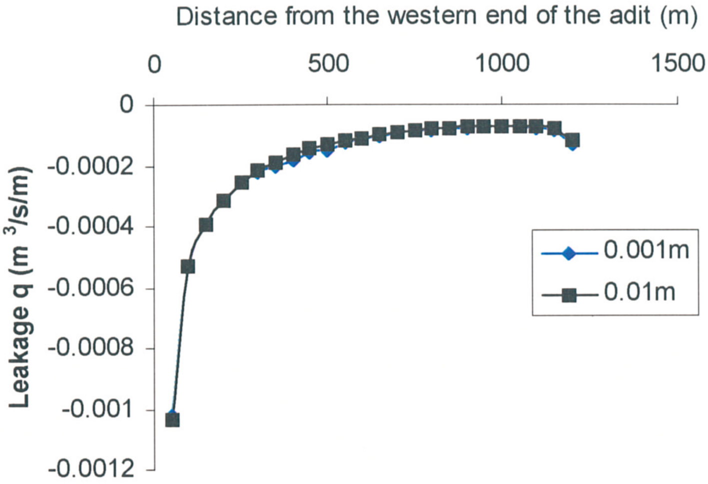

Fig.6 Comparison of leakage for 0.01m and 0.001m slot

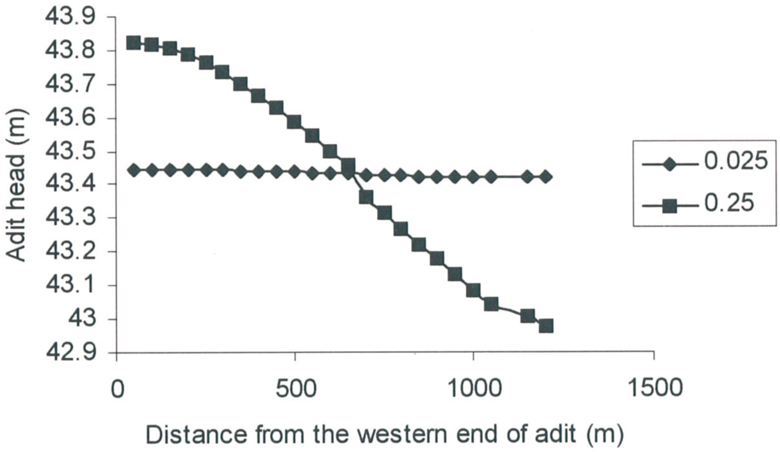

Fig.7 Comparison of Adit flow heads caused by various resistance coefficients.

4.WILMINGTON CASE STUDY

Wilmington pumping station is one the largest groundwater sources Thames Water Utilities Ltd has in south east London, with a peak discharge of 20 Ml/day (see Fig.8). The site has two wells, each 33 m deep. One well is operated as the duty well while the second is used as demand dictates. To increase the yield of the site, the wells are linked at their base by an adit. Further adits extend eastwards and to the south. Like most UK adits, Wilmington adits have a height of 1.8m and a width of 1.2m. They are about 30m below the ground surface. The main adit is 110m long, which is rather short. Observation boreholes were drilled around the site and are illustrated in Fig.8

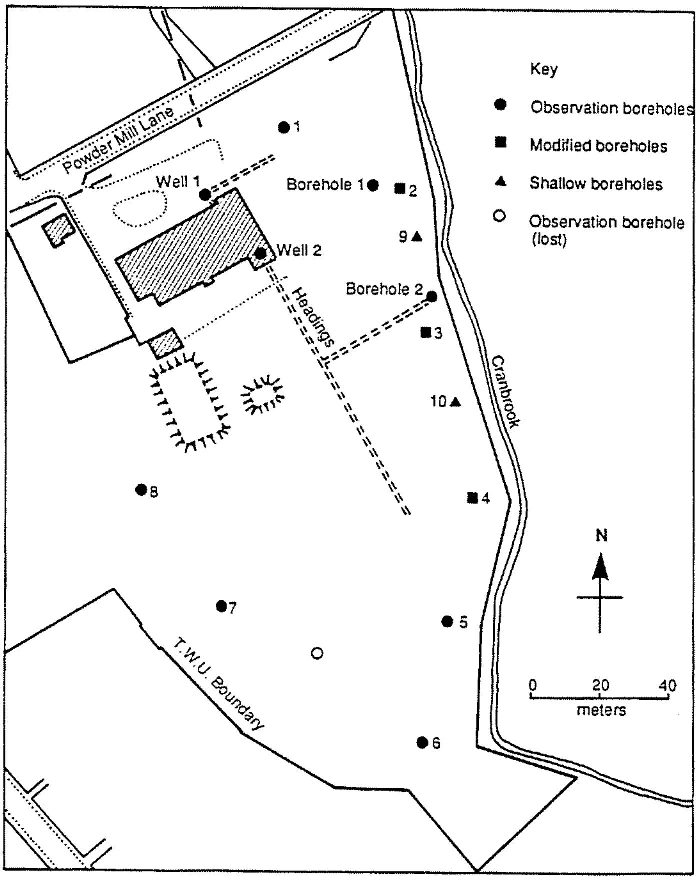

Fig.8 Wilmington adit layout

Wilmington is located in the Darent Catchment, which is in the southern limb of the London basin. The site is underlain by alluvial deposits which overlie the Chalk. The regional groundwater flow is generally in a northern direction, towards the River Thames. The existing Darent Catchment regional model includes an area of 600 km^2 and is divided into two layers, the alluvium and the Chalk. The boundaries are a constant head along the River Thames to the north, groundwater divides along the western and southern boundaries, and a no flow boundary to the east.

The model presented in this paper has an area of 4km by 5km and total thickness of 120m, and is taken from the existing regional model by means of Telescopic Mesh Refinement (TMR)(Ward et al, 1987). This incorporates the regional controlling factors into the smaller study domain. Head values from the regional model are assigned to the appropriate boundaries of the local model. The local modelling was carried out by both MODFLOW and MODBRNCH separately. To assign the adits into the aquifer, the chalk layer is further divided into three layers. One layer is above the adits, the second has the adits in it with a thickness of 4 meters, and the lowest layer is underneath the adits. A 0.01m wide slot is constructed to simulate the adit by MODBRNCH.

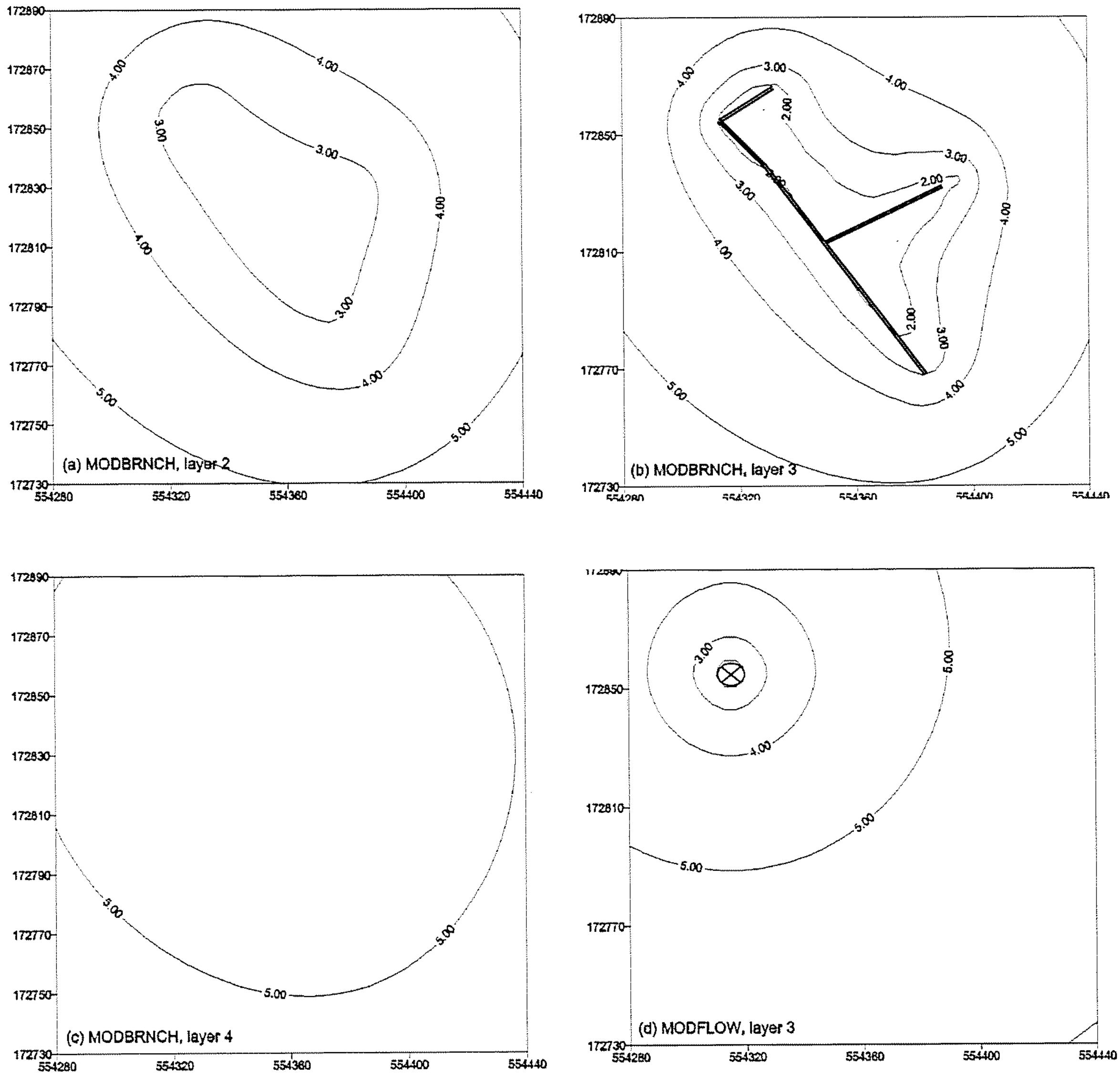

Fig.9 Comparison of heads around adits generated by MODBRNCH and MODFLOW

Fig.9 shows MODBRNCH predictions of the effect of the adit on groundwater heads in the three layers, and compares these to MODFLOW. The adits affect groundwater heads in the layer above, and the layer containing the adit (Fig.9a, 9b), but have little effect on the layer below (Fig.9c). The difference between the models can be seen by comparing Fig.9b and 9d, which show the middle Chalk layer for MODBRNCH and MODFLOW respectively. The area of drawdown is much larger than MODFLOW suggests.

Fig.10.presents the MODPATH pathlines based on groundwater head distributions produced by MODBRNCH and MODFLOW respectively. A 50-day marker is used. The figure shows that the 50-day protection zone of MODBRNCH enclosed by the dash line is moved in the south eastern direction compared with the one of MODFLOW because of adit's south eastern extension. This effect could be much stronger if the adit was bigger, as many of them are.

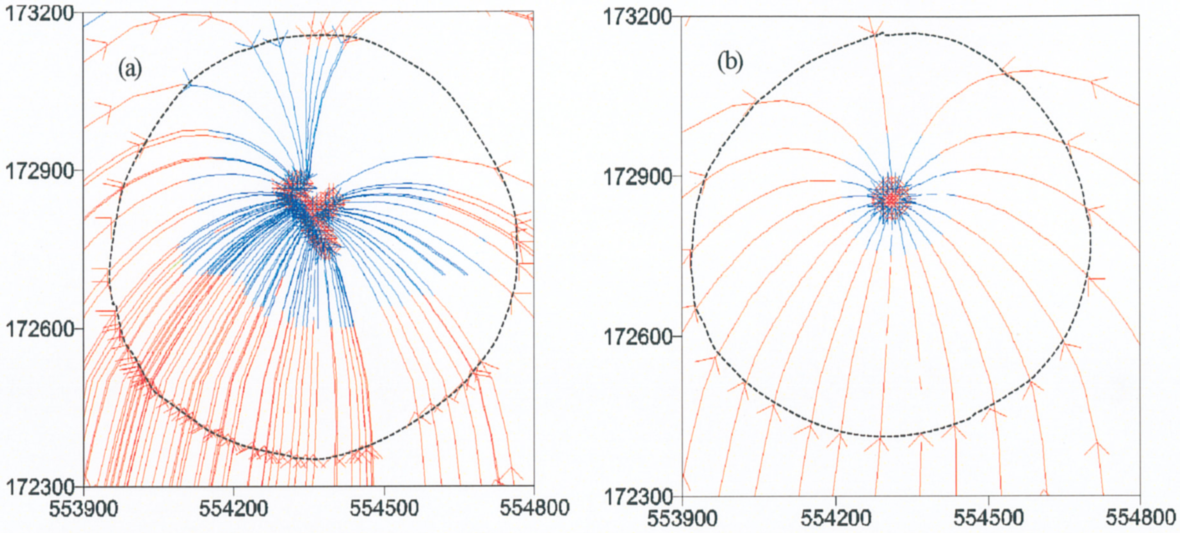

Fig.10 Comparison of 50-day time-of-travel zones (a) MODBRNCH, (b) MODFLOW

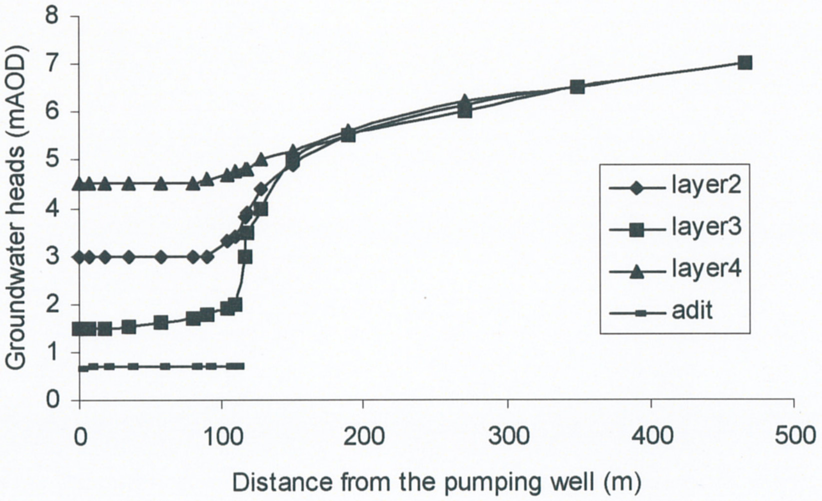

Fig.11 Simulated groundwater heads along the main adit direction

Fig.11 shows the groundwater heads simulated by MODBRNCH along the main adit direction. The heads for the layers above and with adits remain stable along 110m main adit, but jump up immediately at the entry of adit, and then increase gradually with increasing distance from the pumping well. Adit heads are around 0.7 m with a little hydraulic gradient.

5. FURTHER STUDIES ON WILMINGTON ADIT

As mentioned in Section 4, Wilmington has a small adit, and it's effect on protection zones is not significant. To see the topic in a general sense, the Wilmington main adit was extended to 1250m long, and all conditions were kept the same.

Fig.12 shows the 50-day time-of-travel zone for 1250m adit. Comparing (a) and (b), Apparently, the protection zone of long adit is extended along adit's extension. This is because the groundwater is pumped out from the adit in MODBRNCH.

Fig.13 shows the simulated contour maps for the three layers. There is little difference between three layers. Comparing Fig.13 with Fig.9, the enlarged adit affects all three layers and has a small drawdown. Apparently, long adits increase yield significantly.

Fig.14 demonstrates the groundwater heads distributions along the adit. It shows the same pattern as Fig.11. However, the differences between three layers are much smaller than that of shorter adit. It is indicated again that longer adit affects the aquifer not only the layer containing it and layer above, but also the layer underneath. Another phenomenon can be seen is that the hydraulic gradient in the adit increases near the pumping well.

This further study on Wilmington indicates that influences of longer adit on yield estimation and protection zone issues are quite different from that of smaller adit. So we should definitely choose a long adit for the next case study.

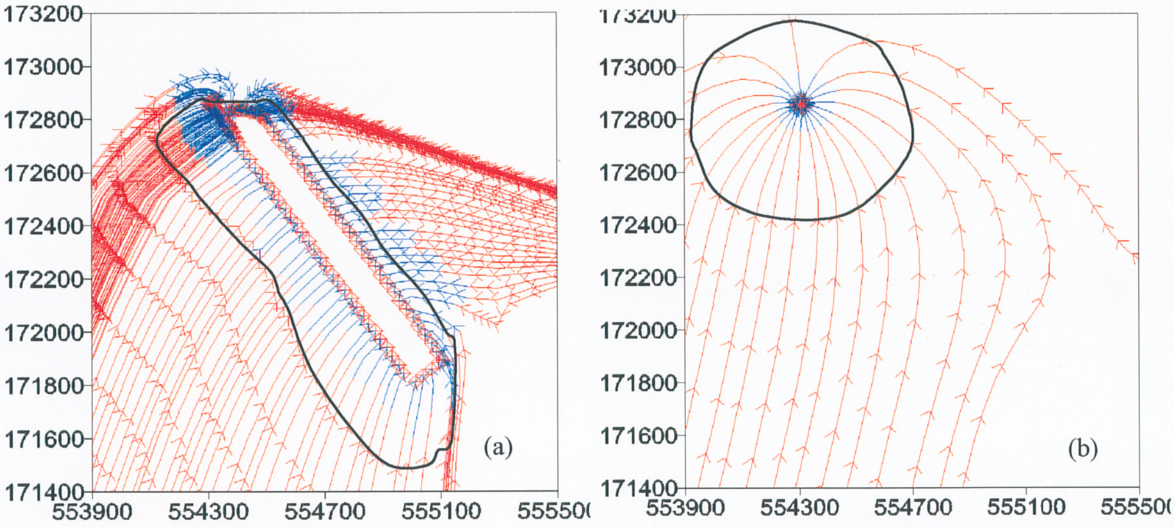

Fig.12 Comparison of 50-day time–of–travel zones (a) MODBRNCH, (b) MODFLOW

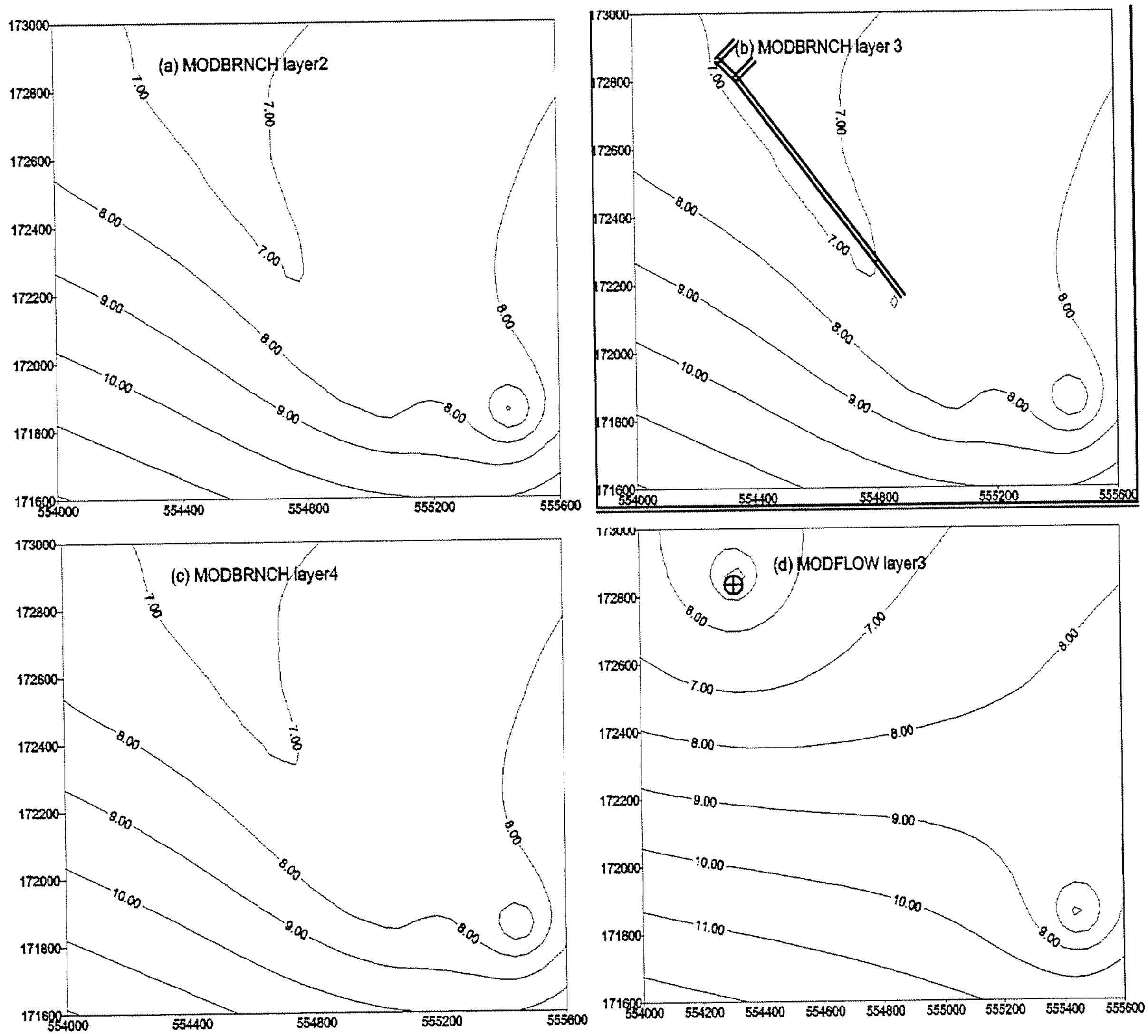

Fig.13 Comparison of heads around long adits generated by MODBRNCH and MODFLOW

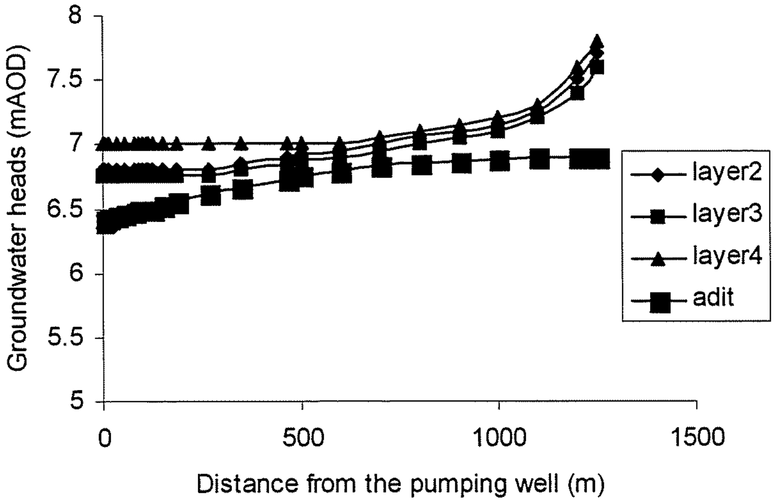

Fig.14 Comparison of Groundwater heads for three layers and adit flow

6. WORKING PLAN FOR NEXT STAGE

The second case study is going to be carried out on Cottingham adit. It is more than 1000m long, which is a normal size. We would like to take this opportunity to do more sophisticated studies, such as simulation of pumping tests, yield estimation, quantitative sensitivity analyses of parameters, and the adit influences on it's protection zones. This will further test the code, as well as providing the detailed understanding of aquifer-adit hydraulics.

In addition, following studies are proposed:

1. One of the important characteristics of British Chalk is that permeability generally decreases with depth (Headworth,et al, 1982). So it is necessary to understand the effect of permeability gradient on adit yield and three dimensional flow pattern.
2. Anisotropy is another characteristic of Chalk due to it's fissure (Atkinson,et al,1974). Therefore, investigating the relation between anisotropy and orientation of adit, exploring the influences of anisotropy on adit yield and protection zones would be necessary.
3. Detailed pumping test simulations should be carried out with a series of general models to understand the hydraulics of adit – aquifer systems.
4. Quantitative sensitivity analyses of the hydraulic parameters and setting out their suitable ranges for general models would be necessary for preparing the guidelines for modelling adit systems.
5. Influences of adits on transport of contaminants. Assuming there was a contaminant source, what would be the influences of adits on contaminant transport. What will be then the preventive measures for protection of adit system from the pollution?

6. Using the model as a tool to analyse the efficiencies of current protection zones, therefore draw up the guidelines for revising protection zones.

Through above approaches, the objectives of the project will be reasonably achieved.

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GPRG

OPERATION AND PROTECTION OF ADIT SYSTEMS IN UK AQUIFERS

THIRD PROGRESS REPORT

November 1998

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SUMMARY

Wilmington case was further studied by model calibration and sensitivity analyses. The model was calibrated for groundwater head distribution in January 1993, and the model predictions of heads were compared to field observations of three multilevel piezometers. The calibrating parameters include both horizontal and vertical permeability, and leakage coefficient.

The sensitivity of the adit model with respect to slot width, resistance coefficient, leakage coefficient and hydraulic conductivity were analyzed. The analyses indicate that the model predictions are sensitive to both horizontal and vertical hydraulic conductivity, and the leakage coefficient affects the model predictions. However, the model predictions are sensitive neither to the slot width of adits when it is small enough for a steady state, nor to the resistance coefficient for a short adit.

Cottingham case is being studied presently. The regional model is a MODFLOW model, which is based on an Environment Agency model — Southern Yorkshire Chalk FLOWPATH GPZ Model. The regional model is calibrated roughly matching the observed groundwater heads in August this year. The Adit model was just built, and it indicates that the adits affect groundwater heads not only on the layer with adits, but also the layer above the adit and the layer below.

The work for next stage includes further calibration of Cottingham regional model, and calibrating the adit model matching the multi-piezometer data which were obtain during pumping test, and drawing up guidelines for modelling of transient and pumping test. Both Yield and GPZ study are main objectives of the project. Therefore preparing guidelines for determining the yield of the adit systems and revising protection zones will be important tasks for next stage. Besides, preparing a user's manual for using the Slot approach and the computer code is probably necessary.

1.INTRODUCTION

1.1 Objectives

The objectives of this study have been kept the same from the proposal, to the inception report and the progress reports, up to present:

1.Providing a suitable computer code for modelling groundwater to adit systems.

2.Preparing guidelines for determining the yield of adit systems.

3.Demonstrating the effects of adit on source protection zones and developing guidelines for revising protection zones.

1.2 Progress against Plan

This research has been proceeding as the proposal and the inception report. A computer code has been provided, first site — Wilmington — has been studied, and the second case study — Cottingham case study — is being carried out.

Model calibration and sensitivity analyses on Wilmington case were carried out after the last steering group meeting according to the steering group's comments.

14 piezometers have been installed near Cottingham recently. The only available monitoring data were obtained from the pumping test, which took place in September. Therefore a regional model representing groundwater in August or September this year is needed. The regional model of Hull area, in which Cottingham is located, is calibrated only roughly because the data were not available until the end of October. The adit model has not been calibrated against piezometer data yet because all the adit monitoring data in depth and the relevant datum is not known yet. Therefore the adit model only shows the trend of head distribution around the adit at the moment. This has delayed the project slightly.

2. MODEL CALIBRATION AND SENSITIVITY ANALYSES ON WILMINGTON CASE

2.1 Model calibration

The Wilmington model was calibrated for groundwater head distribution in January, 1993. The calibrating parameters include both horizontal and vertical permeability, and leakage coefficient. Model predictions of heads are compared to field observations of three multilevel piezometers. The calibration results are shown in Figure 2. The calibration of OBH3, which is the nearest borehole(see Figure 1), is quite good for all three layers. However the calibrations for OBH2 and OBH4 are not ideal. Lack of data for local heterogeneity is probably one reason of the poor calibration. A value of 0.05 s/m $^{1/3}$ was used for resistance coefficient; and values of 20 m/d, 2 m/d and 10 /d were used for horizontal hydraulic conductivity, vertical hydraulic conductivity and leakage coefficient, respectively.

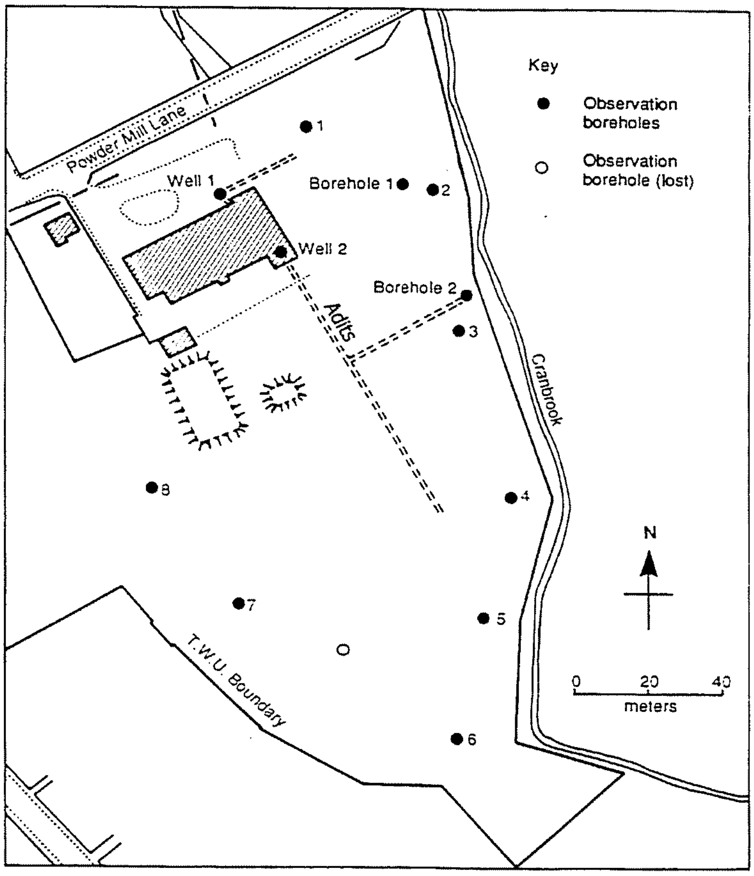


Figure 1 Wilmington Adit layout

The permeability of the Chalk generally decreases with depth in the UK (Downing, R.A. et al., 1993). It is suggested by the members of steering group that values of the permeability should be decreased with the aquifer depth. A small value of permeability for the layer below the adit was tested during the model calibration. However Figure 3 shows that the same values for the layer with adit and the layer below is better, it's heads are closer to the observed heads.

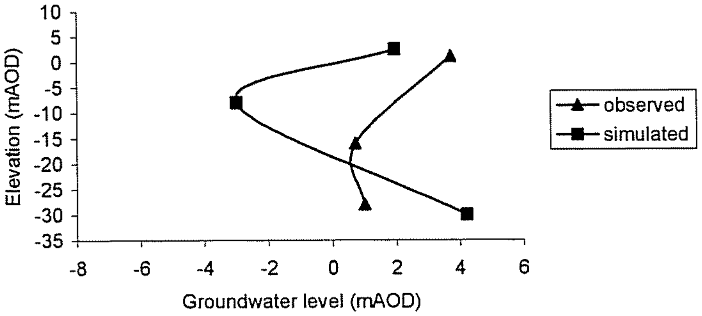


Figure 2a Calibration of BOH 2

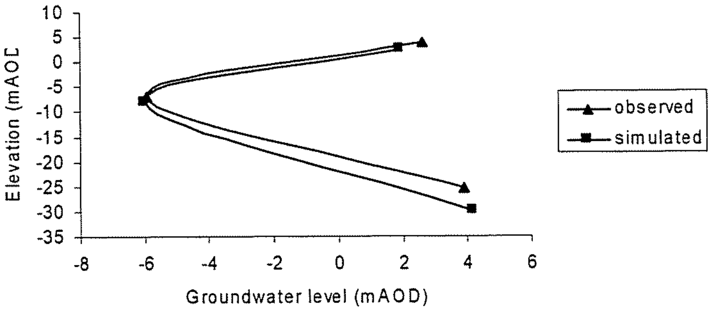


Figure 2b Calibration of BOH 3

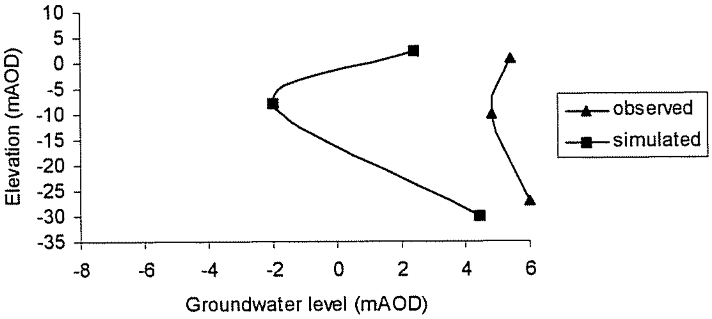


Figure 2c Calibration of BOH 4

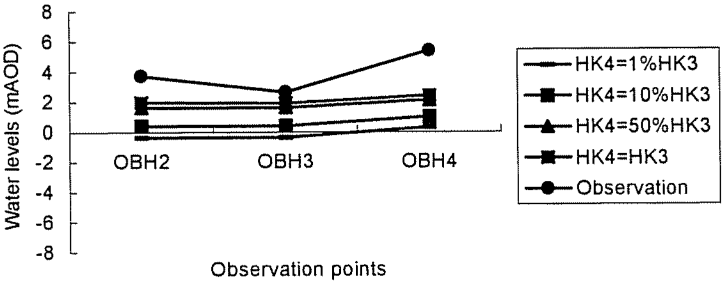


Figure 3a Groundwater heads for the layer above the adit

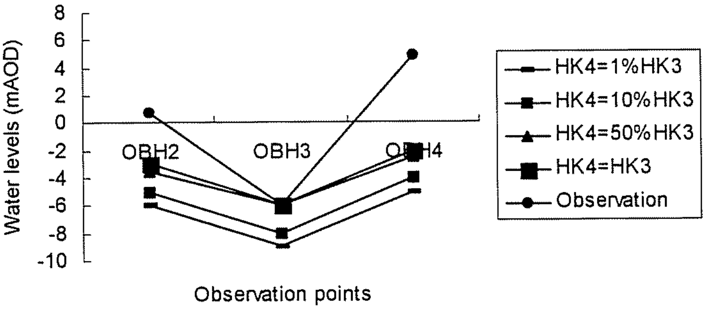


Figure3b Groundwater heads for the layer with the adit

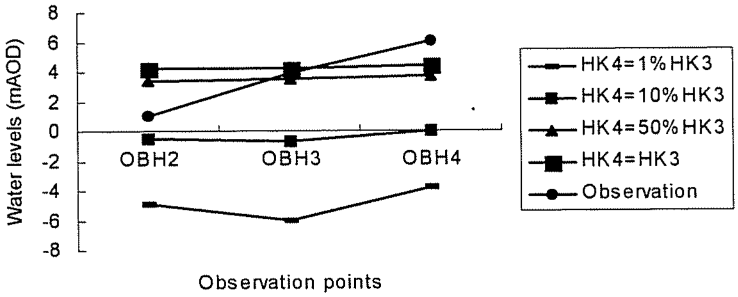


Figure3c Groundwater heads for the layer below the adit

2.2 Sensitivity analyses

The sensitivity of the adit model with respect to slot width, resistance coefficient, leakage coefficient and permeability were analyzed. The model prediction is not sensitive to the slot width of adits when it is 0.01 m or smaller for a steady state system (transient cases have not been studied yet). Neither is it sensitive to the resistance coefficient for a short adit, the variation of the water head is only 0.02 m while the resistance coefficient varied within a range of 0.02 — 0.1 s/m$^{1/3}$.

Figure 4 shows the sensitivity to the leakage coefficient. The difference between the adit and aquifer heads increases with decreasing leakage coefficient. This is because of the reversed proportional relation between leakage coefficient and head difference for a fixed pumping rate. (See Equation (1)). The leakage coefficient was initially assigned as the value of horizontal permeability, assuming b′ is 1 m, and adjusted to half of initial value during the model calibration.

$$q = \frac{k'}{b'} W_p (Z - h) \qquad (1)$$

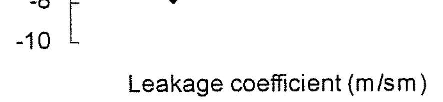


Figure 4 Sensitivity of adit model to Leakage coefficient

Figure 5 indicates that the permeability has strong impact on model output. Because the permeability of the Chalk generally decreases with depth in the UK (Downing, R.A. et al., 1993), the horizontal permeability of Layer 4 (HK4)has been varied to test the importance of this effect. Figure 5a, 5b and 5c show the model head at OBH2, OBH3 and OBH4 respectively. All three figures show the same phenomenon. That is, the model head is not sensitive to HK4 when HK4/HK3 is greater than 0.5, but there is an effect

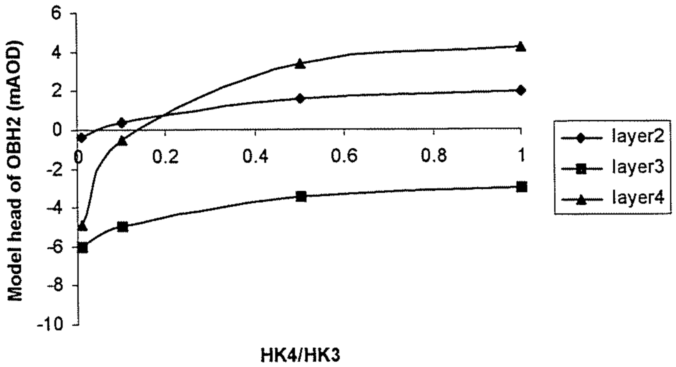


Figure 5a Sensitivity of Adit model to horizontal hydraulic conductivity (OBH2)

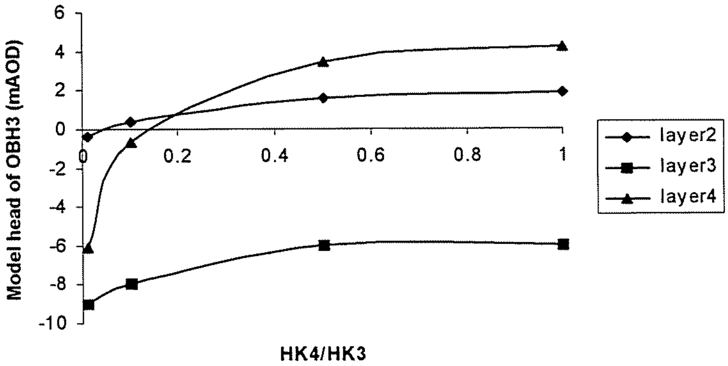


Figure 5b Sensitivity of Adit model to horizontal hydraulic conductivity (OBH3)

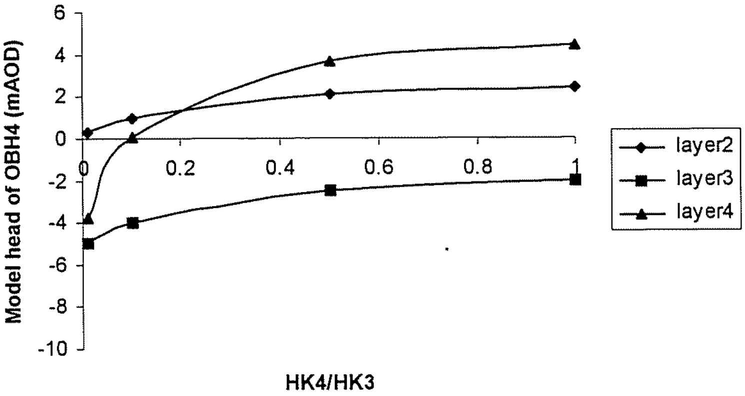


Figure 5c Sensitivity of Adit model to horizontal hydraulic conductivity (OBH4)

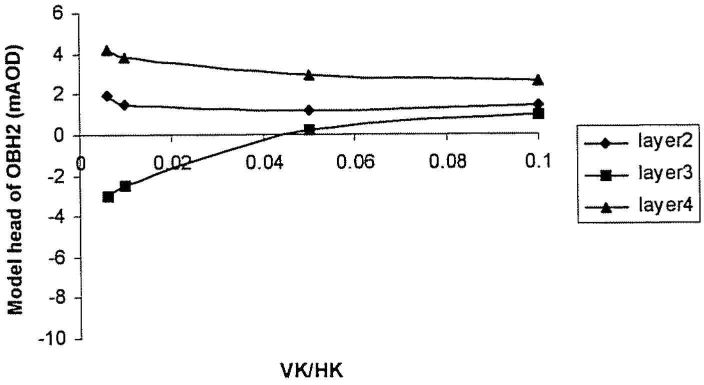


Figure 6a Sensitivity of Adit model to vertical hydraulic conductivity (OBH2)

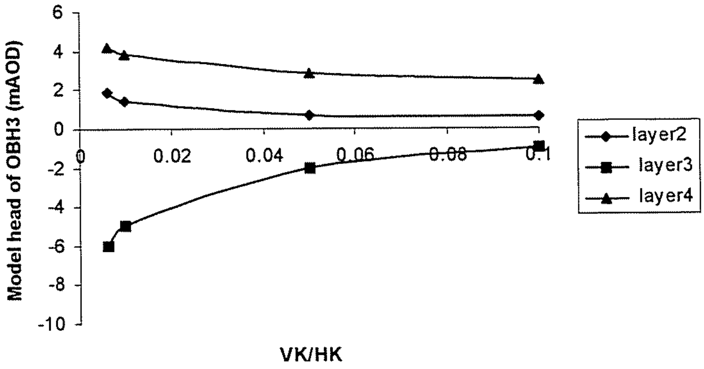


Figure 6b Sensitivity of Adit model to vertical hydraulic conductivity (OBH3)

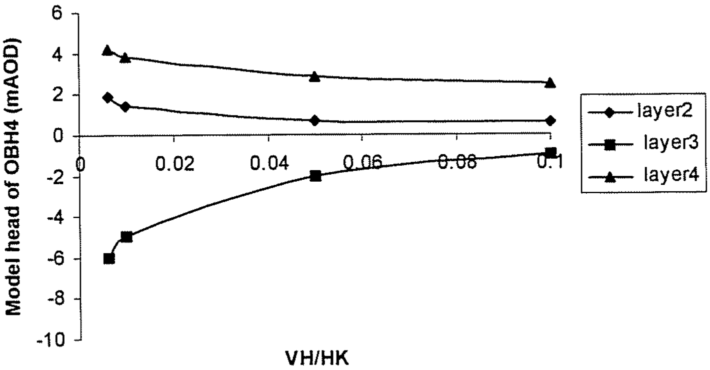


Figure 6c Sensitivity of Adit model to vertical hydraulic conductivity (OBH4)

when HK4/HK3 is smaller than 0.5, particularly on heads in Layer 4. The head of Layer 4 will be even lower than Layer 2 if HK4/HK3 is smaller than 0.2. Note that these tests are only indicative, as they do not preserve the convention of TMR. Corresponding changes to the transmisivity of the Chalk layer in the regional model were not made.

Figure 6 shows the influence of vertical permeability — VK. Figure 6a, 6b and 6c show the model head at OBH2, OBH3 and OBH4 respectively. It is shown that the vertical permeability is influential only for values less than 5% of HK, horizontal permeability, and the layer with adit — Layer 3 — is the most influenced layer. The head of Layer 3 decreases with decreasing vertical hydraulic conductivity. In contrast, the heads of Layer 2 and Layer 4 increase with decreasing vertical hydraulic conductivity.

3 COTTINGHAM CASE STUDY

Cottingham pumping station is one the largest groundwater sources of Yorkshire Water Services has in Hull area, with a licensed abstraction of 68182 m^3/d, and the mean of actual abstraction is 24000 m^3/d. The Cottingham source is extremely complex, comprising of two operation pumping shafts, 20 other shafts and about 1000 m of adits in use(see Figure 7). The Cottingham adits consist of two main systems at -15 maod and -29 maod. The lower system is not used and not connected to the higher system. The existing bores below the higher adits were plugged to ensure there was no connection with the lower adits (Crease, 1998).

Cottingham source is located in the "Yorkshire Chalk", to the north of the Humber Estuary. The outcrop of the Chalk appears in the west, and the Chalk is covered by a thick sequence of Boulder Clay and thin sandy drift in the east (see Figure 8). The regional groundwater flows in a southeast direction to the abstractions. Over the bulk of the outcrop the Chalk is unconfined, and the Chalk becomes confined away from outcrop (Aspinwall & Company, 1995).

The model presented in this report is a MODFLOW model, which is based on a FLOWPATH model of Environment Agency. The original FLOWPATH model has an area of 540 km^2, and was simplified as one layer model with a thickness of 35 m, from -15 maod to 20 maod. The area was discretized into 119 by 120 nodes, and a steady state was modeled. The boundary conditions were: No flow boundary along groundwater divide in west, flow perpendicular to groundwater contours in north, constant head along Humber Estuary to the south and North Sea to the east.

To focus on the Cottingham adits, the new model is refined around Cottingham area with maximum grid spacing of 30 m. The top of the model has been increased to 60 maod because the groundwater head in the west is up to 45 maod. In order to see the effect of the adit on the layer below the adits, which is located at -15 maod, the bottom of the model is extended to -30 maod. The model is divided into three layers, one layer is above the adit, one layer has adit in it with a thickness of 3 m, and one layer is below the adit.

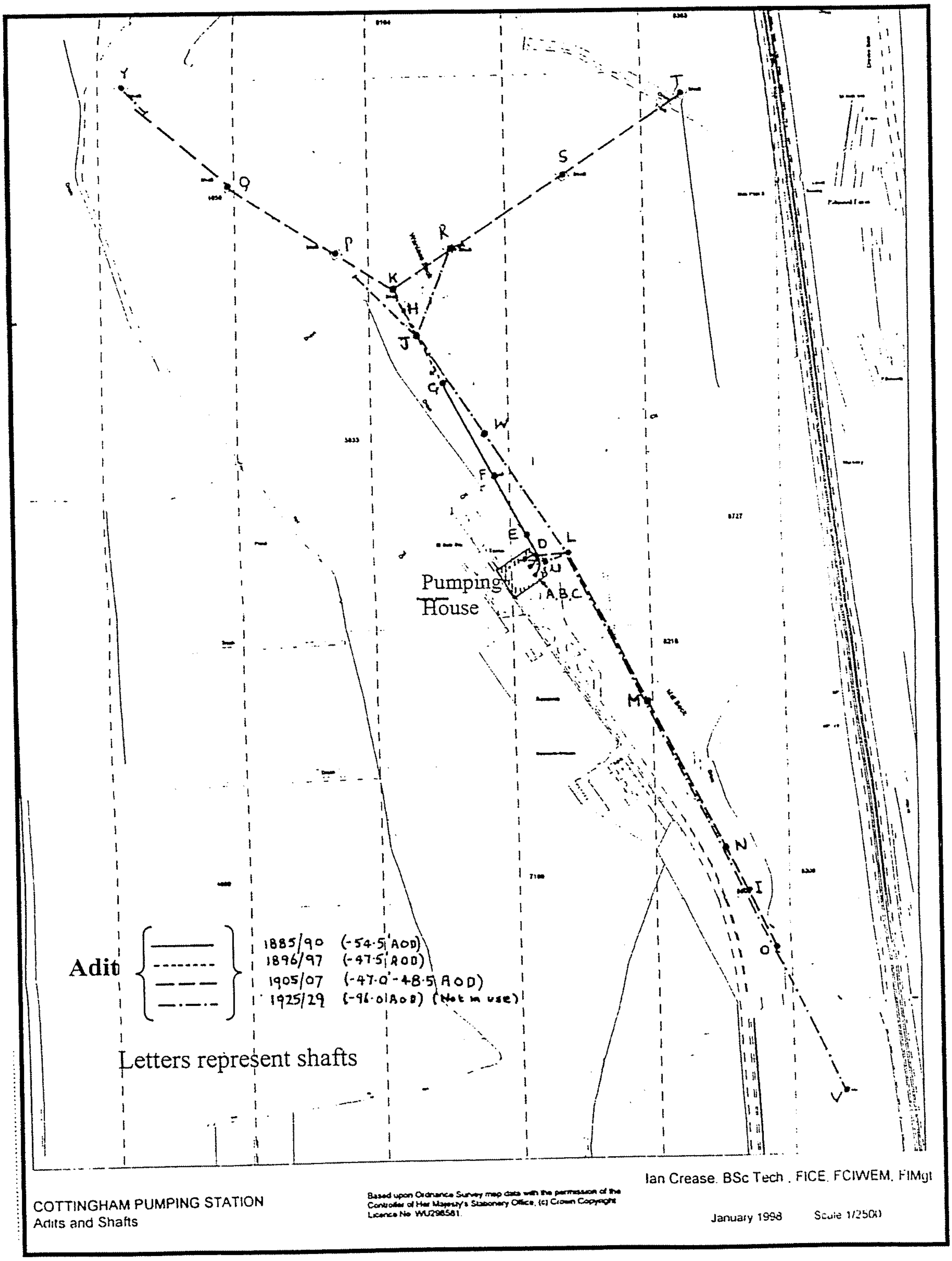


Figure 7 Cottingham Adit layout

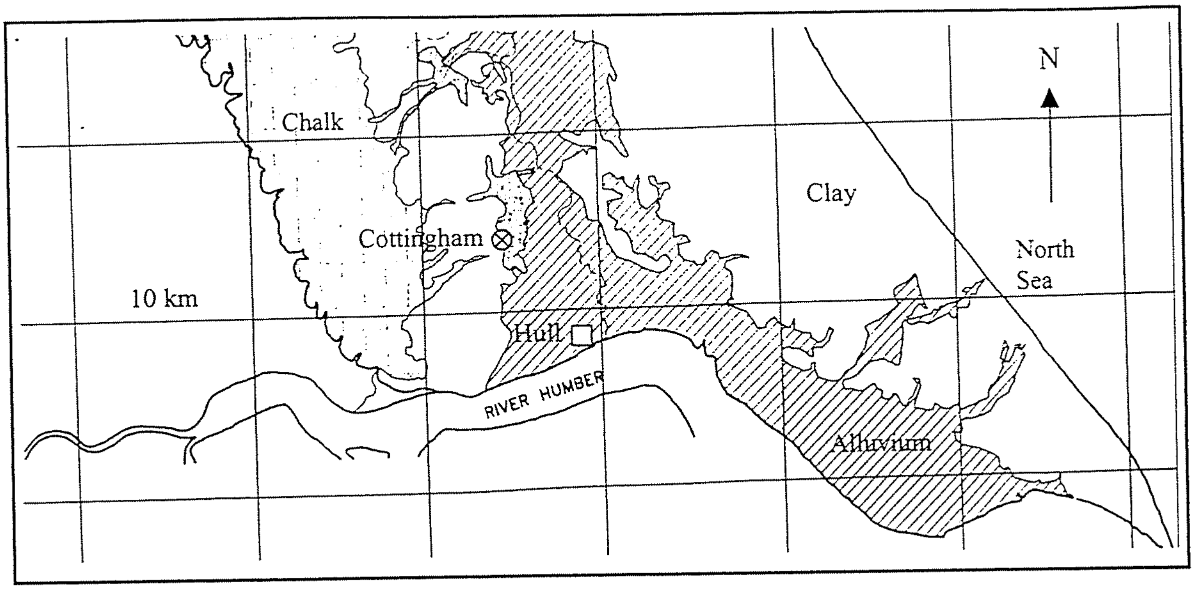


Figure 8 Regional Geology of Hull Area

14 piezometers have been installed recently, and the only available monitoring data were obtained from the pumping test, which took place in September. Therefore a model representing groundwater in August or September this year is needed. The model was re-calibrated to match the groundwater distribution in August. During the model calibration, the values of permeability and porosity were kept unchanged, while the recharge is slightly adjusted and the abstraction is specified according to the actual abstraction this summer.

Figure 9 shows the regional groundwater head distribution modeled with the configuration described above. Figure10 shows the MODBRNCH predictions of the effect of the adit on groundwater heads in the three layers, and compares these to MODFLOW. The adit affects groundwater heads not only the layer with adit, but also the layer above and the layer below. The MODFLOW model was simulated distributing abstraction along adits which was used in the Environment Agency FLOWPATH model. The difference between the models can be seen by comparing Fig.10b and 10d, which show the middle layer for MODBRNCH and MODFLOW respectively. The area of drawdown is much larger than MODFLOW suggests.

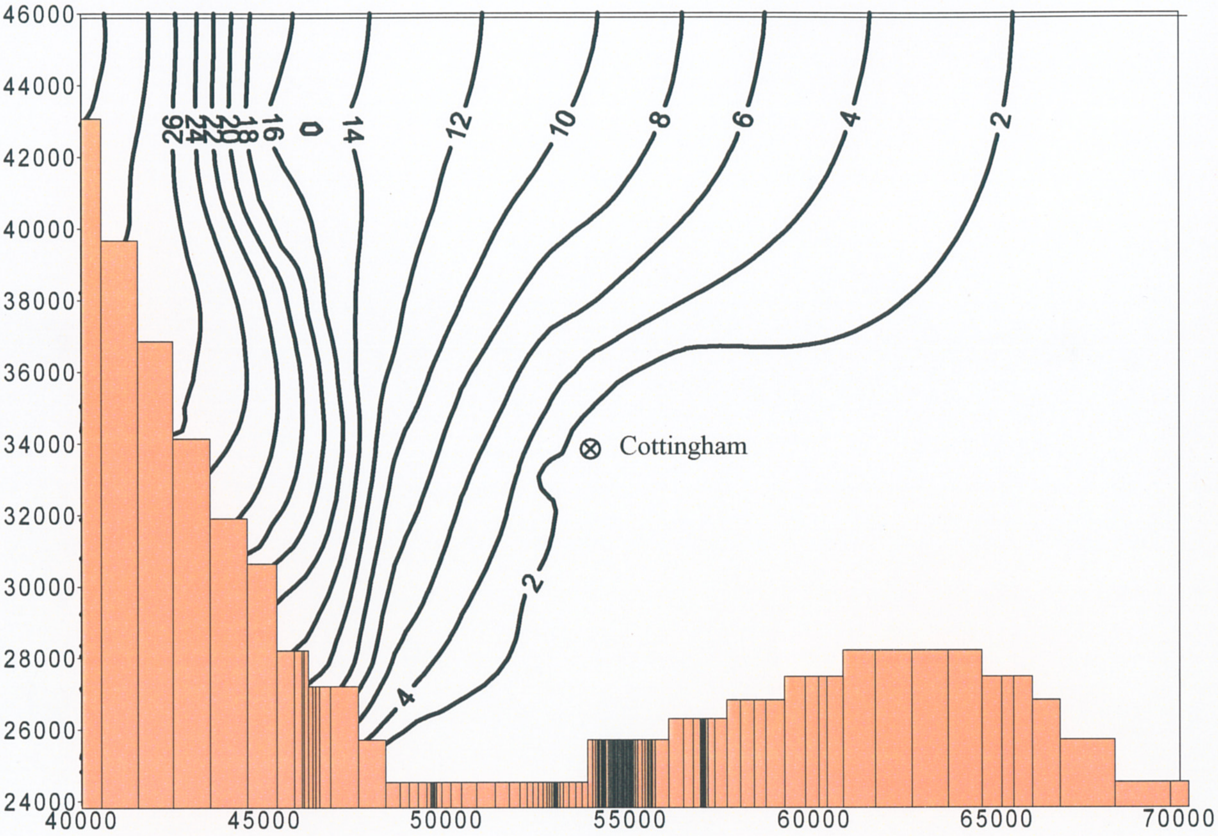
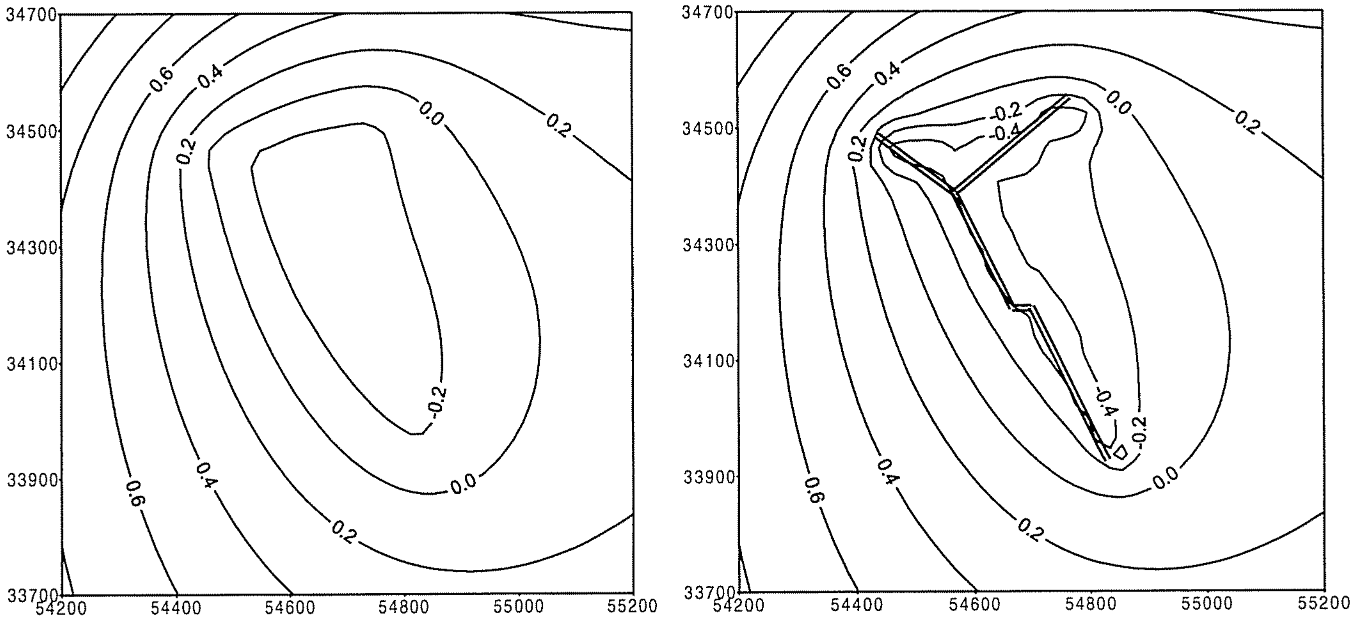
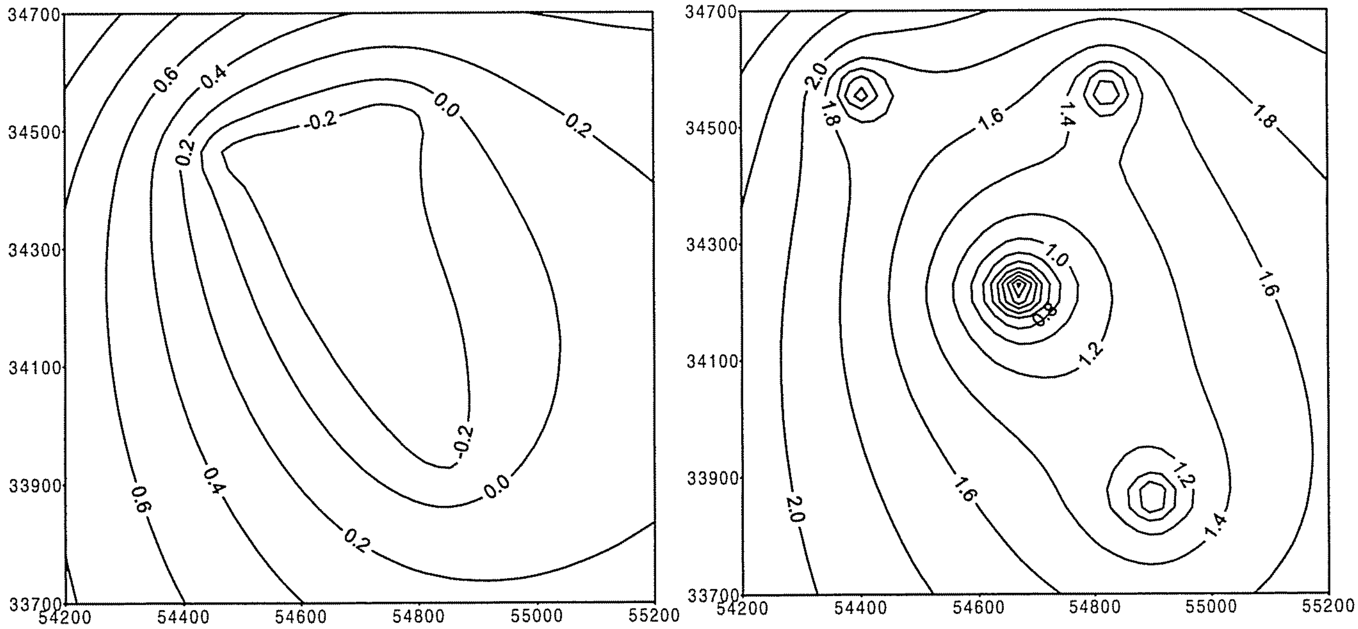


Figure 9 Simulated groundwater head distribution in Hull area



(a) MODBRNCH, Layer 1 (b) MODBRNCH, Layer 2



(c) MODBRNCH, Layer 3 (d) MODFLOW, Layer 2

Figure10 Comparing of heads around adits generated by MODBRNCH and MODFLOW

4 WORKING PLAN FOR NEXT STAGE

Calibrating the Adit model matching the multi-piezometer data during the pumping test, and drawing up the guidelines for modelling of unsteady state and pumping test

Yield study using both Wilmington and Cottingham cases. Preparing guidelines for determining the yield of adit systems.

Demonstrating the effect of adit on Groundwater Source Protection Zones using Cottingham case and other general hypothetical cases. Developing guidelines for revising protection zones.

Preparing a user's manual for using the proposed approach and computer code, and final report.

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GPRG

OPERATION AND PROTECTION OF ADIT SYSTEMS IN UK AQUIFERS

FOURTH PROGRESS REPORT

April 1999

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SUMMARY

The Cottingham modelling consists of regional modelling and local modelling. Each modelling includes steady state and transient model. Both steady and transient local models were taken from corresponding regional models using TMR. Steady state models were at the condition of August 1998, while transient models represent the condition of 2nd-20th September1998. The output of steady state models was taken as initial head of transient models.

Regional models are MODFLOW models while the local models are Adit models, which are MODBRNCH plus Slot approach. This allows us focusing on adit local model also integrating regional controlling factor into local model. The regional models were simplified as one layer model, while the local models were split to 5 layers according to adit elevation, lithology and transducer elevations. Adit is located at Layer 4, Layer 3 is considered as shaft seepage horizon (part of water flows into adit through shafts), and Layer 1 is drift formation. The thickness of layers was adjusted during model calibration.

A lot of time was spent on model calibration. Both horizontal and vertical permeability was main calibrating parameter for steady state model. Transient model calibration was focused on storage coefficient and recharge. Leakage coefficient was also adjusted during model calibration.

A literature review has been undertaken regarding yield study. Very few papers talks about yield of single groundwater source. However, **A Methodology for the Determination of Output of Groundwater Sources,** which was developed by GDC in 1995 on behalf of UK Water Industry Research, is recognized key document for groundwater source yield assessment by all water companies. Both advantages and disadvantages of this method were discussed. A modelling method for adit yield study was proposed to overcome the disadvantages of the standard method.

Work for next stage will include adit yield study, adit protection zone study and modelling of multi-level adit systems. The yield study will be carried out using Cottingham Case study, and the guidelines will be drawn up. Adit protection zone will be studied with Cottingham case and some general hypothetical cases. Methods for modelling of multi-level adit need to be explored and applied to the third case.

1. INTRODUCTION

1.1 Objectives

1. Providing a suitable computer code for modelling groundwater to adit systems including both steady and transient models, multiple-interconnected branches and multi-level adit systems.

2. Preparing guidelines for determining the yield of adit systems.

3. Demonstrating the effects of adit on source protection zones and developing guidelines for revising protection zones.

1.2 Progress against Plan

This research has been proceeding as the proposal and the inception report. A computer code has been provided, and two case studies, Wilmington case study and Cottingham case study have been carried out, and a plan of yield study is proposed.

The project is extended to 30 December 1999 to develop a method, which simulates the adit systems with multi-levels, and will be applied to the third case study. The proposal for the project extension is attached in the Appendix 1.

The Cottingham case study has been focused on the simulation of pumping test, which took place in September 1998. The availability of both regional and local data were delayed for a while, and the complexity of Cottingham adit system makes it's calibration extremely difficult. This has delayed the project slightly.

2 COTTINGHAM CASE STUDY

Cottingham pumping station is one the largest groundwater sources of Yorkshire Water Services has in Hull area, with a licensed abstraction of 68182 m^3/d, and the mean actual abstraction is 28000 m^3/d. The Cottingham source is complex, comprising of two operation pumping shafts, 20 other shafts and about 1000 m of adits in use(see Figure 1). The Cottingham adits consist of two main systems at -15 maod and -29 maod. The lower system is not used and not connected to the higher system. The existing bores below the higher adits were plugged to ensure there was no connection with the lower adits (Crease, 1998).

Cottingham source is located in the "Yorkshire Chalk", to the north of the Humber Estuary. The outcrop of the Chalk appears in the west, and the Chalk is covered by a thick sequence of Boulder Clay and thin sandy drift in the east (see Figure 2). The

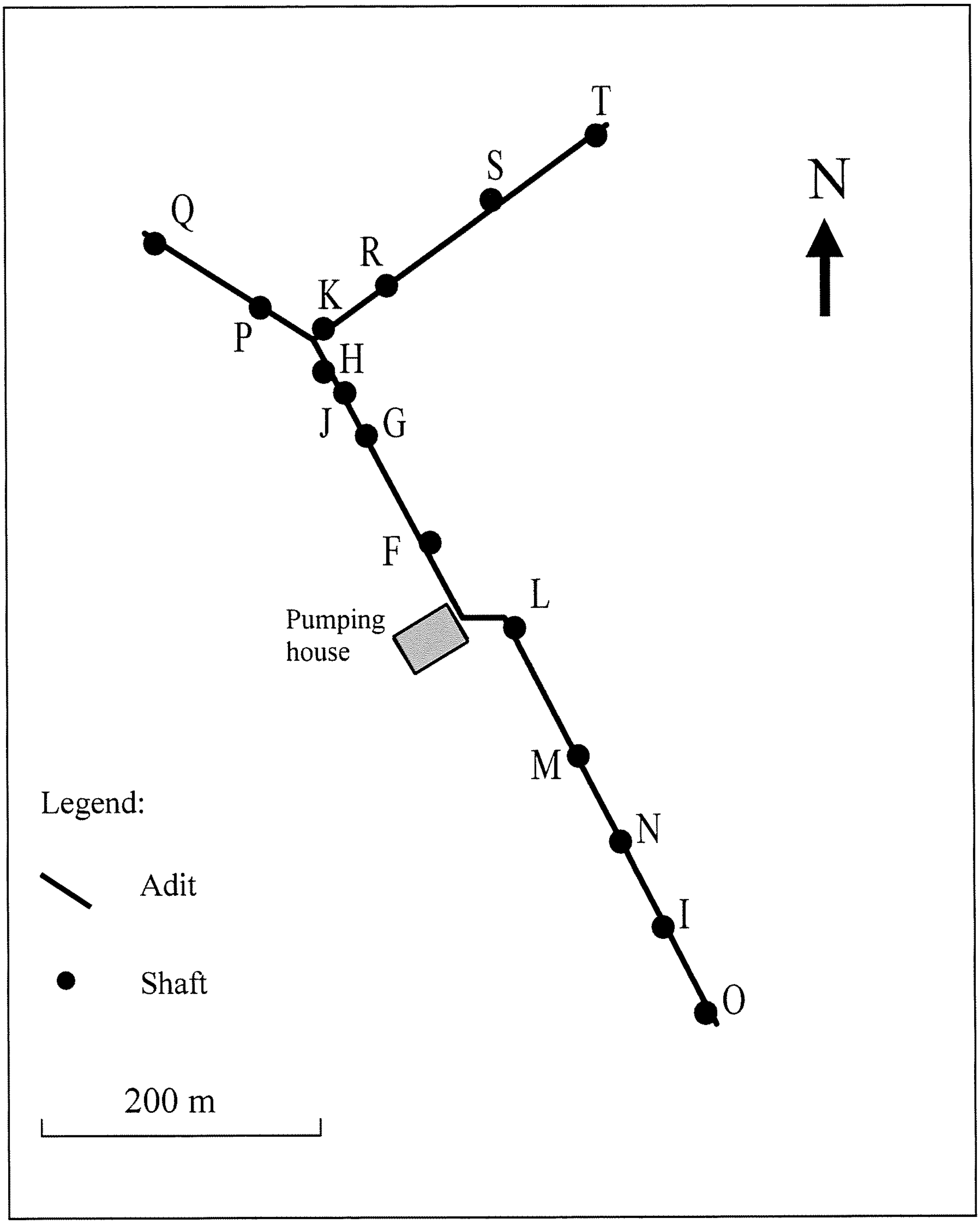


Figure 1 Cottingham Adit layout

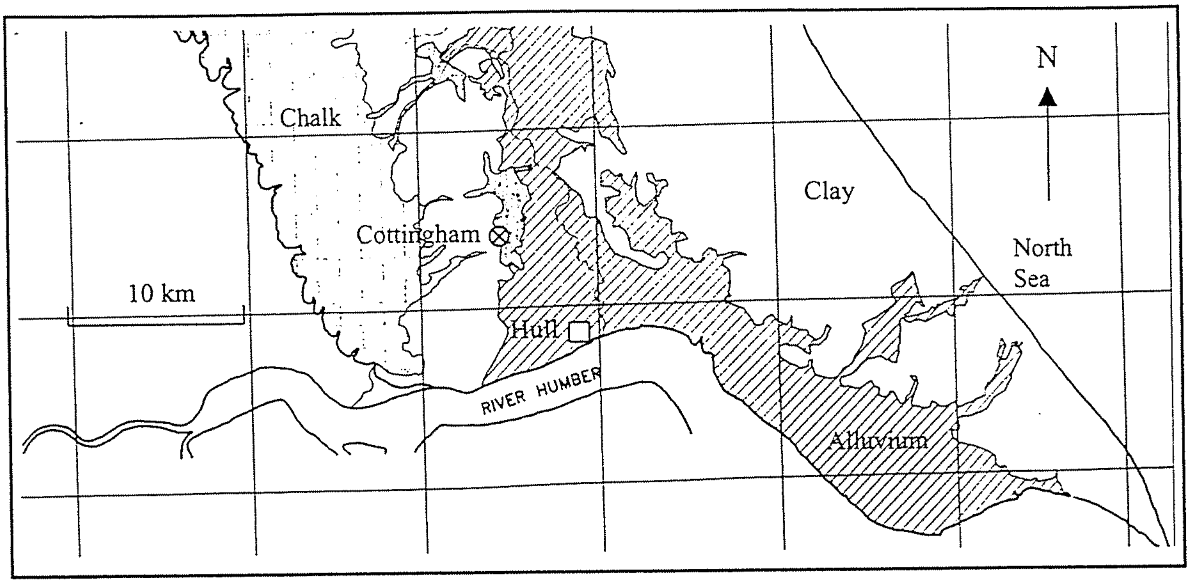


Figure 2 Regional Geology of Hull Area

regional groundwater flows in a southeast direction to the abstractions. Over the bulk of the outcrop the Chalk is unconfined, and the Chalk becomes confined away from outcrop (Aspinwall & Company, 1995).

2.1 Modelling procedures

The first case study — Wilmington case study — was focused on a steady state model. It would be interesting to build a transient model for Cottingham case study. To simulate Cottingham pumping test, which took place between 2nd - 19th September 1998, using Adit model, a transient model should be built. In order to get a start point for the transient model, a steady state model representing August 1998 condition was calibrated first. This reduces uncertainties of transient model in some way, the groundwater head distribution simulated by the steady state model can be taken as initial head of transient model.

To focus on adit and also incorporate regional controlling factor into Cottingham model, Telescope Mesh Refinement (TMR)(Ward, et al., 1987) approach is applied. The modelling procedures is illustrated in Figure 3.

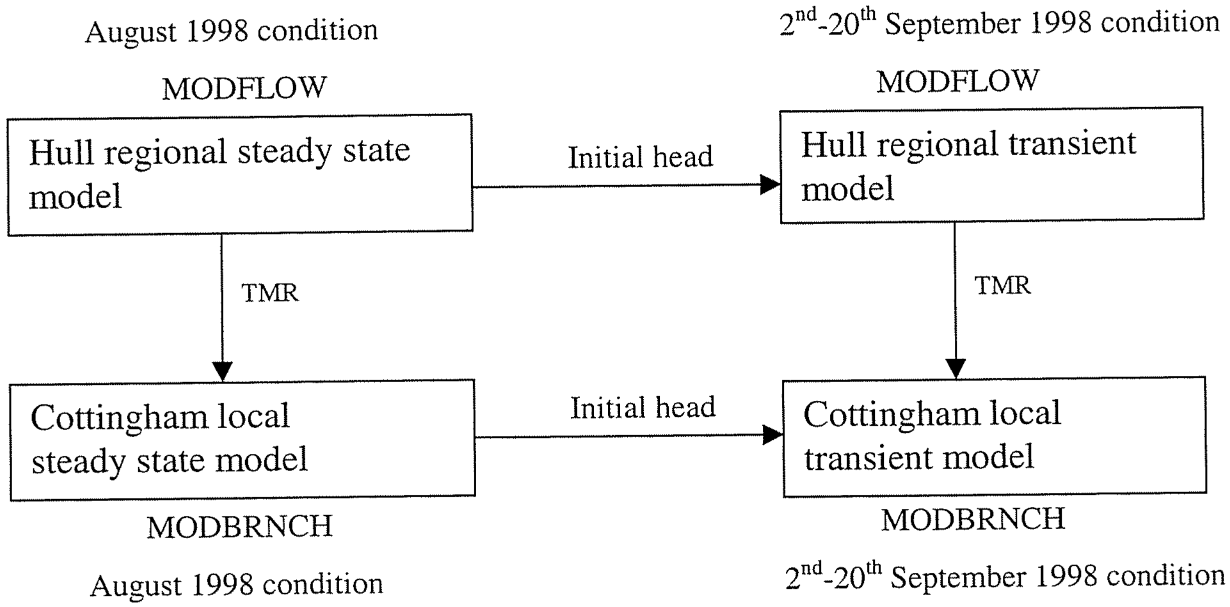


Figure 3 Modelling procedures

2.2 Summary of Cottingham pumping test

Cottingham pumping test can be divided into three stages shown in Table 1

Table 1 Pumping test stages

Date	Stage	Pumping rate
Before 2ndSeptember 1998	prior initial recovery	31095m^3/d
2nd-3rd September 1998	Initial recovery test	0
3rd-19th September 1998	Constant rate test	51000m^3/d
19th-20th September 1998	Final recovery test	0

Recovery and constant rate tests were conducted over a period of 18 days. Through out the testing, local groundwater levels were continually monitored by pressure transducers. There were installed in 13 observation boreholes, distributed among 3 locations. The approximate locations are given in Figure 4, and the elevations of transducers are indicated in Table 2

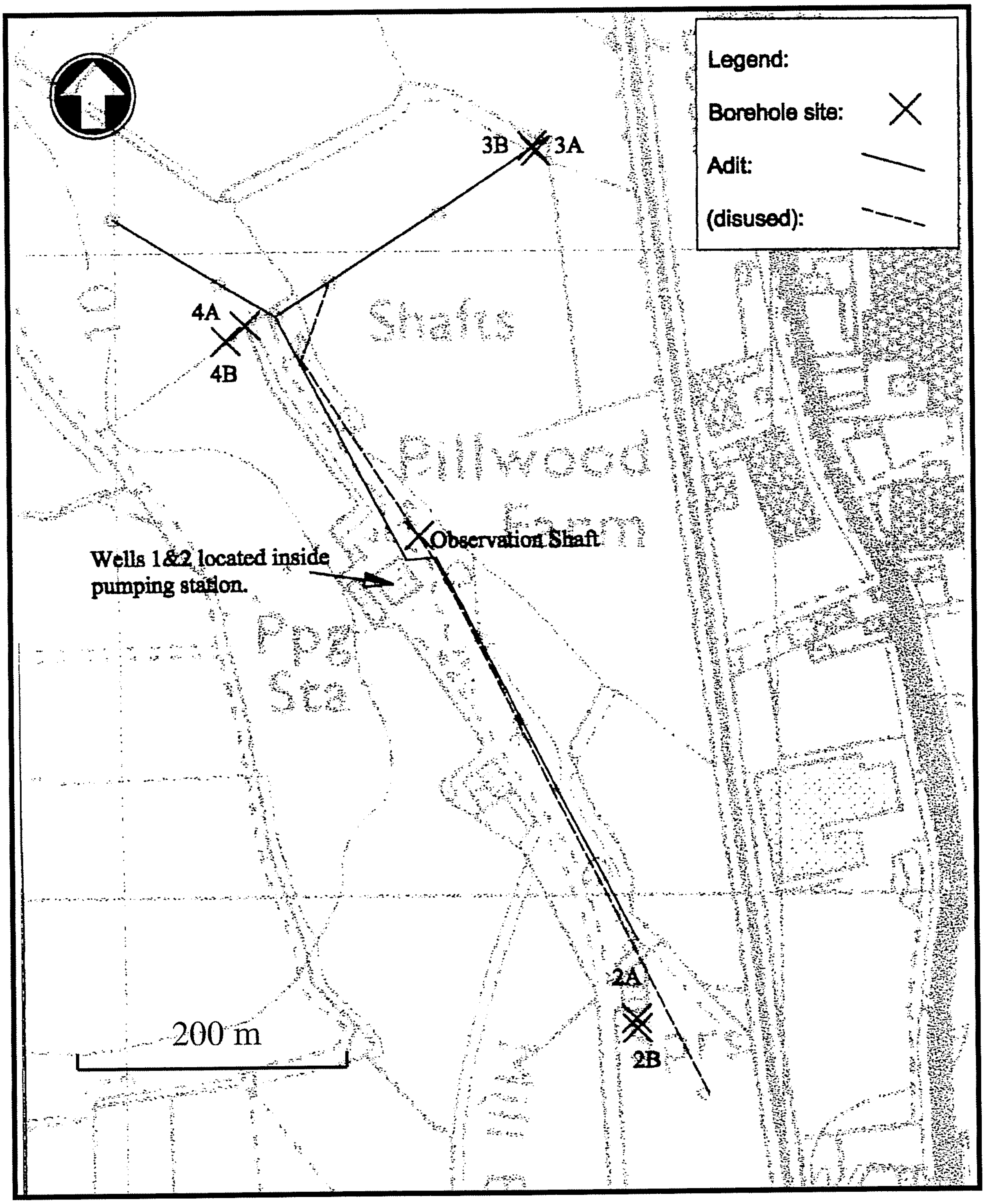


Figure 4 Locations of observation boreholes at Cottingham

Table 2 Elevations of transducers

Transducer	*Elevation*	*Transducer*	*Elevation*	*Transducer*	*Elevation*
2Ai	0.77 maod	3Ai	1.046 maod	4Atop	2.586 maod
2Aii	-9.2 maod	3Aii	-6.55 maod	4Alower	-2.11 maod
2Bii	-13.7 maod	3Bi	-9.65 maod	4Btop	-9.3 maod
2Bi	-22.7 maod	3Bii	-15.95mao	4Bblank	-14.8 maod

2.3 Regional model

The regional model presented in this report is a MODFLOW model, which is based on a FLOWPATH model of Environment Agency (Hodgson & Aldrick, 1997). The model has an area of 660 km^2 and is simplified as one layer. The boundary conditions are: No flow boundary along groundwater divide in west, flow perpendicular to groundwater contours in north, constant head along Humber Estuary to the south, and constant head to the east.

The base of the aquifer has been considered variously from -15 maod to -50 maod in previous modelling study. According to a recent report on Cottingham pumping test analysis and assessment by Mott MacDonald (Pippon,et al.1998), the base of aquifer was considered as -23 maod. In order to see the effect of adit, which is located from -12 maod to -18 maod, on the layers, -30 maod is taken as the elevation of the aquifer bottom.

To simulate the pumping test, the model calibration was focused on the groundwater head distribution in August and on 2nd September, right before the initial recovery of the pumping test. So that the 2nd September can be taken as a starting point of transient model, and simulated head distribution can be taken as initial head for transient model.

During the steady state regional model calibration, the values of permeability and recharge were adjusted, and a pumping rate of 31,000m^3/d was used, which is average rate of July and August for Cottingham pumping station. The analysis of Cottingham pumping test for aquifer properties was taken into account for model calibration. The transmissivity of 2900m^2/d and 700 m^2/d were calculated for early and late stages of pumping test separately (Rippon & Pennington, 1998). The value of 2100m^2/d was taken for this model. The calibrated regional groundwater distribution is shown in Figure 5.

The transient regional model simulated 18 day pumping test including initial recovery stage, constant pumping stage and final recovery stage. The water head distribution calculated by steady state model was taken as initial head. Storage coefficient and recharge were calibrating parameters.

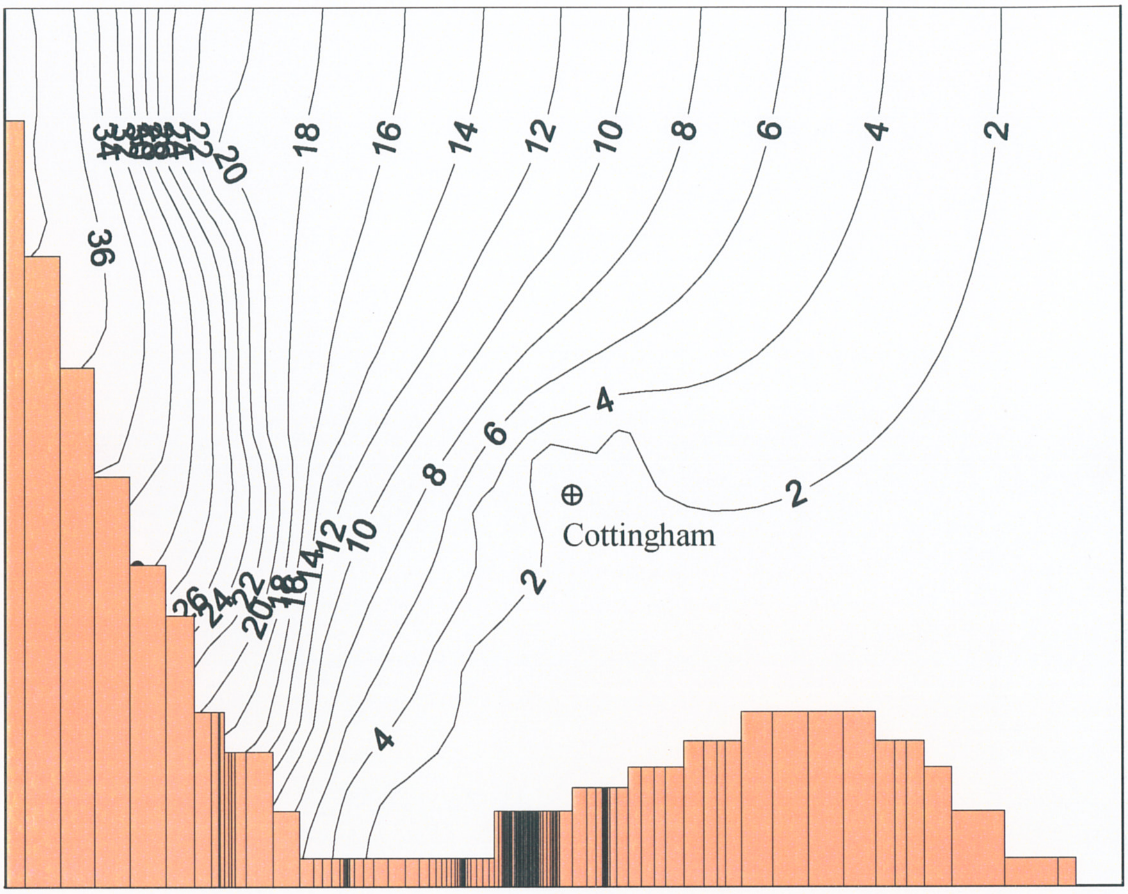


Figure 5 Calibrated regional groundwater distribution

2.4 Cottingham local model

2.4.1 Cottingham steady state local model

The steady state Cottingham local model was taken from it's regional model by means of TMR. Both regional and local models are shown in Figure 6. Constant head boundaries are specified at all the boundaries for steady state. The local model has an area of 2.5 km by 2 km, and the grid space around adit area is 20 m. The model is split into 5 layers according to adit elevation, lithology, and transducer elevations. The elevations of layers are described in Table 3

Table 3 Model layers and their Lithology

Layers	Elevation (maod)	Lithology
1	~ -2	Drift
2	-2 ~ -6	Chalk
3	-6 ~ -12	Chalk
4	-12 ~ -18	Chalk
5	-18 ~ -30	Chalk

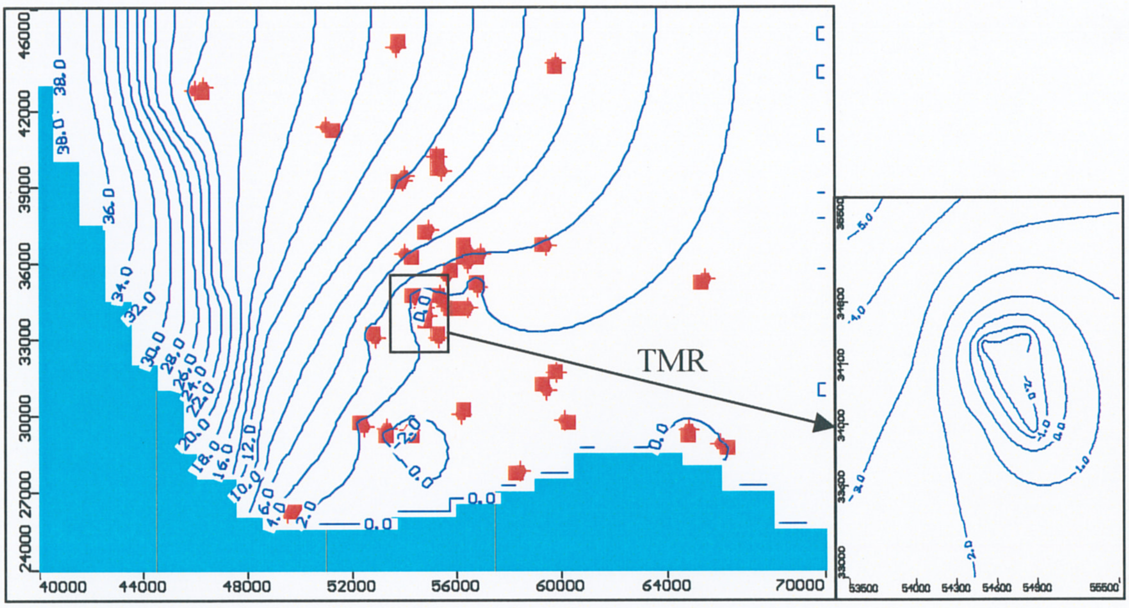
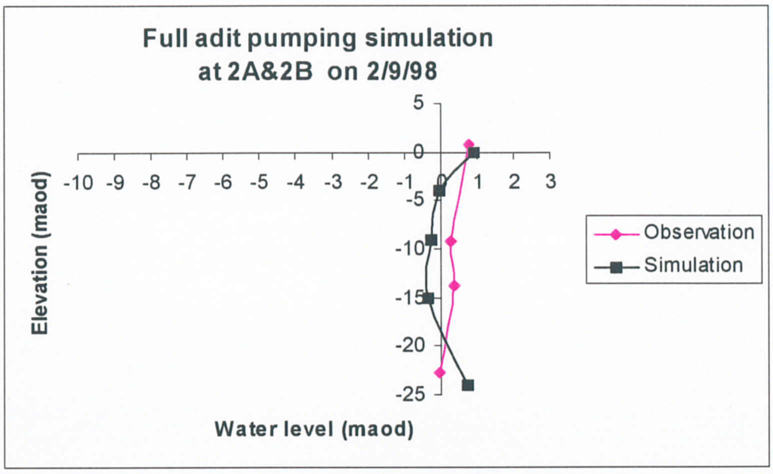
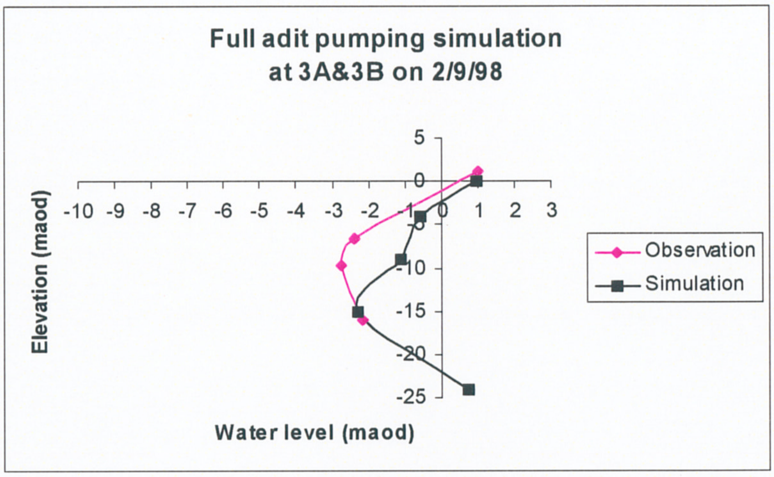


Figure 6 Cottingham local model is taken from it's regional model.

The local model is a MODBRNCH model plus Slot approach. The calibration of steady state local model were focused on matching observed borehole data in August and 2nd September, which is just before initial recovery. At first stage of the model calibration, water was pumped from adit only, and simulated groundwater heads are shown in Figure 7. Apparently, it does not match very well. The simulation shows the lowest water level is located about -15 maod, which is adit elevation. While the observation shows water level at -10 maod is the lowest, and all the observations in August show the same trend, which is show in Figure 8.

To find the answer and a right conceptual model, We discussed with this matter with Dr. John Aldrick, Environment Agency; Mr. Gerd Cachandt, Yorkshire Water; and Mr. Dave Smith, previous principal hydrogeologist in Yorkshire Water. It is agreed that part of water flows into adit through shafts due to the corrosion of old brickwork. This





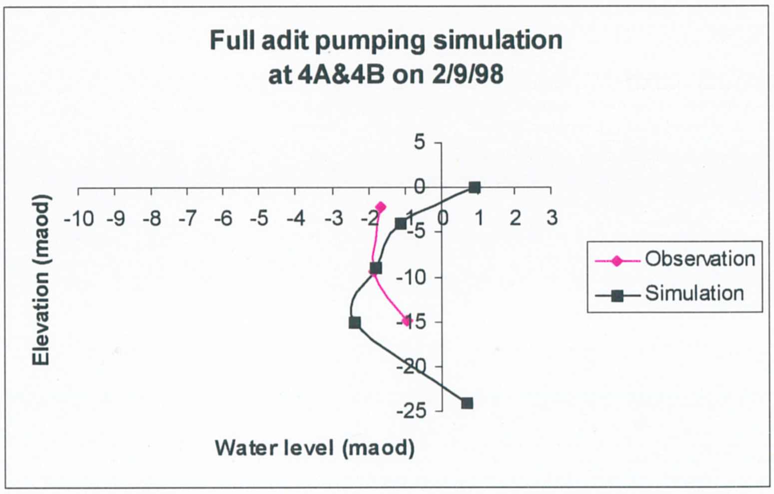


Figure 7 Simulation of full adit pumping

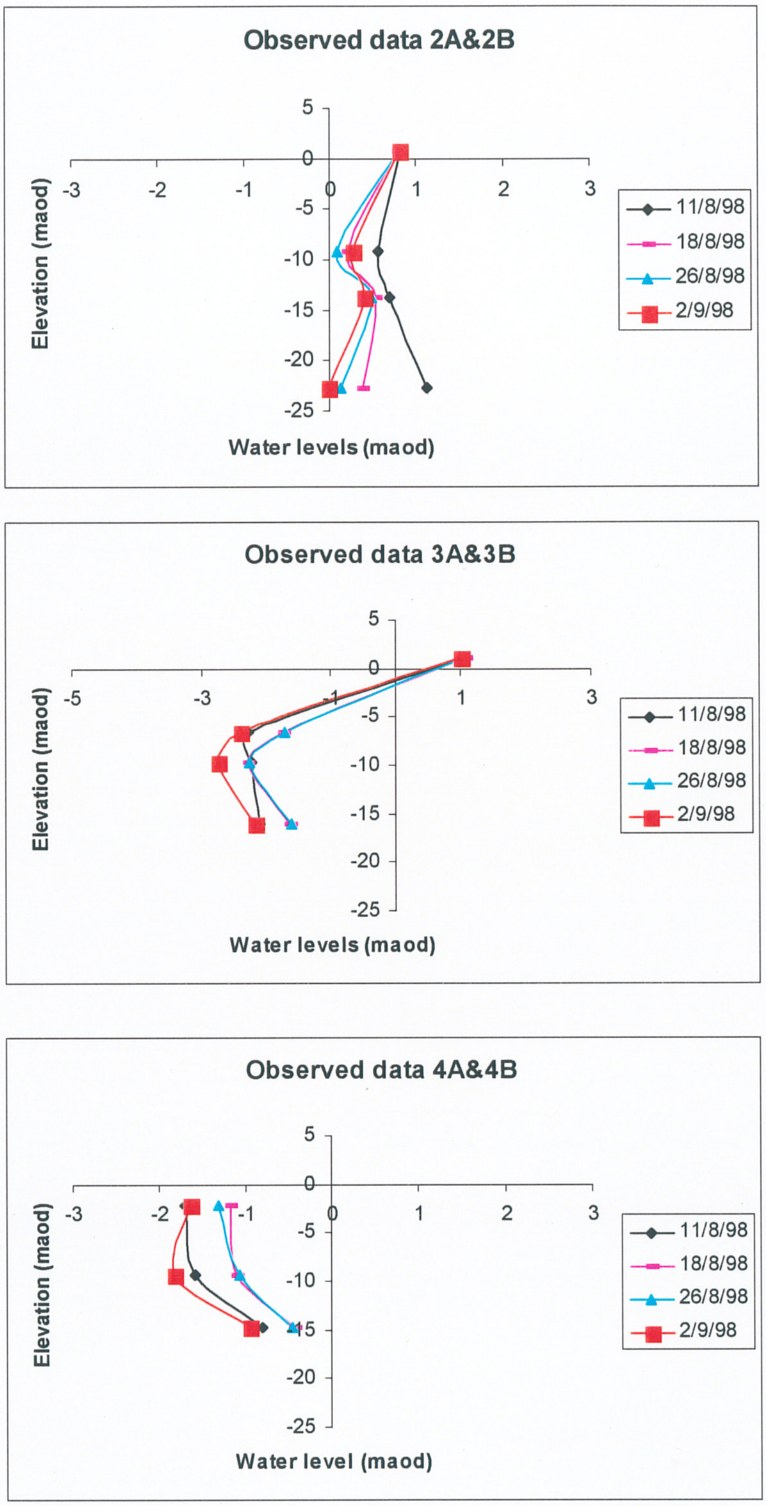


Figure 8 Observation data before pumping test

phenomenon is also indicated in a survey report (Crease,1998). The following comments are mentioned in the report:

- The brick shafts have occasional brick omitted probably to allow inflow to the shaft, and there are slotted iron sections about 15 m down on the earliest shafts at Cottingham.
- Most of the shafts show seepage through joints in the brickwork, or between the joints of the tubbing, both above and below water level.

Taking these comments into account, simulations tested contributions through shafts between 25% and 50%. Finally, 33% of water flows through shafts is used to match the observation best. The seepage horizon is assumed located in Layer 3, right above adit.

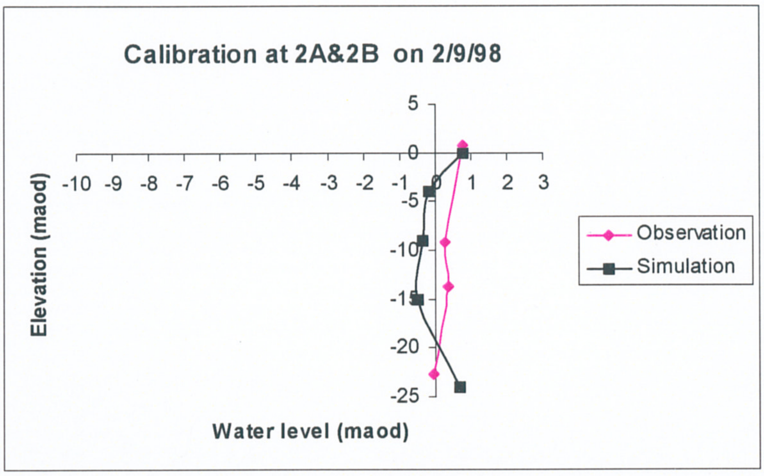
The other calibration parameters include both horizontal and vertical permeability for various layers. These values are also adjusted during transient model calibration. In other words, the calibrated permeability has to satisfy both steady and transient model. The calibrated permeability is listed in Table 4.

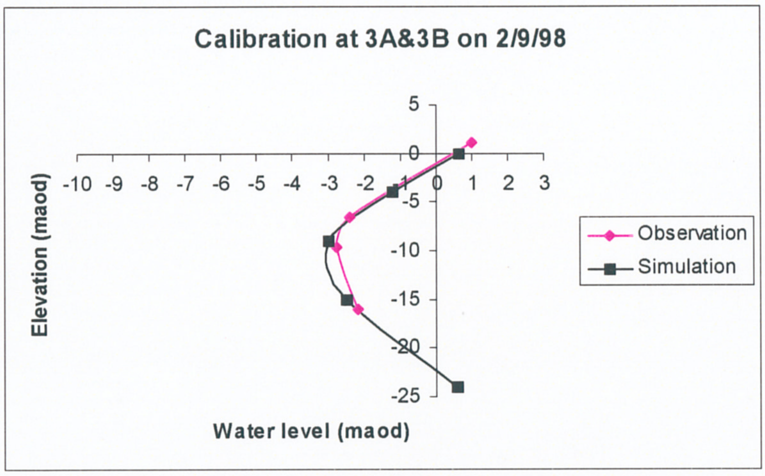
Table 4 Calibrated permeability

Layers	Horizontal permeability	Vertical permeability	
1	60 m/d	0.1 m/d	
2	60 m/d	0.1 m/d	
3	80 m/d	0.8 m/d	Seepage horizon
4	80 m/d	0.8 m/d	Adit elevation
5	60 m/d	0.05 m/d	

The total transmissivity keeps consistent with regional model. The values for vertical permeability are smaller than expected, and quite sensitive. The elevation and thickness of layers were also adjusted which is shown in Table 1. The simulated borehole water level for steady state is presented in Figure 9. The simulated water levels for various layers are presented in Figure 10. Figure 10 shows that adit affect Layer 4, the layer contains adit; Layer 3, shaft seepage layer; and Layer 2, but has little effect on Layer 1 and layer below. Actually, the influence of adit on the layer below depends on the vertical permeability of layer below. The smaller the vertical permeability of layer below, the little the effect of adit on the layer below.

Another interesting phenomenon is that the cones of depression in Layer 1 and Layer 5 are shifted to east of the adit, between the northern-east wing and southern-east wing of adit, although these cones are very small.


Calibration at 2A&2B on 2/9/98


Calibration at 3A&3B on 2/9/98

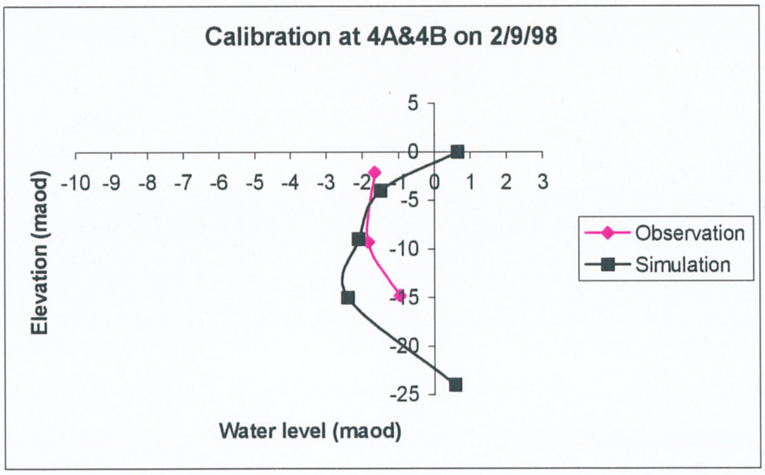

Calibration at 4A&4B on 2/9/98

Figure 9 Cottingham steady state local model calibration

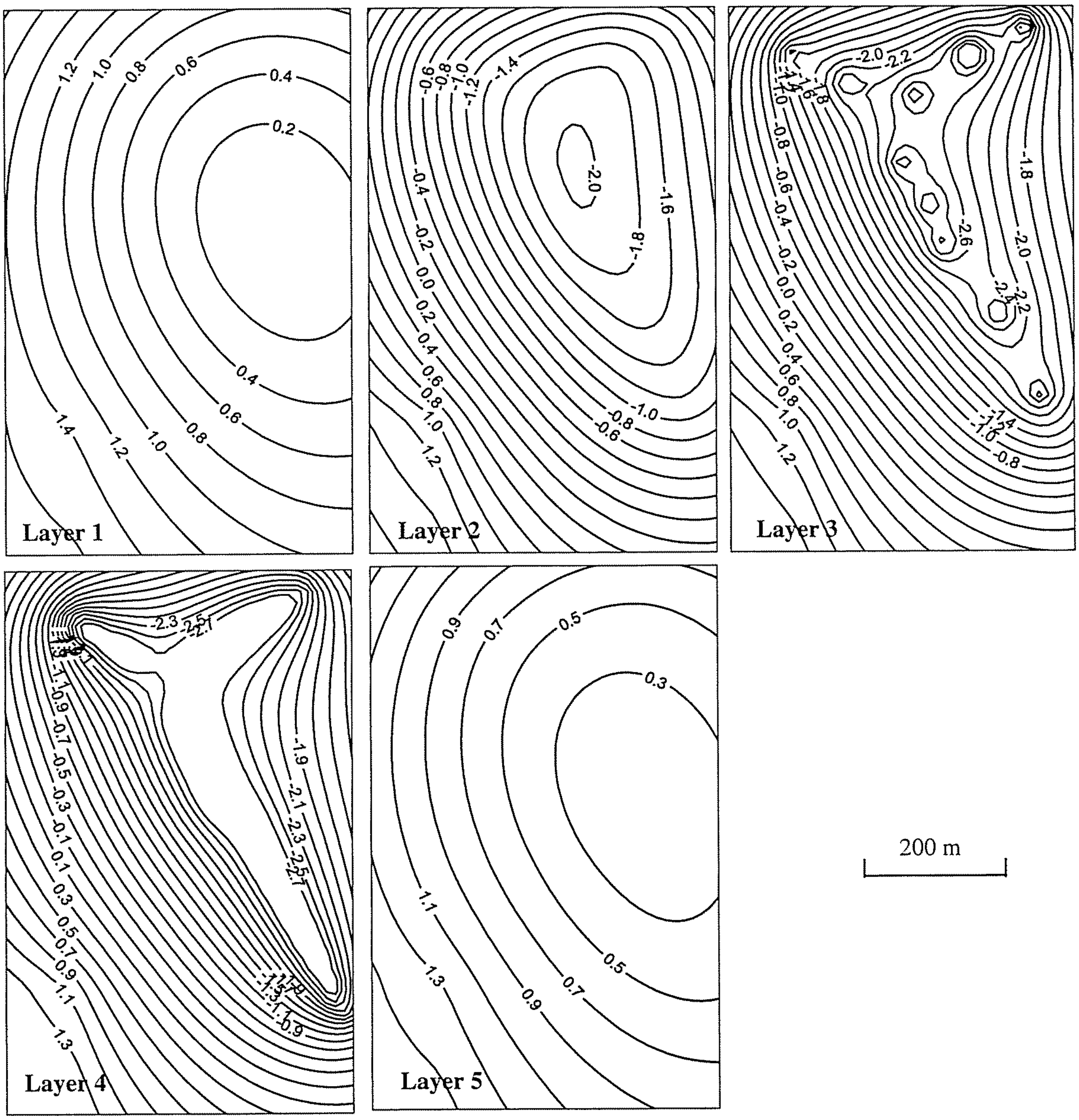


Figure 10 Water head distribution for 5 layers

2.4.2 Cottingham transient local model

As mentioned in previous section, steady local model was taken from steady regional model, while transient local model was taken from transient regional model by TMR. General head boundary was specified to all boundaries. Although the pumping test includes only 3 stress periods, 16 day constant pumping stage was divided into 16 stress periods during transient modelling because the TMR software we used only memorizes in stress period basis instead of time step basis. Together with 1 day initial recovery and 1 day final recovery stages, total 18 stress periods were simulated. Because water levels, velocities, etc. changes from time to time, 3 hour time step was selected, therefore total 144 time steps were simulated. This is tremendous computer time and memory consuming.

The same as steady local model, the transient local model was also simulated by MODBRNCH with slot approach. Although transducers were installed in all the observation boreholes shown in Figure 3, some of logger data are not reliable or only reliable periodically. Therefore model calibration was focusing on the observations when manual dips available. These dates are indicated in Table 5

Table 5 Dates of Calibration

Date	Stages
3rd September	End of initial recovery
10th September	7th day of constant pumping
16th September	13th day of constant pumping
19th September	End of constant pumping

For steady state model, 33% of 31095 m^3/d was assumed flows through shafts. However, the transient model can not be calibrated by using 33% of 51000 m^3/d (constant pumping rate during pumping test). Therefore it is assumed that only a certain amount of water flows through shaft, and 33% of 31095 m^3/d was still selected as shaft seepage for transient model, rest of 51000 m^3/d flows directly into adit. The other calibrating parameters include specific storage for confined layers, and specific yield for Layer 1, which is a semi-confined layer. Recharge was also a calibrating parameter. The calibrated specific storage and specific yield are listed in Table 6.

Table 6 Calibrated specific storage and specific yield

Layers	Specific yield	Specific storage(1/m)
1	0.05	
2		0.001
3		0.00001
4		0.00001
5		0.00001

Figure 11, 12, 13 and 14 show the calibration of transient model at the end of initial recovery, 7th day of constant pumping, 13th of constant pumping and end of constant pumping test, respectively. The simulated data are quite close to the observed data.

The simulation of whole pumping test is demonstrated in Appendix 2. Most simulated data fit the observed data. However the simulation of adit water level is not very good.

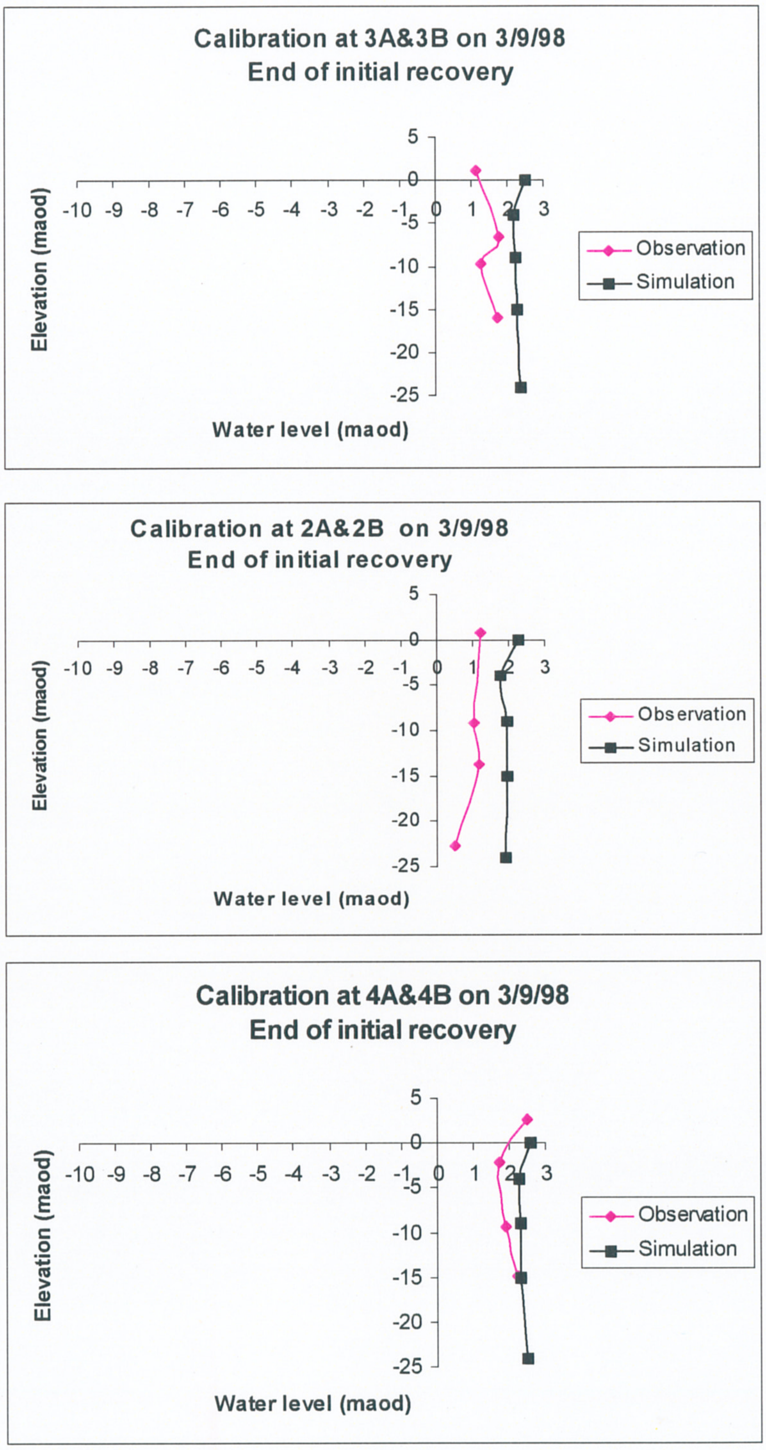


Figure 11 Cottingham Transient model Calibration on 3/9/98 (End of initial recovery)

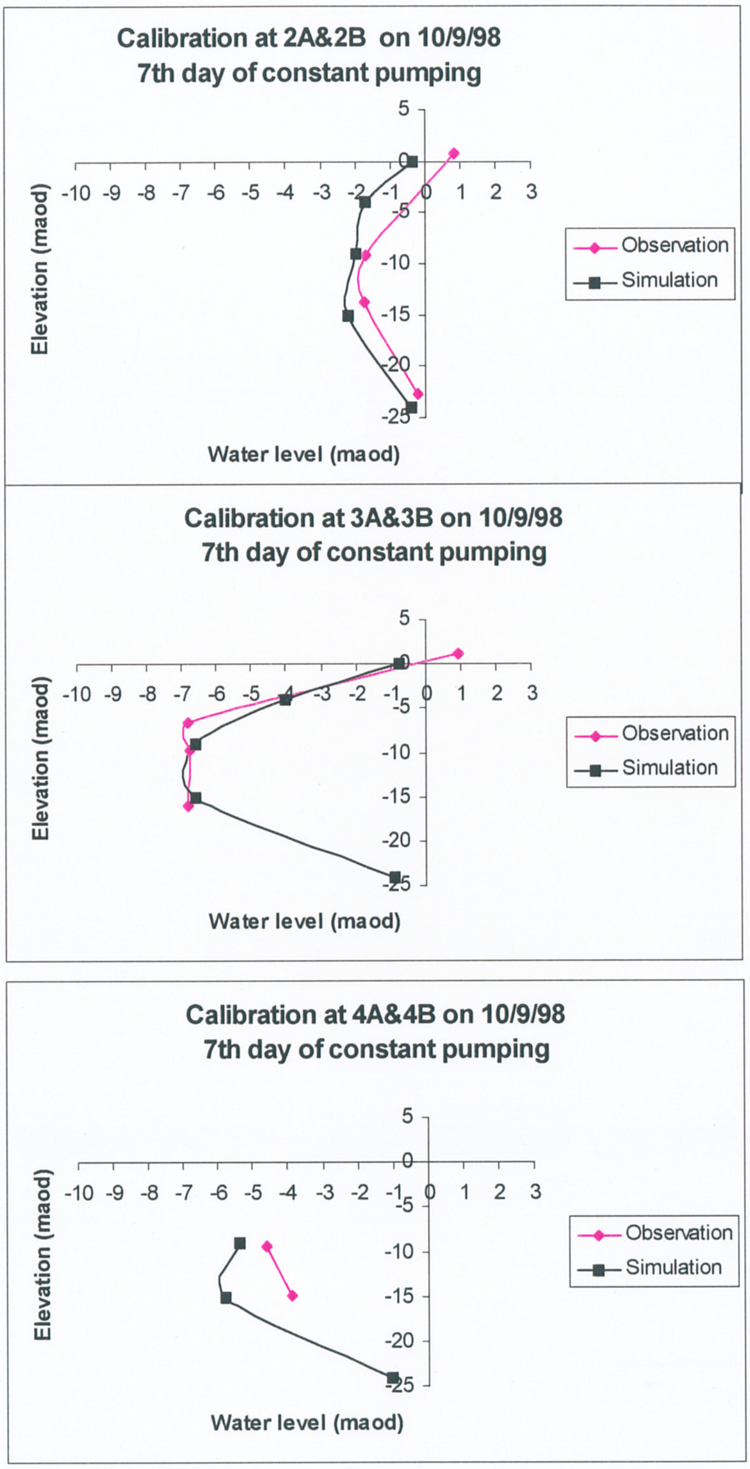


Figure 12. Cottingham transient model Calibration on 10/9/98 (7th day of constant pumping)

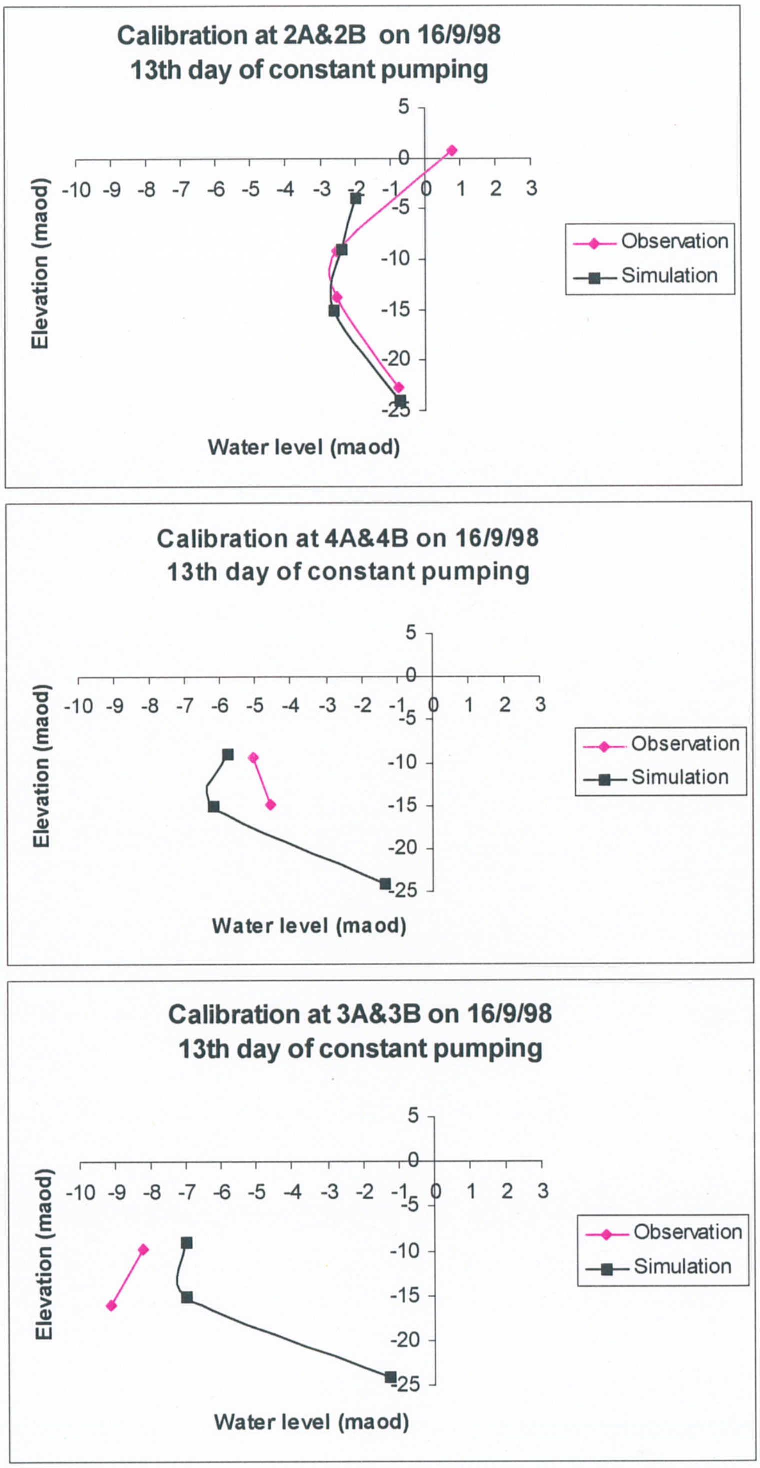
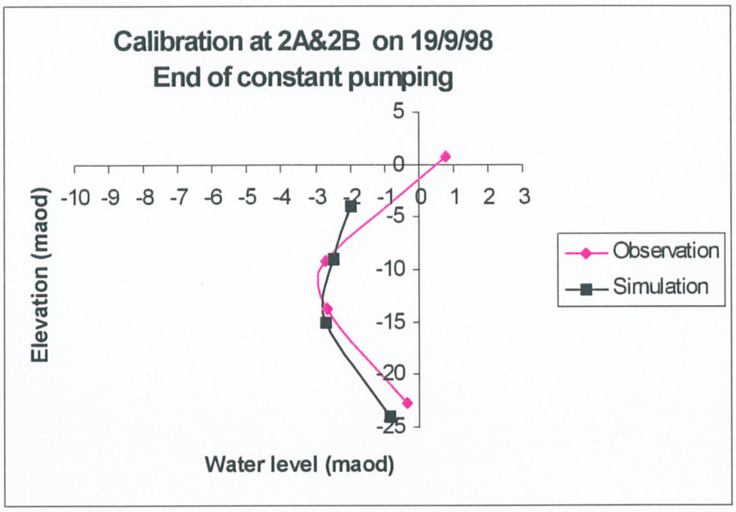
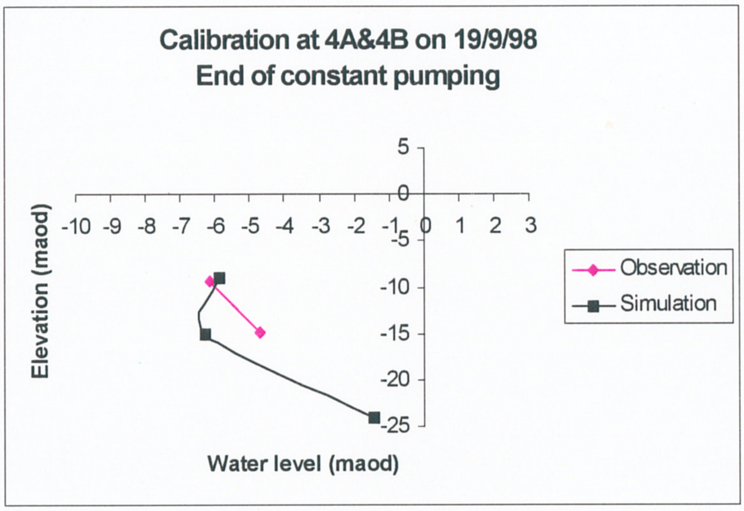


Figure 13. Cottingham transient model Calibration on 16/9/98 (13th day of constant pumping)





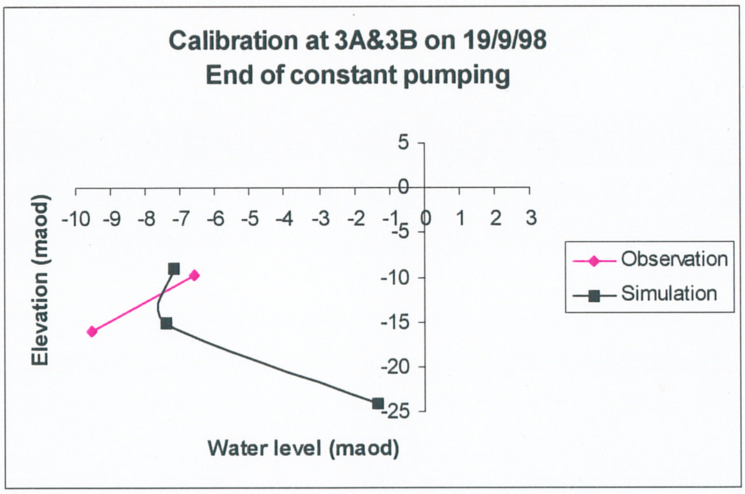


Figure 14. Cottingham transient model Calibration on 19/9/98 (End of constant pumping)

3.PLAN OF YIELD STUDY

3.1 Background

One of the objectives of this project is preparing guidelines for determining the yield of adit systems. The term **yield** is often used in groundwater resources planning and management, and it usually refers to aquifer yield. The definition of yield has been changed from time to time. The term safe yield was used as early as 1915 (Lee, 1915). At that time safe yield was regarded as the amount of water that could be pumped " regularly and permanently without dangerous depletion of the storage reserve." Now a days, increasing concerns in environment issue has been integrated into the definition of yield. Fetter proposed following definition in 1994: safe yield is the amount of water of naturally occurring ground water that can be withdrawn from an aquifer on a sustained basis, economically and legally, without impairing the native groundwater quality or creating an undesirable effect such as environmental damage.

An adit system is a single groundwater source. Very few papers talks about yield of a single groundwater source. However, **A Methodology for the Determination of Outputs of Groundwater Sources** was developed by Groundwater Development Consultants in 1995 on behalf of UK Water Industry Research (UKWIR)(Beenson, et al.,1995). The report tried to establish standard definitions of terms for the industry and is key document for the groundwater source yield assessment undertaken by all water companies. The methodology is summarized as following.

3.2 Summary of "A Methodology for the Determination of Outputs of Groundwater Sources"

3.2.1 Definitions

Deployable Output

The output of commissioned source or group of source or of bulk supply as constrained by:

- Licence
- Water quality
- Environment
- Treatment
- Raw water main and/or aqueducts
- Pumping plant and/or well/aquifer properties
- Transfer and/or output main

For specified conditions and demands.

Potential Yield

The yield of a commissioned source or group of sources as constrained only by well and/or aquifer properties for specified conditions and demands.

Specified conditions here are referred to drought conditions. The distinction between output and yield is made here. Output is associated with the mechanical process of plant, while yield is associated with the natural process.

Deepest Advisable Pumping Water Level

The deepest level to which water in a well should be allowed to decline so as to prevent undesirable effects were the level to decline further.

3.2.2 Methodology

The methodology can be divided into two categories, the operational approach (options A, B and C) and the analytical approach (option D). The former uses data from normal operational practices, and the choice of options depends on the amount and quality of the data availability. The analytical approach (option D) requires pumping test data and non-pumping water levels and assumes continuous pumping.

Option A
Users with simple sources and /or sparse data may choose Option A to obtain the deployable output.

Option B
Use relationship between total outputs and water levels, which is defined by a drought curve. The deployable output corresponds to the output where the curve intersects the well intake level, or is constrained by licence and/or pump capacity.

Option C
Potential yield can be defined, requires a knowledge of the deepest advisable pumping water level (DAPWL) for each well at the source. The potential yield corresponds to the yield where the curve intersects the DAPWL.

Option D
Drawdowns are estimated for a range of total yields for continuous pumping lasting 200 days (average demand) or 7 days (peak demand) and converted to pumping water levels using a representative non-pumping drought water level. The relationship between total yield and estimated water levels is then indicated by a drought curve, and the deployable output and potential yield are defined accordingly.

3.2.3 Advantages and disadvantages

Advantages

1. Allows simple estimation of deployable output where only few data, yet, permits more sophisticated predictions of potential yield where good data are available.
2. Enable the users to assess the deployable output and potential yield for a variety of water levels and for average or peak demand.
3. Is capable of being applied to a various types of sources from a single well to a complex well field including adit.

Disadvantages

Only local aspects have been taken into account regardless regional aspects, environmental issue and historical change.

3.3 Proposal for adit yield study

In assessing the reliable yield of a source, it is important to assess the resources and flow mechanisms of the associated groundwater catchment. Many problems of low and declining yield are due to the lowering of water levels in the vicinity of a pumping station, and the inability of the source to draw sufficient water through aquifer. Groundwater flow modelling is a good tool to identify the recharge mechanism and integrate all hydraulic factors into yield study. The following method is proposed for adit yield study.

Objectives

Developing a modelling method to determine the yield of adit systems.

Testing the influence of other abstractions at drought condition.

Assessing various risks (eg. Testing whether the catchment of a source at drought condition is beyond it's protection zones)

One case study is planed for adit yield study. Cottingham probably should be the site because it's adit model has been built and A yield study using standard method just be carried by GDC. It is good to have a comparison of both standard method and modelling method. However, the reliability of yield study using modelling method depends on the reliability of the model itself. From this point of view, Cottingham adit model needs to be further calibrated.

Work plan

1. Calibrating Cottingham model with drought condition including both regional and local models. Steady state models for drought period of either 1989-1992 or 1995-1997 would be feasible (Long period transient models including drought periods would be more accurate but can not be finished in a couple of months).

2. Working out yield for Cottingham pumping station corresponding various water levels including recognized Deepest Advisable Pumping Water Level for adit — adit top elevation.

3. Comparing the difference between two results derived by modelling method and standard method.

4. Testing the catchment of Cottingham source to see whether it is beyond current protection zones at drought condition.

5. Testing effect of Dunswell abstraction on Cottingham source. Either fixing pumping rate to see the influence on water level or vice versa. The influence of Springhead abstraction could be tested if time allows (Springhead is not included in current Cottingham local model).

6. Predicting future yield in future drought period if the long period transient model is built (Regressing historical precipitation data in time series and predicting next drought period).

4 WORK PLAN FOR NEXT STAGE

Further calibrating Cottingham model.

Yield study using Cottingham cases. Preparing guidelines for determining the yield of adit systems using modelling method.

Demonstrating the effect of adit on Groundwater Source Protection Zones using Cottingham case and other general hypothetical cases. Developing guidelines for revising protection zones.

Developing a method for modelling of adit with steps and applying to a case study.

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GPRG

OPERATION AND PROTECTION OF ADIT SYSTEMS IN UK AQUIFERS

FIFTH PROGRESS REPORT

September 2000

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SUMMARY

A much more improved calibration of the Cottingham model has been achieved. The calibration approaches include considering declining regional groundwater level, decreasing portion of shaft water contribution, expanding local model size, and varying values of parameters systematically. The model has been well calibrated regarding all the data for adit head and aquifer layers, and steady state and transient conditions.

Cottingham model calibration indicates that: 1 The combination of slot approach and modified MODBRNCH can successfully simulate transient conditions in adits. 2 A transient model simulating a pumping test is a necessary approach for modelling adit in order to understand the hydraulics and hydrogeology of adit systems. 3 The aquifer layer containing and below the adit at Cottingham have low hydraulic conductivity. 4 At Cottingham there is a portion of abstraction from shaft contribution which various from 65% of abstraction to zero depending on groundwater level.

The effect of adits on the Source Protection Zones (SPZs) has be preliminarily tested on Cottingham modelling. Following modelling methods were used: 1 Combination of slot approach and MODBRNCH. 2 Replacing adit by multiple pumping boreholes. 3 Adit is presented by a high value of conductivity.

The defined zones using above methods are very similar, therefore the following hypotheses are proposed: 1 Using multiple boreholes is a good approximation for delineation of SPZs. 2 using high value of conductivity is a good approximation for delineation of SPZs. The above hypotheses are going to be further tested on general cases, including finding out whether there is an upper limit on adit length for these hypotheses, suitable number of artificial boreholes, value of high conductivity and adit layer thickness and spacing.

Please note that it does not mean the combination of slot and MODBRNCH is not necessary even if the above hypothetical is correct. Because the other two methods were applied on the model calibrated by MODBRNCH. Moreover, the adit head is important calibration target, which is not a variable of MODFLOW.

Regarding the stepped adit, 3 flow patterns were analyzed. Among them, the flow pressurized in both upstream and downstream of adits is the pattern existing in the reality. It also can be considered as a gated culvert or 2 90° elbows, which can be formulated easily.

Bricketwood is selected for stepped adit case study.

1. INTRODUCTION

1.1 Objectives

1. Providing a suitable computer code for modelling groundwater to adit systems including both steady and transient conditions, multiple-interconnected branches and multi-level adit systems.

1. Drawing up guidelines for modelling adit systems.

2. Demonstrating the effects of adit on source protection zones and developing guidelines for revising adit source protection zones.

1.2 Progress against Plan

The research has been proceeding as the proposal and the inception report. A computer code has been provided, and two case studies, Wilmington case study and Cottingham case study have been carried out, and the influence of adit on Source Protection Zone (SPZs) has been studied preliminarily.

This stage of the research has been focused on Cottingham model calibration, the difficulty of the model calibration has delayed the project slightly. However, Cottingham model has been successfully calibrated finally.

2. FURTHER CALIBRATION OF COTTINGHAM MODEL

As introduced in the Fourth Progress Report (4PR) and last steering group meeting, Cottingham model simulations are quite close to the observation data for all manual dips including both steady state and pumping test transient models. However, regarding the entire pumping test process, especially the trend of adit water head against elapsed pumping time, there is a significant difference between observed and simulated curve in the previous model calibration (4PR). It is illustrated in Figure 1.

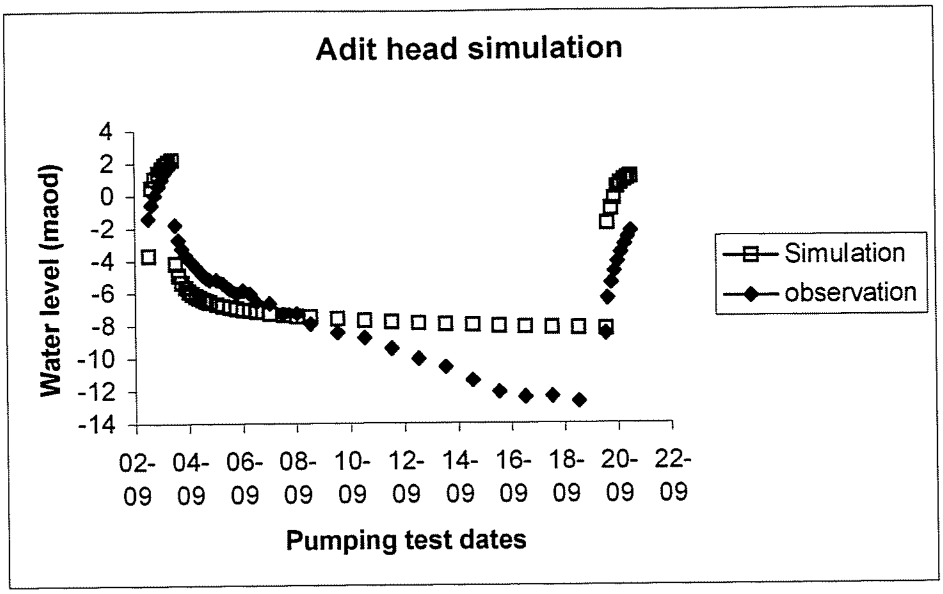

Figure 1 Comparison of simulated pumping test and observed curves for adit head Simulation of Fourth Progress Report (4PR)

To solve the problem, a model calibration workshop was organised on 28 May 1999 in Groundwater Protection and Restoration Group (GPRG), University of Sheffield. Dr. John Aldrick from the Environment Agency and Ms Matilda Beatty of Yorkshire Water were also invited. The workshop analysed the possible reasons of the problem and made some suggestions. A lot of testing work has been done after the workshop. It is summarised as following:

2.1 Decline in regional groundwater level

The pumping test simulated in this study took place in September 1998. The regional groundwater level has been declining during the summer prior to the pumping test because there was no rain in summer. Figure 2 shows how the groundwater level observed in Cottingham observation borehole declines in summer. However, the regional steady state model was built only matching the regional ground water level prior to the pumping test, and a steady state model usually represent an average situation instead of groundwater declining situation. An error is probably introduced here which is illustrated in Figure 3.

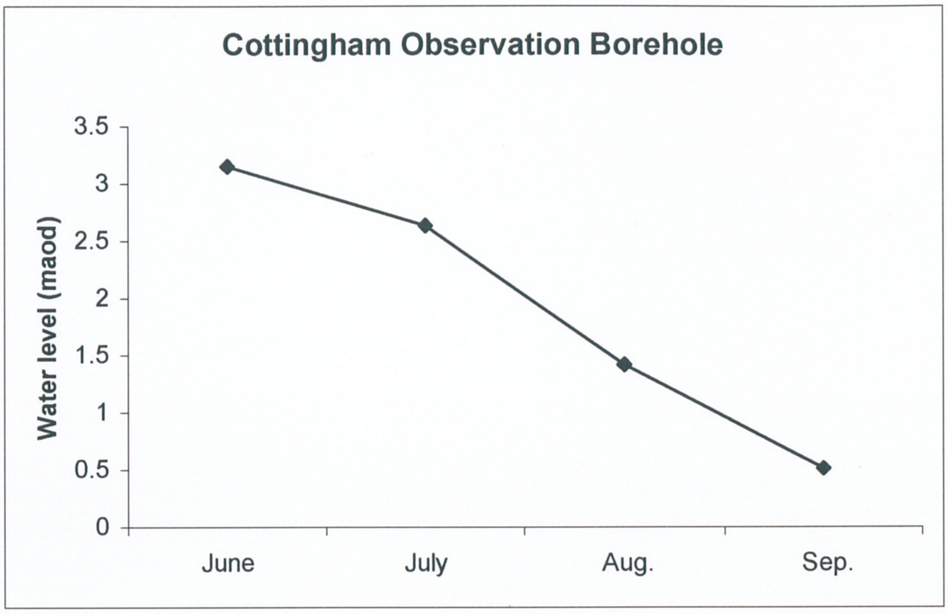

Figure 2 Groundwater level observed in Cottingham Observation Borehole in summer

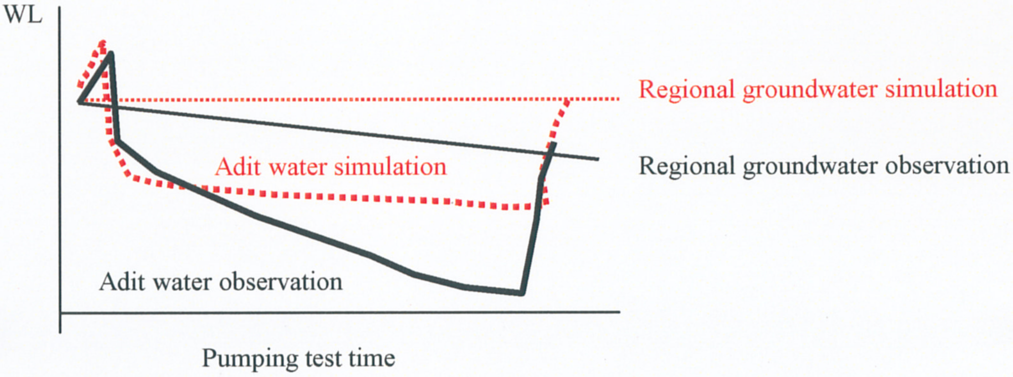

Figure 3 Illustration of error introduced by neglecting regional groundwater level changes

To improve this issue, the recharge of the steady state regional model was reduced about 10% of the original recharge, and the recharge of the 18 day transient regional model was reduced to 0. The simulated regional groundwater level against pumping test time is shown in Figure 4. The corresponding adit head simulation (5PR-a) is shown in Figure 5

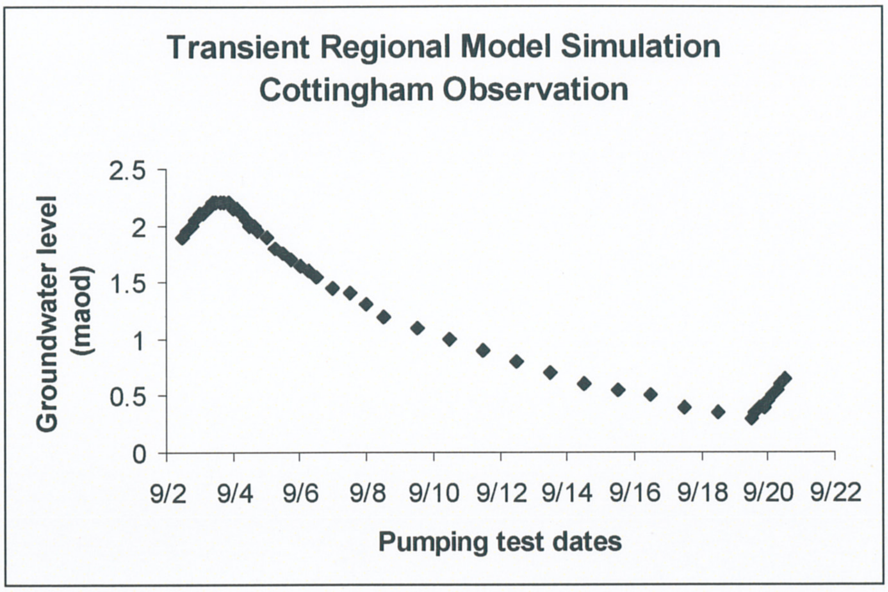

Figure 4 Simulated regional groundwater level against pumping test time

Figure 4 shows the simulation of Cottingham observation borehole, which is the simulation of the transient regional model. One can see that the regional groundwater level generally declines during the pumping test, and the initial and final recoveries.

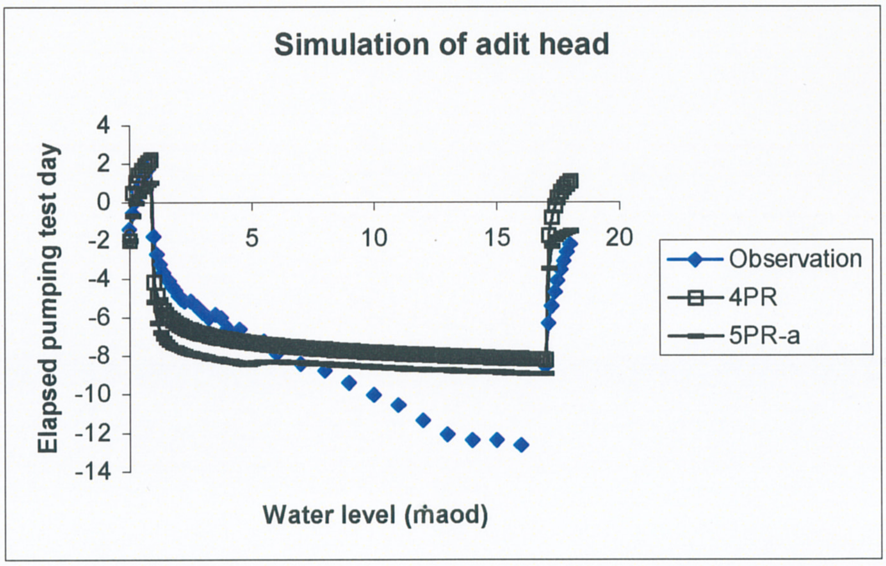

Figure 5 Comparison of simulation of 4PR and 5PR-a

The comparison of 4PR and 5PR-a adit head simulations with observation is shown in Figure 5. Although the drawdown of 5PR-a is deeper than the one of 4PR, the trend has not been improved that much.

2.2 Decreasing proportion of shaft water

In simulation 4PR, it was assumed that 20% of abstraction is contributed from shafts. However, the water head in the Layer 3 decreased during pumping test from –3 to –8 maod. The layers of Cottingham local model is shown in Figure 6. From the Figure 6, one can see that the shaft layer was confined with a head of –3 maod before the pumping test, and dropped to –8 maod, becoming an unconfined layer. So it is possible that the portion of shaft contribution decreased during the pumping test, therefore an increasing adit abstraction and decreasing of shaft contribution simulation was carried out, which is illustrated in Figure 7. The simulation 5PR-b is compared with 5PR-a and is shown in Figure 8. It has some improvement, but still not satisfactory.

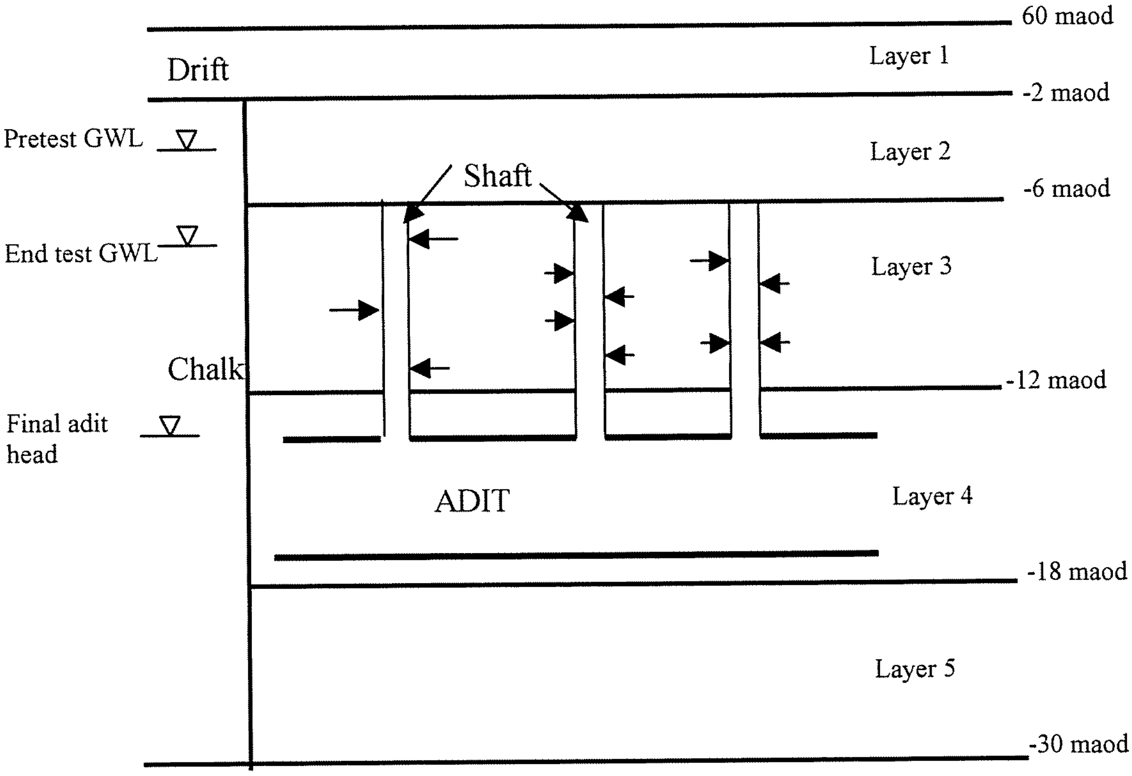

Figure 6 Cottingham local model layers

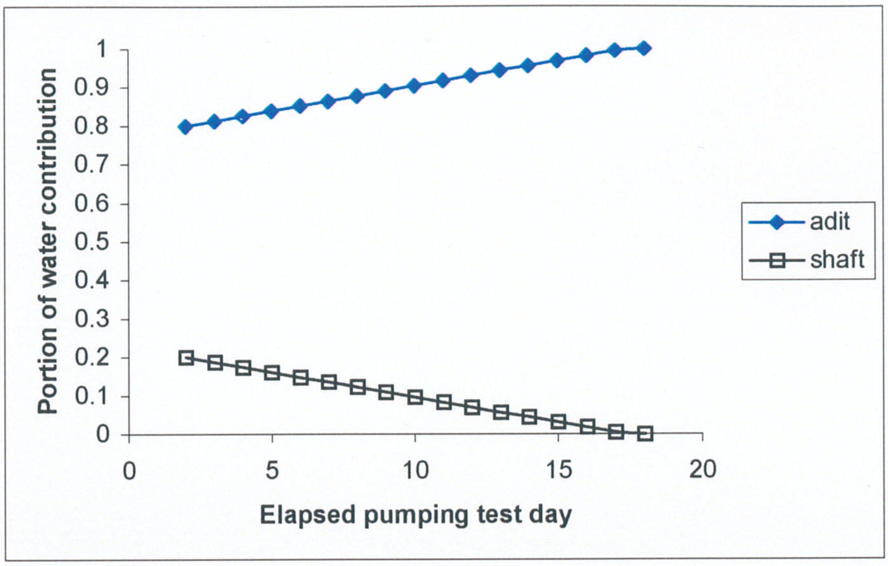

Figure 7 Water contribution from adit and shafts during the pumping test for Simulation 5PR-b

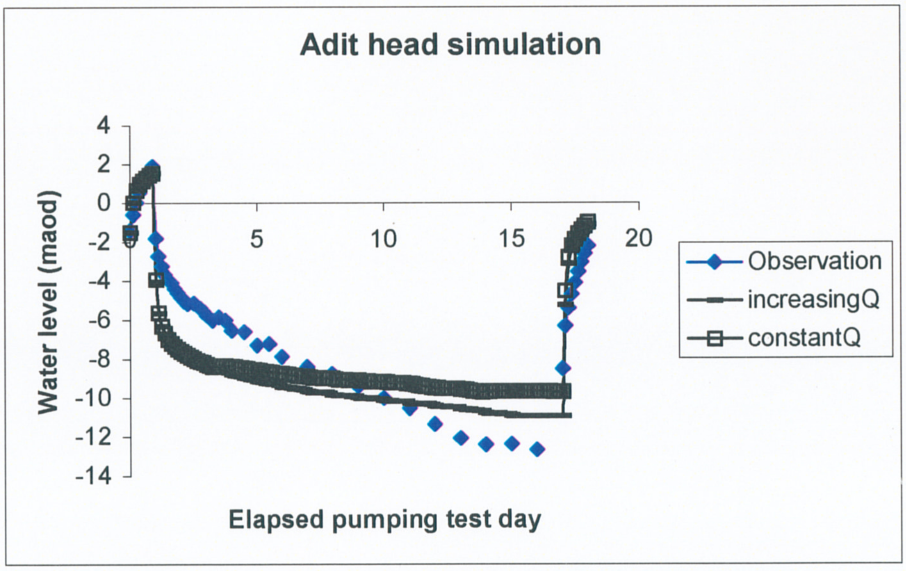

Figure 8 Comparison of Simulation 5PR-a and 5PR-b

2.3 Expanding local model size.

It was questioned whether the local model size is big enough to get right head or flow from the regional model? So a larger local model with an area of 3 km by 3 km was extracted. The expanded local model and the original smaller local model are shown in Figure 9. Figure 10 shows the comparison of steady state groundwater contour maps of adit layer generated from original local model and expanded local model respectively, and Figure 11 shows the comparison of pumping test adit water level simulations using small and large local models separately. From both Figure 10 and 11, one can hardly see the difference between the two models. This indicates that the size of the original local model is big enough to get right boundaries.

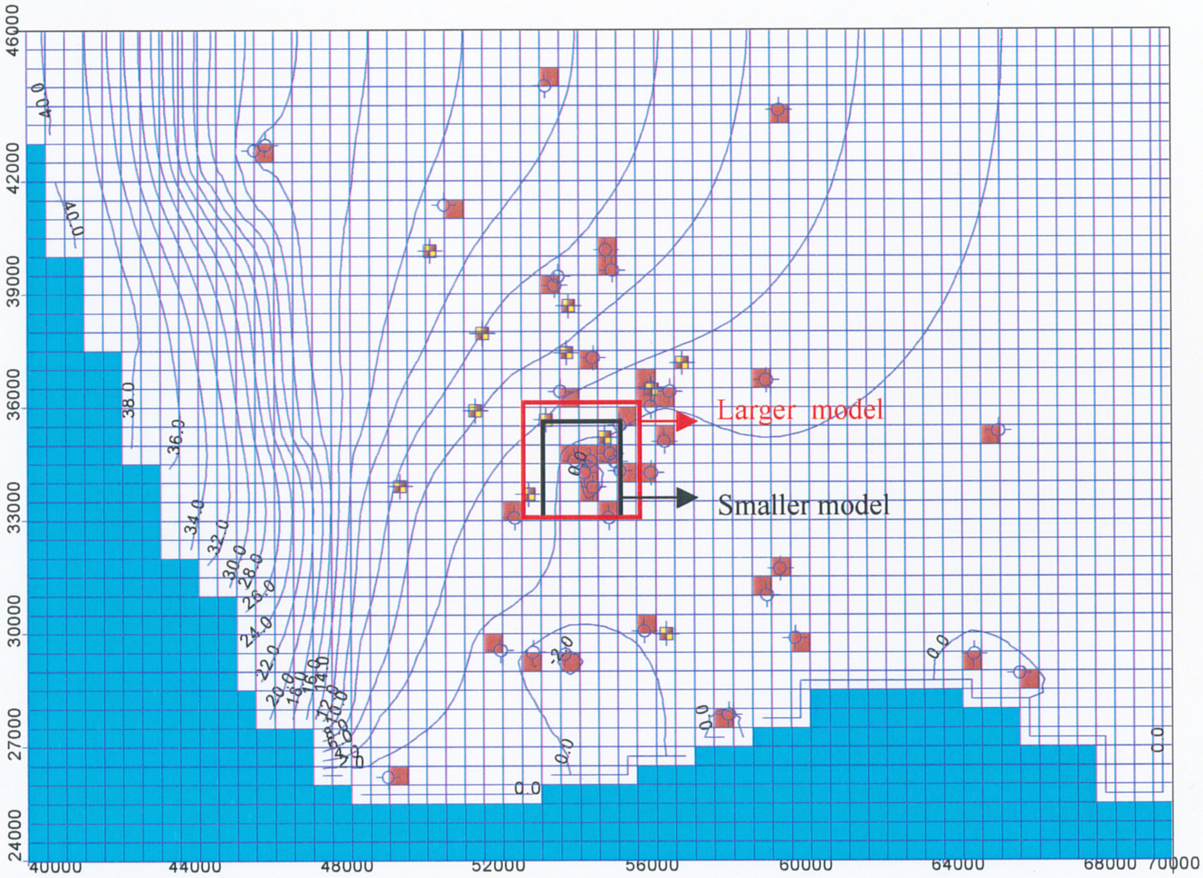

Figure 9 The regional model and original local model and expanded local model

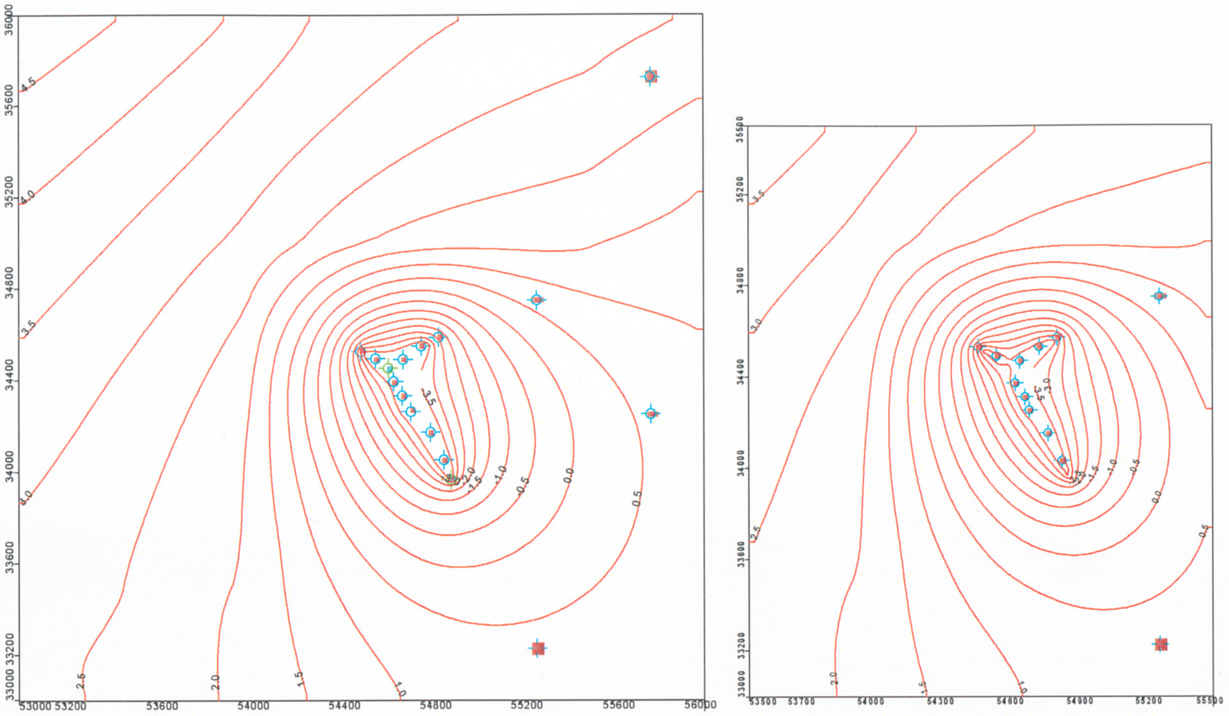

Figure 10 Comparison of steady state groundwater contour maps of adit layer generated from original local model and expanded local model respectively

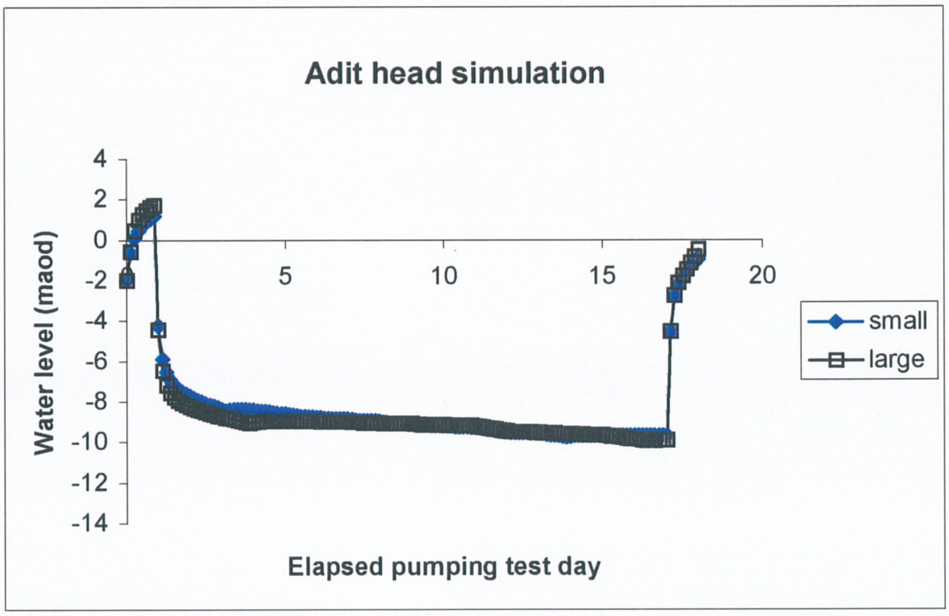

Figure 11 Comparison of pumping test adit water level simulations using small and large local models separately

2.4 Varying values of parameters

All the influential parameters were varied one by one to find the most suitable values. Although this was done with the previous model focusing on manual dip data especially steady state, it is worth to do it again with the new model focusing on adit head curve of pumping test. The test results are shown in following figures.

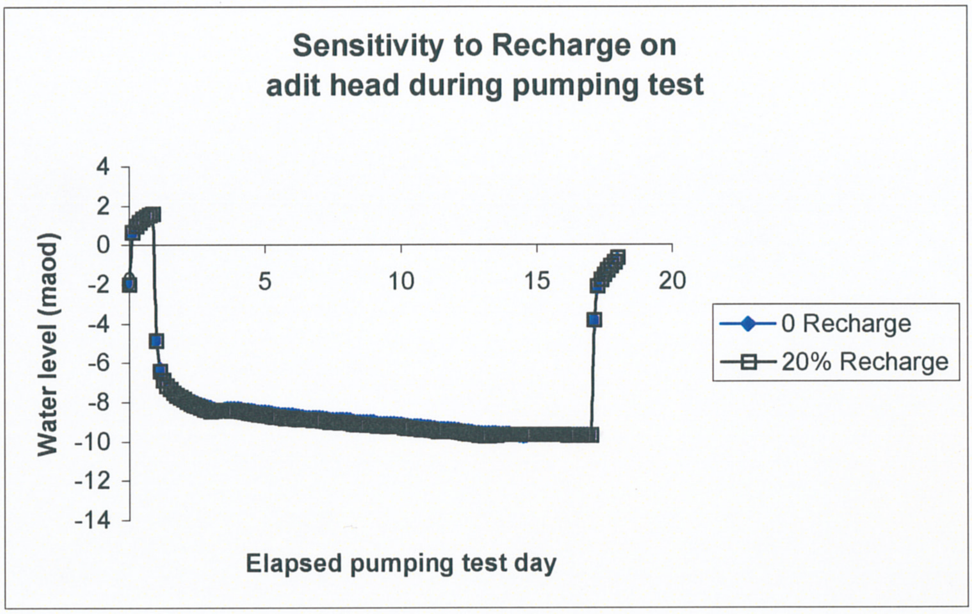

Figure 12 Comparison 0 recharge and 20% of steady state recharge during 17day constant pumping test

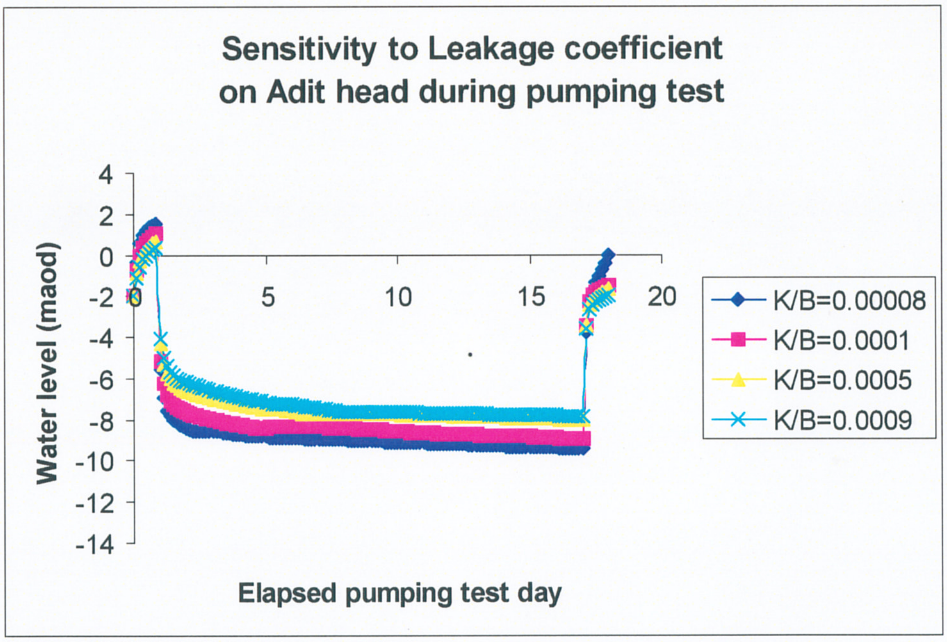

Figure 13 Test of sensitivity to Leakage coefficient

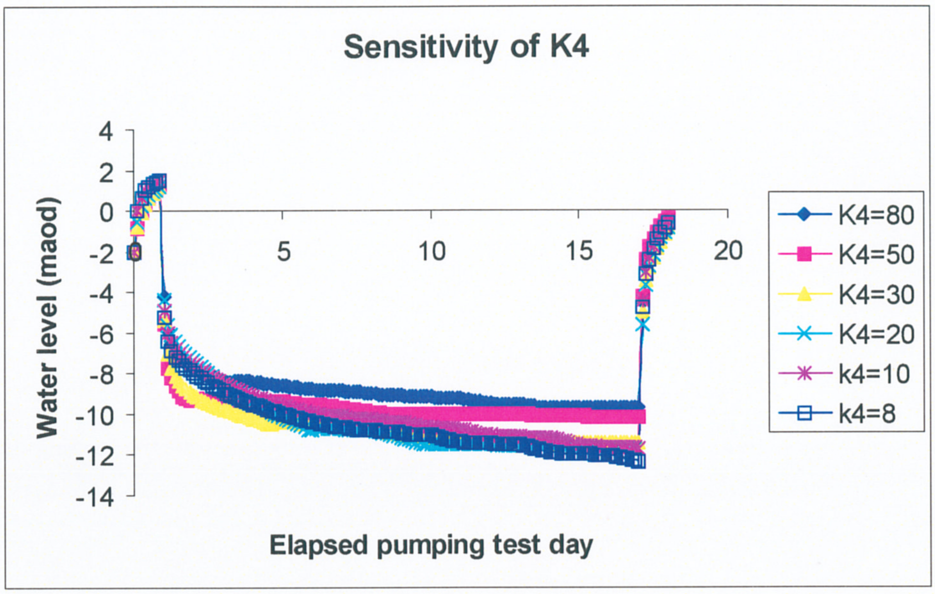

Figure 14 test of sensitivity to hydraulic conductivity for the Layer 4

Figure 12 indicates that the recharge has little effect on adit head for the 17 day transient model. This is not surprising because the recharge only affect top layer directly especially for such a short period.

Figure 13 shows the influence of the leakage coefficient on the adit head. We can see that the smaller the leakage coefficient, the lower the adit head, but no effect on the trend of drawdown. Although the slowest leakage value of 0.00008 /d has deepest drawdown, it's final recovery tail is too high. So the value of 0.0001 /d is selected which was also used in previous models.

The influence of conductivity on adit head is shown in Figure 14. It shows the values of 20 m/d, 10 m/d and 8 m/d for the Layer 4 fit the adit head curve better. The value of 80 m/d was used in previous model because it fit the steady state model better. The Table 1 shows the relevant values of conductivity for other layers. All scenarios have the consistent transmissivity.

Table 1 List of hydraulic conductivity (m/d) for various scenarios (Figure14)

Layer	Scenario1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
1	60	150	150	180	180	180
2	60	150	150	180	180	180
3	80	50	100	120	180	180
4	**80**	**50**	**30**	**20**	**10**	**8**
5	60	50	30	10	10	5

According to the above test, Scenario 6, K_4 of 8 m/d and leakage coefficient of 0.0001 /d were selected for the rest of test. Figure 15 shows the test of specific storage for the Layer 4, S_{S4}. Apparently, 0.0001 /m and 0.001 /m are the better values.

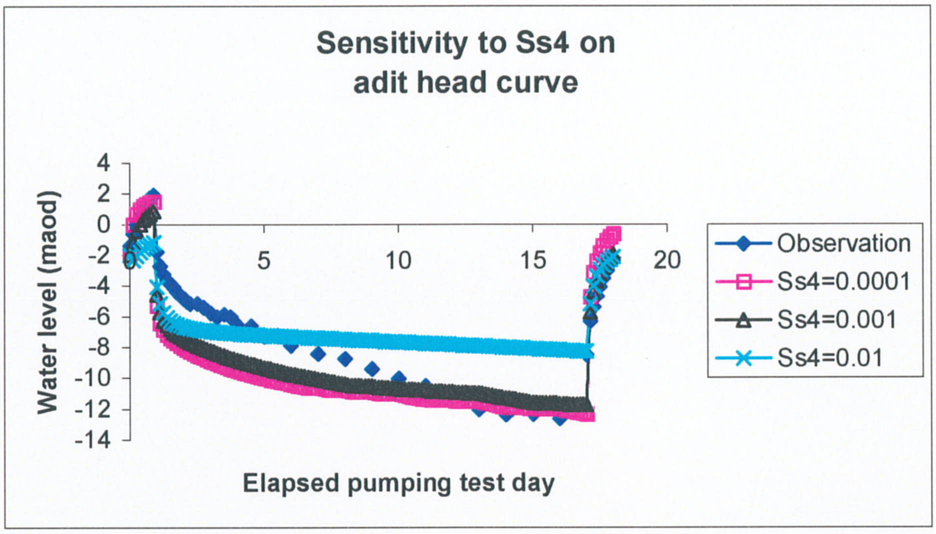

Figure 15 Test of specific storage

Figure 15 indicates that the adit head simulation could reach the observed head at the end of the pumping test by using suitable parameters, i.e. 0.0001 /d leakage coefficient, 8 m/d K_4 and 0.0001 /m S_{S4}. This gives us some hope. Let us look at Figure 8. By decreasing shaft water contribution and increasing adit contribution with pumping test time, the trend of adit curve has been improved a little bit, in which 80 m/d K_4 value was used. A test of decreasing shaft contribution and increasing adit contribution with time using value of 8 m/d K_4 was carried out. The starting allocation was varied to match the adit head curve. It is found that the scenario of 65% shaft water contribution at beginning of the pumping test and decreasing to zero at the end of the pumping test, and adit contribution starting from 35% and increasing to 100% of the abstraction matches the adit curve best. Figure 16 shows the abstraction allocations to shafts and adit against pumping test time. Figure 17 shows the simulation result, which is the best result we have so far regarding the curve of adit head against test time, which is named 5PR-c.

All the tests has been focusing on matching the adit curve, and we have found the most suitable conceptual model and parameter values for it. To match the all data for aquifer layers, the vertical hydraulic conductivity was adjusted, and the final calibrated parameters are listed in Table 2. The comparisons of simulation and observation for aquifer layers, including both steady state and transient data are shown in appendix.

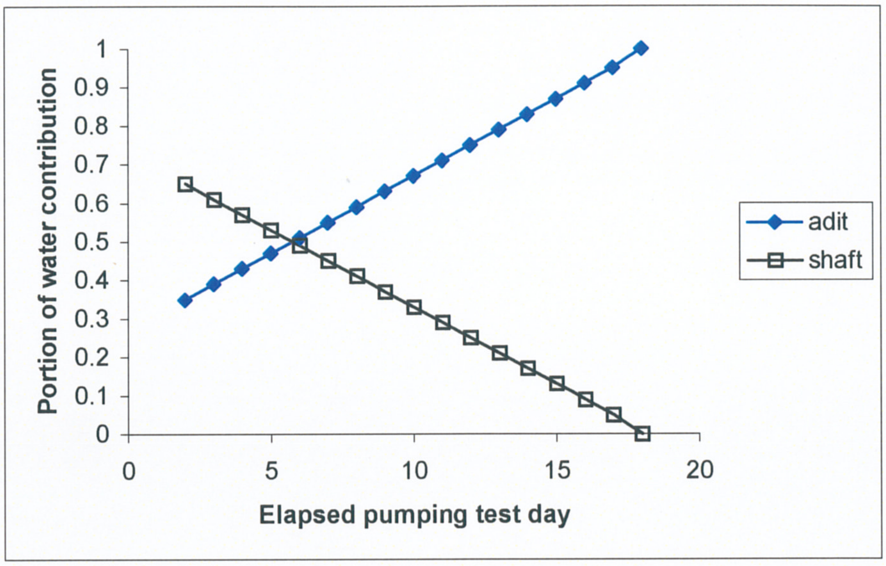

Figure 16 Water contributions from shafts and adit for Simulation 5PR-c

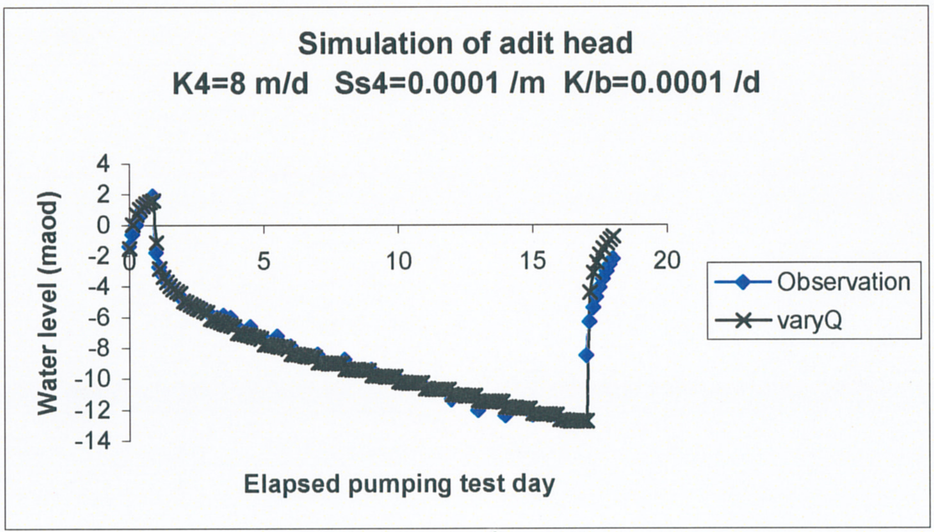

Figure 17 Simulation 5PR-c

Table 2 Calibrated parameters for aquifer layers (5PR-c)

Layers	$K_{horizontal}$ (m/d)	$K_{Vertical}$ (m/d)	S_s (m^{-1})	S_y
1	180	0.5	0.001	0.01
2	180	0.9	0.001	0.01
3	180	1.8	0.0001	0.01
4	8	2	0.0001	0.01
5	5	0.01	0.0001	0.01

2.5 Discussion and conclusions

1. The combination of slot approach and modified MODBRNCH can successfully simulate transient conditions in adits.
2. There is a portion of abstractions from shaft contribution which various depending on groundwater level from 65% of total abstraction to zero. Shaft water contribution decreases to zero when groundwater level is below –8 maod. This indicates that shaft seepage occurs above –8 maod.
3. The adit layer and below have lower values of hydraulic conductivity although some documents mention that the characteristic of conductivity decreasing with depth in the Chalk aquifer can not be applied to Yorkshire Chalk.
4. The hydraulics and hydrogeology of adit can not be studied correctly by only modelling steady state due to it's too many uncertainties. A transient model simulating pumping test is a necessary approach for modelling adit in order to understand the hydraulics and hydrogeology of adit systems.
5. The curve of adit head against time in a transient situation should be considered as a main calibration target because it reflects real hydraulics and hydrogeology of adit systems. It is also a quicker way to calibrated adit model. So the ranges of important parameters can be set up in this stage of the model calibration. The parameter values can be adjusted regarding the aquifer layer observation data.

3 SOURCE PROTECTION ZONES (SPZs) STUDY

One of the objectives of this project is testing the impact of adits on Source Protection Zones (SPZs). Some preliminary tests have been carried out with Cottingham modelling. Also, some simple tests on this issue were done with Wilmington case study, and they are repeated here.

3.1 Delineation of SPZs on Wilmington

MODPATH pathlines were tracked based on groundwater head distributions produced by MODBRNCH and MODFLOW respectively. A 50-day marker is used. Figure 17 shows that the 50-day protection zone of MODBRNCH enclosed by the dash line is moved in the south eastern direction compared with the one of MODFLOW because of adit's south eastern extension. This effect is not significant due to Wilmington adit is unusually short, and it could be much stronger if the adit was longer, as many of them are.

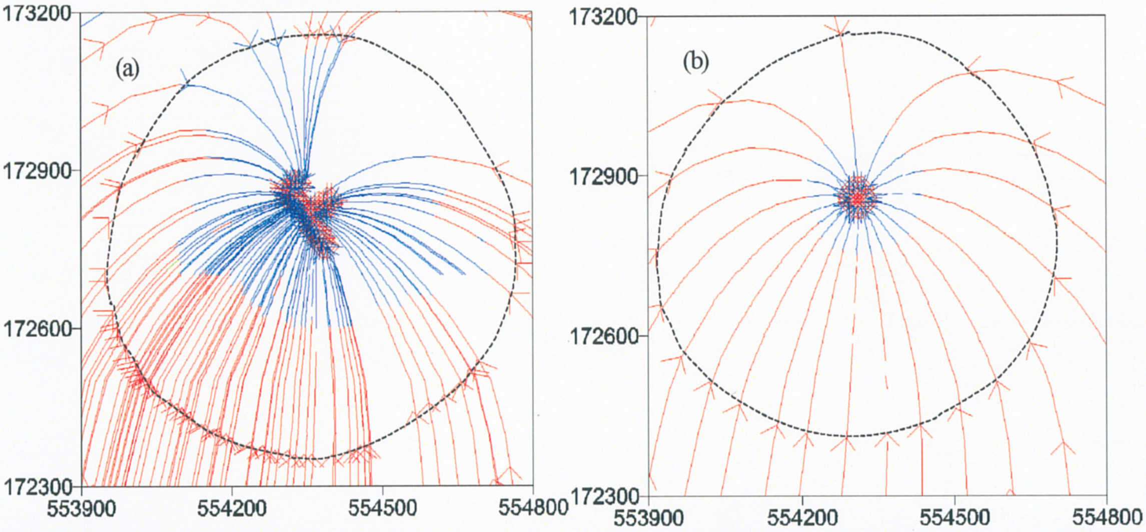

Figure 18 Comparison of 50-day time-of-travel zones (a) MODBRNCH, (b) MODFLOW

3.2 Extending Wilmington adit

To see the impact of adit on the source protection zones, Wilmington main adit was artificially extended to 1250 m, and all conditions and parameters were kept the same. Figure 19 shows the 50-day time-of-travel zone for 1250m adit. Again it was based on MODBRNCH and MODFLOW head distributions respectively. Comparing (a) and (b), Apparently, the protection zone of long adit is extended along adit's extension. This is because the groundwater is pumped out from the whole adit in MODBRNCH.

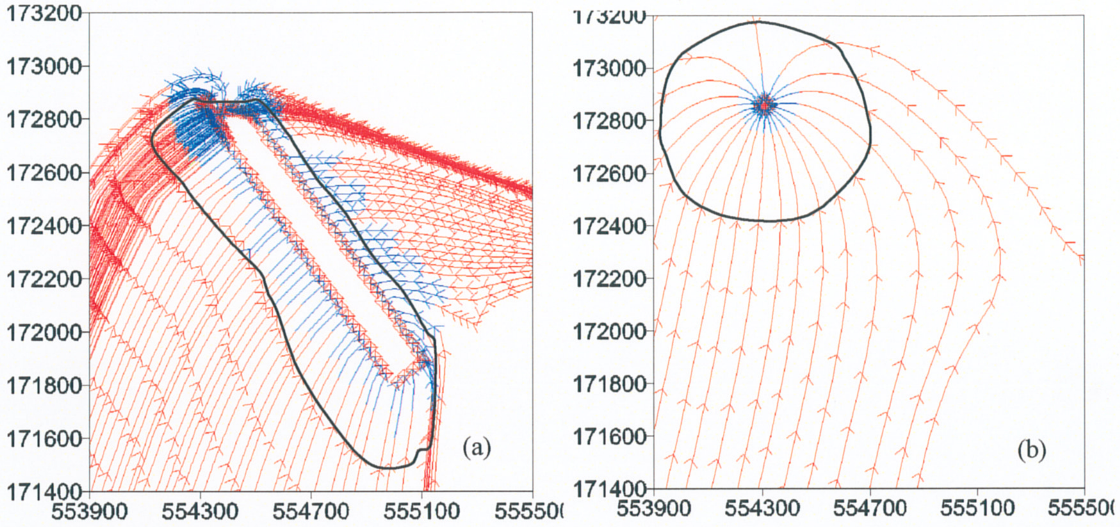

Figure 19 Comparison of 50-day time–of–travel zones of long adit (a) MODBRNCH, (b) MODFLOW

3.3 Delineation of SPZs on Cottingham

MODPATH pathlines were initially tracked using available local model with an area of 2 by 2.5 km. Kinematic porosity of 0.01 was used which is value of calibrated specific yield. Abstraction of 31000 m3/d was used which is average abstraction of Cottingham adit. Unfortunately, even the 50-day travel zone is out of the model. We also have a local model having an area of 3 by 3 km, which was built for testing the effect of model size. However, it is still not big enough. So we had to construct one more local model with an area of 4 by 5 km. The newly constructed local model area and previously available model areas are shown in Figure 20.

The SPZs was delineated using MODPATH and according to the head distributions of following methods: 1 Adit model — combination of slot approach and MODBRNCH. 2 Replacing adit by several pumping boreholes and using MODFLOW. 3 A large value of conductivity (K_{adit}=2000 m/d) was assigned along adit and using MODFLOW. The comparisons of 3 methods are shown in Figure 21 and Figure 22.

Figure 21 shows 50-day time-of-travel zones, in which kinematic porosity of 0.01 was used. Figures (a), (b) and (c) in Figure 21 were derived using Methods (1), (2) and (3) described in the above paragraph, respectively. Figure (d) of Figure 21 is the comparison of 3 methods. One can see that the areas and shapes of 50 day time-of-travel zones from these 3 methods are quite similar.

Figure 22 shows 400-day time-of travel zones. 0.04 of kinematic porosity was used to avoid constructing another local model. The same as Figure 21, Figures (a), (b) and (c) represent the results of Methods (1), (2) and (3), respectively, and Figure (d) shows the comparison of 3 methods. Again, these 3 results are very similar.

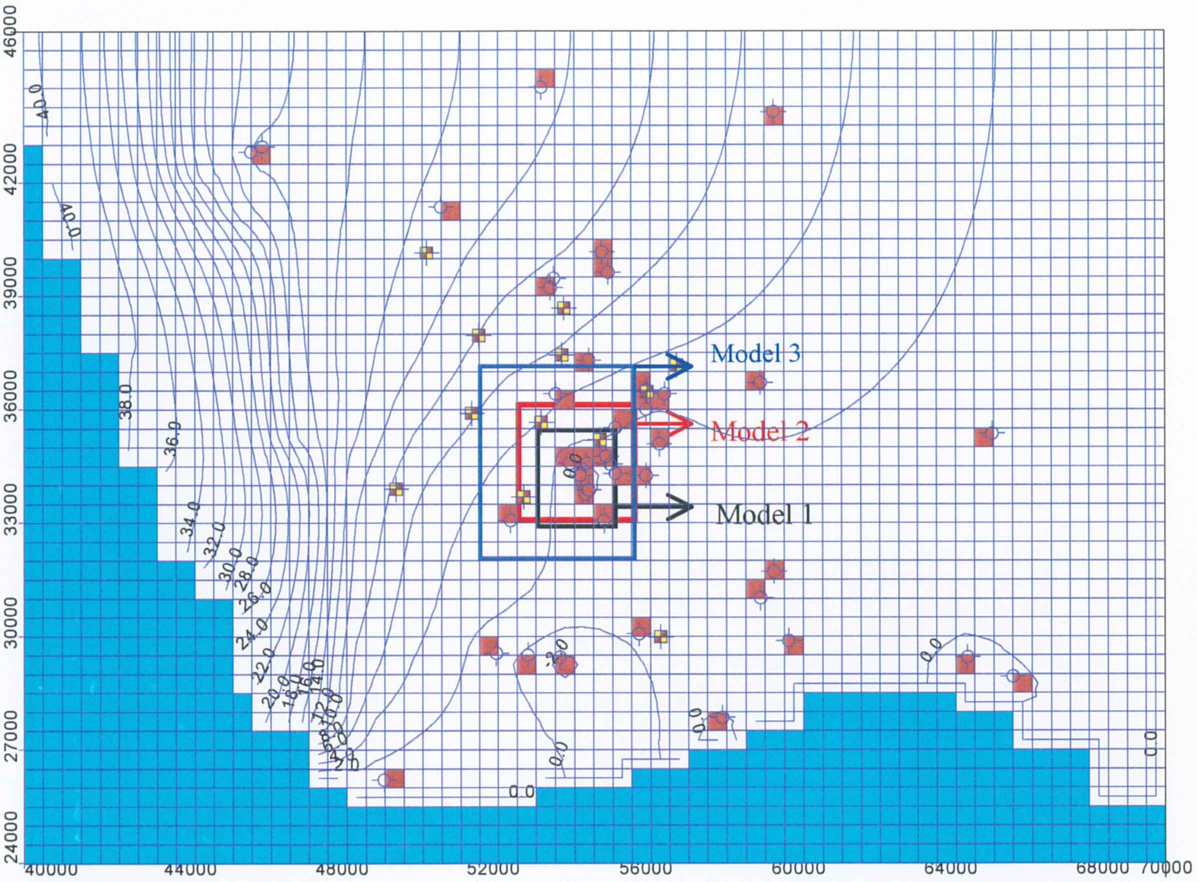

Figure 20 Regional model and various local models

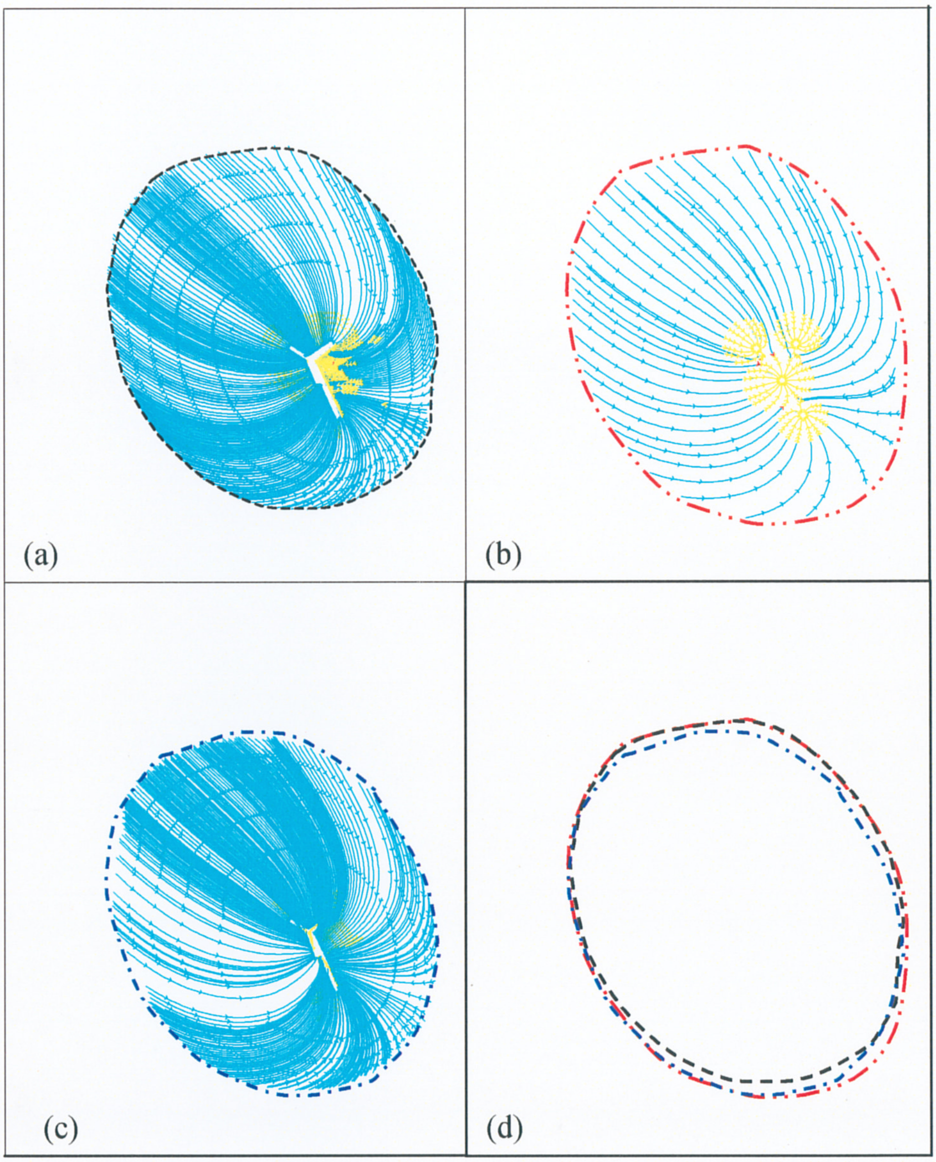

Figure 21 50-day time-of-travel zones, value of 0.01 was used as kinematic porosity. (a) MODBRNCH simulation; (b) MODFLOW simulation and adit was replaced by multi-boreholes; (c) MODFLOW simulation and conductivity was specified as 2000 m/d along adit; (d) Comparison of 3 methods

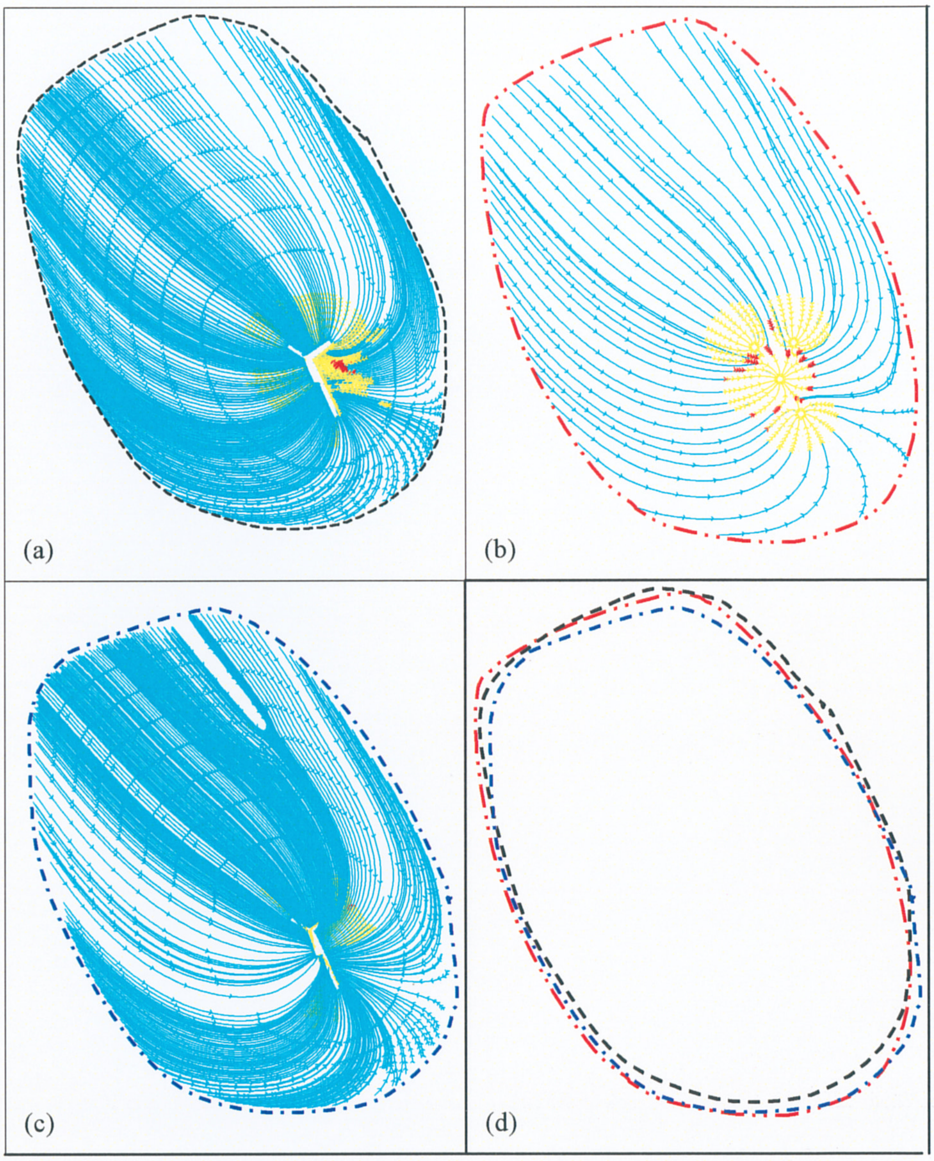

Figure 22 400-day time-of-travel zones, value of 0.04 was used as kinematic porosity. (a) MODBRNCH simulation; (b) MODFLOW simulation and adit was replaced by multi-boreholes; (c) MODFLOW simulation and conductivity was specified as 2000 m/d along adit; (d) Comparison of 3 methods

3.4 Discussion and future work on SPZs

Figure 21 and 22 indicate that the SPZs derived from 3 different methods are quite similar. Therefore following hypotheses are proposed:

1. Using multiple boreholes replacing adit is a good approximation for delineation of SPZs
2. Using high value of conductivity is a good approximation for delineation of SPZs

Although Conttingham adit is relative long comparing with Wilmington, the total length of 1000 m is the sum of 3 branches. The adit in the UK can be up to 7 km, therefore there still is a question mark whether the above hypotheses are suitable for very long adit. Following examines are suggested:

1. What is the upper limit of length for above hypotheses?
2. How is the number of artificial boreholes related to adit length for the Hypothesis 1?
3. What is the best value of conductivity representing the adit, and the thickness and spacing of adit layer for the Hypothesis 2? Because one has to assign the high conductivity into whole model cell if use this method. On the contrast, MODBRNCH allows user defining the accurate adit geometry. Perhaps, we can find out how is high value of conductivity related to value of background conductivity, and how are the thickness and spacing of adit layer related to the adit length.
4. Is any impact of ratio of abstraction and adit length on these hypotheses? Do the hypotheses apply when abstraction is small relative to adit length?
5. Do the hypotheses apply to the sandstone case where the thickness and depth are much larger than that of Chalk aquifer?
6. would a single well be less risk than an adit if there is a pollution source near adit?

Please note that the MODFLOW models of both multiple boreholes and high conductivity used the parameter values obtained by calibrating MODBRNCH. Furthermore, the curve of adit head against pumping test time was main calibration target. But the adit head is not a dependent variable in MODFLOW. Therefore we think the combination of slot and MODBRNCH is still a necessary approach even if the above hypotheses are correct.

4 PRELIMINARY STUDY OF STEPPED ADIT

As the first stage of the study on stepped adit, the possible flow regimes are analyzed and shown in Figure 23.

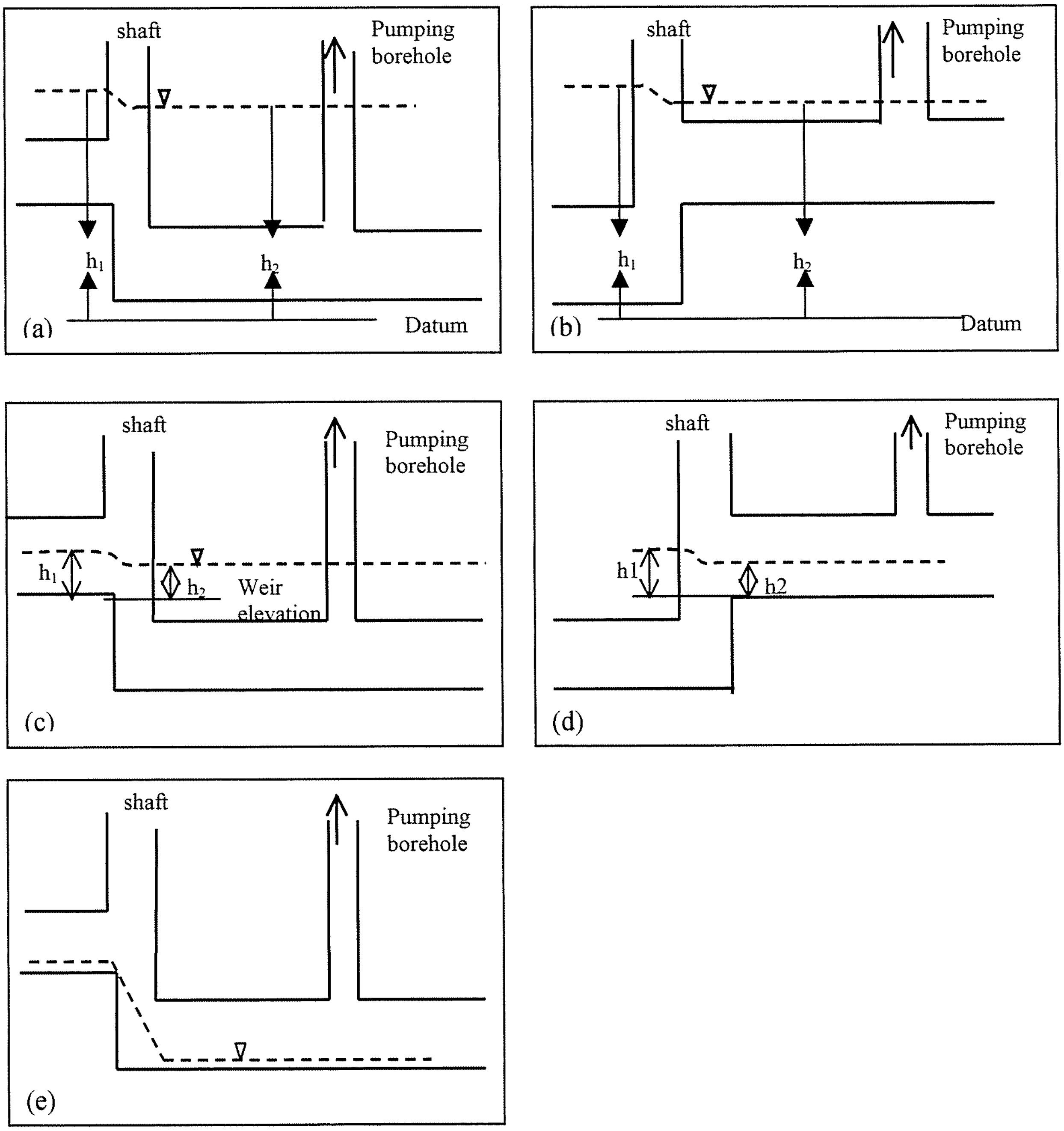

Figure 23 The patterns of flow regime in the stepped adits: (a) & (b) flow is pressurized in both upstream and downstream of the stepped adit; (c) & (d) open channel flow in one side but pipe flow in the other side of step; (e) open channel flow in both sides of step.

4.1 Pressurized flow in both upstream and downstream of the stepped adit

The flow pattern shown in Figure (a) & (b) is pressurized flow in both upstream and downstream and the adit. It could be considered as fully submerged gated culverts, which is generally rated by the equation (French, 1985):

$$h_1 - h_2 = C_C \frac{v^2}{2g} \qquad (1)$$

Where, h_1 is the upstream head

h_2 is the downstream head

C_c is the resistance coefficient for the gate of the culvert and depends on the type of valve and percentage of closure

v is the flow velocity

g is the gravitational acceleration

This flow pattern can also be formulated as two elbows of pipe flow. In addition to the spatially continuous head loss due to friction, local head loss at each elbow is (Featherstone & Nalluri, 1982):

$$\Delta h = K_c \frac{v^2}{2g} \qquad (2)$$

where K_c depends on the angle and size of the elbow and pipe, for a 90° elbow, $K_c=1$

Comparing equation (1) and (2), one can see that basically they are the same.

4.2 Open channel flow in one side but pipe flow in the other side of the step

The flow type shown in Figure (c) and (d) can generally be assumed as subcritical. It can be considered as a gated spillway with submerged weir. Neglecting friction loss, it can be formulated as (Collins, 1977):

$$h_1 + \frac{a_1 v_1^2}{2g} = h_2 + \frac{a_2 v_2^2}{2g} \qquad (3)$$

where h_1 is upstream stage measured relative to the weir

h_2 is downstream stage measured relative to the weir

a_1 is upstream energy coefficient

a_2 is downstream energy coefficient

v_1 is mean velocity in the upstream

v_2 is mean velocity in the downstream

g is gravitational acceleration.

According to the methodology for the determination of outputs of groundwater sources (Beeson et al. 1995), the Deepest Advisory Pumping Water Level (DAPWL) for the adits is elevation of the highest adit roof, therefore it to be unlikely the real case. However, it may happen during a pumping test. We would like to discuss with steering group on this issue.

4.3 Open channel flow in both sides of steps

The flow pattern shown in Figure (e) is viewed as free orifice with free weir, which is typically supcritical and is difficult to be coped with finite difference. Again it unlikely is the real case, so it will not be considered in this project.

4.4 Modelling stepped adit with a case study

According above discussion, the pressurized flow in both upstream and downstream adit will be modeled including some artificial stepped adits and a case study. Bricketwood of GUP is selected for this topic.

The adit system in Bricketwood has a step of 13 m. Both constant and step pumping test data are available. 4 boreholes located at various distances from the adit. Each borehole had 3 piezometers at different levels. Adit head data can be available from two observation shafts. A regional model of FLOWPATH is available, and a transient model is under calibration.

5 WORK REMAINING

The following works are left for the remaining time:

1. Further study on Source Protection Zones
2. Modelling stepped adit
3. Final reporting
4. Software manual and training programme

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GPRG

OPERATION AND PROTECTION OF ADIT SYSTEMS IN UK AQUIFERS

SIXTH PROGRESS REPORT

January 2000

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SUMMARY

An artificial aquifer having an area of 17 km by 10 km, with a thickness of 30 m was constructed. Various boundary conditions, different adit lengths and pumping rates were specified. Methods of (1) Specifying a high value of hydraulic conductivity for adit cells in MODFLOW; (2) Replacing the adit by multiple abstraction boreholes using MODFLOW; (3) MODBRNCH + slot were employed respectively. In addition, the differences between two-dimensional and three-dimensional models were examined to decide when a two-dimensional model is sufficient to delineate the adit protection zones.

The study of this stage indicates:

For a long adit (3 km and above), MODBRNCH and high K derive similar 50-day time-of-travel zones and projection of inflow zone for both big or small abstractions. While the multiple-borehole method can generate similar projection of inflow zone as other methods for a big abstraction, its 50-day time-of-travel zone is separated by individual boreholes. Its projection of inflow zone for a small abstraction is also divided by the individual boreholes.

For a short adit (1 km and below), all three methods derive not only similar projection of inflow zone, but also similar 50-day time-of-travel zones for a big abstraction. This indicates that the method of multi-boreholes can define similar 50-day time-of-travel zone as other methods for a short adit with its bigger abstraction. For a small abstraction, the 50-day time-of-travel zone of multiple-borehole is divided by the individual boreholes.

Values of high K along adit for high K depend on the adit length. The suitable ranges of high K values are 10^3-10^4 m/d, 10^4-10^5 m/d and 10^5-10^6 m/d for 1 km, 3 km and 7 km respectively.

The grid spacing has little effect on the model outputs for MODBRNCH, but has some influences on groundwater levels for both high K and multiple-borehole methods. Nevertheless, the effects of grid spacing for using high K and multiple-borehole methods are not significant.

A 2D model is sufficient for most adit sources in the UK with abstractions of 10 000 m^3/d and over from the point view of delineation protection zones.

An artificial stepped adit case was studied, which indicates that step does not affect the adit simulation. The data from Bricketwood stepped adit also confirms this conclusion.

A draft outline for the final report is included.

1.INTRODUCTION

1.1 Objectives

1. Providing a suitable computer code for modelling groundwater to adit systems including both steady and transient conditions, multiple-interconnected branches and multi-level adit systems.

2. Drawing up guidelines for modelling adit systems.

3. Developing guidelines for delineation of adit source protection zones.

1.2 Progress against Plan

The research has been proceeding as the proposal and the inception report. A computer code has been provided, and two case studies, Wilmington case study and Cottingham case study have been carried out, the guidelines for delineation of adit source protection zones have been developed, and modelling of stepped adit has been studied. All objectives of the project seem having been achieved.

This stage of the study has been focused on the delineation of groundwater source protection zones for the adit sources and modelling of stepped adit.

2. DELINEATION OF GPZS FOR GROUNDWATER SOURCE WITH ADITS

One of the objectives of this project is demonstrating the effects of adit on source protection zones and developing guidelines for delineation of adit source protection zones. To achieve this objective, several artificial models were built, and the particle tracking program MODPATH was employed using the head distribution generated from following three methods: (1) Specifying a high value of hydraulic conductivity for adit cells in MODFLOW. (2) Replacing the adit by multiple abstraction boreholes using MODFLOW. (3) MODBRNCH + slot. In addition, the differences between two-dimensional and three-dimensional models were examined to decide when a two-dimensional model is sufficient to delineate the adit protection zones.

Some of definitions should be addressed here:

Catchment or **Recharge area** defined as the area around a source within which all groundwater recharge is presumed to be discharged at the source.

Projection of inflow zone comprises the projection of zone, through which groundwater flow from catchment to the well, on to the ground surface.

2.1 Adit is parallel to the impervious upstream boundary

A 17 km by 10 km aquifer with a thickness of 30 m was constructed. An impervious boundary was assigned to the north, and 15 m constant head was specified along its southern boundary. A 200 mm/year homogeneous recharge was assumed, so the base flow is caused by the recharge alone.

2.1.1 Adit with a length of 7 km

An adit with a length of 7 km was constructed between elevations of 8-9.8 m, at the. center of aquifer in plan view, and is parallel to the impervious boundary and constant head boundary. Figure 1 shows the aquifer and the position of adit

For the 7km adit, abstractions of 50 000 m^3/d and 30 000 m^3/d were specified separately, The modelling methods of high K, multiple-borehole and MODBRNCH were employed respectively. Figure 2 shows 50-day time-of-travel zone and projection of inflow zone derived from three methods with an abstraction of 50,000m^3/d. Figure 3 shows 50-day time-of-travel zone and projection of inflow zone generated from three methods with an abstraction of 30,000m^3/d.

Figure 2 and 3 indicate that both MODBRNCH and high K derive similar 50-day time-of-travel zones and projection of inflow zone for both big or small abstractions. While

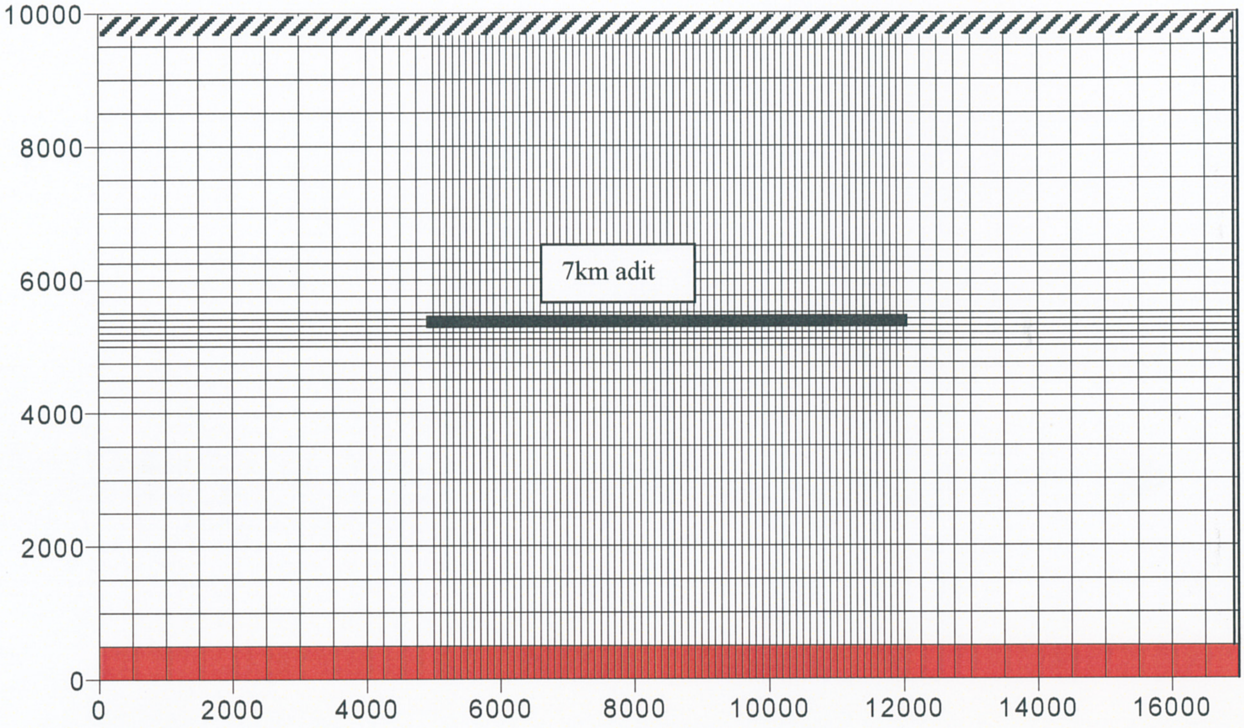

Figure 1 Boundaries and 7 km adit position in the aquifer

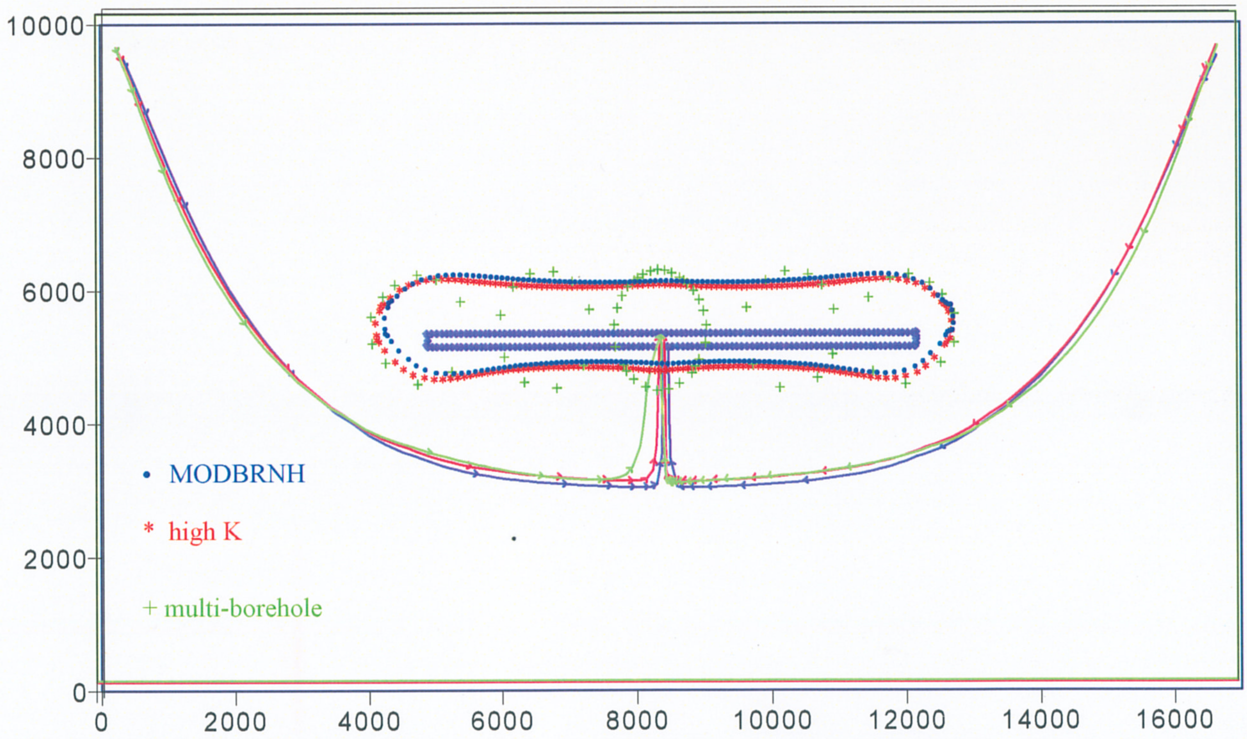

Figure 2 50-day time-of-travel zones and projection of inflow zone derived from three methods with a 50,000 m^3/d abstraction for the 7 km adit

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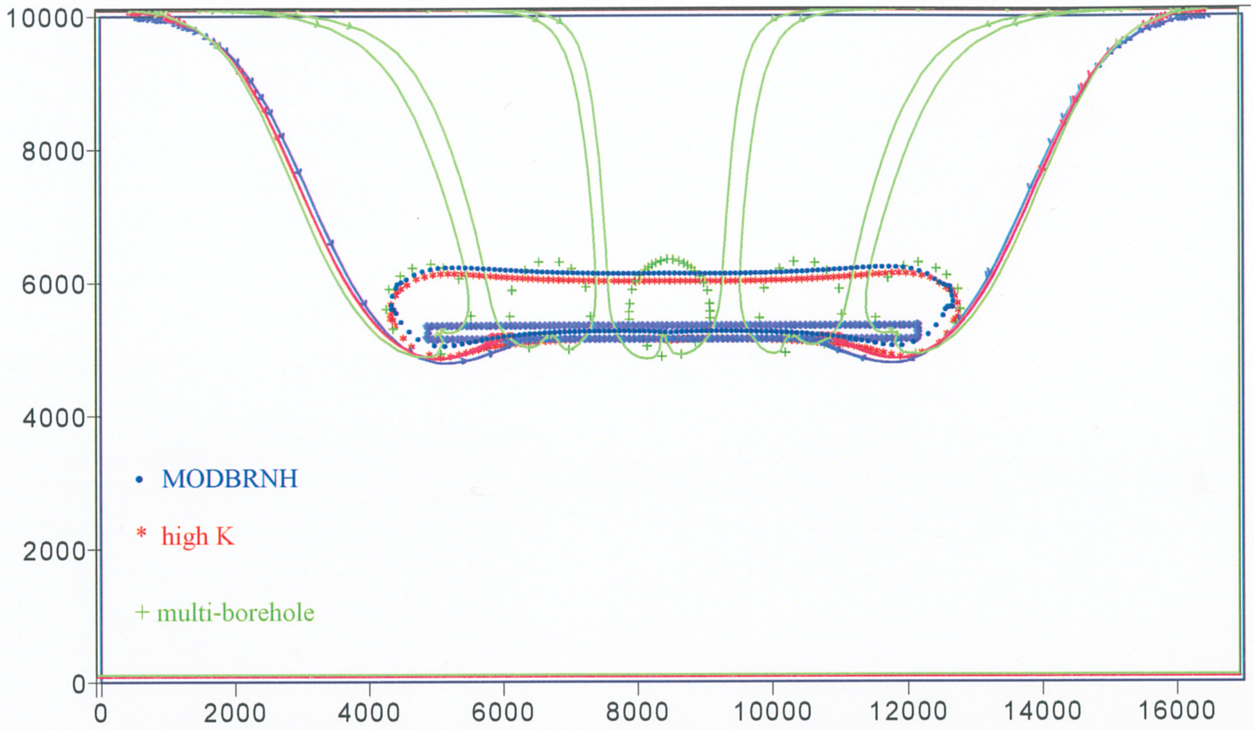


Figure 3 50-day time-of-travel zones and projection of inflow zone derived from three methods with a 30,000 m^3/d abstraction for the 7 km adit

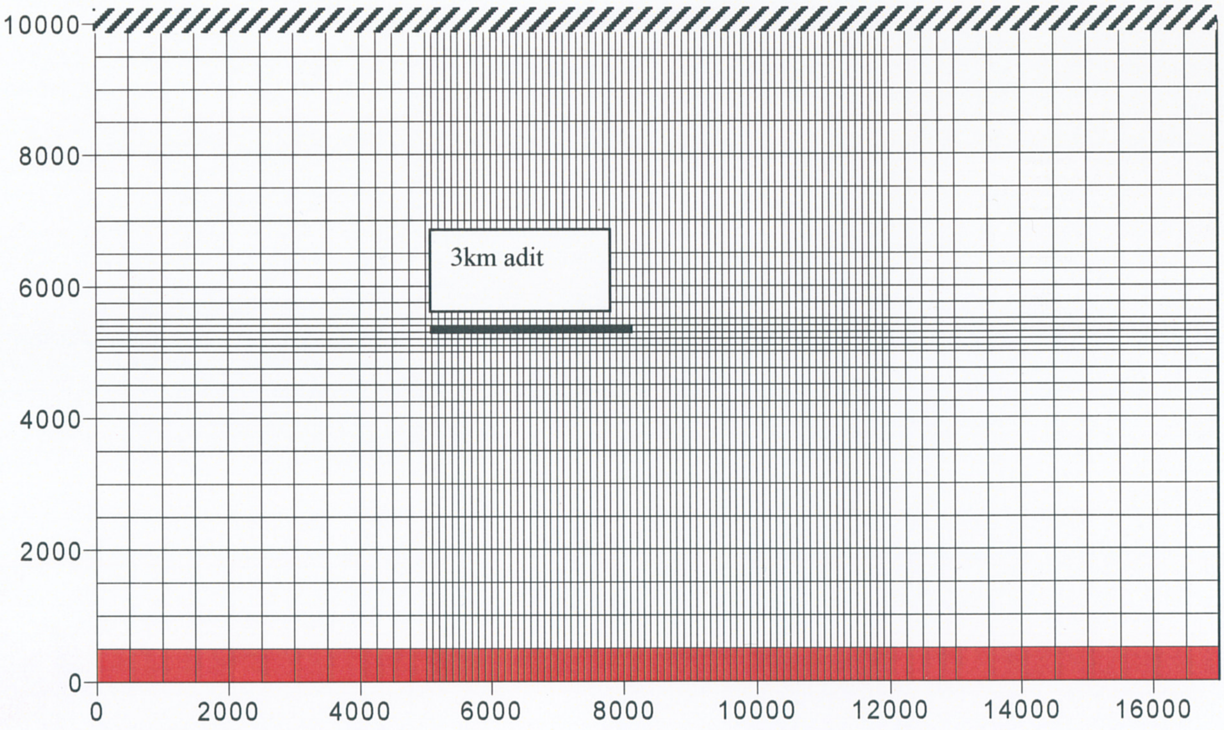


Figure 4 Aquifer has a 3 km adit in it.

multiple-borehole method can generates similar projection of inflow zone as other methods for big abstraction, but its 50-day time-of-travel zone is different from those of other methods. Moreover, its projection of inflow zone for small abstraction is different, due to the influence of individual boreholes

2.1.2 Adit with a length of 3 km

A 3 km adit was constructed in an aquifer with the same condition as the previous aquifer. Figure 4 shows the position of the 3 km adit. Figure 6 shows 50-day time-of-travel zones and projection of inflow zone derived from three methods with a 10,000 m^3/d abstraction for the 3 km adit

Figure 5 and 6 show the same phenomena as Figure 2 and 3, that is both MODBRNCH and high K derive similar 50-day time-of-travel zones and projection of inflow zone for either big or small abstractions. While multiple-boreholes can generates similar projection of inflow zone as other methods for big abstraction, but its 50-day time-of-travel zone is different from other methods. Moreover, its projection of inflow zone for the small abstraction is different, due to the influence of individual boreholes.

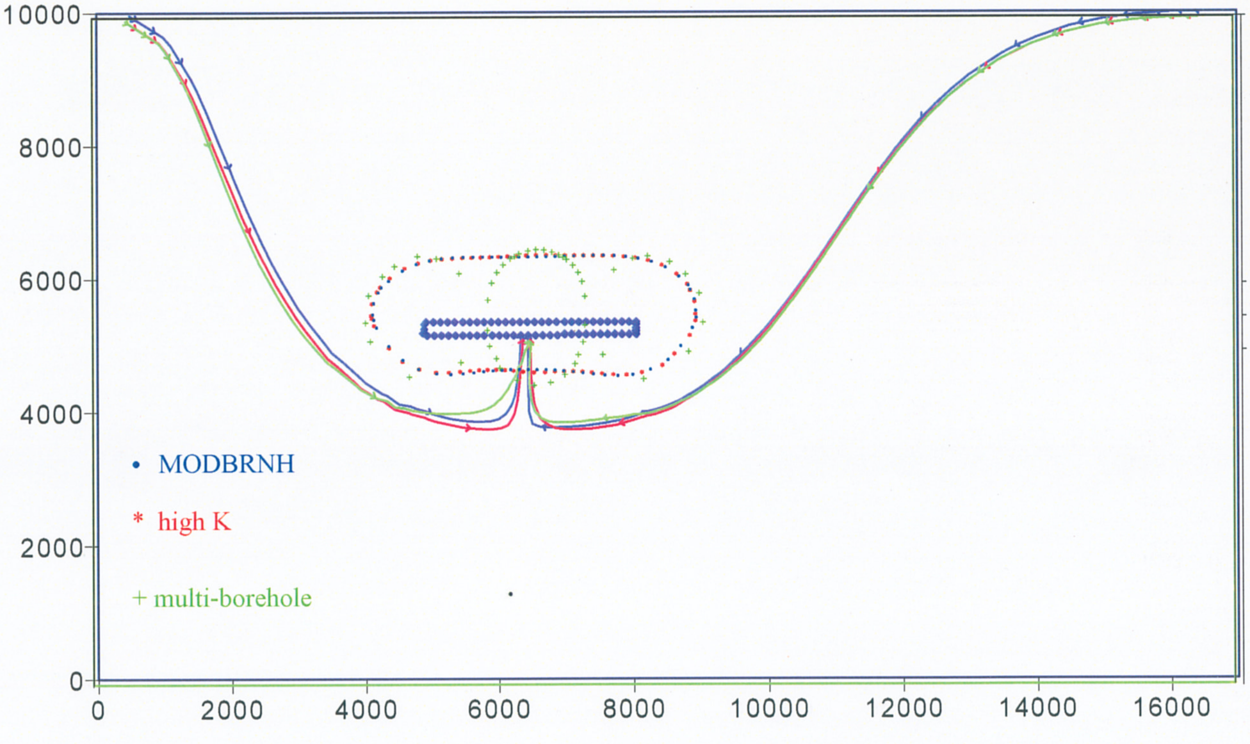


Figure 5 50-day time-of-travel zones and projection of inflow zone derived from three methods with a 30,000 m^3/d abstraction for the 3 km adit

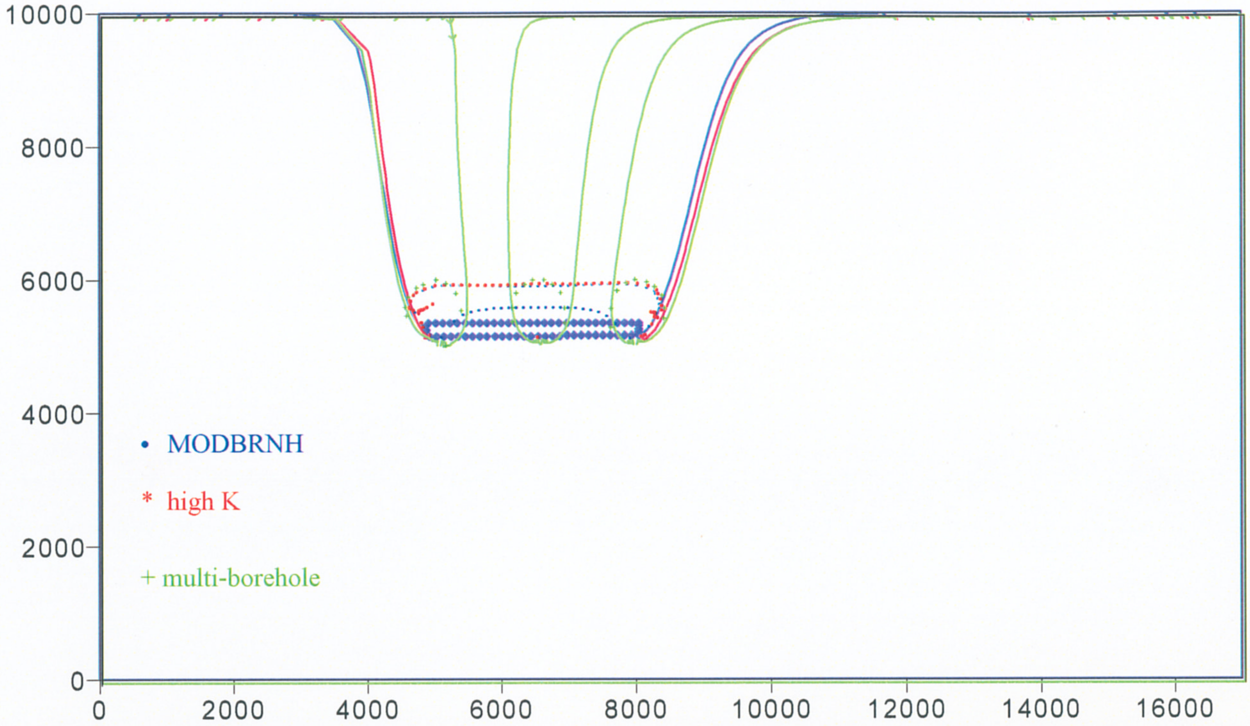


Figure 6 50-day time-of-travel zones and projection of inflow zone derived from three methods with a 10,000 m^3/d abstraction for the 3 km adit

2.1.3 Adit with a length of 1 km

A 1 km adit, which is the most common adit length in UK, was constructed in an aquifer with the same condition as the previous aquifers. Figure 7 shows the position of the 1 km adit.

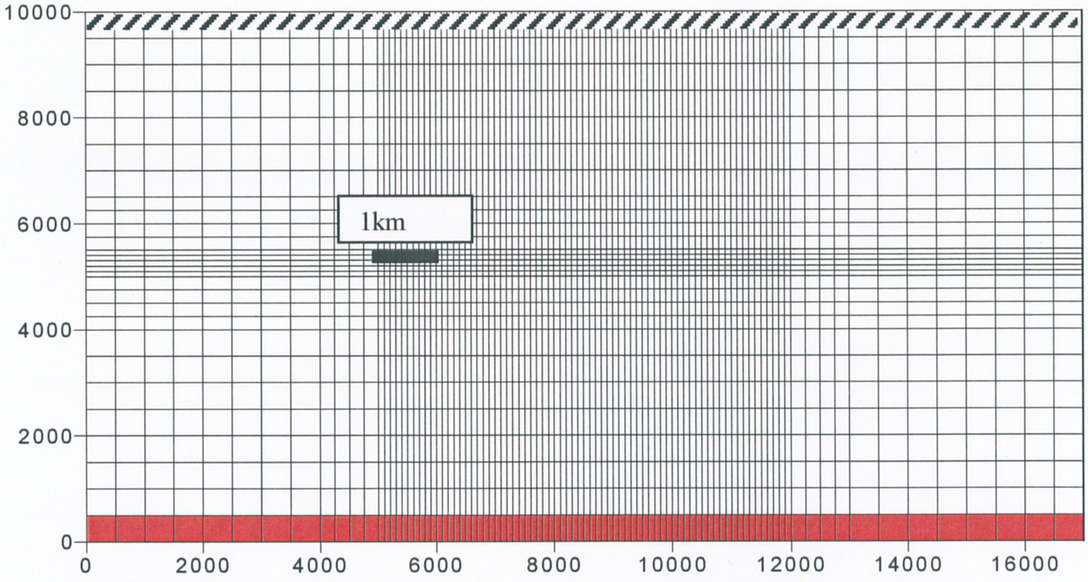


Figure 7 Boundary conditions of the aquifer and position of 1 km adit.

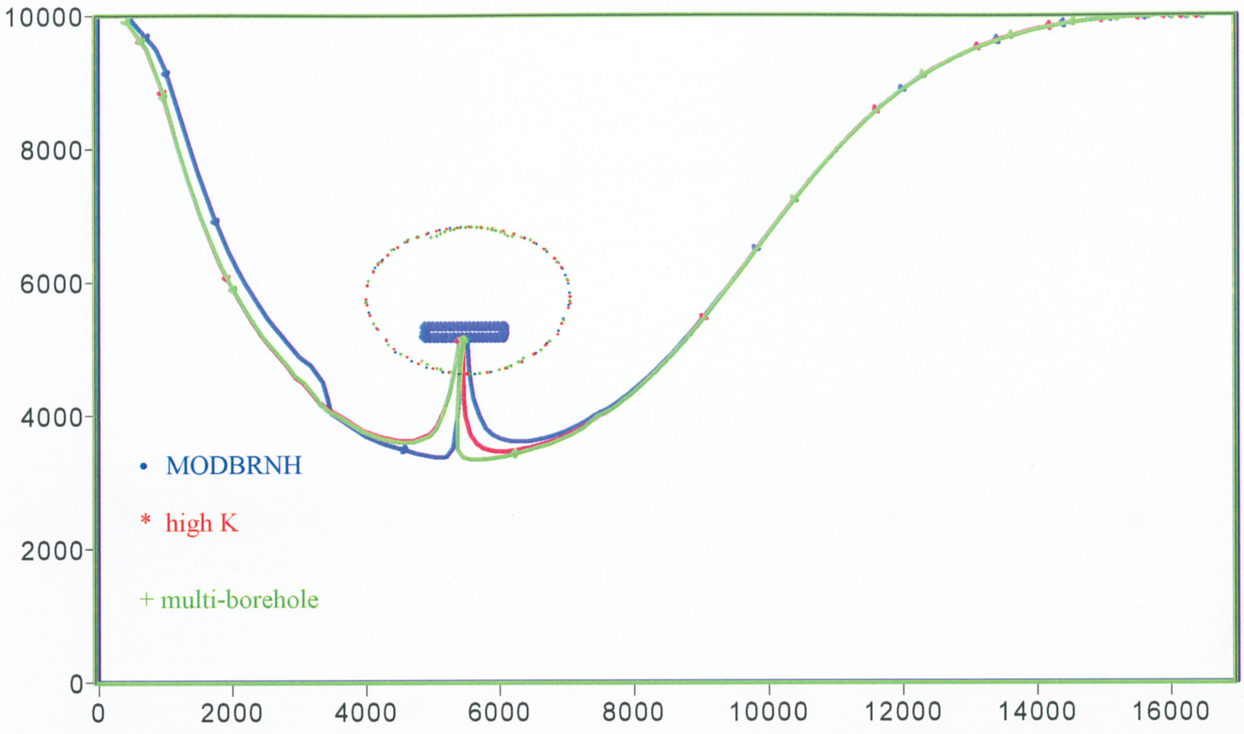


Figure 8 50-day time-of-travel zones and projection of inflow zone derived from three methods with a 30,000 m^3/d abstraction for the 1 km adit

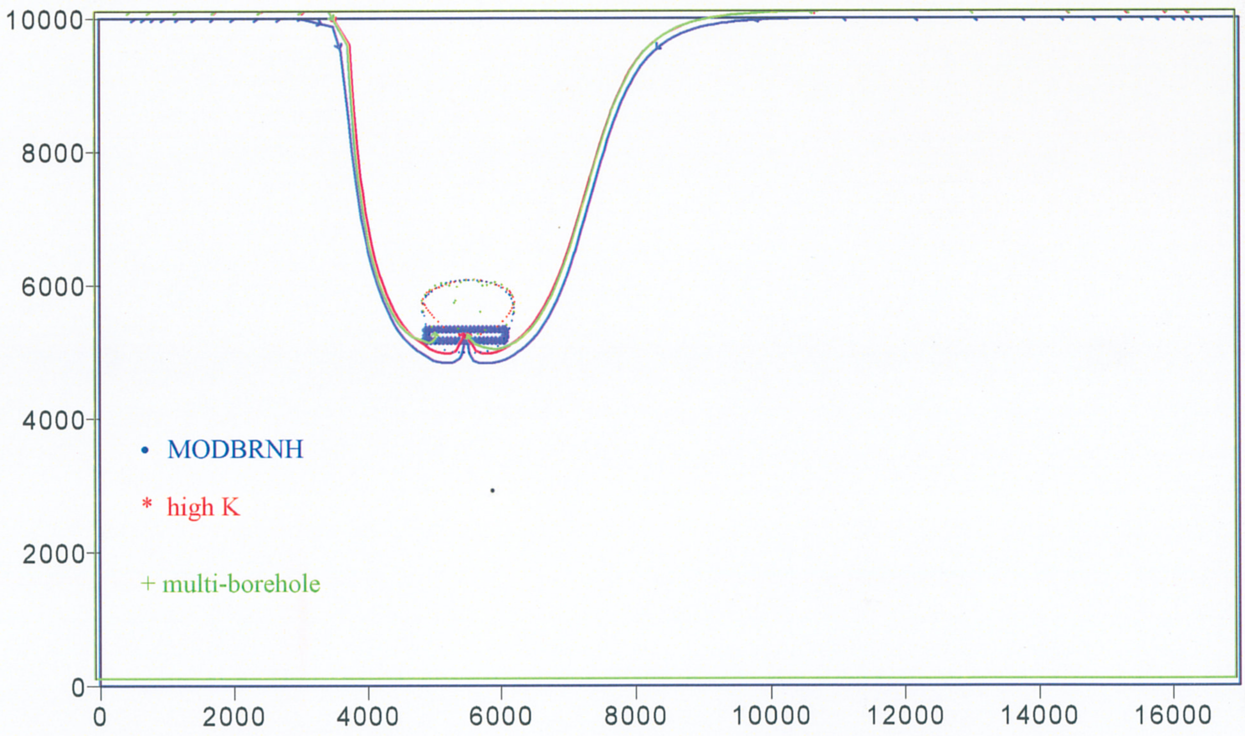


Figure 9 50-day time-of-travel zones and projection of inflow zone derived from three methods with a 10,000 m^3/d abstraction for the 1 km adit

Abstractions of 30,000 m^3/d and 10,000 m^3/d were simulated separately. Figure 8 shows that all three methods derived not only similar projection of inflow zone, but also similar 50-day time-of-travel zones. This indicates that the method of multi-boreholes can define similar 50- day time-of-travel zone as other methods for short adit, say 1 km, with its bigger abstraction. For the small abstraction, one can not draw the same conclusion (Figure 9).

2.2 Adit is perpendicular to the impervious boundary

The same size of aquifer as previous one was constructed again, However the upstream impervious boundary was moved to the west, the east boundary was defined as 15 m constant head boundary. The plan view of aquifer and adit is shown in Figure 10.

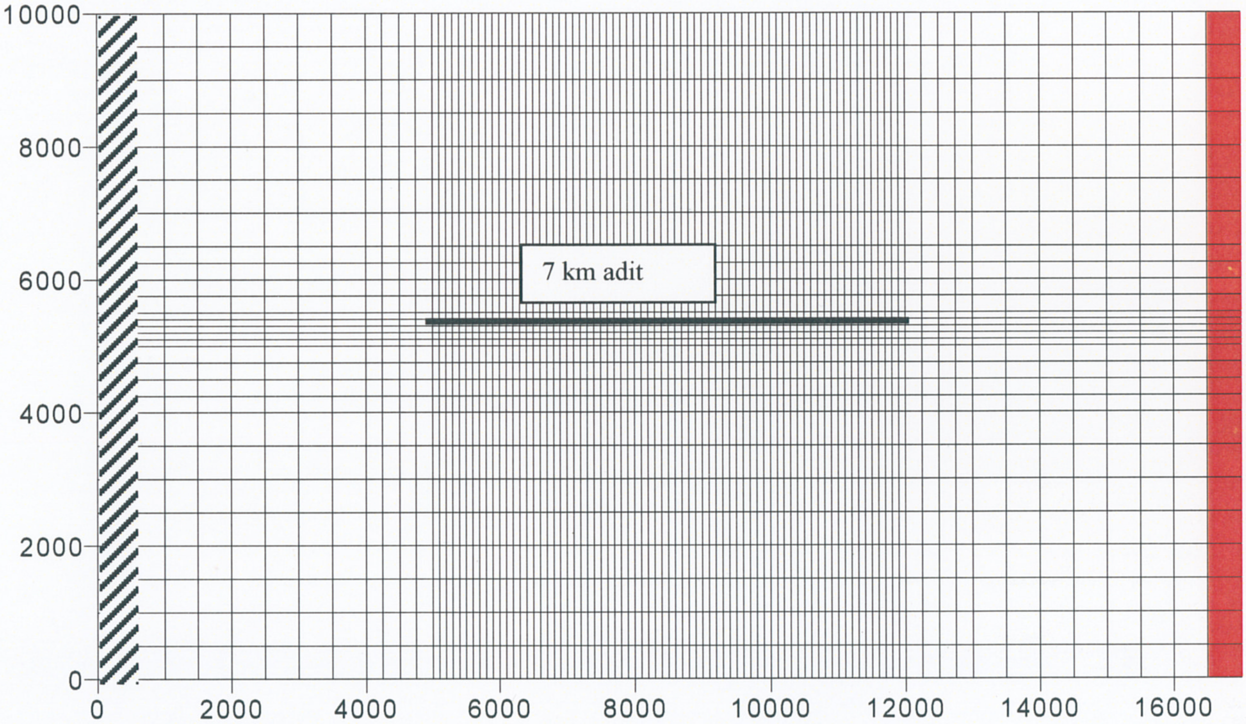


Figure 10 Boundaries and 7km adit position in the aquifer

Figure 11 shows the similar phenomenon as that adit is parallel to the impervious upstream boundary, that is both MODBRNCH and high K derive similar 50-day time-of-travel zones and projection of inflow zone. While multiple-boreholes can generates similar projection of inflow zone as other methods, but its 50-day time-of-travel zone is different from other methods.

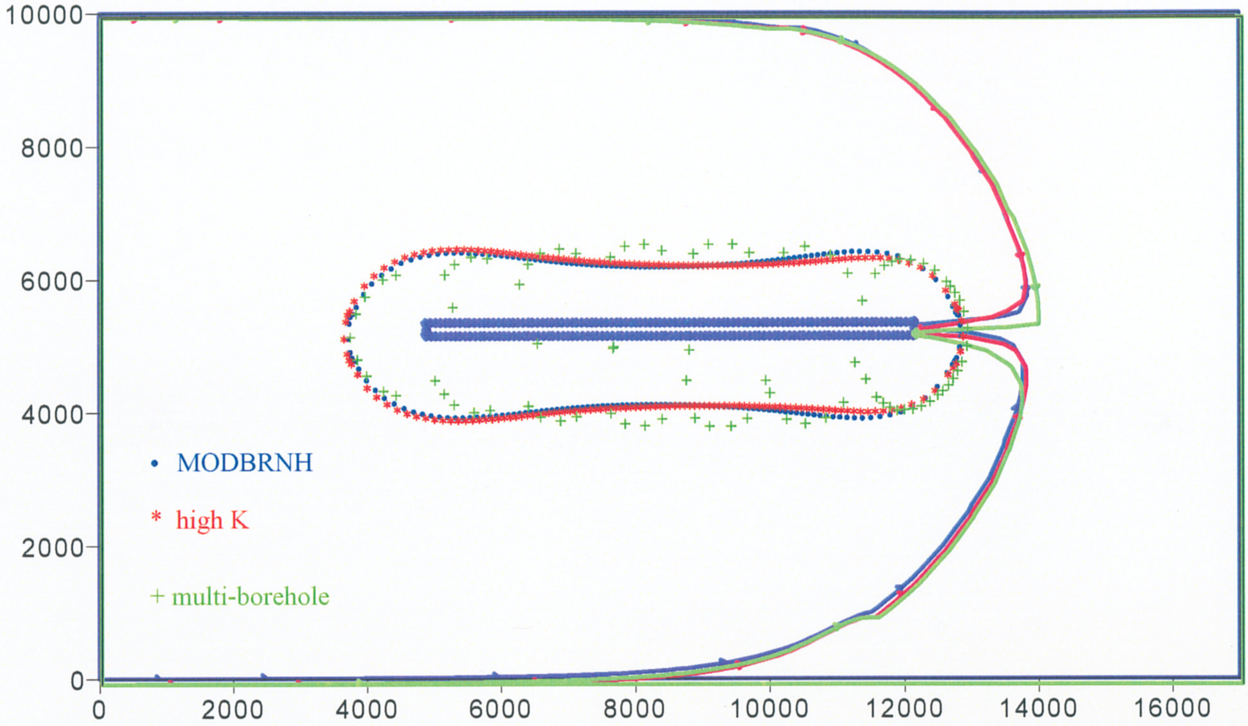


Figure 11 50 day of time travel zones and projection of inflow zone derived from three methods with a 70,000 m^3/d abstraction for the 7 km adit perpendicular to the impervious boundary.

2.3. Two parallel straight line fixed head boundaries

Analogously the situation for an adit between two parallel strait line fixed head boundaries is analyzed. The same size of aquifer with 25 m and 15 m constant head boundaries along western and eastern boundaries is simulated. In this case the base flow is not caused by recharge alone, but is superimposed on a contribution from hydraulic gradient between two fixed head boundaries. A 7 km adit and 1km adit were constructed separately, abstractions of 50,000 m^3/d and 42,000 m^3/d were carried out respectively. Figure 12 shows the boundary conditions and 7 km adit, Figure 13 and 14 show the 7 km and 1km protection zones. Again, similar conclusion could be drawn from these two figures, that is for long adit with big abstraction, three methods could derived similar total protection zones, but multi-boreholes generates different 50-day time-of-travel zone. For the short adit with its big abstraction, three methods can generate similar projection of inflow zone and 50-day time-of-travel zones.

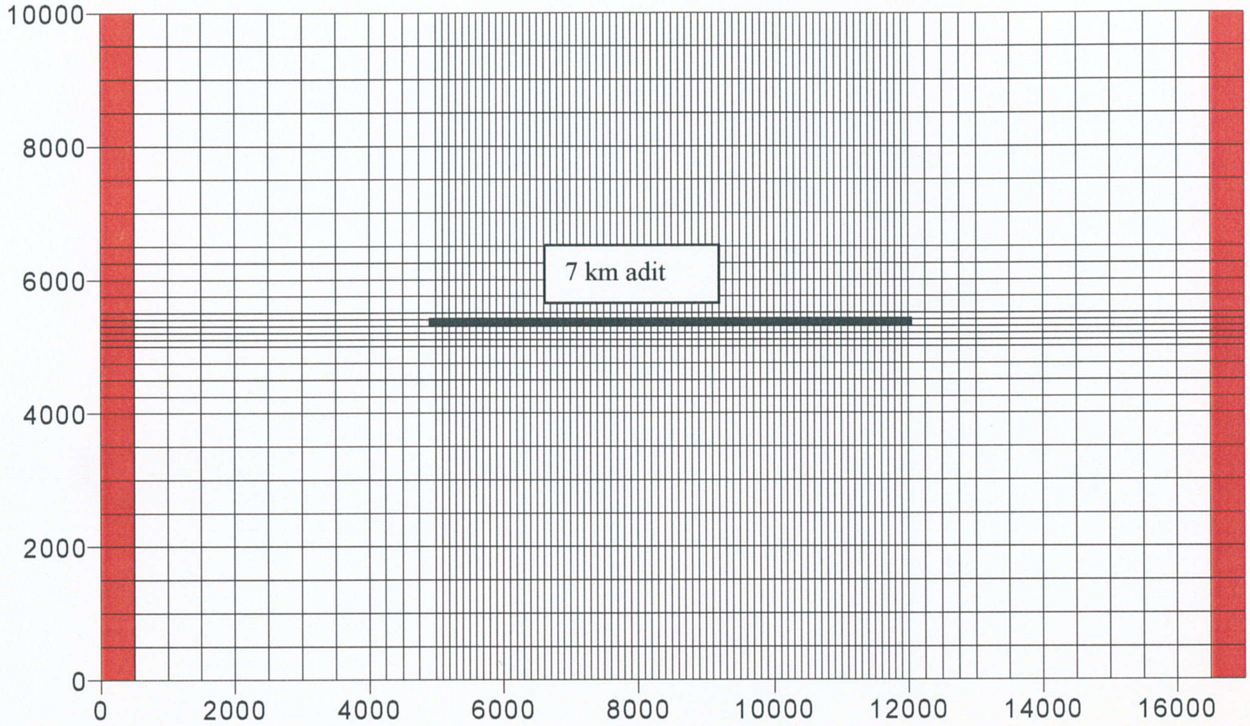


Figure 12 Boundaries and 7km adit position in the aquifer

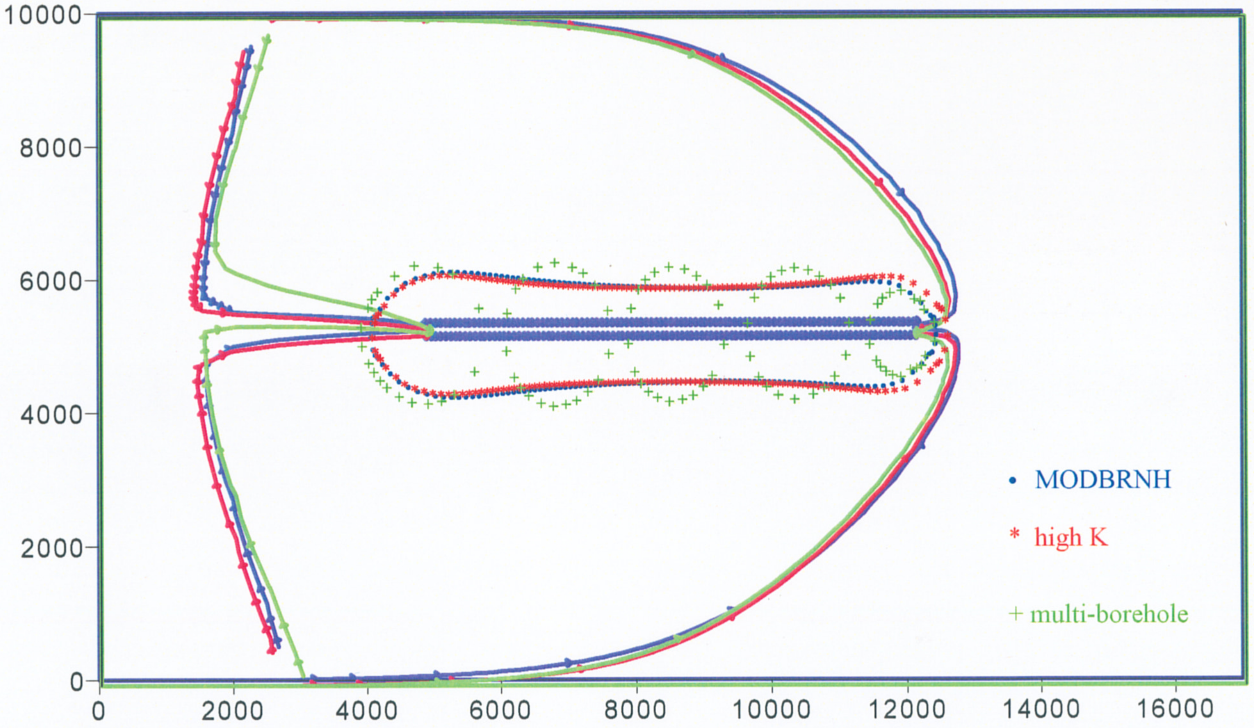


Figure 13 50-day time-of-travel zones and projection of inflow zone derived from three methods with a 50,000 m^3/d abstraction for the 7 km adit between two parallel straight line fixed head boundaries.

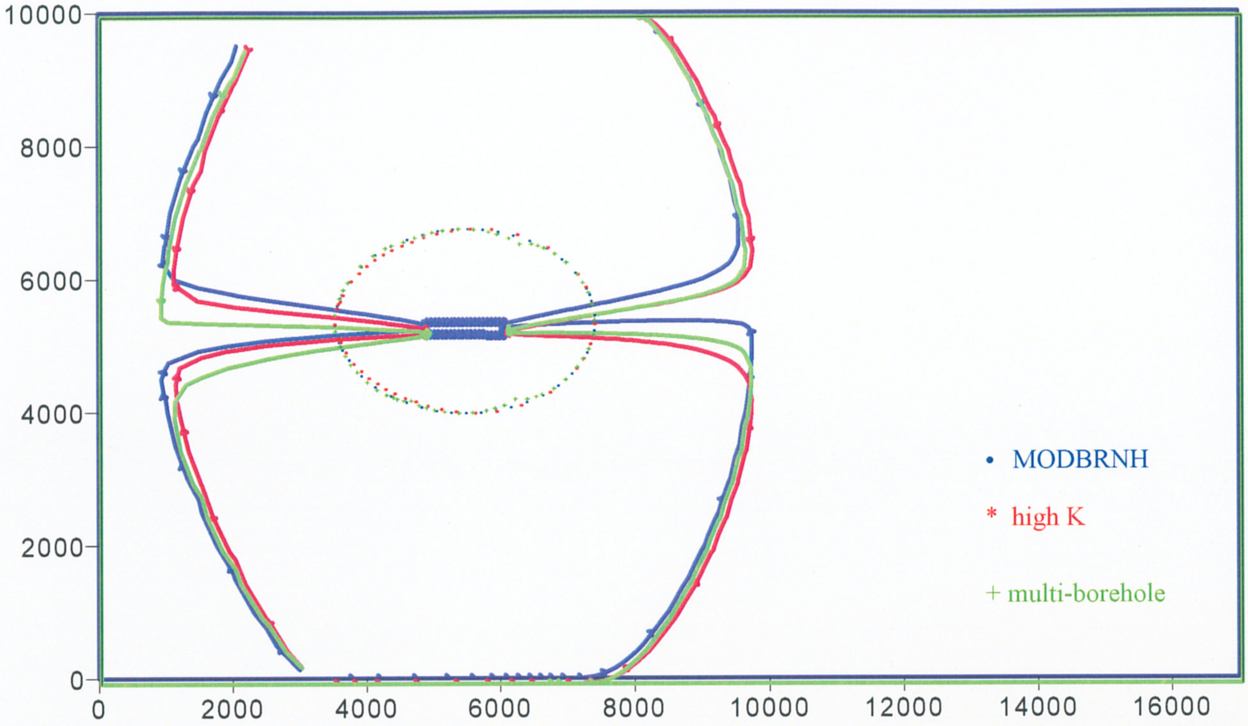


Figure 14 50-day time-of-travel zones and projection of inflow zone derived from three methods with a 42,000 m^3/d abstraction for the 1 km adit between two parallel straight line fixed head boundaries.

2.4.Values for the high K along the adit cells

Values of high K along adit cells for high K method were adjusted to get similar groundwater head distributions and protection zones as those generated from MODBRNCH. It is found that the suitable values of high K depend on the adit length and is listed in the Table 1.

Table 1 Range of high K values

Adit length (km)	Range of high K values (m/d)
1	$10^3 \sim 10^4$
3	$10^4 \sim 10^5$
7	$10^5 \sim 10^6$

Figure 15, 16 and 17 show the projection of inflow zone and 50-day time-of-travel zones generated from MODBRNCH and high K methods using various values of high K. The projection of inflow zone and 50-day time-of-travel zone for 7 km, 3 km and 1km adits are shown in Figure 15, 16 and 17 separately, the 3 aquifers have the same conditions and uniform abstraction of 30,000 m^3/d. The suitable high K values for 7 km, 3 km and 1 km

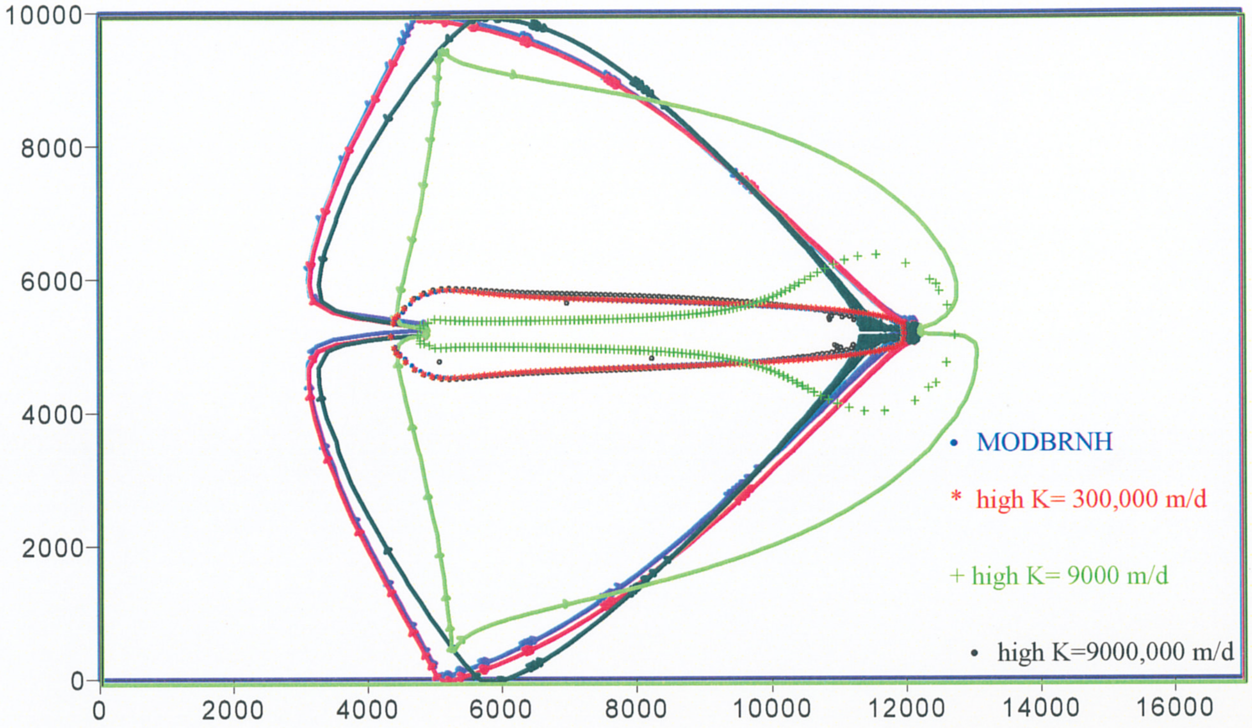


Figure 15 Comparison of 50-day time-of-travel zones and projection of inflow zone generated from various values of high K and MODBRNCH at a 7 km adit.

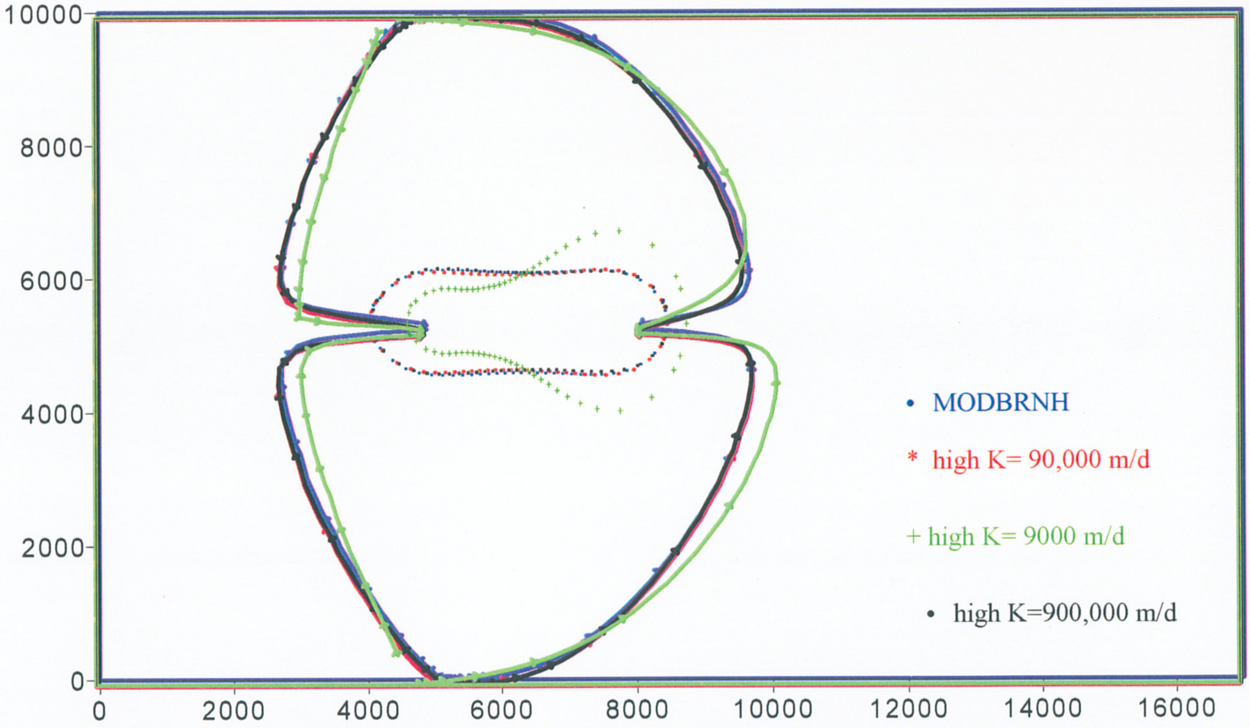


Figure 16 Comparison of 50-day time-of-travel zones and projection of inflow zone generated from various values of high K and MODBRNCH at a 3 km adit

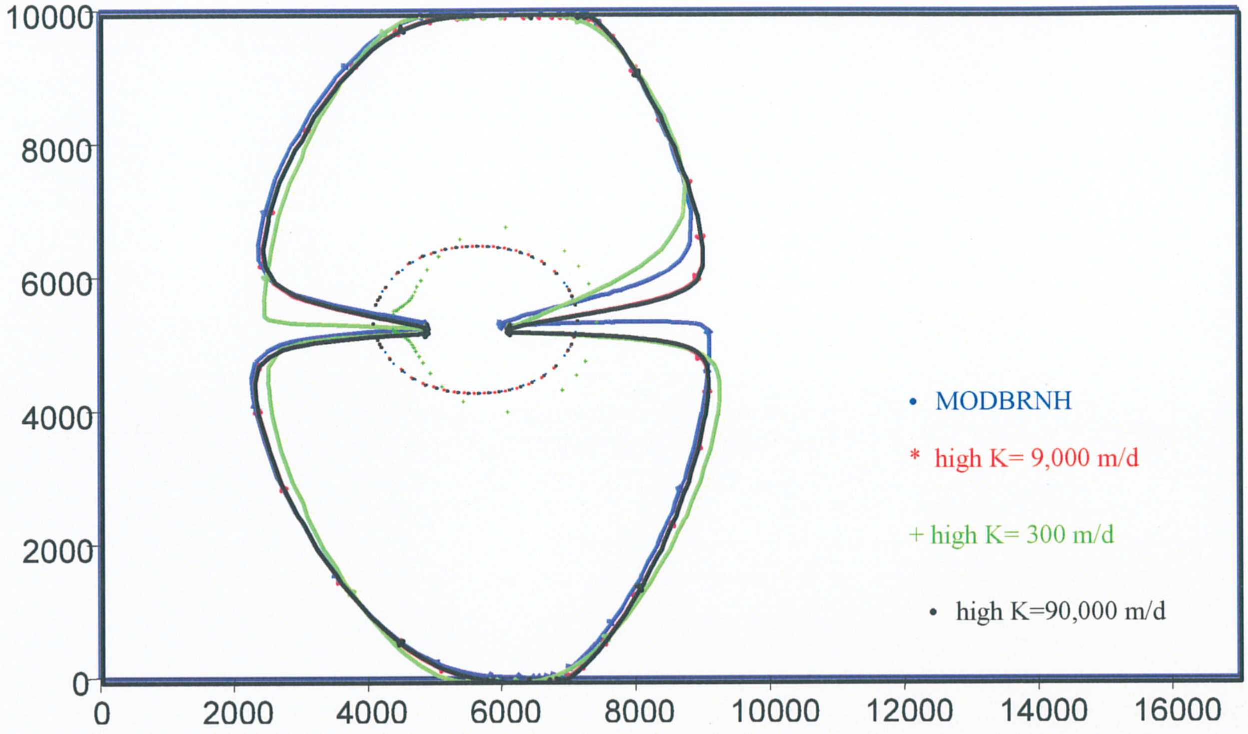


Figure 17 Comparison of 50-day time-of-travel zones and projection of inflow zone generated from various values of high K and MODBRNCH at a 1 km adit.

adit are 300,000 m/d, 90,000 m/d and 9000 m/d, respectively. This indicates that suitable value of high K increase with the increasing of adit length, but is nonlinear.

From Figure 15, one can see that the high K method with value of 300,000 m/d (red line) generates very similar 50-day time-of-travel zones and projection of inflow zone to those from MODBRNCH (blue line). The results from value of 9000 m/d (green line) are very different from MODBRNCH. For the value of 9000,000 m/d (black line), its 50-day time-of travel zone is similar to MODBRNCH, while its projection of inflow zone is different. Figure 15 indicates that the value of high K is sensitive at its lower range, but less sensitive at its higher range.

Figure 16 shows that the suitable high K value for this case is 90,000 m/d (red line), its results are just the same as those of MODBRNCH (blue line). The lower value of 9000 m/d (green line) makes different results. However, its higher value (900,000 m/d, black line) makes no difference. A slight different conclusion can be draw from Figure 16, that is the high K value is sensitive at its lower range, but not sensitive at its higher range.

Figure 17 shows that its suitable value of high K is 9000 m/d (red line). Regarding the sensitivity of high K value, the same conclusion can be drawn as the one from Figure 16.

The sensitivity of these 3 cases, probable can be explained by Figure 18. It shows adit positions and groundwater levels. Black line, blue line and red line represent 1 km, 3 km and 7 km adits, respectively. From the figure, one can see that there is no contour line cross 1km and 3km adits, and these adits have little hydraulic gradient within them, therefore hydraulic conductivity is less sensitive. In contrast, there is contour line cross the 7 km adit, which indicates a hydraulic gradient within adit, therefore hydraulic conductivity is more sensitive to 7 km adit.

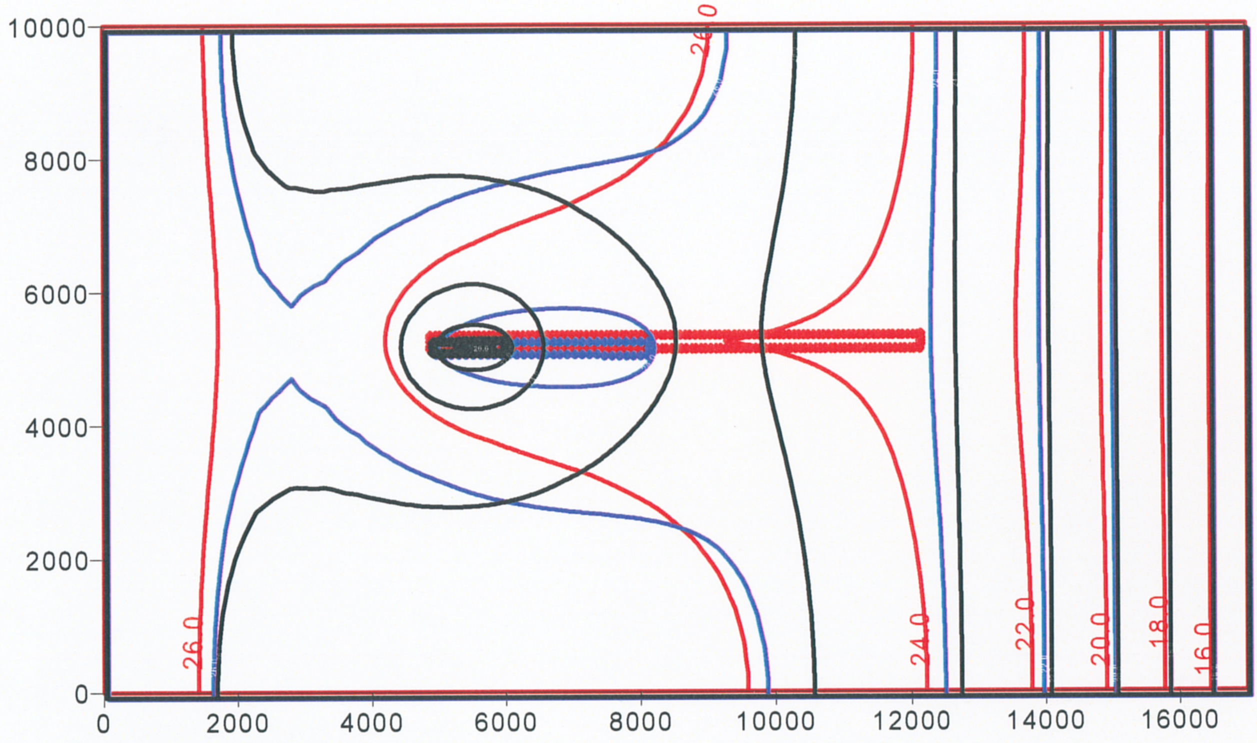


Figure 18 Adit positions and groundwater levels. Black line, blue line and red line represent 1 km, 3 km and 7 km adits, respectively.

2.5. Influences of grid spacing on delineation of Protection Zones

One of the limitation of finite difference is influences of grid spacing. The sensitivity of grid spacing has been tested. 100 m spacing was used in the adit area in previous section. The model outputs of 20 m spacing and 100 m spacing were compared. Figure 19, 20 and 21 show the comparisons of 50-day time-of-travel zones, projection of inflow zone and groundwater levels using 100 m and 20 m spacing generated by MODBRNCH, high K and multiple-borehole methods, respectively. It is indicated that the grid spacing has little effect on the model outputs for MODBRNCH, but has some influences on groundwater levels for both high K and multiple-borehole methods. This probably is because using either high K or multiple-borehole methods, one has to replace adit by either specifying

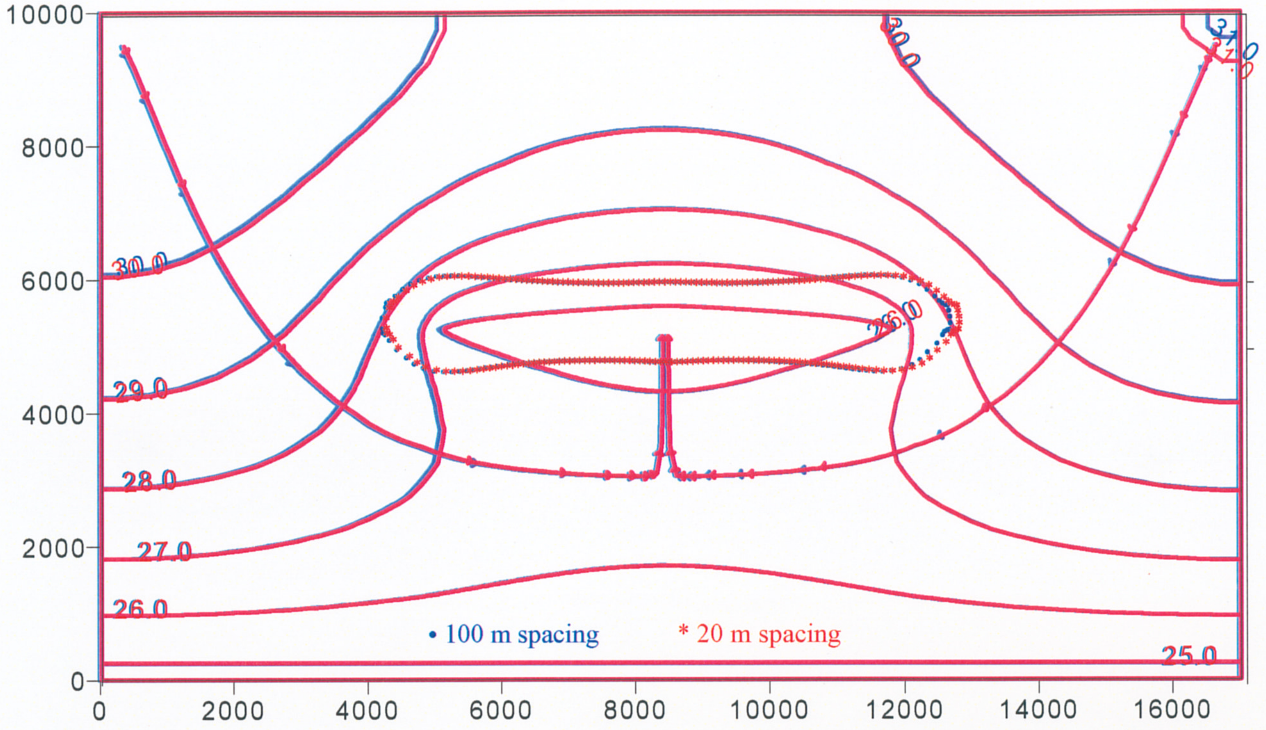


Figure 19 Comparison of 50-day time-of-travel zones, projection of inflow zone and groundwater levels generated by MODBRNCH using 100 m and 20 m grid spacing.

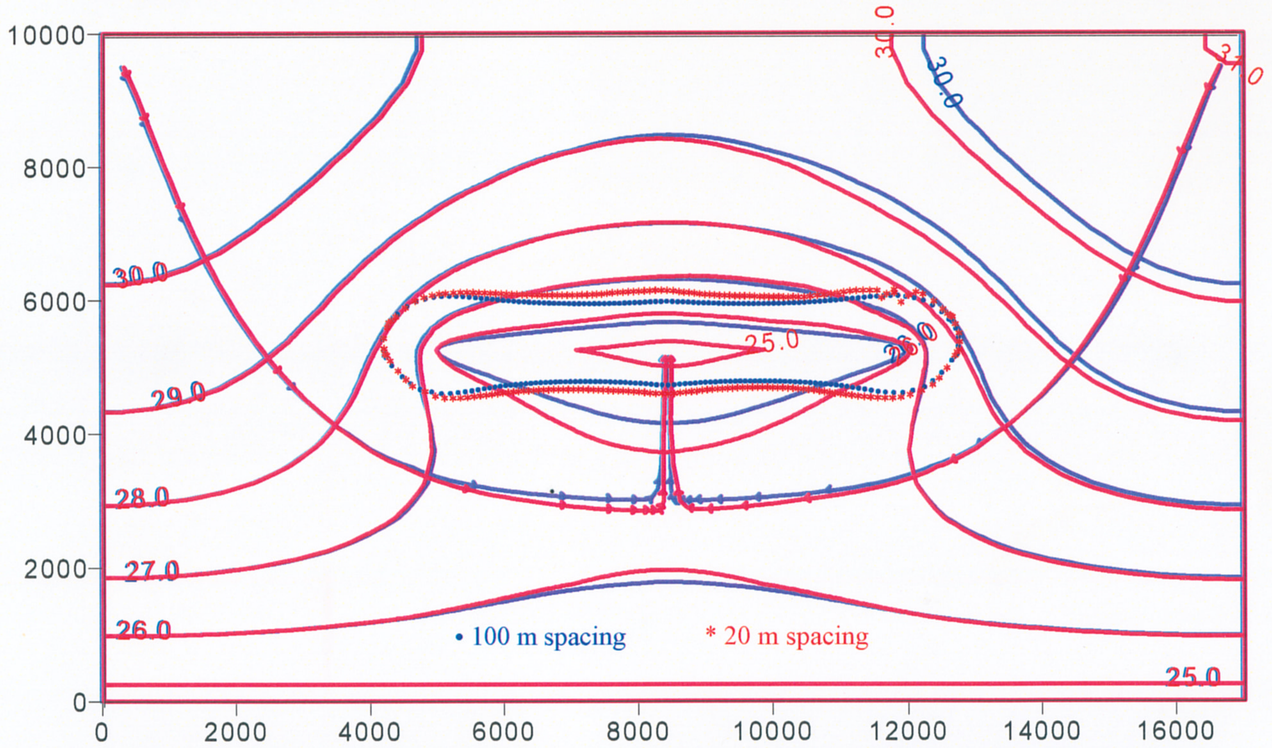


Figure 20 Comparison of 50-day time-of-travel zones, projection of inflow zone and groundwater levels generated by high K method using 100 m and 20 m grid spacing.

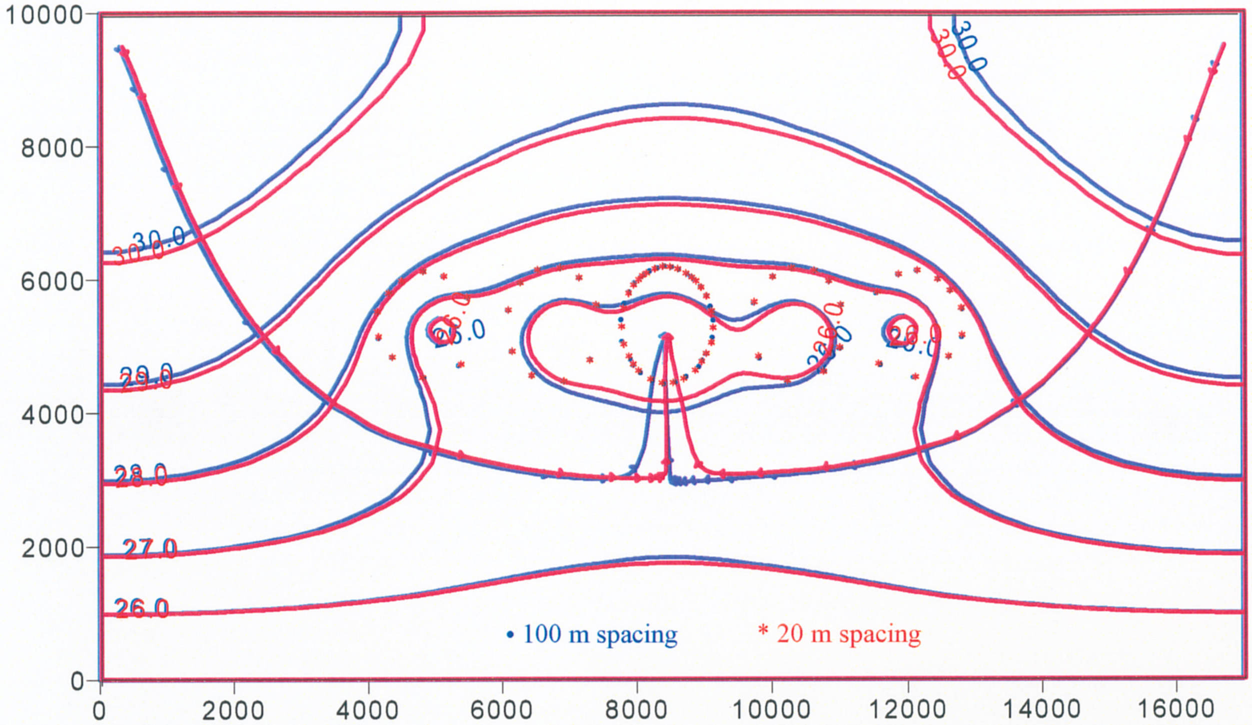


Figure 21 Comparison of 50-day time-of-travel zones, projection of inflow zone and groundwater levels generated by multiple-borehole method using 100 m and 20 m grid spacing.

high K along adit into whole model cell, or assigning several pumping rates into model cells. Therefore it is not a surprising that grid spacing affects the model output by using high K and multiple-borehole methods. While, MODBRNCH allows users to construct adit as its true geometry, so that spacing has little effect for using MODBRNCH. Nevertheless, the effects of grid spacing for using high K and multiple-borehole methods are not significant.

2.6. Distribution of abstractions for the multiple-borehole method

The distribution of abstractions for the multiple-borehole method depends on the relation between orientations of adit and boundary conditions. One can just evenly distribute the abstractions along adit if the adit is parallel to the impervious or constant head boundaries. In the case that adit is perpendicular to the impervious or constant head boundaries, the abstractions should be decreasingly specified in the downstream direction.

2.7. Background conductivity decreasing with depth

Because the hydraulic conductivity often decreases with aquifer depth in the UK, so the situation of low conductivity for adit layer and below was tested. Figure 22 shows 50-day

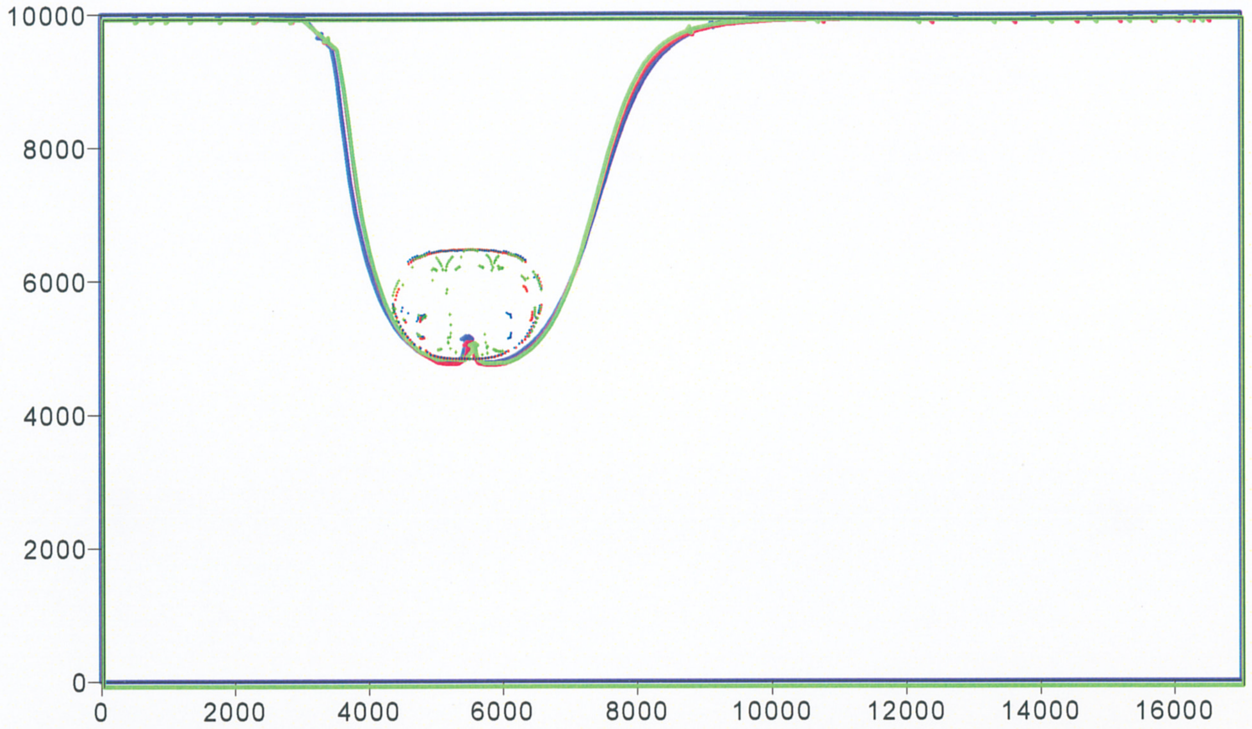


Figure 22 50-day time-of-travel zones and projection of inflow zone derived from three methods with an abstraction of 10,000 m^3/d for a 1 km adit, its lower layers have low conductivity.

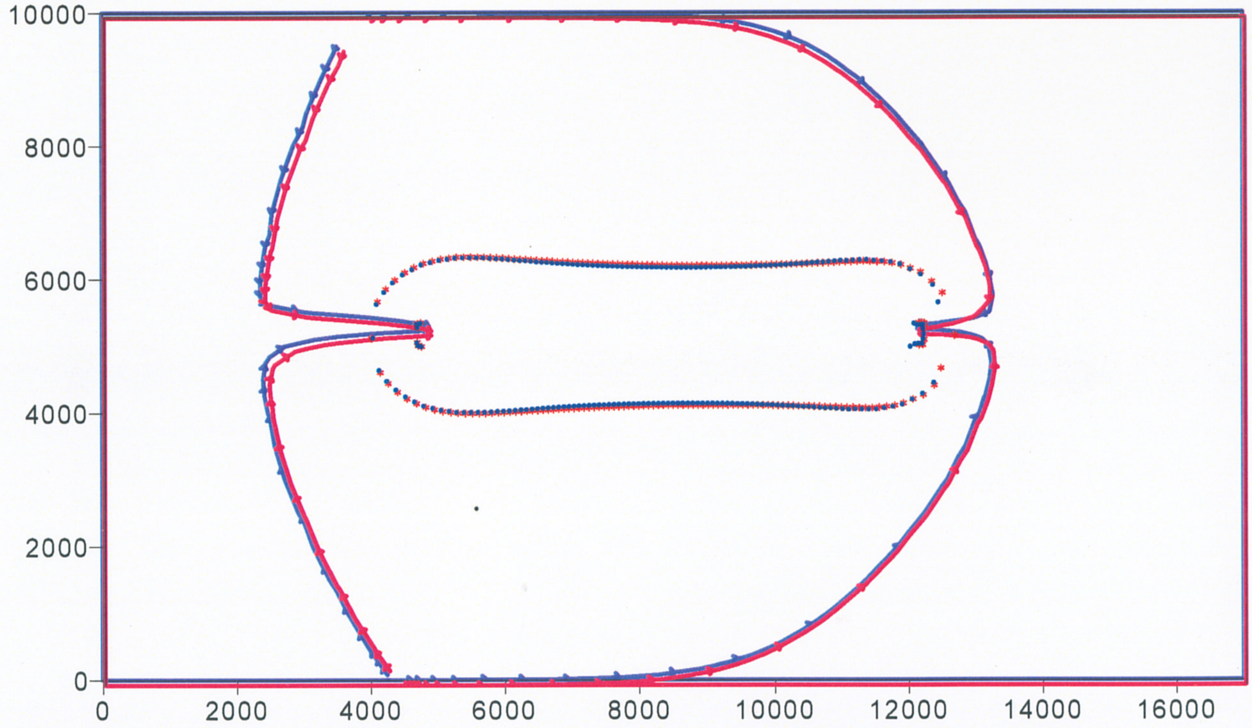


Figure 23 50-day time-of-travel zones and projection of inflow zone derived from high K method and MODBRNCH with an abstraction of 50,000 m^3/d for a 7 km adit, its lower layers have low conductivity.

time-of-travel zones and projection of inflow zone by using different methods for a 1km adit with an abstraction of 10,000 m^3/d. The adit position and boundary conditions are shown in Figure 7, which is exactly same as the conditions for Figure 9, except the low conductivity for adit layer and below. Comparing Figure 9 and Figure 22, one can find that they are very similar. These figures indicate that the conclusions drawn from uniform conductivity situation for short adit with small abstraction are also valid for the situation of low conductivity in lower layers. That is the three methods can derive similar projection of inflow zone for short adit with small abstraction, but the 50-day time-of-travel zones from multiple-borehole method is different from the one generated by the other methods.

Figure 23 shows a 7 km adit having an abstraction of 50,000 m^3/d, its boundary conditions are shown in Figure 12, which is the same as the conditions of Figure 13. Figure 23 indicates that the method of high K and MODBRNCH can delineate similar 50-day time-of-travel zone and projection of inflow zone for long adit with big abstraction. However some boreholes were dry when the multiple-borehole method was used. So this method can not be applied to the situation of low conductivity in lower layers with big abstraction.

The high K value used for Figure 22 is the same value as that for the Figure 9, which is 9000 m/d, and the value for Figure 23 is the same value for Figure 13. This indicates that the value of background conductivity does not affect the values of high K, and the values listed in Table 1 is still valid for the case of low conductivity in lower layers.

2.8. Determination of protection zones in 2D and 3D

Currently, groundwater protection zones are widely determined by 2-dimensional models. It is questioned that are 2D models sufficient to delineate the protection zones for the groundwater sources with adits? When do we need 3D models?

For a single well, Kinzelbach (Kinzelbach et al 1992) pointed out that the catchment of a fully penetrating well can always be determined by a 2D approximation, which is shown in Figure 24.

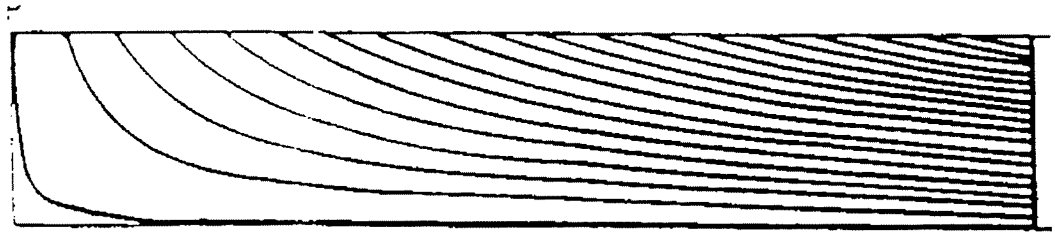


Figure 24 Pathlines in a vertical section through the well axis: case of fully penetrating well.

Figure 25 shows that for a partially penetrating well, the catchment may be not bounded by the impervious upstream boundary.

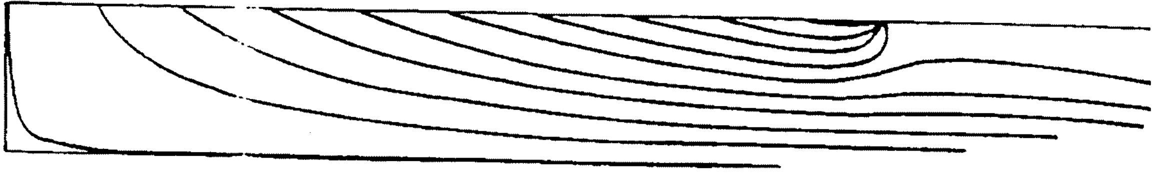


Figure 25 Pathlines in a vertical section through the well axis: case of the partially penetrating well at the aquifer top.

Figure 26 shows a well at the aquifer bottom. With increasing depth of the abstraction well the catchment area moves towards the impervious upstream boundary. The projection of the well to the aquifer top is no longer contained in the catchment area.

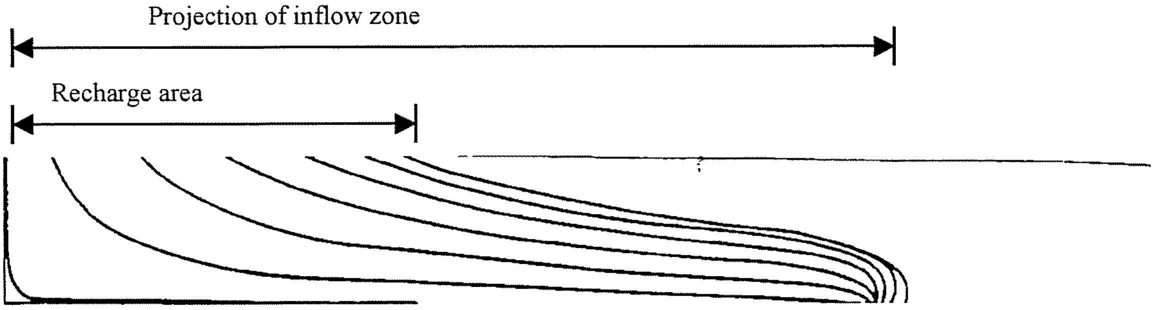


Figure 26 Pathlines in a vertical section through the well axis: case of the well screen at the aquifer bottom.

For a partially penetrating well, a characteristic number *k* is proposed by Kinzelbach:

$$k = \frac{Q}{NLM} \qquad (1)$$

where Q is pumping rate
N is recharge
L is distance between pumping well and the impervious upstream boundary
M is aquifer thickness

When value of *k* is equal or larger than 5, the difference between 2D and 3D vanish. Please note that the aquifer thickness M here is referred to isotropic aquifer thickness. For the anisotropic aquifer, the equivalent isotropic aquifer is constructed by coefficient of the ratio Z_r, where

$$Z_r = \sqrt{\frac{K_{xx}}{K_{ZZ}}} \qquad (2)$$

If hydraulic conductivity in the vertical direction is smaller than in the horizontal direction, the equivalent isotropic aquifer has a correspondingly larger thickness (fold of Z_r).

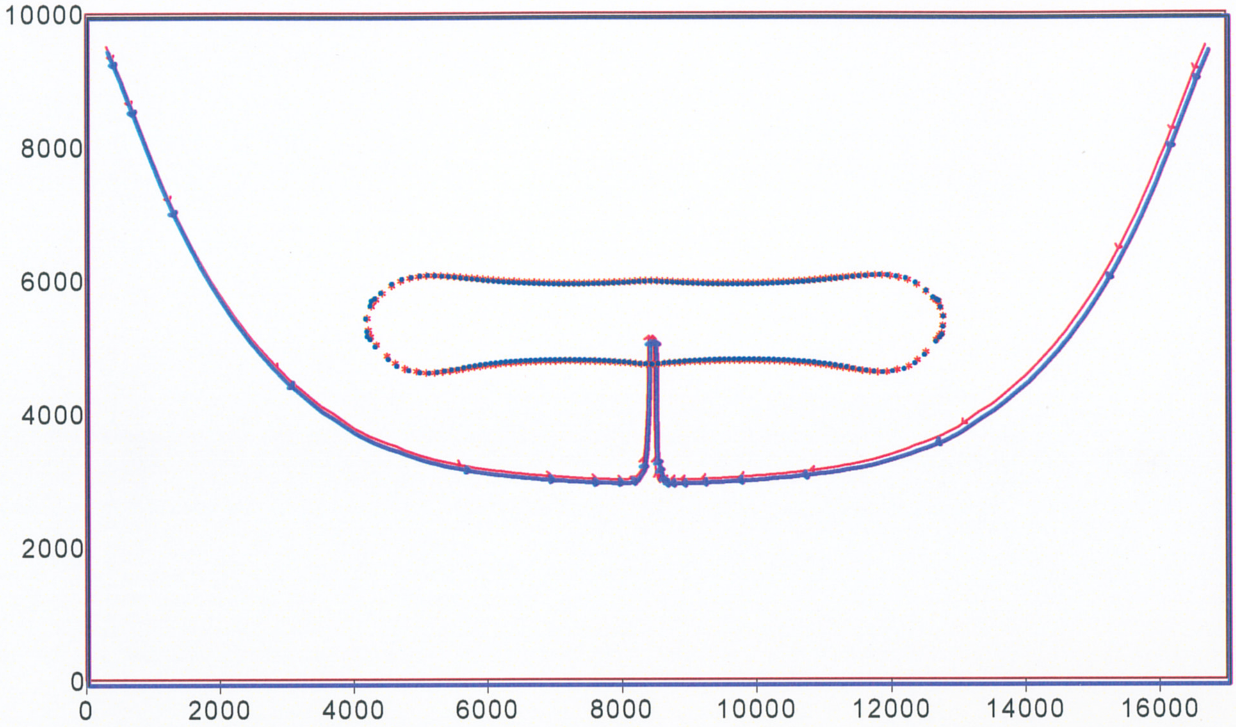


Figure 27 Comparison of 50-day time-of-travel zones and projection of inflow zone from 2D and 3D with conditions of Figure 2

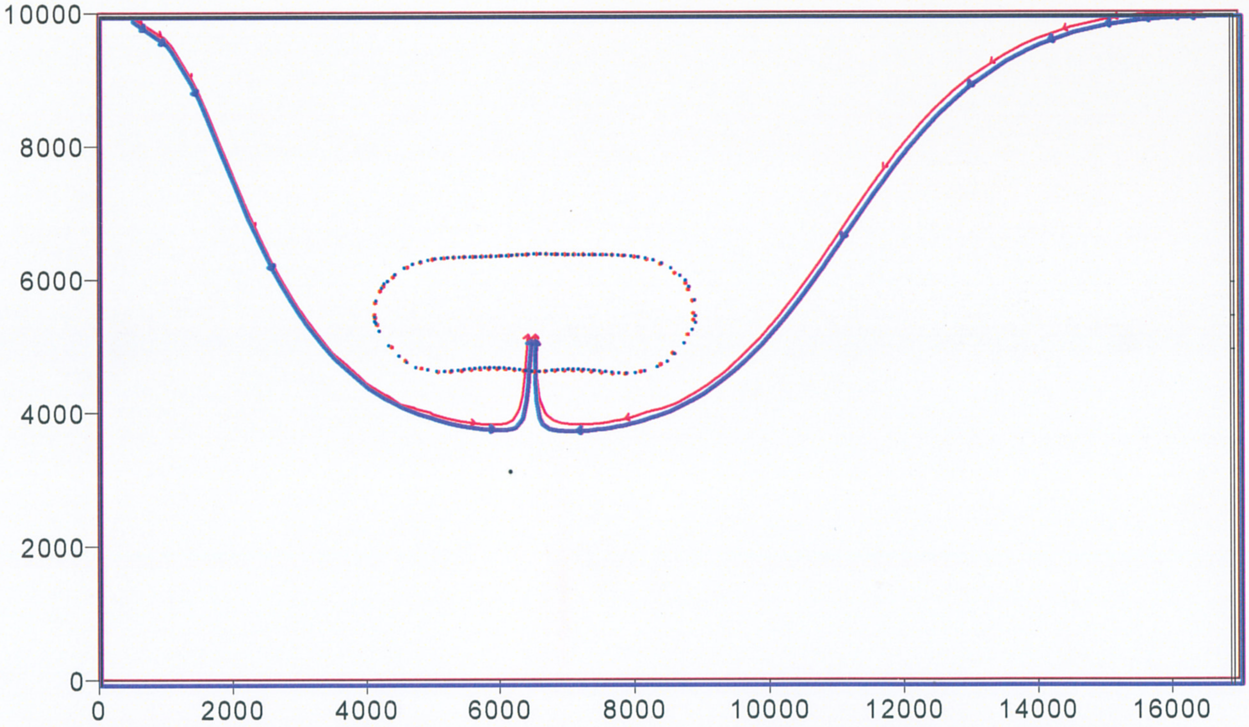


Figure 28 Comparison of 50-day time-of-travel zones and projection of inflow zone from 2D and 3D with conditions of Figure 5

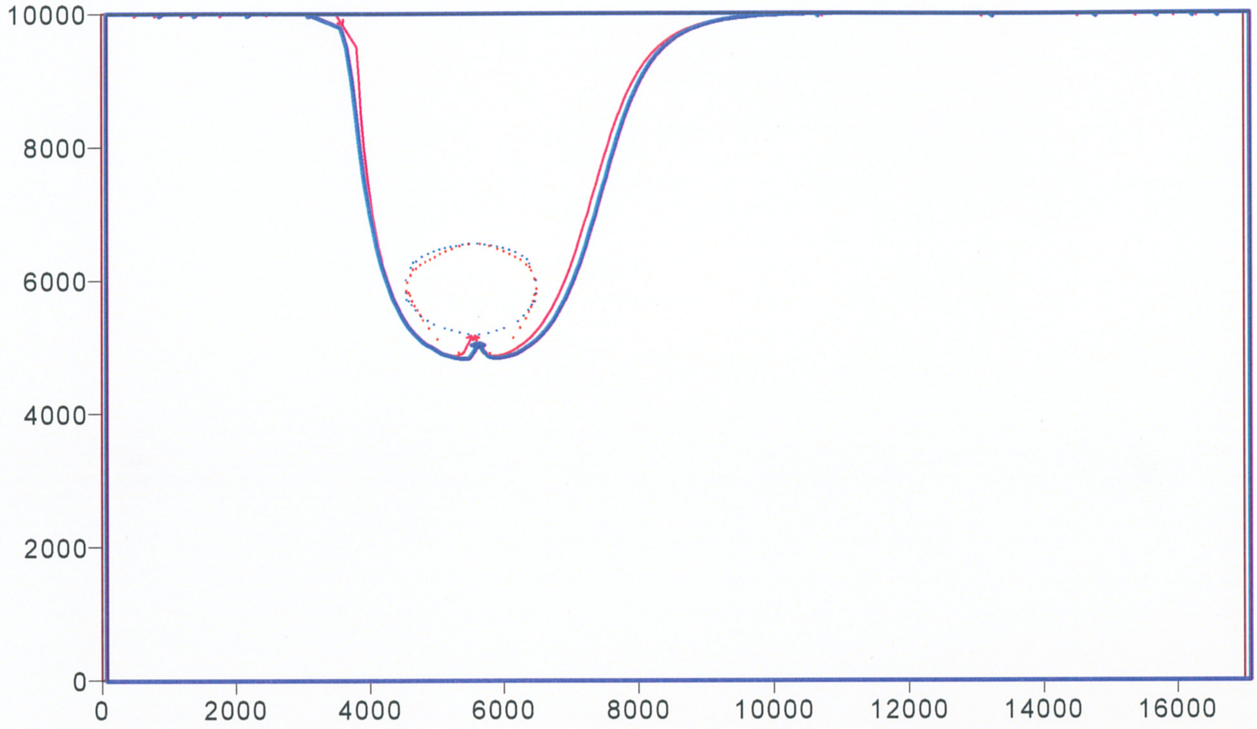


Figure 29 Comparison of 50-day time-of-travel zones and projection of inflow zone from 2D and 3D with conditions of Figure 9

All aquifer conditions, adit lengths and pumping rates used in previous sections were tested with respect to 2D&3D. High K method was used. Almost identical projection of inflow zone and 50-day time-of-travel zones were obtained from 2D and 3D models. Figure 27, 28 and 29 show some of tests. One can see that the differences between 2D and 3D are little. This can be explained by the characteristic number *k* derived from Equation (1). Following values have been used:

Recharge N, 200 mm/year;

Distance from adit to the impervious upstream boundary L, 5000 m;

Equivalent aquifer thickness M, 300 m (30 m real aquifer thickness with a coefficient of 10, 1% of horizontal conductivity was used for the vertical conductivity):

Pumping rate, Q, 10,000 m^3/d, which is minimum of pumping rate for most of adits in the UK. Therefore we have

$$k = \frac{Q}{NLM} = \frac{10000}{0.000548 \times 5000 \times 300} = 12$$

which is greater than 5, so the difference between 2D and 3D solutions vanish. Some of projection of the inflow zone is the same as their real catchment, while others are different. Figure 30, 31 and 32 show the cross-sections of Figure 27, 28 and 29. One can easily see that the projections of inflow zones are the same as their corresponding

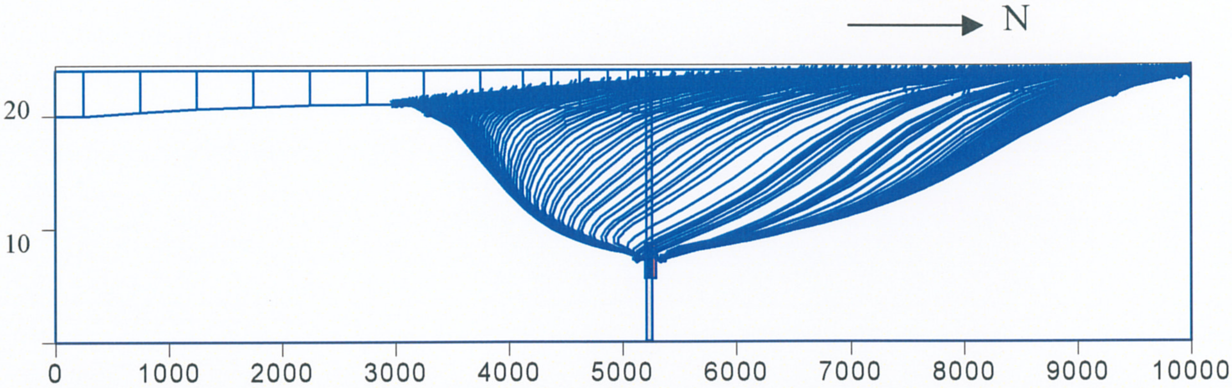


Figure 30 Cross-section corresponding to Figure 27 showing that the projection of inflow zone is identical to the recharge area.

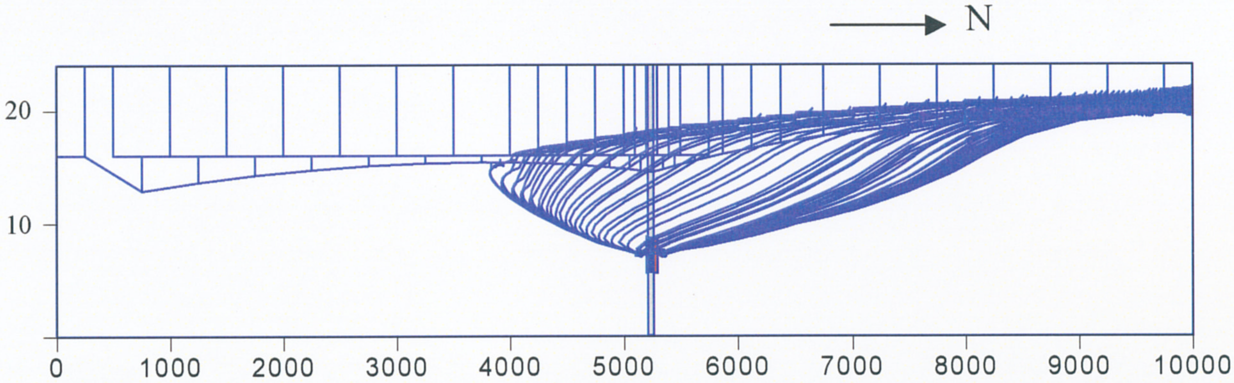


Figure 31 Cross-section corresponding to Figure 28 showing that the projection of inflow zone is identical to the recharge area.

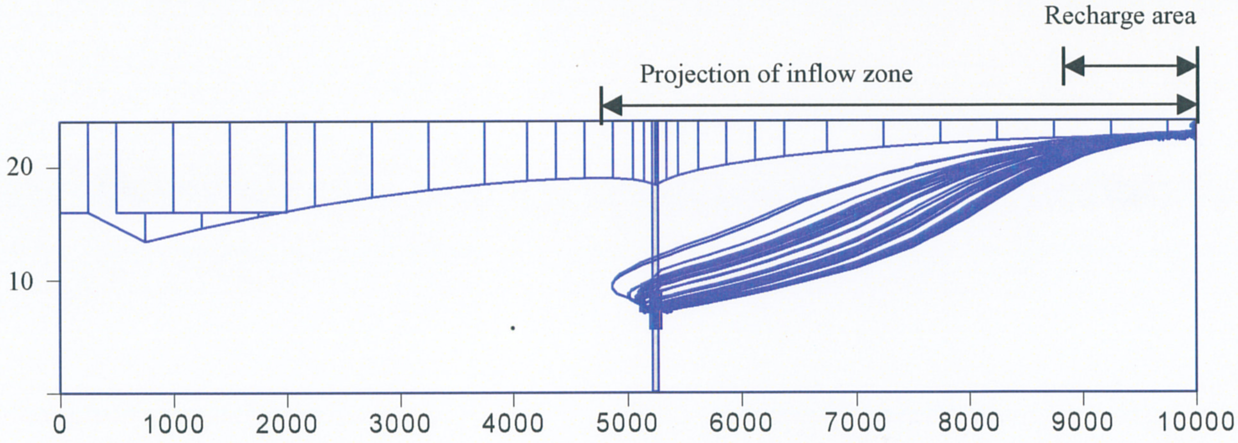


Figure 32 Cross-section corresponding to Figure 29 showing that the projection of inflow zone is greater than the recharge area.

catchment for Figure 30 and 31, while the projection of inflow zone of Figure 32 is greater than its catchment.

However, confining the protection zone to the actual catchment area which furnishes the recharge abstracted by the well is not sufficient for well protection. The region between well and catchment area should be protected as the penetration of pollutants into the subsurface flow to the well is possible if an immiscible pollutant with density greater than 1 is discharged into the underground. Therefore, the protection zone should comprise the complete projection of inflow zone of the well on to the ground surface (Kinzelbach et al 1992).

It should be mentioned that the characteristic number is applied to catchment area or recharge area for a single well in Kinzelbach's paper. However, we found that it is also valid for the projection of inflow zone of the adit sources.

When the adit is parallel to the impervious upstream boundary, there are some drawbacks for the backward tracking, one is that the derived minimum projection of inflow zone is

$$A = L \times l \qquad (3)$$

where A is area of projection of inflow zone,
L is distance between adit and upstream boundary,
l is adit length.

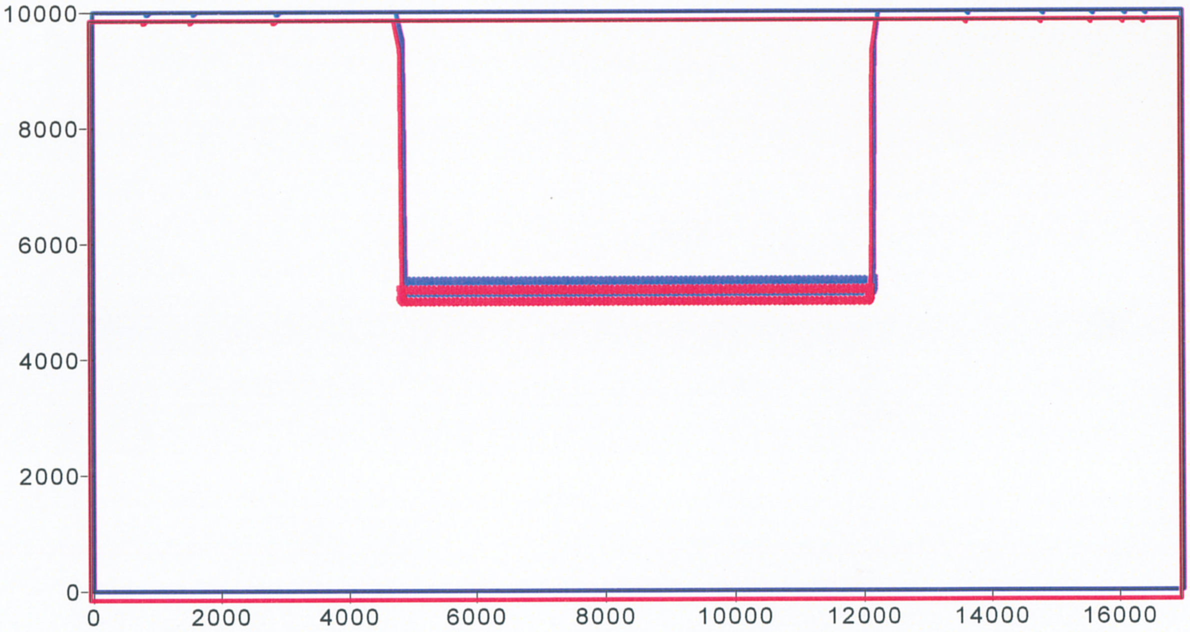


Figure 33 Comparison of projection of inflow zones with pumping rates of 1000 m^3/d and 2000 m^3/d for a 7 km adit

The catchment water balance Equation

$$A = \frac{Q}{N} \qquad (4)$$

is not valid any more when Q is less than L × l × N

Figure 33 shows comparison of projection of inflow zones with pumping rates of 1000 m^3/d and 2000 m^3/d for a 7 km adit. One can see that two projection of inflow zones are exactly the same regardless the pumping rates.

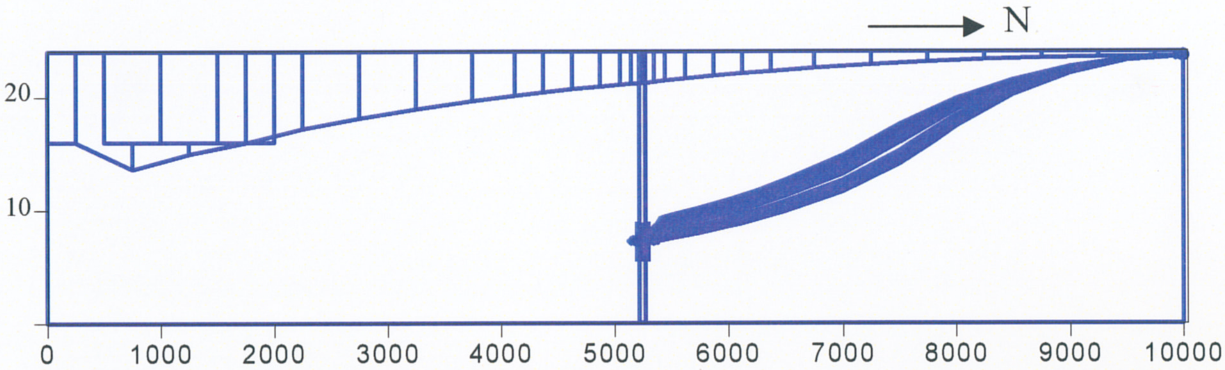


Figure 34 Cross-section of backward tracking showing the catchment reaches the impervious upstream boundary

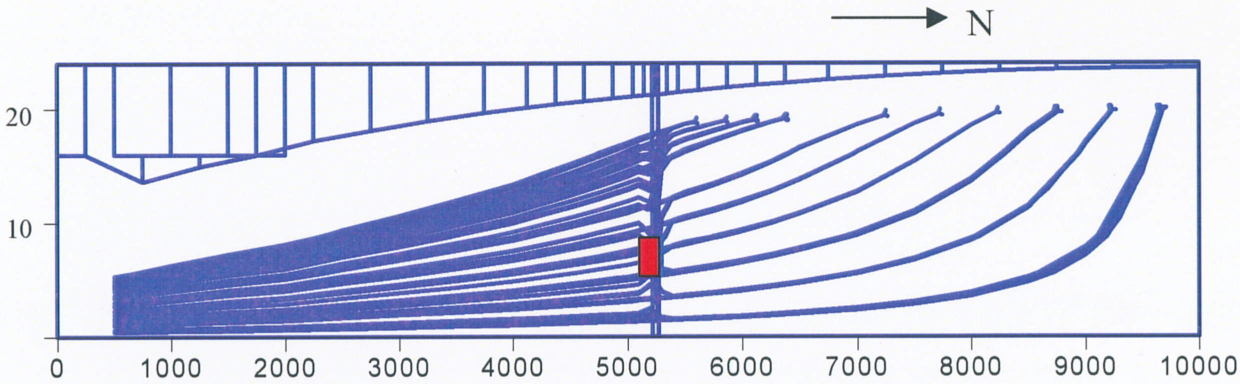


Figure 35 Cross-section of forward tracking showing that the particles from the impervious upstream boundary pass underneath the adit, so the catchment does not reach the impervious upstream boundary.

Another drawback of backward tracking for adit sources is that the catchment can always reach the upstream impervious boundary of 3D model even if the pumping rate is very small. In contrast, for the forward tracking, the catchment of small pumping rate do not reach the upstream boundary. Figure 34 and Figure 35 show the comparison of catchment using backward tracking and forward tracking.

2.9. Conclusions

1. For a long adit (3 km and above), MODBRNCH and high K derive similar 50-day time-of-travel zones and projection of inflow zone for both big or small abstractions. While multiple-borehole method can generates similar projection of inflow zone as other methods for big abstraction, but its 50-day time-of-travel zone is separated by individual boreholes. its projection of inflow zone for small abstraction is also divided by the individual boreholes.
2. For a short adit (1 km and below), all three methods derive not only similar projection of inflow zone, but also similar 50-day time-of-travel zones for a big abstraction. This indicates that the method of multi-boreholes can define similar 50-day time-of-travel zone as other methods for a short adit with its bigger abstraction. For a small abstraction, the 50-day time-of-travel zone of multiple-borehole is divided by the individual boreholes.
3. Values of high K along adit for high K method were adjusted to get similar groundwater head distributions and protection zones as those generated from MODBRNCH. It is found that the suitable values of high K depend on the adit length. The suitable ranges of high K values are 10^3-10^4 m/d, 10^4-10^5 m/d and 10^5-10^6 m/d for 1 km, 3 km and 7 km respectively.
4. The grid spacing has little effect on the model outputs for MODBRNCH, but has some influences on groundwater levels for both high K and multiple-borehole methods. Nevertheless, the effects of grid spacing for using high K and multiple-borehole methods are not significant.
5. 2D model is sufficient for most adit sources in the UK with abstractions of 10 000 m^3/d and over from the point view of delineation protection zones.

3. MODELLING STEPPED ADIT

For a stepped adit, additional energy loss due to step needs to be considered. The step could be considered as gated culverts, which is generally rated by the equation (French, 1985):

$$\nabla h = C_C \frac{v^2}{2g} \qquad (1)$$

Where, h_1 is the upstream head
h_2 is the downstream head
C_c is the resistance coefficient for the gate of the culvert and depends on the type of valve and percentage of closure
v is the flow velocity
g is the gravitational acceleration

The step can also be formulated as two elbows of pipe flow. In addition to the spatially continuous head loss due to friction, local head loss at each elbow is (Featherstone & Nalluri, 1982):

$$\Delta h = K_c \frac{v^2}{2g} \qquad (2)$$

where K_c depends on the angle and size of the elbow and pipe, for a 90° elbow, $K_c=1$

Comparing equation (1) and (2), one can see that basically they are the same. This was incorporated into MODBRNCH.

3.1. An artificial case study

An artificial stepped adit case was studied. The aquifer condition is set the same as Figure 1.

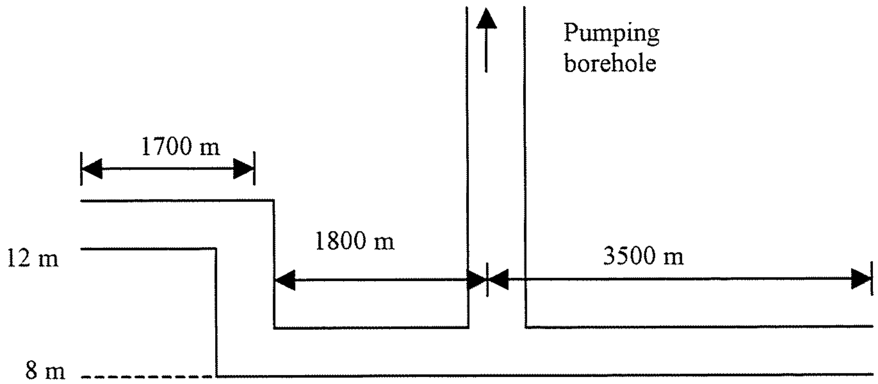


Figure 36 Cross-section of stepped adit structure

The cross-section of the stepped adit is shown in Figure 36. The geometry of the step was specified in the data input file of cross-section adit.

The comparison of stepped adit and non-stepped adit simulations are shown in Figure 37, 38 and 39.

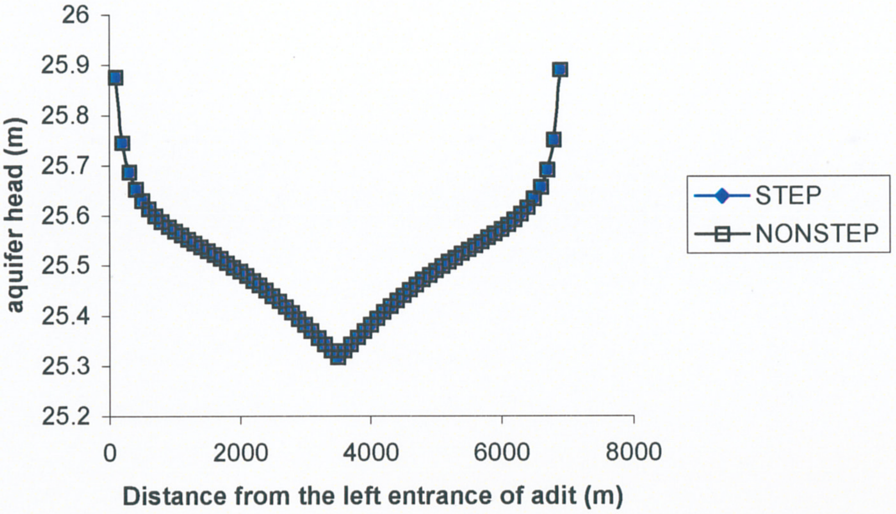


Figure 37 Comparison of simulated aquifer heads along adit for stepped adit and non-stepped adit.

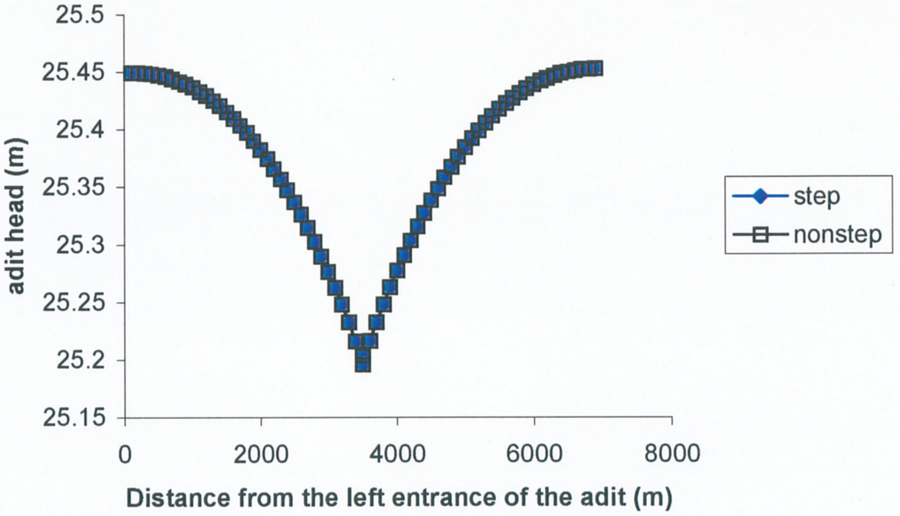


Figure 38 Comparison of simulated adit heads for stepped adit and non-stepped adit.

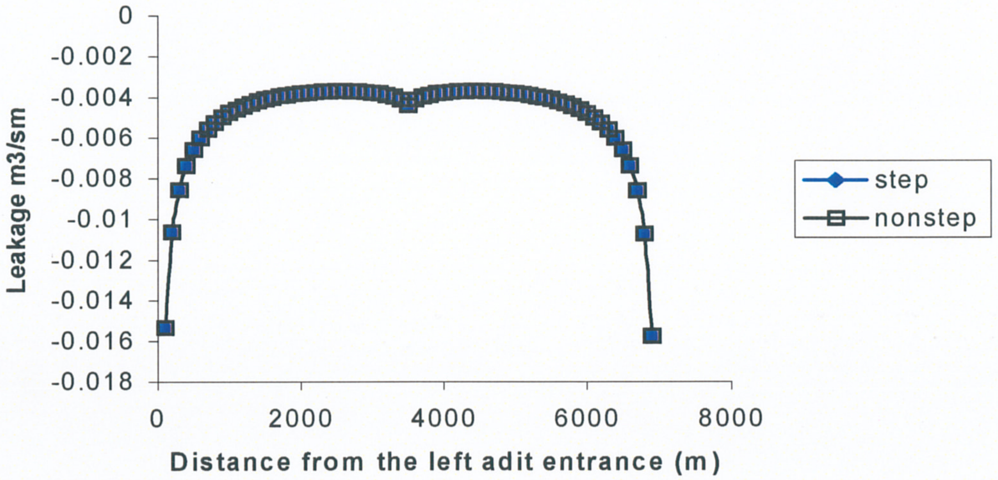


Figure 39 Comparison of simulated leakage along adit for stepped adit and non-stepped adits.

The comparison of simulated aquifer heads, adit heads and leakage indicates that step does not affect the simulation results at all. This can be explained by the Equation (2). Take K_c as 1 for a 90° elbow, pumping rate Q as 50,000 $m^3/d = 0.5787\ m^3/s$,

Velocity $v = \frac{Q}{A} = \frac{0.5787}{1.2 \times 1.8} = 0.2679 m/s$

Therefore, head loss due to step

$$\Delta h = 2 \times K_c \frac{v^2}{2g} = 2 \times \frac{0.2679^2}{2 \times 10} = 0.007178 m \qquad (3)$$

From Equation (3), one can see that the head loss due to step for the stepped adit is small, therefore the influence of step on groundwater simulation is negligible.

3.2. Bricketwood case study

Bricketwood pumping station is one of the groundwater sources of GU Project, which has a stepped adit. The adits located higher and lower levels are at 23 maod and 10 maod respectively. The pumping rate of Bricketwood pumping station varies from 15 000 m^3/d to 27 000 m^3/d. Figure 40 shows the layout of Bricketwood adit, Access shaft and Main shaft are connected to the adit at 23 maod and 10 maod separately. Figure 41 shows the comparison of adit heads measured at adits of 23 maod and 10 maod, respectively. From Figure 41, one can hardly see any difference between two measurements, this confirms that step does not affect the adit head.

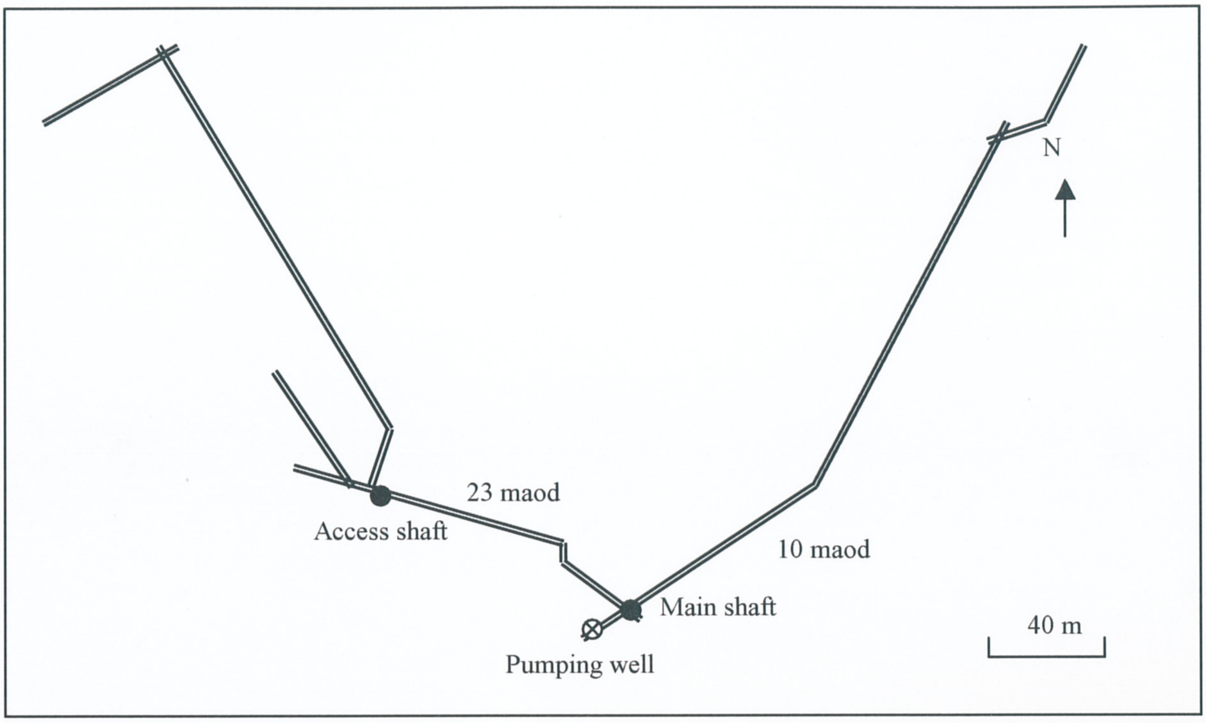


Figure 40 Bricketwood adit layout

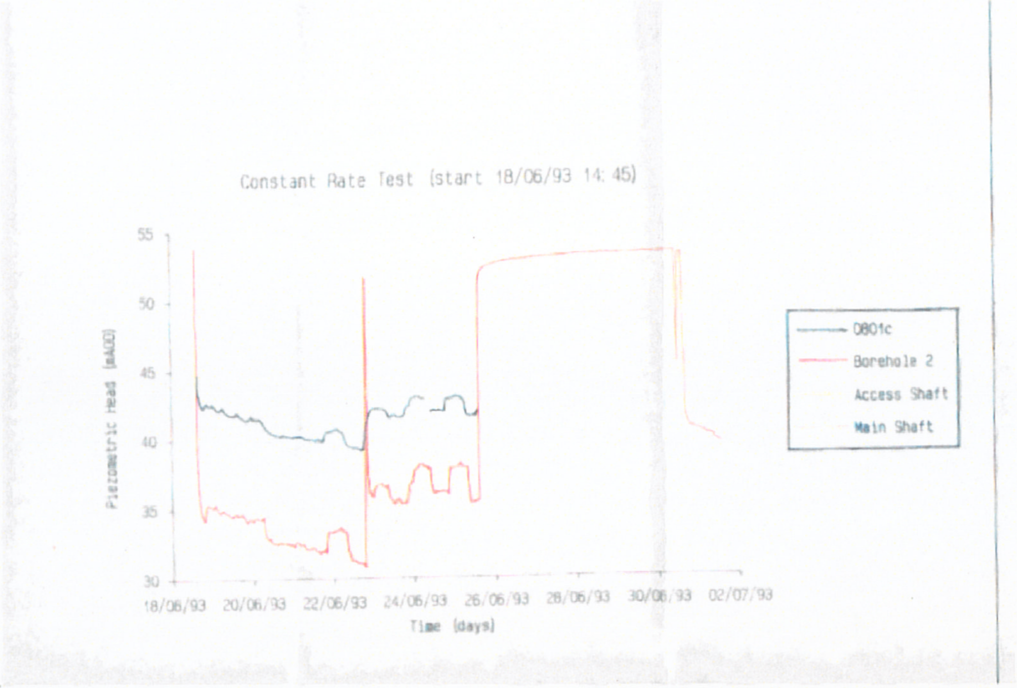


Figure 41 Comparison of adit heads measured from access shaft and main shaft during a 20-day constant pumping test in 1993

APPENDIX 1

Initial Project Proposal and Extension Proposal

Operation and protection of adit systems in UK aquifers

Outline research proposal (4 June 1996)

Professor David Lerner, Groundwater Protection and Restoration Research Unit,
University of Bradford

Background

A number of major groundwater sources have adits, horizontal tunnels up to 6km long, often with a number of vertical boreholes and shafts penetrating them. The hydraulics of these systems are not understood well enough to predict their behaviour and reliable yield, nor are there well defined techniques for field testing systems to estimate yield. Adits are often close to the water table and probably place the source at greater risk of pollution. Adits will cause a distinct three dimensional pattern of groundwater flow and influence the shape and position of source protection zones - these effects cannot be quantified at present. In summary, there is a need for research to understand the hydraulics of these important systems and provide tools for analysis and prediction of their behaviour.

Objectives and deliverables

1. Provide a suitable computer code for modelling flow to adit systems,
2. Prepare guidelines for determining the yield of adit systems,
3. Demonstrate the effects of adits on source protection zones and develop guidelines for revising protection zones.

Work plan

Work will start with a review of previous studies, both in the published literature and by the sponsors. Readily available computer models will be assessed to chose the most suitable for modification, and which will handle groundwater flow and particle tracking. MODFLOW and MODPATH may be most suitable in view of their widespread acceptance and the availability of good user interfaces such as Visual MODFLOW.

Calibrated models will be developed for two field sites of differing characteristics. Both will be in the Chalk, one confined and one unconfined. This will test the codes, as well as providing detailed understanding of the two sites. The models, and a series of generalised models not specific to sites, will be used to explore how field tests of adits need to be designed to estimate their reliable yield.

Field data will be required for the two sites, including multi-level piezometry and pumping tests. Several instrumented sites have been identified, and a yield test will be conducted on a confined system by Yorkshire Water. If feasible, multiport sock samplers will be used to provide multi-level piezometry during the test. Available data for unconfined sites (one Lee Valley, one Thames Water) will be reviewed and a programme of further field measurements designed and executed. Pollution risk and source protection issues will be explored through the generalised and calibrated site models.

The work programme is shown in Figure 1. An October 1996 start is planned.

Costing

The project will be carried out by a full time research assistant. The cost are detailed below, and include provision for field installations and measurements.

Item	Year 1	Year 2	Total (£)
RA, salary, NI, superannuation	22000	23000	45000
Computer, printer, software	4000	-	4000
Travel and subsistence:			
2 x progress meetings/year)			
)			
6 x discussions or visits/year)	1500	1500	3000
)			
2 x scientific meetings/year)			
Consumables	4500	4500	4500
Academic supervisors, 1 day/month	4000	4000	8000
Field investigations:			
monitoring equipment (2 sites)	20000		
conduct yield tests (site 1)	5000		30000
conduct piezometric/quality monitoring (site 2)		5000	
Overheads (40% of RA costs)	8800	9200	18000
	69800	47200	117000

Figure 1. Work plan for adits study

Activity	Year 1	Year 2
1. Mobilisation and review	0 2	
2. Code development	2 6	20 22
3. Modelling site 1	6 11	
4. Modelling site 2	11 15	
5. Yield estimation study		15 17
6. Source protection zone study		17 20
7. Reporting		
working paper	6 11	17
final		22 24
8. Review meetings	2 6 11	17 24

MODELLING OF GROUNDWATER FLOW TO MULTI-LEVEL ADITS

A proposal for an extension to the research project

OPERATION AND PROTECTION OF ADIT SYSTEMS IN UK AQUIFERS

Rationale

The objectives of the existing project are

1. Providing a suitable computer code for modelling groundwater to adit systems.
2. Preparing guidelines for determining the yield of adit systems.
3. Demonstrating the effects of adit on source protection zones and developing guidelines for revising protection zones.

The research is proceeding as the proposal and the inception report. A computer code (modified MODBRNCH) has been provided, and first site — Wilmington — has been studied. The code has been tested, and Wilmington adit has been understood better in some respects. The second case study is currently being carried out. The project objectives appear to be achievable.

However some adits are at several levels, connected by shafts (Figure 1). This arrangement cannot be handled by MODBRNCH. As it is a common situation, further development and testing of the model are proposed:

Approach

There are three flow conditions that can occur in an adit: 1) full pipe flow, 2) part full subcritical flow, and 3) part full supercritical flow. Supercritical flow is probably uncommon and can not be handled by finite difference models such as MODBRNCH and will not be considered.

For the full pipe case, two approaches will be tried. Firstly, the step will be replaced by a steep slope. Secondly, the step will be replaced by a term representing the energy loss term due to changes of adit elevation. These options will be compared for numerical stability and accuracy.

For the subcritical part full case, water flows from a higher level to a lower level, the velocity and water stage will not be continuous. The velocity must increase to compensate it's potential energy loss. A new boundary condition of WATERFALL will be added to the model

$$V_2 - V_1 = \frac{h}{c}\left(\frac{Z_1 + Z_2}{2Z_2}\right)g$$

where

$$c = \sqrt{\frac{gZ_1}{2Z_2}(Z_1 + Z_2)}$$

$$h = Z_1 - Z_2$$

the variables are illustrated in Figure 1.

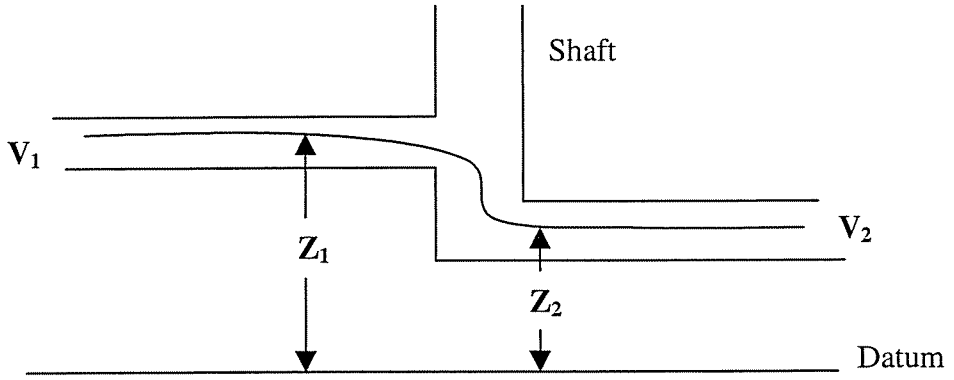


Figure 1 Illustration of WATERFALL boundary condition and variables.

It is likely that adjustments to the solution technique will be needed to ensure stable solutions.

The new code will be tested on a new case study. This will be chosen in conjunction with the Steering Group and may be a site from GU Projects.

Working plan and schedule

1. Half month. Literature searching to find out other possible approaches
2. Two months. Formulation of coefficient matrix and programming.
3. Half month. The approach and program test with hypothetical cases.
4. Three months. A case study for an application of modelling of adit with steps and reporting.

Costs

Research Assistant Beiyan Zhang, 6 months	13 000
Supervision and management, Prof. D.N.Lerner	2 000
Travel for data collection, meetings	1 000
Consumables	2 000
Overheads (50% of staff costs)	7 500
Total	25 500

Note: This costing assumes no significant field work will need to be carried out.

APPENDIX 2

List of adits in the UK

Adits in Southern Region

This is a provisional list and as such may not be complete.

Source Name	Licence No.	Aquifer	Location	Approx. Adit Length
Isle of Wight				
Chillerton	12/101/3/G/39	Up Greensand	SZ 490 844	c. 120 m
Knighton	12/101/1/G/76	Chalk & L. GreenSand	SZ 567 871	c. 365 m
Calbourne	12/101/4/G/8	Chalk	SZ 425 859	c. 200 m
Carisbrooke	12/101/3/G/41	Chalk	SZ 488 882	c 3000 m (odd)
Eastbourne Chalk				
Friston & Deep Dean	10/41/151301	Chalk	TV 5445 9860	c 4000 m
Thanet Chalk				
Lord of the Manor & Whitehall	4/0049//GR	Chalk	TR 3535 6510	c 7000 m
Rumfields	4/0049//GR	Chalk	TR 3774 6775	c 1500 m
Sparrow Castle	4/0049//GR	Chalk	TR 3185 6752	c 1050 m
Linksfield	4/0049//GR	Chalk	TR 3193 6933	c 1500 m
Dane	4/0049//GR	Chalk	TR 3655 7017	c 1500 m
Brighton Chalk				
Falmer	10/41/260103	Chalk	TQ 205 102	c 3250 m
Balsdean	10/41/260103	Chalk	TQ 378 046	c 900 m
Patcham	10/41/260103	Chalk	TQ 295 094	c 4000 m
Goldstone	10/41/260103	Chalk	TQ 285 066	c 900 m
Lewes Road	10/41/260103	Chalk	TQ 320 060	c 800 m
Ardrington	10/41/260103	Chalk	TQ 266 059	c 300 m
Mile Oak	10/41/260103	Chalk	TQ 243 079	c 3250 m
Whitelands	10/41/312504	Chalk	TQ 314 138	c 150 m
Clayton	10/41/312504	Chalk	TQ 304 137	c 100 m
Coombe Down	10/41/312504	Chalk	TQ 317 134	c 100 m
Steyning	10/41/311008	Chalk	TQ 205 102	c 200 m
East Kent				
Skeete	4/0060/GR	Chalk	TR 1433 4091	c 200 m
Ottinge	4/0060/GR	Chalk	TR 1723 4251	c 200 m
Terlingham	4/0062/GR	Chalk	TR 2122 3859	c 500 m
Connaught	4/0248/GR	Chalk	TR 3217 4212	c 800 m
Lower Standen	4/0065/GR	Chalk	TR 2410 4043	c 700 m
Drellingore	4/0065/GR	Chalk	TR 2433 4121	c 310 m
Ford	4/0281/GR	Chalk	TR 2039 6547	c 725 m
Wingham	4/0058/GR	Chalk	TR 2432 5532	c 2800 m
Martin's Mill, Deal	4/0272/GR	Chalk	TR 3369 4719	c 375 m
St. Richards	4/0279/GR	Chalk	TR 3641 5086	c 550 m
North Kent & Darent				
Henwood	4/0270//GR	L. Greensand	TR 0194 4281	c 400 m
Empire	1/0088/B/GR	Chalk	TQ 6120 7294	c 500 m
Northfleet	1/0092/B/GR	Chalk	TQ 624 737	c 80 m
Hartley	1/0148/A/GR	Chalk	TQ 616 664	c 775 m
Cuxton	1/0511//G	Chalk	TQ 6899 6692	c 400 m
Higham	1/0511//G	Chalk	TQ 7140 9219	c 80 m
Northfleet	1/0511//G	Chalk & L Greensand	TQ 636 691	c 375 m
Three Crutches	1/0511//G	Chalk	TQ 707 703	c 320 m
Strood	1/0511//GR	Chalk	TQ 730 692	c 100 m

Windmill Hill	1/0511//GR	Chalk	TQ 650 732	c 340 m
Halling	1/0121//GR	Chalk	TQ 698 643	c 110 m
Capstone	2/0236//G	Chalk & L Greensand	TQ 780 655	c 75 m
Luton	2/0216//G	Chalk	TQ 776 662	c 1625 m
Nashenden	2/0236//G	Chalk	TQ 733 656	c 100 m
Rainham	2/0236//G	Chalk & L Greensand	TQ 8043 6625	c 10 m
Snodhurst	9/40/2/157/GR	Chalk	TQ 755 651	c 760 m
Keycol	2/0237//G	Chalk	TQ 874 645	c 25 m
Southfleet	1/0511//GR	Chalk	TQ 6099 7238	c 21 m
Wilmington	1/0118//GR	Chalk	TQ 5430 7280	c 180 m
Darenth	1/0133/GR	Chalk	TQ 554 719	c 220 m
Orpington	1/0127//GR	Chalk	TQ 459 652	c 100 m
Boxley	3/0383//GR	Chalk	TQ7740 5938	c 950 m
Copton	2/0252//G	Chalk	TR 0127 5954	c 70 m
Highsted	2/0237//G	Chalk	TQ 910 607	c 75 m
Bexley	1/0130//GR	Chalk	TQ 486 727	c 250 m
Sheerness				
Trinity Road	9/40/2/157//GR	London Tertiary Beds & Chalk	TQ 922 746	c 70 m
Worthing Chalk				
Broadwater	10/41/310210	Chalk	TQ 143 054	c 350 m
Patching	10/41/310210	Chalk	TQ 0918 0743	c 900 m
Upper Test				
Faberstown	11/4218.6.2/277	Chalk	SU 2786 5036	c 16 m
Lower Test				
Timsbury	11/42/18.12/384	Chalk	SU 3454 2552	c 1000 m

Region	Source Name	Aquifer	Approximate length (m)
North East	**Cottingham**	**Chalk**	**1500**
North East	**Dunswell**	**Chalk**	**950**
North East	**Springhead**	**Chalk**	
North East	**Langthwaite**	**Carboniferous Limestone (CL)**	
North East	**Condenser Wood**	**CL**	
North East	**Eagle level**	**CL**	
North East	**Lanshaw level**	**CL**	
Welsh	**Big Well**	**CL**	**256**
Welsh	**Rogerstone Grange**	**Sandstone**	
South West	**Grenville Area**	**Granite**	**6000**
Anglian	**Melbourne**	**Chalk**	**196**
Anglian	**Lyng Forge**	**Chalk**	
Anglian	**Bedford**	**Limestone**	**547**
Anglian	**Southfield**	**Chalk**	
Anglian	**Fleam Dyke**		**86**
Anglian	**Bowring Fuller**	**Chalk**	**165**

Adits in Thames Region

LEAD SOURCE NAME	Adit ref	Type	Aquifer
Beenham's Heath	TH/BH/BH	B, A	CHALK
Bricket Wood	TH/BW/BW	A	CHALK
Bricket Wood	TH/BW/BW	A	CHALK
Bricket Wood	TH/BW/TT	A	CHALK
Bricket Wood	TH/BW/TT	A	CHALK
Bricket Wood	TH/BW/SX	A	CHALK
Bricket Wood	TH/BW/FW	H	CHALK
Bricket Wood	TH/BW/NG	A	
Bricket Wood	TH/BW/LG	A	
Bricket Wood	TH/BW/BW	A	CHALK
Bricket Wood	TH/BW/BH	A	CHALK
Bricket Wood	TH/BW/BW	A	CHALK
Gerrard's Cross	TH/BW/BW	A	CHALK
Greywell	TH/GW/CL	A	
Greywell	TH/GW/GW	A	
Greywell	TH/GW/IT	A	
Greywell	TH/GW/LPS	A (filled?)	CHALK
Greywell	TH/GW/WH	A (filled?)	
Kennet Valley	TH/KV/PB	A	
Kennet Valley	TH/KV/UP	A	CHALK & UGS
Kennet Valley	TH/KV/SS	A	CHALK & UGS
Kennet Valley	TH/KV/OG	A	CHALK
Kennet Valley	TH/KV/OG	A	UGS
Latton	TH/KV/OG	B, A	GT. OOL. SERIES
Lea Valley	TH/LV/TF	HT	
Lea Valley	TH/BW/SX	A	CHALK
Leatherhead	TH/LH/WH	A	
Leatherhead	TH/LH/CL	A	
LGS	TH/LGS/HH	A	
LGS	TH/LGS/TPS	A	
LGS	TH/LGS/ST	A	LGS
North Downs	TH/ND/ES	A	CHALK
South West Chilterns	TH/SWC/CA	A	
South West Chilterns	TH/SWC/CH	A	CHALK
West Hagbourne	TH/WHBPS	B, A	UGS

Adits in Northwestern Region

Region	Project	Source Name	Aquifer
NW	GPZ III	Bickerstaffe	Sst.
NW	GPZ III	Butterworth Hall	Sst/Coalmine
NW	GPZ III	Dark Lane	Sst.
NW	GPZ III	Forest Farm	Sst.
NW	GPZ IV	Gambleside	Sst/Coalmine
NW	GPZ III	Grange	Sst.
NW	GPZ III	Green Lane	Sst.
NW	GPZ III	Houghton Green	Sst.
NW	GPZ III	Knowsley	Sst.
NW	GPZ II	Lymm	Sst.
NW	GPZ IV	Millrigg	Metaseds.
NW	GPZ II	Mouldsworth	P/T Sst.
NW	GPZ III	Netherley	P/T Sst.
NW	GPZ III	Prenton	P/T Sst.
NW	GPZ IV	Roughton Gill	Metaseds/Ign
NW	GPZ III	Springfield	P/T Sst.
NW	GPZ III	Springhill	P/T Sst.
NW	GPZ III	Whiston	P/T Sst.
	GPZ III	Winwick	P/T Sst.

APPENDIX 3

List of Project Board

Details of the Agency Project Manager and Project Board

Sarah Evers, National Groundwater & Contaminated Land
John Aldrick, North East
Paul Shaw, Southern
Steve Fletcher, Midlands (part)
Trevor Muten, Anglian (part)
Shelagh Hartley, South West (part)

Water companies Project Board:

Dave Smith / Gerd Cachant, Yorkshire Water Services Ltd;
Rob Sage / Phillip Bishop, Thames Water Utilities Ltd.
Nick Sinclair / Rob Sage, General Utilities Partnership;
Simon Eyre, Anglian Water Services Ltd;

APPENDIX 4

Meeting notes

Operation and Protection of UK Adit Systems

Minutes of Meeting at University of Sheffield on 13 January 1998

Present: Rob Sarge (TWU), Simon Eyre (AWS), David Lerner (UoS), Beiyan Zhang (UoS), Paul Shaw (EA), Steve Fletcher (EA), Sarah Evers (EA)

1. Apologies

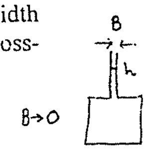
Nick Sinclair (GUP), Yiping Chen (UoS)

2. Development of Adit Model

Employing USGS river package BRANCH and interface package MODBRNCH, modified to work underground, for 2 cases:

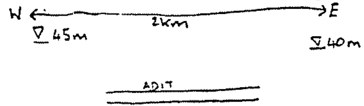
(i) Open Channel - adits partially full
Code modified by BZ to make it run at a deeper level.
It is not yet clear how frequently this case occurs.

(ii) Conduit Flow - adits full
The conduit flow is simulated as an extreme case of open channel flow by making the width of the channel opening infinitessimally small. This is open channel flow with constant cross-sectional area and pressure is given by head in the slot.

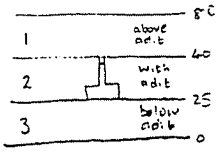


This 'vanishingly small slot' concept is at the testing stage, need to ensure that there is no interaction at slot, ie all interactions are resticted to the aquifer.

An example was shown:



represented by 3layer model:

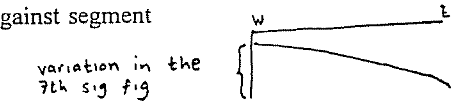


Adit flow stage vs width of slot plotted for 1mm to 10mm slot aperture.

Need to test for decreasing slot size. Hopefully the curve is asymptotic as slot width decreases, and further, it is hoped that the limiting aperture is not so small as to introduce numerical errors, due to rounding etc.

plot of inflow against segment

Adit flow stage against segment



The head varies in the 7th significant figure over length of adit: v. small gradient driving flow.

RS: Is the hydraulic conductance the same in adit and aquifer?
DNL: yes in the present example, but this can be different.

NS: Can multiple junction be simulated?
DNL: yes, because package originally devised to simulate tributaries (See 1st Progress Report)

PS commented that validation is very important. He suggested the reference Strack 'Analytical Models' which maybe useful and sets out analytical functions for networks and branches of drains and flow distribution along drains.
DNL: Maybe the project will not achieve perfect verification. May have to settle with 'this is believable' qualitative form of verification. Will refer to Strack.

RS suggested comparing the 2 piezometries and flow patterns in level 2 with and without adits in level 2. Look at the head in aquifer at abstraction point with and without adit to see if it feels right.
DNL: Could model the adit as single node or in a succession of nodes verical plane as a borehole.

3. Field data requirements and plans

Site1: Cottingham at Hull
The project has funded some multi level piezometers to complement the data collection occuring at this site.

Site 2: Wilmington.

TWU to provide BZ with report	**ACTION RS**
Sheffield will require GDC model by June, contact Ian Hogg at Kent	**ACTION PS**
Arrange meeting with GDC and Ian Hogg	**ACTION DNL**
Cost implication of data request? Advise SE this fy	**ACTION DNL**

4. Work plans for next period

- attempt validation
- friction coefficient in adit, how important is slot?
- test of calculating method for pumping
- steady and unsteady state, single & multi layer test
- sensitivity analysis

5. Next meeting

Thursday 18 June at 2:00pm at Sheffield University.

6. AOB

SE: GW Vistas has TMR up and running. Also it is likely that Agency will converge on this package. Also ESL have offered to support the Adits package.
DNL & BZ: TMR has bugs. **ACTION: SE will inform ESL**

6th July 1998

Adits R&D project

Beiyan Zhang Sheff U

David Lerner Sheff U

Gerd Cachandt YWS
Paul Shaw EA
Nick Sinclair GUP
John Aldrick EA
Rob Sage Thames
Trevor Muten EA

Apologies: Simon Eyre AWA
Sarah Evers EA

Update on modelling.
A Secon Progressreport outlining work completed was circulated prior to the meeting.
The main items were:

- Incorporating BRANCH into MODFLOW and the adit onto a layered model.
- Investigation of slot width - model code changed to adit perimeter and slot width becomes insignificant.
- Wilmington site modelled using a telescope area from Motts Regional Model - MODFLOW will have telescope facility. Groundwater countours look ok.

Wilmington results

* Some further calibration required - looking at piezo date from site and company with larger 1,2,3

- 50 day travel time shows small shift (but a short adit)
- No permeability contrasts between each layer

Longer adits - added to Wilmington model. 1250m. Same abstraction rate.

* A comparison of 50 day zone from adit model - with wells distributed along the line of the adit as done with some Flowpath models would be valuable.

Progress against plan
computer code appears ok &tested against Wilmington.

Model could not cope with adits at different levels at present or significant step between them (step virtually up to 6m)

* Sheff U. Will report back on wether multi-level adit system could be modelled. Model can cope with partially full adit.

The problem of weak sinks in MODPATH - where particles may pass through the adit was mentioned

Future work
Data required for further modelling was discussed with regard to **Cottingham**

- Geometry
- GW Modelling report

- Flow path model
- Multiple GW levels required & Pump test data constant rate & step test
- Monthly GW level 75-96

YWS want to do long pump test, but WL's too high at present - poss September
also doing CCTV survey of adit
- No monitoring data from peizometer at moment.

AWA have a site with some data
- Complex adit geometry [with steps]
- River system over adit
- Some piezo's data

Possible options:
1. Use Cottingham - data needed by October
2. AWA site
3. Further generic development

Some work needed on:
Parameter sensitivity
Leakage/aquifer/adit
Vertical conductivity

*YWS/EA Discuss Cottingham situation on 11/8 GC & RJA to discuss how to obtain data

Future Work
- Transient stimulation works ok
- Yield estimation
- Sensitivity analysis Kv:Kh and different Kh1, Kh2
- Adit influence on protection zones

*EA Photocopy of UKWIR methodology to DL

DL has submitted a paper to MODFLOW 98 - Colrado

Deliverables
- Report

- Modified version of MODBRANCH to those involved in the project (not avalibale to all and sundry)

- Publish approach, could possibly do studies for people, but DL would not want to run large contract.

Next meeting: Tuesday 1st December 13.00hrs Sheffield Uni

Operation and Protection of Adit Systems in UK Aquifers
— Summary of Steering Group meeting on 5th October 1999

Many people were missing from the Steering Group meeting on Tuesday, 5th October due to various reasons, therefore the meeting is summarized briefly below.

People who attended the meeting:

John Aldrick	(JA)	Environment Agency
Paul Shaw	(PS)	Environment Agency
Matilda Beatty	(MB)	Yorkshire Water
David N Lerner	(DNL)	University of Sheffield
Beiyan Zhang	(BZ)	University of Sheffield

Because every one in the meeting has been read though the Fifth progress report, a formal presentation of the work as usual was canceled. DNL briefly introduced the work that has been done since last meeting, and answered the questions and comments from PS, which were sent to BZ by email a day before. Then a general discussion was carried out.

Regarding the Cottingham model calibration, people think the amount of shaft water contribution is still an uncertainty, and the calibrated conductivity for adit layer is lower than what expected. Nevertheless people agreed that the simulated adit heads match the observed heads perfectly well, and are fairly happy with the model calibration.

For Source Protection Zones (SPZs) study, it is agreed that the hypotheses and related issues in Page 19, Fifth progress report should be tested. In addition, the following tests were suggested:

1. When do we need a 3D model?
2. What if adit is in a high K layer (at Cottingham, adit is in a low K layer)
3. Focus on 50 day SPZs.
4. What if adit systems are long relative to the diameter of SPZ.

For the stepped adit, it is agreed that the flow patterns (a), (b), (c) and (d) in Page 20 are to be studied, which are pipe flow in both sides of the step, and open channel flow in one side while pipe flow in the other side of the step.

Finally, the following remaining work was agreed:

1. Further study on Source Protection Zones.
2. Modelling stepped adit
3. Final reporting
4. Software manual and training programme

The next Steering Group meeting will be held on 25th January 2000. Beiyan Zhang will continue into next year until 30 June to finish software manual, training and final report.

A training program in using the software is proposed (1-2 day) to be held in April or May. The agency and water companies who intended to send people to the course please let us know by end of January. The software is quite complex, and we would only recommend the training if you have in-house modellers who are likely to carry out studies themselves.

APPENDIX 5

Progress Schedule

Progress Schedule

	Jul97	Aug97	Sep97	Oct97	Nov97	Dec97	Jan98	Feb98	Mar98	Apr98	May98	Jun98	Jul98	Aug98	Sep98	Oct98	Nov98	Dec98	Jan99	Feb99	Mar99	Apr99	May99	Jun99	JuL99	Aug99	Sep99	OcT99	Nov99	Dec99	Jan00	Feb00	Mar00	Apr00
Literature review	▨	▨																																
Code development			▨	▨	▨	▨																												
Wilmington case study							▨	▨	▨	▨	▨	▨																						
Sensitivity analyses													▨	▨	▨	▨	▨																	
Cottingham case study																		▨	▨	▨	▨	▨												
Cottingham model calibration																							▨	▨	▨	▨	▨							
Source GPZ study																											▨	▨	▨	▨	▨			
Modelling of stepped adit																													▨	▨	▨			
Working report		Y				Y						Y					Y					Y					Y				Y	▨	▨	▨ Y
Meeting			Y				Y					Y					Y					Y					Y				Y			

APPENDIX 6

Publications

Modeling of Ground Water Flow to Adits

by Beiyan Zhang[a] and David N. Lerner[a]

Abstract

Many of the large ground water sources in the Chalk Aquifer have adits, horizontal tunnels below the ground water table, which are connected to pumped wells. The flow in an adit may be pipe or open channel flow. Adits in the United Kingdom are normally full of water, so that the adit flow is pressurized. Darcy's formula is not applicable to the adit, and conventional ground water models are inappropriate to model the aquifer-adit system. The U.S. Geological Survey (USGS) model BRANCH simulates one-dimensional unsteady, nonuniform, multiple-branch interconnected open channel flow. MODBRNCH incorporates BRANCH into MODFLOW simulating open channel and aquifer interaction using deterministic responses of both systems. An aquifer-adit model can be created by two steps. First, an integrated surface-ground water model (MODBRNCH) enables open channel flow to be simulated. Second, introducing a fictitious narrow slot (Preissmann slot) above the adit allows pipe flow to be simulated by open channel flow equations. The slot does not affect the adit cross-section area, and the water level in the slot represents the pressurized adit head, which can be used by MODBRNCH to calculate the water exchange between aquifer and adit according to their head difference. The approach has been tested on the Wilmington public supply source in southeast England.

Introduction

The Chalk forms the most important aquifer of southern England and in many parts of northwest Europe (Downing et al. 1993). Many chalk ground water sources in England have adits, which are horizontal tunnels below the ground water table. The adits are connected to pumped wells from which ground water is pumped to surface. Most adits are 1.8 m high and 1.2 m wide with arched roofs, and vary in length from tens of meters to 7000 m. Their depth varies between 10 m to 100 m below ground surface. A wide variety of layouts have been constructed, from simple linear adits to patterns with radial lines, loops, and branches. Figure 1 shows the layout at Wilmington (the example studied in this paper), and Figure 2 shows one of the most complicated systems in southern England, at the Eastbury pumping station, Watford.

Adits were constructed to increase the yield of water supply wells by tunneling through permeable horizons or intercepting fissures (where most of the flow in the Chalk takes place). Adits can be expected to alter the hydraulics of the well and aquifer. There are no analytical methods, such as pumping test analysis, of estimating yields. In addition, the source protection zones (or wellhead protection areas) can be expected to have different shapes than those for a simple well of equivalent capacity.

Velocity measurements indicate that Reynolds numbers for flow in adits are typically > 2300. These values are typical of turbulent flow. However, flow in the adits can be formulated as pipe flow or open channel flow for the purposes of modeling if they are partially dewatered. Flow in the aquifer remains laminar, and Darcy's law applies. A model with adit flow linked to ground water flow is required. The purpose of this paper is to introduce a new approach for modeling aquifers containing adits and to illustrate its application with a case study. Note that elevations and heads are given as maod (meter above ordnance datum) throughout the paper.

Review of Possible Approaches

The current methods for modeling adits in the United Kingdom are pragmatic simplifications and either assign a larger value of hydraulic conductivity along the adits or distribute abstraction as several wells to replace the adit. This makes the estimation of appropriate parameter values for modeling problematic and the model itself would be incorrect.

Other possible approaches for modeling adits include karst and mine water approaches, as these deal with coupled pipe and ground water flow. Four different model representations could be identified for karst ground water modeling (Teutsch and Sauter 1991). The simplest model is the single-continuum porous equivalent (SCPE), but using this approach, individual fractures or conduits cannot be adequately represented (Baoren and Xuming 1988). The double-continuum porous equivalent (DCPE) approach, with one contin-

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Received January 1999, accepted September 1999.

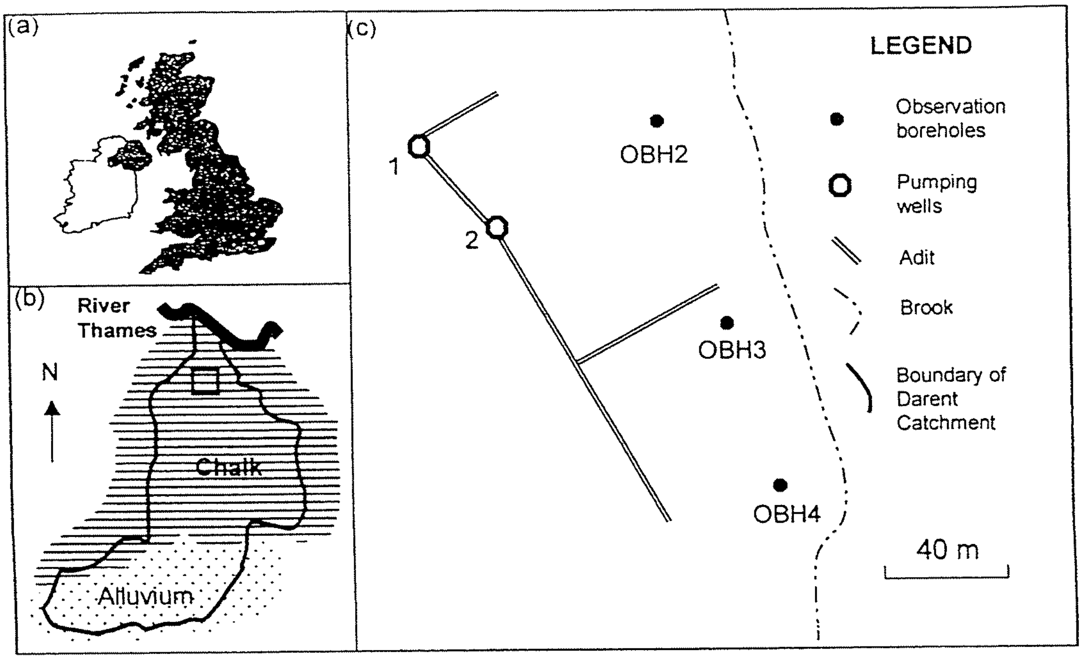

Figure 1. Setting of the Wilmington adit: (a) location southeast of London; (b) regional geological setting; (c) layout of adit, wells, and observation boreholes.

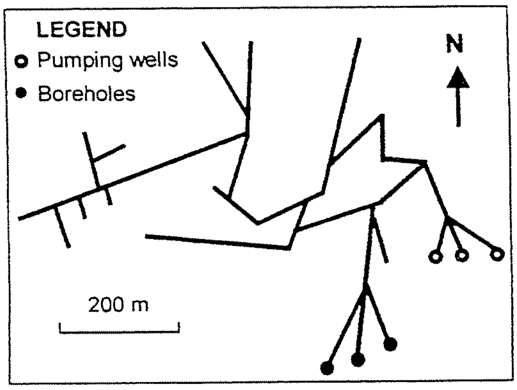

Figure 2. Example of a complex adit layout at the Eastbury pumping station, Watford, United Kingdom.

uum representing conduit flow and the other representing matrix flow, has the same inadequacy (Yilin et al. 1988; Sauter 1990). A better representation of the real karst system would be achieved by models of a discrete single fracture set (DSFS) or discrete multiple fracture sets (DMFS). An example is the program CAVE (carbonate aquifer void evolution), which was developed for the simulation of the development of karst aquifers (Sauter et al. 1996). The karst ground water is divided into two components: A fissured system is modeled by a continuum approach, and a conduit network is represented by a pipe network model. The conduits are assumed to be cylindrical and permanently saturated. The components are coupled hydraulically by an exchange term proportional to the head difference between the fissured system and pipe network. This program cannot represent partially full conduits.

Hydrogeology of abandoned mines often includes a complex mixture of unsaturated zones, saturated aquifers, and fast flow regions. Applications of two-dimensional ground water model codes to abandoned mines have varying success (Toran and Bradbury 1988). Finite-element ground water codes have been modified to estimate inflows into working mine systems in the United Kingdom (Fawcett et al. 1984). The unusual characteristics of mines and data limitations appear to have restricted the success of these models.

A lumped parameter model GRAM (ground water rebound in abandoned mineworkings) has been developed (Sherwood and Younger 1997). This is a simple transient model that conceptualizes a minefield as a group of ponds. Each pond is an area of mineworking that has been extensively worked and can be considered as a single hydraulic unit. The ponds can form any shape in the plan; however, they must be bounded by vertical walls of intact mine through which no flow is assumed. The hydraulic gradient within ponds is assumed to be flat. This means that all flow to and from the pond is applied over its entirety. The ponds are connected by roadways along which pipe flow is assumed. This model does not simulate the aquifer nor the dynamics of flow within ponds.

Preissmann Slot

The basic requirement for a model of adits in aquifers is that it can couple ground water with either open channel or pipe flow. The pipe flow case can be made equivalent to open channel flow

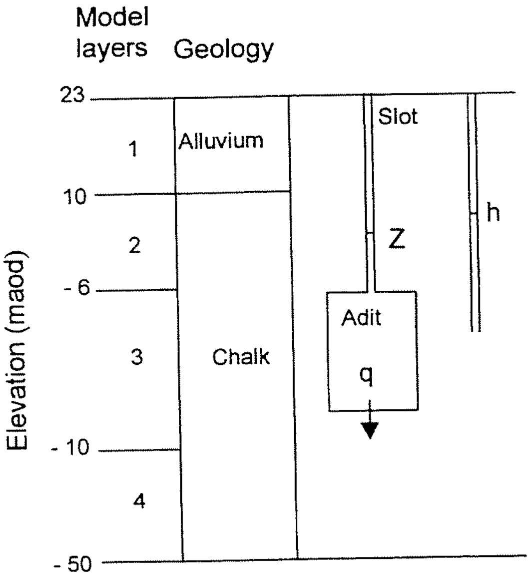

Figure 3. Representation of adit with a slot and details of Wilmington model layers. The symbols are for Equation 5 (not to scale).

by introduction of a hypothetical, narrow slot above the adit (Figure 3). This is called a Preissmann slot after Preissmann and Cunge (1961). The concept has been used for modeling sewers (Cunge et al. 1980; Abbott and Cunge 1982), but we have not come across any previous uses in coupled ground water/open channel flow cases.

The slot allows open channel equations to be used for all cases. If the adit is full, the calculated cross section remains as the true conveyance cross-sectional area, because the slot is narrow and has negligible cross-sectional area. However, the elevation of the water surface in the slot enables the hydraulic head in the pressurized adit to be correctly represented. Figure 3 illustrates the hypothetical slot and the model layers introduced in this paper.

Adapting MODBRNCH

Once the slot had been recognized as a way to simplify the coupling of the adit with the aquifer by replacing it with an open channel system, the need was to find a suitable ground water/surface water modeling code that could be adapted. We decided to try to select a public domain code with a good user interface.

BRANCH (Schaffranek et al. 1981) is a USGS model widely used to simulate one-dimensional unsteady, nonuniform, multiple-branch open channel flow by solving the following nonlinear momentum and continuity equations of flow:

$$\frac{\partial Q}{\partial t} + \beta\frac{Q}{A}\frac{\partial Q}{\partial x} + Q\frac{\partial(\beta Q/A)}{\partial x} + gA\frac{\partial Z}{\partial x} + \frac{gk}{AR^{4/3}}Q|Q| = 0 \qquad (1)$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad (2)$$

where Q is the channel discharge, Z is the river stage, x is the distance in the longitudinal direction, t is the elapsed time, A is the cross section area of water in the channel, g is the acceleration of gravity, R is the hydraulic radius, k is a function of the flow resistance coefficient, with $k = \eta^2$ in the metric system, where η is a roughness coefficient similar to Manning's n. BRANCH handles only subcritical flows; that is the case with a gentle sloping bed.

More than 20 published applications of BRANCH have proven it to be a reliable and useful code for simulation of open channel flow. For example, Bergquist and Ligteringen (1988) used BRANCH for the Segara Anakan study, and Jeffcoat and Jennings (1987) computed unsteady flows in the Alabama River using BRANCH. BRANCH has been and continues to be used extensively within the Water Resources Division of the USGS. Moreover, it continues to be widely used by government and consultants in the international arena as well (personal communication, anonymous reviewer, May 1999).

MODFLOW (McDonald and Harbaugh 1988) is a widely accepted ground water modeling code that has a number of user-friendly preprocessors available, including Visual MODFLOW (Waterloo Hydrogeologic Inc.), which was used for this study. The original version of MODFLOW includes a surface-ground water exchange package, STREAM (Prudic 1989), but it handles only steady and uniform flow in rectangular channels.

The MODBRNCH (Swain and Wexler 1996) package incorporates BRANCH into MODFLOW. The coupling of BRANCH with MODFLOW gives a more powerful simulation capability for stream-aquifer interactions, including the routing of surface flows in a network of interconnected open channels while accounting for the effects of stream velocity and discharge through the solution of Equations 1 and 2. The linkage between BRANCH and MODFLOW by MODBRNCH is a water exchange term similar to those in the widely accepted RIVER and STREAM packages. The water exchange term is added to the continuity Equation 2, which becomes

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} + q = 0 \qquad (3)$$

where q is outflow per unit length of channel and is calculated from

$$q = \frac{k'}{b'}B(Z - h) \qquad (4)$$

where k'/b' is the leakage coefficient of the river bed, B is the channel top width, and h is the head in the corresponding aquifer cell (Figure 3). The water exchange term—q—is also added to the continuity equation in MODFLOW.

A small modification is needed to handle the Preissmann slot in MODBRNCH. Equation 4 is a good approximation only for streams whose top width is much larger than the flow depth. However, when the slot is introduced, the top width would become the narrow slot width. A better approximation is to use the adit perimeter as the area of water exchange, replacing Equation 4 with

$$q = \frac{k'}{b'}W_p(Z - h) \qquad (5)$$

where W_p is the wetted perimeter of the adit and depends on the adit water level. Because the slot is fictitious, there is no water exchange across its perimeter, and the slot is not included in the calculation of W_p.

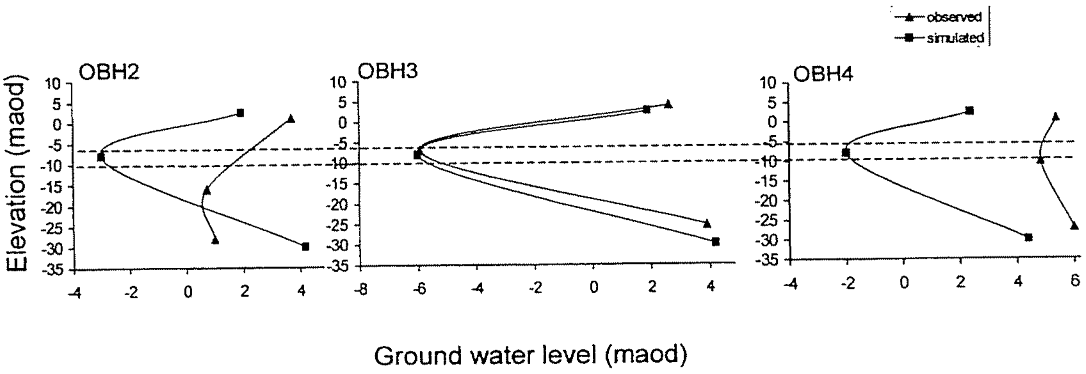

Figure 4. Comparison of model simulation with multilevel piezometers at Wilmington.

For an adit, the leakage coefficient is the summation of a number of real processes and modeling artifacts, much as the well loss coefficient is in pumping test analysis. These include resistive skin effects, curvature of flow lines close to adit, local heterogeneity, the size of MODFLOW cells containing the adit, and the continuity jump between the two domains. Hence, it is not a parameter thatcan be directly measured or easily estimated, and is likely to be obtained only by model calibration.

Although MODBRNCH is a relatively new code, its application has been documented (Swain 1994; Swain et al. 1996), which indicates that MODBRNCH is a reliable and powerful code.

Wilmington Case Study

The Wilmington pumping station (Figure 1) is one the largest ground water sources owned by Thames Water Utilities Ltd. in southeast London, with a peak discharge of 20 mL/day (Sage 1998). The site has two wells, each 33 m deep. One well is operated as the duty well while the second is used as demand dictates. To increase the yield of the site, the wells are linked at their base by an adit and more adits extend eastward and to the south. Like most adits in the United Kingdom, those at Wilmington have a height of 1.8 m and a width of 1.2 m. They are about 33 m below the ground surface. The main adit is 110 m long, which is untypically short. The site was chosen for this initial study because of the availability of multiple level piezometer data and an existing regional ground water flow model (Rippon et al. 1987). Observation boreholes around the site are shown in Figure 1.

Wilmington is located in the Darent catchment, which is in the southern limb of the London basin. The regional geology is shown in Figure 1. The site is underlain by alluvial deposits that overlie the Chalk. The regional ground water flow is generally in a northern direction, toward the River Thames. The existing Darent catchment regional model covers an area of 600 km^2 and is divided into two layers, the alluvium and the Chalk (Rippon et al. 1987). The boundaries are a constant head along the River Thames to the north, ground water divides along the western and southern boundaries, and a no-flow boundary to the east.

In order to represent the adit and the position of observation boreholes, a fine grid and multilayer representation were required around the pumping station. A minimum grid spacing of 10 m was found satisfactory. However, such a fine grid in a multilayer regional model would make the model clumsy. Therefore, a local model was constructed for Wilmington with an area of 4 km by 5 km and total thickness of 120 m. It was taken from the existing regional model by means of telescopic mesh refinement (TMR) (Ward et al. 1987). This incorporates the regional controlling factors into the smaller study domain. Calibrated steady-state head values from the regional model simulation are interpolated and applied as constant head boundaries on the local model. Calibrated parameters in the regional model are used for an initial local model. To incorporate the adits into the aquifer being modeled, and to see the three-dimensional flow pattern, the chalk layer was divided into three layers (Figure 3). One layer is above the adits, the second has a thickness of 4 m and contains the adits, and the lowest layer is underneath the adits. Because the regional model had only one layer, the boundary head values for the local model are the same for all layers within each vertical column. Some error is introduced in this process. However, considering the model objectives, these small boundary errors are acceptable (Ward et al. 1987). A 0.01 m wide slot was used to simulate the adit by MODBRNCH.

Model Calibration

The local Wilmington model was calibrated for ground water head distribution in January 1993. The calibrating parameters included both horizontal and vertical hydraulic conductivity, and leakage coefficient. No attempt was made to recalibrate the regional model because it had been accepted by the commissioning client, and the proprietary code and data files were unavailable to us.

Model predictions of heads are compared to field observations of three multilevel piezometers (Figure 4). The locations of observation boreholes OBH2, OBH3, and OBH4 are illustrated in Figure 1. OBH3 is the nearest borehole. One of its piezometers was located in the adit layer, so the calibration was focused on OBH3. The calibration of OBH3 is good for all three layers. However, the calibrations for OBH2 and OBH4 are not ideal. Lack of data for local heterogeneity is probably one reason. Also, there are no piezometers located in OBH2 and OBH4 at the level of the adit, so direct comparison is not possible. A value of 0.05 s/m$^{1/3}$ was used for the resistance coefficient; and values of 3×10^{-4} m/s, 3×10^{-6} m/s, and 1×10^{-4}/s were used for horizontal hydraulic conductivity, vertical hydraulic conductivity, and leakage coefficient, respectively. Calibration of aquifer-adit models for practical studies will clearly

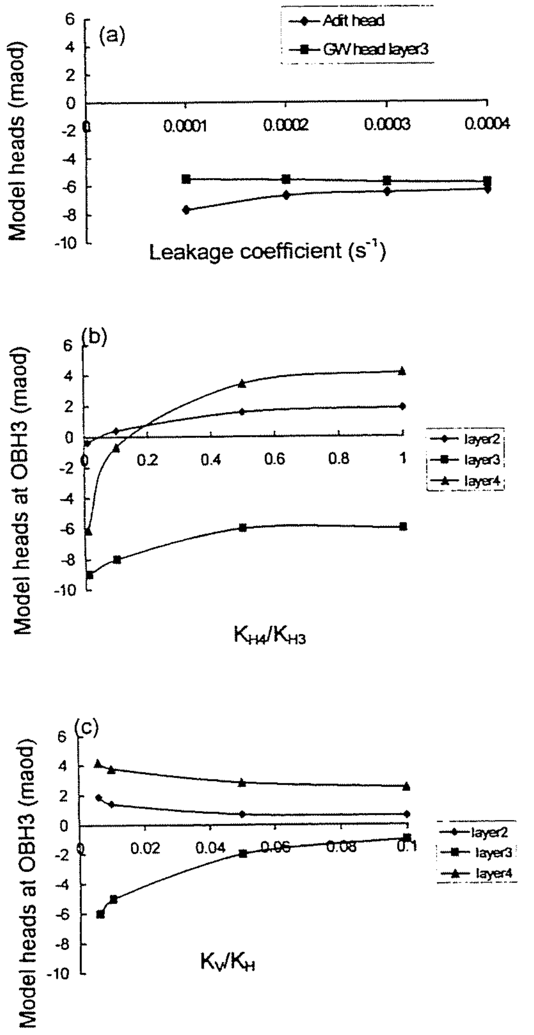

Figure 5. Sensitivity of the heads in adit model to (a) leakage coefficient, calibrated value is 0.0001/s. (b) Horizontal hydraulic conductivity in lowest layer of the Chalk, identical values of K_{H4} and K_{H3} are used in the model. (c) Vertical hydraulic conductivity between layers, the value of 1% of horizontal hydraulic conductivity was used. K_{Hi}—horizontal hydraulic conductivity in layer i; H_V—vertical hydraulic conductivity.

require additional data over and above that normally available for regional modeling studies. Multilevel piezometer data from levels above, at, and below the adit will be valuable, especially if there are observation points at several distances from the adit. Measurements of heads in the adit itself will also be valuable for calibration.

Sensitivity Analyses

The sensitivity of the adit model with respect to slot width, resistance coefficient, leakage coefficient, and hydraulic conductivity was analyzed. The model prediction is not sensitive to the slot width of adits when it is 0.01 m or smaller for a steady-state system (transient cases have not been studied yet). Neither is it sensitive to the resistance coefficient for a short adit, as the variation of the head in the adit was only 0.02 m when the resistance coefficient varied within a range of 0.02 to 0.1 s/m$^{1/3}$.

Figure 5a shows the sensitivity to the leakage coefficient. The difference between the adit and aquifer heads increases with decreasing leakage coefficient. This is because of the inverse relation between leakage coefficient and head difference for a fixed pumping rate (Equation 5). The leakage coefficient was initially assigned as the value of horizontal hydraulic conductivity, assuming b′ is 1, and adjusted to 33% of initial value during the model calibration.

Because the hydraulic conductivity of the Chalk generally decreases with depth in the United Kingdom (Downing et al. 1993), the horizontal hydraulic conductivity of layer 4 has been varied to test the importance of this effect. From Figure 5b, one can see that there is an important effect, particularly on heads in layer 4, even though this layer does not contribute a lot of flow directly to the adit. Note that these tests are only indicative, as previously explained: corresponding changes to the transmissivity of the Chalk layer in the regional model were not made.

Figure 5c shows the influence of vertical hydraulic conductivity, K_V. It shows that the vertical hydraulic conductivity is influential only for values less than 5% of K_H, horizontal hydraulic conductivity, and the layer containing the adit—layer 3—is the most influenced layer. The calibrated vertical hydraulic conductivity is 1% of horizontal hydraulic conductivity.

Effects of Adits on Ground Water Heads

Currently, the most common way to simulate adit systems is to replace them by one or more wells in a conventional ground water model. Figure 6 compares this approach to the use of MODBRNCH. It shows the predicted ground water heads near the adit, and compares these to a MODFLOW simulation in which a well pumps the same quantity. The results are for layer 3 (containing the adit). To simplify the presentation of the effect that the adit layout has, the same hydraulic conductivity was used for both models. The water was pumped only from the adit in MODBRNCH, while MODFLOW pumped water from both layer 2 and layer 3 because cells dried up when water was pumped only from layer 3. Only a small portion of the aquifer is shown (160 m × 160 m). The drawdown patterns of MODBRNCH and MODFLOW are different for the adit layer. Although the maximum drawdowns are similar in both cases (to about –5 maod), the area drawdown below, say, 0 maod is much greater for the adit case than the well. A small area of the layer above the adit was dry in the MODFLOW simulation.

Figure 7 shows the adit and ground water heads simulated by MODBRNCH along the main adit direction. The adit head is lowest. The ground water head for the adit layer (H3) is approximately 1 m higher near the adit. The layer below the adit (H4) has the highest head. The heads for the three layers are different and remain stable along the 110 m adit, but jump up at the entry of adit, and then join together gradually with increasing distance from the pumping well.

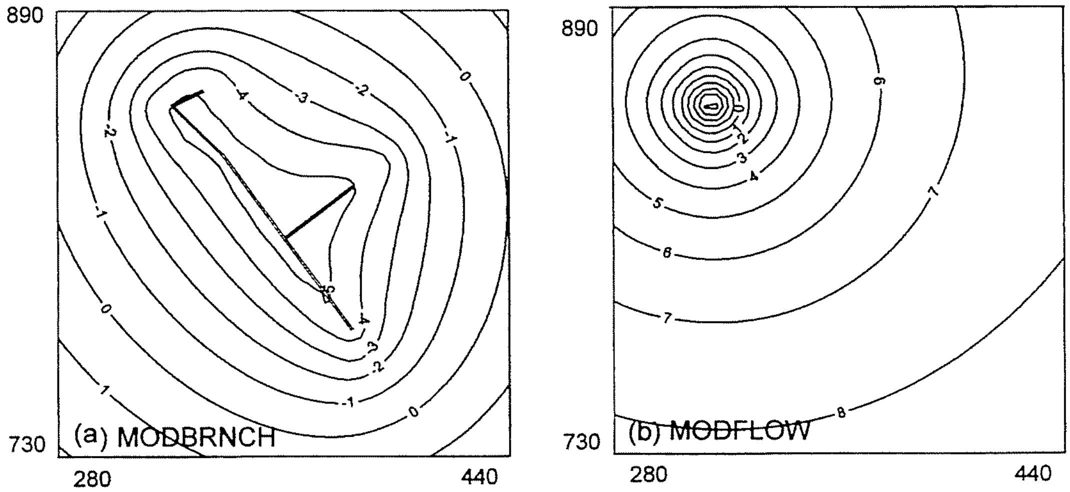

Figure 6. MODBRNCH and MODFLOW simulations of ground water levels at Wilmington (layer 3). The numbers on the axes are meters from arbitrary region.

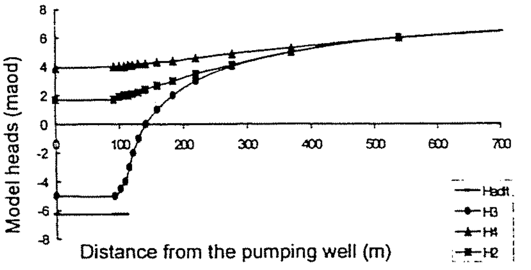

Figure 7. Simulated model heads along the main adit direction.

Further Developments

This is a steady-state and full adit case. The cases of transient flow, partially full adits, and adits with steps (adits are located at various levels but connected) will be studied in the remainder of the research program. The standard and modified versions of MODBRNCH are going to be implemented into Visual MODFLOW and released by June 2000 (Guiguer 1999).

One of the main objectives of this study is to demonstrate the effects of adits on source protection zones. However, the Wilmington adits are small adits, and the influences of the adits are not significant. A normal-size adit (more than 1000 m long) is currently being studied to understand the hydraulics of adits and demonstrate the impacts of adits on source protection zones.

Conclusions

The Chalk Aquifer forms the most important aquifer in the United Kingdom, and many chalk aquifers contain adits. However, there has been no good method simulating aquifer-adit interactions. The combination of the Preissmann slot approach and the modified MODBRNCH is able to simulate aquifer-adit interaction for the steady and full-adit case, and we are testing it for partially full and transient cases.

The Wilmington model output indicates that even a short adit affects the ground water head distribution for a distance of several adit lengths around it. The adit also causes a strong vertical effect on heads, as would perhaps be expected, and with least drawdown in the layer below that adit. Horizontal hydraulic conductivity has a strong impact on model predictions. Vertical hydraulic conductivity affects the head for the layer containing the adits, and its calibrated values are unusually small. The difference between aquifer and adit head increases with decreasing leakage coefficient. The model predictions of head are not sensitive to the slot width for steady-state simulations when it is below a threshold, nor are they sensitive to the resistance coefficient for short adits simulated. Predictions are more sensitive to the hydraulic conductivity values between and within layers, as is commonly found in ground water flow models.

A fine grid in a multilayer model will normally be required to obtain the spatial resolution required to simulate adits with MODBRNCH; in the Wilmington example, a 10 m grid space and a four-layer model were used. It is likely that TMR techniques will be used to create a local model for the area of the aquifer containing the adit with an associated, regional model that uses a coarser grid. For calibration purposes, several multilevel piezometers and head measurements in the adit will be valuable.

Acknowledgments

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Proceedings of MODFLOW98, October 4-8, 1998, Golden, Colorado. Volume 2, pp 667-674

Modelling of Groundwater Flow to Adits by Using MODBRNCH and Introducing a Preissmann Slot above the Adit

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ABSTRACT

Many of the large groundwater sources in the Chalk aquifer have adits, horizontal tunnels below the groundwater table, which are connected to pumped wells. The flow in an adit is pipe flow, and Darcy's formula is therefore not applicable to the adit, consequently,conventional models are inappropriate to model the aquifer-adit system. The USGS model BRANCH simulates one-dimensional unsteady, nonuniform, multiple-branch interconnected open channel flow. MODBRNCH incorporates BRANCH into MODFLOW through water exchange between open channel flow and aquifer. However, adits in the UK are normally full of water, so that the adit flow becomes pressurised. The problem can be overcome by introducing a fictitious narrow slot (Preissmann slot) above the adit, so the adit cross-section area remains similar, The water level in the slot represents the pressurized adit head which can be used by MODBRNCH to calculate the water exchange between aquifer and adit according to their head differences. The approach has been tested on Wilmington case study to demonstrate the application of the technique. The model will be used to explore how adits affect wellhead protection zones.

INTRODUCTION

The Chalk forms the most important aquifer of southern England. Approximately 15% of chalk groundwater sources in the England have adits, which are horizontal tunnels below the groundwater table. Adits are connected with pumped wells from where groundwater is pumped to surface. Most adits are 1.8m high and 1.2 m wide with arched roofs. Adits vary in length from tens of meters to 7000m. The depth of adit varies between 10m to 100m below ground surface. The plan views of adit layout have patterns of straight lines, radial lines, T shapes, loops and branches, etc. Fig.1 shows the adit layout at Wilmington.

Pumping tests indicate that the groundwater in adits flows just like in pipes. The basic groundwater formula - Darcy's law - is therefore not applicable to adit flow. Consequently, conventional groundwater flow models are inappropriate to model adit systems.

The purpose of this paper is to introduce a new approach for modelling groundwater flow to adit systems and illustrate it's application.

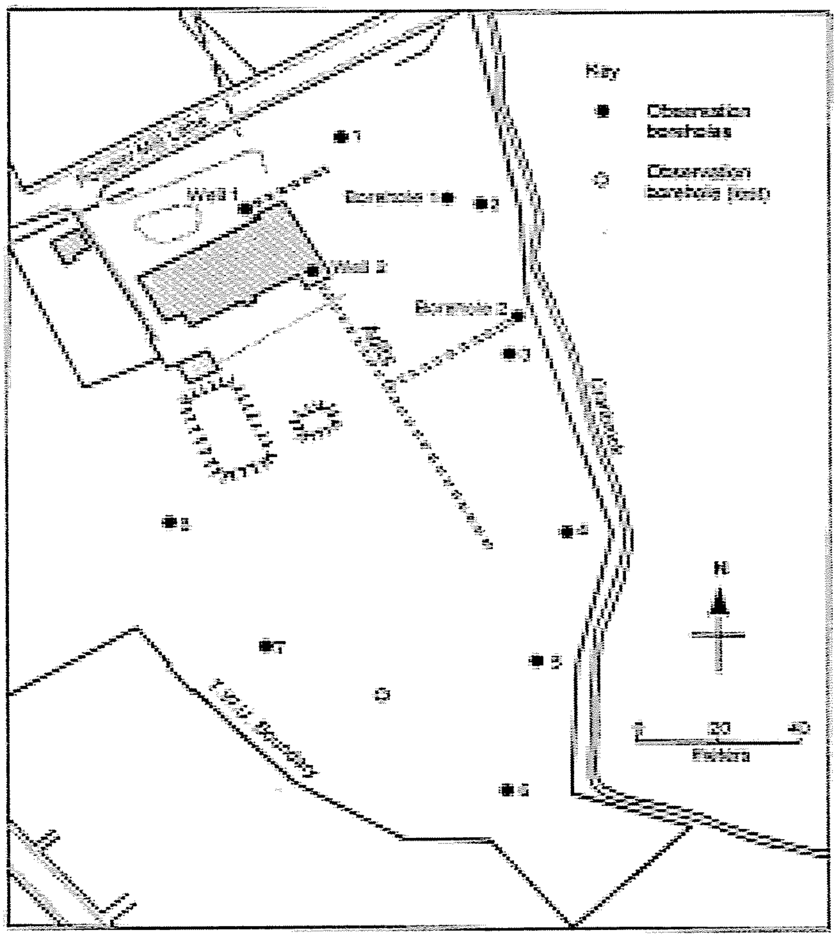

Fig.1 Wilmington adit layout

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MODBRNCH ADAPTION

BRANCH (Schaffranek, et al,1981) is an USGS model widely used to simulate one-dimensional unsteady, non-uniform, multiple branch interconnected open channel flow by solving the following non-linear momentum and continuity equations for open channel flow

$$\frac{\partial Q}{\partial t}+\frac{\partial(\beta Q^2/A)}{\partial x}+gA\frac{\partial Z}{\partial x}+\frac{gk}{AR^{4/3}}Q|Q|=0 \qquad (1)$$

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad (2)$$

where Q is the channel discharge, Z is the river stage, x is the distance in the longitudinal direction, t is the elapsed time, A is the channel water cross section area, g is the acceleration of gravity, R is the hydraulic radius, k is a function of the flow resistance coefficient, with $k=\eta^2$ in metric system, where η is similar to Manning's n.

The MODBRNCH (Swain and Wexler,1996) interface incorporates BRANCH into MODFLOW(Harbaugh and McDonald, 1988). The coupling of BRANCH with MODFLOW expands the simulation capability of stream-aquifer interactions including routing of surface flows in a network of interconnected open channels while accounting for the effects of stream velocity and discharge.

SLOT APPROACH

MODBRNCH simulates relations between open channel flow and groundwater successfully. However, adits in the UK are normally full of water, so that the adit flow becomes pressurised, a situation which is not normally handled in MODBRNCH. To overcome the problem, we introduce a fictitious slot (Preissmann Slot; Preissmann and Cunge,1961) above the adit, as schematized in Fig.2.

This approach makes the calculated adit cross sectional area remain similar to the actual adit water conveyance area, while the pressurized adit head can be accounted and represented by the water level in the slot, and used by MODBRNCH to calculate the water exchange between aquifer and adit according to their head differences. MODBRNCH allows users to construct a slot above the adit as the actual channel geometry is assigned by defining the channel cross section.

MODIFICATION OF MODBRNCH

A small modification is needed to handle Preissmann slot in MODBRNCH. MODFLOW and BRANCH are linked by water exchange as mentioned previously, for which the leakage term to be added to the continuity equation (2) for the BRANCH model is

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}+q=0 \qquad (3)$$

where q is outflow per unit length of channel and is calculated as

$$q=\frac{\mathrm{k}'}{\mathrm{b}'}B(Z-h) \qquad (4)$$

where k'/b' is the leakage coefficient of the river bed, B is the channel top width, and h is the head in the corresponding aquifer cell.

Equation (4) is only a good approximation for streams whose top width is much larger than the flow depth. However, when the slot is introduced, the top width would become the narrow slot width. A better approximation is to use the adit perimeter, instead of the top width, replacing Equation (4) by

$$q=\frac{\mathrm{k}'}{\mathrm{b}'}W_p(Z-h) \qquad (5)$$

where W_p is the adit perimeter.

The leakage term – q, is also added to the continuity equation in MODFLOW.

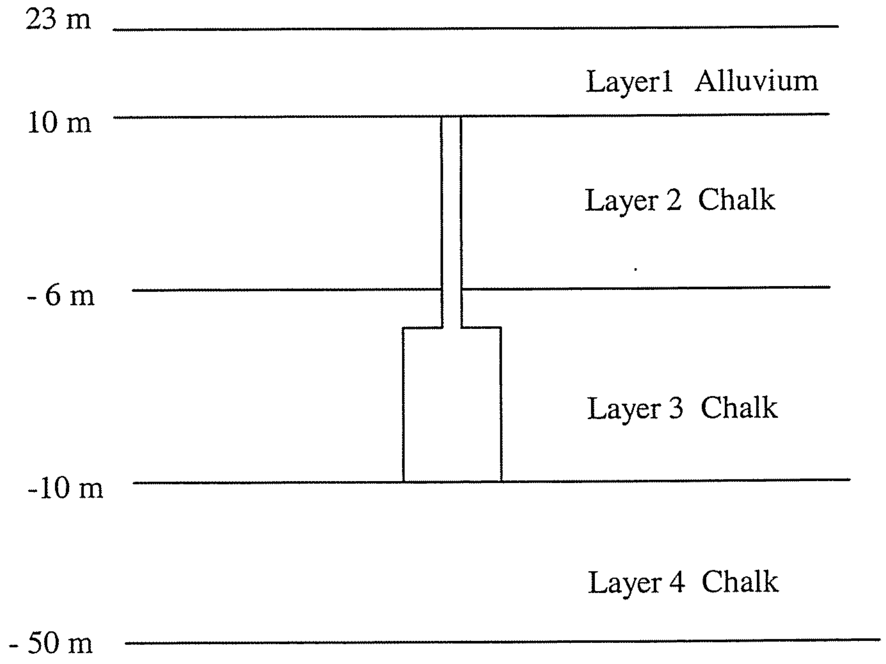

Fig.2 Profile of slot illustration and Wilmington model layers (not to scale)

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WILMINGTON CASE STUDY

Wilmington pumping station is one the largest groundwater sources Thames Water Utilities Ltd has in south east London, with a peak discharge of 20 Ml/day (see Fig.1). The site has two wells, each 33 m deep. One well is operated as the duty well while the second is used as demand dictates. To increase the yield of the site, the wells are linked at their base by an adit. Further adits extend eastwards and to the south. Like most UK adits, Wilmington adits have a height of 1.8m and a width of 1.2m. They are about 30m below the ground surface. The main adit is 110m long, which is rather short. Observation boreholes were drilled around the site and are illustrated in Fig.1.

Wilmington is located in the Darent Catchment, which is in the southern limb of the London basin. The site is underlain by alluvial deposits which overlie the Chalk. The regional groundwater flow is generally in a northern direction, towards the River Thames. The existing Darent Catchment regional model includes an area of 600 km^2 and is divided into two layers, the alluvium and the Chalk. The boundaries are a constant head along the River Thames to the north, groundwater divides along the western and southern boundaries, and a no flow boundary to the east.

The model presented in this paper has an area of 4km by 5km and total thickness of 120m, and is taken from the existing regional model by means of Telescopic Mesh Refinement (TMR)(Ward et al, 1987). This incorporates the regional controlling factors into the smaller study domain. Head values from the regional model are assigned to the appropriate boundaries of the local model. The local modelling was carried out by both MODFLOW and MODBRNCH separately. To assign the adits into the aquifer, the chalk layer is further divided into three layers. One layer is above the adits, the second has the adits in it with a thickness of 4 meters, and the lowest layer is underneath the adits. A 0.01m wide slot is constructed to simulate the adit by MODBRNCH.

Fig.3 shows MODBRNCH predictions of the effect of the adit on groundwater heads in the three layers, and compares these to MODFLOW. The adits affect groundwater heads in the layer above, and the layer containing the adit (Fig.3a, 3b), but have little effect on the layer below(Fig. 3c). The difference between the models can be see by comparing Fig.3b and 3d, which show the middle Chalk layer for MODBRNCH and MODFLOW respectively. The area of drawdown is much larger than MODFLOW suggests.

Fig.4.presents the MODPATH pathlines based on groundwater head distributions produced by MODBRNCH and MODFLOW respectively. A 50-day marker is used. The figure shows that the 50-day protection zone of MODBRNCH enclosed by the dash line is moved in the south eastern direction compared with the one of MODFLOW because of adit's south eastern extension. This effect could be much stronger if the adit was bigger, as many of them are.

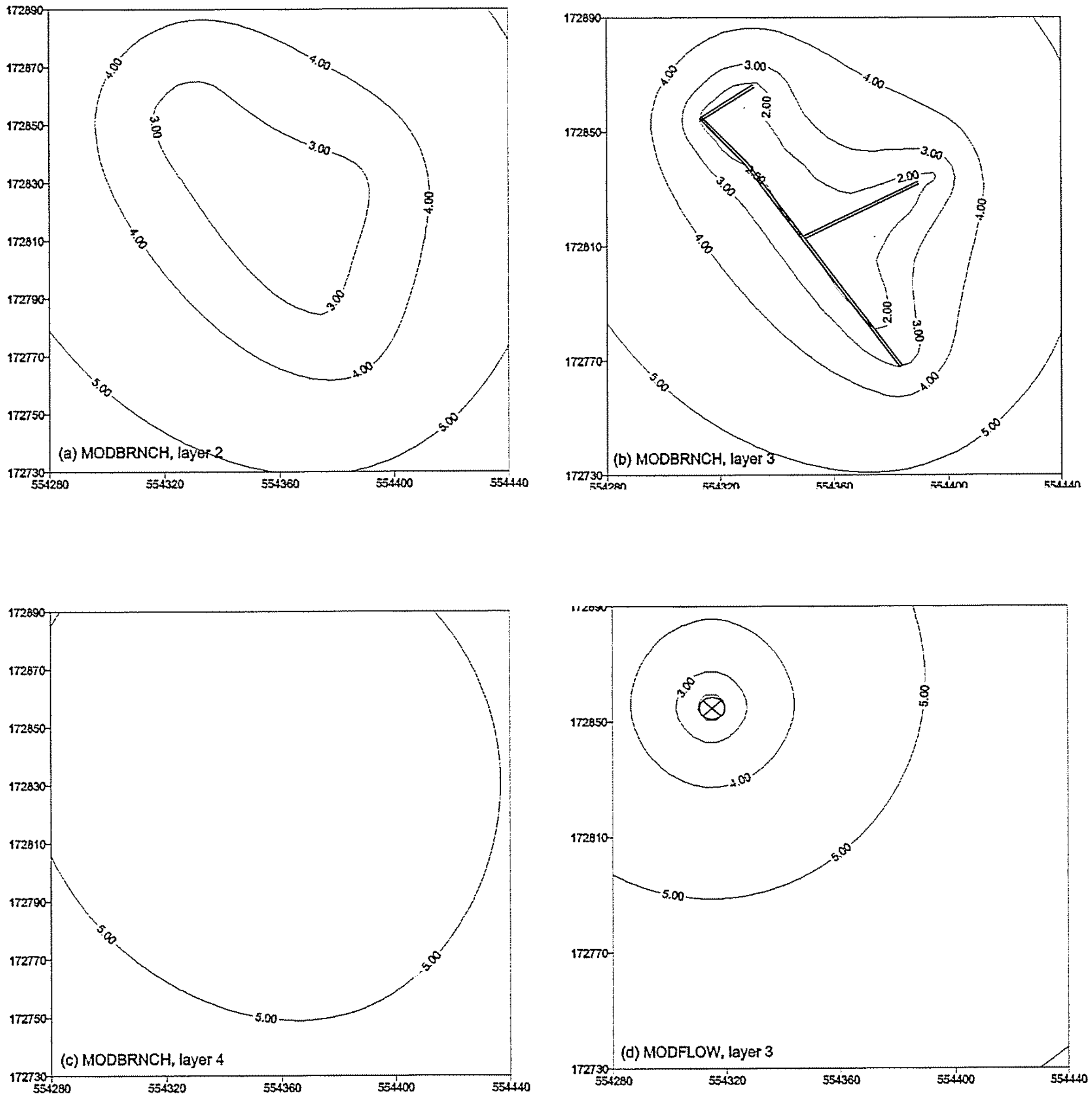
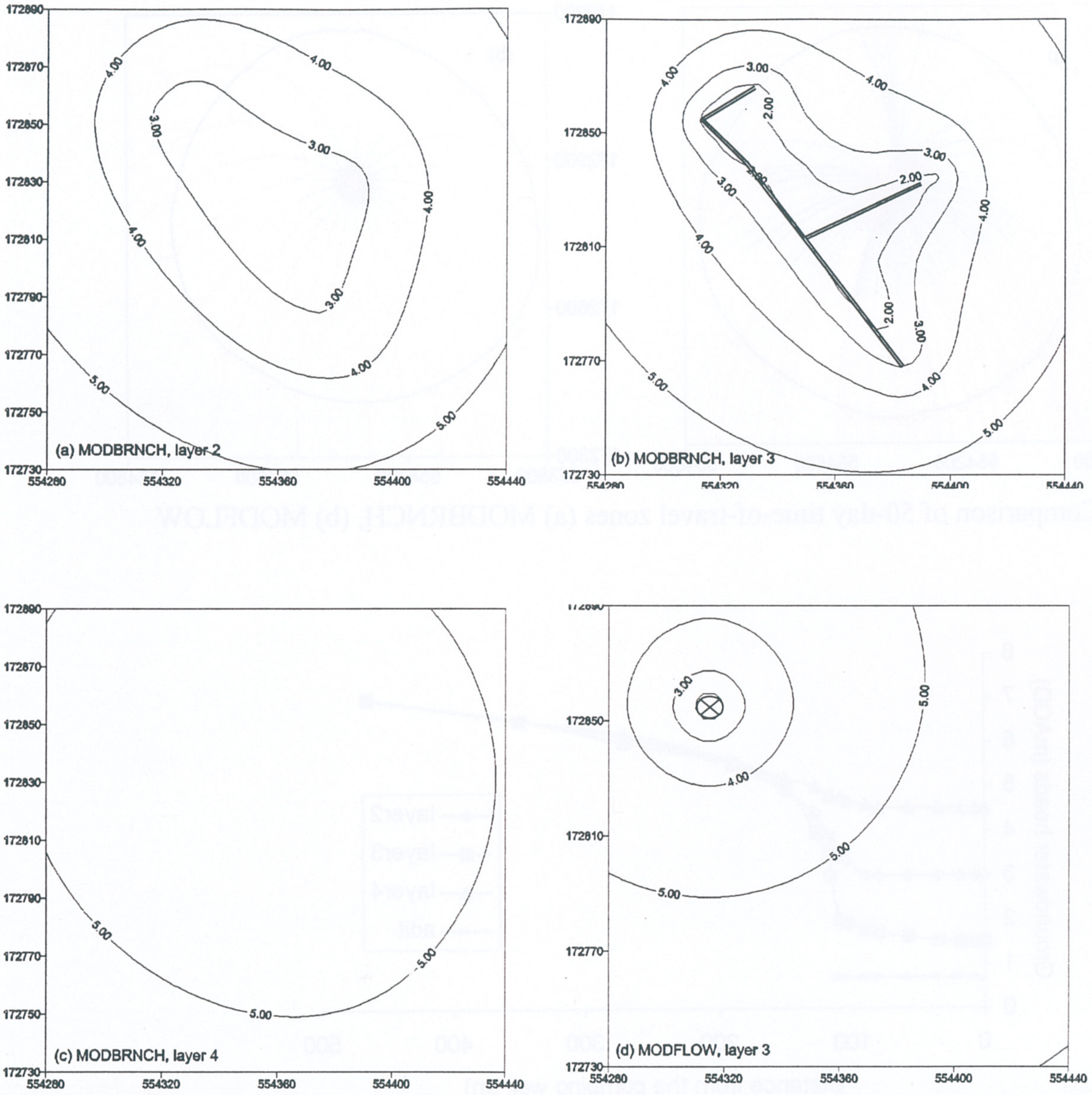


Fig.3. Comparison of heads around adits generated by MODBRNCH and MODFLOW

Fig.5 shows the groundwater heads simulated by MODBRNCH along the main adit direction. The heads for the layers above and with adits remain stable along 110m main adit, but jump up immediately at the entry of adit, and then increase gradually with increasing distance from the pumping well. Adit heads are around 0.7 m with a little hydraulic gradient.



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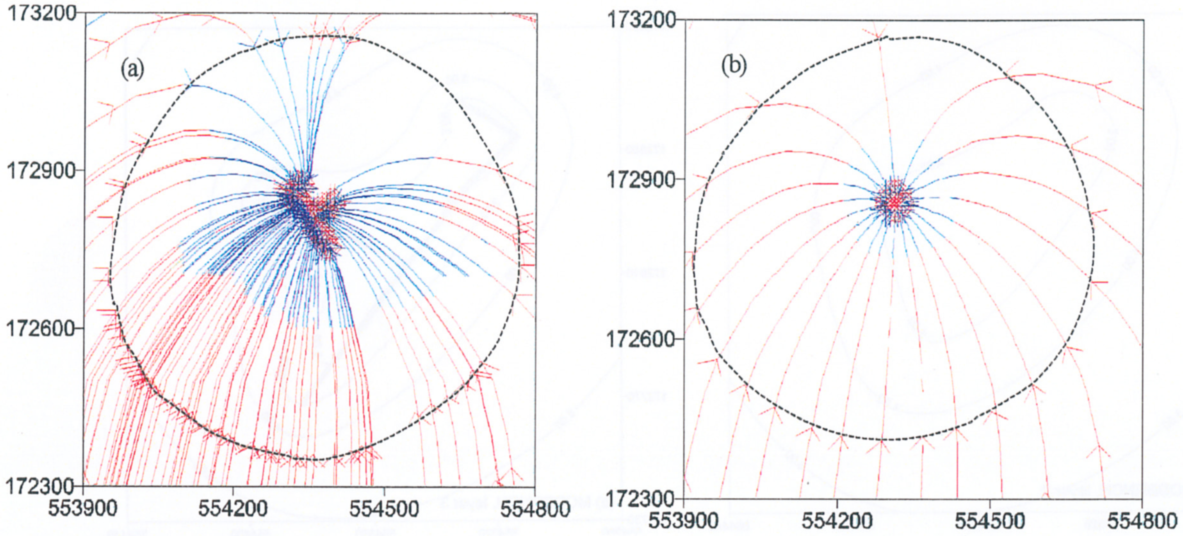

Fig.4. Comparison of 50-day time-of-travel zones (a) MODBRNCH, (b) MODFLOW

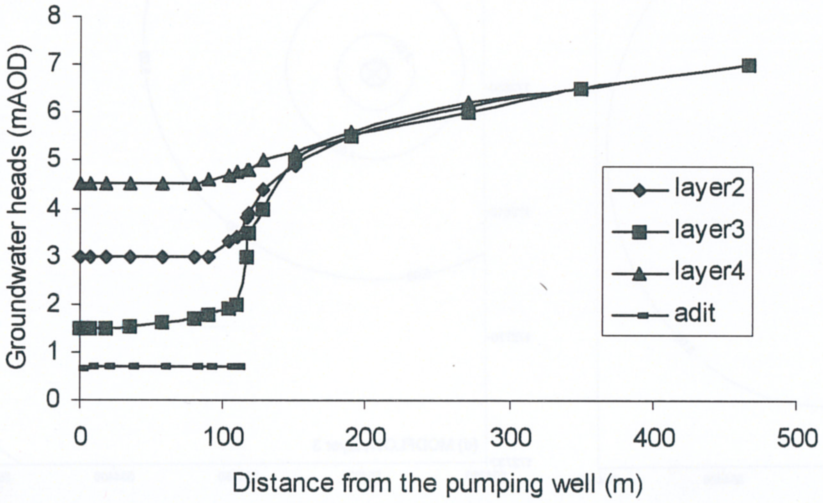

Fig.5 Simulated groundwater heads along the main adit direction

DISCUSSION

One of the main objectives of this study is to demonstrate the effects of adits on source protection zones. However, the Wilmington adits are small adits, and the influences of the adits are not significant. A normal size of adit (more than 1000m long) is going to be studied soon, understand the hydraulics of adits and demonstrate the impacts of adits on source protection zones.

ACKNOWLEDGEMENTS

This study is mainly sponsored by the Environment Agency of UK, who also provided access to a previous regional model of the area. Thames Water Utilities Ltd provided the data for Wilmington. The authors would like to thank them for their help.

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An integrated groundwater, pipe and open-channel flow model for simulation of aquifer-adit systems

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Abstract The Chalk is the most important aquifer in the UK. In the Chalk aquifer, the yield from the wells was often increased by driving adits (or tunnels) in different directions. The flow in an adit is pipe or open-channel flow. Introducing a fictitious narrow slot (Preissmann slot) above the adit makes equations for open-channel flow also valid for pipe flow. MODBRNCH, an integrated groundwater and open-channel flow model, is adopted. The combination of slot approach and modified MODBRNCH enables us to simulate groundwater-adit interrelation by coupling groundwater with pipe flow, groundwater with open-channel flow, and groundwater with transition from pipe flow to open-channel flow. An application to Cottingham pumping station including both steady state and transient modelling demonstrates that the model calibration is good, and the method is successful and valuable.

INTRODUCTION

The Chalk forms the most important and most widespread aquifer in the UK. 60% of groundwater abstraction is from the Chalk in the UK (Beeson *et al.*, 1995). In the Chalk aquifer, the yield from wells was often increased by driving adits (or tunnels) in different directions and at different levels or by inter-linking wells with adits. Figure 1 shows the Cottingham adit layout, which is the case study introduced in this paper. Systems of adits, typically 1.2 m wide and 1.8 m high, are usually below the groundwater table and can be up to 7 km long. Generally the adits were driven to intersect the principal fissure direction. Velocity calculations indicate that the flow in the adit is turbulent when the pumping is taking place, so it is difficult to predict groundwater flow and delineate source protection zones in these area.

However, the turbulent adit flow can be represented as pipe flow (adit is full of water) or subcritical open channel flow (adit is partially full) for groundwater modelling purposes. Therefore, a model, which couples groundwater with pipe flow, groundwater with open-channel flow, and groundwater with transition from pipe flow to open channel flow, is needed for simulation of aquifer-adit systems.

The CAVE (Carbonate Aquifer Void Evolution) is a model coupling groundwater flow and pipe flow (Clemens *et al.*, 1996), and the conduits are assumed to be permanently saturated. MODBRNCH (Swain & Wexler, 1996) is a model that couples groundwater flow and open-channel flow models to simulate the groundwater and open-channel flow and their interaction. However, a scheme, which couples groundwater with pipe flow, groundwater with open-channel flow, and transition from pipe flow to open channel flow, has not been developed.

This paper introduces a new approach to modelling adits and an application.

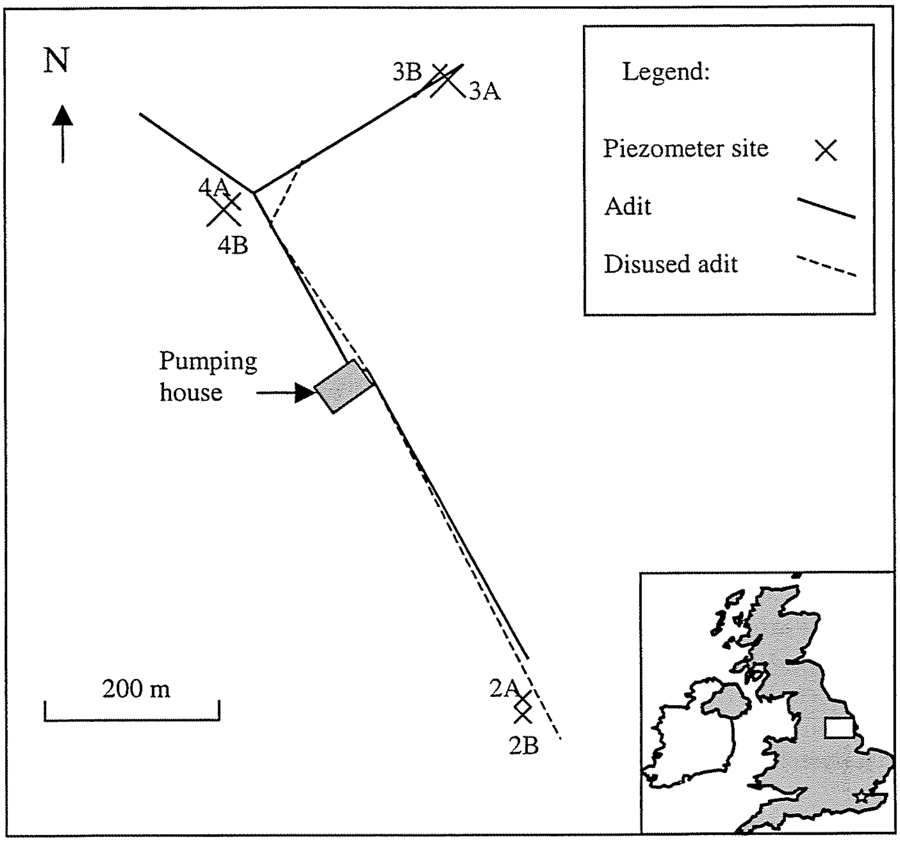

Fig.1 Cottingham adit layout.

ADIT MODELLING APPROACH

Modelling of aquifer-adit systems requires a model handling all following situation: groundwater with pipe flow, groundwater with open-channel flow, and groundwater with transition from pipe flow to open channel flow. The pipe flow case can be made equivalent to open channel flow by introducing an artificial, narrow slot above the adit (Preissmann slot, Preissmann & Cunge, 1961). The slot allows the open-channel equations to be valid for all cases. If the adit is full, the calculated cross-section remains the same as the actual water conveyance cross-sectional area because the slot is narrow (1 to 10 mm). The water level within the slot represents the pressurized water head, which can be used to calculate water exchange between aquifer and adit according to their head difference. Figure 2 illustrates the slot approach and the aquifer layers for the case study introduced in this paper.

The USGS model BRANCH (Schaffranek *et al.,* 1981), which simulates one-dimensional, unsteady, nonuniform flow by solving the St. Venant equations, is a model commonly used for simulation of open-channel flow. MODBRNCH incorporates BRANCH into MODFLOW (McDonald & Harbaugh, 1988). The coupling of BRANCH and MODFLOW simulates aquifer-stream interaction using deterministic response of both systems, and is a highly dynamic model. It allows users to define the channel geometry by defining channel cross-sections. Therefore MODBRNCH was selected for adit modelling because the slot can be constructed by defining the channel cross-section. A small modification has been made for handling slot approach (Zhang & Lerner, 1998).

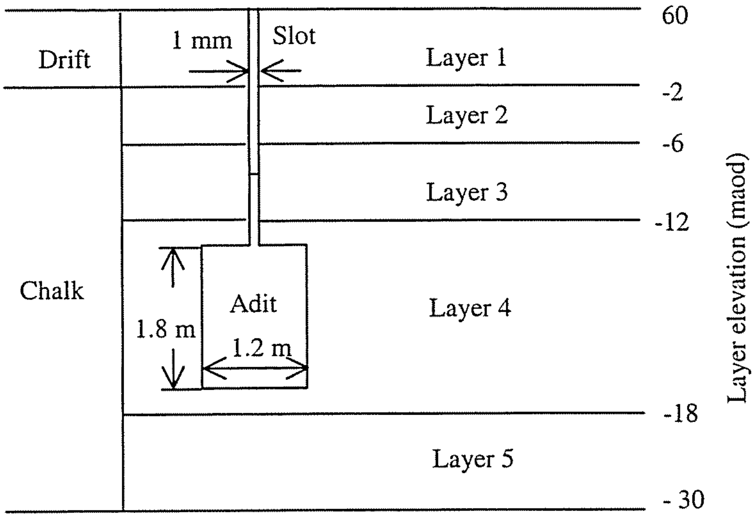

Fig. 2 Illustration of artificial slot, and aquifer layers in the Cottingham case study for this paper (not to scale).

APPLICATION TO COTTINGHAM STATION

Cottingham pumping station is one the largest groundwater sources that Yorkshire Water Services has in the Hull area, with a licensed abstraction of 68 182 m^3 day^{-1}. The Cottingham source is complex comprising of two pumping shafts, 20 other shafts and about 1000 m of adit in use (see Fig.1). The Cottingham adits consist of two main systems at -15 maod and -29 maod (Meters Above Ordnance Datum). The lower system is not used and is not connected to the higher system. The existing bores below the higher adits were plugged to ensure there was no connection with the lower adits (Crease, 1998).

Cottingham source is located in the "Yorkshire Chalk" to the north of Humber Estuary (Green, 1950). The outcrop of the Chalk appears in the west, and the Chalk is covered by a thick sequence of Boulder Clay and thin sandy drift in the east. The regional groundwater flows in a southeast direction to the abstractions.

The regional model presented in this paper uses MODFLOW. It covers an area of 660 km^2 and is simplified as one layer model. The Cottingham local model, having an area of 2 km by 2.5 km, was taken from its regional model by means of Telescopic Mesh Refinement (TMR)(Ward *et al.*, 1987), and is simulated using slot approach and modified MODBRNCH.

To simulate the pumping test, which took place in September 1998, the modelling started from a steady state model representing the condition in August 1998. The calibrated groundwater head distribution in the steady state model was taken as the initial head for the transient model. The permeability and leakage coefficient were mainly calibrated in the steady state model calibration, while the storage coefficient was calibrated with the transient model.

Cottingham adits and shafts were constructed in the end of last century and early this century. Most of shafts show seepage through joints in the brickwork, and have occasional brick omitted, probably to allow inflow to the shaft (Crease, 1998). To integrate this phenomenon into the modelling, it assumed that a proportion of the pumping water is contributed by shaft seepage in Layer 3. This proportion was adjusted during model calibration.

The Cottingham local model was divided into five layers (see Fig. 2) according to adit geometry and elevation, seepage horizon and elevation, lithology, and piezometer elevation. Although the local groundwater levels were continually monitored by pressure transducers throughout the pumping test, the model calibration was focused on the dates when the manual dips were carried out because some of the logger data are not reliable. The locations of the observation boreholes are shown in Figure 1. All piezometers were grouped in pairs, set into a small borehole but at different elevations. Also, all observation boreholes were grouped in pairs (i.e. 2A&2B etc.), Therefore the 4 piezometers grouped in two nearby boreholes were considered as one location during model calibration. The elevations of piezometers can be seen from Figure 3. Figure 3 shows the comparison of observed data and simulated data for both steady state and transient models. The simulated data are quite close to the observed data. The simulated steady state groundwater head distribution for various layers is shown in Figure 4. It is indicated that the adit affects Layer 4 (the layer containing the adit), Layer 3 and Layer 2, but has little effect on Layer 1 and Layer 5. Figure 5 shows the simulation of the whole pumping test. 3Bi&3Bii are the nearest piezometers to the adit, so are selected and compared with Layer 3 and Layer 4 simulations at that location, respectively.

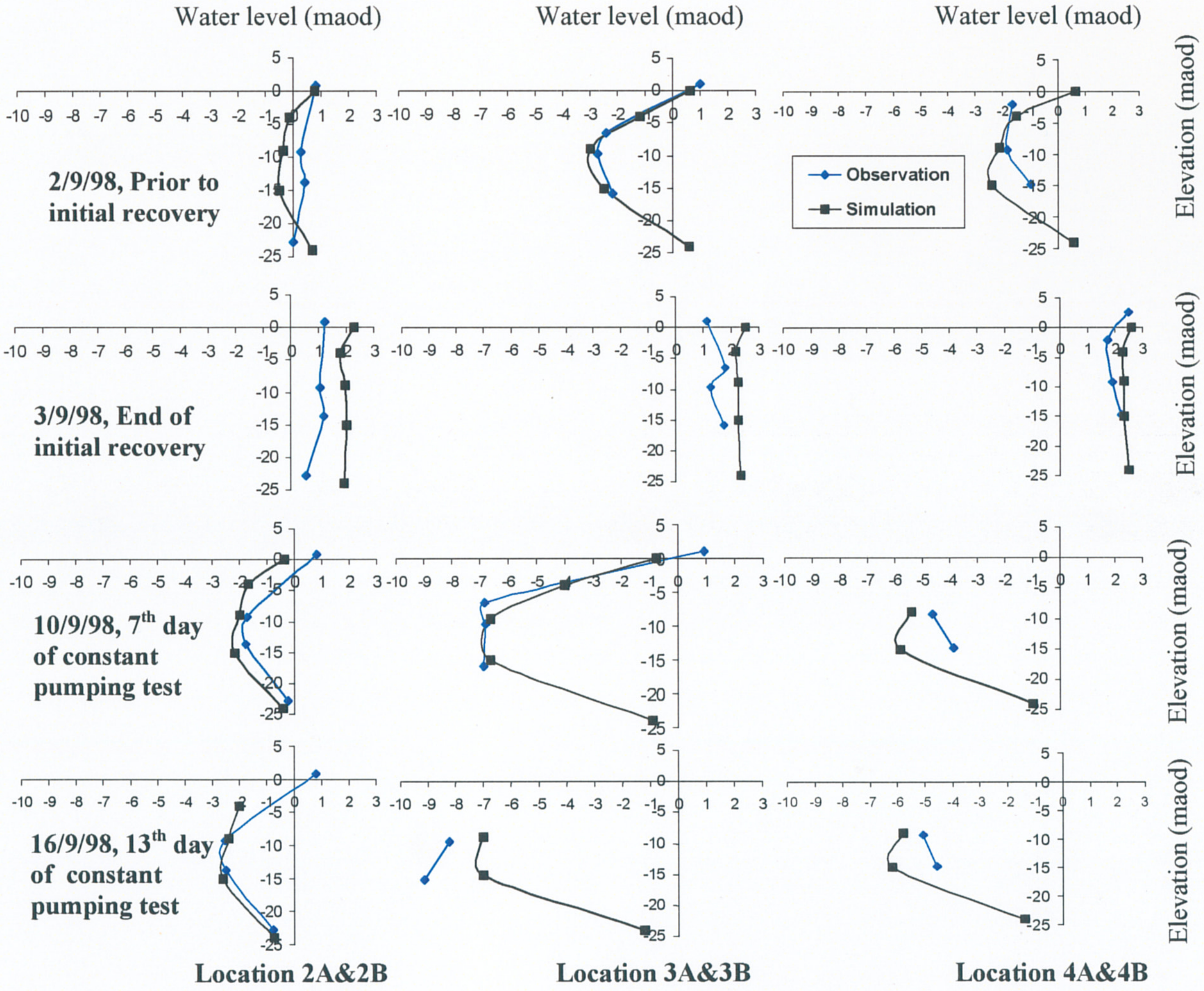

Fig. 3 Model calibration for both steady state (prior to initial recovery) and transient models.

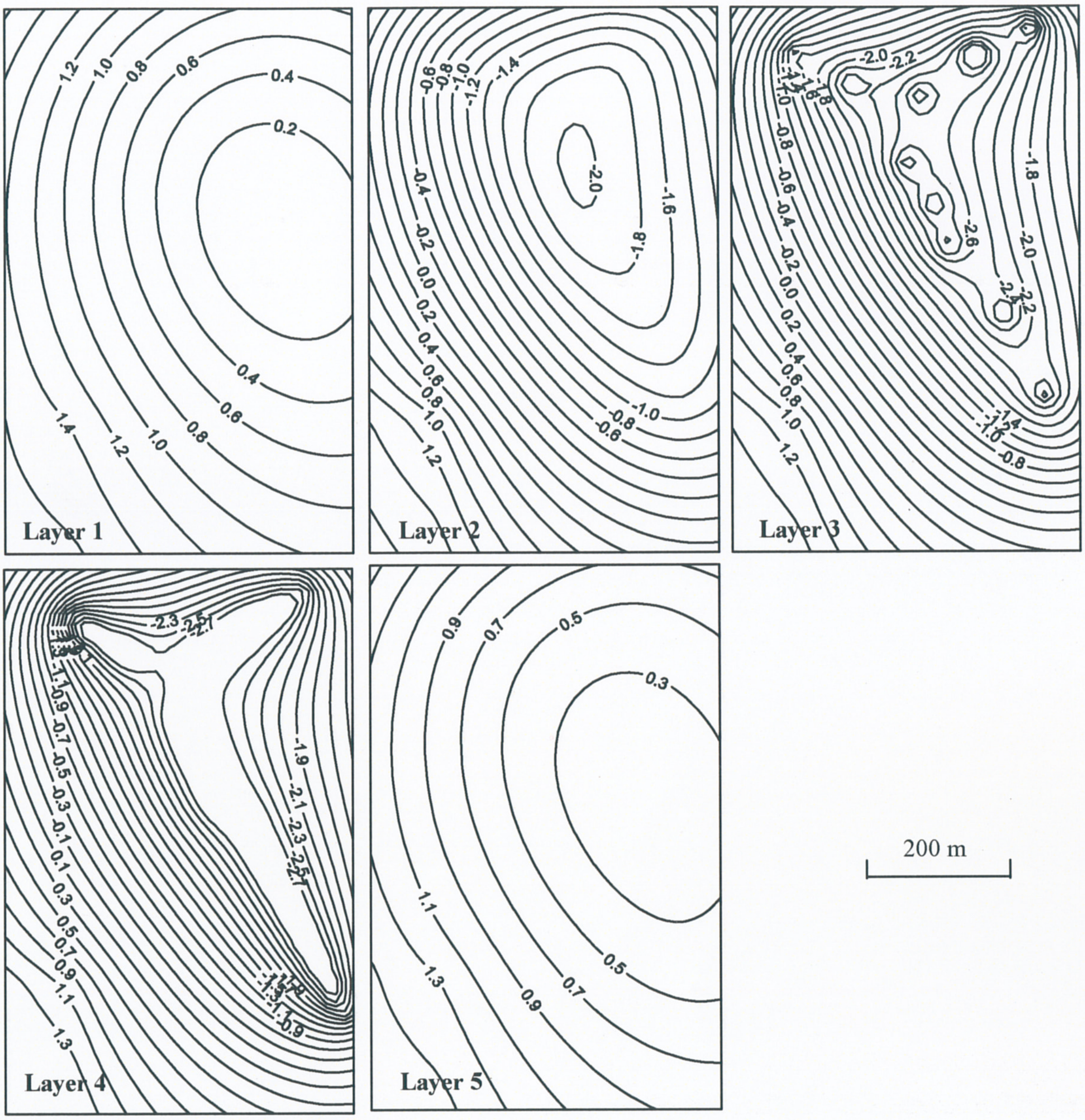

Fig. 4 Simulated groundwater contour maps for steady state model.

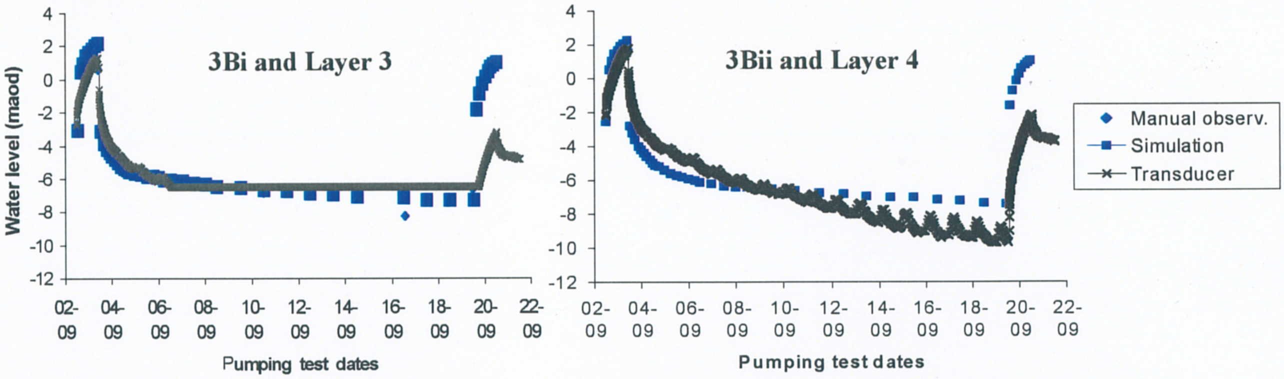

Fig. 5 Comparison of 3Bi&3Bii observations and simulation of Layer 3 & Layer 4 at that location for whole pumping test.

DISCUSSION

The model calibration is generally good. The simulated data are quite close to the observed data for all manual dips (see Fig. 3). This indicates that the adit modelling approach is reasonable for modelling of aquifer-adit interrelation and is able to simulate both steady state and transient hydrogeological situations.

Regarding the entire pumping test process, the simulation of initial recovery and early stage of constant pumping test is good. However, there is a discrepancy between simulated and observed data for the later stages of the pumping test, especially for the layer containing the adit (3Bii and Layer 4 in Fig. 5). This probably has two reasons. The Chalk aquifer is a fissured aquifer, and the distribution of fissures is unknown, so MODFLOW can not simulated it accurately enough. The other reason is that the permeability was mainly calibrated with steady state model, representing water level prior to the pumping test, whereas it was not really a steady state situation. The regional groundwater level declines in summer, therefore the steady state model can not fully present the real hydrogeological controlling factors although the steady state model could produce the similar groundwater level distribution as the observed data.

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Understanding complex adit and shaft groundwater source in a Chalk aquifer

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Abstract

The Cottingham groundwater source is complex, comprising two operational pumping shafts, 17 other shafts and 1000 m of used adit. Understanding the interaction between aquifer, adit and shafts is very important to assess the yield and vulnerability of the source. Numerical models are good tools to assemble and analyse field data and formulate ideas about system dynamics. An integrated groundwater, pipe and open-channel flow computer code has been developed by a combination of a Preissmann slot and MODBRNCH, and used to simulate aquifer-adit systems. Introducing a fictitious narrow slot (Preissmann slot) above the adit makes the equations for open-channel flow also valid for pipe flow. MODBRNCH, an integrated groundwater and open-channel flow model, is adopted. A model of Cottingham was calibrated against multiple targets including steady state and transient conditions, aquifer and adit heads, the head profiles for the quasi steady state, and the temporal changes of heads during a pumping test. Temporal changes of the heads during the pumping test are crucial targets for model calibration. Three alternative conceptual models were tested, each with different hydraulic assumptions about interaction between aquifer, adit and shafts. Only one model was well calibrated to all targets, and had a variable ratio of shaft to adit contributions. The study developed a new understanding of the hydraulics and hydrogeology of the complex Cottingham adit and shaft system, indicates that the integrated code is able to simulate aquifer-adit interaction under transient conditions, and demonstrates that a transient model simulating a pumping test is a necessary approach for modelling adits.

Keywords: Adit; Shaft; Groundwater; Pipe flow; Open-channel flow; Model calibration

1. Introduction

The Chalk is the most important and most widespread aquifer in the UK, 60% of UK groundwater abstraction is from Chalk (Beeson et al., 1995). Figure 1 shows the geology of "Yorkshire Chalk", within which, Cottingham groundwater source studied in this paper is constructed. Many Chalk groundwater sources have adits, which are horizontal tunnels below the groundwater table. The adits are connected to pumped wells to increase the groundwater yield, and often have a number of vertical shafts penetrating them. Adits are typically 1.8 m high and 1.2 m wide, from tens of meters up to 7 km long, and several tens of meters below ground surface. A wide variety of adit layout have been constructed, from simple linear adits to the patterns of radial lines, loops, and branches. Figure 2a shows the adit layout at Cottingham.

The flow in an adit is pipe or open channel flow, and Darcy's formula is not applicable to the adit. An integrated groundwater, pipe and open channel flow model code has been developed to simulate aquifer-adit interactions. This integrated model was applied to steady state conditions at Wilmington pumping station, and the application was successful (Zhang and Lerner 2000). This paper introduces its application under a transient condition.

Cottingham pumping station is one the largest groundwater sources that Yorkshire Water Services has in the Hull area, with a licensed abstraction of 68,182 m^3 d^{-1}, and a mean actual abstraction of 24,000 m^3 d^{-1}. The Cottingham source is very complex comprising two operational pumping shafts, 17 other shafts and about 1000 m adit in use. Understanding the hydraulics and behavior of the Cottingham source is very important to assess the vulnerability of the source and protect it. This paper develops our understanding of the hydraulics of the complex Cottingham adit and shaft water supply system by testing alternative conceptual models against pumping test data.

Three objectives have been achieved in this paper, (1) testing the validity of the integrated groundwater, pipe and open channel flow model under transient conditions, (2) understanding the hydraulics of the Cottingham source by testing alternative conceptual models, (3) demonstrating the essential components and key steps for modelling a complex adit and shaft groundwater source.

2. The Numerical Model

2.1. Adapting MODBRNCH

A model, which couples groundwater with pipe or open channel flow, is needed to simulate aquifer-adit systems. BRANCH (Schaffranek et al., 1981) is an USGS model widely used to simulate one-dimensional unsteady, non-uniform, multiple-branch, interconnected, open-channel flow by solving the following non-linear momentum and continuity equations for open channel flow

$$\frac{\partial Q}{\partial t}+\beta\frac{Q}{A}\frac{\partial Q}{\partial x}+Q\frac{\partial(\beta Q/A)}{\partial x}+gA\frac{\partial Z}{\partial x}+\frac{gk}{AR^{4/3}}Q|Q|=0 \tag{1}$$

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{2}$$

where Q is the channel discharge, Z is the river stage, x is the distance in the longitudinal direction, t is the elapsed time, A is the channel water cross section area, g is the acceleration of gravity, R is the hydraulic radius, k is a function of the flow resistance coefficient, with $k=\eta^2$ in metric system, where η is similar to Manning's n.

The MODBRNCH (Swain and Wexler, 1996) interface incorporates BRANCH into MODFLOW (Harbaugh and McDonald, 1988). The coupling of BRANCH with MODFLOW expands the simulation capability of stream-aquifer interactions including routing of surface flows in a network of interconnected open channels while accounting for the effects of stream velocity and discharge. The linkage between BRANCH and MODFLOW by MODBRNCH is a water exchange term, which is added to the continuity equation (2), and becomes

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}+q=0 \tag{3}$$

where q is outflow per unit length of channel and is calculated from

$$q=\frac{\mathrm{k}'}{\mathrm{b}'}B(Z-h) \tag{4}$$

where k'/b' is the leakage coefficient of the river bed, B is the channel top width, and h is the head in the corresponding aquifer cell. The water exchange term – q – is also added to the continuity equation in MODFLOW.

2.2. *Preissmann slot*

MODBRNCH simulates relations between open channel flow and groundwater successfully. However, adits in the UK are normally full of water, so that the adit flow becomes pressurised, a situation which is not normally handled in MODBRNCH. To overcome the problem, we introduce a fictitious slot (Preissmann slot; Preissmann and Cunge,1961) above the adit. The Preissmann slot is a computational artifice, which makes the equations and numerical methods for a network of open channels also valid for a pressurised pipe network when necessary. This technique is frequently used in modelling of sewerage systems (e.g., Cunge et al., 1980; Abbot and Cunge, 1982). This approach makes the calculated adit cross sectional area remain similar to the actual adit water conveyance area, while the pressurized adit head can be accounted and represented by the water level in the slot, and used by MODBRNCH to calculate the water exchange between aquifer and adit according to their head differences. MODBRNCH allows users to construct a slot above the adit as the actual channel geometry is assigned by defining the channel cross section.

2.3. *Modification to MODBRNCH*

A small modification is needed to handle a Preissmann slot in MODBRNCH. Equation (4) is a good approximation only for streams whose top width is much larger than the flow depth. However, when the slot is introduced, the top width would become the narrow slot width. A better approximation is to use the adit perimeter as the area of water exchange, instead of the top width, replacing Equation (4) by

$$q = \frac{k'}{b'} W_p (Z - h) \tag{5}$$

where W_p is the adit perimeter of the adit and depends on the adit water level. Because the slot is fictitious, there is no water exchange across its perimeter, and the slot is not included in the calculation of W_p.

3. Geology and Hydrology

The Cottingham source is constructed in the Chalk aquifer to the north of the Humber Estuary, part of the "Yorkshire Chalk" (Figure 1). The hydrogeological aspects of this area were studied in some detail in the 1970s (Foster, 1974; Foster and Milton, 1974; Foster and Crease, 1975; Foster and Milton, 1976). The northern part of the Chalk was modeled by University of Birmingham (1985). A model covering the whole Chalk aquifer was developed by Aspinwall and Company (1995). A model covering the Hull area to the north of Humber estuary was developed more recently by Environment Agency (Hodgson and Aldrick, 1996). All of these models represented adits as one or more wells. The following description is derived from the references mentioned above.

Regionally, the Chalk outcrops as the Yorkshire Wolds in the northwest, where the elevation is 100-150 meters above ordnance datum (maod). To the southeast of the outcrop area the Chalk becomes overlain by variable drift cover to the North Sea, and the ground surface is relative flat at 2-15 maod. The drift cover (Boulder Clay, alluvium, sand and gravel) is generally less than 10 m thick west of the buried coastline, but rapidly increase in thickness further east, to a maximum thickness of 50 m. The aquifer varies from unconfined Chalk at outcrop, through semi-confined Chalk in the Hull area, to the fully confined Chalk in the east. The eastern Chalk is rarely used as an aquifer due to restricted groundwater circulation and poor quality. Recharge mainly occurs in the northwest part of aquifer and is pumped from semi-confined aquifer, so the regional groundwater is to the east and southeast directions (see groundwater contours, Figure 1). The River Hull rises as a series of springs from the south of the northern Chalk outcrop, and drains south through Hull to join the Humber Estuary.

The hydraulic conductivity of unfissured Chalk is very low. In practice, high borehole yields imply very high conductivities associated with fissured Chalk. Foster and Milton (1976) developed a schematic interpretation of the Chalk aquifer, which indicates that in the Wolds area there are two well developed fissure zones. The upper fissure zone with a high hydraulic conductivity is the zone of water table fluctuation, and the lower fissure zone with a fairly high hydraulic conductivity is approximately 20 m below the minimum water level. These two zones join together in the semi-confined aquifer and disappear to the southeast Chalk. Figure 3 illustrates this schematic interpretation, for a section running approximately NW — SE. It was successfully used in the model of Aspinwall and Company (1995).

The aquifer properties for the unconfined aquifer are affected by seasonal water level changes. Foster and Milton (1974) found that a significant variation in transmissivity between times of low and high water level. When the water level is above the higher fissured zone the calculated transmissivity is 2200 m^2/d, compared to 1000 m^2/d when the water level is below the higher fissured zone. Very high transmissivity values are found at the area of the buried coastline: Foster and Milton (1976) reported 6000 m^2/d, which is probably due to enlargement of fractures by marine erosion at the time of formation, or the concentration of flow towards springs which emerge above the buried coastline. The transmissivity in the east of the Chalk aquifer is very low (less than 50 m^2/d). This is thought to be the consequence of the lack of groundwater circulation which has meant little enlargement of fissures by dissolution.

Foster (1974) suggested values of specific yield varying from 0.005 to 0.015, which were calculated from the recession of groundwater levels. Higher storage values are associated with the top of the semi-confined Chalk. Modelling studies have used other values; 0.001-0.1 and 0.1-0.15 were used by Aspinwall and Company (1995), and University of Birmingham (1985) respectively.

4. Available Data

The information available on regional hydrogeology includes previous hydrogeological investigations, published papers and the previous modelling studies, listed above, together with observed groundwater levels and rainfall data. This section focuses on the new data, local to the adit, collected for this study.

The Cottingham adits consist of two main systems at –15 maod and –29 maod. The lower system is not used and not connected to the higher system. The shafts were plugged below the higher adits to ensure there was no connection with the lower adits (Crease, 1998).

Thirteen piezometers were installed around Cottingham source prior to a pumping test, which took place in September 1998. One was set within the adit to measure its head, and the other twelve piezometers were separated into three groups and set up around the adit. Each group includes four piezometers located at various levels and installed in two observation boreholes. The locations of the observation boreholes are shown in Figure 2a. The elevations of individual piezometers are shown schematically in Figure 4. Two types of piezometers were selected. Piezometers 1a, 3a and 3b are 50 mm HDPE pipes with 1.5 m slotted screens and filters, and the rest are 19 mm standpipe piezometers with 30 cm casagrande tips. Each pair of boreholes was sealed by a concrete lid. Piezometer measurements were recorded prior to and through the whole pumping test (2nd-19th September 1998). There were two objectives for the pumping test. The first was understanding the fracture development in superficial clays in order to assess the aquifer protection provided by clay cover, which is the subject of another study. The second was characterising vertical variations in hydraulic conductivity and the influences of the adit. The pumping test consisted of a 1-day initial recovery, 15-days constant pumping, and a 1-day final recovery. The pumping schedule is shown in Figure 5a, and the observed groundwater head is shown in Figure 5b.

5. Modelling procedures

It is generally recognized that both head and fluxes should be used as calibration targets (Anderson and Woessner 1992). However, groundwater head is the most commonly used calibration target in the real world. Kim et al. (1999) used multiple targets including steady state head, transient head, head gradient and flowpath information. To understand the Cottingham source and increase the likelihood of obtaining an unique model calibration, we aim to match all available groundwater head measurements from regional to local scale, from steady state to transient conditions, and both aquifer and adit heads. Prior to the pumping test, the system is in a quasi steady state. The relative stable groundwater head before pumping test can be seen in Figure 5b. The heads measured on 2nd September 1998, prior to the initial recovery period, were calibration targets for the local quasi steady state model. The 17-day pumping test was simulated as a transient process.

The model grid around the Cottingham source is required to be sufficiently fine and three dimensional in order to specify the exact positions of adit, shafts, piezometers, and the distinct three dimensional pattern of groundwater flow caused by the adits. However, fine grids need more computer memory and computer time. Moreover the available regional data are not detailed enough to construct a multi-layer model. To focus on the adit site and also to incorporate regional controlling factors into the Cottingham model, the Telescope Mesh Refinement (TMR)(Ward et al. 1987) approach was applied. Local models were extracted from regional models with corresponding pumping stresses.

Head values from the calibrated regional quasi steady state simulation were interpolated and applied as constant head boundaries on the local quasi steady state model. Calibrated parameters in the regional model were used for the initial local model. The calibrated regional quasi steady state model heads were applied as initial heads of the transient regional model. The pumping test was divided into three stress periods, an initial recovery (24 hours), constant pumping (15 days) and final recovery (24 hours). The local transient model was extracted from its regional transient model. The transient head values from the regional transient model were applied to the local model boundaries as general head boundaries for the local transient model.

There are no significant groundwater discharges to the river in the area modelled, so no possibility to use flow data for calibration. Only head data were used as calibration targets, and both qualitative and quantitative criteria were set for both the regional and local models

In the regional model, the simulated groundwater contour map should have similar gradients and patterns to the contour map drawn from 1990 field data (Aspinwall and Company, 1995), which covers the whole model area. Recent field data are available for an area of 50 km^2 around Cottingham. The main calibration target was to match these values within +/- 1 m, as root mean of the squared differences in measured and simulated heads (RMS). This is about 10% of the difference between maximum and minimum heads across the whole model area. In addition, the deviations should be randomly distributed across the model area.

Calibration of the local model focused on matching the head profiles from piezometer groups, and Group 2 was considered the most important as it is nearest the adit. The first target for the quasi steady state simulations was that the simulated head profiles should have similar patterns to the field data, particularly for the heads in the adit and shaft layers because these reflect the interaction between aquifer, adit and shafts. The second target was that the difference between the calculated and observed heads should be around 1 m or less, which is about 25% of the range within a group. Thirdly, the simulated transient heads should have similar temporal trends as the field observations, especially for the adit and Piezometers 2c and 2d, nearest the adit.

6. Regional model

The regional model is a two dimensional MODFLOW model with an area of 550 km^2. It is based on the Environment Agency model, which used the numerical code FLOWPATH (Franz and Guiguer, 1990). The new model is one layer and discretised as a 60 by 44 grid with a spacing of 500 m. The model area and simulated quasi steady state groundwater contours are shown in Figure 1. A no-flow boundary was placed along the groundwater divide to the west, a no-flow boundary perpendicular to groundwater contours in north, constant heads along the Humber Estuary to the south, and a constant head boundary representing equilibrium between sea level and the Chalk aquifer some distance beyond the coast of the North Sea to the east. River nodes were specified along the River Hull. Although the elevation of Chalk base varies from 0 maod in the west to –420 maod in the east, Figure 3 indicates that only well developed fissure zones act as effective aquifer, and rest of Chalk has very low hydraulic conductivity. The base of the aquifer was set up according to Figure 3, and is line with commonly adopted conceptual models of Yorkshire Chalk.

The calibration of the regional quasi steady state model was checked against observed heads for late August 1998. The average pumping rate of August was used. The adit was represented by pumped wells. Recharge was reduced to 50-80% of the FLOWPATH model values while keeping the spatial variation of original. The original model represented average conditions whereas the new model represents the conditions in August 1998. Hydraulic conductivity was based on the FLOWPATH model with some adjustments. The water balance is shown in Table 1. The water balance indicates that abstractions take 84% of the recharge, and 16% of inflow goes to the constant boundaries in the south and east. Very little groundwater discharges to the River Hull in the model area because most inflow is pumped. As mentioned above, the River Hull rises as springs from the south of the northern Chalk outcrop, which is north of the model area. The water in the river is not counted in the water budget. The simulated groundwater contour map has similar gradient and pattern to the measured one. Figure 6 shows the scattered plot of observed against simulated heads for the regional quasi steady state. The deviation of the points is randomly distributed, and the root mean of the squired differences in measured and simulated heads (RMS) is 1.12 m which satisfies the criteria set out previously for the regional model.

7. Cottingham local model

The Cottingham local model has an area of 2 by 2.5 km and is discretised on a 95 by 70 grid. The grid spacing varies from 50 m around the edge of the model to 20 m at Cottingham source. At Cottingham, the Chalk is overlain by about 9 m of drift deposits comprising sandy clay and gravel lenses (Singleton et al., 1998). The elevation of the aquifer base at Cottingham, was estimated at –22 maod by pumping test data analyses (Rippon, 1998) in which the adit was represented by an equivalent borehole. However, the model built by Aspinwall & Company (1995) used –30 maod as the aquifer base at Cottingham, which is approximately the base of high conductivity zone at the abstraction area (Figure 3). So –30 maod was selected as aquifer base at Cottingham. Average hydraulic conductivity is 70 m/d, which is the result of model calibration both for regional and local models. The local model was divided into five layers (Figure 4) according to the lithology, elevation of adit and elevations of multi-level piezometers, in spite of the regional model having only one layer. Some error is introduced in this process. However, considering the model objectives, these small boundary errors are acceptable (Ward et al. 1987), and were not found to cause a problem in the previous study (Zhang and Lerner, 2000).

8. Testing alternative Cottingham local conceptual models

Although several modelling studies have been done at the regional scale, there was no previous modelling study of Cottingham at a local scale. Cottingham is a very complex source comprising 17 shafts and 1000 m adit in use. The model calibration was very difficult and we had to test several alternative conceptual models to obtain good fits for all head measurements including steady state and transient, aquifer and adit heads. The models are:

- Pumped water is fully supplied by the adit.

- Constant part of the inflow is contributed by the shafts.
- Variable ratio of shaft to adit contributions.

8.1. Conceptual Model 1 — pumped water is fully supplied by the adit

It was assumed that pumped water is totally intercepted by the adit directly from aquifer, and shafts were not important because all shafts are lined. Hydraulic conductivity was adjusted between layers in a way that kept the total transmissivity consistent with the regional model. Because hydraulic conductivity usually decreases with the depth in the UK as the fissure density and fissure aperture reduces (Price et al. 1993), the conductivity was initially specified decreasing with depth. Many patterns of vertical distributions of hydraulic conductivity were tried. Values in the range of 100 to 0.01 was tested for the ratio of conductivity in the top layer to the bottom layer. A range of 10 to 100 was tried for the ratio of horizontal to vertical conductivity. The simulated quasi steady state heads were compared to head profiles observed on 2 September 1998. The model could not match the key target of the pattern of head profiles. Comparison of the profiles for the observed heads and Model 1 is shown in Figure 7. The field data shows that the piezometers around –15 maod do not have the lowest heads even though the adit is at this level. For the simulations of conceptual Model 1, the adit elevation always has the lowest head. The difference between observed and simulated heads at piezometers 2c and 3d is nearly 2 m, which does not meet the calibration criterion set out previously. The hydraulic conductivities which gave the best fit for Model 1 are shown in Figure 8. A higher value of conductivity was used for the adit layer to get a higher head in this layer, even though this still does not produce the observed head profile. Transient simulations were not conducted for this model in view of the poor steady state calibration.

8.2. Conceptual Model 2 — Constant part of the inflow contributed by the shafts

A recent survey report states that "Most of the shafts show seepage through joints in the brickwork, both above and below the water table... The brick shafts have occasional bricks omitted probably to allow inflow to the shaft and there are slotted iron sections about 15 m down on the earliest shafts." (Crease 1998). It was realized that part of groundwater inflow probably comes into the shafts first and then flows into the adit. Figure 4 shows the elevation of these shaft inflows (15 m below ground) is –7.5 maod, about the elevation with the lowest head (Figure 7). Taking this information into account, the second conceptual model tested was that a constant part of the inflow is contributed by the shafts.

The shafts were represented by wells pumped from Layer 3, where most shaft leakage takes place. A range of 20% to 50% of total pumping was tested for the shaft contribution. A contribution of 33% matches the quasi steady state observed head profile best. The comparison of the observed heads and Model 2 is shown in Figure 7. Although there is not much difference between simulations of Model 2 and Model 1 for Piezometer Group 1, Model 2 is much better for Piezometer Groups 2 and 3. The simulated head profiles for Piezometer Groups 2 and 3 are very similar to the observed patterns, and differences between observed and simulated heads are all around 1 m or less. The hydraulic conductivities used in Model 2 are shown in Figure 8. The vertical variation of the hydraulic conductivity is small although a little higher value is used for shaft inflow and adit layers. The simulated groundwater contours for the adit layer are shown in Figure 2b. The shape of the contours is very similar to the adit layout.

It was thought that the hydraulic conductivity was well calibrated, so the transient model calibration focused on adjusting the storage coefficient. The heads in aquifer layers and the adit generated from the quasi steady state model were taken as initial heads of the transient model. The shaft water contribution was fixed as 33% of the pumping rate throughout the pumping test. The simulated heads were compared against measurements for the whole pumping test. More attention was paid to Piezometers 2c and 2d and the adit head because the Group 2 is the nearest piezometer set to the adit (Figure 2a), 2d is in the adit layer and 2c is just above the adit. These observations are compared to the simulations of Model 2 in Figure 9a, 9b and 9c. The simulations are not ideal especially for temporal changes of the adit head (Figure 9c) and Piezometer 2d (Figure 9b).

A lot of sensitivity tests were done with this conceptual model. The influences of local model size, hydraulic conductivity, storage coefficient and leakage coefficient were tested to find the best calibration. It was found that reducing the conductivity below and in the adit layer improved the temporal trend of heads but not enough. It was impossible to improve the model calibration significantly with sensible parameters, and so a new conceptual model was needed.

8.3. Conceptual Model 3 — Variable ratio of shaft to adit contributions

The heads of Layer 3 at the end of initial recovery (1.41 maod) and end of constant pumping (-8.11 maod) are shown for Piezometer 2c (just above the adit) in Figure 4. At the end of the test, the head is lower than the likely shaft leakage elevation of -7.5 maod. So it is possible that the shaft contribution decreased to zero over the test. This is the third conceptual model tested.

From the observed temporal change of adit heads (Figure 9c) and aquifer heads in the adit layer (Figure 9b) recorded by Piezometer 2d, one can see that these heads decrease almost linearly, except at the very beginning of the constant pumping. Therefore the decrease in the shaft contribution and increase in adit contribution were taken to be linear with time; a daily stress period was used to simulate these changes. By adjusting the initial and final proportions we found that Model 3 (Figures 9b and 9c) matched the observed trends very well. They are significantly improved over those of Model 2. The best fit was given by an initial shaft contribution of 65% of total pumping which decreased to zero by the end of the constant pumping. Conversely, the adit contribution grew from 35% to 100%. Figure 9d shows these proportions. The hydraulic conductivities used in Model 3 are shown in Figure 8, in which hydraulic conductivity decreases with depth, which is in accord with commonly expected pattern in the Chalk. The ratio of horizontal to vertical conductivity used in Model 3 is 100. The storage coefficients used in Model 3 are 0.01 (unconfined) and 0.0001 m^{-1} (confined), which are within the range of the previous Aspinwall and Company regional model.

The steady state profiles for Model 3 are shown in Figure 7. Although they are not as close to the observations as Model 2, they are much improved over Model 1. This is especially so for Piezometer Groups 2 and 3, for which the differences between observations and simulations are all around 1m or less. The patterns of the head profiles are close to those observed. The simulation of Piezometer Group 1 is not improved. This is further from the adit than the other piezometer groups, and is less sensitive to the abstraction. Overall, Conceptual Model 3 is the best against all the set of calibration targets, including steady state and transient condition, aquifer and adit heads, the head profiles and temporal changes of the heads. The three conceptual models and their calibrations are summarised in Table 2.

9. Discussion and conclusions

An integrated groundwater, pipe and open channel flow model has been created by combining the Preissmann slot approach and a slightly modified MODBRNCH. The new model can successfully simulate aquifer-adit systems under transient conditions.

The model provides a new understanding of the complex Cottingham flow system, with its interactions between aquifer, adit and shafts. In particular, there is a portion of the inflow which enters through many shafts. There is evidence that this shaft inflow has been encouraged, for example by removing bricks from the linings. We speculate that this was done to increase yield. The shaft inflow depends on groundwater level, which will have consequences for sustained yield and security of supply. Groundwater levels were decreasing linearly at the end of the pumping test, and it is probably that this pumping rate (51,000 m^3/d) can not be sustained indefinitely. The shaft inflows will be sensitive to regional groundwater level, and are likely to reduce during a prolonged drought.

The aquifer layer containing and below the adit has low values of hydraulic conductivity. This low conductivity zone corresponds to the lower part of the fissure zone in Figure 3. The model calibration indicates that the hydraulic conductivity in the lower part of the fissure zone is probably 1-2 orders of magnitude smaller than that in upper part of the fissure zone. A storage coefficient of 0.0001 m^{-1} was used for the confined layer.

The test of alternative conceptual models reveals that calibration of groundwater models can not always be achieved by adjusting parameter values, and it is necessary to build a correct conceptual model. Hydraulic and hydrogeologic judgement is essential for conceptualizing a hydrogeological system. Consideration of shaft inflows gave the correct head profiles for the quasi steady state model (from Model 1 to Model 2). A pumping test was necessary in order to fully understand the hydraulics and hydrogeology of adit and shaft systems; this required a transient numerical model. Without the transient model we would not have discovered that the shaft contribution depends on aquifer head and the lower layers have lower hydraulic conductivities (from Model 2 to Model 3). The temporal changes of heads during a pumping test is a crucial calibration target, and the heads within the adit are particularly useful for analysing adit systems.

Acknowledgement

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Captions for tables and figures

Table 1 Water balance for the quasi steady state regional model

Table 2 Summary of the calibrations of the conceptual models

Figure 1 Solid and Drift geology of the Hull area, regional model area and simulated regional groundwater levels, and location of Cottingham.

Figure 2a Cottingham adit layout, shaft and piezometer locations

Figure 2b Simulated groundwater head around adit prior to the pumping test

Figure 3 Schematic hydrogeological interpretation of Yorkshire Chalk

Figure 4 Elevations of aquifer layers and piezometers in maod (see Figure 2 for locations).

Figure 5 Pumping schedule (a) and groundwater responses in Piezometer 2d (b).

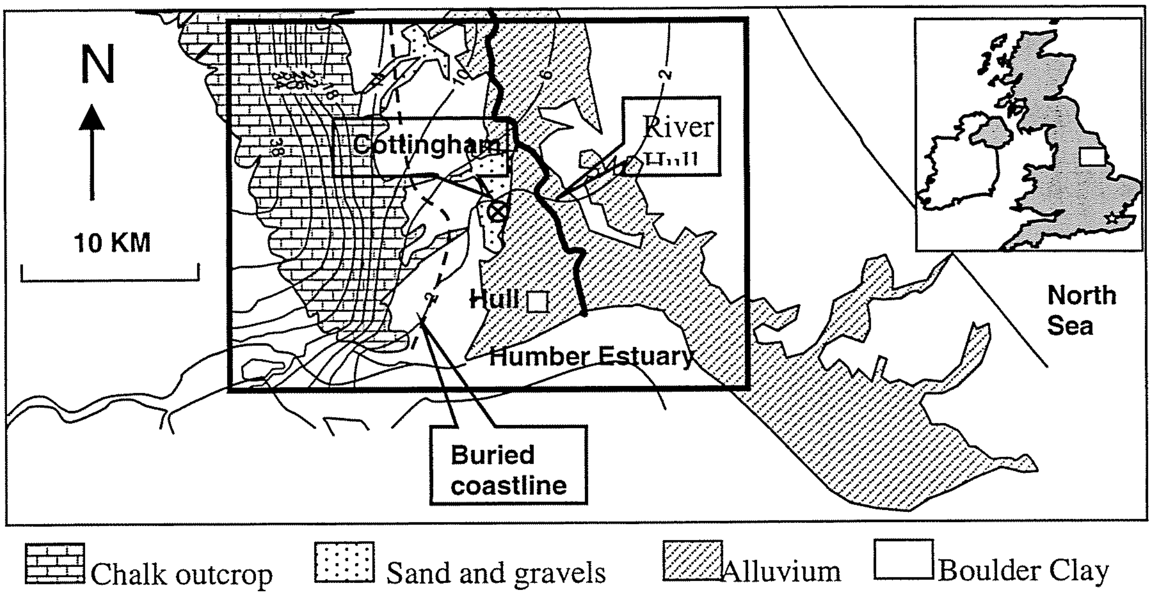
Figure 6 Calibration of regional model, RMS is 1.12 m

Figure 7 Comparisons of observed heads and simulated heads for alternative models at quasi steady state condition

Figure 8 Comparison of hydraulic conductivities used in various conceptual models

Figure 9a, b and c Comparison of observation and simulations of Model 2 and Model 3

Figure 9d Comparison of proportions of shaft inflow selected in Model 2 and Model 3



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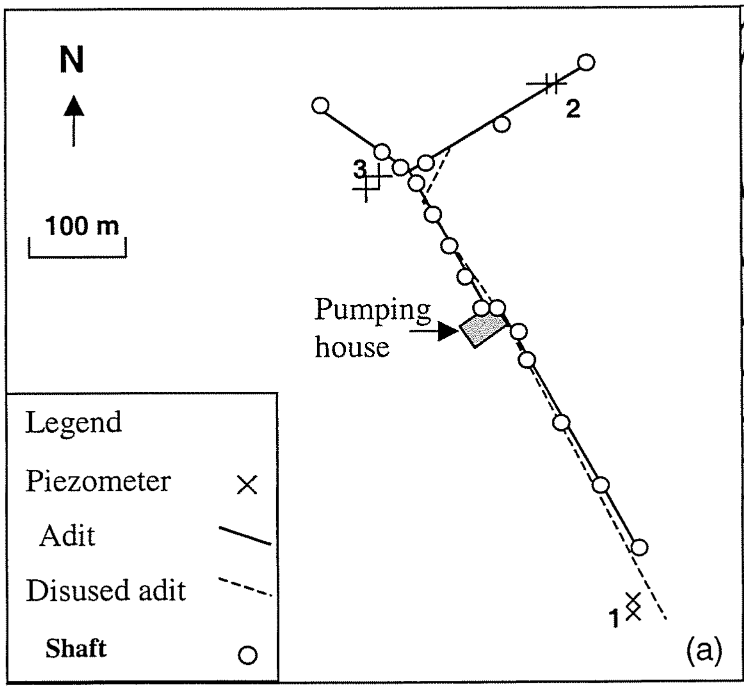

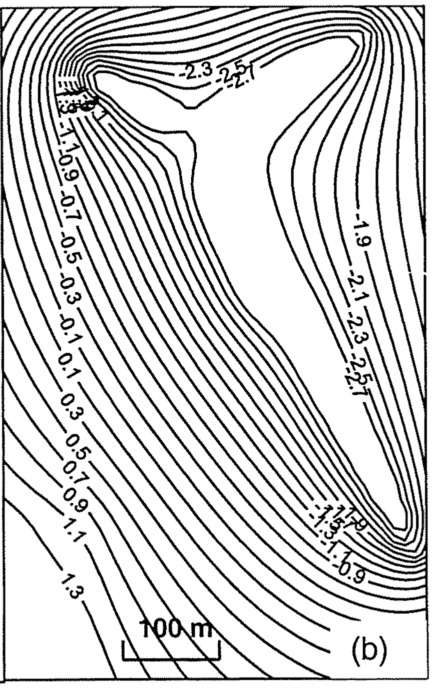

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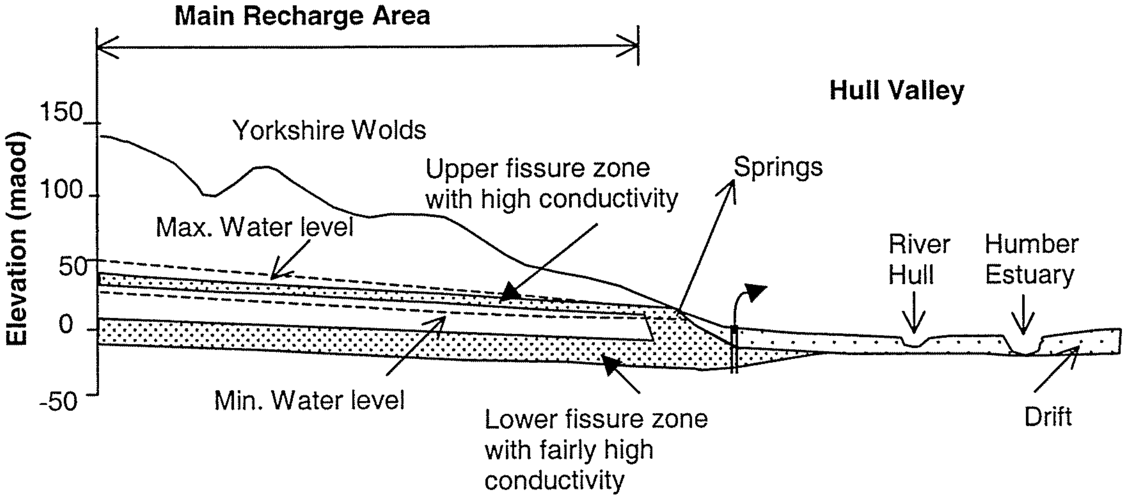

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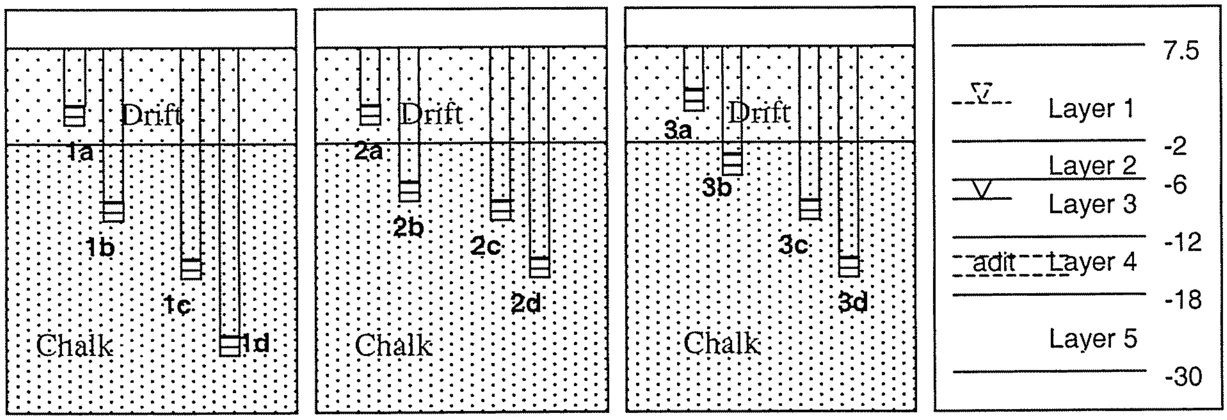


Legend: ⊟ Piezometer;
_▽_ Head in Piezometer 2c at the end of initial recovery;
—▽— Head in Piezometer 2c by the end of constant pumping.

Figure 4 Elevations of aquifer layers and piezometers in maod (see Figure 2 for locations).

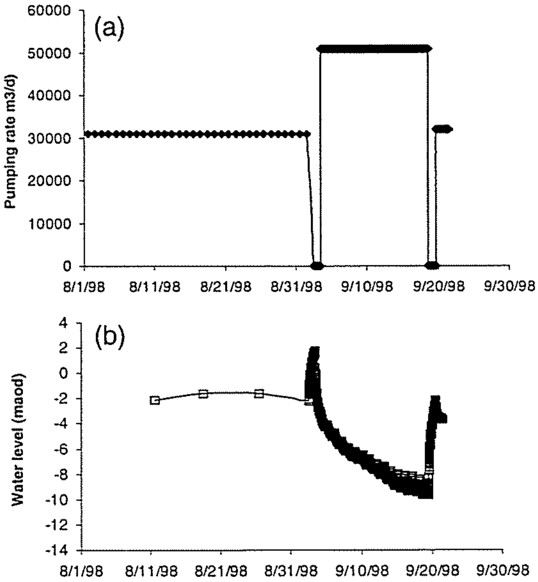


Figure 5 Pumping schedule (a) and groundwater responses in Piezometer 2d (b).

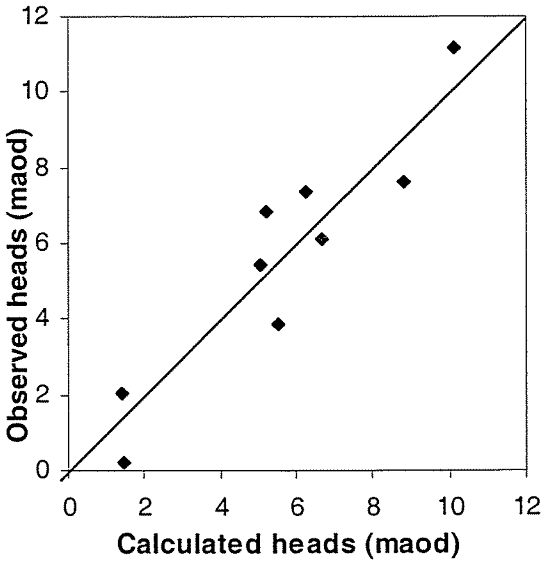
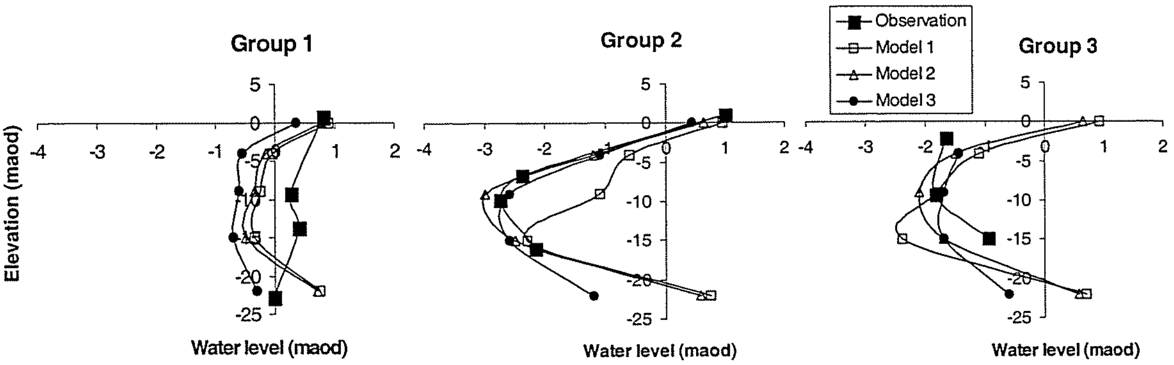


Figure 6 Calibration of regional model, RMS is 1.12 m



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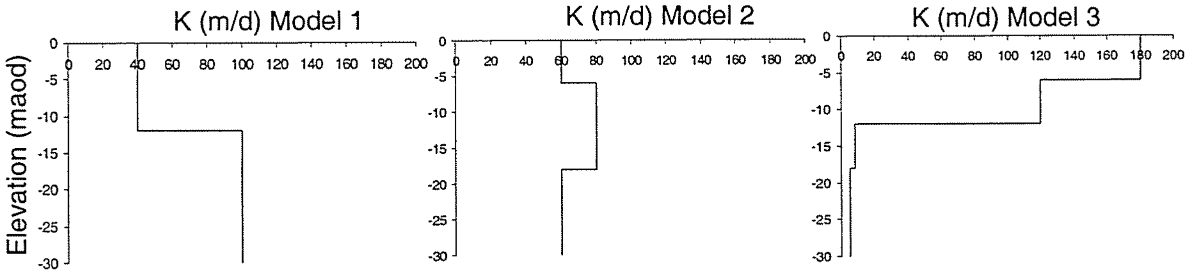

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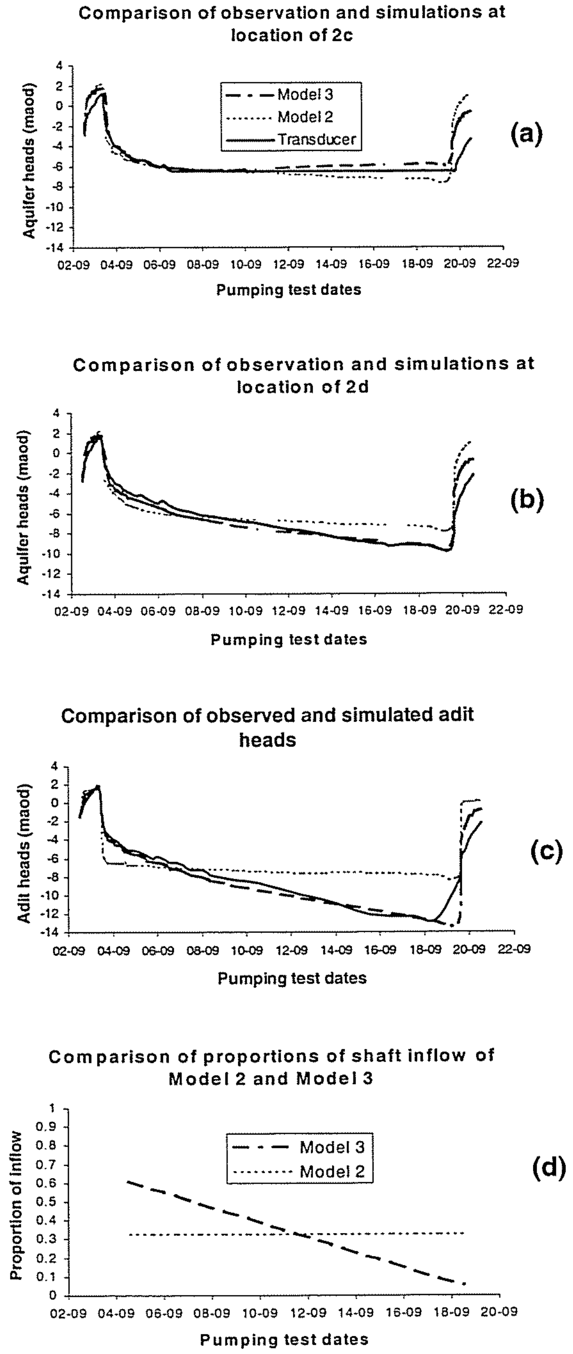

Figure 9a, b and c Comparison of observation and simulations of Model 2 and Model 3

Figure 9d Comparison of proportions of shaft inflow selected in Model 2 and Model 3

Submitted

Delineation of Projected Flow and Time-of-Travel Zones for the Adit Sources

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ABSTRACT

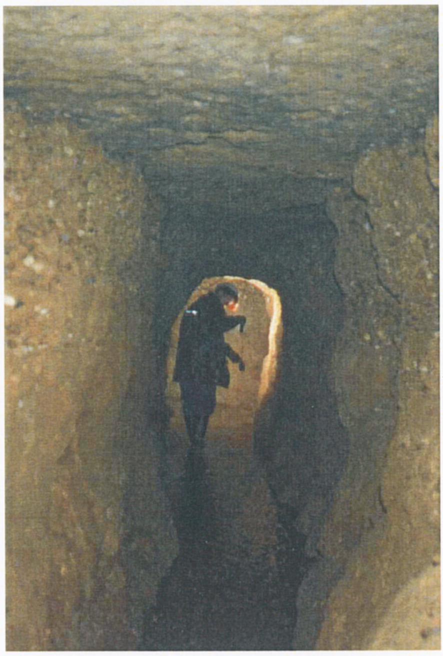
Ground water protection requires delineation of protection zones for various types of ground water sources. A numerical model coupling ground water and pipe flow has been developed to calculate the flow field around adits, which are tunnels below the water table used to increase the yield of many ground water sources in the UK Chalk aquifer. MODPATH was used to compute pathlines and to delineate protection zones. The concept of Projected Flow Zones (PFZs) and Time-of-Travel Zones (PTTZs) has been used. PFZs always include both catchment area and PTTZs. The influences of boundary conditions, abstraction, recharge, hydraulic gradient and adit length on the position, shape and size of PFZs were examined. This numerical model was also compared with other modeling methods, such as assigning a high value of hydraulic conductivity along the adit and replacing the adit by multiple boreholes. The comparison indicates that the high K method is a good approximation although very high values of K are required (10^3-10^6

m/d). A criterion is given which allows one to judge when the multi-borehole method is valid. Finally 2D models are shown to be adequate to simulate PFZs and PTTZs around adits for the conditions likely to be found in the UK Chalk.

INTRODUCTION

The Chalk has always been recognized as a source of water supply, and is the most important and widespread aquifer in the United Kingdom (Downing et al. 1993). Many Chalk ground water sources have adit systems which are horizontal tunnels under the water table. Yields were often increased by driving adits in different directions. Systems of adits are typically 1.2 m wide and 1.8 m high (Figure 1), up to 7 km long, and several tens of meters below ground surface. Adit systems have various patterns of layout including linear adits, radial lines, loops and branches. The flow in an adit may be pipe or open channel flow, and will cause a distinct three dimensional pattern of ground water flow.

Figure 1 Dewatered adit



The protection of ground water supplies is usually based on identifying wellhead protection areas (WHPAs) (USEPA 1987). These are called ground water source protection zones (GPZs) in England and Wales (NRA 1995). One of the most important zones is the well catchment, the area from which recharge will eventually reach the well. Time-of-travel zones are areas encompassed by equal travel time and are contained by and smaller than their catchment.

Previous work

A number of computational methods have been developed to determine the catchments and time-of-travel zones for a single well. The first attempt to estimate the catchment was made by Todd (1959) in an infinite, homogeneous, isotropic aquifer where the recharge is homogeneously distributed over the aquifer surface. Starting from the stagnation point determined by zero velocity, the area within the separating stream line is integrated in the upstream direction until it reach the area given by the equation below

$$A = \frac{Q}{R} \tag{1}$$

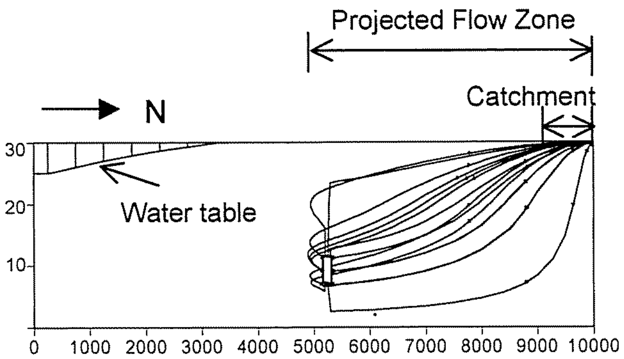
where A is catchment area (L^2), Q is pumping rate (M^3T^{-1}) and R is recharge (LT^{-1}). As an approximation, he used the separating streamline of a well in uniform parallel flow without areal recharge which is given by an analytical solution (Muskat 1937). Bear and Jacobs (1965) derived the general equation of isochrones under the same assumptions. Their result for the infinite time-of-travel isochrone is identical to Jacob's (1950) stream function for infinite time. Brown (1963) calculated the catchment of a well in the center of an aquifer receiving uniform recharge and bounded by two streams at the same elevation. He did this by calculating water table elevations and then manually drawing the catchment. In more recent publications, Nelson (1978a, b) developed the first semi-analytical computer model for path line tracing. Keely and Tsang (1983) used the same methods as Nelson but present their work in terms of capture zones. This work was extended by Javandel and Tsang (1986) to look at nondimensional expressions of capture zones. Aquifer boundaries and areal recharge were not taken into account in these models. The United States Environmental Protection Agency published the WHPA models (Blandford and Huyakorn 1991). One of their semi-analytical models called GPTRAC included boundaries and areal recharge. Another semi-analytical path line tracing model called ROSE was developed by Lerner (1992). He generalized shapes of catchment and time-of-travel zones for aquifers with recharge. Nowadays numerical models are widely used tools for delineation of catchment and time-of-travel zones. The ground water flow model MODFLOW (McDonald and Harbaugh 1988) and the linked pathline tracing code MODPATH (Pollock 1989) are widely used.

The current method for delineation of GPZs for adit sources in the United Kingdom is to use a numerical model and either assign a large value of hydraulic conductivity in the adit cells or to distribute the abstraction as several wells to replace the adit. The efficiency of these methods has never been evaluated. The only published relevant work was presented by Schafer (1996). He delineated three-dimensional capture zones for horizontal drains using the analytical solution. The study assumed that the horizontal drains were in homogeneous, anisotropic and infinite aquifers in a uniform flow field.

Projected Flow Zone

Ground water protection has been focused on delineation of catchment and time-of-travel zones. However Kinzelbach et al. (1992) pointed out that confining the protection zone to the actual catchment area is not sufficient. Figure 2 shows an example in which an adit with a length of 1 km is located in the center of an aquifer with dimensions of 17 by 10 km, a thickness of 30 m, an impervious boundary to the north and a constant head boundary to the south. The adit is located between the elevations of 8-10 m. A uniform recharge of 200 mm/year was used and 10,000 m^3/d was abstracted. The aquifer was homogeneous and isotropic. Figure 2 illustrates that the adit is not included in, and is far from, the catchment, but the projected flow zone covers the adit, the catchment, and all of the aquifer through which flow to the adit takes place. The region between the adit and the catchment area should be protected to cover the risks of spills of dense nonaqueous liquids. Therefore the protection zone should comprise the complete projection of flow zone on to the ground surface (Kinzelbach et. al. 1992). Martin and Frind (1998) also used the projection of three-dimensional flowpaths as capture zones. The definitions of catchment and projected flow zone are:

Figure 2. Pathlines in a cross-section showing the difference between the catchment and PFZ for an adit (see text for details of simulation).



Catchment or Recharge Area is defined as the area from which all recharge discharges at the well.

Projected Flow Zone (PFZ) comprises the projection on to the ground surface of the subsurface zone through which passes all ground water flow to the well.

By analogy to PFZs, Projected Time-of-Travel Zones (PTTZs) are used. This paper introduces a technique of delineating PFZs and PTTZs for adit sources by numerical modeling, in which the real boundary conditions and aquifer heterogeneity can be integrated. Three objectives have been achieved: (1) demonstrating the shapes of PFZs and PTTZs, and some influences of boundary conditions and hydrogeological parameters; (2) evaluating alternative methods of delineation; (3) evaluating necessity of using three-dimensional models.

THE NUMERICAL MODELS

The computation of pathlines requires knowledge of the flow field at any point in the aquifer. Although Chalk aquifers are fissured aquifers, Darcy's law is also valid for flow in fissures provided the Reynolds number is less than about 2300 (Barker 1993). Barker (1993) indicates that an equivalent porous medium with parameters chosen to be characteristic of the fissured rock can be used satisfactorily in modeling, as has commonly be done for Chalk aquifers (e.g., Aspinwall & Company 1995). So modeling adit systems in the Chalk aquifers requires a model coupling porous flow in the aquifer with pipe flow in the adit. The spatial ground water head distributions and inter-cell flow rates were calculated by a numerical flow model coupling pipe and ground water flow, which is compatible with MODFLOW. The pathline code MODPATH, a post-processor of MODFLOW, was selected to compute three-dimensional pathlines and the position of particles at specified points in time.

The Flow Model

A model, which couples ground water with pipe or open channel flow, is required to simulate aquifer-adit interactions. BRANCH (Schaffranek et al. 1981) is an USGS model widely used to simulate one-dimensional unsteady, non-uniform, multiple-branch, interconnected, open-channel flow by solving the St. Venant equations. The MODBRNCH (Swain and Wexler 1996) interface which is also an USGS code incorporates BRANCH into MODFLOW. The coupling of BRANCH with MODFLOW expands the simulation capability of stream-aquifer interactions including routing of surface flows in a network of interconnected open channels while accounting for the effects of stream velocity and discharge. The linkage between BRANCH and MODFLOW by MODBRNCH is a water exchange term which is added to continuity equations in MODFLOW and BRANCH respectively.

MODBRNCH simulates relations between open channel flow and ground water successfully. However, adits in the United Kingdom are normally full of water, so that the adit flow becomes pressurized, a situation which is not normally handled in MODBRNCH. To overcome the problem, we introduce a fictitious slot (Preissmann slot; Preissmann and Cunge 1961) above the adit. The Preissmann slot is a computational artifice, which makes the equations and numerical methods for a network of open channels also valid for a pressurized pipe network when necessary. This technique is frequently used in modeling of sewerage systems (e.g., Cunge et al. 1980; Abbot and Cunge 1982). This approach makes the calculated adit cross sectional area remain similar to the actual adit water conveyance area, while the pressurized adit head can be accounted and represented by the water level in the slot, and used by MODBRNCH to calculate the water exchange between aquifer and adit according to their head differences. MODBRNCH allows users to construct a slot above the adit as the actual channel geometry is assigned by defining the channel cross section. A small modification has been made to handle a Preissmann slot in MODBRNCH (Zhang and Lerner 2000). Pumping from the adit is handled by setting a constant discharge from the pipe flow network at the position of the pumping well. Experience has shown that the position of this pumping point does not affect the PFZs. The combination of Preissmann slot and MODBRNCH produces a model coupling pipe and ground water flow, and its application has been successful for steady state (Zhang and Lerner 2000) and transient problems (Zhang and Lerner submitted).

MODPATH and Backward Tracking

MODPATH is widely used for calculations of pathlines based on the output from steady-state simulations obtained with MODFLOW. MODPATH uses a semi-analytical particle tracking scheme. The method is based on the assumption that each velocity component varies linearly within a grid cell. This assumption allows an analytical expression to be obtained describing the flow path within a grid cell. The linear interpolation scheme for velocities based on the inter-cell flow rates from MODFLOW guarantees the continuity of the velocity field within each individual cell.

In order to calculate the PFZs and PTTZs for adit sources, particles were placed around the adit and tracked backwards. The particles were placed along external faces of adit cells (the cell face between two adit cells is an internal face). The plan view projection of the three-dimensional pathlines delineates the PFZ. Particles are stopped when they reach inflow boundaries or when they enter cells containing strong internal sources.

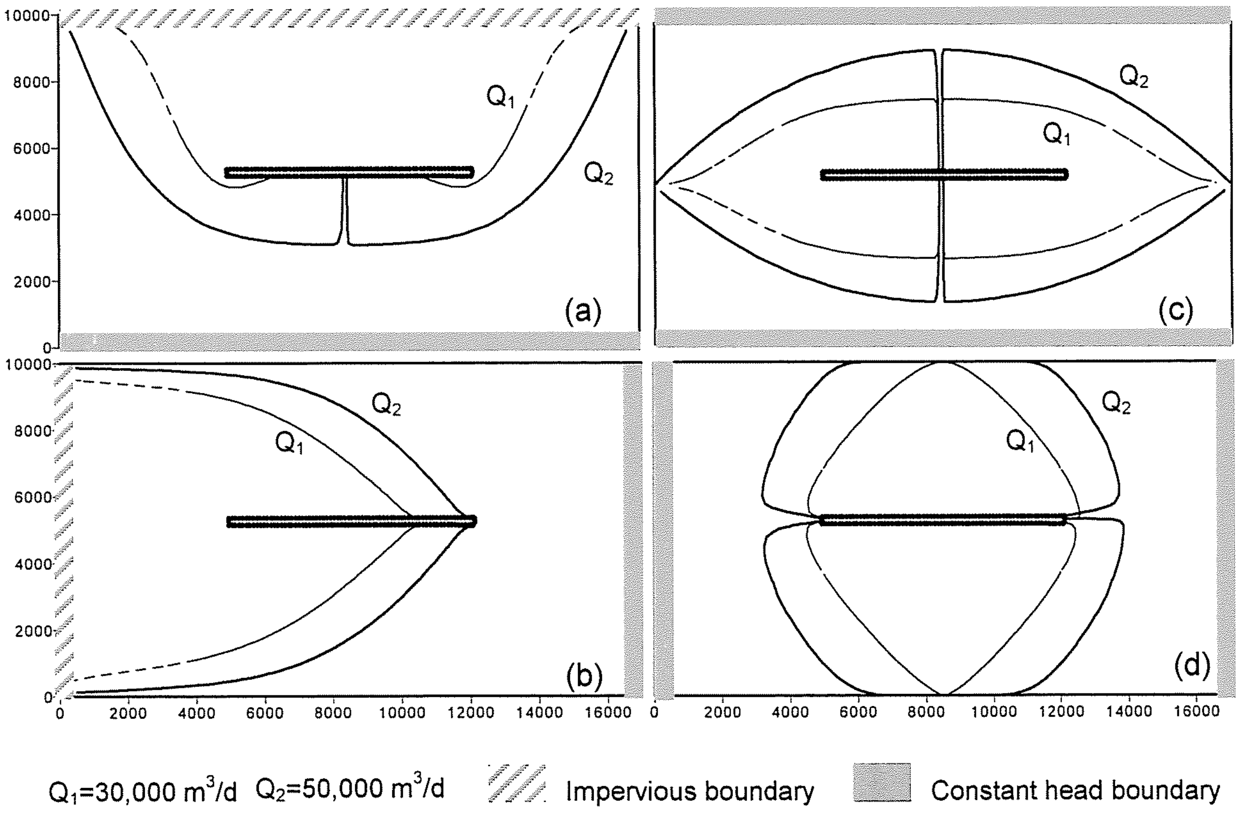
The backward tracking works well if the hydraulic gradient is caused by abstraction alone (e.g., adit is between two equal constant head boundaries). The size and shape of the envelope of pathlines depends on the adit's orientation, length, pumping rate, recharge and the distances from the adit to the boundaries. Backward tracking also works if there is an impervious upstream boundary, and the adit has a large abstraction, is close to the impervious upstream boundary, or is located at bottom of the aquifer. However, with an impervious upstream boundary, and a small or distant abstraction and a shallow well screen, the backward tracking does not work satisfactorily. In these circumstances, the backward pathlines should not reach the impervious upstream boundary (Kinzelbach et al. 1992), but they always do reach it with MODPATH. This problem has not been reported previously probably because most work on the delineation of catchment has been done in two-dimensional models. These assume that the well is fully penetrating so the pathlines should reach the impervious upstream boundary. Forward tracking works correctly, with particles starting near the impervious upstream boundary passing underneath the well. However forward tracking is an inefficient way to delineate catchments or PFZs.

A solution is possibly by defining the water table as a specific zone because MODPATH allows pathlines to be stopped at specified zones. However this can only be done outside the interface (Visual MODFLOW) which requires a lot of extra work especially when the water table has a strong gradient. Fortunately, our study focused on adit sources in the Chalk aquifers which generally have a small effective aquifer thickness (<50 m)(Price 1993). The adits usually have large abstractions and are located near the bottom of the effective aquifer. Therefore this weakness of MODPATH has not affected our results.

SHAPES OF PFZS

A 17 by 10 km artificial aquifer with a thickness of 30 m was selected for the simulation, an uniform recharge of 200 mm/year, and hydraulic conductivity of 80 m/day was used, which are common values for fissured Chalk in the UK (Zhang and Lerner 2000, submitted). A vertically uniform value of horizontal hydraulic conductivity K_h was used so the 2D and 3D models can be compared easily. 10% of K_h was used for vertical conductivity K_v as we found that PFZs are not sensitive to K_v. An adit having a length of 7 km was positioned at the center of the aquifer in plan view, and is parallel to the longer sides of the aquifer (Figure 3, the numbers on the axes are meters on this and other figures). The aquifer is discretized on a grid of 94 by 28 with a spacing of 100 m around the adit, and is divided into 4 layers. The top layer represents the Tertiary deposits, and the other 3 layers represent Chalk aquifer. One layer is above the adit, one layer has the adit in it, and one layer is below the adit, so the adit is located in Layer 3 about 20 m below the ground surface. The water was pumped out from the center of the adit.

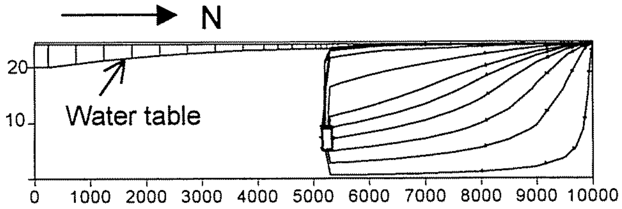
Figure 3. Plan views of PFZs with various boundary conditions, orientations and pumping rates. The numbers on the axes are meters.



4 types of aquifer-adit systems were simulated: (1) adit parallels the upstream impervious boundary (Figure 3a, northern boundary); (2) adit is perpendicular to the upstream impervious boundary (Figure 3b, western boundary); (3) adit is parallel to two constant head boundaries (Figure 3c, northern and southern boundaries); (4) adit is perpendicular to two constant boundaries (Figure 3d, western and eastern boundaries). These 4 types of systems were selected because it is found that the boundary conditions and the relative orientation between boundaries and adit are controlling factors on the shapes of PFZs.

Figure 3 demonstrates that the shapes of PFZs for adit sources depend on the boundary conditions and the orientations of adits. For presentation purposes, most pathlines were deleted, only outer lines were left to mark the areas of PFZs. For the systems shown in Figure 3a and b, the PFZs reach the upstream impervious boundaries. For the bigger abstraction (50,000 m^3/d), PFZs enclose the adits. For the smaller abstraction (30,000 m^3/d), some sections of the adits are not clearly encompassed by the outer pathlines. Figure 3a indicates that the ground water divide on the downstream side of the adit could reach the edge of the adit when the pumping rate is small. In this situation the water comes from upstream side of the adit and the two ends of the adit, but little water comes from downstream side of the adit. Figure 4 shows the pathlines in cross-section at center of the adit when the abstraction is 30,000 m^3/d in Figure 3a. Figure 3b indicates that part of the adit does not contribute to the abstraction if the adit is perpendicular to the upstream impervious boundary and the pumping rate is small. However, the whole adit should be protected in case of changes in flow conditions.

Figure 4. Pathlines in a cross-section perpendicular to the adit in Figure 3a when the abstraction is 30,000 m^3/d.



For the systems shown in Figure 3c and d, the two constant head boundaries have equal heads. The gradients in Figure 3c and d are only caused by pumping from their adits. So the PFZs in these two systems are symmetrical in both north-south and west-east directions.

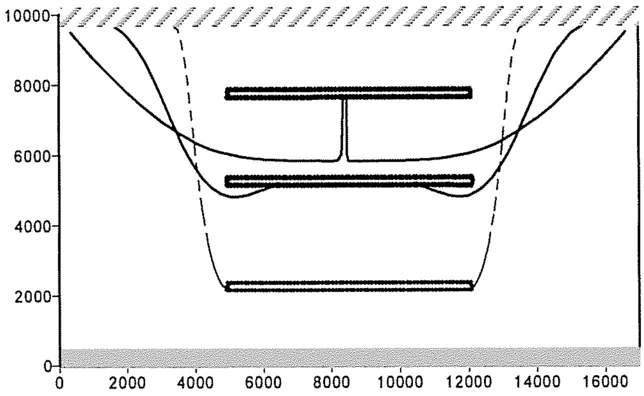
Influences of pumping rate Q and recharge R

Several authors have shown the size and shapes of the catchments of single wells are invariant if the ratio of Q:R is kept constant as would be expected from water balance considerations (Kinzelbach et al. 1992; Lerner 1992). This study found a similar result for PFZs of adit sources.

Influence of the distance from adit to the upstream boundary

Figure 5 shows the influence of the distance from the adit to the upstream impervious boundary. The aquifer has the same boundary conditions as Figure 3a, i.e., an impervious upstream boundary to the north and a constant head boundary to the south. A pumping rate of 30,000 m^3/d was used for all three cases. Decreasing the distance from the upstream boundary shortens the PFZ in the flow direction but lengthens it in the adit direction. Water comes from both upstream and downstream sides when the adit is closer to the impervious upstream boundary. With increasing the separation, more or even all of the water comes from the upstream side of the adit.

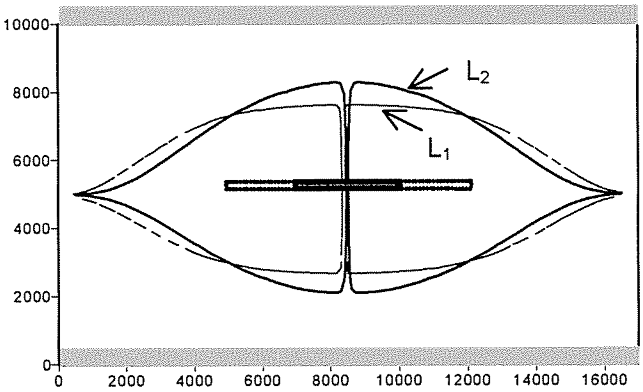
Figure 5. The shapes and positions of PFZs from various distances between the adit and the upstream impervious boundary.



Influence of adit length

Figure 6 has the same boundary conditions as Figure 3c, i.e., the adit parallels two constant head boundaries. Figure 6 compares the PFZs where the same amount of water (30,000 m^3/d) is pumped from adits with lengths of 3 km and 7km. The longer the adit, the narrower and longer the PFZ.

Figure 6. Comparison of shapes of PFZs pumped from adits with different lengths respectively.

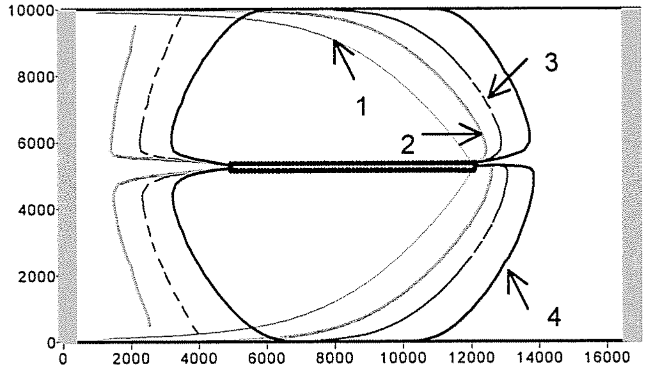


L_1=7 km, L_2=3 km

Influence of hydraulic gradient

Figure 7 shows the influence of hydraulic gradient on the positions and shapes of PFZs. An abstraction of 50,000 m^3/d was pumped from the middle of the adit between two constant head boundaries. Each curve represents a different value of regional gradient. With increasing hydraulic gradient the PFZ approaches the shape in Figure 3b. As long as the gradient is small enough, the PFZ does not reach the upstream boundary and confined by a water divide at its upstream end.

Figure 7. Influence of regional hydraulic gradient on the positions and shapes of PFZs.



1: • h=15 m, 2: • h=10 m
3: • h=5 m, 4: • h=0

Influences of other parameters

The influences of other parameters on the position and shape of PFZs such as aquifer thickness, adit elevation and anisotropy were also tested. The range of aquifer thickness tested was 30-100 m. The anisotropy ratio of 1 to 0.01 (K_v to K_h) were tested. Adit depths of 20 m and 80 m below the ground surface were tested for 100 m thick aquifer. The position and shape of PFZs are not sensitive in these parameter ranges.

COMPARISON WITH OTHER METHODS

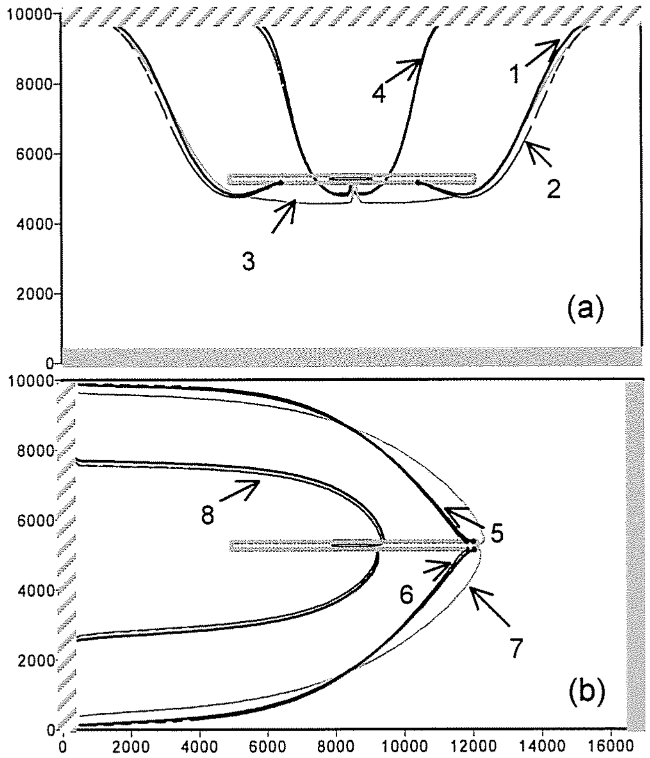
The PFZs delineated in the previous sections were computed by MODPATH using the head distribution from MODBRNCH. The results are compared here with other methods. MODPATH was still used to calculate the pathlines, but the ground water head distributions were from MODFLOW using either a high value of hydraulic conductivity to simulate the adit or replacing it with multi-boreholes. The two methods are currently used by the Environment Agency. The tests were carried out with the four systems shown in Figure 3. Various lengths of adits and different pumpages were used. Almost identical PFZs were obtained by using three different methods for the systems of Figure 3c and d in which the PFZs are symmetrical in both directions.

For the boundary conditions shown in Figure 3a and b in which there are impervious upstream boundaries, MODBRNCH and the high K method derive very similar PFZs. However there are discrepancies between the PFZs generated by the multi-borehole method and other two methods in some cases. The discrepancies depend on pumping rate, recharge, distance to the impervious upstream boundary and adit length. An empirical criterion has been determined to show when the discrepancies are significant. This is a feature number which is given by

$$f = \frac{Q}{RaL} \tag{2}$$

where f is feature number, L is adit length (L), and a is the separation between the upstream boundary and the downstream end of the adit (L). For f• 2.5 the three methods generate almost identical PFZs. Figure 8 shows the similarities and discrepancies of PFZs obtained by the three methods for various values of f. Examples 4 and 8 have f • 2.5 and very similar PFZs were obtained by three methods. For all the other examples, $f < 2.5$ and the PFZs from the multi-borehole method are different from the PFZs obtained by the other methods.

Figure 8. Comparisons of PFZs derived by MODBRNCH, high K and multi-borehole methods for various values of f.



1: f=1.6, Q=30,000 m^3/d, L=7 km, MODBRNCH
2: f=1.6, Q=30,000 m^3/d, L=7 km, high K
3: f=1.6, Q=30,000 m^3/d, L=7 km, multi-borehole

4: f=3.6, Q=10,000 m^3/d, L=1 km, three methods

5: f=1.1, Q=50,000 m^3/d, L=7 km, MODBRNCH
6: f=1.1, Q=50,000 m^3/d, L=7 km, high K
7: f=1.1, Q=50,000 m^3/d, L=7 km, multi-bore

8: f=4.1, Q=20,000 m^3/d, L=1 km, three methods

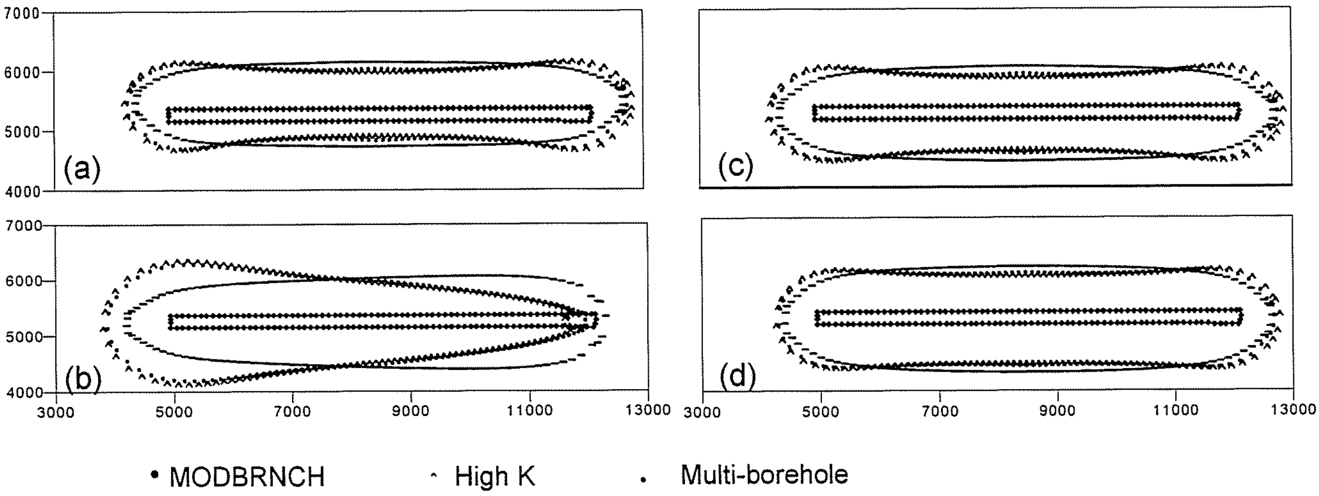
In general, the high K method is a good approximation of MODBRNCH to delineate PFZs. The high K values used in this study are very high, about 10^3-10^6 m/d. With decreasing adit length, the high K value can be reduced. For an adit of 1 km, a K of 10^3 m/d works fine. For an adit of 7 km, one has to use a K value of 10^5-10^6 m/d. The PFZ is sensitive if the K value is not high enough, but is not sensitive when the K value is higher than it is required.

DELINEATION OF PROJECTED TIME-OF-TRAVEL ZONES (PTTZs)

A 50-day time-of-travel zone is used as Inner Zone I in Britain (NRA 1995), and protection zone II in Germany (DVGW 1975). This essentially guarantees a protection of drinking water against bacterial pollution on the commonly used basis of a 50 or 60 day residence time for the attenuation of microbiological pollutants (Matthess et al. 1985). In analogy to the PFZs, the delineation of PTTZs for adit sources is discussed here.

Unlike PFZs or catchments, kinematic porosity is an influential factor for PTTZs. A low value of 0.01 was used for the simulation of PTTZs to make them sufficiently large to inspect. A similar effect would be obtained with a thin aquifer. Figure 9 shows the positions and shapes of PTTZs for adit sources using MODBRNCH, high K and multi-borehole methods. The boundary conditions and orientations are the same as their counterparts in Figure 3. An abstraction of 50,000 m^3/d was used. Figure 9 clearly shows the impact of boundary conditions. When the adit is in the middle of two constant head boundaries (Figure 9c and d), the PTTZs are symmetrical in both directions. In the contrast, if there is an upstream impervious boundary (Figure 9a and b), PTTZs are shifted upstream. Figure 9 also indicates that MODBRNCH and the high K method derive very similar PTTZs, but those generated by the multi-borehole method are slightly different especially for the system in Figure 9b, where the adit is perpendicular to the upstream impervious boundary. The multi-borehole method cannot reflect the effects of boundary conditions on PTTZs well enough. A similar conclusion as that from the study of PFZs, i.e., high K method is a better approximation.

Figure 9. Comparison of shapes and positions of PTTZs derived by various methods. The boundary conditions in Figures a-d correspond to those in Figure 3a-d (Q=50,000 m^3/d).



DETERMINATION OF PFZS IN 2D AND 3D MODELS

Currently, the catchment of ground water sources are widely determined by 2-dimensional models. Are 2D models sufficient to delineate the PFZs for the adit sources? When do we need 3D models? PFZs from 2D and 3D models were compared using different combination of boundary conditions and parameter values. Almost identical PFZs were obtained from the 2D and 3D models in all the cases examined.

For a single well, Kinzelbach et al. (1992) pointed out that the catchment of a fully penetrating well can always be determined by a 2D approximation. For a partially penetrating well, they proposed a characteristic number k

$$k = \frac{Q}{Rab} \tag{3}$$

Where b is aquifer thickness (L). When k • 5, the differences between 2D and 3D solutions vanish. Although the above characteristic number was proposed for the catchment area of a single well, we used it to roughly assess whether 2D models are sufficient for delineation of PFZs for adit sources. Equation (3) indicates that if the pumping rate is larger, or recharge, distance from abstraction to the upstream boundary or aquifer thickness is smaller, 2D models are good approximations. Table 1 gives the ranges of relevant parameters in the UK. The k value in the typical row was calculated from typical values of all parameters. However the lowest k was calculated using lowest Q but highest R, a and b. The lowest k is 6.5 which is greater than the critical number of 5. So for most adit sources in the United Kingdom, a 2D model is sufficient for delineation of PFZs because adit sources usually have large abstractions and the Chalk aquifers have small aquifer thickness.

Table 1. Ranges of parameters for adit sources in Chalk aquifer in the UK

	Q (m^3/d)	R (mm/year)	a (km)	b (m)	k
Lowest likely	10 000	50	5	15	6.5
Typical	30 000	200	10	30	182.0
Highest likely	60 000	350	20	80	5839.0

DISCUSSIONS AND CONCLUSIONS

The combination of the Preissmann slot approach and MODBRNCH can successfully compute the ground water head distributions and inter-cell velocities for adit sources. MODPATH can be used for computation of the pathlines correspondingly and therefore for delineation of PFZs and PTTZs. The numerical modeling allows one to integrate real boundary conditions, heterogeneity and anisotropy into the ground water systems. However the influences of heterogeneity on PFZs and PTTZs were not tested in this study.

The shapes of PFZs are controlled by boundary conditions and adit orientations. The PFZs are symmetrical in both the adit direction and perpendicular to it and confined by ground water divides if the hydraulic gradient is caused by abstraction alone. In contrast, the PFZs reach the upstream boundary if it is impervious. The shapes and sizes of PFZs are also strongly influenced by pumping rate, recharge and the distance from adit to boundaries. The adit length affects the shapes of PFZs as well.

The comparisons of PFZs and PTTZs derived by this model and other methods indicates that assigning a high value of hydraulic conductivity (10^3-10^6 m/d) to the adit is a good approximation for delineation of PFZs and PTTZs. Two-dimensional models are sufficient for delineation of PFZs for adit sources in the range of conditions found in the UK Chalk.

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