Impact of Groundwater Abstractions on River Flows

Draft for Agency Presentation
29 April 1999

Environmental Simulations Limited

National Groundwater & Contaminated Land Centre Project WR1

Impact of Groundwater Abstractions upon River Flows

Prese[illegible] Workshop

Prepared by Environmental Simulations Limited

for

The Environment Agency

Presented at the Hilton National Coventry

29 April 1999

Environmental Simulations Limited

20 High Street, Shrewsbury SY1 1SJ UK Tel +44(0)1743 369504
Fax +44(0)1743 248600 email markfermor@eslgroundwater.enta.net

Workshop timetable

	Introduction	
10:30	Welcome, Introduction to project and workshop objectives	SF&SK
10:45	Background – Need for an Agency Methodology and overview of issues	DB
	River-aquifer interactions	
11:00	The state of the art – scientific literature and current practice for initial assessments	JH
11:20	River-Aquifer Interaction and the approach selected for an Initial Assessment of the impact of groundwater abstractions	AWH
12:00	Software tools giving access to the analytical solutions	JH
12:30	*Buffet lunch and hands-on demonstration of the software tools*	ESL
	A methodology for the initial assessment of the impact of groundwater abstraction on river flow	
14:00	The role of analytical solutions in a tiered assessment	MMF
14:25	A procedure for the assessment of the impact of groundwater abstraction on river flow	AWH
14:40	Demonstration of the procedure – Otterton Borehole 4	AWH
	Summary	
15:40	Summary and Way Forward - Discussion	SF
16:00	*Close of workshop*	

Contents

Impact of Groundwater Abstractions upon River Flows

Environment Agency workshop

Introduction

By

Steve Fletcher

and

Stuart Kirk

Environment Agency National Groundwater and Contaminated Land Centre

Aims of the project

- The primary aim is to present a reasoned, robust and technically supportable rationale for the evaluation of the effects of groundwater abstraction on river/groundwater interaction.

specific objectives of the project:

- To review the current available methods.
- To produce an assessment of the applicability and likely accuracy of a selection of these methods
- To evaluate an agreed selection of methods by trialling
- To produce a guidance document

Role of workshop

- 'The methodology presented is to incorporate, prior to its finalisation, the results of feedback arising from a seminar addressed to relevant Environment Agency staff towards the end of the project.'

Scope for this project specifically excludes:

- Impact of groundwater abstraction on wetlands.
- Impact of groundwater abstraction on or from springs.
- Use of numerical modelling methods

The State of the Art

Interpretation of River - Aquifer Interaction

J Hatherall

The State of the Art - Interpretation of River - Aquifer Interaction

- Literature Survey
- Questionnaire
  - Environment Agency
  - UK Science Base

Literature Survey

- Conceptual Understanding
- Analytical Solutions

- Excludes
  - Wetlands
  - Site Specific Numerical Modelling

Key Papers

- Jenkins (1968) - basic solution and method
- (Hantush (1965) - Stream bank properties)
- Wallace *et al* (1990) - Periodic abstractions
- Spalding & Kahleel (1991) - Review
- Hunt (1999) - Stream bed and partial penetration
- Bullock *et al* (1994) - NRA Key Report - available from WRc (R & D No. 274)

Agency and Science Base Survey

- **Good response to questionnaires**

- Methods
  - 1) Jenkins or variations
  - 2) Numerical models

- Jenkins
  - quick and easy to use
  - limited amount of data required
  - over simplified
- Numerical models
  - more realistic prediction
  - time consuming
  - data hungry
  - good for cumulative impacts.
- ***The choice is often limited by licensing conditions***

Questionnaire responses

Respondent and Agency region or area.	Methods stated in questionnaire.
Keith Seymour (Warrington, NW)	No preferred method, but numerical methods highlighted.
Julie Sherwood (Exeter, SW)	Numerical models where available.
Len Careless (St Austell, SW)	Jenkins commonly used. Numerical methods on fissured strata.
John Ellis (Worthing, Southern)	Jenkins and Theis. Some field evaluation including pumping tests and stream gauging.
Vin Robinson (Reading, Thames)	Glover and groundwater models where available.
Paul Sadler (Exeminster, Devon area)	Jenkins.
Tony Jenkins (Shrewsbury, Midlands)	Method supplied by John Lloyd
David Seccombe (Ipswich, Anglian)	Jenkins and pumping tests.
Rob Cunningham (Nottingham, Midlands)	Jenkins and groundwater modelling in complex scenarios.
Peter McConvey (Lincoln, Anglian)	Regional models and others unspecified.
John Aldrick (NE)	**The method of John Aldrick (NE) has a pragmatic approach - different to analytical solutions. Method to be covered later.**

River-Aquifer Interaction

Alan Herbert

River-aquifer conceptual models

- PERENNIAL or Ephemeral
- CONNECTED or Disconnected (Remote)
- Gaining or Losing
- Fully penetrating or Partially penetrating river

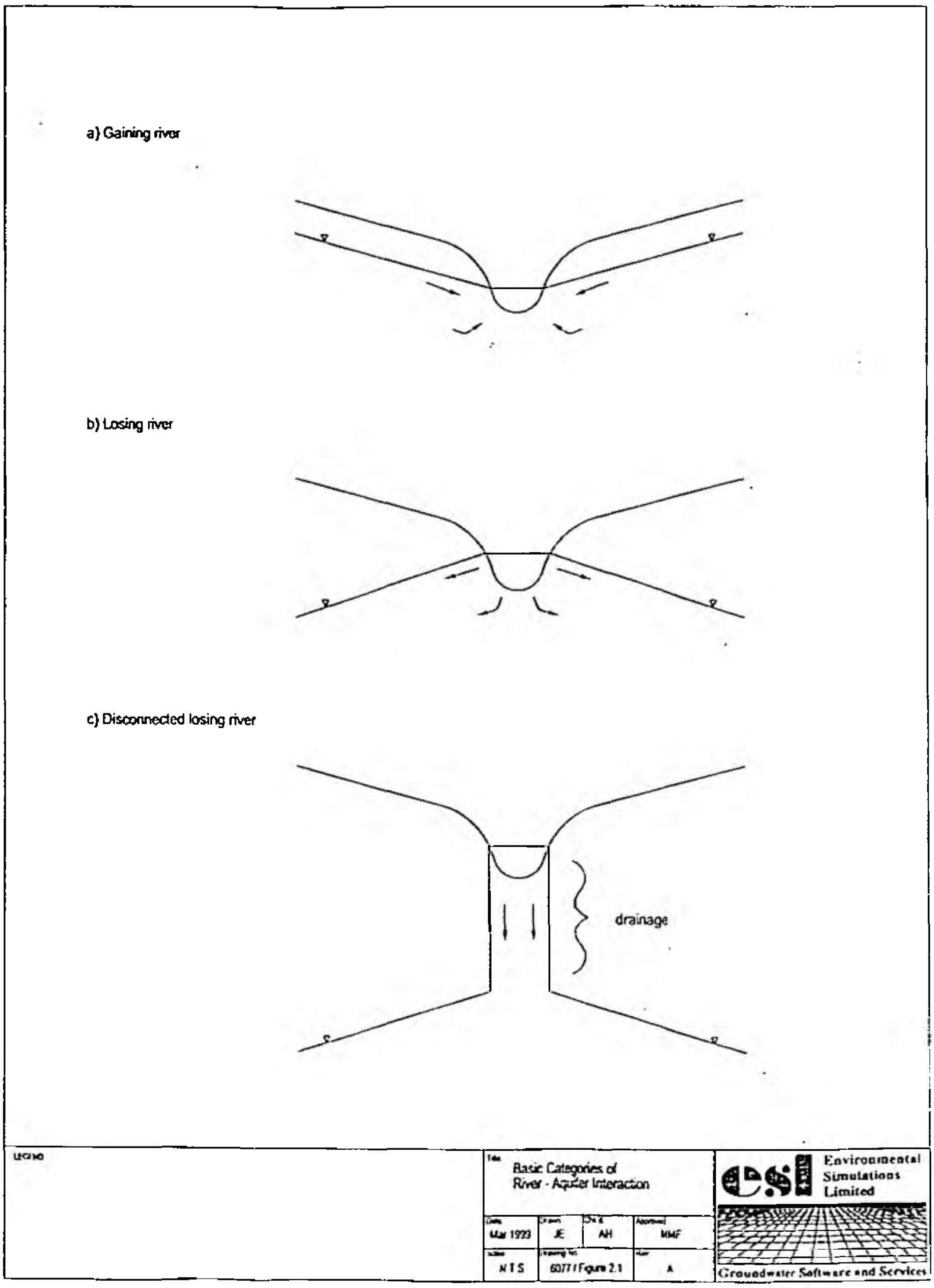
Aquifer conditions

- Confined
- Unconfined (water table)
- Leaky

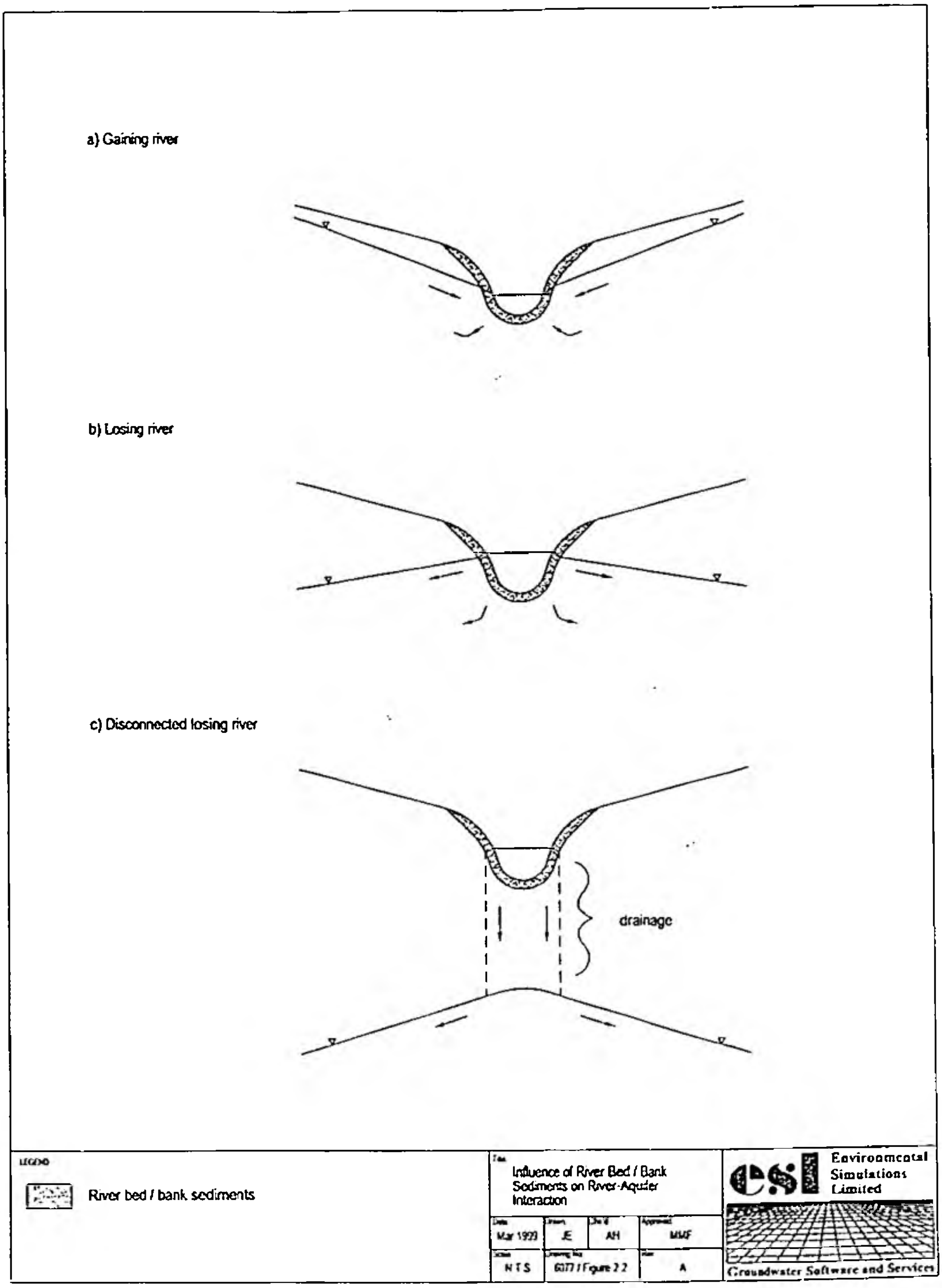
Complexity!

- STEADY or Time varying
  - seasonal
  - storms
- Spatially varying
- Heterogeneous
  - layered conductivity
  - random distribution
  - river bed sediments

Conceptual models



Influence of river bed/bank



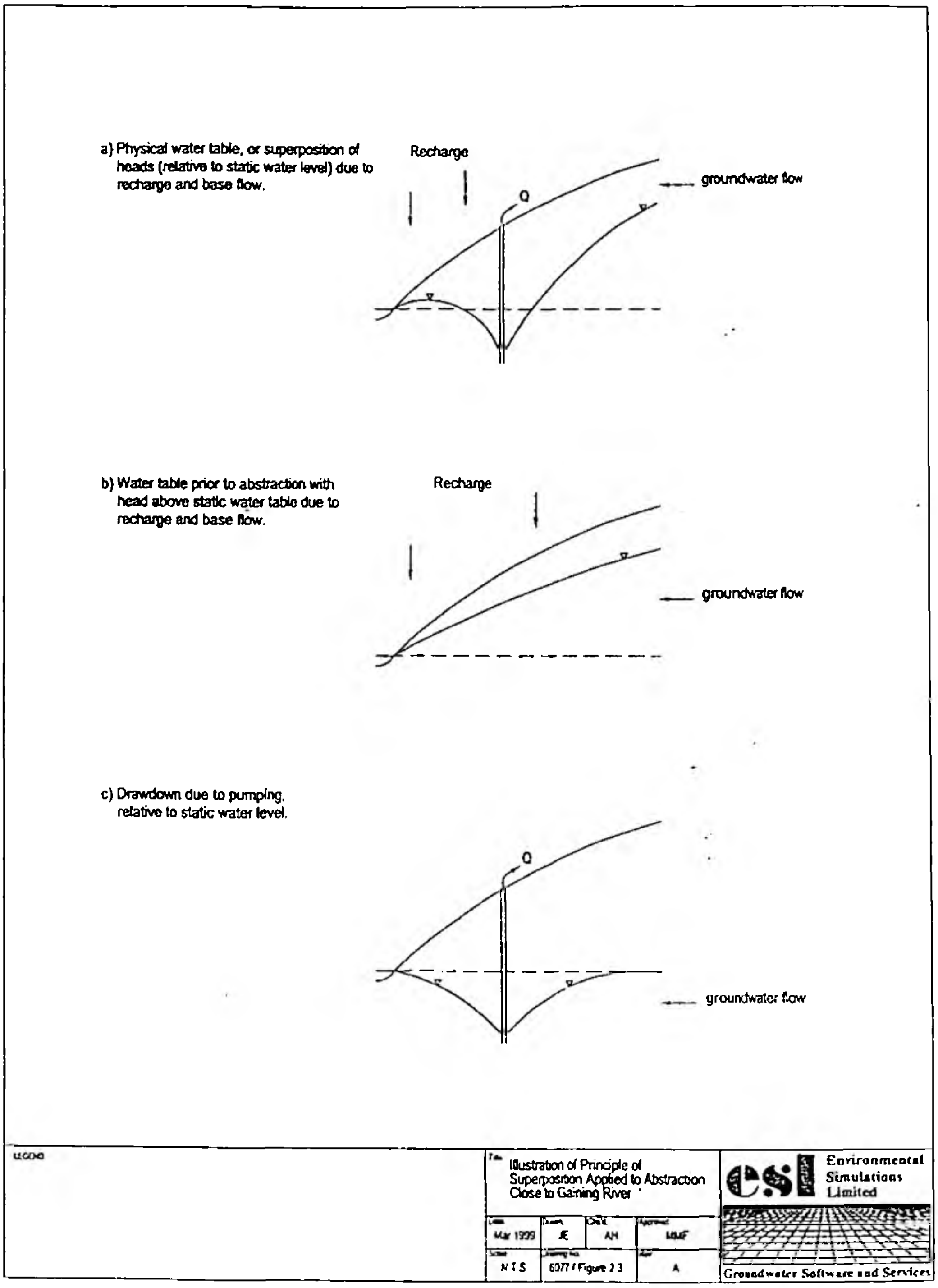
Simplified conceptual model

- Need simplifications for analytical results
  - infinite aquifer
  - straight infinite river
  - homogeneous isotropic properties
  - horizontal flow
  - transmissivity unchanged by abstraction
  - horizontal rest level of water equal to river stage

Horizontal rest water level?

- Neglects recharge in the catchment!
- Poor approximation if water quality problem
- Principle of Superposition to evaluate net impact on flow

Superposition



Simplifications of the real conceptual model

- Desirable for rapid evaluation
- Aids understanding of key processes
- Not always possible at complex sites
  - e.g. depth dependent conductivity
- FIRST STEP towards more detailed representation
  - if appropriate

Three simplified conceptual models

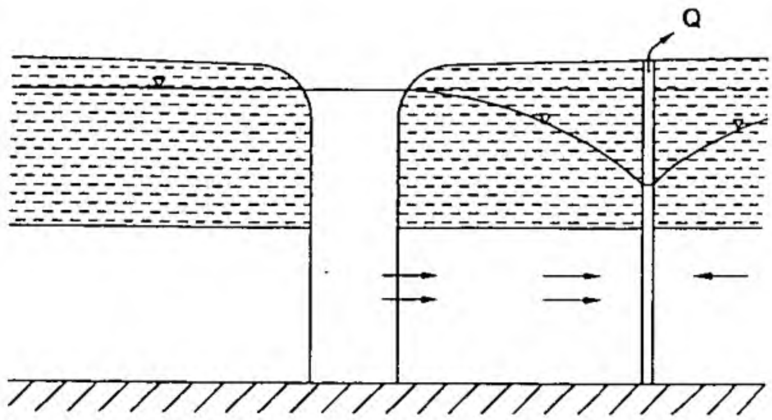
- Three basic analytical results available
- Regularly republished 1941-1999!

Theis

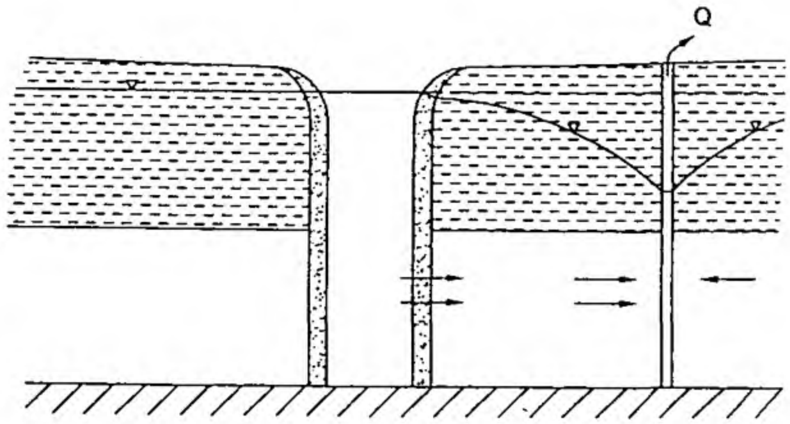
Hantush

Stang

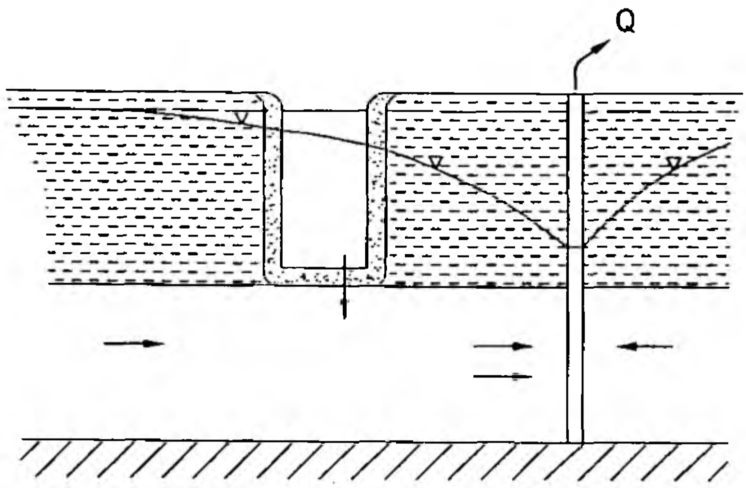
Theis



Hantush



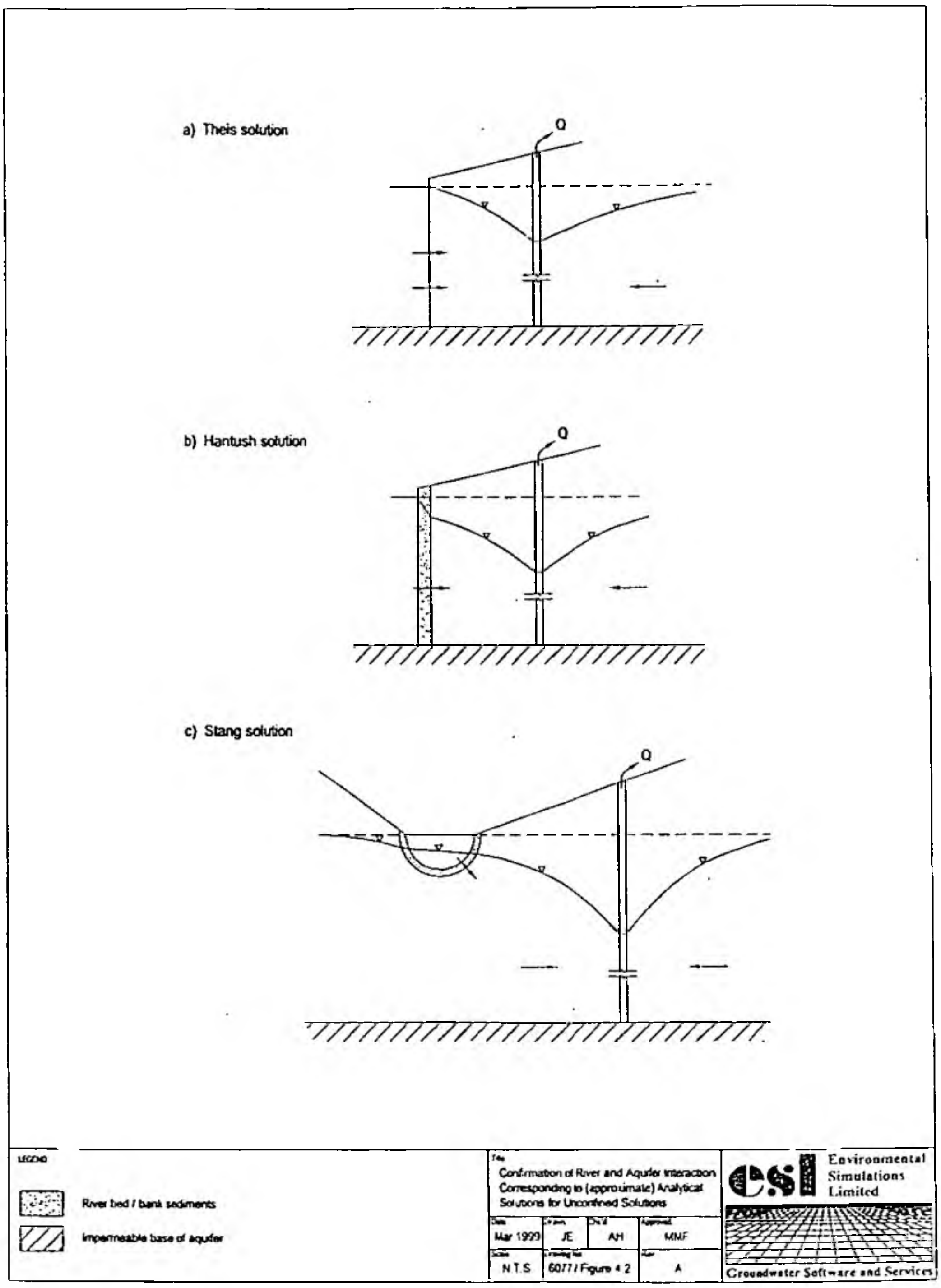
Stang



Applicability

- Leaky and unconfined aquifers too
  - Transmissivity constant
  - Horizontal flow
- Superposition

Unconfined conditions

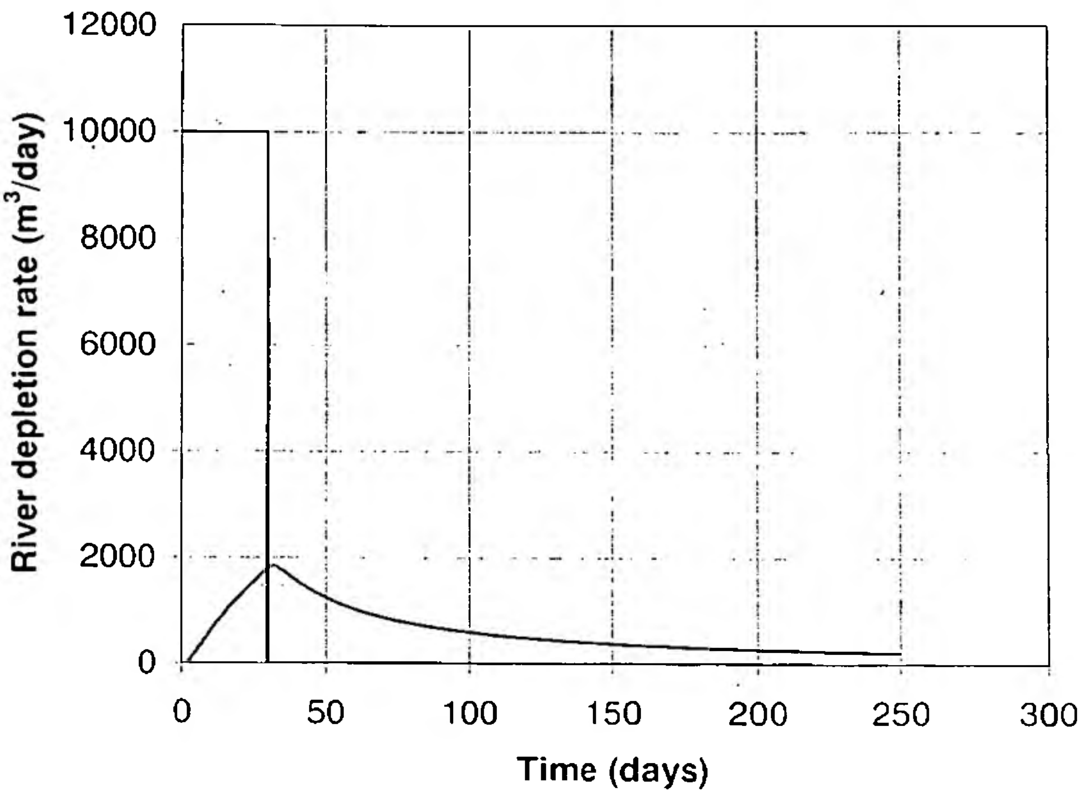


Model summary

- Theis
  - Fully penetrating
  - Storage on one side of river only
  - No sediments
- Hantush
  - Fully penetrating
  - Storage on one side of river only
  - River bank sediments
- Stang
  - Partially penetrating
  - Storage on both sides of river
  - River bed sediments

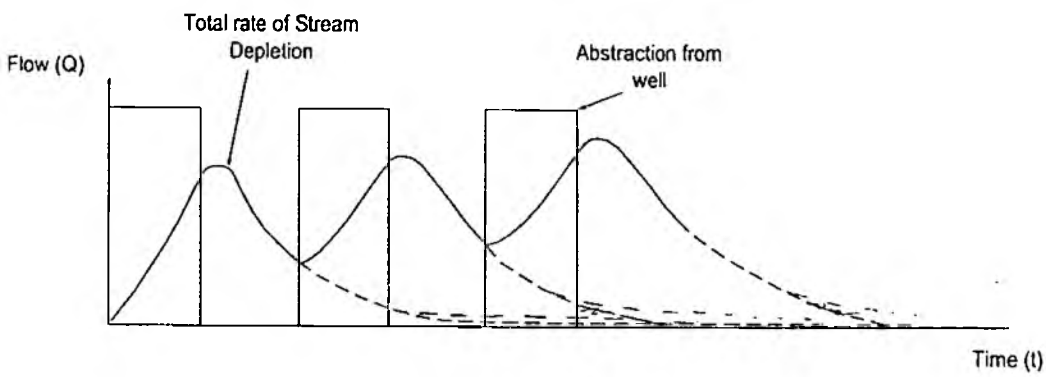
Finite abstraction period -
pumping test

- Impact delayed
- Slow decline



Periodic abstraction

- Build up over cycles
- May not see maximum impact in first year



Software Tools

For the use in the Interpretation of
River - Aquifer Interaction

J Hatherall

Spreadsheet Implementation of -

- Theis
- Hantush
- Stang
  - As covered in the previous section
  - Apply principle of superposition

- Implements the method of Jenkins/Wallace

Use of the tools

- Pumping Test
  - Single finite abstraction event
  - Continuous evaluation of depletion

- Periodic Abstractions
  - Regular monthly abstraction rates
  - Predicts cumulative periodic river depletion
  - Very long responses (>10 yrs) averaged

Inputs

- **Theis**
  - Transmissivity
  - Storage coefficient
  - Perpendicular distance to river
- **Hantush**
  - Thickness of the river bank sediments.
  - Depth of river bank
  - Hydraulic conductivity of river bank sediments
- **Stang**
  - Thickness of the river bed sediments..
  - Width of river bed
  - Hydraulic conductivity of river bed sediments

Inputs (cont.)

- **Required for all solutions**
  - Pumping rates
  - Abstraction Rate (by month)
  - (Compensation Rate (by month))

- **Pumping test inputs**
  - Duration of pumping test
  - Constant rate of pumping for the pumping test
  - Time axis limit for plot.

Outputs - Pumping test design

- **Pumping test river depletion rate**

Outputs - Periodic abstractions

- **Ultimate river depletion rate in each month**

Annual Pumping

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	year
pumping (m^3/d)	0	0	0	0	3630	3630	0	0	0	0	0	0	
compensation returns	0	0	0	0	0	0	0	0	0	0	0	0	
day	0	31	59	90	120	151	181	212	243	273	304	334	365
vol abs	0	0	0	0	112530	108900	0	0	0	0	0	0	221430
vol comp	0	0	0	0	0	0	0	0	0	0	0	0	0
river depletion	7867.98	6930.370481	7477.841	7041.444	44128.16	56357.85	28789.32	19900.87	14967.08	11314.16	8516.522	8138.41	221430
day depletion (m^3/d)	253.8	247.5	241.2	234.7	1423.5	1878.8	928.7	642.0	498.9	365.0	283.9	262.5	

Theis Hantush and Stang

Transmissivity	Trans	400	m^2/d
Storage coefficient (S or Sy)	S	0.01	
Perpendicular distance to stream	a	25	m

Total abs specified	221430
Total abs evaluated	198339.6
percentage evaluated	89.57%

error check - must have pumping rate greater than compensation returns'

OK

Hantush

stream bank sediments conductivity	K bank	0.1	m/d
stream bank depth	depth bank	5	m
stream bank thickness	thick bank	0	m

error check - cannot have bed and bank

OK

Stang

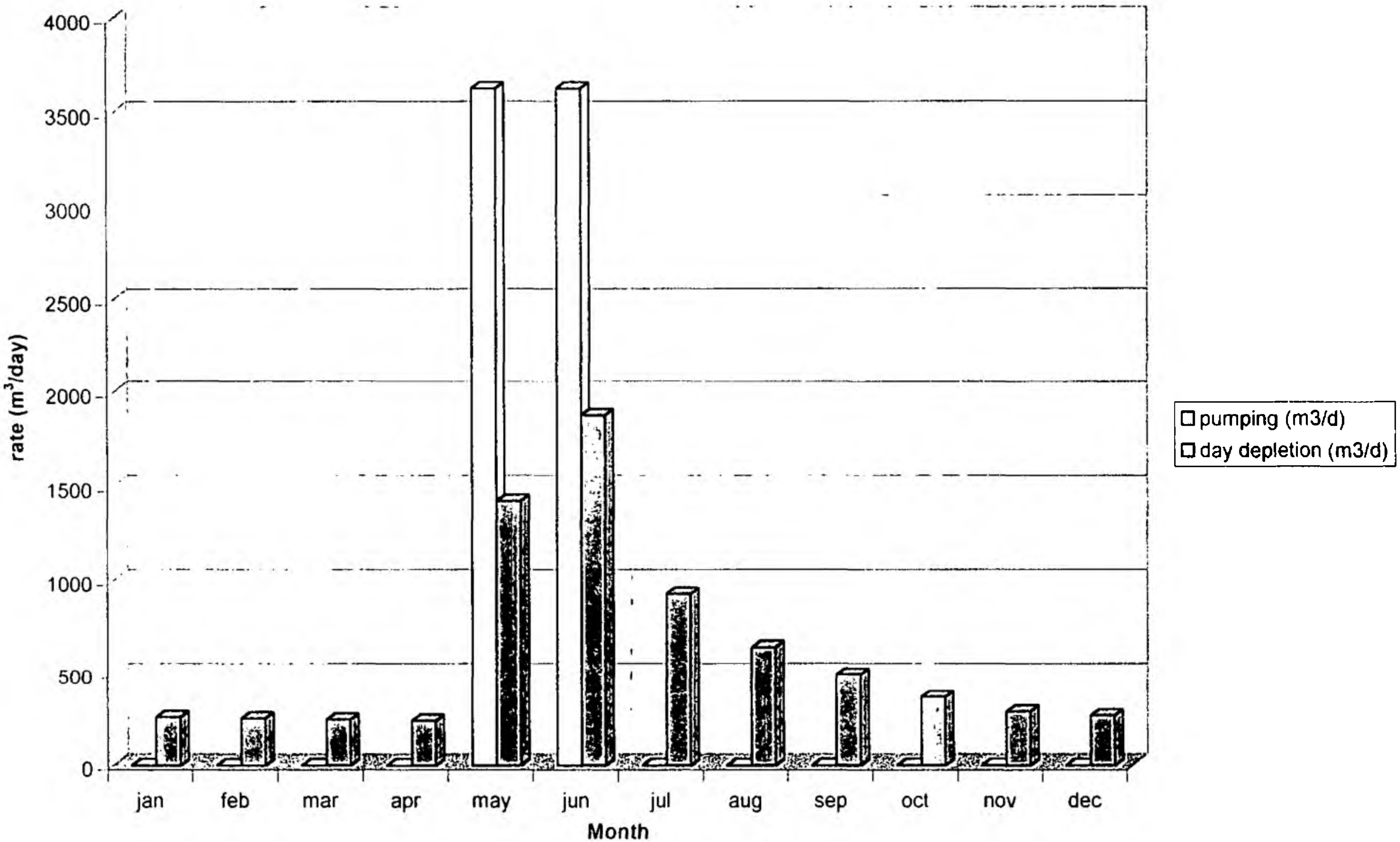
stream bed sediments conductivity	K bed	0.1	m/d
stream bed width	width bed	5	m
stream bed thickness	thick bed	1	m

Conceptual model selected

STANG

Pumping test design

Duration of test	146	days
axis limit	20.00%	final percentage of depletion
Pumping rate for test	11810	m^3/day



4000
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3000
2500
2000
1500
1000
500
0
rate (m3/day)
jan
feb
mar
apr
may
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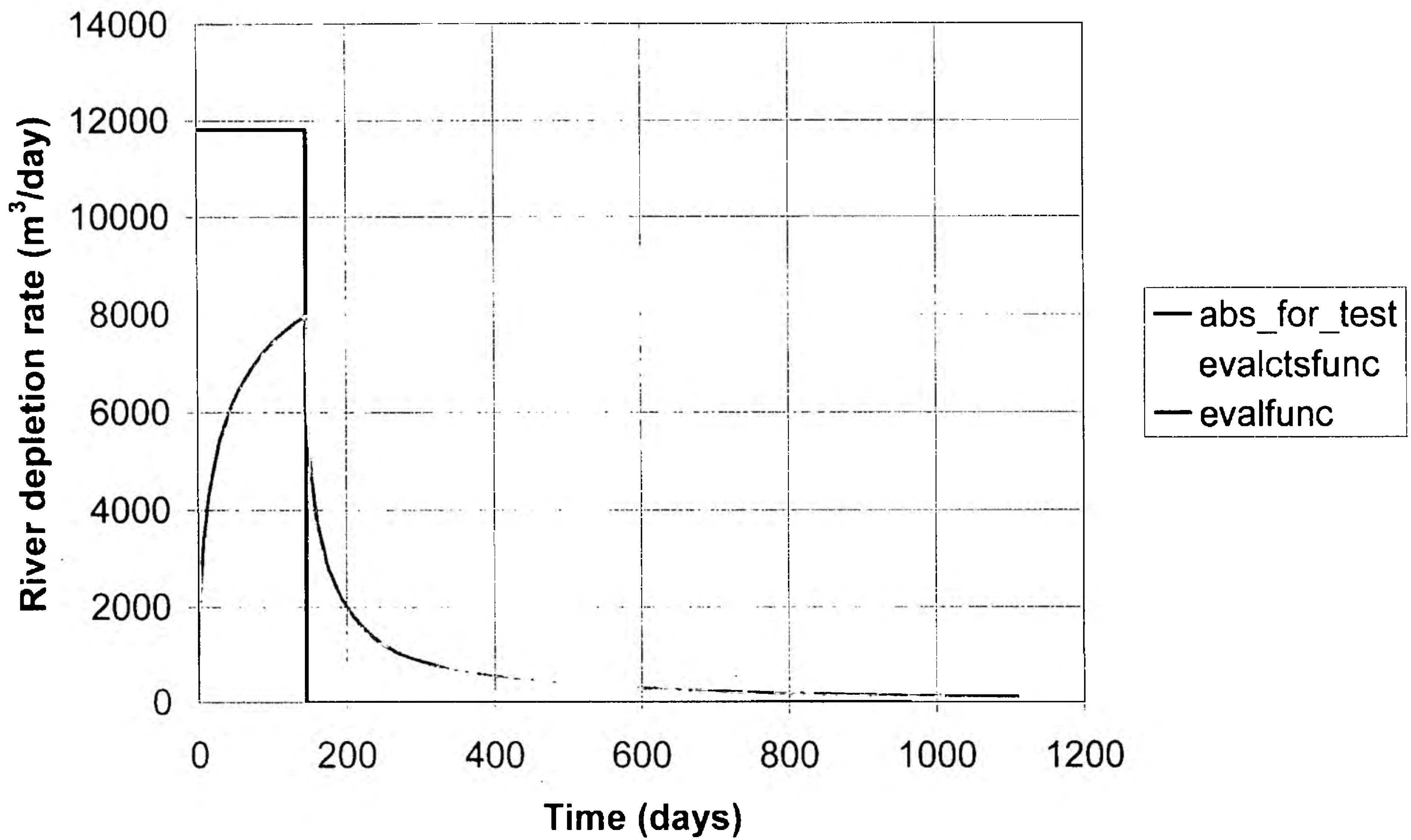
jul
aug
sep
oct
nov
dec
Month
pumping (m3/d)
day depletion (m3/d)

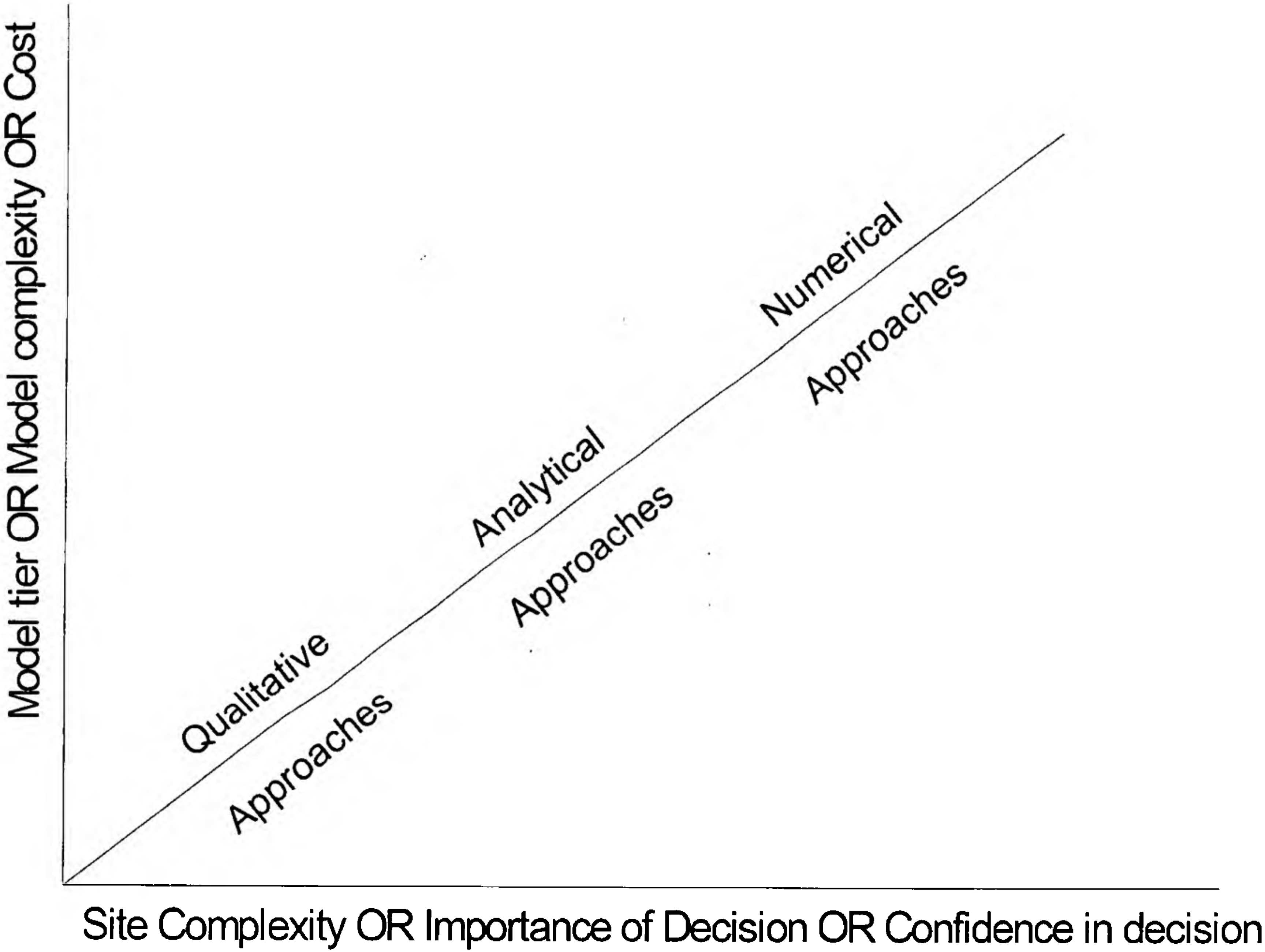


14000
12000
10000
8000
6000
4000
2000
0
River depletion rate (m3/day)
0
200
400
600
800
1000
1200
Time (days)
abs_for_test
evalctsfunc
evalfunc

The role of analytical solutions in a tiered assessment

Hierarchy of approaches

- Start with easy to apply methods
- Increase to more complex methods based on:
  - More complex hydrogeology
  - More important issues
  - Borderline cases
  - Availability of data


Model tier OR Model complexity OR Cost
Qualitative
Approaches
Analytical
Approaches
Numerical
Approaches
Site Complexity OR Importance of Decision OR Confidence in decision

Advantages of tiered approach

- Consistent with risk-based methodologies
- Avoids unnecessary effort
- Concentrates resources where issues demand it
- Can select approach according to 'goodness of fit' with conceptual model

Problems with a tiered approach

- Lower tiers of assessment have significant potential errors and *may* not be protective of the environment
- Simple approaches may not represent the conceptual model sufficiently to be useful (more analytical and numerical tools needed)

Choose approach based on conceptual model

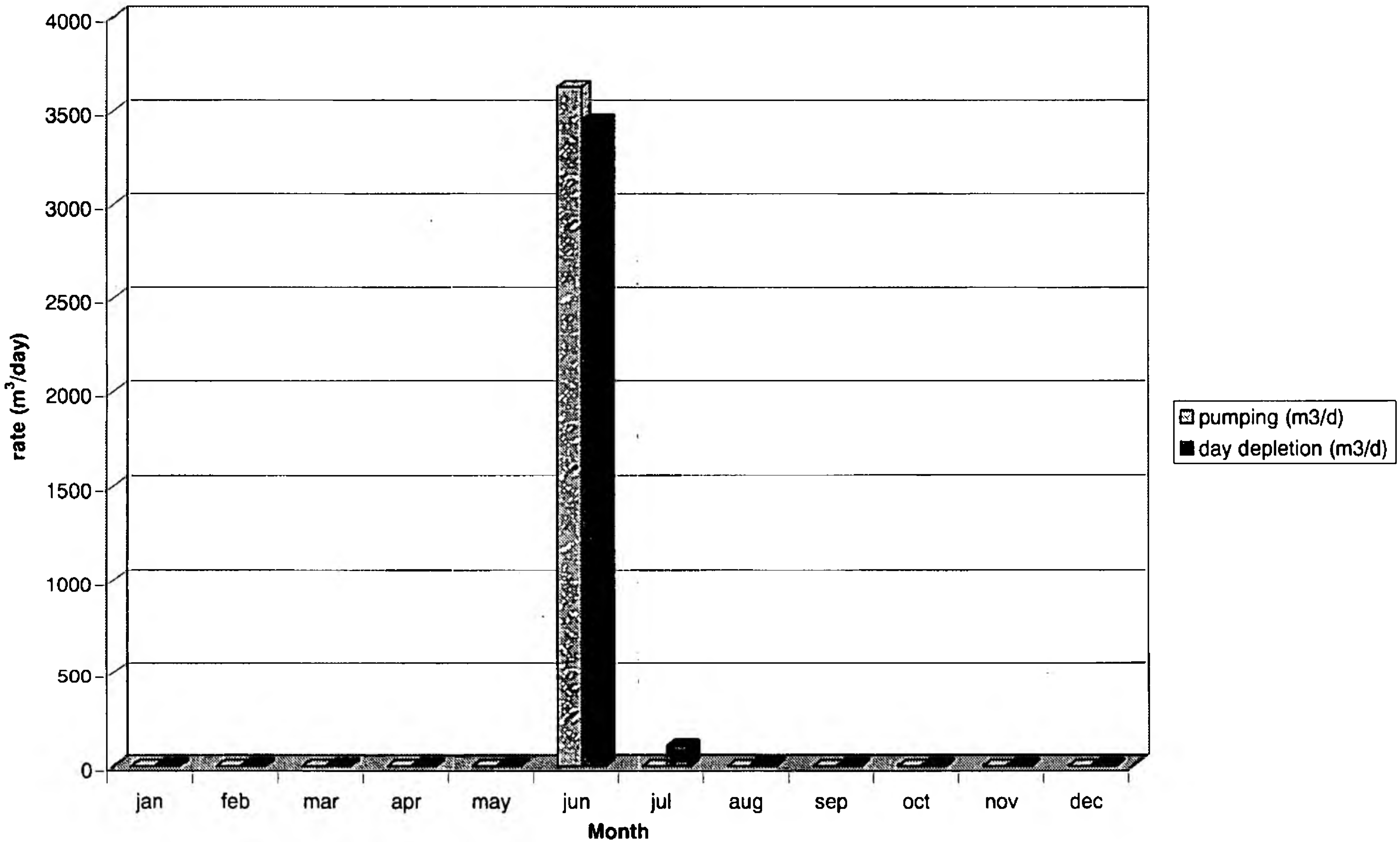
- A good conceptual model is a robust representation of the real site
- Needs to recognise all significant flow mechanisms
- Translate into *appropriate* computational model if quantitative approach needed
- Level 1=Analytical
- Level 2=Numerical

Uncertainties to consider

- Conceptual uncertainty (e.g. not sure what mechanisms are important)
- Oversimplifications (so look at different simplifications)
- Parameter uncertainty (needs sensitivity analysis/data collection)
- Assess what contributes most to 'worst case'

Conservatism

- Model conservatism is ‘site specific’
- e.g. Theis solution predicts a more immediate and concentrated response, so *generally* more conservative (but consider impact of June abstraction on a low river flow problem)



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rate (m3/day)
jan
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may
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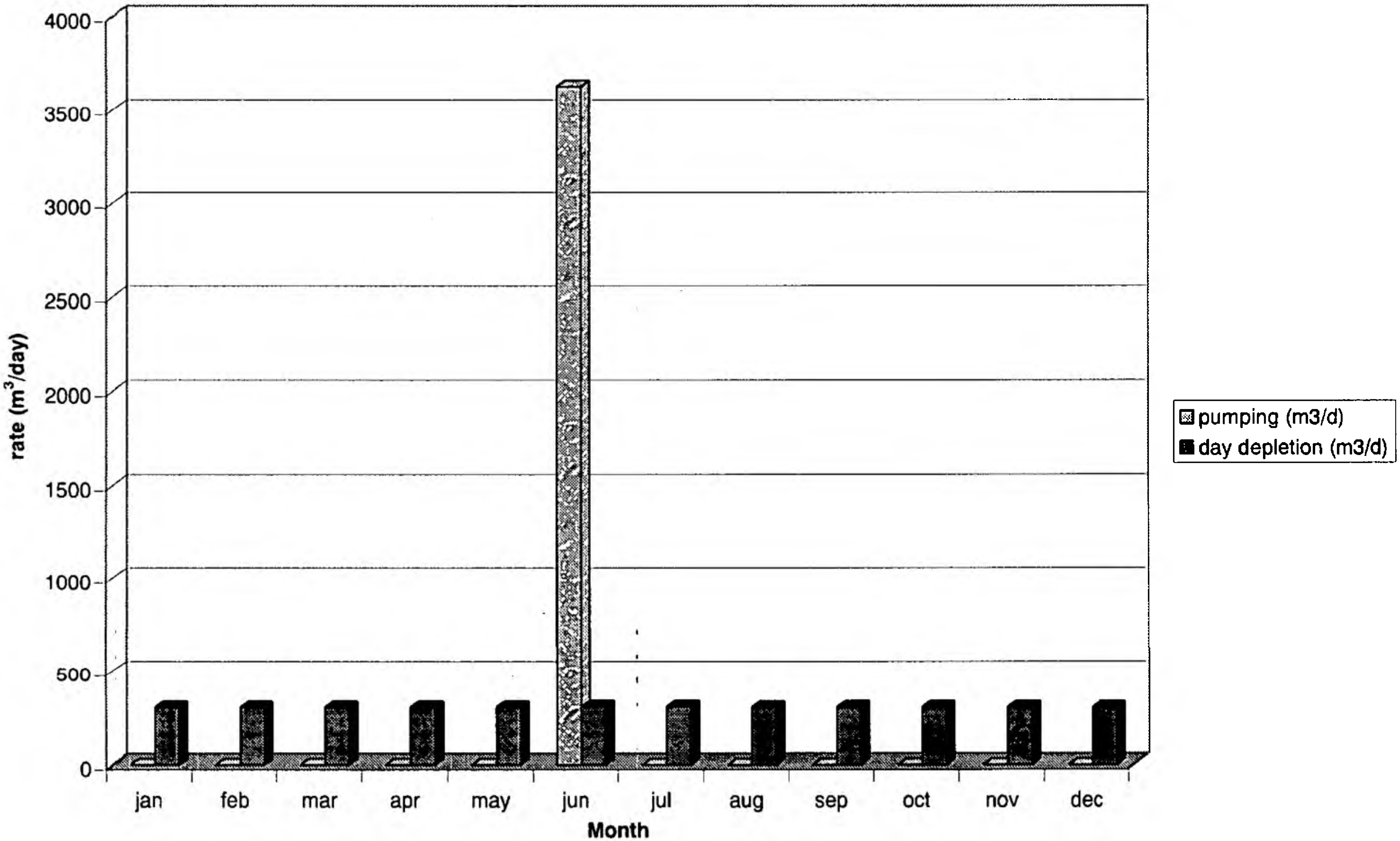
aug
sep
oct
nov
dec
Month
pumping (m3/d)
day depletion (m3/d)



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0
rate (m³/day)
jan
feb
mar
apr
may
jun
jul
aug
sep
oct
nov
dec
Month
pumping (m3/d)
day depletion (m3/d)

Look out for poor fit with conceptual model

- Conceptual understanding is key to choices
- Cases not considered:
  - Limiting drainage from disconnected river
  - Induced recharge (limiting recharge on saturated ground)
  - Wetlands

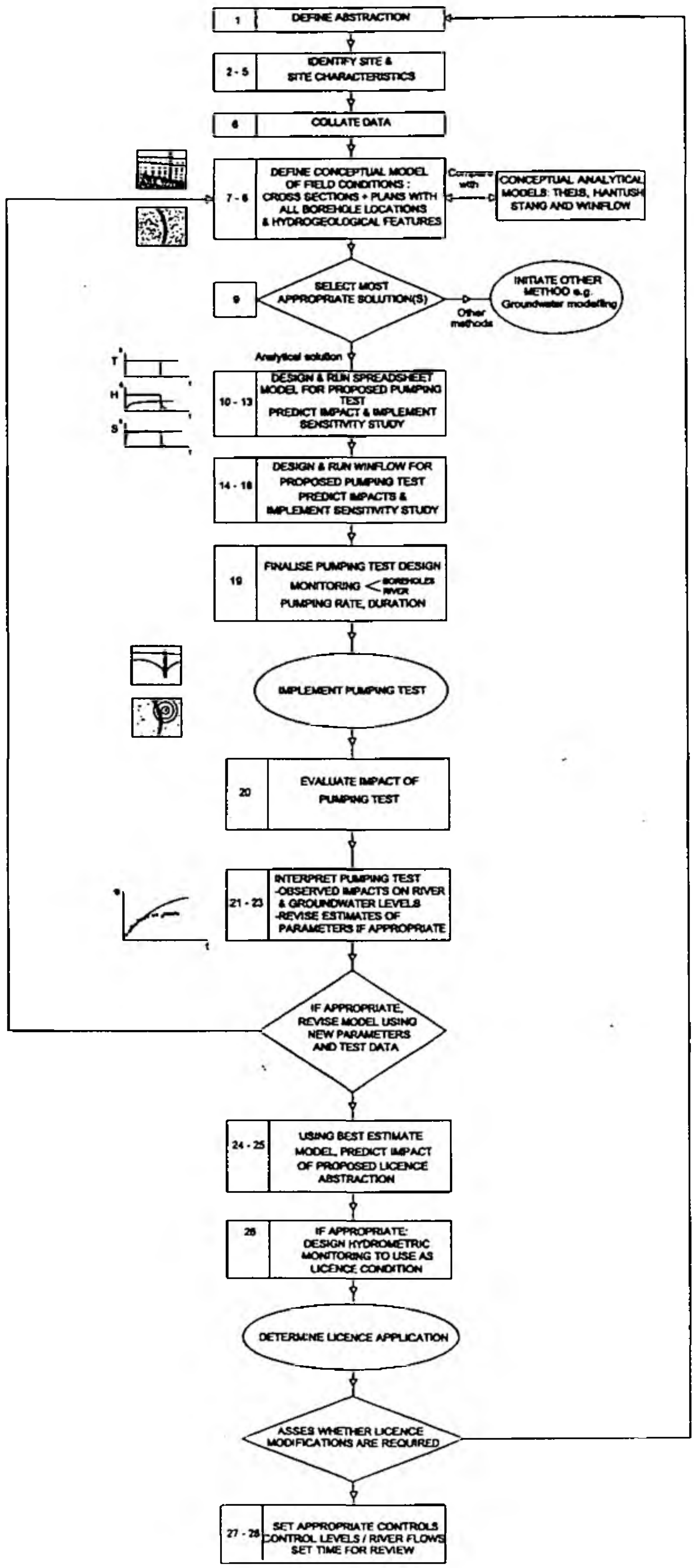
Conclusions

- Abstraction water will come from depletion of river flow
- Different tiers of analysis or modelling will tell you more detail about how long the depletion takes and where it is distributed
- Conceptual model and understanding is key

Impact of Groundwater Abstraction on River Flow - Procedure

Alan Herbert

Flow diagram



Structured process

- Site characterisation
- Conceptual model
- Pumping Test
- Assessment

Consistency

- Formalise assessment process
- Consistent across Agency
- Incorporate current best practise
- Accessible tools to facilitate assessment

IGARF methodology 4

Impact of Groundwater Abstractions on River Flows

Project Report
Draft for Agency Presentation

Environmental Simulations Limited

National Groundwater & Contaminated Land Centre Project WR1

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Project Report
Draft for Agency Presentation

A W Herbert, J P Hatherall & M M Fermor

Research Contractor:
Environmental Simulations Limited

Environment Agency
National Groundwater & Contaminated Land Centre
Olton Court
10 Warwick Road
Olton
Solihull
West Midlands
B92 7HX

National Groundwater & Contaminated Land Centre Project WR1

Publishing organisation:
Environment Agency
Rio House
Waterside Drive
Aztec West
Almondsbury
Bristol BS12 4UD
Tel: 01454 624400 Fax: 01454 624409

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External: Not Released to Public Domain

Statement of use
This report summarises the findings of research into the impact of groundwater abstraction on river flows. A methodology for assessing such impacts is presented and demonstrated. The information within this document is for use by EA staff and others involved in managing water resources.

Research contractor
This document was produced under a National Groundwater & Contaminated Land Centre Project by:

Environmental Simulations Ltd
20 High Street
Shrewsbury
SY1 1SJ

Tel: 01743 369 504 Fax: 01743 248 600

Environment Agency's Project Board
The Project Board consisted of Steve Fletcher, David Burgess and Stuart Kirk.
The Project Manager was Stuart Kirk.

National Groundwater & Contaminated Land Centre Project WR1.

CONTENTS

1 INTRODUCTION

1.1 Background

This Report has been prepared by Environmental Simulations Limited (ESL) on behalf of the Environment Agency (the Agency) under a contract to review current practice for the evaluation of groundwater abstractions on river and stream flows when assessing groundwater abstraction licence applications.

The primary objectives of the project were to;

1. Present a reasoned, robust and technically supportable rationale for the evaluation of the effects of groundwater abstraction on river/groundwater interaction.

2. Present a 'User Manual' for use by Agency staff in the determination of abstraction licence applications and reviews.

The scope of work for the study is summarised by the following tasks performed during the project, and encompasses the specific objectives described above.

Task 1. Literature Review. A thorough literature search and review, including published sources, research reports and other UK university information documenting the available methodologies and quantitative approaches to evaluation of river/groundwater interaction and the impact of abstractions was performed.

Task 2. Consultation with Agency. A programme of consultation with Agency Regions was undertaken, including use of questionnaire and discussions to elicit current practice and views regarding methodologies identified from the Literature Review.

Task 3. Pilot trials. The preferred methodologies identified from Tasks 1 and 2 were applied to the selected trial areas in order to evaluate the success of each method against criteria established, including ease of use, accuracy, data requirements, applicability to different hydrogeological terrain.

Task 4. Development of Methodology. A review of the Pilot trial results in conjunction with theoretical considerations provided the basis for recommendations for a suitable tiered approach to evaluation of the impact of groundwater abstractions on river flows. The findings were used to develop a draft 'User Manual' of practical techniques for Agency staff, including detailed guidance notes.

Task 5. Seminar and Review. A seminar was presented focusing on the draft User Manual and allowing exploration of all relevant issues regarding Agency requirements, feedback from Agency staff, and enhancement of the User Manual for its optimum use in operational situations.

Task 6. Reporting. A final report was presented providing a concise summary of the work undertaken and the results of the assessment and User Manual development, together with recommendations for the most appropriate use of numerical modelling methods and other techniques not within the project scope. Presentation of a Project Record was also undertaken.

The User Manual presents a methodology that is intended to form part of the Agency's approach to assessing the impact of groundwater abstraction on river flow. In common with many assessment activities, a tiered approach is seen as most appropriate. In some cases it will be clear that there is no issue to address and simple hydrogeological judgement can be used: this represents the simplest tier of assessment (level 0). If an impact is conceivable, then an initial assessment using the methodology developed by this project should be used (level 1). Again, in many cases this will enable a clear decision to be made. For borderline judgements, far more complicated sites where there is significant uncertainty, or for sites of particular importance, a more detailed level of assessment is appropriate so that a more confident understanding of the impact can be made (level 2). Such detailed assessment is most appropriately undertaken with site specific numerical modelling and field data collection.

This report presents the methodology for an initial quantitative assessment of the impact (level 1)

There are three specific uses of the methodology:

- evaluation of the impact of periodic abstractions;
- evaluation of the impact of steady abstractions;
- design of tests to gather information for the above.

The benefits in terms of river flow of pumping groundwater to discharge directly into a river so as to augment river flow can also be scoped.

The scoping assessment methodology was specified to use very simple tools incorporating analytical solutions or other methods with an equivalent level of sophistication. Analytical models are a well established, rapid, idealisation of reality. They can be usefully used at the start of hydrogeological investigations on the path from a simple model with little data to more complex models with more data. Analytical models are of limited accuracy but can be deployed quickly and cheaply, but are useful in directing further data collection . By contrast numerical models, such as MODFLOW, require time and money in the form of data collection and calibration, which would involve a greater level of effort in order to be used effectively than is appropriate at the scoping stage of assessment. The methodology presented here is based on the use of a simple spreadsheet model incorporating several common analytical solutions, and detailed user information for the use of this tool is given in the User Manual.

The methodology has been largely based on current practice across the Agency, as elicited from a survey of Agency Region and Area offices. Across the country, a wide range of different hydrogeological conditions exist, with different priorities for the protection of the environment in different Regions. Nevertheless, from a regulatory perspective, it is important to have a consistent and defensible approach to licensing groundwater abstractions. The methodology presented in the User Manual should not obstruct current methods in the Regions, but instead, should make all the appropriate analytical solutions readily available in a consistent format across the Agency. In general, most Agency responses indicated that initial assessment of licence applications with a possible river impact used analytical solutions based on the Theis (1941) solution such as Jenkins (1968) or Glover and Balmer (1954). These have been incorporated into the methodology which provides the first Agency guidance document for addressing the impact of groundwater abstraction on river flows.

The spreadsheet model developed as part of this methodology is not intended to be used as a 'black box' tool. It should inform rather than replace hydrogeological judgement.

The simple conceptual models on which the analytical solutions are based will in general be crude oversimplifications of the real situation. Results from their use will help identify whether there is a problem to be addressed or not, but in many cases more accurate representations of the physical situation will be needed to provide good predictions of the impact of the abstraction. It is intended that further detailed guidance, beyond the scope of this document, will be prepared to address the issues for sites where this initial scoping assessment does not clearly indicate the appropriate course of action.

The user should be aware that the analytical tools provided incorporate simplified conceptual models of the real system. This will lead to errors, particularly in the time period over which impacts are predicted. Often, with suitable choice of parameters, these simplifications will overestimate the river flow depletion. However, particularly where the impact is spread over more than one year, they may underestimate the river flow depletion.

2 TECHNICAL BACKGROUND

2.1 Hydrogeology of river aquifer interactions

The interaction between rivers and groundwater systems is complex.

The response of the aquifer to river-aquifer flows will depend on the aquifer characteristics: the aquifer transmissivity and specific yield if unconfined or storativity if confined. Confined or leaky aquifers will show the most rapid and most significant head response to pumping and thus can induce the most significant head differences and fluxes at the river where connections between rivers and aquifers exist.

Rivers may either gain water from or lose water to aquifers, depending on the degree of hydraulic connection and the difference between river stage elevation and the connected groundwater heads. This flux between river and aquifer may vary during the year as groundwater heads and river stage elevation vary, and also with position along the river. It may vary over very short timescales as flood runoff will lead to rapid variations in river stage elevation on timescales of hours, and vary over longer timescales as groundwater heads change.

The stage of the river is related to the river flow rate. There will generally be a direct relationship between flow and river stage. This may be established directly from river gauging, or may be estimated by one of a number of general hydrological flow equations such as Manning's formula (for example in Shaw, 1994) or more sophisticated hydrograph relations. The baseflow aquifer discharge to rivers is determined by groundwater interactions and this will generally be slowly varying. It is likely to rise during periods of recharge in parts of the aquifer providing the baseflow. This is generally followed by periods when the aquifer has reduced or no recharge, and during which there is a typical exponential decline in the baseflow whilst the groundwater system discharges to the river at a rate proportional to the difference between a typical aquifer head and the river stage.

The flux of water between a river and the aquifer depends most importantly on the degree of connection between the river and the aquifer. The degree of connection will depend on the properties of the material comprising the river bed and river bank, the existence of aquitard or unsaturated aquifer material between the river and the aquifer, and the extent to which the channel of the river intersects the saturated part of the aquifer.

The range of circumstances leading to flows between the aquifer and the river may be considered by taking the different configurations of aquifer head and river stage in turn as shown in Figure 2.1.

1. When the aquifer head is above the river stage there is potential for flow from the aquifer to the river as illustrated in Figure 2.1a. The flux is generally proportional to the difference between the aquifer head and the river stage.

2. When the aquifer head is below the river stage, then the flow is reversed and the river potentially loses water to the aquifer as illustrated in Figure 2.1b. Again, this is generally proportional to the difference in elevation of the river stage and the aquifer head.

3. For a partially penetrating river (one where the aquifer extends beneath the river, as is often the case) the aquifer head may continue to fall below the base of the river. When the groundwater head first falls below the base of the river, the material below the river remains saturated and a mound of groundwater will be formed by the infiltrating river water.

4. As the aquifer head falls further, a column of draining water will form in the aquifer material between the base of the river bed and the water table as illustrated in Figure 2.1c. This water will drain under gravity with a unit head gradient, and this flux will no longer depend on the elevation of the groundwater head next to the river. This situation corresponds to a limiting infiltration rate and the river losses will not increase as the aquifer head falls further.

The nature of river aquifer interactions will also depend on the properties of the material lining the river. Many rivers have a zone around the river bed and river banks where fine sediments have been deposited or have invaded the aquifer material leading to lower permeability than the main aquifer. This can result in a very significant resistance to flow between the river and the aquifer, and is illustrated in Figure 2.2a to c for the gaining river, losing river and disconnected river respectively. Where the river is disconnected, the flow may be undersaturated below the river bed since the flux will be limited by gravity drainage at the rate determined by the Darcy flow through the low conductivity sediments. In some situations the presence of river bed or river bank sediments can have a similar effect on the response to pumping the aquifer as that due to an increased distance between the abstraction borehole and the river.

The rate of change of river flow, and attenuation of short term river flow changes (flood runoff), can be strongly influenced by the storage provided by the river bank. As river stage increases, the water is able to saturate material along the river bank and access this additional storage. When aquifer heads are reduced, then this water saturated zone will provide an additional source of water and reduce the immediate impact of an abstraction, for example, on the river flow. This phenomenon of bank storage is not taken into account in the methodology for an initial assessment.

The extent of river aquifer interactions will be dependent on the variations in aquifer properties through time and space. Typical analysis or approaches such as the analytical solutions presented in the User Manual will rely on simplification of the aquifer properties to a representative single storage and transmissivity parameter. In real systems, the aquifer will be heterogeneous and often highly anisotropic. The aquifer thickness may vary, and there will often be heterogeneous cover restricting recharge and leading to locally varying heads and aquifer characteristics. Similarly, the potential impact of groundwater abstractions will be influenced by the path of the river relative to the abstraction borehole. *

In the analytical solutions it is also implicit that the aquifer can be characterised by a single value of head. This will not be the case, as the aquifer will be recharged by precipitation and head distributions will result from the interaction of numerous inputs and outputs from the aquifer. In general there will be a reduction of aquifer head towards the river when the river is gaining baseflow from the aquifer. The effect of abstraction will be to create a zone of depression around the well. Using analytical solutions this drawdown can be simplified with assumptions of idealised radial flow to calculate the shape of drawdown zone that can be superimposed on the distribution of head due to the natural behaviour of the system. The superposition of a zone of depletion around a pumped well on a typical recharging aquifer head distribution near a gaining river is illustrated schematically in Figure 2.3. In this figure, the physical distribution of head (Figure 2.3a) is obtained by superposition of the drawdown due to abstraction (Figure 2.3c) on the natural head distribution without abstraction (Figure 2.3b). As a consequence of groundwater gradients which occur towards rivers the abstraction will usually intercept recharge that would otherwise contribute to baseflow, rather than taking water directly from the river. The net effect on the water balance of the river is however the same, with the **net flow** to the river being depleted as a function of time and position in a very similar way to the depletion due to abstraction from the horizontal rest water level in the aquifer assumed by analytical solutions. Note that the principle of superposition would make this an exact equivalence for an ideal confined aquifer or leaky aquifer. With an unconfined aquifer (or one where there is some contribution to the aquifer properties due to a leaky cover layer) the equations are non-linear and the solution can only be an approximation. Note also that the principle of superposition will not apply when the depletion from the stream is at the limiting percolation rate due to the aquifer head falling below the effective stream bed.

The zone of depression will extend away from the borehole and will approach the river. For an ideal, well connected and fully penetrating river, this will be bounded by the river which will form a zero drawdown boundary, however for partially penetrating rivers, the zone of depression can extend under the river and will be influenced by the storage of the aquifer beyond the river.

The list of possible combinations of aquifer type, aquifer head and river sediment properties, river penetration and river stage distributions, all of which may vary in space and over time, is long. There will generally not be data to clearly identify which situation pertains at any given reach of a river close to a proposed or existing licensed groundwater abstraction. There is often, therefore, no definitive answer to the question of how to evaluate the impact of the abstraction on the river without very significant levels of investigation and modelling, which will not generally be practical. The approach will have to be based on hydrogeological judgement, although the tools presented here will aid and support that judgement.

A key point however is that local abstractions will eventually take their water from the river, or intercept water that would otherwise have discharged into the river.

The only ways this can fail to be the case are as follows.

1. The abstracted water would have discharged to the sea or lake.

2. The abstracted water would have discharged to another river.

3. The abstraction derogates another borehole.

These first three possibilities essentially require consideration of a larger system than is considered directly in the User Manual.

4. The abstraction affects crops or other plants by removing water that would have been used for evapotranspiration. This is only likely where the water table is particularly close to ground surface and would be the case, for example, near a wetland (**specifically excluded from consideration in the project**).

5. If the river is effectively disconnected from the aquifer, limiting percolation applies (although even in this case, one is depleting the aquifer and at steady-state, the region across which limiting percolation applies will be extended so as to supply the water). For example rivers perched over impermeable clay drift will be isolated from the underlying aquifer, and will not be affected by nearby abstraction. **This condition is not considered by any of the analytical solutions used in the User Manual. It is important that a judgement is made as to whether the river might be isolated (no drainage) or disconnected (limiting gravity drainage) over a significant reach of the river under consideration.** If so, then the analytical solutions will overestimate the river depletion, and other approaches would be needed to estimate a more realistic impact.

Thus, whilst it is almost inevitable that the abstraction will eventually be taken from the river flows, the timing and distribution along the river of the net depletion will be affected by the aquifer properties, river characteristics and the well location. The position of greatest net river flow depletion will generally be centred on the closest point to the abstraction. This will be the case whenever the equations are nearly linear, even when the groundwater naturally (prior to abstraction) flowing past the borehole location would have contributed to baseflow some distance downstream. It will be spread up and downstream affecting a significant reach at steady-state depletion (see Winflow trialling models in Appendix B). The time to reach steady state can however be long, as much as several years if there is a low permeability barrier between the river and the aquifer. This may not influence the evaluation for long term steady abstractions for a sustainable resource management, but will be important for the assessment of periodic or temporary abstractions. If the water is taken from the aquifer during summer low flow periods, the net depletion of the river may be spread over a longer period (at a corresponding reduced rate). It may be delayed until winter months when the depletion will reduce higher flows when the river environment is less sensitive to river flow depletion.

If there is a periodic abstraction on a regular annual schedule, then the impact of a given year's pumping period may extend for more than a year. In this case, when the second year's pumping begins, its impact will be superposed on the declining residual impact from the previous year. In this way, once periodic abstraction begins, it may take several years for the maximum cycle of river flow depletion to be established as illustrated in Figure 2.4.

In assessing abstractions therefore, one needs to have a logical, tiered approach. At a preliminary stage it is useful to assess the consequences of simplified representations of the river aquifer system in order to make **an informed expert judgement** of the consequences for the water table and the river flow. Decisions can then be made regarding whether the issues require further tiers of assessment drawing on additional field investigations and numerical modelling techniques.

2.2 Use of analytical solutions

As discussed above, the interaction between rivers and groundwater systems is complex. Analytical solutions provide well established, rapid, idealisations of reality and are often seen as an important part of a staged investigation process. They are useful scoping tools but inevitably oversimplify the interaction between the aquifer and river. Analytical solutions are usefully deployed in the early stages of any hydrogeological investigation where there is little data and a quick and cheap means of directing further investigation is required. Accurate models will inevitably require numerical methods to be used and will require significant field data to be collected to confirm key parameters and provide head and flux targets against which the model can be calibrated. These methods require more time and money, resources which are often lacking. Used by hydrogeologists, the analytical models presented here can be useful tools. The results obtained can help to clarify the need for further more detailed evaluation, for example using numerical models.

2.3 Use of pumping tests

Pumping test data is an essential tool for estimating the aquifer parameters which are used in this approach. The interpretation of pumping tests generally relies on analytical solutions, similar to those used here and there are inevitable oversimplifications associated with the interpretations. It is important that such interpretations are carried out by suitably qualified and experienced individuals.

The interpretations should generally be made on the basis of fully penetrating observation wells so as to minimise errors arising from vertical flows which would generally require anisotropy of aquifer properties to be accounted for. Monitoring wells or piezometers should be used, if available, rather than the pumped borehole where flow rates will be highest and thus well losses and deviation from the underlying conceptual model will be most likely to affect interpretation. The results from each of several monitoring wells should be separately interpreted since there will generally be a range of inferred effective values, which will give an indication of the impact of local scale heterogeneity and the extent to which the simplifications influence results.

It should be noted that the pumping test interpretation models will usually be inconsistent with the assumptions underlying the analytical models used for the river aquifer interaction. In particular, most standard pumping test interpretations will not account for the boundary condition for the aquifer associated with the river. Where the pumping test has been conducted in boreholes very close to the river, or where the observation wells are very close to the river, then the resulting data should be inspected to see whether the influence of the river can be identified. The river will leak additional water to the aquifer (or gain less) than prior to pumping. This extra water has the effect of reducing the drawdown seen at monitoring wells as compared to a test remote from the river. The largest reduction in drawdown being seen close to the river.

Eventually, with a river boundary a steady state is reached, in contrast to a simple Theis response. Thus in interpreting a test, care should be taken to interpret only data at sufficiently early times that the drawdown is not affected by the river boundary. Note that the consequences are similar to those seen in a leaky aquifer test (although the spatial distribution of the reduced drawdown is different). If either process is possible, care will be needed to distinguish vertical leakage through an aquitard layer from river leakage. Some interpretation techniques however, are able to explicitly account for constant head boundaries and these might usefully be applied (for example Stallman's type curves (Ferris et al., 1962)). In any case, an observable influence or the absence of any observable influence on the aquifer drawdown may be useful to constrain the range of conceptual models applied to the interaction between the river and the aquifer.

The evaluation of the impact of the abstraction on the river should be carried out in the context of all other data available concerning the behaviour of the hydrogeological system. It should not form an isolated and mechanically applied procedure.

3 REVIEW OF METHODS

3.1 Literature survey summary

Several authors have produced reviews of the development of water resources from groundwater abstractions in an integrated surface water-groundwater system. The interaction between rivers and aquifers is complex and continues to pose challenges for water resource planning and management as discussed in the previous section. Useful reviews relevant to UK aquifers include Downing et al. (1974), Owen (1991) and Downing (1993). This report focuses on the consequence of individual abstractions of the flow in nearby rivers, and in particular, identifies simple approximate results that can be used to aid in an initial assessment of these impacts.

The first paper to evaluate the impact of pumping near rivers using analytical solutions is by Theis (1941) as discussed in the classic report on this subject by Jenkins (1968). Theis used an analytical solution to calculate the quantity of water supplied from an infinite straight line recharge boundary due to a constant rate abstraction from an aquifer. This result is used by Jenkins to estimate the total depletion of stream flow as a function of time due to nearby abstraction with the following assumptions:

the aquifer is isotropic, homogeneous, semi-infinite in aerial extent, bounded by an infinite straight fully penetrating unpuddled stream;

water is released instantaneously from storage;

the well is fully penetrating;

the pumping rate is steady;

and the residual effects of previous pumping are negligible.

The model further assumes that the aquifer is confined or that, for a water table aquifer, the drawdown is negligible compared to the saturated thickness (that is the transmissivity does not change).

The mathematical solution gives the stream flow depletion as a proportion of the abstraction as

$$\frac{q}{Q} = \mathrm{erfc}\left(\frac{1}{2\tau}\right), \qquad (3.1)$$

where

$\tau = \frac{1}{a}\sqrt{\frac{tT}{S}}$ is a dimensionless length scale for the system, and

T is the aquifer transmissivity (m^2/d);

S is the aquifer storage coefficient (specific yield for unconfined aquifer approximations (dimensionless);

a is the perpendicular distance of the well to the line of the river (m);

Q is the abstraction rate at the well (m^3/d);

q is the total river depletion rate (m^3/d); and

t is time (days).

This is a very useful analytical result. Although for most applications of interest the assumptions behind the model are over simplifications, it can be used to provide an overestimate of the impact of abstraction on river flow, and an underestimate of the timescales over which the flow reduction develops. By neglecting stream bed and stream bank sediments and assuming full penetration, the impact of pumping on the stream flow is over estimated, and the time delay between abstraction starting and the impact of pumping on stream flow is underestimated. A further assumption behind the result is that prior to pumping the piezometric surface is flat and equal to the constant water level of the stream. In fact this is not a major limitation since the impact of recharge and baseflow can be accounted for by superposing the drawdown predicted by this model on the head distribution without abstraction, and interpreting the stream depletion as a reduction from the baseflow.

The same result is presented by Glover and Balmer (1954). Jenkins (1968) extends this to the case where the abstraction is taken for a finite period, by using the principle of superposition. Jenkins's report makes a very useful and applicable summary of the use that can be made of Theis's or Glover and Balmer's result with worked practical examples. Spinazola (1998) has recently implemented Jenkins (1968) approach in a spreadsheet model and demonstrated this on a case study in Idaho.

Whereas Jenkins considers the impact of a single finite period of pumping, such as might be expected to result from a pumping test, Wallace et al. (1990) extend this to investigate the practical issue of regular seasonal abstractions over several years. For cases where the impact develops over long timescales due to the distance between the well and the river, the aquifer properties and possible the role of riverbank/riverbed sediments, Wallace et al. show that the impact may develop over several annual cycles. The maximum impact in later years might exceed the first years' maximum river depletion. This is a potentially important feature of sustainable catchment management to avoid low river flow problems.

Hantush (1959) discusses the drawdown due to the pumping near such an idealised river-aquifer interface and illustrates how to obtain the aquifer properties from time-drawdown data. Stallman has incorporated this solution into a family of type curves that might be used in the traditional type curve analysis for aquifer properties using time-drawdown data from piezometers near fully penetrating rivers in good connection with the aquifer (in Ferris et al., 1962).

Boulton (1942) addresses a related problem, evaluating the steady drawdown due to continuous steady pumping with the same assumptions regarding the aquifer and stream properties, but with the river assumed to flow over the top of the aquifer. He calculates the steady state drawdown as a function of all three coordinates and also the steady state location of the water table and the depth averaged head. This is particularly useful to confirm that the river and aquifer do not become disconnected during the abstraction for cases where Theis's approach is being applied as a bounding estimate of the impact of abstraction near a partially penetrating stream.

A number of extentions of this result to increasingly complex conditions are possible, as follows:

Newsom and Wilson (1988) consider how this is modified when there is baseflow from the aquifer to the river. Essentially, this is a superposition of a uniform flow field with the steady drawdown due to Theis's pumping solution. It does not affect the impact of the pumping on the net flow in the river, but it does identify how much of the impact is due to depletion of the river flow directly, and how much is taken from intercepted baseflow. The overall evolution of the impact on the river flow is unaffected, but the quality of the abstracted water depend on the quantity of water draining directly from the river. Conrad and Beljin contrast a similar solution reported by Wilson with a numerical model, finding that neglecting order of magnitude contrasts between river bank sediment and aquifer hydraulic conductivity lead to discrepancies of the order of 50% between analytical and numerical models. Neglecting partial penetration produced errors of typically 20%, although these errors are indicative, and depend on the values of the parameters characterising the interaction. Note that here and elsewhere, where the interest is water quality, the key result is the quantity of water abstracted that has infiltrated through the river bed as opposed to intercepted baseflow that is taken directly from recharge. In the current study, the head distribution in the aquifer is not considered and the drawdown relative to a horizontal initial head distribution is evaluated. The principle of superposition is used to evaluate the **net** impact on the river flow and the approach discussed elsewhere in the report cannot predict the relative proportions of water coming from direct recharge and from indirect recharge to the aquifer derived from river flow.

A more significant development of the result is to consider the influence of low permeability river bank or river bed sediments. The role of these sediments is discussed in detail by Rorabaugh (1963). Hantush (1965) extends the analytical solution to include the impact of semi-permeable sediments adjacent to the river. The corresponding solution to (3.1) is given by

$$\frac{q}{Q} = \operatorname{erfc}\left(\frac{1}{2\tau}\right) - \exp\left(\frac{1}{2}\lambda + \frac{1}{4}\lambda^2\tau^2\right)\operatorname{erfc}\left(\frac{1}{2\tau} + \frac{1}{2}\lambda\tau\right), \qquad (3.2)$$

where

$\tau = \frac{1}{a}\sqrt{\frac{tT}{S}}$ is a dimensionless length scale for the system and

$\lambda = \frac{a}{2}\frac{bp'}{Tm'}$ is a dimensionless river bank resistance parameter, and

b is the river bank depth (m);

m' is the river bank thickness (m);

p' is the river bank hydraulic conductivity (m/d);

and other parameters are as above. He also expresses his result in terms of an effective distance of the pumped well from the river. The two representations are equivalent but the explicit consideration of the river bank properties is conceptually clearer. The difficulty with the conceptual model for calculating the flow in the aquifer, is that the river is assumed to be fully penetrating. This corresponds to no vertical components to flow and no account taken of storage beneath the river or on the opposite side of the river to the well (as also assumed by Theis).

Jenkins (1969) takes his analytical approach to the application of Theis's solution further by using electrical analogue and numerical finite difference models to consider the case where there are more complex boundary conditions, and to evaluate the corresponding results using Hantush's model representing a fully penetrating stream with semi-pervious stream bank sediments. A more detailed discussion of the treatment using Green's functions of a range of simple recharge and no-flow boundaries for homogeneous isotropic confined aquifers is given by Kruseman and de Ridder (1981). This discussion includes the evaluation of drawdown and stream depletion due to pumping near right angled recharge boundaries and between recharge and no-flow boundaries.

The final useful extension to Theis's solution that is discussed in the literature in the extension to a partially penetrating river with a semi-permeable base. This is reported in a very detailed paper by Hunt (1999) (although a partial analysis is attributed earlier to Stang (1980) by Bullock et al., 1994). The river depletion is given by

$$\frac{q}{Q} = \operatorname{erfc}\left(\frac{1}{2\tau}\right) - \exp\left(\lambda + \lambda^2\tau^2\right)\operatorname{erfc}\left(\frac{1}{2\tau} + \lambda\tau\right) \qquad (3.3)$$

where now

b is the river bed width (m);

m' is the river bed thickness (m);

p' is the river bed hydraulic conductivity (m/d);

and other parameters are as given for 3.2 above.

Hunt also gives an expression for the drawdown in terms of integrals of the well function (i.e. integrals of the exponential integral E_1) which might be integrated numerically. He shows with this solution that the correct approach to dealing with partial penetration is by modifying the streambank sediment resistance parameters rather than by using an effective distance to the well that is modified from the physical distance (which was incorrectly suggested by Hantush). Nawalany et al. (1994) suggest a similar correction, but do not account for the storage on the far side of the river. Zlotnik and Huang (1998) present a slightly more sophisticated solution that better accounts for the region beneath the river where the confined storage coefficient applies, even in an unconfined aquifer, with the assumed continuous contact between the groundwater and the riverbed sediments. Their result is for a related problem posed in terms of the response of the aquifer to head variations but might be modified to address the impact of abstraction on river flow. It was judged however to be introducing too much detail given other inherent simplifications to the aquifer properties and river geometry.

The above mathematical work develops relatively sophisticated analytical solutions to an idealised river-aquifer interaction. This may often aid an initial assessment of the impact of groundwater abstraction on river flows. However, they all simplify the aquifer properties, represent the course of the river as an infinite straight line, ignore transmissivity variation within the zone of depletion, and ignore the possibility the groundwater becoming disconnected from the river along some reaches. There are a number of useful reviews of the application of these analytical solutions to approximate the river-aquifer interaction. Particularly useful is the report by Bullock et al. Which summarises many of the findings presented here in its appendix B, in the context of using and verifying the Micro LOW FLOWS program. The work reported in this and the companion report by Watts et al. (1995) is very similar to that discussed here but is aimed at a more detailed assessment of river low flows over river catchments.

Another particularly useful review paper that compares the results from the Theis and Hantush solutions against a numerical model of a partially penetrating river is Spalding and Khaleel (1991). The comparison with a numerical model is useful, since the numerical model is based on a conceptual model which will often be most appropriate for real systems. Comparison against a numerical model allows the consequence of conceptual model simplification to be evaluated independently from issues of uncertainty in measurement or transience in real field case studies. The shortcoming in the paper is that it does not evaluate the Stang/Hunt solution, which was developed later. Spalding and Khaleel show that the storage beyond the river might lead to significant errors of half an order of magnitude in the time to approach steady state (or a significant overestimate of 20% or more in peak impact for a two month test with the example parameters). Neglecting also the role of sediments produced much larger errors (about twice the error for the example parameters). Both of these investigated errors are avoided by using the Stang solution.

Sophocleous et al. (1995) also contrast analytical solution results with numerical model (MODFLOW) results. Again it is seen that partial penetration significantly increases the timescale of development of the impact of steady abstraction on river flow (or reduces the maximum impact of finite abstractions). They comment that neglecting the role of streambed sediments can render the use of Theis completely inappropriate (as one might expect!) with very much shorter timescales for the development of the impact. They also note the role of aquifer heterogeneity, seeing significant differences between numerical model results and analytical estimates. They report errors of the order of 50%, although their numerical model meshes are coarse and their results will be strongly influenced by detailed specification of the structure of the heterogeneity and of the properties adjacent to the well and the river.

Detailed assessment of particular river aquifer interaction is best carried out with a combination of field work and distributed numerical modelling using models that accurately incorporate the correct conceptual model. That is not always feasible, particularly in an initial assessment, however it is useful to review case studies of more detailed assessments. Particular case studies within UK aquifers include Morel (1980), Rushton et al. (1989), Younger et al (1993), Chen et al. (1997), Chen and

Soulsby (1997). A modelling study with a different emphasis is given by Nield et al. (1994) who use a numerical model to explore the wide range of possible configurations for river aquifer interaction.

3.2 Agency Regions survey summary

The results of a questionnaire issued to all Agency Regions is given in the project record report of NGCLC WR1. These questionnaires were issued to obtain feedback from the Agency as to the current practices undertaken by staff and to obtain views as to the types of approaches that staff would find useful.

Table 3.1 shows the most common methods used by the respondents. The salient points of these questionnaires are summarised below under the appropriate questions.

Table 3.1 Summary table of methods used in responding regions.

Respondent and Agency region or area.	**Methods stated in questionnaire.**
Keith Seymour (Warrington, NW)	No preferred method, but numerical methods highlighted.
Julie Sherwood (Exeter, SW)	Numerical models where available.
Len Careless (St Austell, SW)	Jenkins commonly used. Numerical methods on fissured strata.
John Ellis (Worthing, Southern)	Jenkins and Theis. Some field evaluation including pumping tests and stream gauging.
Vin Robinson (Reading, Thames)	Glover and groundwater models where available.
Paul Sadler (Exeminster, Devon area)	Jenkins.
Tony Jenkins (Shrewsbury, Midlands)	Method supplied by John Lloyd
David Seccombe (Ipswich, Anglian)	Jenkins and pumping tests.
Rob Cunningham (Nottingham, Midlands)	Jenkins and groundwater modelling in complex scenarios.
Peter McConvey (Lincoln, Anglian)	Regional models and others unspecified.

Q1. Under what circumstances/hydrogeological conditions would you seek to estimate the impact on river flows of groundwater abstractions? (eg proximity, abstraction rates, geology, hydraulic connectivity, shape/size/hydraulic characteristics of the aquifer, others.)

Most replies stated that there is a need to investigate the impacts where there is a licence application, resource evaluation or where there is a potential for impact on habitats. In terms of the hydrogeological characteristics there was general feeling that where the river was in close proximity to the borehole or where there was a high hydraulic conductivity of the aquifer, the case should be assessed.

Q2. How do you evaluate the impact a borehole abstraction will have upon river flows? i.e. which is the preferred method(s) / established procedure for your Region/Area? (Are cross sections/conceptual models used in every case?).

In general the factors governing the method were dependent on the requirements. Where only a quick evaluation was required then the method used was simple. Where the hydrogeological environment is more complex or where the depletion may be more critical, the use of groundwater models was noted. Field evaluation studies (i.e. pumping tests results) were also identified where there was a lack of data or more analysis was required. A detailed look at the hydrogeology/geology was identified by a number of respondents as being important in the evaluation of impacts.

Q3. Which factors govern the choice of your method? What range of hydrogeological conditions apply in your Region and do they affect the choice of method?

A number of Regions did not state a preferred method saying that the choice was site specific. However, where the requirement was for a quick first pass assessment, the method of Jenkins was the most popular. More complex assessments meant that regional models were also used where available. Most regions appeared to prefer the regional models where they were constructed but the use of these was generally dependent on the time available. Radial flow models were also highlighted by Dave Seccombe (Anglian region) as being a preferred method, but he noted that this was currently not available.

Q4. Is a combination of any methods used? If so which methods and why? Have you found the results of any particular methods to be comparable? Which methods?

Combinations of methods were generally used where the hydrogeological environment was complex or there were a number of regional models available. The use of these techniques was noted to be dependent on the time involved and the likely importance scale of impact. Field techniques such as pumping and gauging were noted as being used to verify the results of predictions.

Q5. Is any additional information used in conjunction with the results of the methods? (e.g. from pumping tests, river gauge data, effects of other abstractions on river flows) If so, is this considered advantageous and why?

Most respondents stated that there was a need for good gauging data where available and used gauging stations to provide this. Pumping test results are also used in the evaluation of depletion.

Q6. Typically, how many evaluations do you undertake per year?

The number of evaluations varied widely from 6-10 to 'hundreds' per years. Generally the number was dependant on the size of the Region.

Q7. What criteria are used for granting / not granting an abstraction licence regarding the impacts on the river aquifer system and river flow depletion only?

The response to this question was variable. In general the Q_{95} for river flow was used to interpret the impact. However, there was no particular consensus as to the interpretation of the impact. Many respondents identified the level of concern being 10% of the Q_{95} whilst others used the 5% level. Furthermore, some staff identified the impact at which concern would be expressed as 'where an adverse effect' was predicted, this being mainly in the flow volume or water level. No quantification was given in these cases.

Please attach any additional information on another sheet and fill out the following 1 page summary for any methods that you have used or that you may have encountered. For each method please provide as much of the following information as you can.

The responses were generally for 1) Jenkins or variations of his method and 2) Numerical models

1) The solution was identified as being quick and easy to use, with a limited amount of data

required. The assumptions were the greatest area of concern and respondents stated that the output was often only approximate.

2) Numerical models to the contrary were seen to provide a more realistic prediction of the impact but were time consuming and data hungry. Large models were identified as having the advantage of representing cumulative impacts.

One distinct approach used is that developed by Surface Water Abstraction Licensing Practice and applied particularly to some of the North-East Region abstractions.This was supplied to the project by John Aldrick as a brief note report outlining the approach. This is a simple pragmatic approach that recognises that for abstractions that are hydrogeologically distant from the river, the impact in terms of river flow depletion will be delayed as discussed by Jenkins (1965) and others. The aproach combines direct river leakage, and intercepted baseflow. For summer abstractions, the approach is essentially equivalent to Jenkins or Wallace, with simplified factors to represent the time over which the depletion of river flow occurs. For continuous abstraction, the approach still distributes the impact from distant abstractions unequally between January to April and May to December, with largest impact in the early part of the year. This is difficult to reconcile with the analytical solutions for continuous abstraction which should result in a continuous net impact on the river flow. Note however that the relative proportions of intercepted baseflow and river leakage induced by the abstraction is likely to vary through the year as the catchment discharges to baseflow and recharges during periods of high precipitation. The only mechanism that might lead to seasonal variation in **net** river flow depletion would be if the water table during the early part of the year recovered to the extent that the ground was saturated and there is enhanced interflow or surface runoff. This case is analogous to the limiting leakage when the water table falls below the base of the riverbed. Again the analytical models and the principle of superposition do not apply in this case. Again, an accurate assessment of the consequence would best be addressed by detailed distributed numerical modelling, however the SWALP methodology, if calibrated against many well observed cases, can provide a pragmatic simplification for routine initial assessment.

3.3 Selection of approach

Based on the results of the literature study of international best practice and current Agency practice, the following approach was selected. A simple spreadsheet tool has been developed that takes the analytical models of Theis, Hantush and Stang and implements them using the principle of superposition and the methods of Jenkins for a finite period of abstraction and of Wallace et al. for periodic abstractions with an annual cycle. This incorporates most of current agency practice within a consistent methodology, with easily accessible tools to guide expert judgement in determining licence applications. It does not always allow a decision to be made and in some cases will lead to a recommendation for more detailed site specific modelling. It incorporates much of the methodology developed for SWALP within a slightly more precise framework of evaluation of analytical solutions, particularly for the SWALP approach to periodic summer abstractions. However, it differs from this approach for continuous abstractions where the methodology presented below will not account for limiting recharge to the catchment. This is a complex situation where more site specific numerical modelling is recommended by this methodology.

The approach goes beyond current Agency practice in introducing Hantush and Stang analytical solutions. This allows in principle for more detailed representation of real systems in the initial assessment tools. However, in most cases, it is unlikely that the river bed or river bank properties will be known. It is inadvisable to make decisions that depend on such unknown parameters, to which the analytical solutions are very sensitive. The spreadsheet tool can be used to scope the range of possible impacts due to plausible parameter values but the final decision must be a hydrogeological judgement. This judgement should use simplified model results given by the analytical solution only as one contribution to the overall decision process.

The Stang solution is a significant extension of previous analytical results. It allows the user to account for storage beyond the river and for a shallow river penetration of the aquifer. These aspects of the solution can be accessed without specifying river bed properties by simply setting the river bed sediment hydraulic conductivity equal to the aquifer hydraulic conductivity (implied by the transmissivity and the aquifer depth).

The spreadsheet tool is to be used by suitably qualified and experienced hydrogeologists.

4 CONCEPTUAL MODELS USED IN ANALYTICAL SOLUTIONS

4.1 General conceptual models used for the aquifer

The analytical solutions make a number of simplifying solutions about the river-aquifer system and about the borehole abstraction. They make the following assumptions which are typical of the assumptions made in other analytical models such as those that generally underlie pumping test analysis methods:

- Homogeneous isotropic aquifer;
- Uniform thickness;
- Infinite areal extent of the aquifer;
- Groundwater flow is horizontal;
- Rest water level is horizontal;
- No well losses;
- Fully penetrating well;
- Water taken immediately from storage.

These are generally not satisfied in real aquifers, but can often be taken as reasonable approximations. The spreadsheet model presented in the User manual incorporates these assumptions.

The use of the steady state model within Winflow is optionally suggested within the methodology. The steady state Winflow model uses the same assumptions listed above and also allows a regional gradient and a **fixed** head to be specified to represent the conditions in the aquifer far from the region of interest. If this close to the region of interest, this will influence the calculated heads and fluxes artificially (the head is fixed and so any predicted changes in head at this location must be compensated for by artificial fluxes required to maintain an unchanged head at the specified point). It should be located far from the region where specific features of the model are predicted to change the groundwater head.

The analytical solutions used in the spreadsheet model assume that the transmissivity is constant. T=K.b This is strictly satisfied for a confined aquifer. For a deep unconfined aquifer, it is a reasonable approximation so long as the drawdown never results in a significant change in saturated thickness, but the spreadsheet conceptual model will be more inaccurate for shallow unconfined aquifers.

Both the spreadsheet and the Winflow models rely on the principle of superposition illustrated in Figure 2.3. In particular, the spreadsheet model does not explicitly account for recharge over the aquifer. The physical system will be recharged, and it is this pattern of recharge that will generally support the baseflow of the river. The principle of superposition allows the results of the spreadsheet calculation of stream depletion, to simply be added to the pattern of river aquifer interaction corresponding to the aquifer system prior to the proposed abstraction and including the consequences of recharge. Thus the river depletion predicted by the spreadsheet model **is a net change in the stream flow** due to the abstraction. For this to be valid requires that the equations are linear, which again corresponds to the requirement that the transmissivity is independent of the head (i.e. is constant) for the combined system. Thus the approach will be reasonable for confined or leaky aquifers, and a good approximation for deep unconfined aquifers.

In order to use the principle of superposition for both confined and unconfined systems, Winflow works in terms of a discharge potential, and converts back to head after combining the analytical solutions. Thus it is able to avoid the assumption of constant transmissivity required by the spreadsheet.

4.1.1 Treatment of the river boundary

The river is treated differently by the three available solutions in the spreadsheet model and by Winflow. These are described in detail below. The choice of conceptual model for the river boundary is the key approximation to be made by the user, and this choice will determine the scale of errors associated with this scoping interpretation.

The spreadsheet models calculate the transient development of the total river depletion rate. Winflow, by contrast, calculates the distribution of a steady state flux between the river and the aquifer along the length of the river reaches.

4.1.1.1 Theis solution

The Theis (1941) model is the simplest representation of a river as a straight line of constant head in the aquifer. The conceptual model is illustrated in Figure 4.1a for a confined or leaky confined aquifer. It can also be applied as an approximation to river aquifer interaction in an unconfined aquifer as indicated in Figure 4.2a if the unconfined aquifer is sufficiently deep that T is approximately constant. It assumes that the flow at the river boundary is horizontal and that water is able to flow between the river and the aquifer at a rate given by the product of the full transmissivity of the aquifer and the head gradient in the aquifer adjacent to the river. Thus it corresponds to a fully penetrating river with no differentiation between river bank properties and the aquifer properties. It assumes an infinitely long river of constant stage equal to the aquifer rest water level.

At large times all the abstracted water will be balanced by depletion from the river. In this model there is both a large contact area between the river (fully penetrating) and the aquifer, and no low permeability sediments between the aquifer and the river. Thus, the Theis solution will correspond to the most rapid predicted impact of the abstraction on the river flow. The time is determined by aquifer properties and the distance to the river.

4.1.1.2 Hantush solution

it more likely to be longer!

The Theis solution (1941) was always recognised as underestimating the time delay between groundwater abstractions and river depletion. Early work investigated the use of *effective* distance parameters greater than the physical distance from the abstraction to the river as an empirical correction to account for the consequences of resistance between the borehole and the river due to river bank and river bed sediments. Hantush (1965) improved on this by developing a solution that explicitly incorporated a river bank zone of altered hydraulic conductivity between the river and the aquifer.

The other assumptions are the same as for the Theis representation of the river. The Hantush solution assumes an infinitely long river of constant stage. The head in the aquifer at the river is equal to the river stage which results in a constant head boundary for the aquifer flow system. The river thus forms a flow divide. There is no drawdown beyond the river, and the storage of the aquifer beyond the river cannot supply water to the abstraction. Flow is again horizontal at the river. Since there is no communication across the river it is generally taken as being appropriate for a fully penetrating river, although the hydraulic connection between the aquifer and the river can be limited by defining the river bank hydraulic conductivity and the thickness and depth of the riverbank connection. The conceptual model is illustrated in Figure 4.1b for a confined or leaky confined aquifer. It can also be applied as an approximation to river aquifer interaction in an unconfined aquifer as indicated in

Figure 4.2b if the unconfined aquifer is sufficiently deep that T is approximately constant.

If the additional resistance due to vertical components of flow can be neglected, then this might be applied to partially penetrating rivers with suitable caution. The main errors of applying this model to partially penetrating rivers are the additional resistance associated with vertical flow components (especially in the case of anisotropic aquifers) and neglecting the hydraulic connection to the aquifer beyond the river.

The assumption of constant transmissivity may also introduce significant errors unless the solution is restricted to confined or leaky aquifers, or to deep unconfined aquifers.

4.1.1.3 Stang solution

Using a symmetry argument Stang (1980) was able to generalise the Hantush solution, and this was further developed by Hunt (1999).

The Stang model considers a well pumping from an aquifer with constant transmissivity and horizontal flow, with a flux from a line source that is proportional to the head difference between a specified river stage and the head of the aquifer beneath. The flow is proportional to a resistance corresponding to river bed sediments. The model still neglects the vertical component of flow, but it does account for drawdown on both sides of the river and flow under the partially penetrating river. Again, it does not account for variations in transmissivity due to head changes and so strictly corresponds to confined aquifers as illustrated in Figure 4.1c, but as discussed above, may be applied to deep unconfined systems for which transmissivity is nearly constant as illustrated in Figure 4.2c. It does not account for conditions where the head falls below the saturated base of the river bed leading to limiting drainage: the flow is strictly proportional to the difference between the river stage elevation and the aquifer head.

4.1.1.4 Winflow solution

Winflow is an interactive, analytical model that simulates two-dimensional steady state and transient groundwater flow. The steady state module of the program simulates groundwater flow in a horizontal plane using analytical functions developed by Strack (1989). The model uses the principle of superposition to evaluate the effects from multiple analytical functions (wells etc.) in a uniform regional flow field.

Winflow offers a more detailed representation of the geometry of the river course than does the other solutions. It is characterised in terms of a uniform base to the aquifer, but uses the aquifer hydraulic conductivity to evaluate transmissivity, which will depend on the aquifer head if the aquifer is unconfined. It represents the river as a series of specified head linesinks, and thus can represent the variation in river stage along the river reaches. Each linesink used to discretise the river is characterised by a line of uniform flux chosen so that the head at the centre of the linesink is equal to the specified head value: the river stage. It has a single head value in the aquifer equal to this river stage and thus corresponds to a fully penetrating river with no hydraulic connection between abstractions on one side of the river and heads on the other side (as with the Theis solution described above). If the linesink is long however, there will be errors introduced by the use of a constant flux along the linesink (leading to artificial head variation along the linesink not related to any user specified head variation).

4.2 The analytical solutions used

4.2.1 Spreadsheet models

The spreadsheet models use analytical solutions due to Theis (1941), Hantush (1965) and Stang (1980). The solutions have been superposed so as to consider the development of river depletion rates resulting from finite or periodic periods of pumping. These superposed results are attributed to Glover and Balmer (1954) and Jenkins (1968) in the case of Theis. The analogous superposition has been incorporated for the other solutions.

4.2.2 Model assumptions

All solutions make the following simplifying assumptions.

- The aquifer is infinite in areal extent.
- The aquifer has a homogeneous isotropic transmissivity which does not depend on head. This is strictly true only for confined or leaky confined conditions but may be a reasonable approximation for deep unconfined aquifers.
- Flow is horizontal and vertical gradients are neglected (Dupuit-Forcheimer approximation for an unconfined aquifer).
- The aquifer has a homogeneous isotropic confined storage coefficient (or specific yield if the tool is being used to approximate a deep unconfined aquifer).
- Either confined or unconfined conditions apply over the whole of the aquifer;
- The head tends to a fixed value at large distances from the well and this value is equal to the river stage; and that the impact of recharge or differences in river stage and aquifer rest water level at infinity can be addressed separately by the principle of superposition
- The river is described by an infinite straight line with a constant water level that is unaffected by discharge to the aquifer;
- Water is released instantaneously from storage in the aquifer;
- The borehole is screened over the full depth of the aquifer.

The following subsections give the analytical solutions due to a continuous steady pumping rate as a function of time from the beginning of abstraction, and describe specific assumptions made by each model about the river.

4.2.2.1 Theis

Theis assumes that there is no zone of altered properties adjacent to the river and that the head in the aquifer is equal to the stage of the river. Thus there is no hydraulic communication across the line of the river and the river has an equivalent hydraulic effect to a fully penetrating river. This is illustrated in Figure 4.3.

The river depletion rate can be given as a fraction of the abstraction rate by

$$\frac{q}{Q} = \operatorname{erfc}\left(\frac{1}{2\tau}\right),$$

where

$\tau = \frac{1}{a}\sqrt{\frac{tT}{S}}$ is a dimensionless length scale for the system, and

T is the aquifer transmissivity (m^2/d);

S is the aquifer storage coefficient (specific yield for unconfined aquifer approximations (dimensionless);

a is the perpendicular distance of the well to the line of the river (m);

Q is the abstraction rate at the well (m^3/d);

q is the total river depletion rate (m^3/d); and

t is time (days).

4.2.2.2 Hantush

Hantush also assumes that the head in the aquifer is equal to the stage of the river at the river, but allows it to fall across the river bank sediments. Thus there is no hydraulic communication across the line of the river and the river has an equivalent hydraulic effect to a fully penetrating river. He assumes that there is a zone of low hydraulic conductivity material adjacent to the river characterised by a river bank hydraulic conductivity and thickness, and a depth. This is illustrated in Figure 4.4. The river bank depth should be equal to the aquifer thickness for full consistency with the conceptual model, but it may be taken to be equal to the depth of water in the river to give a more accurate measure of the resistance posed by the river bank. This approximation involves neglecting the consequences of vertical flow near the river.

The river depletion rate can be given as a fraction of the abstraction rate by

$$\frac{q}{Q} = \mathrm{erfc}\left(\frac{1}{2\tau}\right) - \exp\left(\frac{1}{2}\lambda + \frac{1}{4}\lambda^2\tau^2\right)\mathrm{erfc}\left(\frac{1}{2\tau} + \frac{1}{2}\lambda\tau\right),$$

where

$\tau = \frac{1}{a}\sqrt{\frac{tT}{S}}$ is a dimensionless length scale for the system and

$\lambda = \frac{a}{2}\frac{bp'}{Tm'}$ is a dimensionless river bank resistance parameter, and

T is the aquifer transmissivity (m^2/d);

S is the aquifer storage coefficient (specific yield for unconfined aquifer approximations (dimensionless);

a is the perpendicular distance of the well to the line of the river (m);

b is the river bank depth (m);

m' is the river bank thickness (m);

p' is the river bank hydraulic conductivity (m/d);

Q is the abstraction rate at the well (m^3/d);

q is the total river depletion rate (m^3/d); and

t is time (days).

4.2.2.3 Stang

The river acts as a line of constant head that can supply a flux of water to the aquifer and which acts as a flow divide in the Hantush model. If one neglects vertical head gradients, this can be conceptualised as arising from a symmetrical two well system with a well on either side of the river, and the water being supplied vertically through the river bed. Neglecting vertical gradients is reasonable for a confined aquifer, but more of an approximation under the river in an unconfined system. However, the river is further assumed to be fully saturated beneath the river bed and thus will behave like a confined aquifer. The consequence of pumping from just one of these wells is simply half the river depletion of the two-well system. This was proven by direct solution of the equations by Hunt (1999). The model assumptions are thus

- there is flow from the river to the aquifer through the river bed due to a difference between the river stage and the aquifer head;
- the aquifer is saturated beneath the river bed, flow is horizontal and there are no vertical head gradients; and
- the river is narrow (can be taken as a line source) and the river width is only used to compute the resistance of the river bed sediments.

Strictly the model corresponds to a confined aquifer. The storage beneath the river and on the far side of the river is accounted for. The conceptual model and parameters used are illustrated in Figure 4.5. The use of this model avoids the need to adapt the Theis or Hantush models to use an 'effective distance' between the river and the well so as to account for neglected storage in those solutions.

The river depletion rate can be given as a fraction of the abstraction rate by

$$\frac{q}{Q} = \mathrm{erfc}\left(\frac{1}{2\tau}\right) - \exp\left(\lambda + \lambda^2\tau^2\right)\mathrm{erfc}\left(\frac{1}{2\tau} + \lambda\tau\right)$$

where

$\tau = \frac{1}{a}\sqrt{\frac{tT}{S}}$ is a dimensionless length scale for the system and

$\lambda = \frac{a}{2}\frac{bp'}{Tm'}$ is a dimensionless river bed resistance parameter, and

T is the aquifer transmissivity (m^2/d);

S is the aquifer storage coefficient (specific yield for unconfined aquifer approximations (dimensionless);

a is the perpendicular distance of the well to the line of the river (m);

b is the river bed width (m);

m' is the river bed thickness (m);

p' is the river bed hydraulic conductivity (m/d);

Q is the abstraction rate at the well (m^3/d);

q is the total river depletion rate (m^3/d); and

t is time (days).

4.2.3 Winflow

The basis of the Winflow solution is described in section 4.1.1.4 above.

Briefly Winflow assumes:

- The aquifer is infinite in areal extent;
- Flow is horizontal and vertical gradients are neglected (Dupuit-Forcheimer approximation for an unconfined aquifer);
- Homogeneous isotropic aquifer hydraulic conductivity, confined storage coefficient, and specific yield;
- Either confined or unconfined conditions apply over different parts of the model area;
- The top and base of the aquifer are uniform and horizontal;
- The regional head distribution away from the river and abstractions is characterised by a fixed head and a uniform gradient corresponding to the average impact of recharge and aquifer flow
- The river is described by a series of short straight linesinks along the course of the river
- The stage of the river is described by a series of linesinks that are automatically chosen to result in a specified head at the centre of each linesink. These fluxes correspond to piecewise uniform river depletion rates.
- There is no river bed or river bank resistance due to low permeability sediments
- The head in the aquifer is equal to the stage of the river at the centre of each linesink representing the river and there is thus no hydraulic communication across the course of the river: the river is thus equivalent to a fully penetrating river.
- The borehole is screened over the full depth of the aquifer.
- Water is released instantaneously from storage in the aquifer;

The precise analytical solutions used are described in the Guide to Using Winflow (Environmental Simulations Inc., 1996).

5 LIMITATIONS OF THE METHODOLOGY

When water is abstracted from a borehole within a catchment, then at steady state, this must always correspond to a consequent reduction in the natural outflows to the system. This may be:

- a reduction in stream flow;
- a reduction in evapotranspiration if soil moisture deficits are increased;
- a reduction in transfers to other aquifers for multi-aquifer systems; or
- a reduction in other abstractions due to changes in the aquifer storage.

This methodology only addresses the first of these. More sophisticated models are required to quantify the other processes.

There are two issues that can be addressed with the tools incorporated in this methodology. How quickly the abstraction is taken from the river as a stream depletion, and where it is taken from spatially.

The two software tools can provide complementary information. The spreadsheet tells you about the time lag between abstraction and stream depletion (which may be large), and Winflow tells you about where the depletion in taken from along the stream.

There are three specific uses of the methodology:

- evaluation of the impact of periodic abstractions;
- evaluation of steady abstractions;
- design of tests to gather information for the above.

The benefits in terms of river flow of pumping groundwater to discharge directly into a river so as to augment river flow can also be scoped.

The principal conceptual errors arising from the models used in the spreadsheet are:

- the usual pumping test interpretation assumptions of isotropy and homogeneity;
- the assumption of fully penetrating boreholes;
- no consideration of limiting drainage rates if the river becomes disconnected from the water table for unconfined systems – this needs to be checked as the model will in this case overestimate the river losses;
- assumption that the transmissivity is constant – this will underestimate time lags if the aquifer is unconfined and the saturated thickness varies appreciably;
- neglect of storage from the far side of the river (i.e. the river is assumed to be a boundary to flow) – this will lead to underestimates of the time lag;
- no consideration of impact on multiple rivers – see use of Winflow below;
- assumption of infinite straight river – this may affect the time lag to more distant reaches of the river.

Recharge and the distribution of head across the region is not considered by the methodology. This does not influence the time or distribution of the stream depletion so long as the drawdown can be superposed on the head distribution. This in turn requires that the groundwater flow equations are linear. For this to be valid, transmissivity must not vary (unconfined aquifer is deep) and the river drainage must not have reached limiting rates. These conditions are indicated in the list above. It may seem that neglecting recharge and the head distribution is a very serious limitation, however the trialling examples (Appendix B) illustrate that the distribution of river flow depletion remains very symmetrical about the closest point, even when there is a significant structure to the total flow system.

The principal errors arising from the use of Winflow within this methodology are:

- discretisation errors in evaluation of the river reaches and evaluation of the solution;
- the assumption of fully penetrating boreholes;
- the assumption of fully penetrating rivers – this will affect the drawdowns predicted and influence where the stream depletion occurs.

Note that there may be errors due to flows across the Winflow model boundaries if small regional models are developed using Winflow (caused by proximity to the constant reference head). It may be necessary to consider large catchments including more distant rivers, since water divide boundaries may move following abstractions.

6 DATA USED IN EVALUATION OF THE IMPACT OF GROUNDWATER ABSTRACTIONS

The calculations discussed here predict the impact of groundwater abstractions in terms of the depletion of river flow as a function of position relative to the borehole and as a function of time. They apply to connected rivers where the abstraction is within the catchment associated with the river (and so none of the four conditions excluded from consideration in section 2.1 above apply). The calculations are simple approximations to real rivers and aquifers, intended to be used as a first scoping assessment of the impact of groundwater abstraction of river flow. The basic inputs are therefore as follows.

6.1 Conceptual model of river aquifer interaction.

This is the most important input to the assessment of the impact of the groundwater abstraction on the river. There is a quite limited choice of conceptual model available within the scoping tools provided, and it is important that the hydrogeologists using these tools are aware of the approximations they are making and have a good conceptual model of the real system. The conceptual models are listed in section 4. The river must be connected (Figure 2.1a and b or Figure 2.2a and b), not disconnected (Figure 2.1c or Figure 2.2c) or isolated from the aquifer.

6.2 Course of river and location of abstraction

The analytical solutions assume an infinite straight line for the river course. It will therefore be necessary to make a reasonable judgement of an effective distance from the groundwater abstraction to a straight line approximation of the river course. Some sensitivity analysis for this parameter in the model will need to be undertaken dependent on the extent to which the real river meanders local to the groundwater abstraction location.

6.3 Aquifer type

The impact of groundwater abstraction on the river flow will be very different dependent on whether the aquifer is confined or unconfined. The analytical solutions used in the User Manual strictly apply to confined or leaky aquifers, but can approximate the behaviour of unconfined aquifers so long as transmissivity does not vary significantly and vertical gradients can be neglected. Consideration needs to be given to whether the aquifer type is locally changed as a consequence of the abstraction reducing the piezometric head so as to lead to locally unconfined aquifer conditions. The analytical models cannot address aquifers where different aquifer types are present within the same region under assessment.

6.4 Typical aquifer base and effective saturated thickness

The analytical solutions assume a flat aquifer of constant saturated thickness. The real geometry of the saturated aquifer will need to be approximated in analytical models.

6.5 Effective transmissivity and storage coefficient for the aquifer

The analytical solutions assume a homogeneous and isotropic aquifer represented by a single value for transmissivity, T, and storage coefficient, S. Thus, appropriate values to represent the average properties for horizontal flow around the well will be required. Care needs to be taken in heterogeneous aquifers or if there is anisotropy. The transmissivity will generally be estimated from pumping tests and should be inferred from the response in a number of piezometers at different distances and in different directions from the pumping well (or from other tests conducted in the neighbourhood of the proposed abstraction). The storage coefficient will generally be more uncertain and should correspond to the specific yield for an unconfined aquifer or the confined storage coefficient for a confined or leaky aquifer. Sensitivity analyses will help to evaluate the influence of these uncertain parameters.

6.6 Proposed abstraction rate

The analytical solutions either assume a constant continuous abstraction rate or assume that an average rate can be defined for each month that is then abstracted during that month every year. The rate specified should take account of where the water is used, and some account might need to be taken of the returns of abstracted water to the aquifer (decreasing the net abstraction) or to the river, effectively compensating for any impact, although with a different time lag. One may also need to consider explicitly requirements for compensation returns to the river.

6.7 River bank and river bed properties

It is assumed in the analytical models that the river remains connected to the aquifer throughout the period of assessment. If it becomes disconnected, then the models will overestimate the impact.

The three analytical solutions each consider a different conceptual model of the river bed or river bank properties. These are discussed in section 4 but briefly the alternatives are: no river sediment material between the fully penetrating river and the aquifer (Theis and Winflow); river bank sediments of specified thickness and hydraulic conductivity separating the fully penetrating river from the aquifer (Hantush); and river bed sediments of specified thickness and conductivity separating a superficial river from the aquifer it flows over (Stang).

The properties of the river bed and river bank sediments will generally not be known but are potentially very important parameters. They can wholly or partially isolate the river from the impact of abstraction. Where sediment material is present in the conceptual model (Hantush and Stang solutions), the numbers that can be specified for the model are:

- the width or depth (that is the length around the river cross section across which water can flow) which can be estimated;
- the thickness of the sediment affected zone which will generally be poorly known due to a gradual variation in properties away from the river as sediments penetrate the aquifer material to a variable extent; and

Predicted impacts of abstraction on river flow will be very sensitive to the river bank or river bed properties. Neglecting river boundary sediment properties will potentially lead to significant over estimates of the impact (underestimates of the timescales for impact). Thus, for a short duration abstraction close to a river, one may predict a rapid response at the time of abstraction with the river flow depleted by approximately the full abstraction rate if the river bed is under represented. If low hydraulic conductivity sediments are present, the true impact might be uniformly spread throughout the year with a correspondingly smaller impact during low flow periods.

Unfortunately, the effective hydraulic conductivity of the river bank or bed material will generally not be known. We do not recommend guessing these parameters, but do recommend that sensitivity calculations be undertaken to inform expert judgement where it is believed that a low conductivity zone is present around the river.

7 TRIALLING

7.1 Introduction

To enable the selected methodologies to be evaluated, it was necessary to implement a programme of trialling using real data from selected Regions. The choice of Region was dependent on a number of factors:

The Chalk of East Anglia was identified as an important aquifer to be assessed. The two other aquifers were the Permo-Triassic Sandstone of Shropshire and the Permo-Triassic Sandstone of Devon. The sites were chosen to have as much data as possible for use in the model. Ideally there should be good stream gauging data, although this is rarely available. Finally, the input of Agency staff was crucial throughout the trialling process. ESL liaised closely with Agency staff and feedback was sought on the Agency's requirements.

The areas chosen for the trialling were as follows.

Otterton Borehole No. 4.

The Otterton number 4 borehole is one of a group of boreholes in the Otter catchment of the Permo-Triassic Sandstone aquifer of South Devon. The selected borehole, Otterton 4, is considered to penetrate a leaky confined aquifer and was subject to a relatively long term pumping test. The example gives a chance to analyse a borehole extremely close to the river (25m).

Houghton St Giles.

An abstraction borehole in Chalk of North Norfolk in close proximity to the River Stiffkey. This is an unconfined high transmissivity aquifer adjacent to a relatively small river system. Some data is available for stream flow gauging and this was to provide a means of verification for the trialling predictions.

Helshaw Grange.

An abstraction in North Shropshire adjacent to the River Tern. The borehole is unconfined in the Permo-Triassic Sandstone aquifer and provides a good example of this system. Little data was available on the impact of abstraction on river baseflows and it serves to identify how important hydrogeological judgement is in the analysis of depletion impacts.

7.2 Results

Following the trialling, a number of general conclusions could be drawn and they are summarised below. Each of the detailed trialling exercises are included as appendices in the User Manual.

There is a large overall uncertainty in many of the parameters used in the trials. There is generally a necessity for the trials to be verified by field-testing.

In all large assessments, the Stang solution provided the most satisfactory conceptual model. The largest impacts are predicted by the Theis solution whilst the smaller impacts are predicted by the Hantush solution.

For all abstractions all the models will eventually result in all the abstracted water coming from a net depletion of the river flow (induced river leakage or intercepted baseflow). There are differences in how the depletion in river flow due to periodic abstraction is distributed in time. In particular, if a finite abstraction (pumping test) results in an impact with a long timescale, the depletion will be spread over time and the peak depletion rate will be reduced. Similarly, regular summer abstractions may be spread throughout the year. In contrast, when the timescale is short, then the abstraction will rapidly reduce the river flow by up to the abstraction rate. The timescale depends on the hydraulic diffusivity of the aquifer, T/S. Often T is reasonably well known and the key sensitivity is to the range of uncertainty in S.

With the Hantush and Stang solutions there is an additional resistance due to the riverbed sediments and the flow through these is limited resulting in a much larger cone of depression due to the test. This requires water to be taken out of a larger volume of storage and a corresponding larger timescale. The extent of the resistance provided by the sediments is simply related to the cross-sectional area of contact and the hydraulic conductivity in the conceptual model.

Finally, for Stang, there is access to storage beyond the river and this too increases the impact timescale. These general principles are exhibited in the trialling examples and can be used to assess whether a given model is likely to over or underestimate the impact.

The results of the trialling show that there are slight differences between the trials, although in all cases the Stang conceptual model is considered to provide the best estimate of impact. There is a rapid impact with a minimal lag time in the case of the Otterton example due to the proximity of the borehole to the river. The Helshaw Grange borehole in Permo-Triassic Sandstone was at a greater distance from the river and showed an increase in the lag time proportional to an increase in specific yield. The Houghton St Giles borehole in Chalk was at a similar distance from the river as the Helshaw Grange example but had a higher transmissivity and showed a proportionally quicker impact.

8 CONCLUSIONS AND RECOMMENDATIONS.

A methodology has been developed for the initial assessment of the impact of groundwater abstraction on river flow. It uses the current state of the art analytical solutions for river-aquifer interaction. These have been implemented in an easilly accessible spreadsheet tool that uses the approach of Jenkins (1968) to consider the distribution in time of the impact of finite or periodic pumping. The methodology has been demonstrated for three example abstractions in the Chalk at Houghton St Giles, and in the Permo-Triassic Sandstones at Otterton and Helshaw Grange.

It should be emphasised that the approach is based on expert hydrogeological judgement and that the spreadsheet tool should only be used to aid that judgement. The crucial step in the methodology, in common with all quantitative hydrogeology, is the identification of an appropriate conceptual model. In the case of this methodology for the initial assessment of the impact of groundwater abstraction on river flow, this involves matching our conceptual understanding of the real site to the simplified conceptual models underlying the available analytical solutions. The inevitable consequence is increased uncertainty which has been considered through the encouragement to consider a broad range of uncertainty, and the consideration of several analytical solution within an assessment, each with a correspondingly different simplified conceptual model.

The key conceptual limitations associated with the analytical models are:

assumed homogeneity of aquifer properties,

constant transmissivity in an abstracted shallow unconfined aquifer,

neglection of vertical head gradients,

infinite straight course of the river in the analytical solutions,

no account being taken of limiting leakage from a disconnected river or limiting recharge to saturated aquifer.

As important is likely to be the limitation in the availability of accurate data, in particular on river bed or river bank sediment properties.

To progress to a more detailed and confident assessment, the use of site specific numerical modelling is recommended where any potential exists for an adverse impact.

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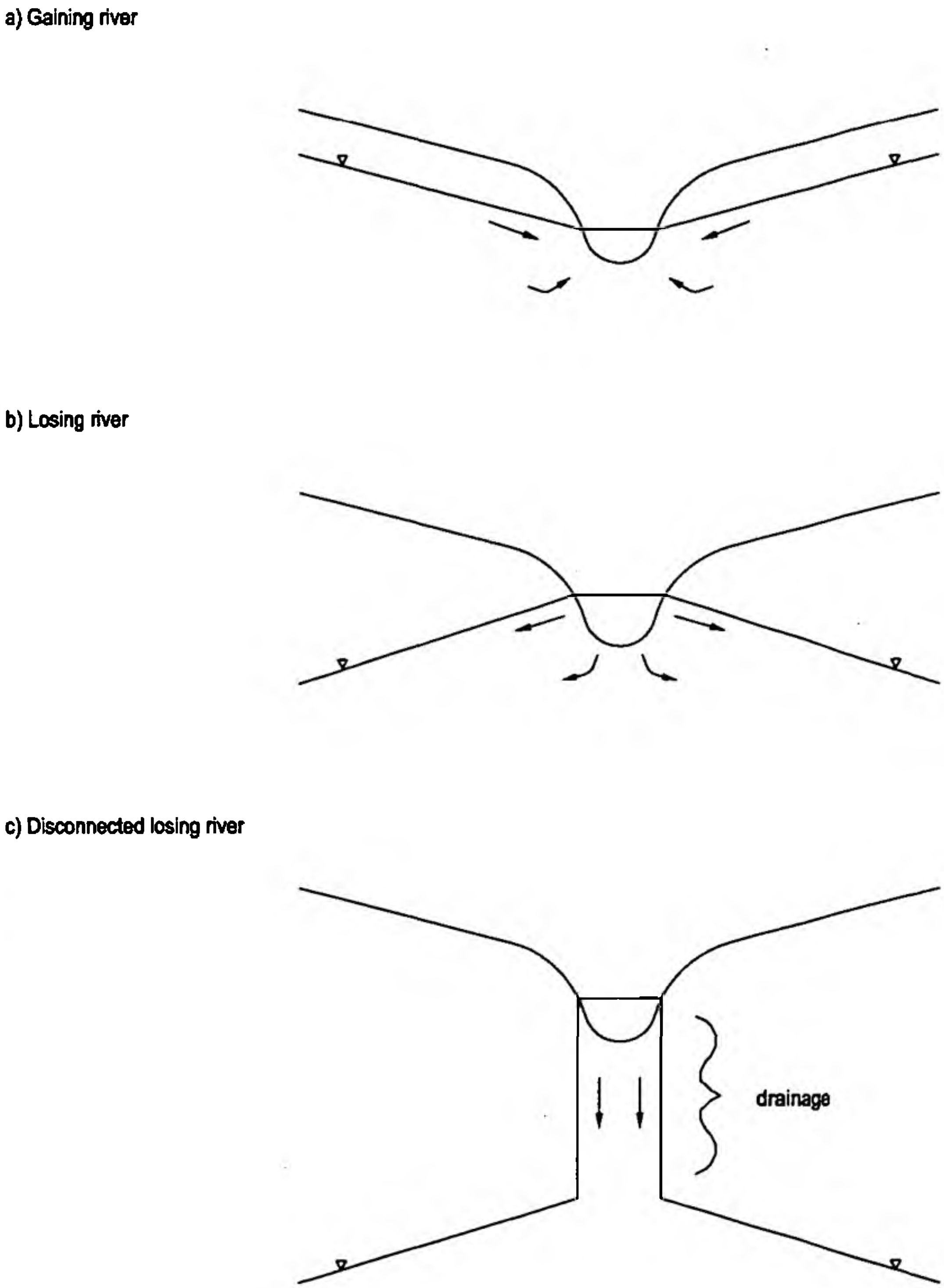
Figure 2.1



Title: Basic Categories of River - Aquifer Interaction			
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Scale: N.T.S.	Drawing No: 6077 / Figure 2.1		Rev: A

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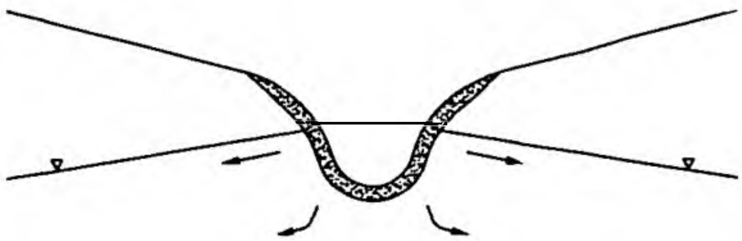
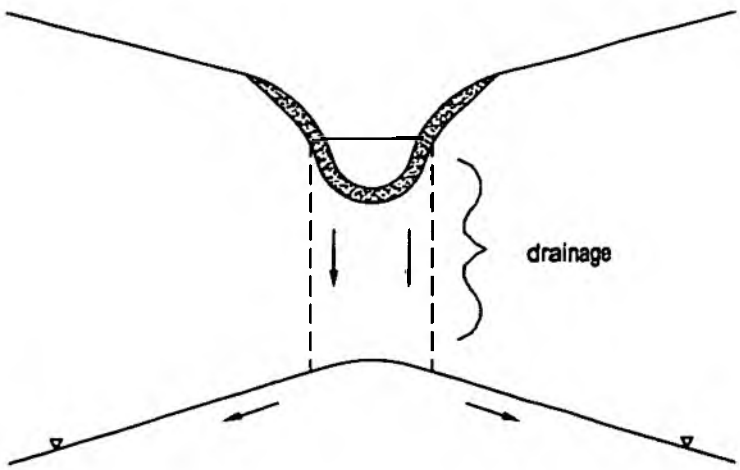
Figure 2.2

a) Gaining river

b) Losing river



c) Disconnected losing river



LEGEND

River bed / bank sediments

Title: Influence of River Bed / Bank Sediments on River-Aquifer Interaction			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
Scale: N.T.S.	Drawing No: 6077 / Figure 2.2		Rev: A

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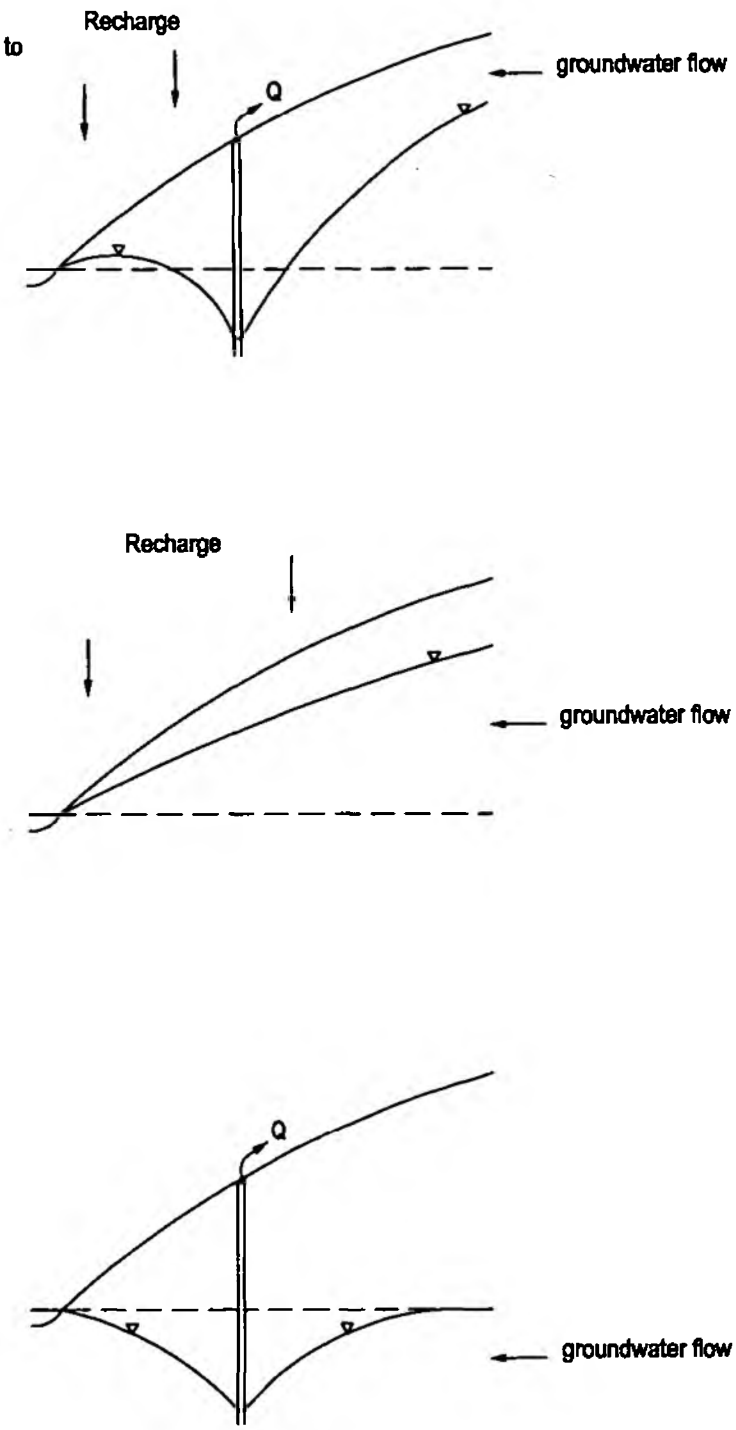
a) Physical water table, or superposition of heads (relative to static water level) due to recharge and base flow.

b) Water table prior to abstraction with head above static water table due to recharge and base flow.

c) Drawdown due to pumping, relative to static water level.



LEGEND

Title: Illustration of Principle of Superposition Applied to Abstraction Close to Gaining River			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
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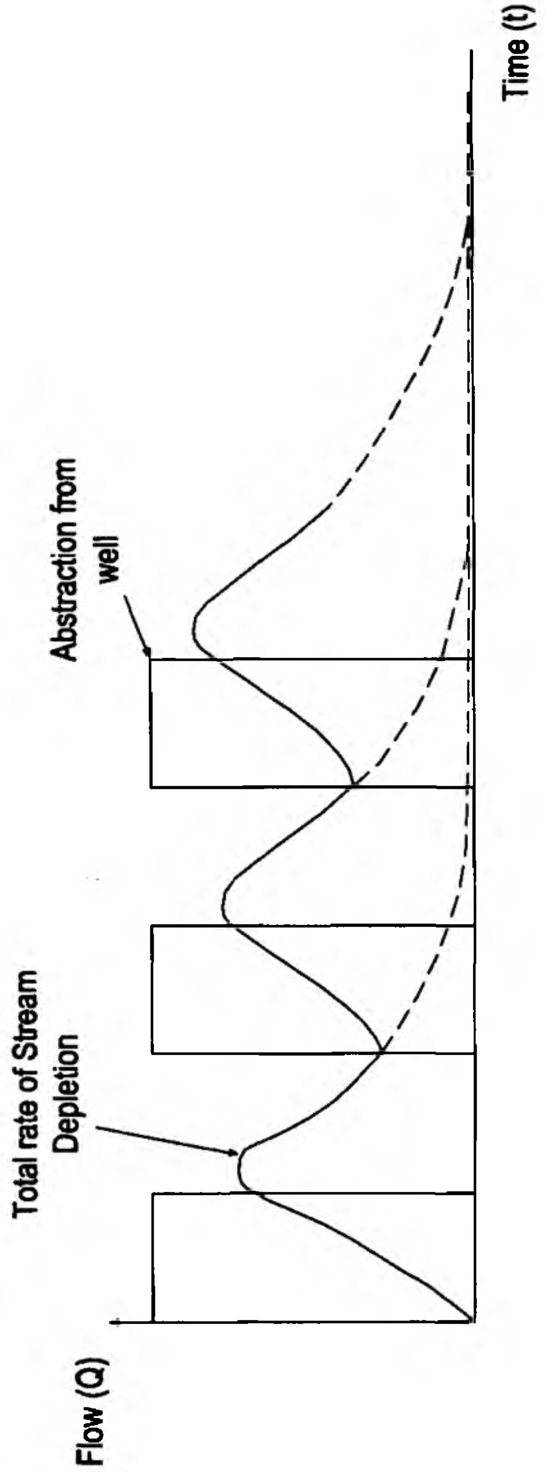
Figure 2.4



LEGEND

Title: Illustration of the growth of stream depletion as a result of several years of periodic groundwater abstraction (after Wallace et al. 1990)			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
Scale: N.T.S.	Drawing No: 6077 / Figure 2.4		Rev: A

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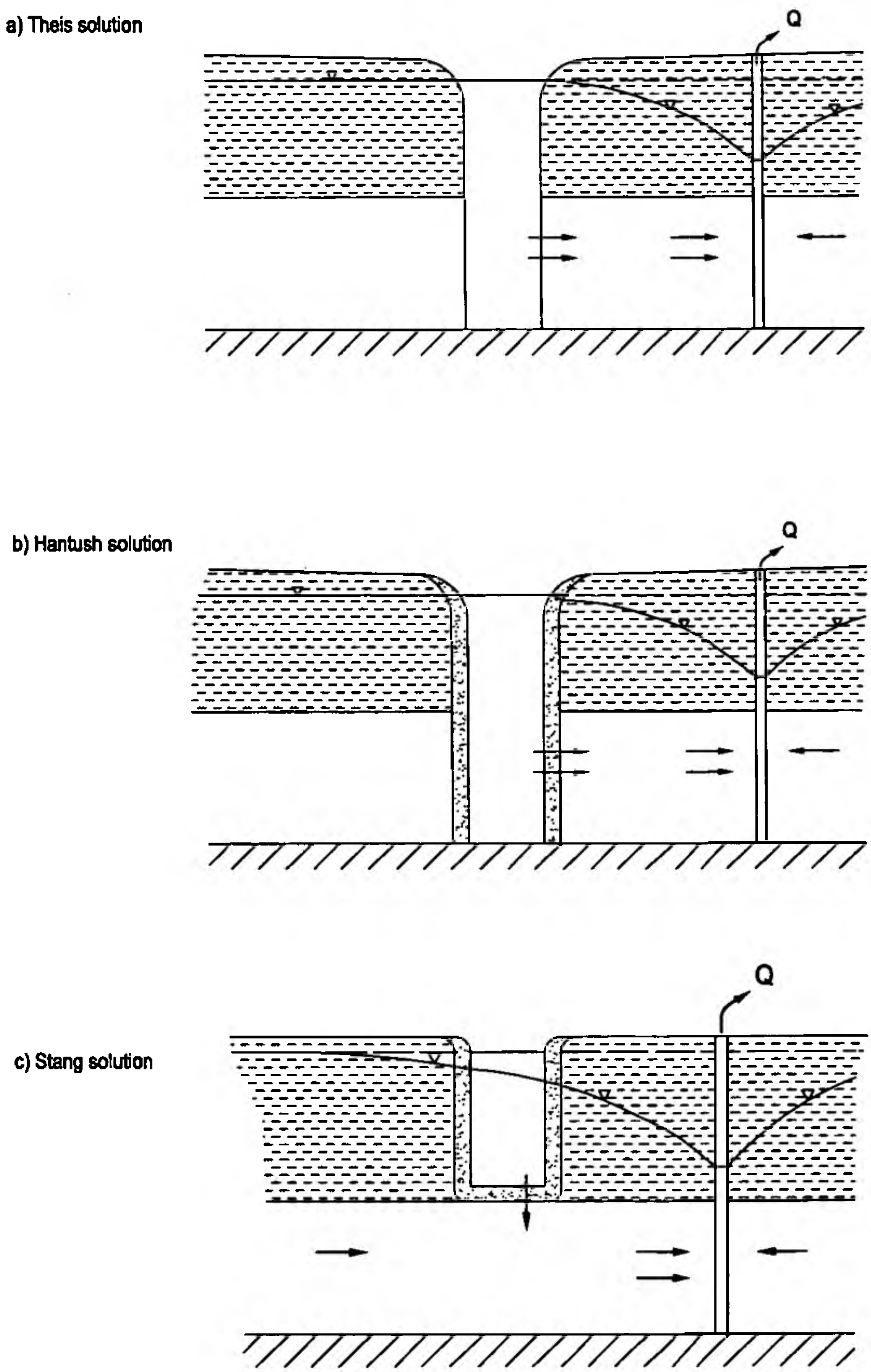
Figure 4.1



LEGEND

- River bed / bank sediments
- Impermeable base of Aquifer
- Aquitard

Title: Idealised Configuration of River-Aquifer Interaction Corresponding to Analytical Solutions for Confined Aquifer Systems.			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
Scale: N.T.S.	Drawing No: 6077 / Figure 4.1	Rev: A	

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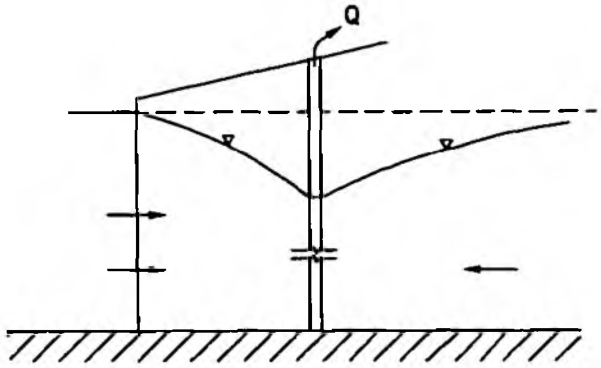
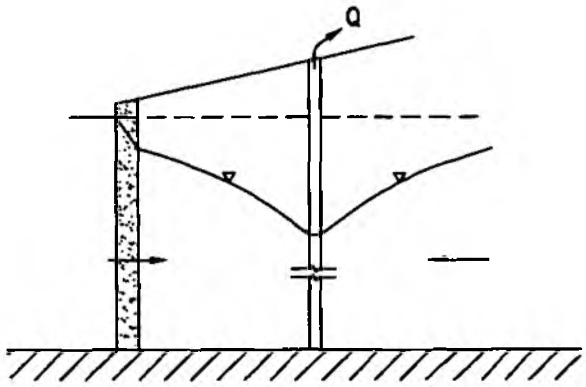
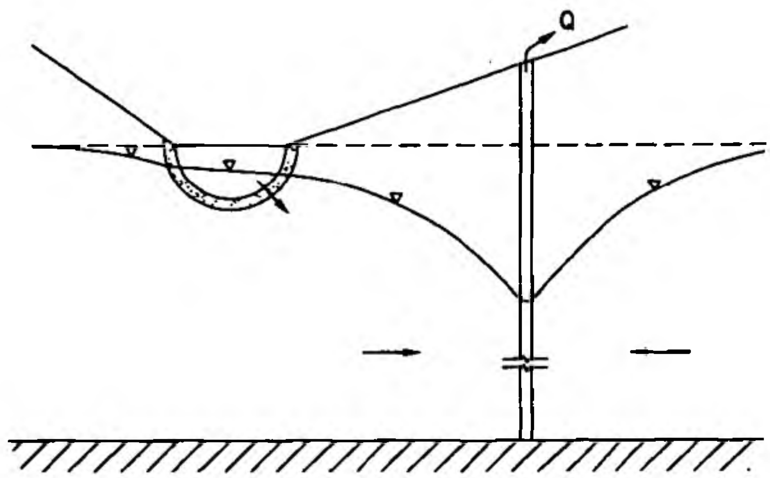
a) Theis solution



b) Hantush solution



c) Stang solution



LEGEND

River bed / bank sediments

Impermeable base of aquifer

Title: Confirmation of River and Aquifer Interaction Corresponding to (approximate) Analytical Solutions for Unconfined Solutions.

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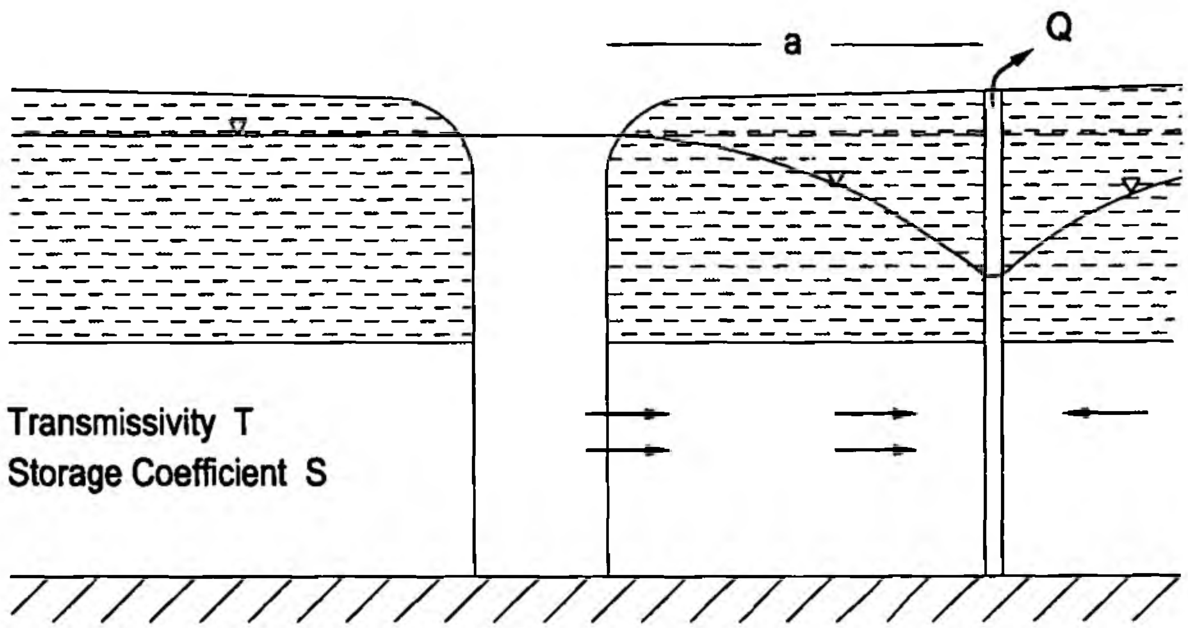

LEGEND

Impermeable base of Aquifer

Aquitard

Title: Conceptual Model for River-Aquifer Interaction used in the Theis Solution

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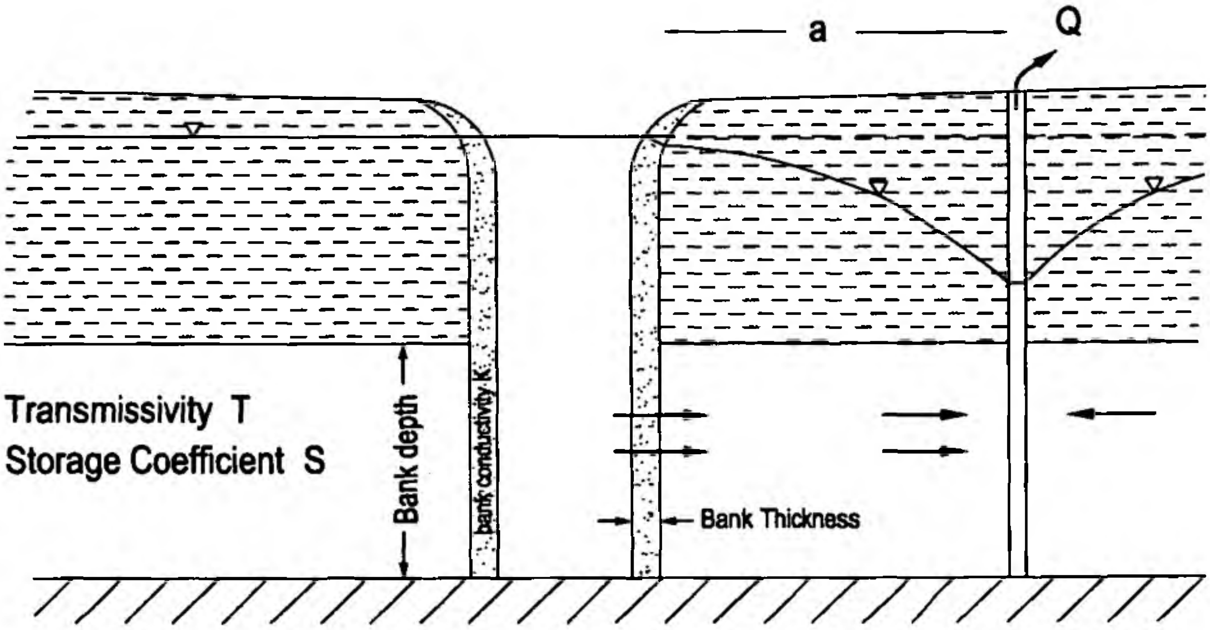
Figure 4.4



LEGEND

Impermeable base of Aquifer

Riverbank Sediment

Aquitard

Title: Conceptual Model for River-Aquifer Interaction used in the Hantush Solution			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
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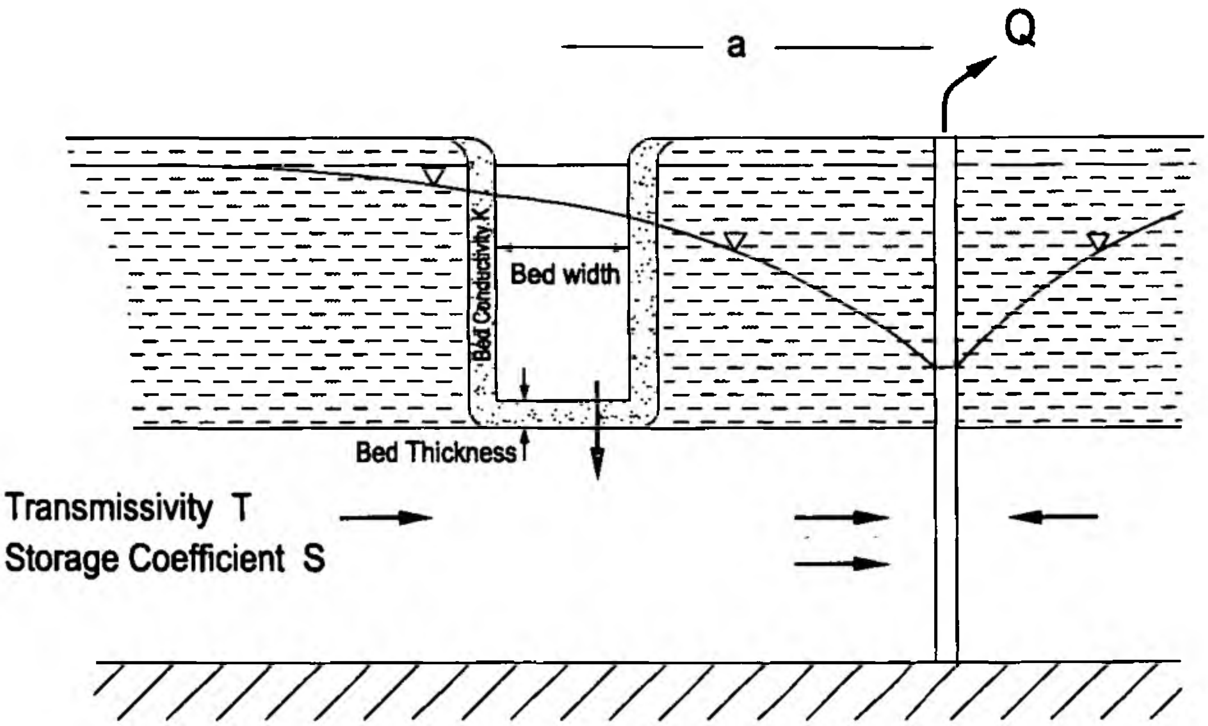

LEGEND

Impermeable base of Aquifer

River bed Sediments

Aquitard

Title: Conceptual Model for River-Aquifer Interaction used in the Stang Solution			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
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Groundwater Software and Services

Impact of Groundwater Abstractions on River Flows

User Manual
Draft for Agency Presentation

Environmental Simulations Limited

National Groundwater & Contaminated Land Centre Project WR1

Impact of Groundwater Abstractions on River Flows

User Manual
Draft for Agency Presentation

A W Herbert, J P Hatherall & M M Fermor

Research Contractor:
Environmental Simulations Limited

Environment Agency
National Groundwater & Contaminated Land Centre
Olton Court
10 Warwick Road
Olton
Solihull
West Midlands
B92 7HX

National Groundwater & Contaminated Land Centre Project WR1

CONTENTS

1 INTRODUCTION

1.1 Background

This User Manual has been prepared by Environmental Simulations Limited (ESL) on behalf of the Environment Agency (the Agency) under a contract to review current practice for the evaluation of groundwater abstractions on river and stream flows when assessing groundwater abstraction licence applications.

The primary aim is to present a reasoned, robust and technically supportable rationale for the evaluation of the effects of groundwater abstraction on river/groundwater interaction.

In order to achieve this the specific objectives of the project were:

a) To review the current available analytical and simple numerical methods for the determination of the impact of groundwater abstraction on river flows.

b) To produce a detailed and critical technical assessment of the applicability and likely accuracy of a selection of these methods in the context of the assumptions and data requirements inherent in the analytical an simple modelling techniques.

c) To evaluate an agreed selection of methods by trialling using data from catchments selected by the Environment Agency.

d) To produce a clear guidance document or User Manual for the selection and application of the most appropriate method of determination of impact on river flow from groundwater abstraction, in accordance with i) the hydrogeological/hydrological characteristics of the catchment and the river reaches concerned; ii) the available information; and iii) the accuracy requirements in the context of the flow requirements of the river. This document is to incorporate, prior to its finalisation, the results of feedback arising from a seminar addressed to relevant Environment Agency staff towards the end of the project.

e) To identify relevant criteria which might be considered in a follow-up project (or projects) to improve on the quality, scope and practical applicability of the outputs of this project. This might include, for example, use of more complex numerical models, and/or methods for addressing shortfalls in required data.

Objective e) above recognises that, for reasons of time constraint, the scope for this project specifically excludes consideration of the following:

Impact of groundwater abstraction on wetlands.

Impact of groundwater abstraction on or from springs.

Use of water quality as an indicator of groundwater abstraction impacts on river flow, such as contribution of river-specific hydrochemical facies to abstracted water following induced leakage.

Use by the contractor of more complex numerical modelling methods; although these may be identified in the User Manual as a potential tool for more detailed analysis of the impact of a groundwater abstraction on a river.

Furthermore, there is no requirement in this project to consider the actions that an abstraction licensing officer, hydrologist or hydrogeologist might take after quantification of streamflow depletion due to groundwater abstraction. The manual is solely to provide the best practical technical input on groundwater impact on river flow to the officer(s) concerned, for consideration along with other factors when determining or reviewing a licence.

Application of selected methodologies to trial areas. These areas were to be determined, but were likely to include a minimum of three, in the Eastern Area (Norwich) and Northern Area (Lincoln) of the Anglian Region; and a Sherwood Sandstone example in the South West Region.

Production of recommendations and a User Manual on the selection and use of the most appropriate method(s), incorporating a seminar given to Environment Agency staff towards the end of the project for obtaining of feedback and incorporation of comments from the staff likely to be using the manual.

The scope of work for the study is summarised by the following tasks performed during the project, and encompass all of the specific objectives described above.

Task 1. Literature Review. A thorough literature search and review, including published sources, research reports and other UK university information documenting the available methodologies and quantitative approaches to evaluation of river/groundwater interaction and the impact of abstractions was performed.

Task 2. Consultation with Agency. A programme of consultation with Agency Regions was undertaken, including use of questionnaire and discussions to elicit current practice and views regarding methodologies identified from the Literature Review.

Task 3. Pilot trials. The preferred methodologies identified from Tasks 1 and 2 were applied to the selected trial areas in order to evaluate the success of each method against criteria established, including ease of use, accuracy, data requirements, applicability to different hydrogeological terrain.

Task 4. Development of Methodology. A review of the Pilot trial results in conjunction with theoretical considerations provided the basis for recommendations for a suitable tiered approach to evaluation of the impact of groundwater abstractions on river flows. The findings were used to develop a draft 'User Manual' of practical techniques for Agency staff, including detailed guidance notes.

Task 5. Seminar and Review. A suitable seminar is to be presented focusing on the draft User Manual and allowing exploration of all relevant issues regarding Agency requirements, feedback from Agency staff, and enhancement of the User Manual for its optimum use in operational situations.

Task 6. Reporting. A final report was presented providing a concise summary of the work undertaken and the results of the assessment and User Manual development, together with recommendations for the most appropriate use of numerical modelling methods and other techniques not within the project scope. Presentation of a Project Record was also undertaken.

This User Manual presents a methodology that can be used as an initial scoping of potential environmental and resource problems, and incorporates best practice from the Agency and from the results of a literature review (Appendix A). It is intended to be used as the first level of quantitative assessment of the impact of groundwater abstraction on river flow. More detailed assessments will be required for complex or particularly sensitive sites. These are beyond the scope of the methodology presented here.

There are three specific uses of the methodology:

- evaluation of the impact of periodic abstractions;
- evaluation of steady abstractions;
- design of tests to gather information for the above.

The benefits in terms of river flow of pumping groundwater to discharge directly into a river so as to augment river flow can also be scoped.

The scoping assessment methodology was specified to use very simple tools incorporating analytical solutions or other methods with an equivalent level of sophistication. It avoids the use of numerical models such as MODFLOW, which would require a greater level of effort to be used effectively than is appropriate at the scoping stage of assessment. The methodology presented here is based around the use of a simple spreadsheet model incorporating several common analytical solutions, and detailed user information for the use of this tool is given below.

The methodology has been largely based on current practice across the Agency, as elicited from a survey of Agency region and area offices. Across the country, a wide range of different hydrogeological conditions exist, with different priorities for the protection of the environment in different regions. Nevertheless, from a regulatory perspective, it is important to have a consistent and defensible approach to licensing groundwater abstractions. The methodology presented below should not obstruct current methods in the regions, but instead, should make all the appropriate analytical solutions readily available in a consistent format across the Agency. In general, most Agency responses indicated that initial assessment of licence applications with a possible river impact used analytical solutions based on the Theis (1941) solution such as Jenkins (1968) or Glover and Balmer (1954). These have been incorporated into this methodology which provides the first Agency guidance document for addressing the impact of groundwater abstraction on river flows.

The spreadsheet model developed as part of this methodology is not intended to be used as a 'black box' tool. It should inform rather than replace hydrogeological judgement.

The simple conceptual models on which the analytical solutions are based will in general be crude oversimplifications of the real situation. Results from their use will help identify whether there is a problem to be addressed or not, but in many cases more accurate representations of the physical situation will be needed to provide good predictions of the impact of the abstraction. It is intended that further detailed guidance, beyond the scope of this document, will be prepared to address the issues for sites where this initial scoping assessment does not clearly indicate the appropriate course of action.

The user should be aware that in some situations use of the analytical tools provided may not represent a safe or conservative means of assessment. Each application must be assessed in terms of the assumptions and limitations of the methods stated in Section three and their applicability to the scenario under investigation.

The spreadsheet model incorporating the analytical solutions has been designed to be used with MicroSoft Excel 97 SR-2 or later.

2 THE ANALYTICAL SOLUTIONS USED

2.1 Spreadsheet models

The spreadsheet models use analytical solutions due to Theis (1941), Hantush (1965) and Stang (1980). The solutions have been superposed so as to consider the development of river depletion rates resulting from finite or periodic periods of pumping. These superposed results are attributed to Glover and Balmer (1954) and Jenkins (1968) in the case of Theis. The analogous superposition has been incorporated for the other solutions.

2.1.1 Model assumptions

All solutions make the following simplifying assumptions.

- The aquifer is infinite in areal extent.
- The aquifer has a homogeneous isotropic transmissivity which does not depend on head. This is strictly true only for confined or leaky confined conditions but may be a reasonable approximation for deep unconfined aquifers.
- Flow is horizontal and vertical gradients are neglected (Dupuit-Forcheimer approximation for an unconfined aquifer).
- The aquifer has a homogeneous isotropic confined storage coefficient (or specific yield if the tool is being used to approximate a deep unconfined aquifer).
- Either confined or unconfined conditions apply over the whole of the aquifer;
- The head tends to a fixed value at large distances from the well and this value is equal to the river stage; and that the impact of recharge or differences in river stage and aquifer rest water level at infinity can be addressed separately by the principle of superposition
- The river is described by an infinite straight line with a constant water level that is unaffected by discharge to the aquifer;
- The only significant recharge to the aquifer is derived from the river and there is no significant recharge from surface percolation to the water table;
- Water is released instantaneously from storage in the aquifer;
- The borehole is screened over the full depth of the aquifer.

The following subsections give the analytical solutions due to a continuous steady pumping rate as a function of time from the beginning of abstraction, and describe specific assumptions made by each model about the river.

2.1.1.1 Theis

Theis assumes that there is no zone of altered properties adjacent to the river and that the head in the aquifer is equal to the stage of the river. Thus there is no hydraulic communication across the line of the river and the river has an equivalent hydraulic effect to a fully penetrating river. This is illustrated in Figure 2.1.

The river depletion rate can be given as a fraction of the abstraction rate by

$$\frac{q}{Q} = \mathrm{erfc}\left(\frac{1}{2\tau}\right),$$

where

$\tau = \frac{1}{a}\sqrt{\frac{tT}{S}}$ is a dimensionless length scale for the system, and

T is the aquifer transmissivity (m^2/d);

S is the aquifer storage coefficient (specific yield for unconfined aquifer approximations (dimensionless);

a is the perpendicular distance of the well to the line of the river (m);

Q is the abstraction rate at the well (m^3/d);

q is the total river depletion rate (m^3/d); and

t is time (days).

2.1.1.2 Hantush

Hantush also assumes that the head in the aquifer is equal to the stage of the river at the river, but allows it to fall across the river bank sediments. Thus there is no hydraulic communication across the line of the river and the river has an equivalent hydraulic effect to a fully penetrating river. He assumes that there is a zone of low hydraulic conductivity material adjacent to the river characterised by a river bank hydraulic conductivity and thickness, and a depth. This is illustrated in Figure 2.2. The river bank depth should be equal to the aquifer thickness for full consistency with the conceptual model, but it may be taken to be equal to the depth of water in the river to give a more accurate measure of the resistance posed by the river bank. This approximation involves neglecting the consequences of vertical flow near the river.

The river depletion rate can be given as a fraction of the abstraction rate by

$$\frac{q}{Q} = erfc\left(\frac{1}{2\tau}\right) - \exp\left(\frac{1}{2}\lambda + \frac{1}{4}\lambda^2\tau^2\right) erfc\left(\frac{1}{2\tau} + \frac{1}{2}\lambda\tau\right),$$

where

$\tau = \frac{1}{a}\sqrt{\frac{tT}{S}}$ is a dimensionless length scale for the system and

$\lambda = \frac{a}{2}\frac{bp'}{Tm'}$ is a dimensionless river bank resistance parameter, and

T is the aquifer transmissivity (m^2/d);

S is the aquifer storage coefficient (specific yield for unconfined aquifer approximations (dimensionless);

a is the perpendicular distance of the well to the line of the river (m);

b is the river bank depth (m);

m' is the river bank thickness (m);

p' is the river bank hydraulic conductivity (m/d);

Q is the abstraction rate at the well (m^3/d);

q is the total river depletion rate (m^3/d); and

t is time (days).

2.1.1.3 Stang

The river acts as a line of constant head that can supply a flux of water to the aquifer and which acts as a flow divide in the Hantush model. If one neglects vertical head gradients, this can be conceptualised as arising from a symmetrical two well system with a well on either side of the river, and the water being supplied vertically through the river bed. Neglecting vertical gradients is reasonable for a confined aquifer, but more of an approximation under the river in an unconfined system. However, the river is further assumed to be fully saturated beneath the river bed and thus will behave like a confined aquifer. The consequence of pumping from just one of these wells is simply half the river depletion of the two-well system. This was proven by direct solution of the equations by Hunt (1999). The model assumptions are thus

- there is flow from the river to the aquifer through the river bed due to a difference between the river stage and the aquifer head;
- the aquifer is saturated beneath the river bed, flow is horizontal and there are no vertical head gradients; and
- the river is narrow (can be taken as a line source) and the river width is only used to compute the resistance of the river bed sediments.

Strictly the model corresponds to a confined aquifer. The storage beneath the river and on the far side of the river is accounted for. The conceptual model and parameters used are illustrated in Figure 2.3. The use of this model avoids the need to adapt the Theis or Hantush models to use an 'effective distance' between the river and the well so as to account for neglected storage in those solutions.

The river depletion rate can be given as a fraction of the abstraction rate by

$$\frac{q}{Q} = \operatorname{erfc}\left(\frac{1}{2\tau}\right) - \exp\left(\lambda + \lambda^2\tau^2\right)\operatorname{erfc}\left(\frac{1}{2\tau} + \lambda\tau\right)$$

where

$\tau = \frac{1}{a}\sqrt{\frac{tT}{S}}$ is a dimensionless length scale for the system and

$\lambda = \frac{a}{2}\frac{bp'}{Tm'}$ is a dimensionless river bed resistance parameter, and

T is the aquifer transmissivity (m^2/d);

S is the aquifer storage coefficient (specific yield for unconfined aquifer approximations (dimensionless);

a is the perpendicular distance of the well to the line of the river (m);

b is the river bed width (m);

m' is the river bed thickness (m);

p' is the river bed hydraulic conductivity (m/d);

Q is the abstraction rate at the well (m^3/d);

q is the total river depletion rate (m^3/d); and

t is time (days).

2.2 Winflow

Winflow is an interactive, analytical element model that simulates two-dimensional steady state and transient groundwater flow. The steady state module of the programme simulates groundwater flow in a horizontal plane using analytical functions developed by Strack (1989). The module uses the principle of superposition to evaluate the effects from multiple analytical functions (wells etc.) in a uniform regional flow field.

2.2.1 Winflow assumptions

Briefly Winflow assumes:

- The aquifer is infinite in areal extent;
- Flow is horizontal and vertical gradients are neglected (Dupuit-Forcheimer approximation for an unconfined aquifer);
- Homogeneous isotropic aquifer conductivity, confined storage coefficient, and specific yield;
- Either confined or unconfined conditions apply over different parts of the model area;
- The top and base of the aquifer are uniform and horizontal;
- The regional head distribution away from the river and abstractions is characterised by a fixed head and a uniform gradient corresponding to the average impact of recharge and aquifer flow
- The river is described by a series of short straight linesinks along the course of the river
- The stage of the river is described by a series of linesinks which are automatically chosen to result in a specified head at the centre of each linesink. These fluxes correspond to piecewise uniform river depletion rates.
- There is no river bed or river bank resistance due to low permeability sediments
- The head in the aquifer is equal to the stage of the river at the centre of each linesink representing the river and there is thus no hydraulic communication across the course of the river: the river is thus equivalent to a fully penetrating river.
- The borehole is screened over the full depth of the aquifer.
- Water is released instantaneously from storage in the aquifer;

The precise analytical solutions used are described in the Guide to Using Winflow (Environmental Simulations Inc., 1996)

3 LIMITATIONS OF THE METHODOLOGY

When water is abstracted from a borehole within a catchment, then at steady state, this must always correspond to a consequent reduction in the natural outflows to the system. This may be:

- a reduction in stream flow;
- a reduction in evapotranspiration if soil moisture deficits are increased;
- a reduction in transfers to other aquifers for multi-aquifer systems; or
- a reduction in other abstractions due to changes in the aquifer storage.

This methodology only addresses the first of these. More sophisticated models are required to quantify the other processes.

There are two issues that can be addressed with the tools incorporated in this methodology. How quickly the abstraction is taken from the river as a stream depletion, and where it is taken from spatially.

The two software tools can provide complementary information. The spreadsheet tells you about the time lag between abstraction and stream depletion (which may be large), and Winflow tells you about where the depletion in taken from along the stream.

There are three specific uses of the methodology:

- evaluation of the impact of periodic abstractions;
- evaluation of steady abstractions;
- design of tests to gather information for the above.

The benefits in terms of river flow of pumping groundwater to discharge directly into a river so as to augment river flow can also be scoped.

The principal conceptual errors arising from the models used in the spreadsheet are:

- the usual pumping test interpretation assumptions of isotropy and homogeneity;
- the assumption of fully penetrating boreholes;
- no consideration of limiting drainage rates if the river becomes disconnected from the water table for unconfined systems – this needs to be checked as the model will in this case overestimate the river losses;
- assumption that the transmissivity is constant – this will underestimate time lags if the aquifer is unconfined and the saturated thickness varies appreciably;
- neglect of storage from far side of river (i.e. the river is assumed to be a boundary to flow) – this will lead to underestimates of the time lag;
- no consideration of impact on multiple rivers – see use of Winflow below;
- assumption of infinite straight river – this may affect the time lag to more distant reaches of the river.

Recharge and the distribution of head across the region is not considered by the methodology. This does not influence the time or distribution of the stream depletion so long as the drawdown can be superposed on the head distribution. This in turn requires that the groundwater flow equations are linear. For this to be valid, transmissivity must not vary (unconfined aquifer is deep) and the river drainage must not have reached limiting rates. These conditions are indicated in the list above. It may seem that neglecting recharge and the head distribution is a very serious limitation, however the trialling examples (see the project record and the summary in the project report) illustrate that the distribution of river flow depletion remains very symmetrical about the closest point, even when there is a significant structure to the total flow system.

The principal errors arising from the use of Winflow within this methodology are:

- discretisation errors in evaluation of the river reaches and evaluation of the solution;
- the assumption of fully penetrating boreholes;
- the assumption of fully penetrating rivers – this will affect the drawdowns predicted and influence where the stream depletion occurs.

Note that there may be errors due to flows across the Winflow model boundaries if small regional models are developed using Winflow (due to proximity to the constant reference head). It may be necessary to consider large catchments including more distant rivers, since water divide boundaries may move following abstractions.

4 INPUT PARAMETERS

The following table lists the input parameters the user should set in the spreadsheet models. These are in the Data Input Sheet and the Pumping Test Design Sheet and are shown highlighted in yellow in the spreadsheet.

Table 3.1 Spreadsheet model input parameters

Parameter	**Description**	**units**
Input Data Sheet		
Trans	Transmissivity of saturated thickness of the aquifer	m^2/d
S	Storage coefficient for the aquifer (confined) or specific yield for unconfined approximations	-
a	Perpendicular distance of well to the assumed straight line of the river course	m
Hantush		
Thick bank	Thickness of the river bank sediments for use in the Hantush solution. If non-zero, then Hantush solution is invoked. NOTE Only one of **Thick bank** and **Thick bed** can be set	m
Depth bank	Depth of river bank for use in the Hantush solution	m
K bank	Hydraulic conductivity of river bank sediments for use in the Hantush solution	m/d
Stang		
Thick bed	Thickness of the river bed sediments for use in the Stang solution. If non-zero, then Stang solution is invoked. NOTE Only one of **Thick bank** and **Thick bed** can be set	m
Width bed	Width of river bed for use in the Stang solution	m
K bed	Hydraulic conductivity of river bed sediments for use in the Stang solution	m/d
Pumping rates		
Abstraction Rate (by month)	Regular abstraction rate for month for long term exploitation of the aquifer at the well	m^3/d

Compensation Rate (by month)	Regular rate of return of water to the river for long- term exploitation of the aquifer at the well	m^3/d
Pumping Test Design Sheet		
Duration	Duration of pumping test	days
Pumping Rate	Constant rate of pumping for the pumping test	m^3/d
Axis limit	The chart for the pumping test will use a time axis that extends to the point where the depletion due to a steady abstraction has evolved to within this percentage of its steady state value.	-

The use of the Winflow tool requires the following additional inputs:

Both the confined storage and the specific yield should be specified where the aquifer is respectively anywhere confined or unconfined. The top and base of the aquifer are specified as horizontal surfaces. For unconfined aquifers, the top is specified as any large value above the elevation of the water table. The course of the river should be digitised as a series of specified head linesinks which a resolution finer than the distance between the well and the river. A reference head and gradient need to be specified consistent with the regional head distribution far from the region of interest.

Note that Winflow does not allow for river bed or river bank properties and thus will overestimate the net depletion of river flow where the river sediments provide a low permeability barrier to flow between the river and the aquifer. It does, however, allow for a more accurate treatment of confined and unconfined systems where the base and top of the aquifer can be specified as horizontal surfaces and the aquifer hydraulic conductivity is homogeneous and isotropic.

These discrepancies between the approximated conceptual model used in the spreadsheet models and the approximated conceptual model used in Winflow need to be considered if both tools are used to provide inputs to the licence determination. Neither types of model provide a complete representation and the nature of likely errors needs to be understood.

5 OUTPUTS OF THE METHODOLOGY

The analytical solutions calculate the river depletion rate which should be interpreted as the net reduction in flow from the aquifer to the river. This may correspond to a reduction in baseflow (reduction in river gains) or to actual flow out of the river into the aquifer. The baseflow itself and its evolution over time is not evaluated by these methods.

The first pumping scenario allows a single finite period of pumping at a steady rate. The model makes a continuous prediction of the rate of river flow depletion as a function of time measured from the start of abstraction. It is intended to allow estimation of the impact of a pumping test on the river flow. It will also indicate the duration of that impact. It is intended to allow the user to optimise the parameters of a pumping test and focus field data collection so as to maximise the likelihood of important impacts being measured. Figure 5.1a shows the output from the spreadsheet and reference should be made to this output.

The second pumping scenario in the spreadsheet models requires the specification of the average pumping rate each month for long term use of the well over many years. The corresponding output histogram shows the corresponding average river depletion rate in each month. Where there is a significant resistance between the aquifer and the river, there may be significant delay in the river depletion arising from a given pumping period. Thus for example, the histogram may show river flow depletion in January when abstraction was only specified for August: the interpretation would be that the January depletion was largely due to the previous year's abstractions. Due to the potentially long response periods, the consequences have been explicitly evaluated for a continuous cyclic abstraction regime extending for 10 years. This is illustrated in Figure 5.1b.

A 'PERCENTAGE EVALUATED' records the proportion of steady-state river depletion covered by looking back over this period. In exceptional circumstances or for more distant abstractions this will begin to fall to significantly less than 100%. In these cases, the analytical solution is predicting that part of the impact of abstraction is taking more than 10 years to be realised in the river flows. For such cases, it is a good approximation to regard the remaining fraction of the impact of continuous periodic abstractions to be spread uniformly throughout the year.

Note that the analytical solution predicts that once regular period abstractions have begun, the impact may well develop over several years, with the first years impact being significantly less than the equilibrium distribution of river depletion rates though the year after many years groundwater abstraction.

The output from the pumping test shows three parameters in graphical form. They are:

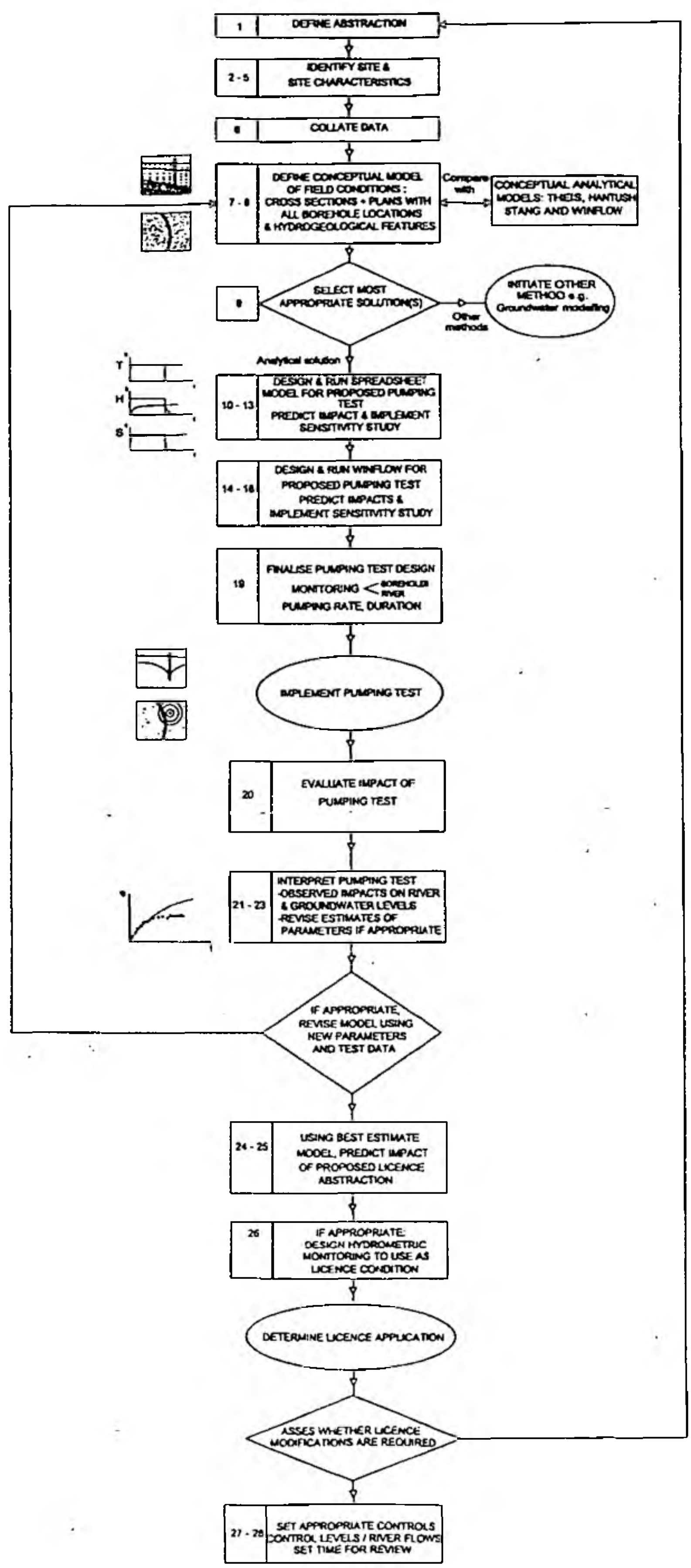
- The pumping rate of the test and the time interval over which the depletion has been evaluated **(abs_for_test).**
- The impact of the abstraction on the river over the period of the test and any lag that may be occurring prior to that impact. This may be used to identify the length of time for which stream gauging should be performed during the test and any the time before impact would be identified **(evalfunc).**
- The predicted time of impact of the test should that test be continued for a period in which the full rate of impact assymptotically approaches the pumping rate of the abstraction borehole. This may also be used in conjunction with hydrometric flow data for the river to predict at what stage in the pumping test an impact would be identified from flow gauging measurements **(evalctsfunc).**

6 PROCEDURE

In this section, a list of issues the specific tasks required to implement the methodology is presented. This is intended to guide the user through the essential steps involved in using the methodology efficiently for a specific assessment. The procedure is not however a simple linear sequence of tasks. As the various tasks are addressed, there will often be a need to reconsider earlier steps and iterate between tasks as an understanding of the behaviour of the hydrogeological system is developed. At all stages, the conceptual model of the river aquifer interaction should be considered and updated if new information or results suggest it might be improved. Similarly, in assessing the impact of abstraction on river flows, there will inevitably be uncertainty, and parallel assessments considering alternative conceptual models or alternative parameter scenarios are likely to be needed.

Use of the methodology requires a sound understanding of hydrogeology, such as might be obtained through a vocational MSc hydrogeology degree course accompanied by practical experience and study.

The procedure is summarised in the following flowchart. The numbered items correspond to the numbered paragraphs which follow.


1 DEFINE ABSTRACTION
2 - 5 IDENTIFY SITE & SITE CHARACTERISTICS
6 COLLATE DATA
7 - 8 DEFINE CONCEPTUAL MODEL OF FIELD CONDITIONS : CROSS SECTIONS + PLANS WITH ALL BOREHOLE LOCATIONS & HYDROGEOLOGICAL FEATURES
Compare with
CONCEPTUAL ANALYTICAL MODELS: THEIS, HANTUSH STANG AND WINFLOW
9 SELECT MOST APPROPRIATE SOLUTION(S)
Other methods
INITIATE OTHER METHOD e.g. Groundwater modelling
Analytical solution
10 - 13 DESIGN & RUN SPREADSHEET MODEL FOR PROPOSED PUMPING TEST PREDICT IMPACT & IMPLEMENT SENSITIVITY STUDY
T
H
S
14 - 18 DESIGN & RUN WINFLOW FOR PROPOSED PUMPING TEST PREDICT IMPACTS & IMPLEMENT SENSITIVITY STUDY
19 FINALISE PUMPING TEST DESIGN MONITORING < BOREHOLES RIVER PUMPING RATE, DURATION
IMPLEMENT PUMPING TEST
20 EVALUATE IMPACT OF PUMPING TEST
21 - 23 INTERPRET PUMPING TEST -OBSERVED IMPACTS ON RIVER & GROUNDWATER LEVELS -REVISE ESTIMATES OF PARAMETERS IF APPROPRIATE
IF APPROPRIATE, REVISE MODEL USING NEW PARAMETERS AND TEST DATA
24 - 25 USING BEST ESTIMATE MODEL, PREDICT IMPACT OF PROPOSED LICENCE ABSTRACTION
26 IF APPROPRIATE: DESIGN HYDROMETRIC MONITORING TO USE AS LICENCE CONDITION
DETERMINE LICENCE APPLICATION
ASSES WHETHER LICENCE MODIFICATIONS ARE REQUIRED
27 - 28 SET APPROPRIATE CONTROLS CONTROL LEVELS / RIVER FLOWS SET TIME FOR REVIEW

Abstraction definition

1. **Define the abstraction.** Consider the purpose of the proposed abstraction and assess what returns, if any, there will be to the groundwater or surface water systems. Groundwater returns may be deducted from the effective abstraction rate if they are returned to an unconfined aquifer close to the abstraction. Surface water returns should be accounted for in any stream gauging, and can be accommodated as compensation returns in the spreadsheet predictions of long term impact (25 below).

Site identification

2. **Identify investigation area and rivers and streams of interest.** Using the approach described in the Abstraction Licensing Manual chapter 3, identify the lateral extent of the investigation area and identify any rivers or streams of interest within this area. Make a brief identification of the catchment of this river and confirm that the abstraction is in the river catchment.

3. **Identify discharge boundaries.** If there is no surface water body within the area identified in 2 above, identify the natural discharge boundaries of the catchment containing the location of the proposed licence. For a steady state or long term abstraction, these discharges will be reduced by the quantity of abstracted water, less any returns to the groundwater/surface water system. In some circumstances, no further consideration will be required, however, in sensitive catchments, continue with the procedure with an increased area of assessment, extending to the river of concern.

4. **Identify river to be assessed.** Identify river to be assessed. If there is more than one river, you will need to repeat the procedure for each river but apportion the abstraction between the two river catchments that will be affected (consider the pessimistic case of all abstraction affecting each river if deemed appropriate).

5. **Obtain distance to river from abstraction.** Assess effective straight line distance from abstraction to the infinite straight line approximation to the river course (in general this will be the shortest distance, but if the river meanders around the abstraction then a smaller estimate will be more pessimistic. This may be considered in sensitivity analyses later.

Data collation

6. **Collate data.** Collect basic hydrogeological parameters to characterise the aquifer:

- Aquifer type – confined/unconfined/leaky;
- Transmissivity;
- Saturated thickness;
- Storage coefficient if confined or specific yield if unconfined;
- Aquifer heterogeneity or anisotropy (to judge reliability of homogeneous isotropic approximations).

Table 6.1 Data requirements for the solving of analytical solutions

Analytical Solution	Parameter requirements for the solving of the analytical solution										
						River Bank			River Bed		
	T (m²/d)	S (dimensionless)	Q – Pumping rate (m³/d)	t – time of pumping (days)	a – distance to BH (m)	Depth (m)	Thickness (m)	K (m/d)	width (m)	Thickness (m)	K (m/d)
Theis	✓	✓	✓	✓	✓	×	×	×	×	×	×
Hantush	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×
Stang	✓	✓	✓	✓	✓	×	×	×	✓	✓	✓

Conceptual model

7. **Conceptual model identification.** Identify the conceptual model for overall river-aquifer configuration. The choice will be helped by considering the schematic cross sections of Figure 6.1 or 6.2, and the corresponding schematics for confined or leaky confined aquifer conditions. Connected rivers (Figures 6.1a or 6.1b and Figures 6.2a or 6.2b) can be addressed in this methodology if they can reasonably be idealised as indicated in either Figure 6.3 for confined or leaky confined aquifers, or Figure 6.4 for unconfined aquifers. The river under consideration may not correspond to one of these idealised conceptual models, and in such cases, the methodology may not be able to provide accurate scoping calculations. If so, consider whether any of the available conceptual models discussed in section 2 above can be used to give bounding estimates of the impact of the proposed abstraction. Expert hydrogeological judgement is required to develop a good conceptual model.

8. **Estimate Stang and Hantush parameters.** If the conceptual model chosen for the central or sensitivity calculations involves river bank or river bed properties, these will need to be estimated. The parameters to be set are:

- the river bank depth or river bed width which may be estimated from the river geometry
- the river sediment zone thickness which will generally not be either known nor sharply defined; and
- the hydraulic conductivity of the sediment zone.

There will not often be adequate direct data for these properties and the best information will generally be indirect (for example from calibration of distributed numerical models using MODFLOW). It is not appropriate simply to guess these parameters, Rather, sensitivity calculations should be undertaken to explore the range of possible parameters that are consistent with observations where available. If there is no available information then expert judgement will be required in determining the licence application guided by bounding estimates of possible parameter ranges.

9. **Selecting most appropriate analytical solutions.** Choose the conceptual models to evaluate from the analytical solution cross sections of Figures 2.1, 2.2 and 2.3. In general no one conceptual model will incorporate all the features of the real system, and several possibilities may need to be assessed, making a judgement as to effective parameters to use when mapping the physical parameters into the idealised conceptual model of the analytical solution.

Pumping test design

10. **Requirements of the pumping test.** If necessary, design a pumping test for assessment of the abstraction as usual from chapter 3 of the abstraction licensing manual. Any pumping test design must consider the design and implementation of hydrometric monitoring as specified in the pumping test section of the manual.

11. **Input parameters used in the test.** For the chosen pumping test configuration input the first estimate parameters from the data collation and conceptual model tasks to the spreadsheet model *Data Input* sheet and view predicted river depletion values. Judge whether there is conceivably a measurable impact at times of low flows (typically towards the end of stream flow recession curve before aquifer recharge period). This would depend on stream gauging and one would only expect to be able to detect impacts of more than 5% of river flow. In the event of flood runoff in the river or varying natural baseflow, even this level of impact may not be possible to detect.

12. **Assess river-aquifer connectivity.** If the Stang solution is used, evaluate (from the complex formulae given by Hunt 1999) or estimate the drawdown at the river noting that the drawdown due to Theis's standard solution in the absence of any river interactions is an overestimate of the drawdown. Now assess whether limiting drainage conditions are likely to apply over a significant reach, violating the conceptual model. If this is the case, the predictions of the model will be overestimates.

13. **Conduct sensitivity study.** Conduct a sensitivity study for the proposed pumping test for the likely range of uncertainties in each parameter. The following table indicates possible ranges of uncertainty, although these will depend on the availability of site specific field data.

All		
Distance to river	a	effective distance may be uncertain to 50%
Transmissivity	T	dependent on available data, an uncertainty factor of 2 may be reasonable
Storage coefficient	S	dependent on available data, an uncertainty factor of 2 – 5 may be reasonable
Hantush		
River bank hydraulic conductivity	K	likely to be poorly known, uncertain by an order of magnitude or more
River bank thickness	w	likely to be poorly known, uncertain by an order of magnitude
River bank depth	d	physical wetted bank depth likely to be well specified subject to variability associated with varying river flows, uncertainty also due to assumption of full river penetration of aquifer being violated. May need to

		consider larger values to allay criticism of conceptual model errors
Stang		
River bed hydraulic conductivity	K	likely to be poorly known, uncertain by an order of magnitude or more
River bed thickness	w	likely to be poorly known, uncertain by an order of magnitude
River bed width	d	likely to be reasonably well known although there will be variable river widths, and dependence on river flow rate.

Winflow

14. If appropriate, before proceeding further, evaluate the distribution of steady state depletion using the Winflow model to identify the proportion of the depletion that would be measured by your gauging as follows.

15. Where obtainable import a basemap to Winflow. Digitise a series of constant head linesinks along the nearest bank of the river. These should be set as a series of fixed head steps with a small head change between adjacent steps (dependent on the scale of the problem, but typically fractions of a metre, corresponding to a mean river stage along each section). Note that Winflow represents a constant head linesink as a flux chosen so as to achieve the specified head at the centre of the linesink. This is an approximation and in order to get meaningful predictions of the variation of stream depletion along the river, it is important that the river is discretised into sufficiently small sections close to the groundwater abstraction. In any event, the linesinks should be shorter than the distance from the well to the river close to the river, gradually extending the acceptable linesink length as one considers regions further from the well.

16. Identify all other abstractions within the area of investigation and specify these as wells within the Winflow model, using average annual abstraction rates. Also include any known spring flows as constant head sources or wells as appropriate.

17. Locate a reference head and typical hydraulic head gradient as far as practical from the river and abstraction locations, and in any case beyond the area of investigation. The hydraulic gradient should reflect the average groundwater flow that would apply in the absence of abstractions or river interactions which will be superposed on the solution.

18. With the proposed abstraction set to zero, record the net inflow or outflow to the river along all reaches of the river. Then, with the proposed abstraction set to the average annual rate to be assessed, record the difference in the inflow or outflow to the river at each reach. The differences should sum to a large proportion of the proposed abstraction. The balance will be taken from other boundaries. If a substantial proportion of the assessed abstraction is not accounted for at the river or other identified boundaries (for example derogated springs) then the model boundaries may need to be extended. Note that the Winflow model uses the Theis conceptual model and does not account for bank or bed properties. Revisit 12 above.

19. **Specify the pumping test in terms of the Licensing manual requirements.** Specify any necessary pumping test as required by the Abstraction Licensing Manual taking into account the desirability of detecting a measurable stream depletion for all conditions where the licensed abstraction is predicted to have an unacceptable impact on the river

flows (see 10 above). Ensure that appropriate stream gauging is specified along with the pumping test. It would be acceptable to not detect an impact during the pumping test for all those cases where the licence would have an impact at an acceptable level. Note that the Winflow model may indicate the likely distribution of the depletion along the river course to aid planning gauging point locations.

Pumping test interpretation

20. **Interpret the pumping test.** Interpret the test with the usual procedures to infer aquifer characteristics. Using these and the chosen conceptual model and the uncertainty analysis above, evaluate the predicted impact of the test on stream flow using the spreadsheet model.

    The pumping test should be interpreted using the guidance from Chapter 3 of the Abstraction Licensing Manual. It is anticipated that a type curve matching approach will be used based on type curves that do not explicitly account for the influence of a river boundary. In this case, one should ensure that only data not influenced by the river are matched. In general, the river will supply additional water which will lead to the time-drawdown curve falling below the type curve at later times (less drawdown), eventually flattening off to a steady state (horizontal) line. A complication arises if the aquifer is leaky confined where vertical leakage through an overlaying aquitard will produce a similar effect.

    In a leaky response however, the consequence of leakage, as interpreted by Walton or Hantush type curves, will be symmetrical about the abstraction of most leakage will occur close to the abstraction borehole. In contrast, river leakage will have a most pronounced effect near the course of the river.

Verification

21. **Verify results.** When pumping test results are available, revisit the model and attempt to match the data to the models available as described in the conceptual model task above. Repeat the pumping test design calculations, and Winflow tasks if the test interpretation gives improved local aquifer property values for T and S or Sy. Note that the new site specific aquifer property values will still be subject to uncertainty and the effective values between the abstraction and the river may be different from those inferred from drawdowns at the observation piezometers.

22. **Assess the adequacy of the results for licence determination.** Consider whether the scoping study approach described here is adequate to determine the licence. If necessary, consider the use of a more detailed assessment approach using site specific numerical modelling.

23. **Assess the results of any stream gauging.** Assess the results from stream gauging with reference to the long term baseflow depletion curve where available. If there is no significant period of gauging data on which to determine the baseflow, then the results will likely be very difficult to interpret with any confidence, especially if there was any storm runoff during the test period and recovery (i.e. any rain).

Prediction

24. **Record the best estimate and uncertainty of model parameters.** From the above results, record a best estimate and range of uncertainty for all the parameters used. Even

if the data is not conclusive, it is likely that you will be able to constrain the prior uncertainty ranges identified in the pumping test design calculations. Consider the possible conceptual models that may apply along different sections of the river reach that may be affected using the results of the Winflow model if used.

25. **Evaluate the licence application.** Input the final parameter choices for evaluation covering a central scenario and a range of uncertainty scenarios in the spreadsheet model (and possibly the Winflow model although this would not provide significant new information if good choices had been made for the initial sensitivity runs). Input also the proposed monthly abstraction rates where specified and consider the monthly stream depletion rates in the long term quasi steady depletion histogram. This identifies the net impact of the proposed abstraction after many years of operation at the specified rates. Confirm that the chosen conceptual model is still justified and if not repeat the procedure with a revised conceptual model or updated choice of parameters.

Assessment

26. **Assess the licence with respect to policy.** Assess the licence with respect to policy. Conditions may be attached to the licence where necessary and a time for review of any licenced granted should be made. Further simulations may be undertaken to consider the impact of restricting the licence or requiring compensation pumping with discharge to the river to support baseflow under certain conditions. If compensation pumping is considered, follow procedures for approving discharges with consideration of water quality implications.

    Note that if the licence requires such conditions, it may be more appropriate to use a more detailed numerical modelling approach.

27. **Set requirements for hydraulic monitoring.** If appropriate specify any stream gauging or piezometry required to monitor the impact of licensed abstractions so that the assessment may be reviewed.

28. **Set review time.** Set a time to review the licence.

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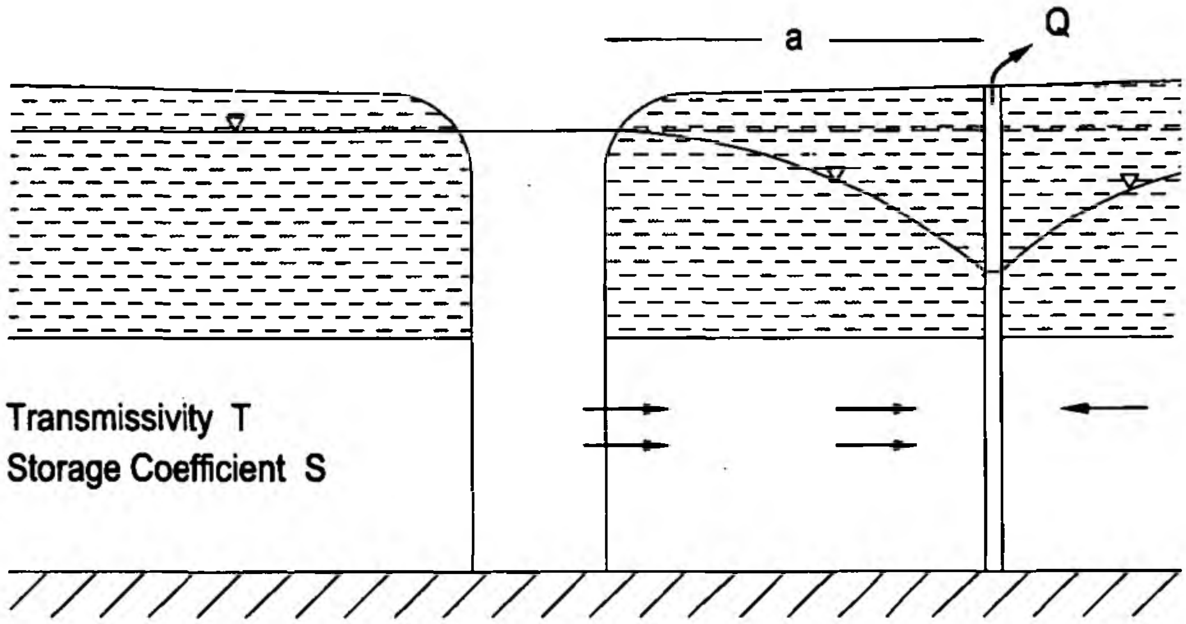
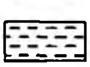
Figure 2.1



LEGEND



Title: Conceptual Model for River-Aquifer Interaction used in the Theis Solution			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
Scale: N.T.S.	Drawing No: 6077 / Figure 2.1		Rev: A

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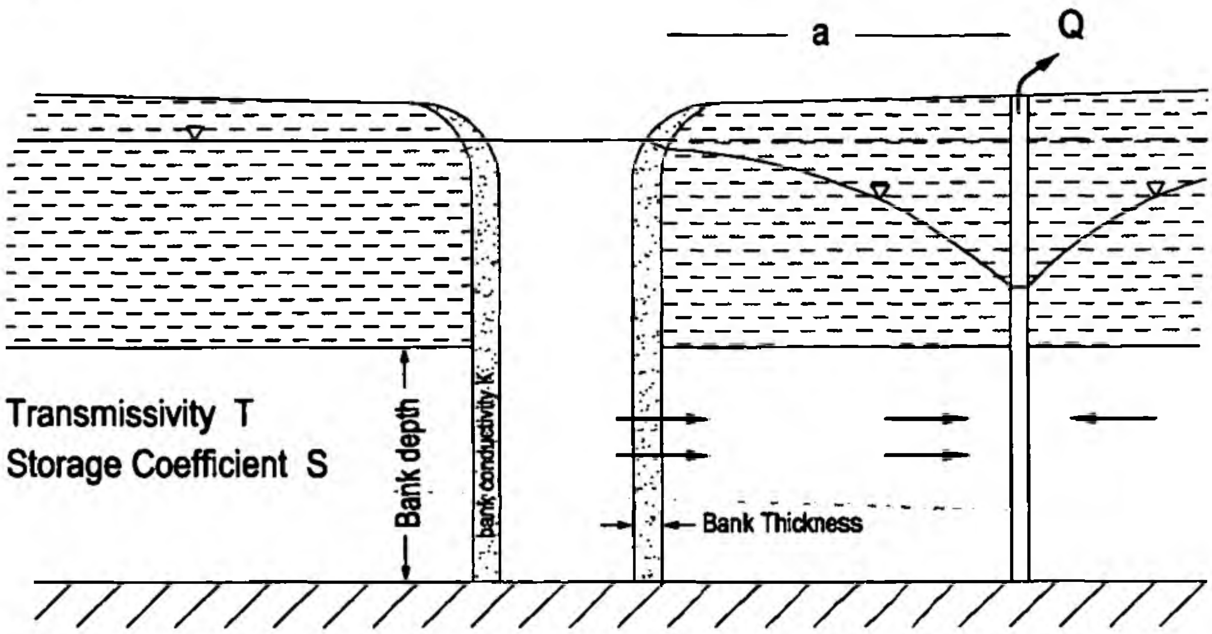
Figure 2.2



LEGEND

Impermeable base of Aquifer

Riverbank Sediment

Aquitard

Title: Conceptual Model for River-Aquifer Interaction used in the Hantush Solution			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
Scale: N.T.S.	Drawing No: 6077 / Figure 2.2		Rev: A

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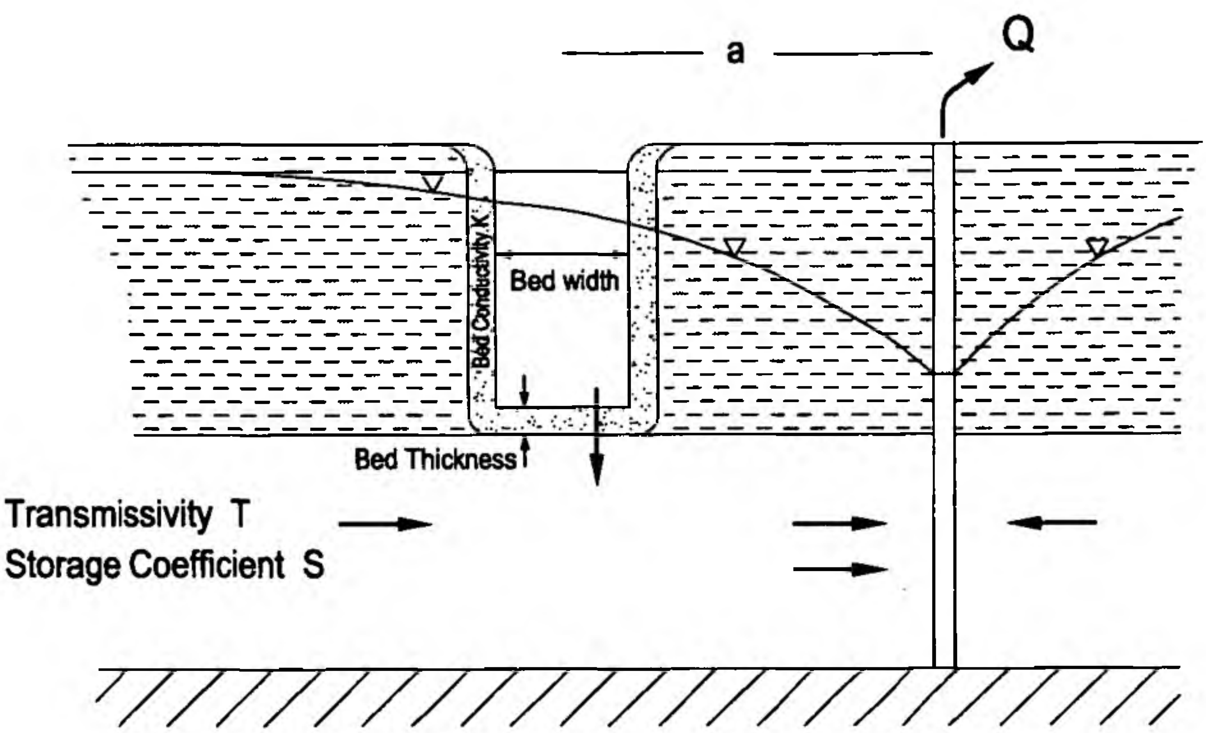
Figure 2.3



LEGEND

Impermeable base of Aquifer

River bed Sediments

Aquitard

Title: Conceptual Model for River-Aquifer Interaction used in the Stang Solution			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
Scale: N.T.S.	Drawing No: 6077 / Figure 2.3		Rev: A

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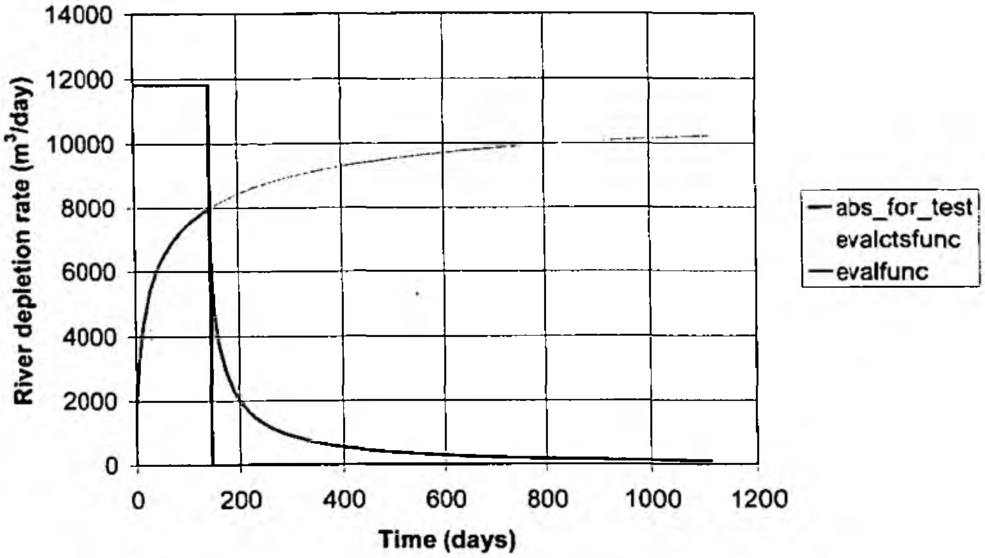
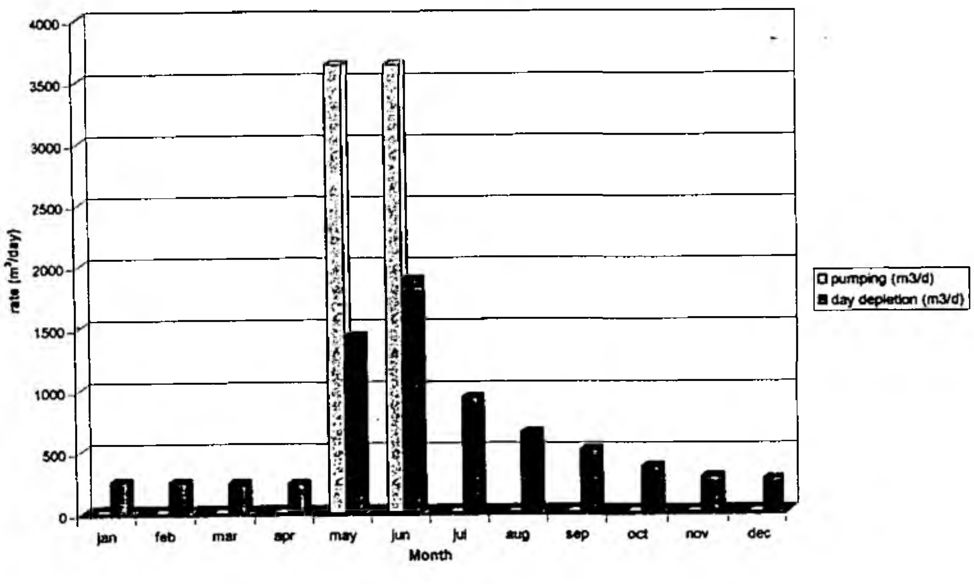
Figure 5.1





LEGEND

Title: The outputs from the spreadsheet			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
Scale: N.T.S.	Drawing No: 6077 / Figure 5.1a & b		Rev: A

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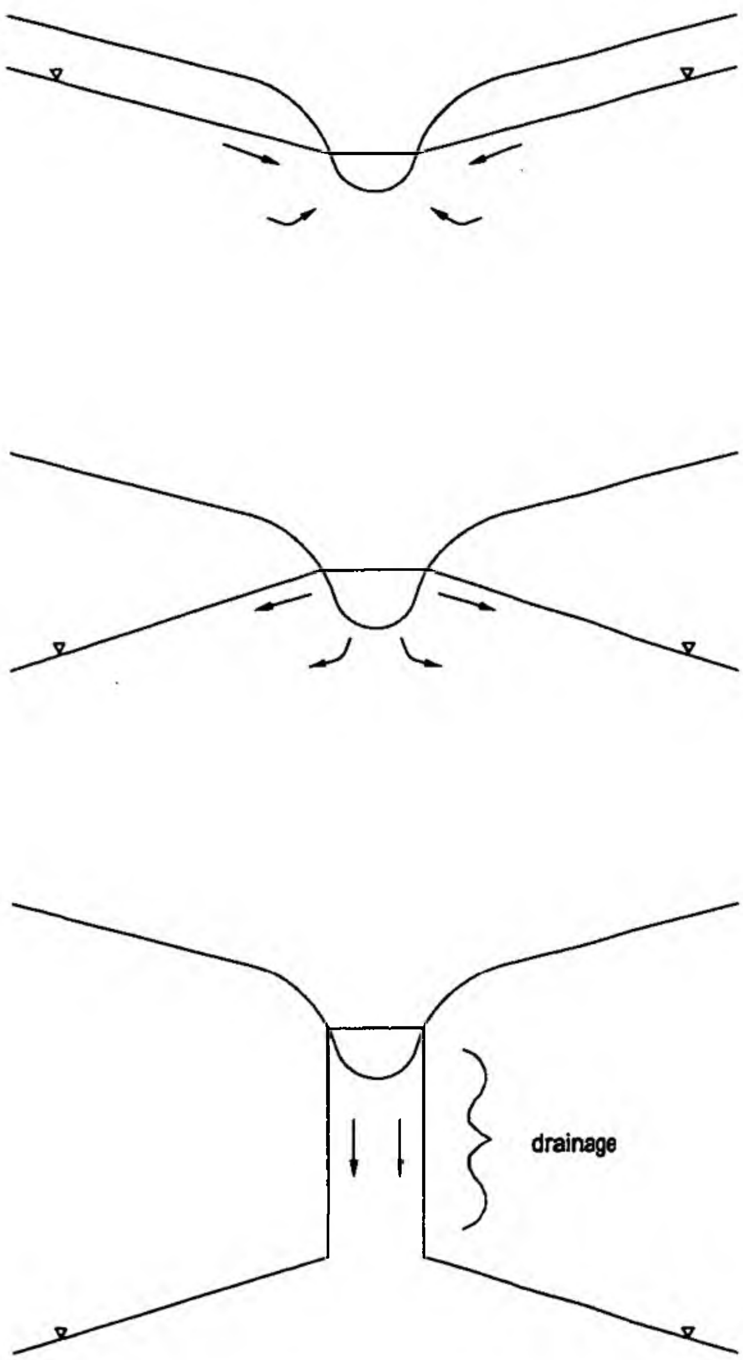
Figure 6.1

a) Gaining river

b) Losing river

c) Disconnected losing river



LEGEND

Title: Basic Categories of River - Aquifer Interaction			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
Scale: N.T.S.	Drawing No: 6077 / Figure 6.1		Rev: A

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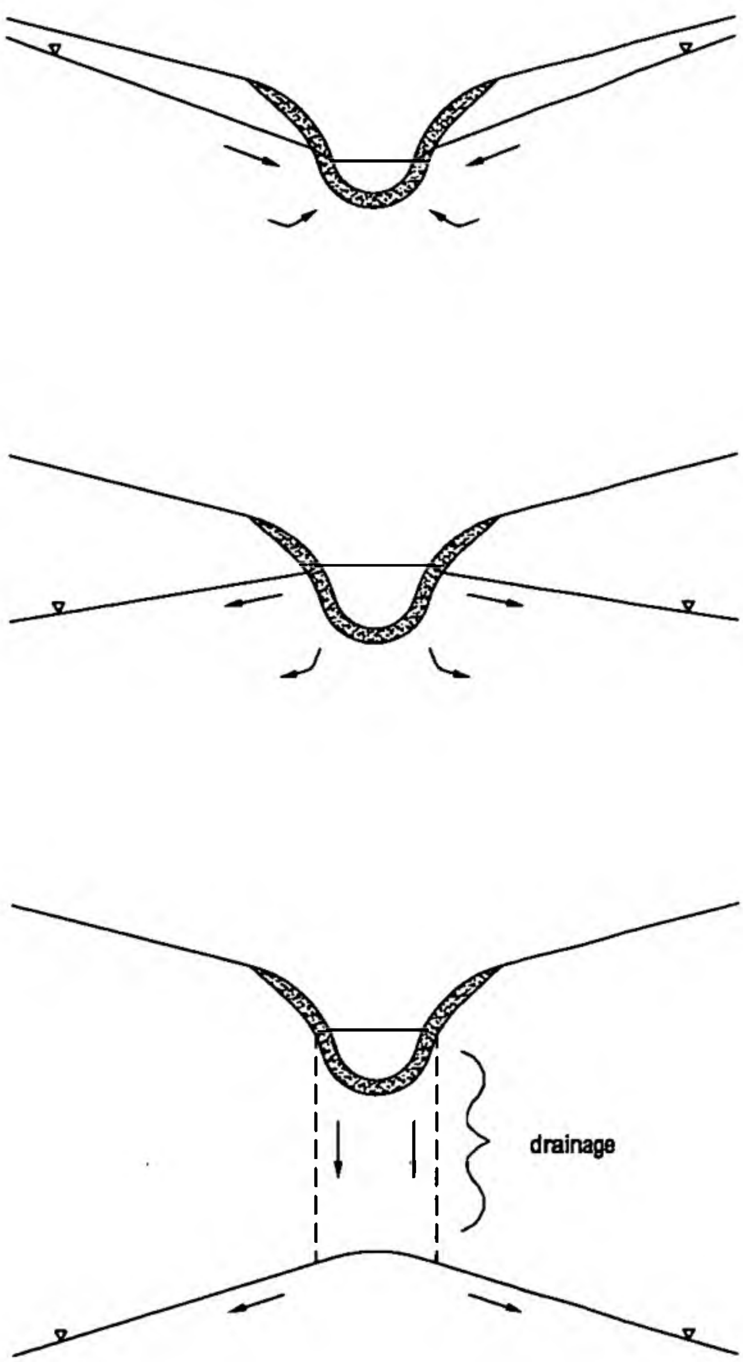
Figure 6.2

a) Gaining river

b) Losing river

c) Disconnected losing river



LEGEND

River bed / bank sediments

Title: Influence of River Bed / Bank Sediments on River-Aquifer Interaction			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
Scale: N.T.S.	Drawing No: 6077 / Figure 6.2		Rev: A

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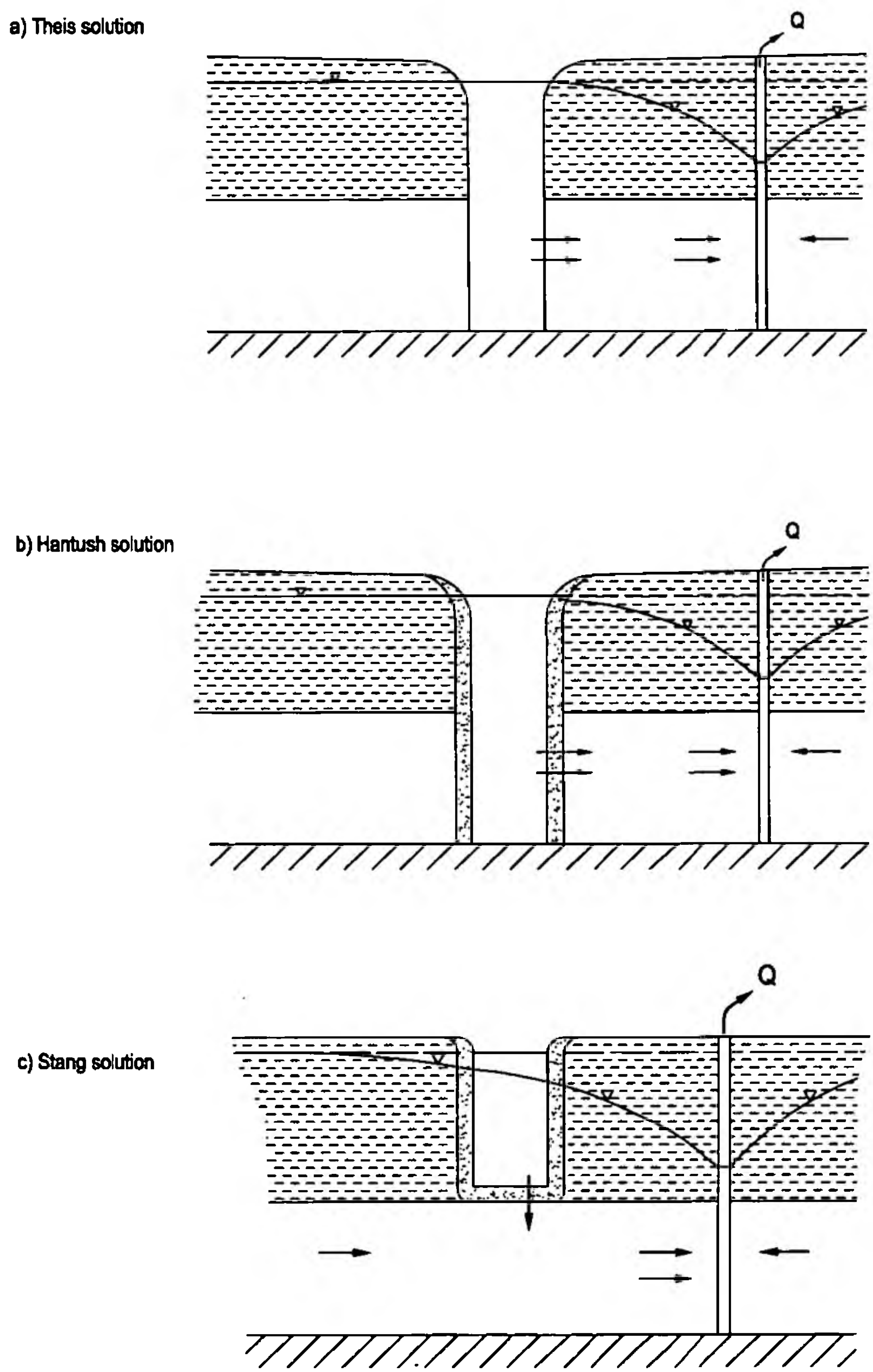

LEGEND

- River bed / bank sediments
- Impermeable base of Aquifer
- Aquitard

Title: Idealised Configuration of River-Aquifer Interaction Corresponding to Analytical Solutions for Confined Aquifer Systems.

Date:	Drawn:	Chk'd:	Approved:
Mar 1999	JE	AH	MMF
Scale: N.T.S.	Drawing No: 6077 / Figure 6.3		Rev: A

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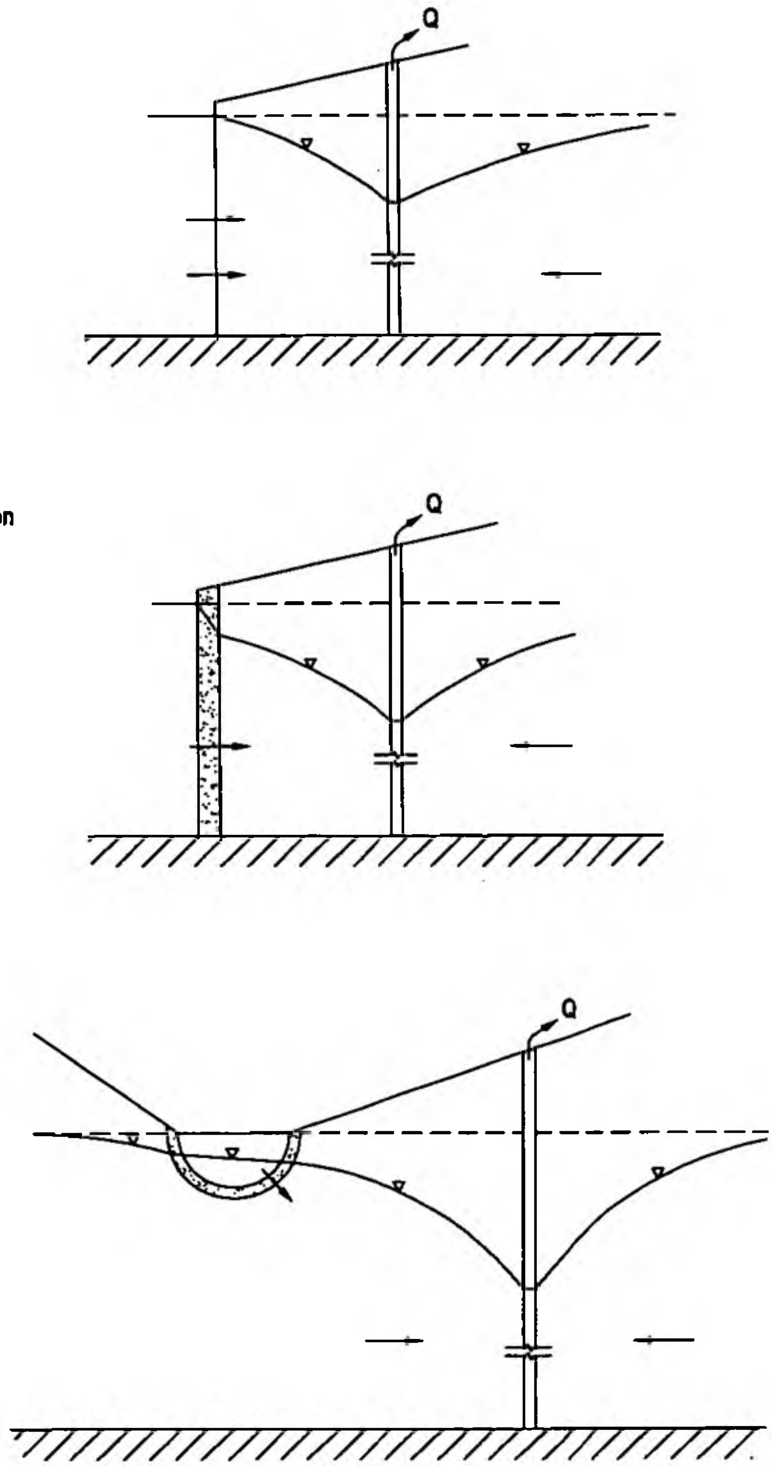
Figure 6.4

a) Theis solution

b) Hantush solution

c) Stang solution



LEGEND

River bed / bank sediments

Impermeable base of aquifer

Title: Confirmation of River and Aquifer Interaction Corresponding to (approximate) Analytical Solutions for Unconfined Solutions.			
Date: Mar 1999	Drawn: JE	Chk'd: AH	Approved: MMF
Scale: N.T.S.	Drawing No: 6077 / Figure 6.4		Rev: A

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Impact of Groundwater Abstractions on River Flows

Appendix – Trialling example
Draft for Agency Presentation

Environmental Simulations Limited

National Groundwater & Contaminated Land Centre Project WR1

Impact of Groundwater Abstractions on River Flows

Appendix – Trialling example
Draft for Agency Presentation

A W Herbert, J P Hatherall & M M Fermor

Research Contractor:
Environmental Simulations Limited

Environment Agency
National Groundwater & Contaminated Land Centre
Olton Court
10 Warwick Road
Olton
Solihull
West Midlands
B92 7HX

National Groundwater & Contaminated Land Centre Project WR1

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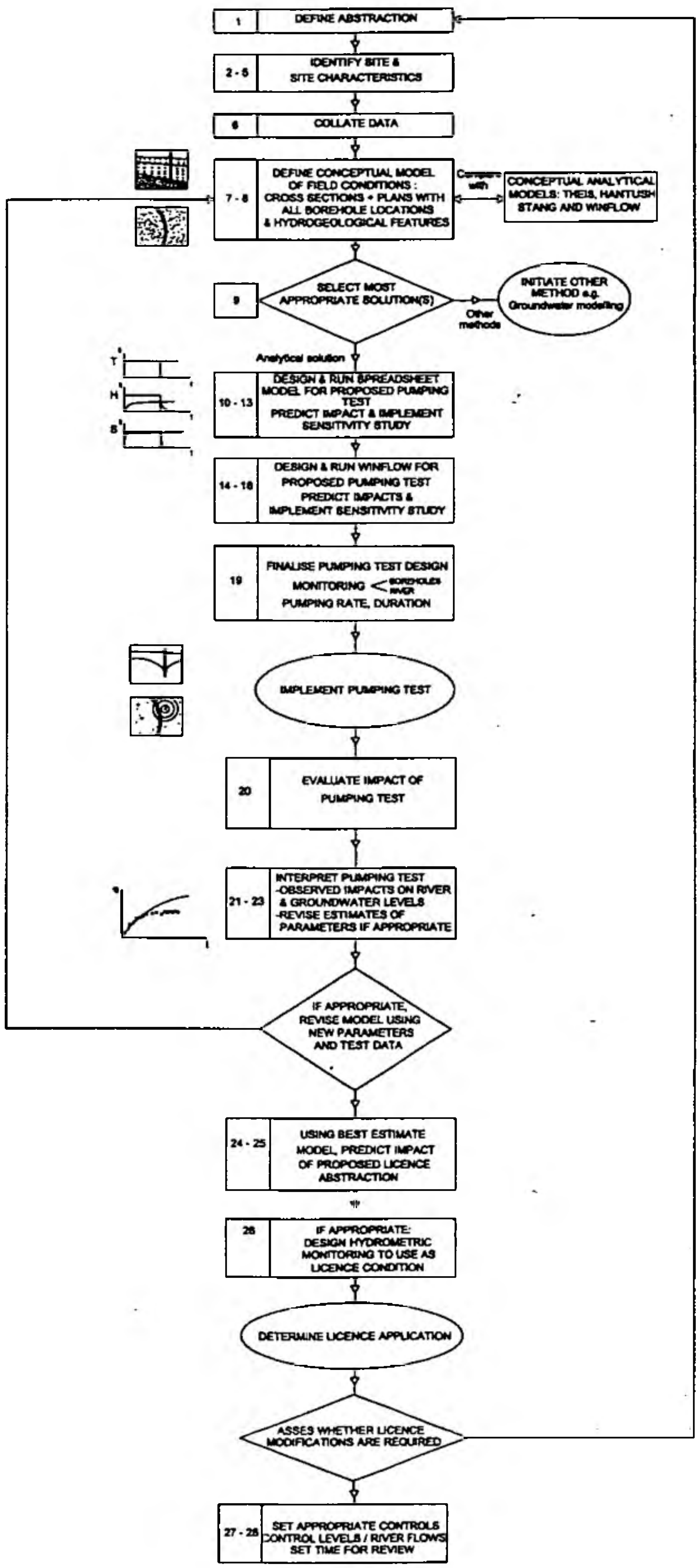
1 Introduction to the Otterton demonstration of the methodology

The Otterton production boreholes are a pair of abstraction wells situated in the catchment of the River Otter, Devon (Figure A1). The boreholes are located in the unconfined Permo-Trias Otter Sandstone of the Sherwood Sandstone group. From the review of a geological section it appears that immediately adjacent to the river there is a degree of clay banding (Figure A2). The hydrogeological characteristics of the aquifer are similar to other Sherwood Sandstone aquifers, as confirmed from pumping tests at the Otterton boreholes undertaken during 1989. The storage coefficient of the aquifer shows a semi-confined characteristic. The River Otter flows from north to south across the outcrop and is understood to gain baseflow from the aquifer. The connectivity between the aquifer and the river is understood to be good in places.

The methodology to assess the depletion impact is being applied to production borehole 4 as a demonstration of the use of the methodology. Borehole number 4 (NGR SY0780 8466) is within 25m of the River Otter.

The borehole was selected as being suitable for the purposes of demonstrating the project methodology because of proximity to the river, because there is believed to be significant depletion of the river flow and the presence of good quality pumping test data. Extensive modelling has been undertaken in the area that can be incorporated into the evaluation of the impact.

The procedure is summarised in a flowchart on the following page.


1 DEFINE ABSTRACTION
2 - 5 IDENTIFY SITE & SITE CHARACTERISTICS
6 COLLATE DATA
7 - 8 DEFINE CONCEPTUAL MODEL OF FIELD CONDITIONS : CROSS SECTIONS + PLANS WITH ALL BOREHOLE LOCATIONS & HYDROGEOLOGICAL FEATURES
Compare with
CONCEPTUAL ANALYTICAL MODELS: THEIS, HANTUSH STANG AND WINFLOW
9 SELECT MOST APPROPRIATE SOLUTION(S)
Other methods
INITIATE OTHER METHOD e.g. Groundwater modelling
Analytical solution
10 - 13 DESIGN & RUN SPREADSHEET MODEL FOR PROPOSED PUMPING TEST PREDICT IMPACT & IMPLEMENT SENSITIVITY STUDY
14 - 18 DESIGN & RUN WINFLOW FOR PROPOSED PUMPING TEST PREDICT IMPACTS & IMPLEMENT SENSITIVITY STUDY
19 FINALISE PUMPING TEST DESIGN MONITORING < BOREHOLES RIVER PUMPING RATE, DURATION
IMPLEMENT PUMPING TEST
20 EVALUATE IMPACT OF PUMPING TEST
21 - 23 INTERPRET PUMPING TEST -OBSERVED IMPACTS ON RIVER & GROUNDWATER LEVELS -REVISE ESTIMATES OF PARAMETERS IF APPROPRIATE
IF APPROPRIATE, REVISE MODEL USING NEW PARAMETERS AND TEST DATA
24 - 25 USING BEST ESTIMATE MODEL, PREDICT IMPACT OF PROPOSED LICENCE ABSTRACTION
26 IF APPROPRIATE: DESIGN HYDROMETRIC MONITORING TO USE AS LICENCE CONDITION
DETERMINE LICENCE APPLICATION
ASSES WHETHER LICENCE MODIFICATIONS ARE REQUIRED
27 - 28 SET APPROPRIATE CONTROLS CONTROL LEVELS / RIVER FLOWS SET TIME FOR REVIEW

2 Application of the procedure

The following steps document the case of Borehole 4. This together with the other two case studies presented, serves as an illustration of how the procedure can be applied to a site specific abstraction scenario.

1 **Define the abstraction.** Otterton Borehole 4 is currently used for the abstraction of groundwater for public water supply. The borehole source is subject to abstraction on a continual basis but with licensing conditions restricting the pumping rate to 2000m^3/d during 8 months of the year (January to March and July to December) and a maximum pumping rate of 3000 m^3/d between April to July.

2 **Identify investigation area and rivers and streams of interest.** The application of the methodology here only considers the impact of abstraction on the River Otter. Note however that real application of the methodology at the site would also consider the impact of the abstraction on other tributaries of the Otter and that the assessment should account for depletion from all susceptible surface water bodies and rivers in the catchment.

3 **Identify discharge boundaries.** For the purpose of this assessment the River Otter is the only surface water body of interest, for modelling purposes forming the only natural discharge for groundwater flow in the vicinity of Borehole 4. The abstraction is in close proximity to the coast. The groundwater contours indicate that locally the groundwater flow is to the river.

4 **Identify river to be assessed.** Only the impact on the River Otter needs to be assessed.

5 **Obtain distance to river from abstraction.** The effective straight-line distance from the borehole to the river is not considered to be influenced by meanders in the River Otter. However, the sensitivity of this parameter to differences in the distance to the river will be assessed.

6 **Collate data.** Aquifer and river bank and bed parameters were collated from the Source Protection Zone Proforma, the regional gradient was taken from the IGS hydrogeological map (1982).

Parameter	Value	Notes
Transmissivity (m^2/d)	500 m^2/d	From a range of 200-700m^2/d. Use hydraulic conductivity in Winflow
Storage	0.001	Regional estimation of semi-confined aquifer
Saturated thickness (m)	140	Agency SPZ Proforma
Regional hydraulic gradient	0.03	From the Permo-Trias and associated minor aquifers of SW England hydrogeological map (IGS, 1982)
Distance to BH (m)	25	From O.S. map

7 **Conceptual model identification.** Conceptual models in any preliminary evaluation of the possible impacts of abstractions on river depletion will include a number of unknown parameters. In considering the conceptual model, the best estimate of the essential input parameters (including T and S) should be made. Other parameters will be known, such as the location of the proposed abstraction and the proposed licensed pumping rate. The basic conceptual model may itself be uncertain and will need to be re-evaluated when new data becomes available.

The conceptual model was defined from available regional data. A schematic cross section is shown in Figure A3. A cross section is shown in Figure A2 and a schematic conceptual model for the Otter Valley is shown in Figure A4. The sandstone, which has a saturated thickness of 140m) is interpreted to be semi-confined or leaky-confined in the vicinity of the site and has a storage coefficient in the region of 0.001. The regional Transmissivity of the aquifer has been estimated to be between 200-700m^2/d. The mean value of T near the Otter is approximately 500m^2/d. A hydraulic conductivity of 2.7m/d was inferred for the Winflow model from the transmissivity. Groundwater flow in the immediate vicinity of the Otterton Borehole 4 is towards the River Otter. The regional groundwater gradient has been calculated from the Permo-Trias and associated minor aquifers of SW England hydrogeological map as 0.03. The river is approximately 25m from the borehole. The depth of the river is estimated to be 2m and the river is approximately 14m wide based on data supplied by the Environment Agency's Exeter office. No other characteristics of the bed or bank are known but through the use of expert judgement, the hydraulic conductivity of both the bank and bed are estimated as 0.1m/d.

8 **Estimate Stang and Hantush parameters.** If the river bed and bank sediments provide a low permeability resistance to flow, the Hantush or Stang conceptual models will be appropriate. Parameters for either (but not both) of these conceptual models may be specified at any time when using the spreadsheet.

If the primary connection between the river and the aquifer is through the river bank, the hydraulic conductivity, depth and thickness of the riverbank should be specified and the Hantush conceptual model applied. If the connection is with the river bed, the hydraulic conductivity and thickness of the riverbed and the width of the river and the Stang solution specified.

For the purpose of this study, both the Hantush and Stang solutions have been applied to assess the sensitivity to changes of parameters. Little or no data is available for many of these parameters and assumed ranges have been used. In many situations 'expert judgement' must be used in the choice of parameters for the model. Parameters have been chosen on the following basis:

- There is little to no data available for the river bank and bed parameters. The river width is most likely to be 14.7m based on measurements taken form the river width adjacent to the borehole.
- The depth of the riverbank is estimated to be 2m.
- The thickness of the riverbank is estimated to be 0.5m for the Hantush model.
- The thickness of the bed is estimated to be 0.5m for the Stang model.
- K is estimated to be 0.1m/d for the riverbed in the Stang model and 0.2m/d in the Hantush model for the bed and bank respectively.

The sensitivity of analytical solutions to these parameters are assessed in the following section.

9 **Selecting most appropriate analytical solutions.** The most likely conceptual model is shown in Figure A3 and has been outlined above. This best matches the conceptual model of Stang (Figure 2.3 in the User Manual) since losses are considered to be predominantly through the base of the river. Alternative analytical solutions were considered during the trial since the configuration of the bed and bank of the river and the river connectivity with the aquifer are not well known. All possibilities should be explored to assess the possible impact of depletion, but as discussed above, the Stang method more closely matches the conceptual model.

10 **Requirements of the pumping test.** The pumping test design must follow the procedures in Chapter 3 of the licensing manual. Any pumping test design must also consider the design and implementation of hydrometric monitoring as specified in the pumping test section of the manual.

11 **Input parameters used in the test.** The impact of the abstraction was initially assessed using the general parameters outlined in section 7.

In general, the test duration is the key pumping test variable that may be varied so as to maximise the likelihood of obtaining useful information about the impact of the abstraction on the river flow.

Often the test duration will be constrained by practical considerations but on this and the following items 12 and 13, alternative test durations should be considered. One aim is to be able to measure the impact of the pumping test on the river flow or to confirm no impact. This may need monitoring to be continued for a significant period after the end of test pumping, as indicated by the predicted time of maximum impact give in the model. If no measurable impact is predicted to follow the pumping test then it will not be possible to constrain uncertainty in the parameters of the river sediments or the river aquifer contact. The pumping test will still enable improved estimates of T and S to be obtained. Guidance on the design of a test for obtaining aquifer properties is given in chapter 3 of the Abstraction Licensing Manual.

The following parameters were specified:

- The length of the pumping test, was specified as 180 days.
- The rate of pumping specified during the pumping test was $3500m^3/d$.
- T and S were assigned to the model based on the results of the analysis of the pumping test. The aquifer shows a semi-confined or leaky aquifer with an S of 0.001 and a T of $500m^2/d$. These values are based on the overall average for the Otter Sandstone aquifer in the area around the Otterton abstraction. However, it is important to establish the contribution of the water to the aquifer as gained from the river when deriving the estimate of T to be used in the model.
- The perpendicular distance to the river from the borehole was interpreted from the location map. This was estimated at 25m.

12 **Assess river-aquifer connectivity.** It is possible that the head in the aquifer might fall below the base of the river bed over the closest reaches of the river to the borehole. In such a case the depletion of river flow would be at no more than the limiting percolation rate through the river bed. It is currently unknown whether the river will become disconnected from the aquifer, although this is considered unlikely at this stage. The prediction would overestimate the river baseflow depletion in this case.

13 **Conduct sensitivity study.** The depletion of baseflow using the parameters in the Theis model, with no account taken of the river bed or bank properties, is predicted to reach a level of approximately $3400m^3/d$ after only 5 days of pumping, (Figure A5, which also shows the general Hantush and Stang models). The sensitivity runs undertaken are shown in Figures A13-A14.

The Stang solution shows a response similar to the Theis solution with a rapid initial impact but then a slowing down to a final impact after 180 days of approximately $3400m^3/d$. Sensitivity analysis has shown that the solutions are sensitive to changes in storativity but relatively insensitive to changes in Transmissivity.

The impact in the Theis model follows a very steep initial rise in the predicted depletion of the river baseflow by the groundwater abstraction eventually reaching 100% loss of the abstraction rate from the river. Very little lag in the impact of the depletion is predicted by the Theis model and upon cessation of pumping the impact of the depletion is seen to fall very rapidly to a minimum depletion after approximately 190 days from the start of the test. The impact of the pumping in the Hantush model shows a slower response rising to a maximum of 3000 m^3/d after 180 days and exhibiting a much slower rise in the rate of depletion from the Otter.

In terms of unknown parameters to be used in the model, the source of essential data can be:

- Data from pumping tests performed in the vicinity of the proposed abstraction.
- Regional values of aquifer parameters reported close to the source of the proposed abstraction.

The above two items may be available from Agency records.

- Parameter values taken from the BGS aquifer properties manual for the aquifer unit of interest.
- The use of expert judgement and the assessment of typical values for the aquifer unit of interest.

Parameters used in the model could have adverse effects on the prediction of depletion where they are poorly constrained. Where the accuracy of any parameter is in doubt, sensitivity analysis should be carried out.

Depletion of the River Otter is probably best described by either Hantush or Stang and the Theis solution should only be used as a comparison for the prediction of worst case impacts.

The 95%ile of flow exceedence for the river (Q_{95}) is assumed as 0.96m^3/s (82944m^3/d), an estimated figure based on data for the Otter gauging station at Dotton (upstream of the abstraction) obtained from the Hydrometric register and statistics (86-90). With a Q_{95} of 82944m^3/d, the loss of approximately 3500m^3/d equates to a 4% loss of baseflow from the river. No site-specific data is available for long term monitoring but an estimate of Q_{95} adjacent to the Otterton abstraction is reported in a Water Management Consultants (WMC) report (1992) that suggests that the Q_{95} for the River Otter (SY779 8484) at a point just downstream of the Otterton borehole shows a flow of 0.856m^3/s (73958m^3/d), or 5% of the baseflow. The loss of flow for each of the pumping tests after 180 days can be given as a flow and as a percentage of the 95%ile exceeded for river flow.

In terms of the depletion impact of the borehole on the River Otter, it is considered that the abstraction should be the subject of further investigation. The Hantush or Stang methods more accurately match the conceptual model for the Otter and the pumping test should be designed to represent this.

14-18 Winflow. At the preliminary stage it was not considered important to evaluate the distribution of drawdown along the reach of the river. The historical pumping test was, of course, designed with an assessment of the predicted radius of influence of the test in the usual way and with appropriate distribution of monitoring locations as described by WMC (1992) Leonard Threadgold (1990). The distribution of drawdown along the river is revisited later in the procedure following the interpretation of the historical pumping test.

19 **Specify the pumping test in terms of the Licensing manual requirements.** At this point the pumping test should be designed using the procedure outlined in the Licensing manual. This test should allow for the determination of any depletion that may be measured but the pumping rate and duration should be designed as reasonable within the timescale and be close to the proposed licensed abstraction rate. Normal practice would require that stream gauging were undertaken from a period prior to the test (to establish the baseflow) until after the impact of the test. This is not always practical but should be undertaken wherever feasible. In the case of the Otterton pumping test, it was considered that monitoring of the river at this point could not be done with sufficient accuracy to detect impact from the abstraction.

20 **Interpret the pumping test.** The pumping test should be interpreted in the usual manner.

21 **Verify results.** The pumping test performed in 1989 provides better estimates of the local T and S for the aquifer than was provided by the original Agency SPZ proforma since this included some data which may not be accurate.

Repeat of Procedures using pumping test data

In the following section, the results of this pumping test are used as an example of the procedure. The model was re-run using these parameters and the points 10-20 in this section forms the basis for the further analysis.

10 **Requirements of the pumping test.** The Otterton Borehole 4 was subject to a pumping test in 1989 to assess the yield of the borehole and the impact on the River Otter and the surrounding abstractions. This took the form of a 6 month pumping test undertaken at the Otterton Borehole 4, (details are in WMC, 1992 & Leonard Threadgold 1990). For the purpose of demonstrating the methodology of IGARF this test is described and the results discussed.

11 **Input parameters used in the test.** The following parameters were used in the model;

The length of the pumping test, was 180 days. This corresponds to the test that was actually performed.

Aquifer properties, T and S, were obtained from a conventional analysis of the pumping test monitoring borehole data using a type curve fitting technique (the data is archived at the Agencys Exeter office).

Note that if during the pumping test there is significant river flow depletion, this will be shown in the drawdown data as a characteristic flattening of the time-drawdown data series below that predicted by a Theis curve (on a log-log plot). Only the data prior to the deviation from a Theis type curve should be matched in the initial interpretation of T and S. Monitoring wells away from the river will be least affected by such deviations and may provide better responses for conventional analysis. As always, any deviations from ideal type curve responses should be identified and considered.

- The rate of pumping during the test was entered into the pumping test spreadsheet. An average rate of 4320m^3/d was achieved during the pumping test.
- T and S were assigned to the model based on the results of the analysis of the pumping test. The aquifer shows a semi-confined or leaky aquifer with an S of 0.001 and a T of 400m^2/d.
- The perpendicular distance to the river from the borehole was interpreted from the location map. This was estimated at 25m.

It is proposed that the Stang solution provides the most accurate approximation to the conceptual model. There is considerable uncertainty in the conceptual model as discussed in item 9 above and all of the analytical solutions will be used.

The calculations performed during the assessment exercise based on Theis show that there is an impact that builds over time to eventually reach a 100% impact of abstraction volume being taken from the river. This is the general result obtained from the Jenkins methodology.

The best estimate Stang model outlined in sections 2.7 and 2.8 is shown in the 'General Solution' figures at the rear of the report. The magnitude of impact is very similar to that outlined in section 2.9 with a final impact after 180 days of 4200m^3/d following an initial steep rise in depletion followed by a very slow asymptotic rise towards 100% loss of water from the river.

12 **Assess river-aquifer connectivity.** It is possible that the head in the aquifer might fall below the base of the river bed over the closest reaches of the river to the borehole. In such a case the depletion of river flow would be at no more than the limiting percolation rate through the river bed. The drawdown shown in the Leonard Threadgold report, suggests that the head falls below the base of the river for a distance of 1500m. A simple Darcy calculation would produce three times the river water depletion taken directly from the river. A more detailed study will lead to the reconcilliation of piezometry with drawdown corresponding to analytical solutions. This is only applicable for the Stang solution since both Theis and Hantush consider no drop in the head at the river or drawdown below the river. This problem highlights the advantage of the distributed modelling approach.

A more detailed calibration would be possible if the drawdown associated with the analytical model were calculated. However, where there is a high degree of uncertainty, the decision to move to a higher level of modelling such as a distributed modelling assessment, should be made if the situation warrants it.

13 **Conduct sensitivity study.** Uncertainty analysis was undertaken on the parameters assigned to the three basic models to assess the suitability of the methodologies. The analysis was applied based on reasonable variation in parameters that may apply to the aquifer and river system.

The results of the variation of these parameters are shown in Tables A1-A3 and the results are summarised graphically in Figures A15-23. A summary of the general conclusions of the sensitivity of the impacts to changes in these parameters has been made in addition to more quantitative measurement of impacts and is included in these tables.

In the Stang method the depletion impact is directly proportional to the width of the river and the hydraulic conductivity of the riverbed. The depletion is inversely proportional to the thickness of the bed sediment. In both the models incorporating the low permeability characteristics, the model is more sensitive to adjustments. However, this is only relative and it is predicted that the depletion will rapidly rise to a level corresponding to the abstraction pumping rate.

The storage coefficient or specific yield is important in the prediction of the depletion rate in the Theis model. In the Hantush method the depletion impact is directly proportional to the depth of the river bank sediments and the hydraulic conductivity of this material. The depletion is inversely proportional to the thickness of the bank sediment.

Some general points can be made concerning the results of the uncertainty analysis. It should be noted that in terms of pumping test design the choice of bed or bank properties can make a great difference to the time before a depletion impact is potentially identified. Changes to the distance of the borehole from the river are shown to be insensitive to change.

14 **Use of Winflow.** Winflow was used to assess the spatial relationship between river depletion and the abstraction borehole.

15 **Input parameters to Winflow.** The inputs to the model are defined here.

- The river length to be used in the model was digitised using a scanned image of the 1:25000 Ordnance Survey map. This scanned .dxf format.line was imported into Winflow to allow reaches to be digitised easily along the river stage.
- The river stage was entered in 25-50m sections using the 1:25000 Ordnance Survey map. The stage was specified with a 0.5-1m change between each section, interpolated from the 5m topographic contour intervals on this map. A stretch of approximately 5km was used in the model, with the Otterton Borehole 4 close to the centre of the whole reach.
- The thickness of the aquifer was set to 140m based on the saturated thickness of aquifer in the abstraction borehole and the hydraulic conductivity was set as 2.7m/d corresponding to a transmissivity of $400m^2/d$.

16 **Identify all abstractions of interest in the model area.** The current demonstrations of the methodology considers only the effect of the abstraction at Otterton Borehole 4. This allows the direct comparison of results obtained from the spreadsheet model and the Winflow model. When considering a real licence application, licensed abstractions should be included in the assessment to enable drawdown and depletion of river baseflow to be computed.

17 **Specify regional groundwater characteristics in Winflow.** Winflow requires that a regional flow field is specified. This is specified in the form of a regional head gradient, reference head and a flow direction. The reference allows the determination of a flow field to be established in which to place the river stage and abstraction borehole. The placement of the reference head should be at a sufficient distance from the area of interest so that the fixed head does not act as an artificial source or sink. To allow representative results to be obtained, the model should be ideally extended to the catchment boundary. However, lack of data often makes this unfeasible and the model should be made as large as possible consistent with the simple homogenous conceptual model used in Winflow. In the current example, no regional gradient was specified and the contours are controlled by the river stage.

18 **Evaluate the depletion using Winflow.** NOTE: No account has been taken of the retardation effects of the properties of the river base in this model this should be considered when interpreting the results. The results will therefore tend to underestimate the drawdown (since water passes more easily into the zone of depression from the river than would be the case if sediment properties were taken into account). The spread of river flow depletion will correspondingly be underestimated. This is generally a conservative error, but if there are sensitive upstream reaches, the impact on these may be underestimated.

Fluxes in each river section can be read by double clicking with the mouse on the length of reach in the Winflow model.

The groundwater model contours produced by Winflow show only a minor deflection from the non-pumping condition (Figure A5). Detailed contours from each model and sensitivity run are not included. Graphed results of the modelling are shown in Figures A6-A11. The analysis includes runs for T = $400m^2/d \pm 20\%$ which are discussed in further detail in the following section. Depletion of the river can be viewed in terms of loss of baseflow per metre of river. There is a loss over a short length of the river centred on the abstraction borehole. The characteristic shape of the loss is symmetric about the nearest point along the river to the borehole. This symmetry will generally be predicted when the river is nearly straight close to the borehole.

Consideration of a water balance at the site suggests that losses from the river should total the abstraction from the borehole. However a mass balance shows that some of the groundwater abstracted is flowing from the model boundaries. The minor fluctuations in the model in the rate of depletion from the river baseflow along the reach lengths most likely result from the meanders in the course of the river. There is a very slight change in the position of the groundwater head contours at the extreme eastern edge of the model where flow across the boundary is induced by the abstraction.

The sensitivity of the Winflow model was assessed on the basis of two parameters, the Transmissivity (±20%), adjusted by changing the hydraulic conductivity of the aquifer and keeping the saturated thickness constant, and the position of the reference head in the model.

The model is considered to be too small to model the effects of the whole of the groundwater catchment of the river as the model is too small to incorporate the influence of the whole catchment of the borehole. Ideally the model should consider the whole of the groundwater catchment of the river but is rarely able to do this due to lack of data and the inability of Winflow to represent heterogenous spatially varying aquifer properties. This is seen in the discrepancy of the abstraction rate and river depletion volume.

Changes to the position of the reference head had some effect on the river losses in the model. However, the change to the overall depletion and the pattern of this depletion was observed to be insignificant and errors due to the flows beyond the model boundaries were judged to be insignificant. No results have been presented here for the movement of the reference head.

Uncertainty analysis of the transmissivity, T, in the model show that the model is generally insensitive to changes in T and that the pattern of depletion from the river is still symmetrical around the pumping well. The results of the sensitivity calculations are given in Figures A6–A11. The insensitivity of the results to transmissivity may be due to the relatively small range used in the model.

19 **Specify the pumping test in terms of the Licensing Manual requirements.** At this point the pumping test should be designed using the procedure outlined in the Licensing manual. This test should allow for the determination of any depletion that may be measured but the pumping rate and duration should be designed as reasonable within the timescale and be close to the proposed licensed abstraction rate. Current practice would require that stream gauging were undertaken from a period prior to the test (to establish the baseflow) until after the impact of the test. This is not always practical but should be undertaken wherever feasible.

20 **Interpret the pumping test.** The pumping test has been interpreted previously and forms the basis of the re-run in this section.

21 **Verify results. See previous section 21 above. This completes the re-run sections of the procedure and the remaining items are summarised below.**

22 **Assess the adequacy of the results for licence determination.** The model that best represents the system in the case of this trial is considered to be Stang since it is assumed that the shallow river would lead the majority of loss through the base of the system.

The model results are sufficient to scope the range of behaviour of the depletion but there is currently insufficient field data to justify more detailed modelling. There remains significant uncertainty in the modelling and the decision to move to the next tier of detailed assessment would depend on the importance of the predicted range of impacts. This decision would be taken at item 26.

23 **Assess the results of any stream gauging.** No significant stream gauging has been carried out in the vicinity of the Otterton borehole and the available data is very difficult to interpret with any degree of confidence. Stream gauging could not be interpreted quantitatively, but did suggest an impact on stream flow.

24 **Record the best estimate and uncertainty of model parameters.** The best estimate and range of parameters is recorded in Tables A2.1-2.3. Winflow predicts that there is a symmetrical distribution of flow depletion from the River Otter around the pumping well.

The results of the pumping test were inconclusive and the full range of parameter uncertainty had to be considered in predicting the impact of the licensed pumping regime.

25 **Evaluate the licence application.** The results of the pumping test have been used for the evaluation of the long-term annual abstraction at the site and the evaluation is given in Figure A12. For evaluation of a periodic annual abstraction, or longer term constant pumping, the main data spreadsheet is used. It should be noted that the months 'wrap around' and that the year runs from January to December. The data used in this evaluation is discussed below.

The abstraction from Otterton Borehole 4 source being assessed is as identified in item 1 above (Note that this may differ from actual historical abstractions).

The best estimate conceptual model is that incorporated in the general Stang solution with the parameters identified in item 24 above. The abstraction is predicted to result in a corresponding depletion of the river Otter flow.

The model predicts the consequence of the licence restriction between April and July. The central prediction is that the river flow depletion will fall to the reduced abstraction rate only during the period of the restriction.

The overall evidence suggests that the proximity of the borehole to the river rapidly leads to the depletion of the river and that long term abstraction will lead to the development of all of the abstraction being derived from the river. Should the abstraction have only been periodic then river bed and bank characteristics would have been more significant in determining the actual extent of depletion. In the case of this model the sensitivity of the bank and bed properties become fairly insignificant over the timescales being considered.

26 **Assess the licence with respect to policy.** The licence application would now be determined in accordance with Agency policy using the procedures described in the licensing manual. The possible impact of the abstraction on the flow of the River Otter assessed here, would be one of the issues to be taken into account.

27 **Set requirements for hydrometric monitoring.** If appropriate specify any stream gauging or piezometry required to monitor the impact of licensed abstracting so that the assessment may be reviewed.

28 **Set review time.** Set a time to review the licence.

3 Summary

The Methodology was successfully applied to Otterton borehole 4 and was able to predict a range of river flow depletion that might be expected in the river Otter following licensed abstraction. No attempt was made to judge the advisability of allowing this licence which is an issue relating to the Agency policy at the time of application or review.

The methodology showed that the Otter flow is likely to be influenced by such a licensed abstraction at borehole 4. The aquifer in the neighbourhood of Borehole 4 is considered to be an leaky aquifer with an This results in relatively rapid responses. The natural flow results in the Otter gaining water from aquifer baseflow. The best estimate conceptual model is the Stang model with low permeability sediments beneath the river, through which there is leakage to the aquifer after pumping.

For the pumping test it was shown that the time of impact of the test on river flow would be expected to only marginally lag behind the time of pumping and to be spread over a longer time. All the abstracted water is expected to ultimately reduce the river flow. This leads to a maximum flow reduction of 90% of the abstraction rate for the best estimate of conceptual model and parameters.

Note that for the pumping test, the water is disposed of to the river (or to groundwater infiltration) and that this would constitute a compensating return of water to the river. The real impact would therefore be expected to be less at point downstream of any returns. The range of uncertainty is large. If stream bed sediments are neglected and good contact assumed then the impact is more rapid and less spread over time. In this case, depletion of the Otter occurs with days of the start of abstraction and rapidly builds up to the abstraction rate. With increased resistance of stream bank sediments, using the Hantush model, the river flow depletion grew more slowly to about 60% of the abstraction rate.

Winflow models showed that the impact would be centred on the nearest point to the borehole and spread over a distance of less than 1 km up and downstream of this point. Unfortunately, as is often the case, there was no data on riverbed sediment properties and no reliable quantitative stream ganging to validate the model. It is however, believed that there is significant induced leakage with evidence for the order of 30% of the abstracted water having infiltrated to the aquifer from the river. The net impact of long term abstraction would be expected to be 100% of the abstraction for such a case when intercepted baseflow is taken into consideration.

Finally, piezomety shows that there is drawdown on the far side of the river, consistent with the choice of the Stang conceptual model. It suggests that close to the abstraction the water-table might fall below the river bed leading to limiting drainage and reducing the impact locally. This results in extending the zone of depression and correspondingly extending the reach of the Otter from which the water would be derived.

This might be investigated further with a numerical model approach.

Table 2.1. Sensitivity analysis of parameters used in the Theis method. Otterton BH4.

THEIS METHOD.		LEVEL OF PARAMETER VARIATION				Notes
Parameters		**+1 order of magnitude**	**-1 order of magnitude**	**X2**	**x0.5**	
GENERAL PARAMETERS T = 400m²/d S = 0.001 a = 25m Maximum Depletion: 4300 m³/d after 183 days	T			*800 m²/d*	*200 m²/d*	Insensitive parameter, possibly due to the proximity of the well to the River Otter.
				Minimal changes to general model. Rapid depletion (within 5 days) during pumping followed by a rapid recovery.	Very similar to general model and to T = 800 m²/d.	
	S	*(x 5) 0.005*	*(x 0.2) 0.0005*	*0.002*	*0.0005*	Relatively insensitive parameter
		Slightly longer for final stages of recovery and the early stage of depletion. Otherwise similar to the general Theis model.	Slightly greater depletion at the onset of pumping and on the final stages of recovery. Maximum depletion occurs after 183 days and is 4300m³/d.	No noticeable change between this run and the run employing the general parameters.	No significant difference between this run and the run employing the general parameters	
	a	*(x 2) 50m*	*(x 0.5) 12.5m*	*+20% 30m*	*-20% 20m*	Established parameter, which has a limited associated uncertainty.
		More gradual recovery and depletion at the extremes of the curve (at 5 days and 185 days respectively)	Sharp changes between initial rapid depletion and steady depletion during pumping.	No changes between this model run and the general Theis model.	No significant changes between this model run and the general Theis model.	

Where T = Transmissivity,
S = Storage coefficient
a = Distance between River and Borehole.

NOTES FOR ALL MODELS

- Please refer to the text for details of the general conceptual models.
- All comments relate to a comparison between the general model specified in the table and show in Figure OTT2.3 unless otherwise stated.
- Not all configurations of parameter changes have been undertaken and the tables are seen to show a representation of the sensitivity of parameters to change. These tables are meant to be used only as an indication of impacts for illustration purposes.

Table 2.2. Sensitivity analysis of parameters used in the Hantush method. Otterton BH4.

HANTUSH METHOD.		LEVEL OF PARAMETER VARIATION				Notes
Parameters		+1 order of magnitude	-1 order of magnitude	x2	x0.5	
GENERAL PARAMETERS T = 400 m^2/d S = 0.001 K = 0.2m/d thick = 0.5m depth = 2m a = 25m Maximum Depletion: 3750 m^3/d after 183 days	K	*2 m/d*	*0.02 m/d*	*0.4 m/d*	*0.1 m/d*	Relatively sensitive parameter, even within the small range representing the uncertainty in this variable.
		Greater depletion established very quickly. A rapid climb steadies off up to 4300 m^3/d after 183 days. Recovery is also rapid with the final 500 m^3/d taking around 70 days.	Limited depletion reaching a maximum of around 1500m^3/d. Both depletion and recovery follow very shallow gradients after an initial short-lived jump.	Rapid onset of depletion to 3500m^3/d after 10 days. This is followed by a steady climb to a maximum of 4000m^3/d after 183 days. Recovery is similar with the final 500m^3/d taking over 150 days.	Rapid depletion up to 2000m^3/d followed by a steady increase to a maximum of 3300m^3/d after 183 days. Recovery represents a mirror image of the depletion.	
	thick	------	*0.05 m*	*1 m*	-----	Relatively sensitive parameter although its range of reasonable values is limited.
			Depletion of 4000m^3/d after only 10 days with a maximum of 4300m^3/d after 183 days. Initial recovery is rapid, the final 500m^3/d taking 50 days	Gradual increase after an initial jump to 1500m^3/d maximum of 3300m^3/d after 183 days. Recovery is again a mirror image of depletion.		
	depth	*Borehole depth 97 m*	-----	*4 m*	*1 m*	When riverbank depth equals the depth of the borehole model output is very similar to the Theis run. Otherwise model is relatively insensitive.
		Initial depletion of 4200m^3 maximum of 4300m^3 after 183 days. Recovery is rapid with 200m^3 left to recover after 185 days.		Depletion occurs rapidly over 20 days to 3500m^3/d, reaching 4000 m^3/d at 183days. After pumping the flow recovers quickly to less than 500 m^3/d after 35-40 days.	Depletion reaches a maximum of 3300m^3/d immediately before the end of pumping. Recovery occurs rapidly followed by a gradual recovery.	
	T	——	-----	*800 m^2/d*	*200 m^2/d*	When considering the range over which the transmissivity has been taken the model is relatively insensitive to the parameter.
				Rapid climb to 2500m^3/d after 25 days followed by a gradual increase to a maximum of 3550m^3/d after 183 days.	Depletion of flow reaches a maximum after 183 days of 3900m^3/d after an initial rapid jump to 3000m^3/d. Recovery is also rapid but flattens out after 50 days post pumping.	
	S	-----	-----	*0.002*	*0.0005*	Fairly insensitive model parameter (see variations in T)
				Gradual increase to a maximum of 3550m^3/d after 183 days after an initial jump to 2000m^3/d Recovery is similar, with an initial jump followed by a steady increase in flow.	Rapid initial increase to 3500m^3/d after 35 days followed by a gradual increase to a maximum of 3900m^3/d at 183 days. Recovery is also rapid with a flattening of the curve some 50 days after cessation of pumping.	
	a	----	------	*+20% 30 m*	*-20% 20 m*	Insensitive parameter in the limited range established for this known variable.
				Similar to general Hantush model.	Similar to general Hantush model.	

Where T = Transmissivity, S = Storage coefficient, K = Hydraulic conductivity of the river bank, thick = Thickness of the river bank, depth = Depth of the river bank

Table 2.3. Sensitivity analysis of parameters used in the Stang method. Otterton BH4.

STANG METHOD.		LEVEL OF PARAMETER VARIATION				Notes
Parameters		**+1 order of magnitude**	**-1 order of magnitude**	**X2**	**x0.5**	
GENERAL PARAMETERS T = 400m^2/d S = 0.001 K = 0.1m/d thick = 0.5m width=14.7m Maximum Depletion: 4300 m^3/d after 183 days	K	*1m/d*	*0.01 m/d*	*0.2m/d*	*0.05m/d*	The model is quite sensitive to riverbed parameters affecting the maximum depletion observed in the river.
	K	Very rapid depletion of flow occurring within 2 days of pumping Recovery is equally rapid, with only 100m^3/d of flow depletion 5 days after cessation of pumping.	Lost flow quickly reaches 200 m^3/d and then gradually goes up to a maximum of 3550 m^3/d at the end of the test. Recovery is initially quite rapid with 1000 m^3/d remaining to be regained 40 days after pumping ceases.	Depletion increases rapidly loss of 4000m^3/d within less than 5 days. Maximum of 4300m^3/d at the end of pumping (183 days) Recovery is also very rapid with only 100m^3 of depletion 15 days after cessation of pumping.	Maximum of 4100m^3/d is reached at the end of the test after an initial jump to 3500m^3/d after around 5 days. Flow recovery is initially very rapid with 1000m^3/d of flow to be regained after less than 5 days following cessation of abstraction.	
	thick	----	----	*1.0 m*	*0.25m*	See above.
	thick			Depletion increases rapidly, with 4000m^3/d reduction in flow after around 3 days. A maximum of 4400m^3/d is lost at the end of the abstraction (183 days). Recovery is also very rapid, with the final 300m^3/d taking 100 days to fully recover.	A maximum depletion of 4200m^3 is reached at the end of the pumping test after a rapid loss of 3000m^3. Recovery is also very rapid, with the recovery of the last 500m^3 taking 150+ days.	
	width	-----	----	*29.4 m*	*7.35 m*	This variable should be relatively well known. Model outputs show that the early stages of the pumping test are sensitive to this parameter but overall the model is overall relatively insensitive to this parameter
	width			Initial reduction in flow is very rapid with 4000m^3/d lost within less than 5 days. The maximum loss of flow is approximately 4300m^3/d, which occurs after 183 days. Recovery is very rapid with 4000m^3/d after 5 days	Rapid loss of 3000m^3/d increasing to a maximum of 4200m^3/d after the 183 days of the test. Recovery is similar with a rapid initial recovery followed by a gradual recovery of the last 500m^3/d	
	T	----	----	*800m^2/d*	*200 m^2/d*	Insensitive parameter
	T			Maximum of 4300m^3/d flow loss at the end f the test. Rapidly reaches 3500m^3/d. Recovery is similar with a rapid change followed by a gradual tapering off.	As T = 800m^3/d but with a maximum of 4300m^3/d. Recovery is also very similar to other T.	
	S	----	----	*0.002*	*0.0005*	Minimal changes are observed over quite a large range of storativity. This parameter is relatively insensitive
	S			Rapid climb to 3500m^3/d followed by a gentler climb to a maximum of 4300m^3/d. Recovery is similar but inverted.	Depletion increases rapidly to 4000m^3/d reaching a maximum of 4300m^3/d. Recovery is also rapid with the last 200m^3/d takes 50 days to fully recover.	
	a	----	----	*+20% 30m*	*-20% 20m*	Relatively insensitive to changes.
	a			Similar to general Stang model.	Similar to general Stang model.	

Where T = Transmissivity, S = Storage coefficient, K = Hydraulic conductivity of the riverbed, thick = Thickness of the riverbed, width = Width of the river.

Figure A1

Location of the Otterton 4 abstraction borehole

Project:	6077 Trials
Figure No.	A1
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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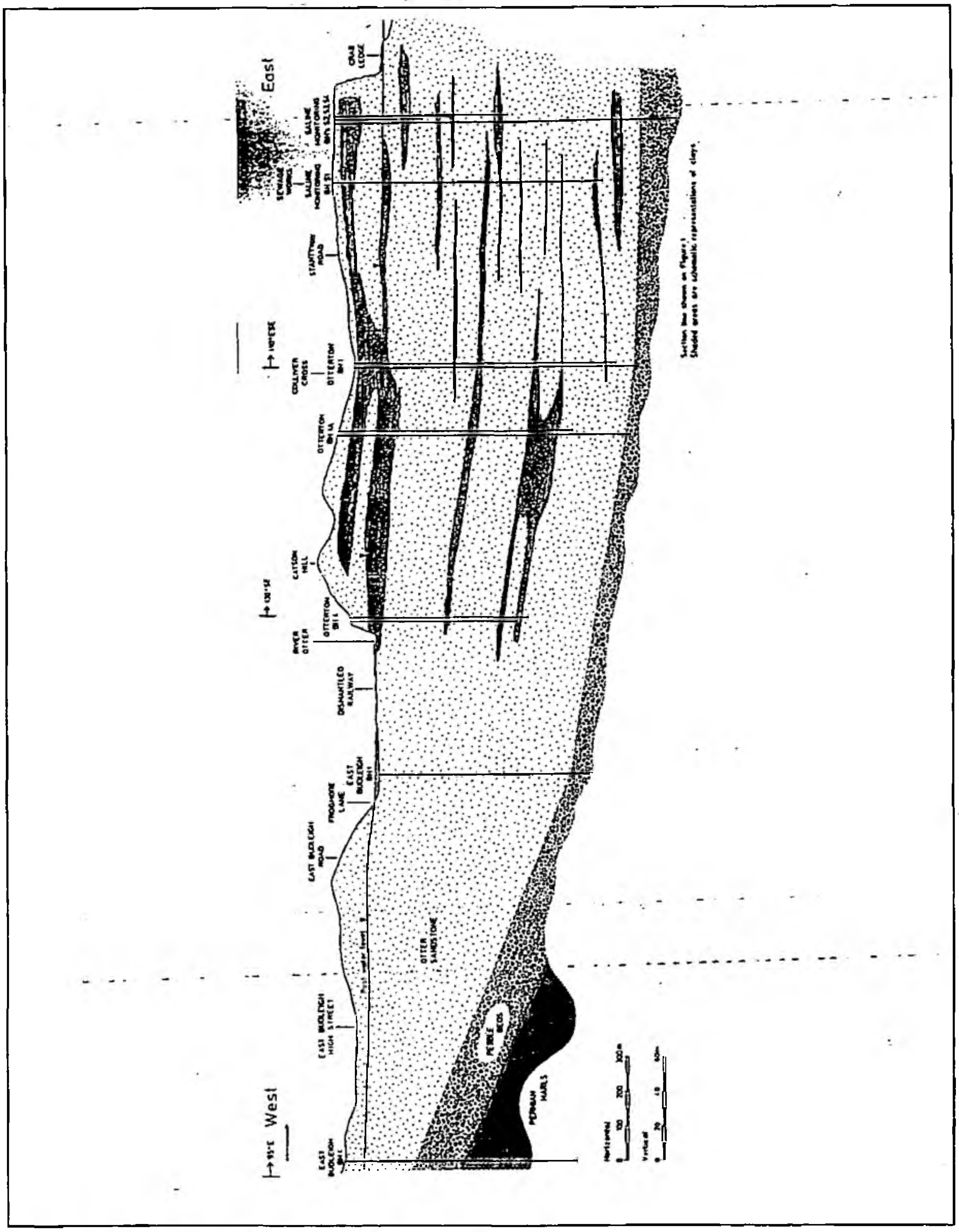
Figure A2



Cross section from Figure 1.1 WMC (1992)

Project:	6077 Trials
Figure No.	A2
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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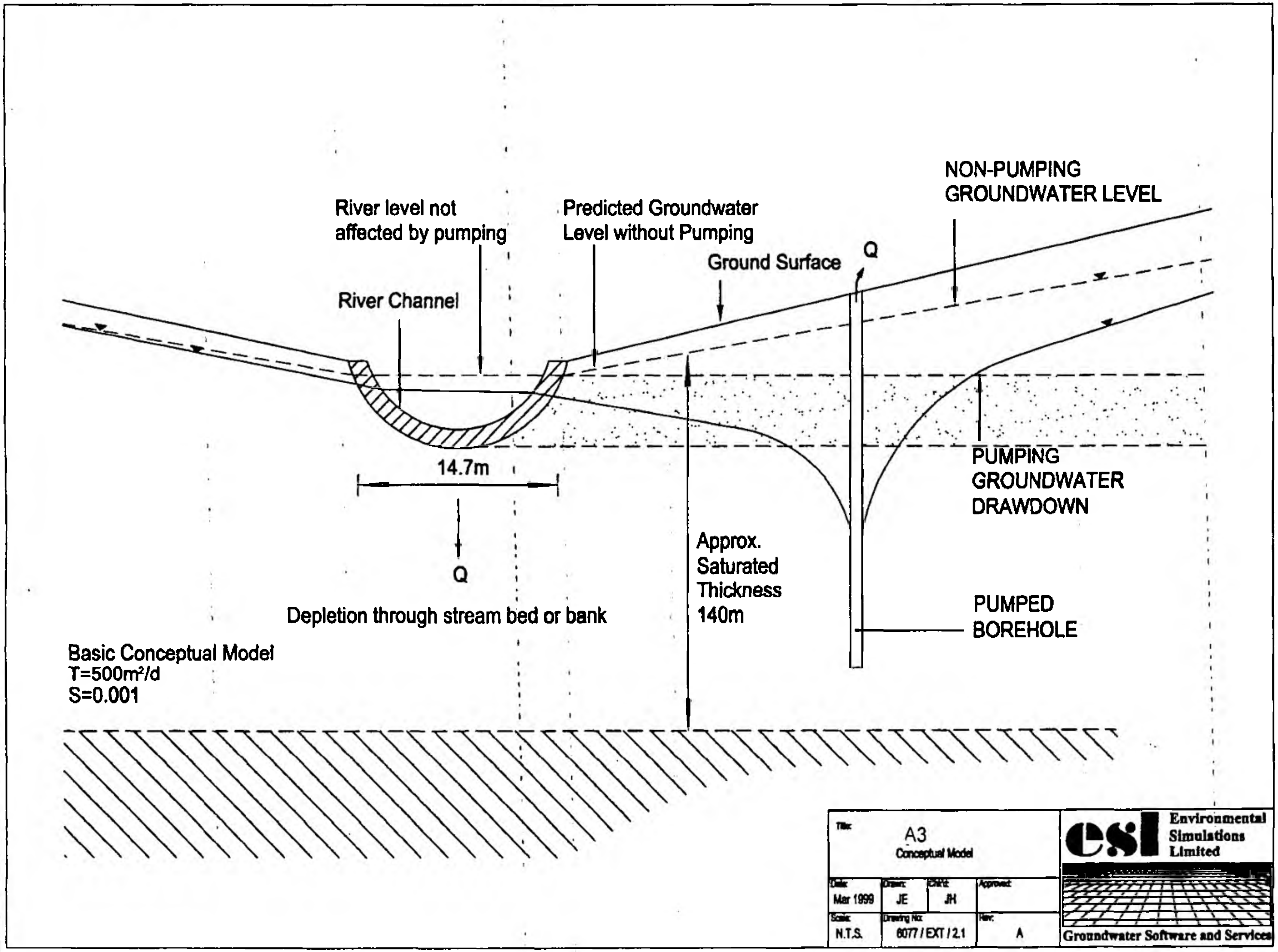
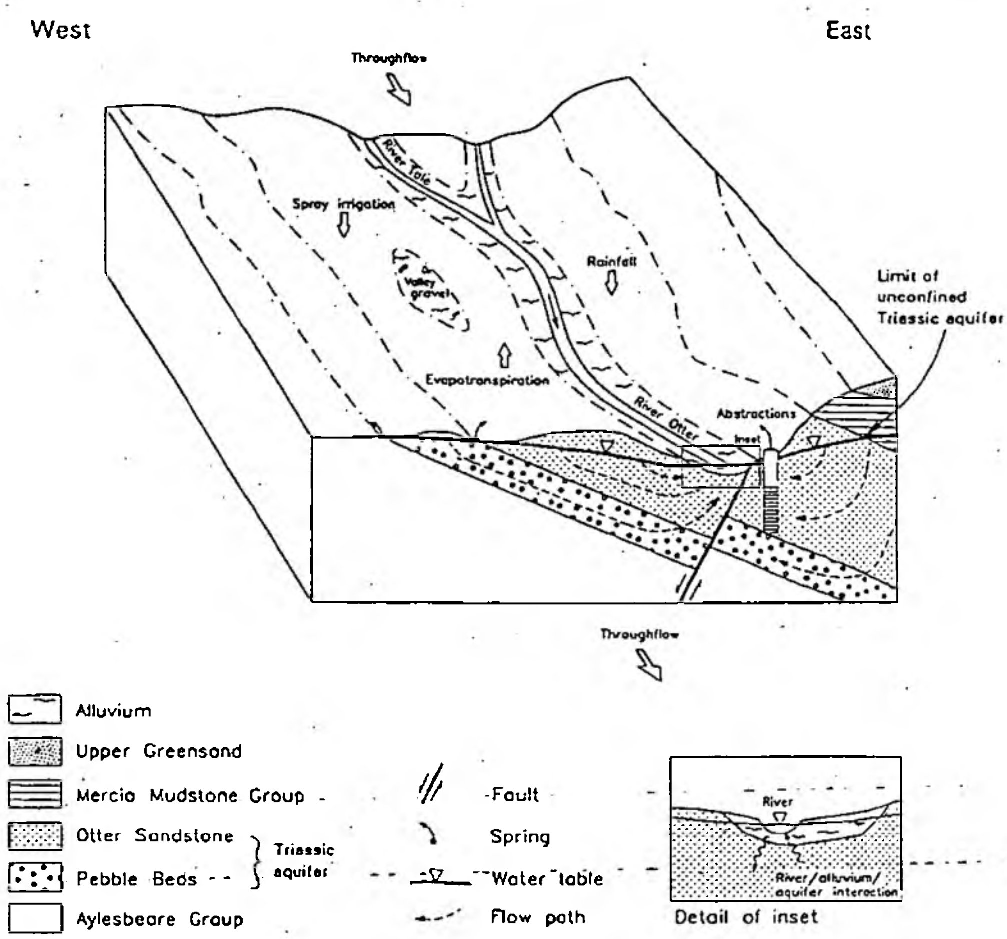

NON-PUMPING
GROUNDWATER LEVEL
River level not
affected by pumping
Predicted Groundwater
Level without Pumping
Ground Surface
Q
River Channel
14.7m
Q
Depletion through stream bed or bank
Approx.
Saturated
Thickness
140m
PUMPING
GROUNDWATER
DRAWDOWN
PUMPED
BOREHOLE
Basic Conceptual Model
T=500m²/d
S=0.001
Title:
A3
Conceptual Model
Date:
Mar 1999
Drawn:
JE
Chk'd:
JH
Approved:
Scale:
N.T.S.
Drawing No:
6077 / EXT / 2.1
Rev:
A
Environmental
Simulations
Limited
Groundwater Software and Services

Figure A3



Schematic conceptual model for the Otter Valley WMC (1992)

Project:	6077 Trials
Figure No.	A4
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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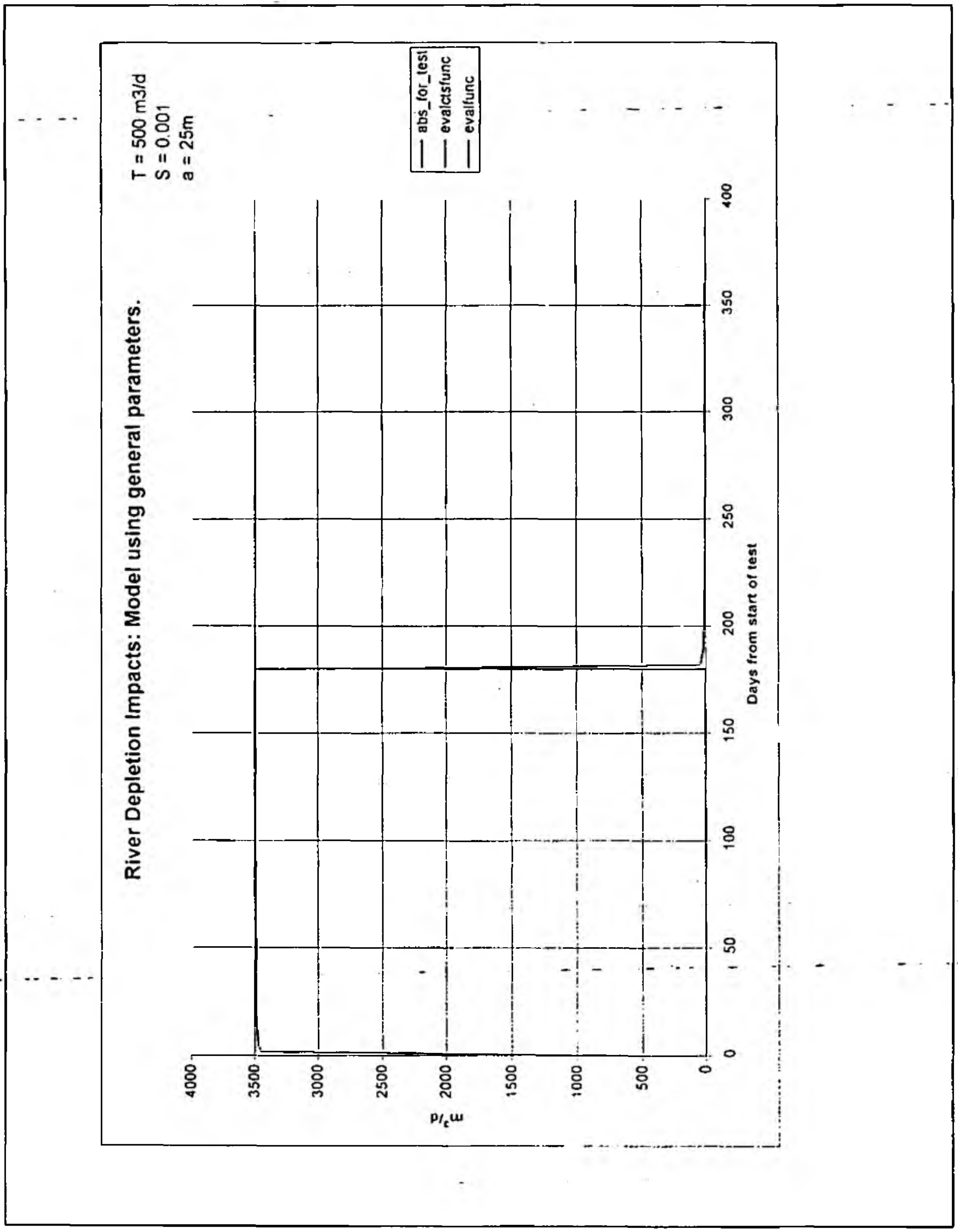
Figure A5



Results of the pumping test for the general model

Project:	6077 Trials
Figure No.	A5 .
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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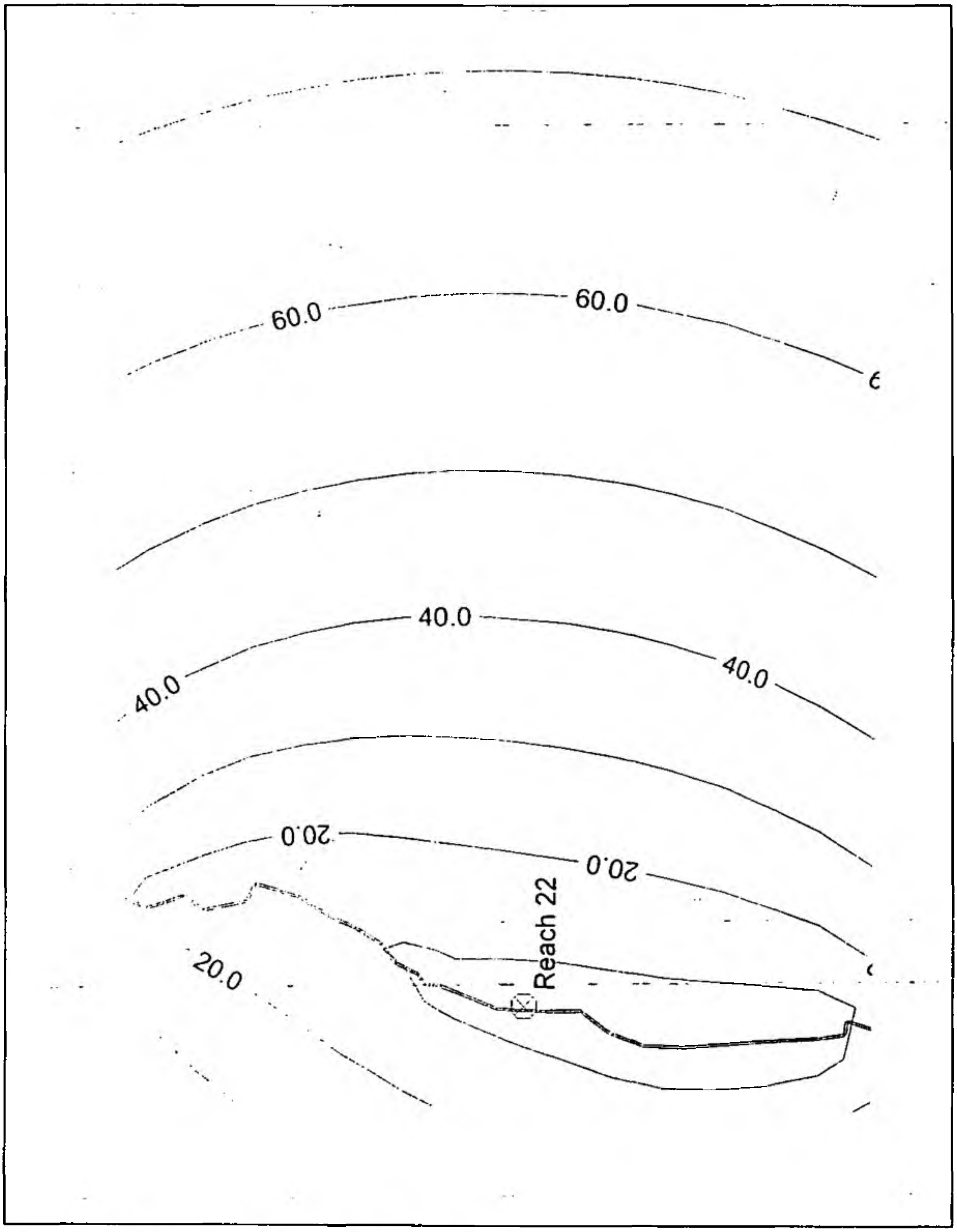
Figure A6



General Winflow model for Otterton BH4.

Project:	6077 Trials
Figure No.	A6
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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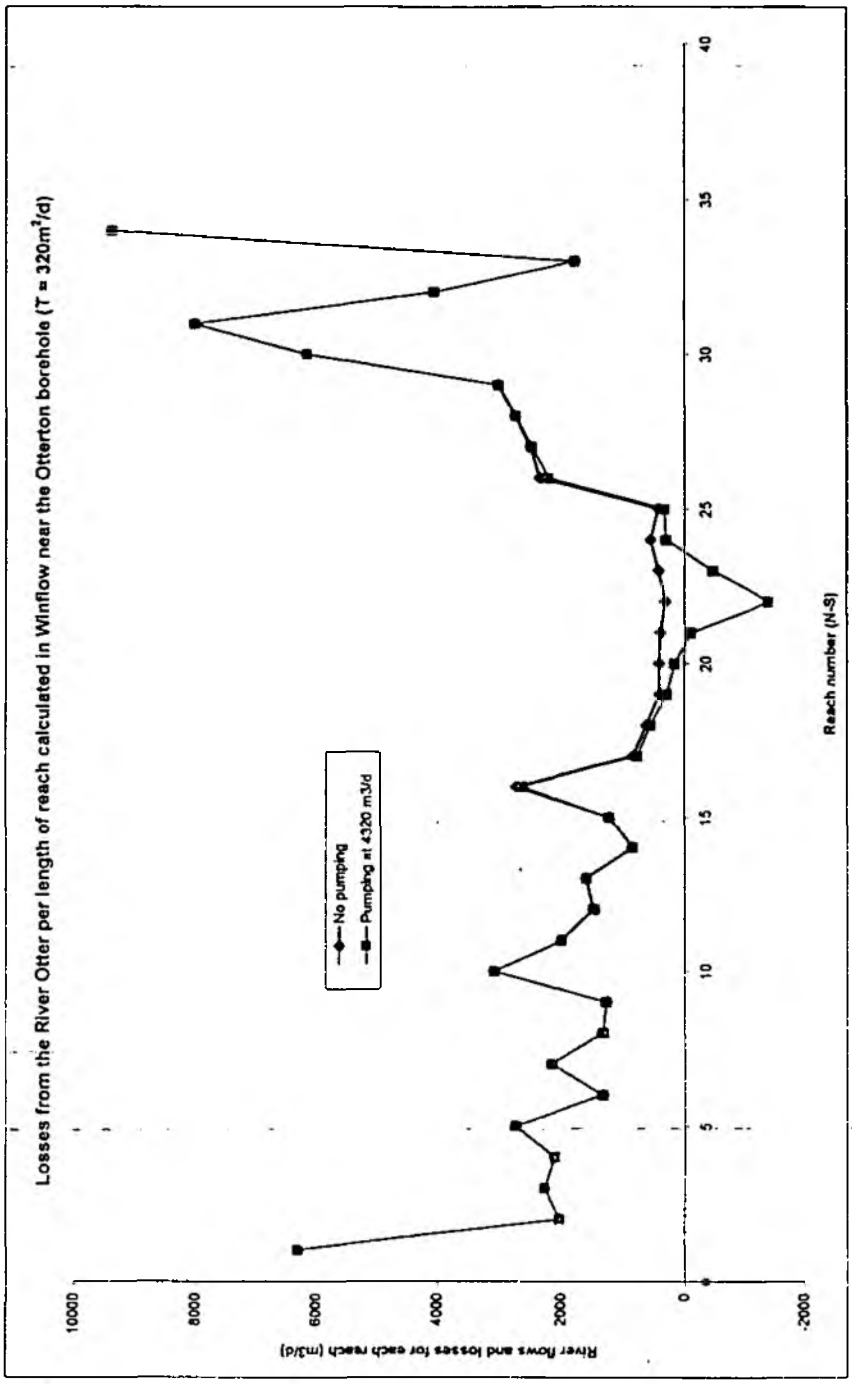
Figure A7



Graph showing river baseflow losses per reach along the modelled stretch of the River Otter ($T=320m^2/d$)

Project:	6077 Trials
Figure No.	A7
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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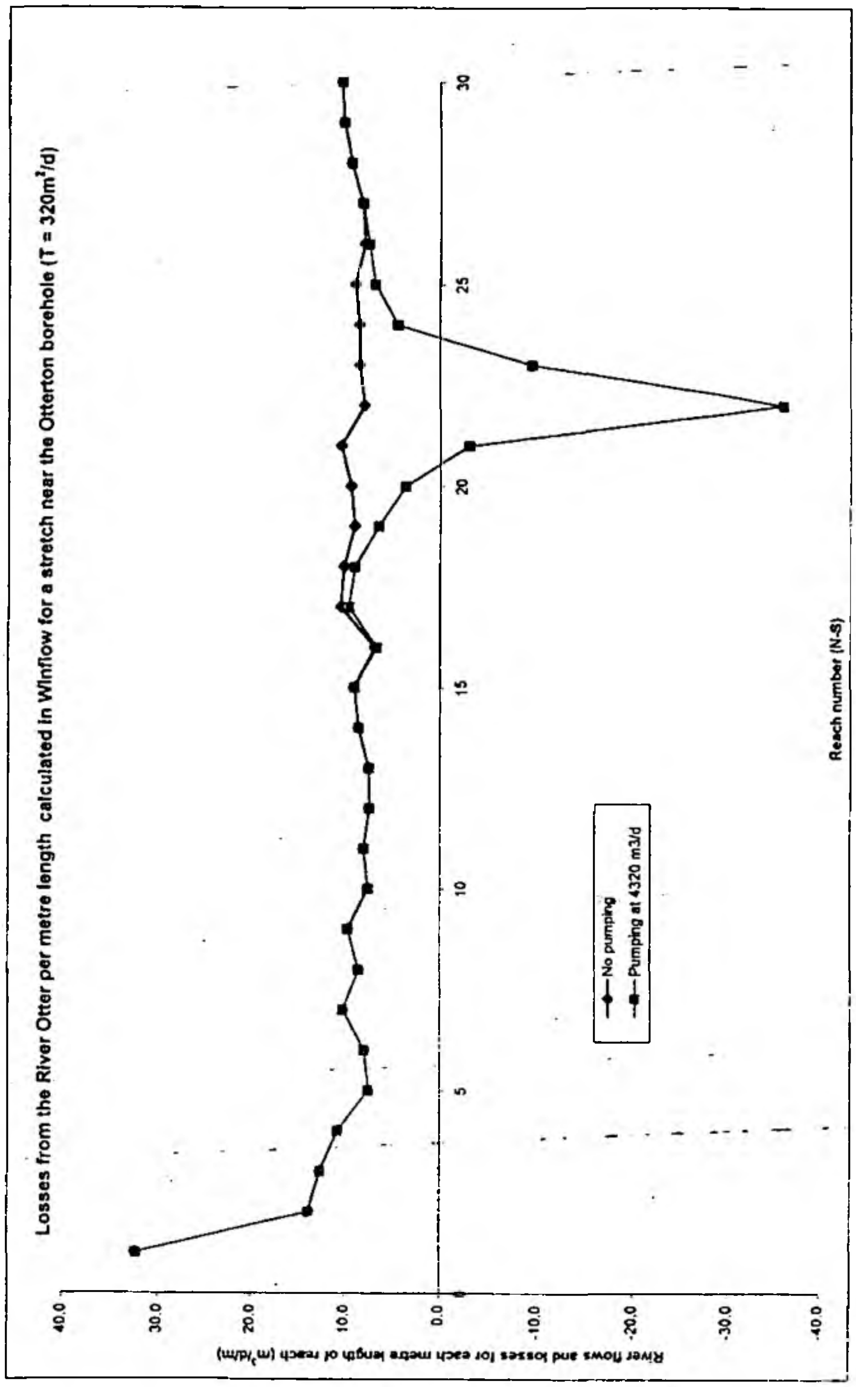
Figure A8



Graph showing river baseflow losses per metre along the modelled stretch of the River Otter (T=320m²/d)

Project:	6077 Trials
Figure No.	A8
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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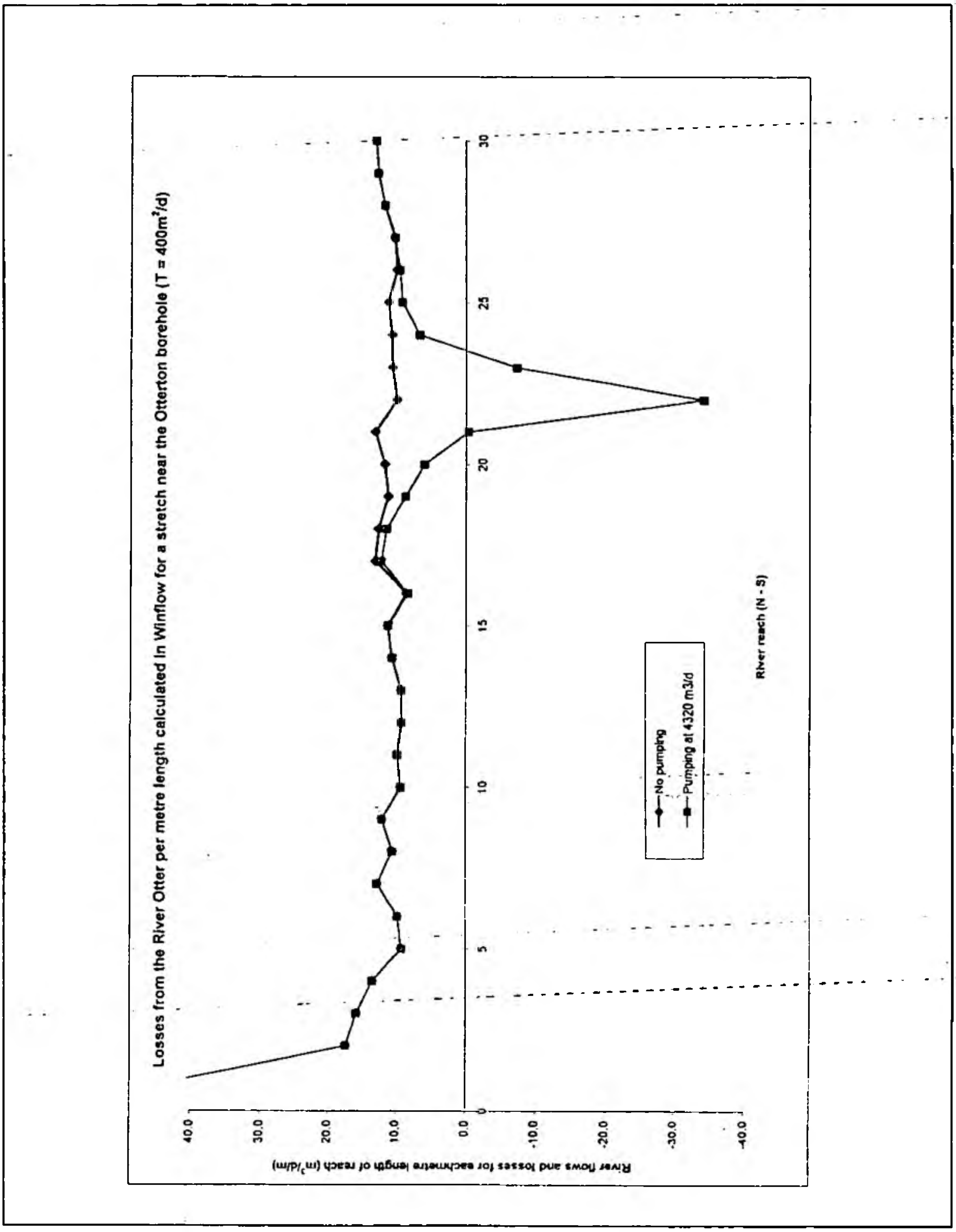

Graph showing river baseflow losses per metre along the modelled stretch of the River Otter (T=400m²/d)

Project:	6077 Trials
Figure No.	A9
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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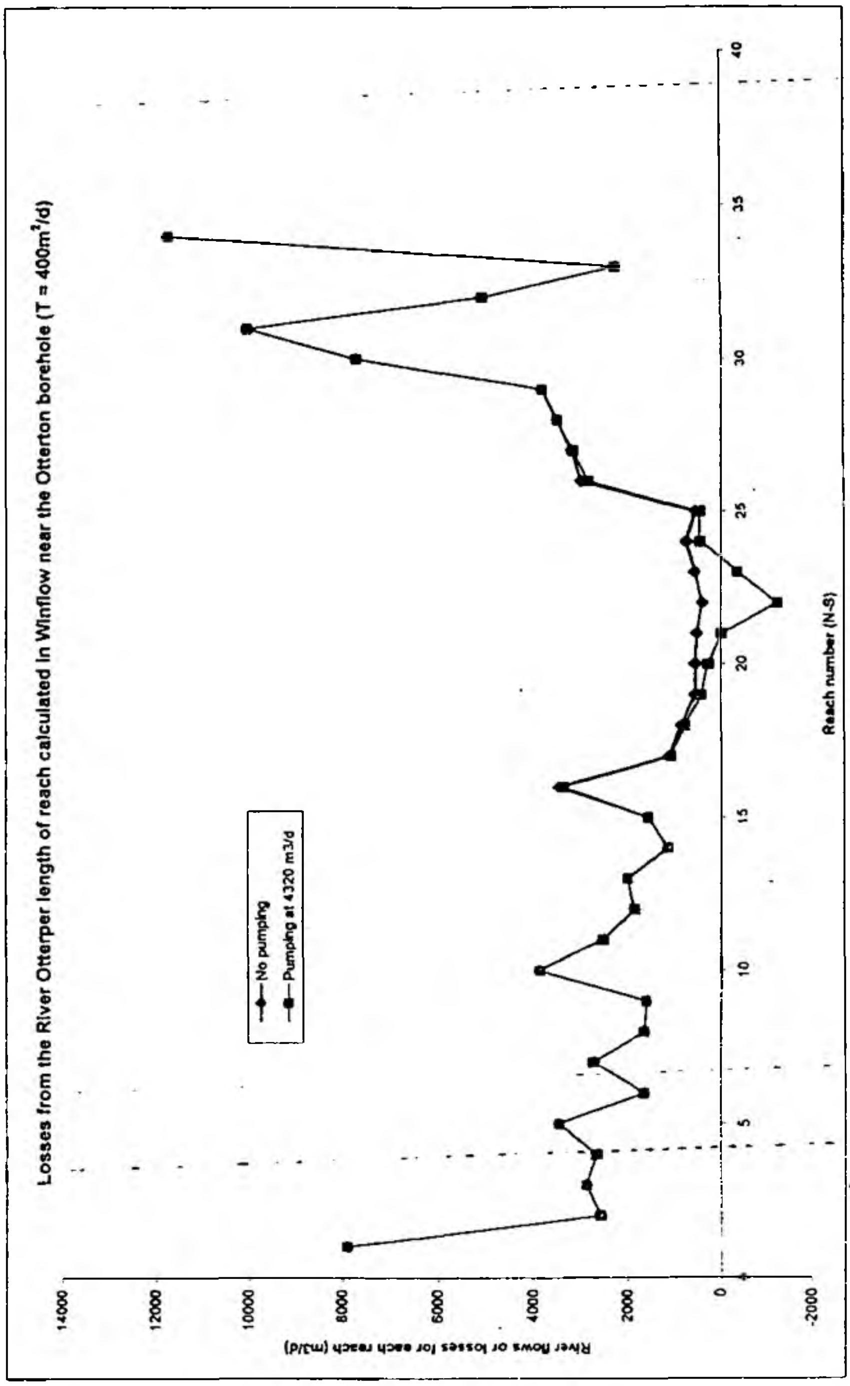
Figure A10



Graph showing river baseflow losses per reach along the modelled stretch of the River Otter (T=400m^2/d)

Project:	6077 Trials
Figure No.	A10
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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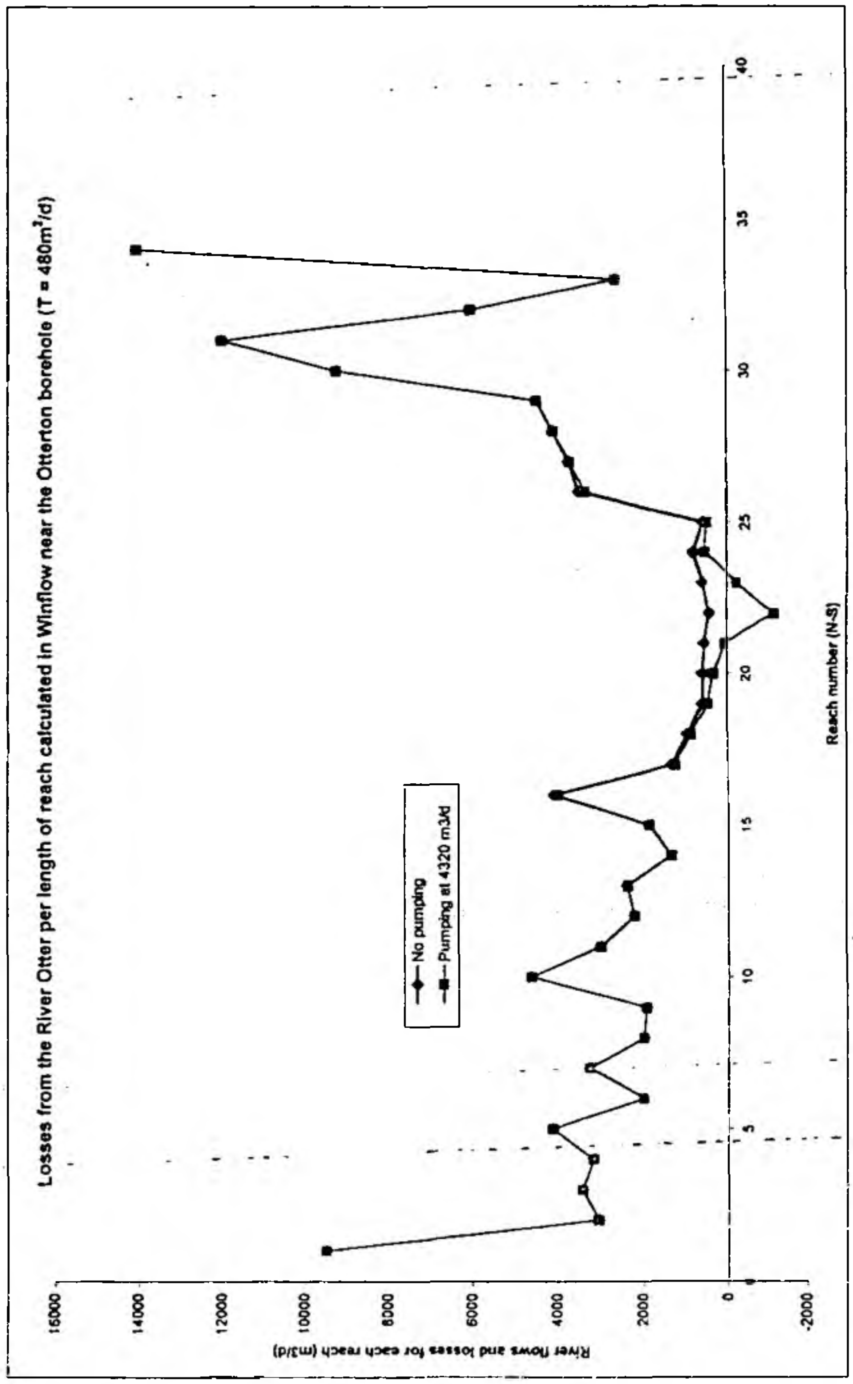

Graph showing river baseflow losses per reach along the modelled stretch of the River Otter (T=480m^2/d)

Project:	6077 Trials
Figure No.	A11
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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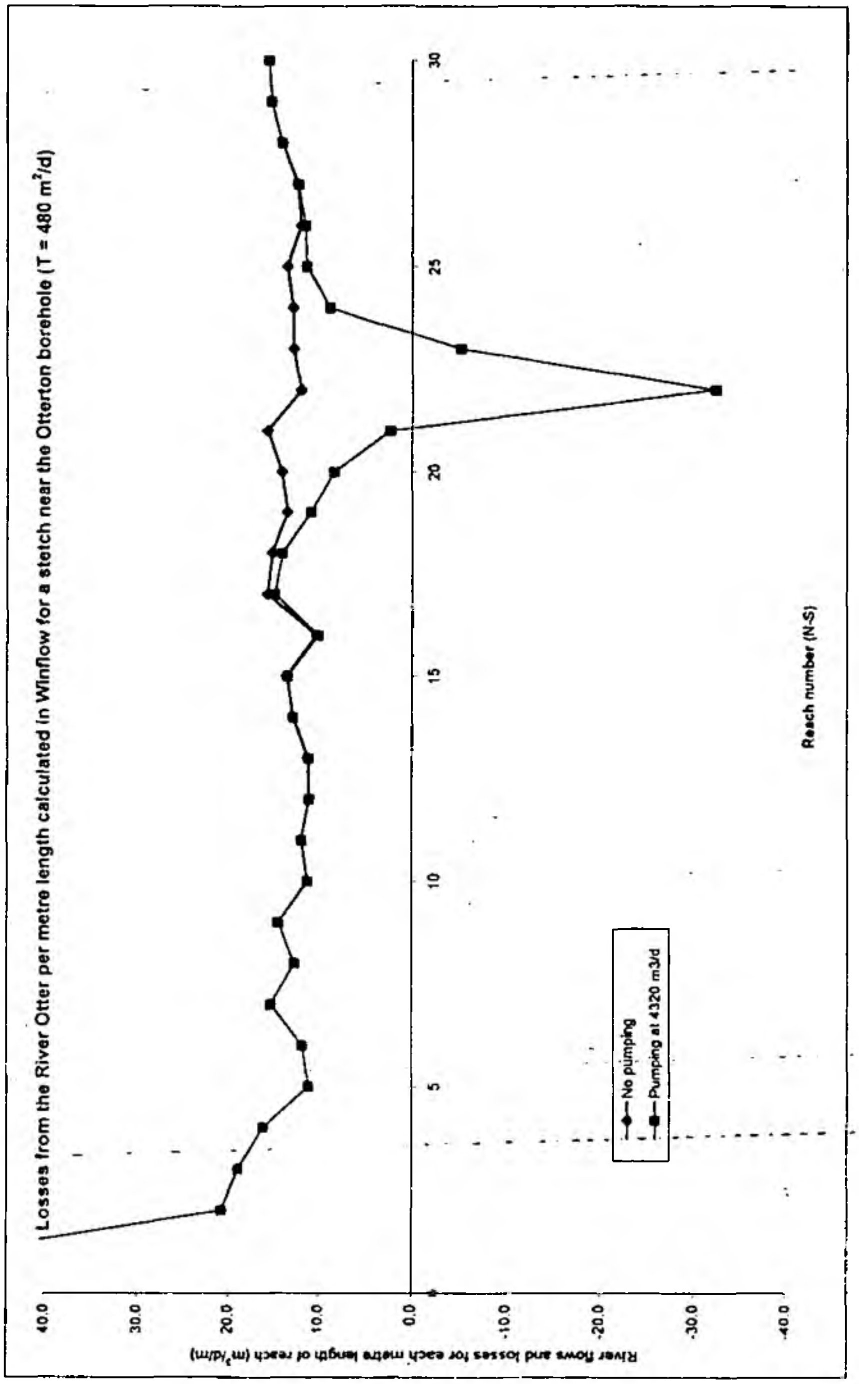
Figure A12



Graph showing river baseflow losses per metre along the modelled stretch of the River Otter (T=480m²/d)

Project:	6077 Trials
Figure No.	A12
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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Annual Pumping

	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	year
pumping (r	3630	3630	3630	3630	3630	3630	3630	3630	3630	3630	3630	3630	
compensa	1820	1820	1820	1820	1820	1820	1820	1820	1820	1820	1820	1820	
day	0	31	59	90	120	151	181	212	243	273	304	334	365
vol abs	112530	101640	112530	108900	112530	108900	112530	112530	108900	112530	108900	112530	1324950
vol comp	56420	50960	56420	54600	56420	54600	56420	56420	54600	56420	54600	56420	664300
river deple	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	660650
day deplet	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

[illegible]

Theis

Transmissi Trans	400	m2/d
Storage co S	0.001	
Perpendicu a	25	m

Hantush

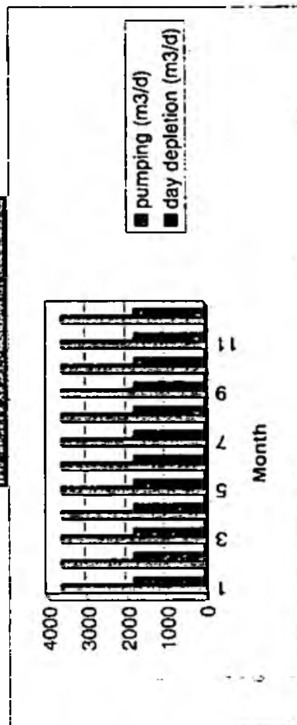
stream bar K bank	0.2	m/d
stream bar depth bank	2	m
stream bar thick bank	0	m

Stang

stream bec K bed	0.1	m/d
stream bec river width	14.7	m
stream bec thick bed	0.5	m

error check - cannot h [illegible]

error check - must hav [illegible]



Impacts of the annual abstraction

Project:	6077 Trials
Figure No.	A13
Scale	NOT TO SCALE
Drawn By	JPH
Checked	AWH

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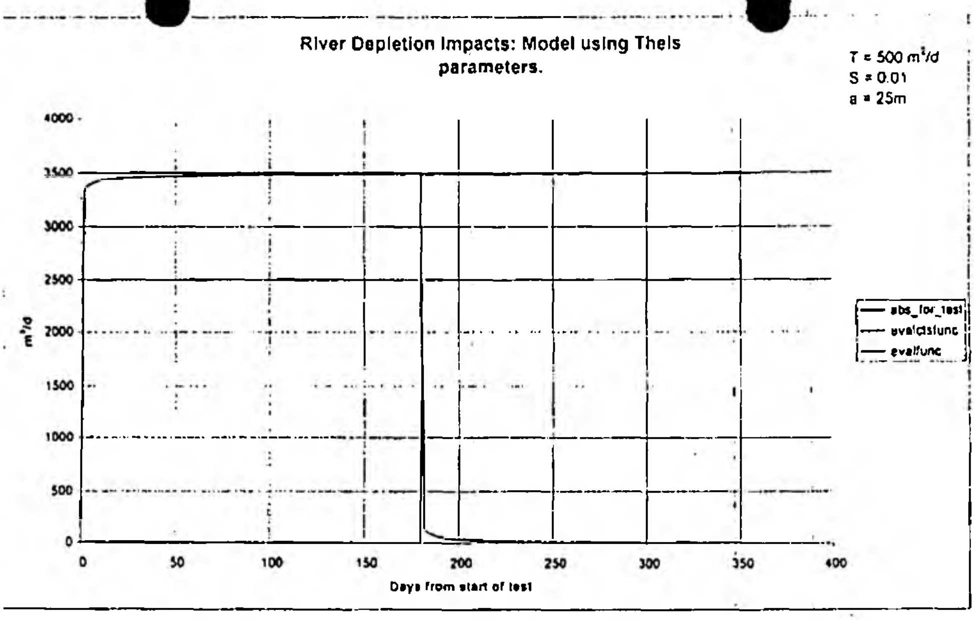
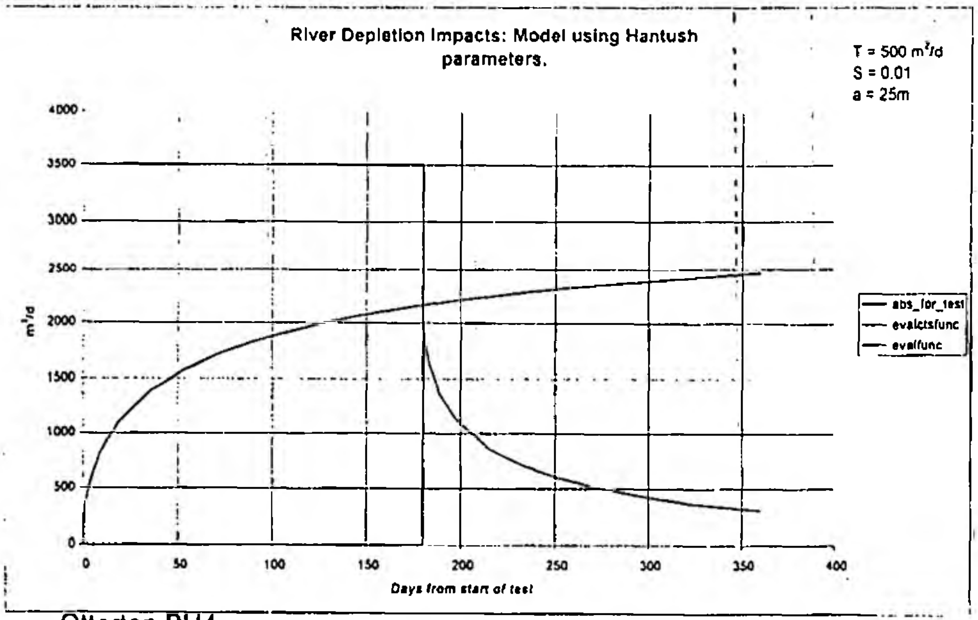




Otterton BH4

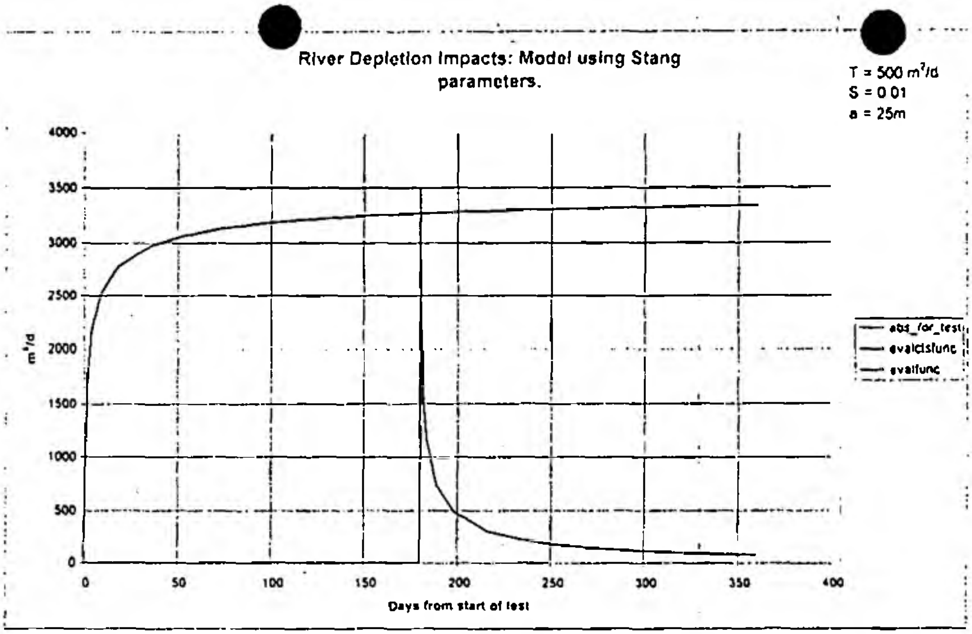
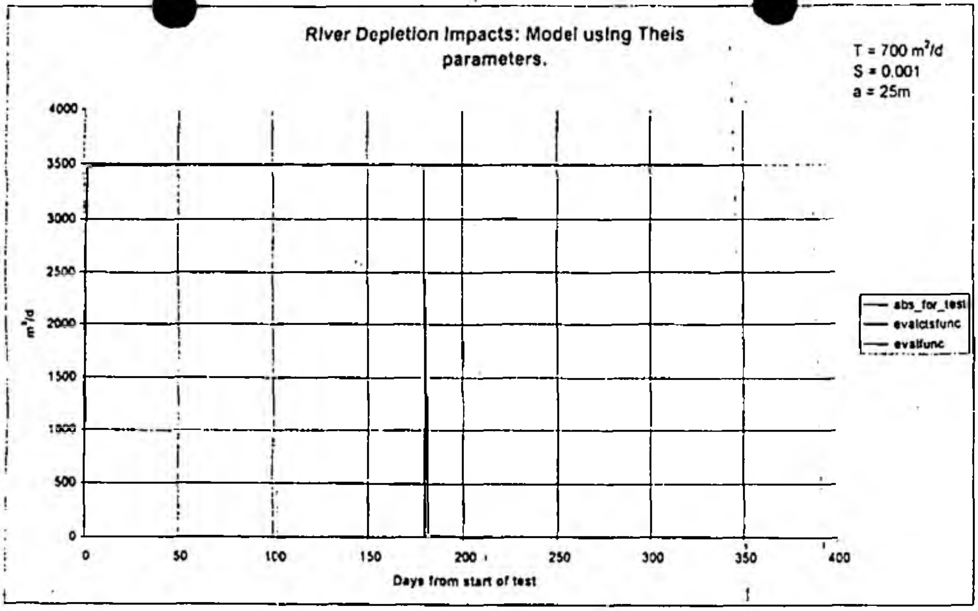
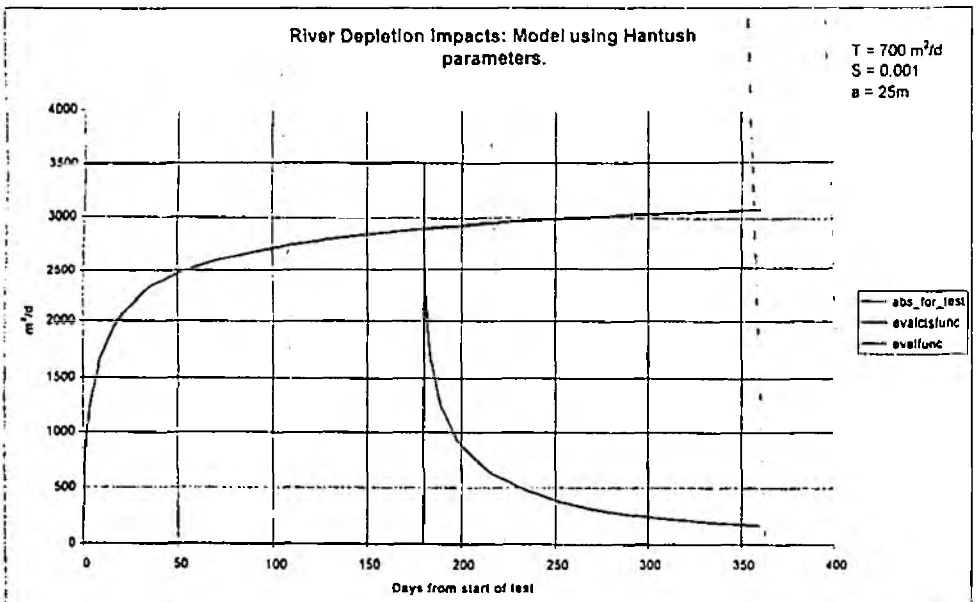


Figure A14

Variations of Storativity





Otterton BH4

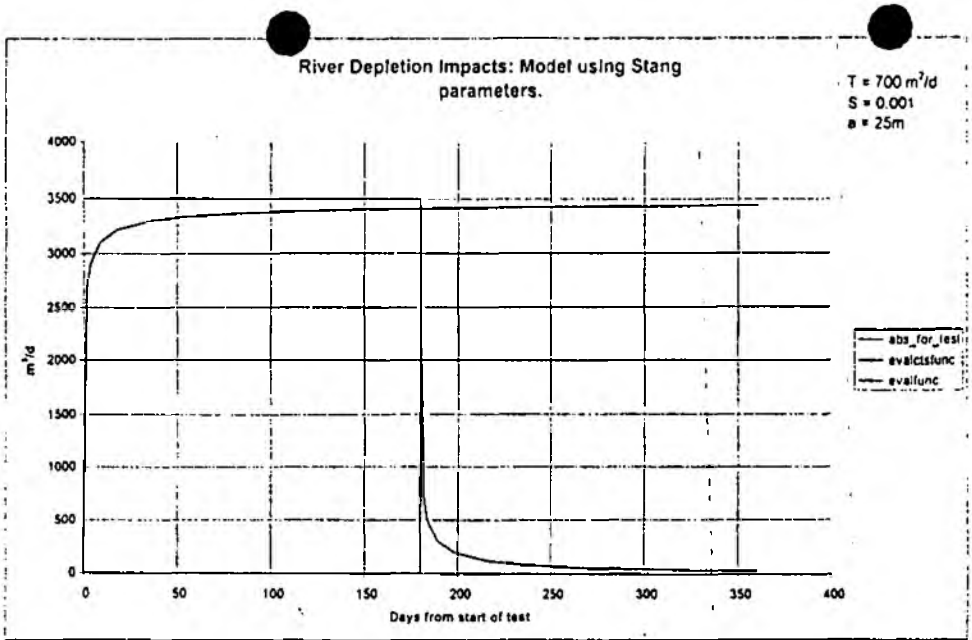
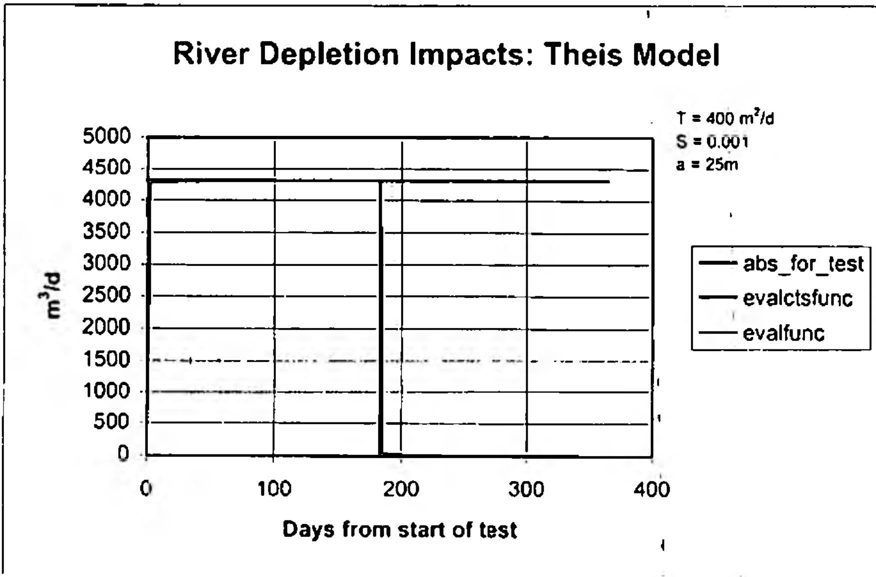
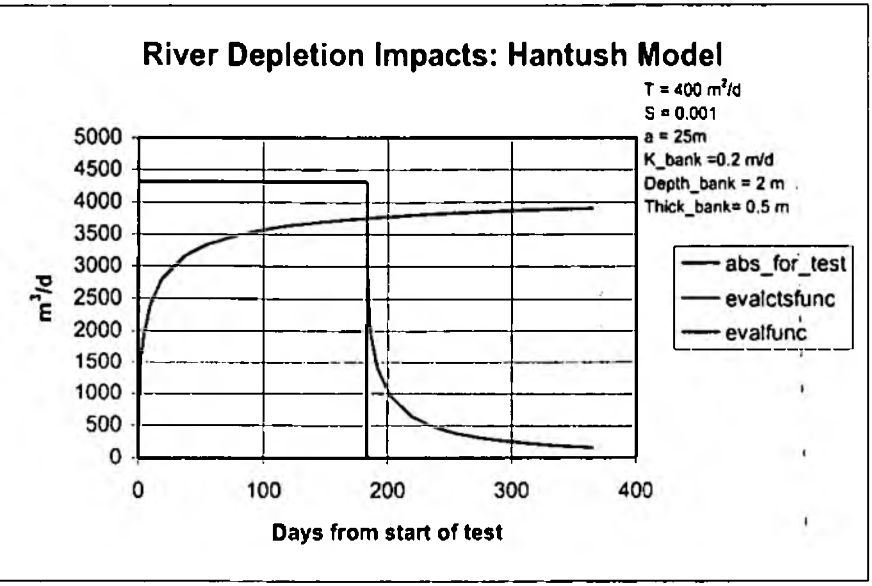


Figure A15

Variations of Transmissivity



Otterton BH4


River Depletion Impacts: Hantush Model
T = 400 m²/d
S = 0.001
a = 25m
K_bank =0.2 m/d
Depth_bank = 2 m
Thick_bank= 0.5 m
abs_for_test
evalctsfunc
evalfunc
m³/d
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
Days from start of test

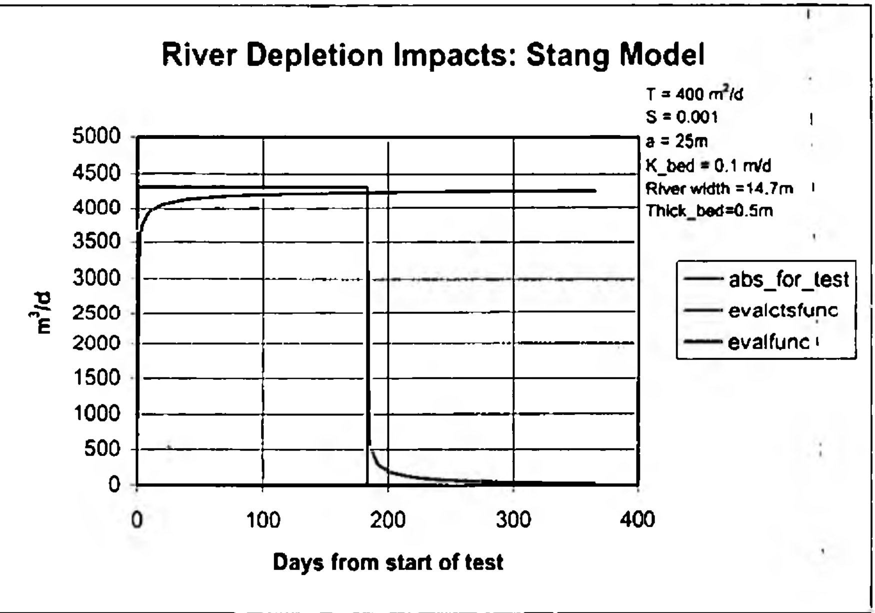
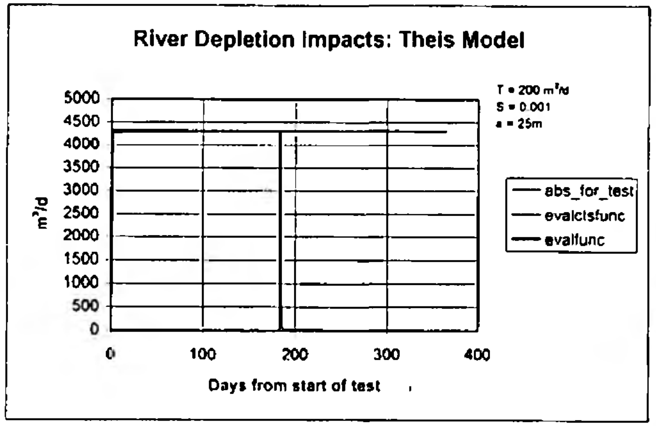
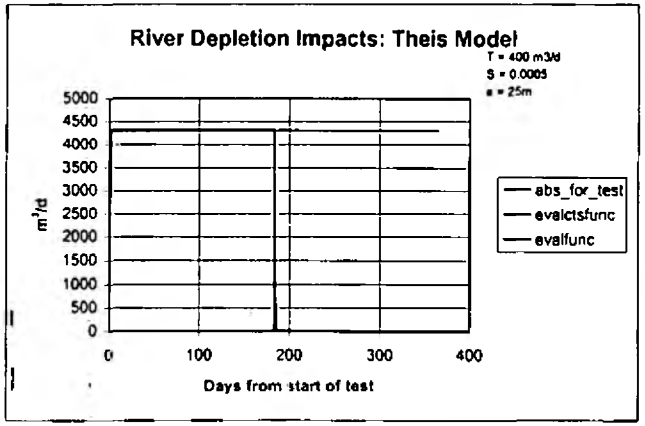
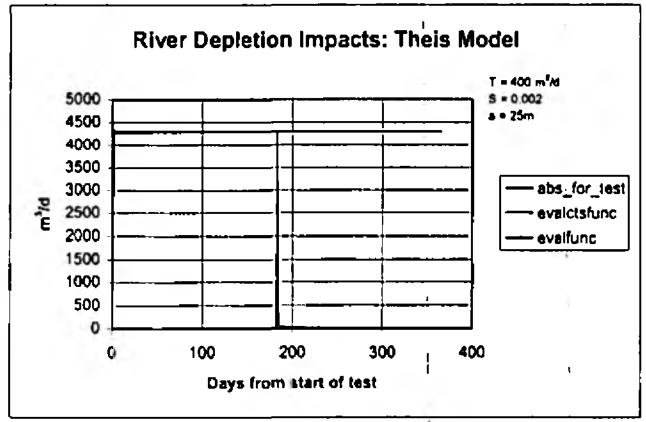
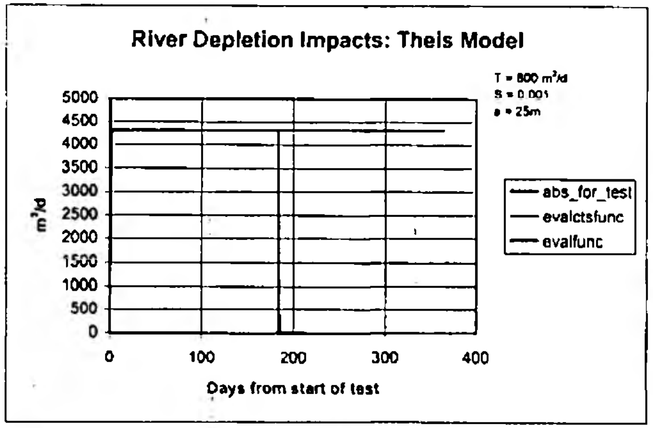

River Depletion Impacts: Stang Model
T = 400 m²/d
S = 0.001
a = 25m
K_bed = 0.1 m/d
River width =14.7m
Thick_bed=0.5m
abs_for_test
evalctsfunc
evalfunc
m³/d
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
Days from start of test

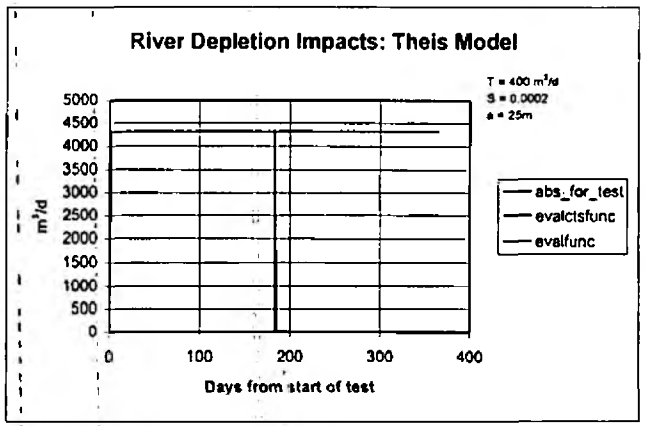
Figure A16


River Depletion Impacts: Theis Model
T = 200 m³/d
S = 0.001
a = 25m
m³/d
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc


River Depletion Impacts: Theis Model
T = 400 m3/d
S = 0.0005
a = 25m
m³/d
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc


River Depletion Impacts: Theis Model
T = 400 m³/d
S = 0.002
a = 25m
m³/d
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc


River Depletion Impacts: Theis Model
T = 800 m³/d
S = 0.001
a = 25m
m³/d
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc


River Depletion Impacts: Theis Model
T = 400 m³/d
S = 0.0002
a = 25m
m³/d
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc

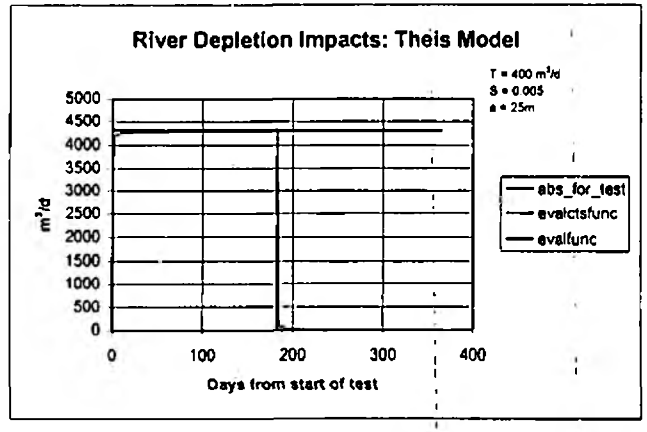
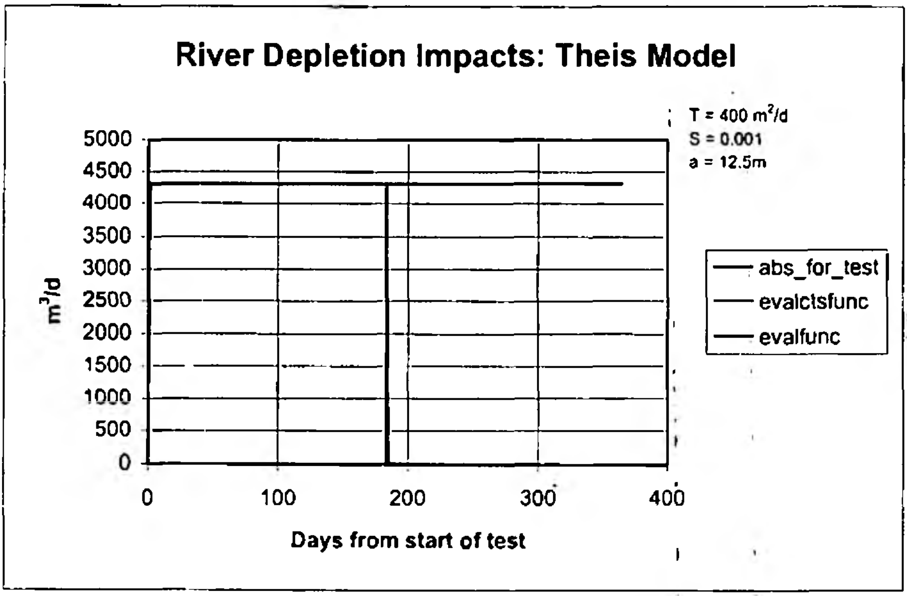
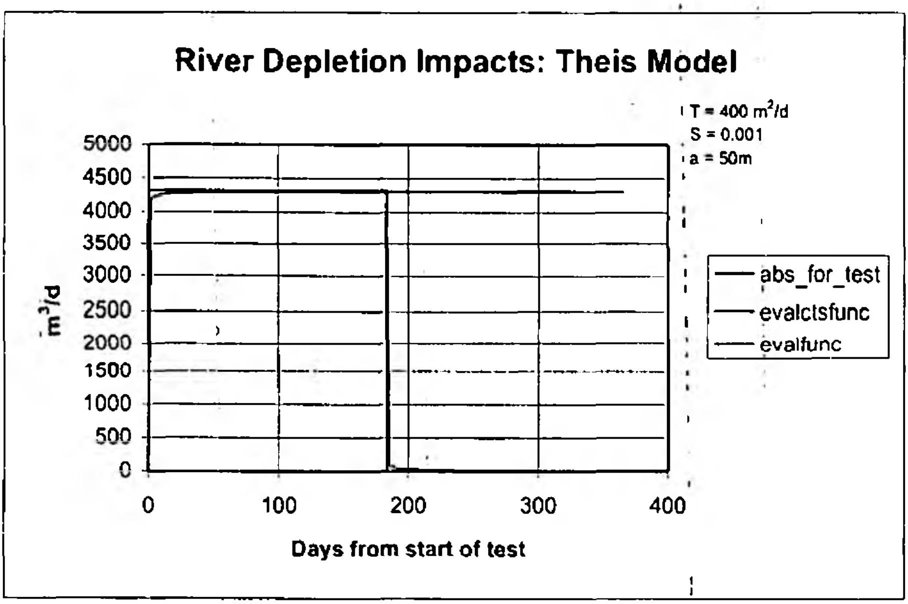
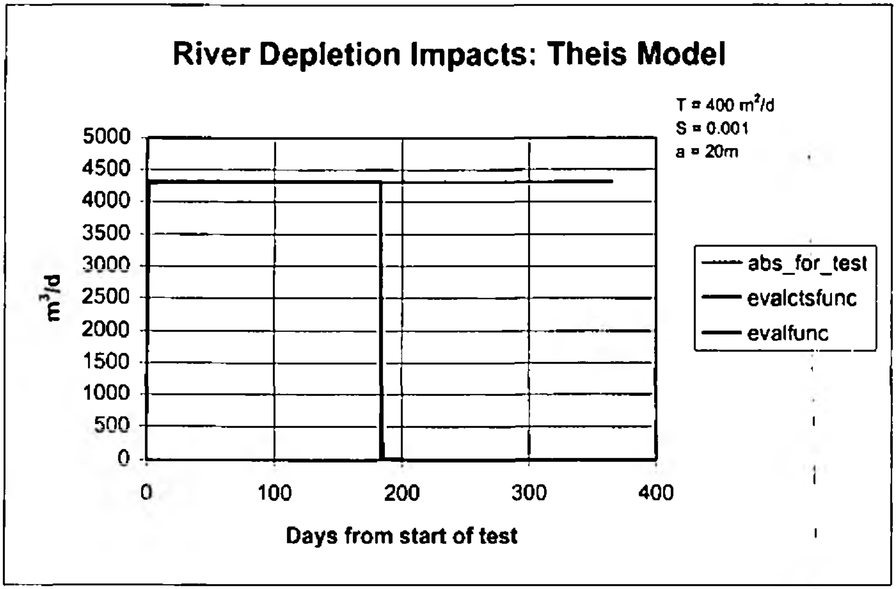

River Depletion Impacts: Theis Model
T = 400 m³/d
S = 0.005
a = 25m
m³/d
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc

Figure A17





Otterton BH4


River Depletion Impacts: Theis Model
T = 400 m²/d
S = 0.001
a = 20m
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
m³/d
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc

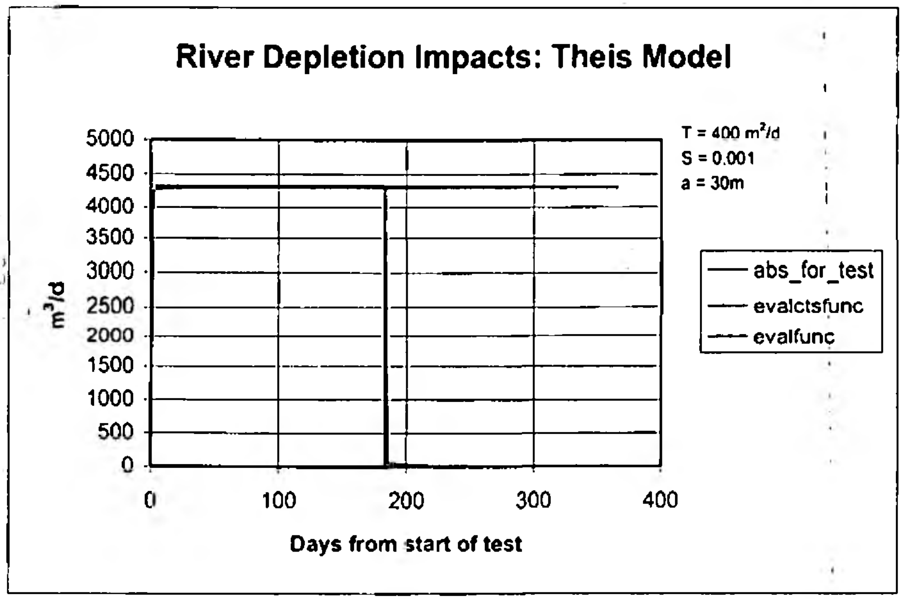
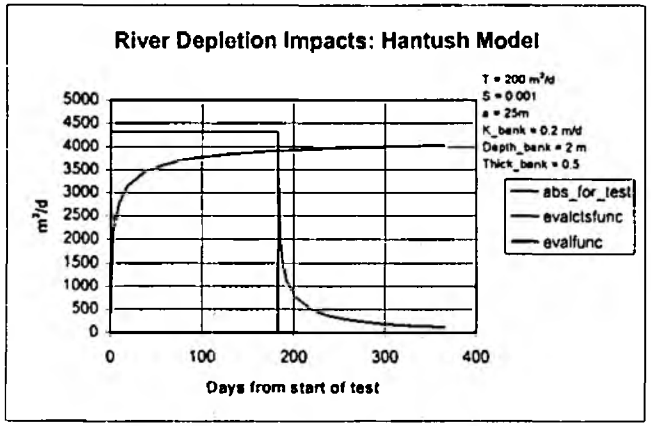
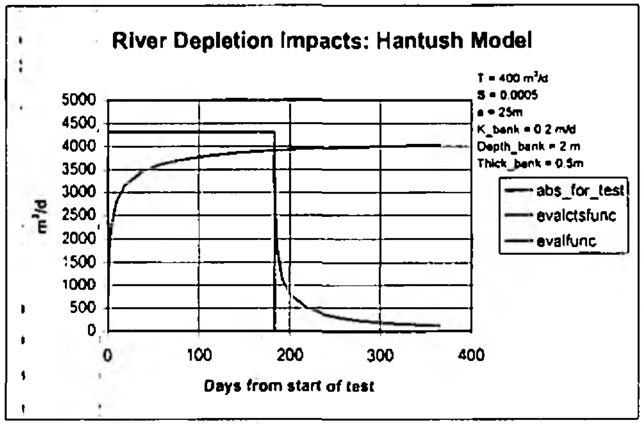
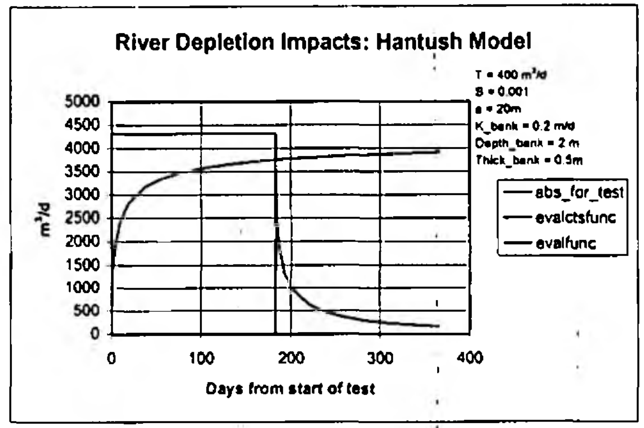
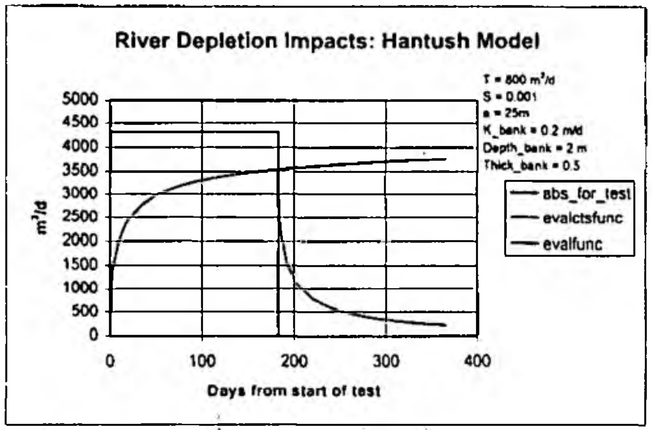

River Depletion Impacts: Theis Model
T = 400 m²/d
S = 0.001
a = 30m
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
m³/d
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc

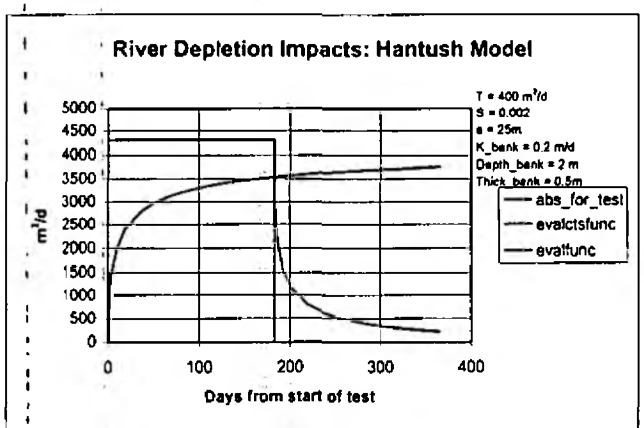
Figure A18


River Depletion Impacts: Hantush Model
T = 200 m³/d
S = 0.001
a = 25m
K_bank = 0.2 m/d
Depth_bank = 2 m
Thick_bank = 0.5
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test


River Depletion Impacts: Hantush Model
T = 400 m³/d
S = 0.0005
a = 25m
K_bank = 0.2 m/d
Depth_bank = 2 m
Thick_bank = 0.5m
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test


River Depletion Impacts: Hantush Model
T = 400 m³/d
S = 0.001
a = 20m
K_bank = 0.2 m/d
Depth_bank = 2 m
Thick_bank = 0.5m
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test


River Depletion Impacts: Hantush Model
T = 800 m³/d
S = 0.001
a = 25m
K_bank = 0.2 m/d
Depth_bank = 2 m
Thick_bank = 0.5
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test


River Depletion Impacts: Hantush Model
T = 400 m³/d
S = 0.002
a = 25m
K_bank = 0.2 m/d
Depth_bank = 2 m
Thick_bank = 0.5m
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test

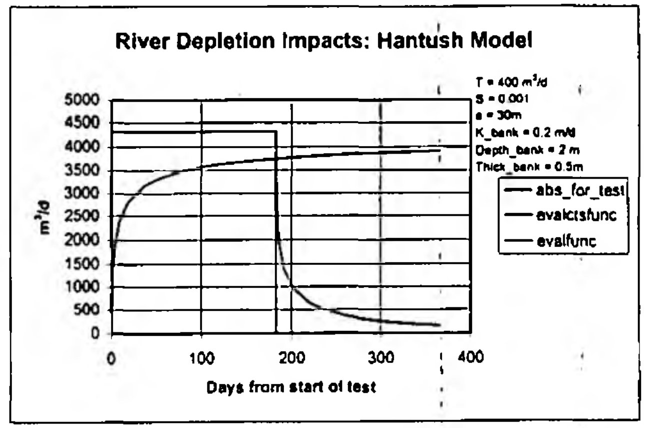
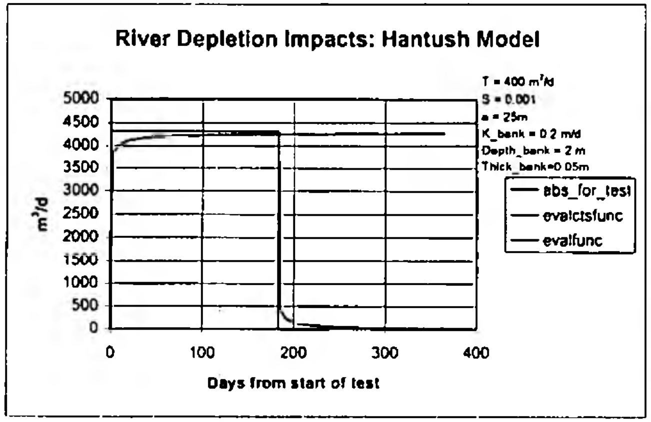
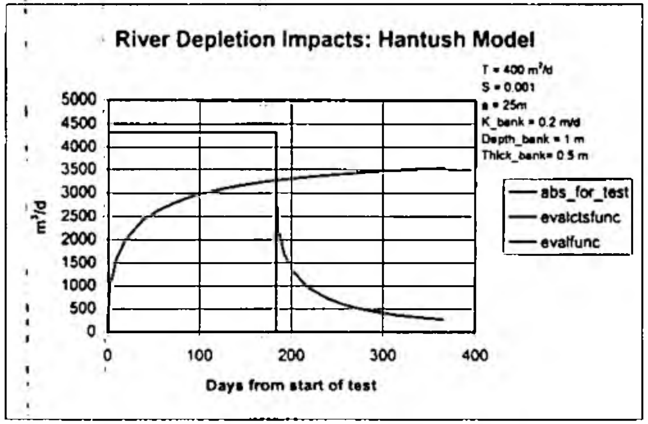
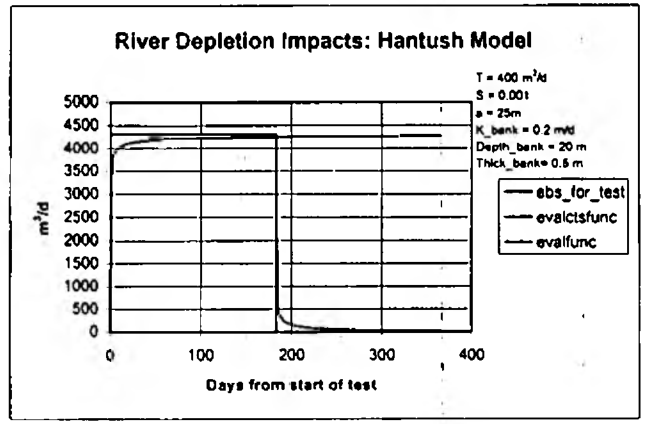
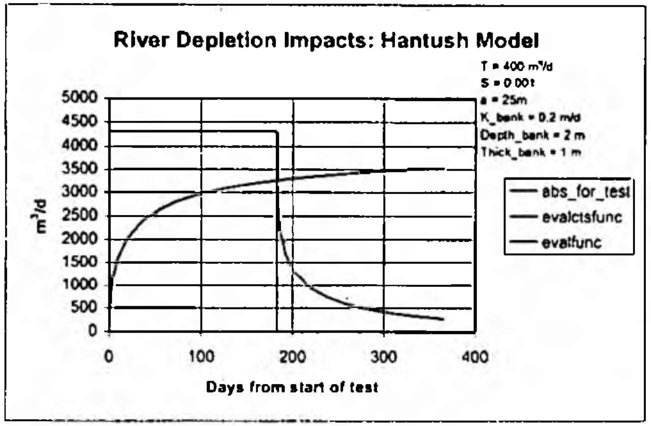

River Depletion Impacts: Hantush Model
T = 400 m³/d
S = 0.001
a = 30m
K_bank = 0.2 m/d
Depth_bank = 2 m
Thick_bank = 0.5m
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test

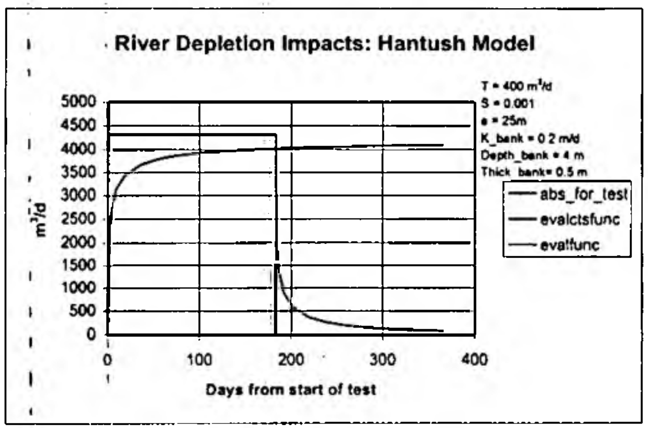
Figure A19


River Depletion Impacts: Hantush Model
T = 400 m²/d
S = 0.001
a = 25m
K_bank = 0.2 m/d
Depth_bank = 2 m
Thick_bank=0.05m
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test


River Depletion Impacts: Hantush Model
T = 400 m²/d
S = 0.001
a = 25m
K_bank = 0.2 m/d
Depth_bank = 1 m
Thick_bank= 0.5 m
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test


River Depletion Impacts: Hantush Model
T = 400 m²/d
S = 0.001
a = 25m
K_bank = 0.2 m/d
Depth_bank = 20 m
Thick_bank= 0.5 m
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test


River Depletion Impacts: Hantush Model
T = 400 m²/d
S = 0.001
a = 25m
K_bank = 0.2 m/d
Depth_bank = 2 m
Thick_bank = 1 m
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test


River Depletion Impacts: Hantush Model
T = 400 m²/d
S = 0.001
a = 25m
K_bank = 0.2 m/d
Depth_bank = 4 m
Thick_bank= 0.5 m
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test

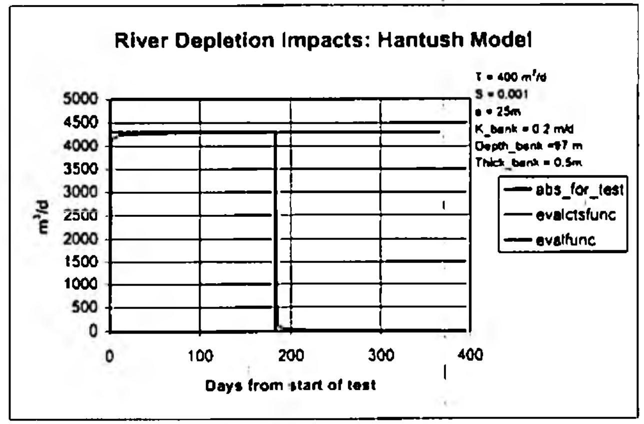
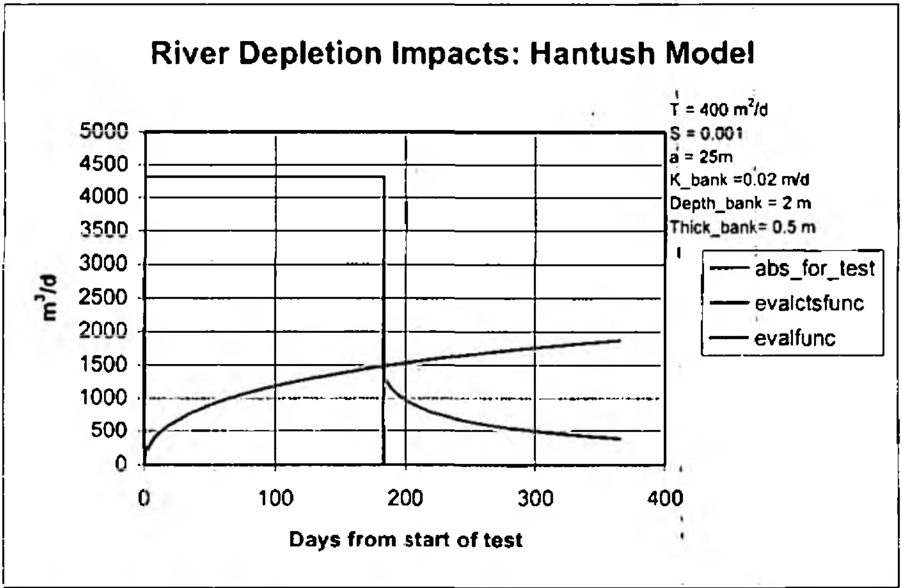
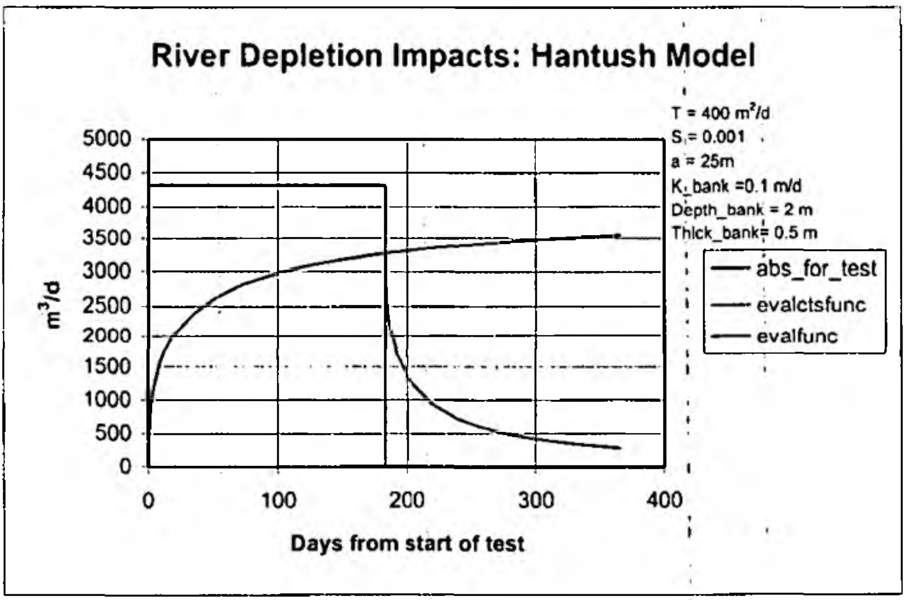
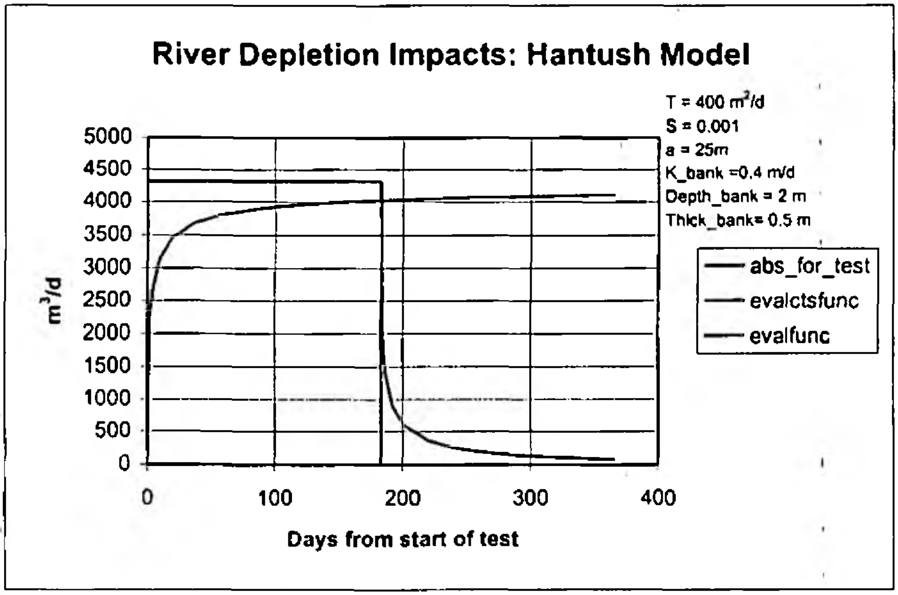

River Depletion Impacts: Hantush Model
T = 400 m²/d
S = 0.001
a = 25m
K_bank = 0.2 m/d
Depth_bank =97 m
Thick_bank = 0.5m
abs_for_test
evalctsfunc
evalfunc
m³/d
Days from start of test

Figure A20





Otterton BH4


River Depletion Impacts: Hantush Model
T = 400 m^2/d
S = 0.001
a = 25m
K_bank =0.4 m/d
Depth_bank = 2 m
Thick_bank= 0.5 m
abs_for_test
evalctsfunc
evalfunc
m^3/d
Days from start of test
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
100
200
300
400

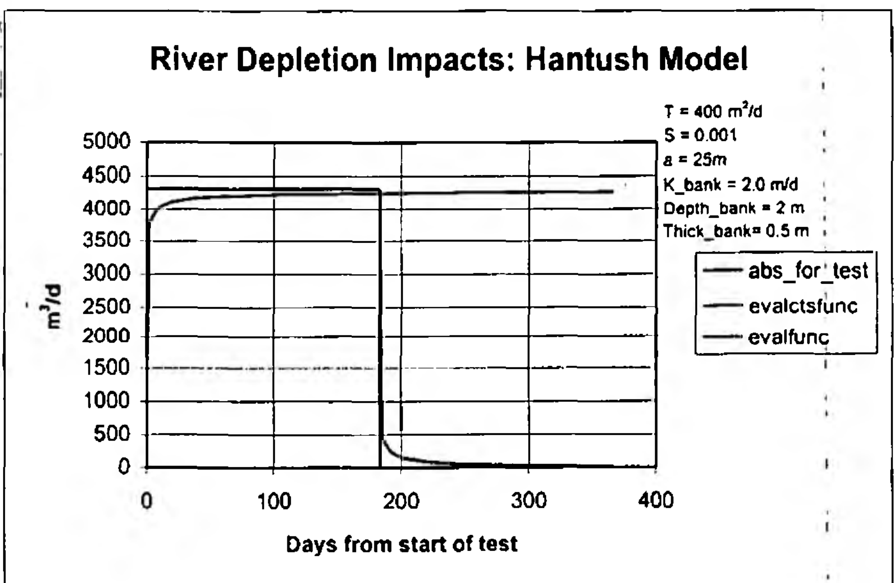
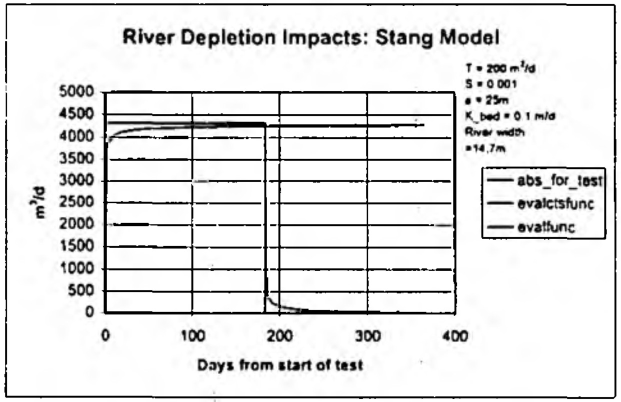
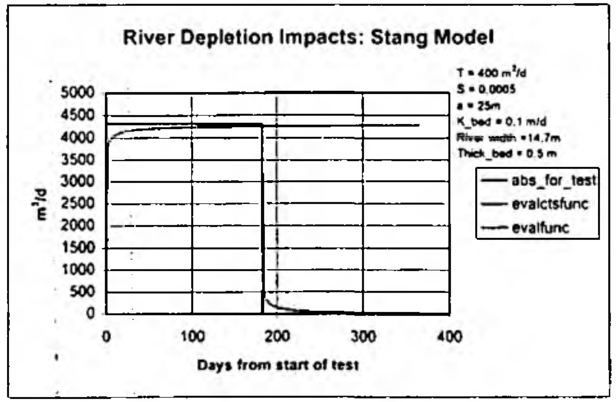
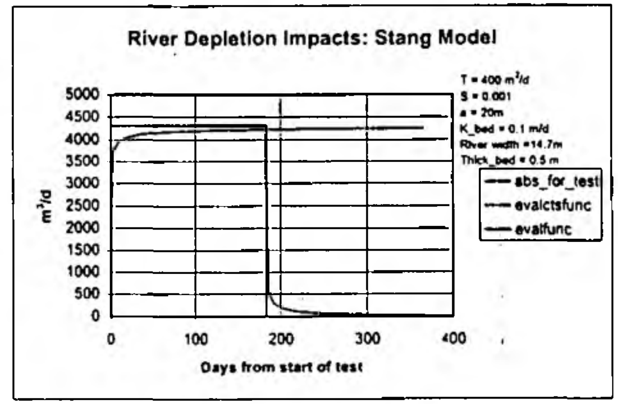
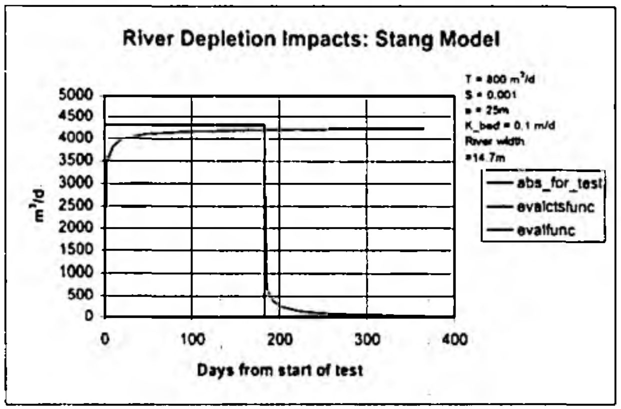

River Depletion Impacts: Hantush Model
T = 400 m^2/d
S = 0.001
a = 25m
K_bank = 2.0 m/d
Depth_bank = 2 m
Thick_bank= 0.5 m
abs_for_test
evalctsfunc
evalfunc
m^3/d
Days from start of test
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
100
200
300
400

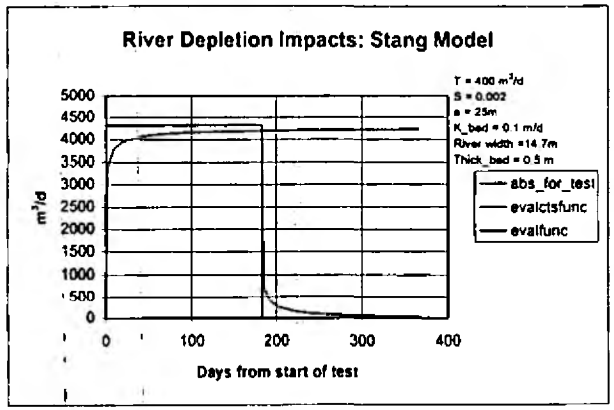
Figure A21


River Depletion Impacts: Stang Model
T = 200 m³/d
S = 0 001
a = 25m
K_bed = 0 1 m/d
River width
=14.7m
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
m³/d
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc


River Depletion Impacts: Stang Model
T = 400 m³/d
S = 0.0005
a = 25m
K_bed = 0.1 m/d
River width =14.7m
Thick_bed = 0.5 m
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
m³/d
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc


River Depletion Impacts: Stang Model
T = 400 m³/d
S = 0.001
a = 20m
K_bed = 0.1 m/d
River width =14.7m
Thick_bed = 0.5 m
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
m³/d
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc


River Depletion Impacts: Stang Model
T = 800 m³/d
S = 0.001
a = 25m
K_bed = 0.1 m/d
River width
=14.7m
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
m³/d
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc


River Depletion Impacts: Stang Model
T = 400 m³/d
S = 0.002
a = 25m
K_bed = 0.1 m/d
River width =14.7m
Thick_bed = 0.5 m
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
m³/d
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc

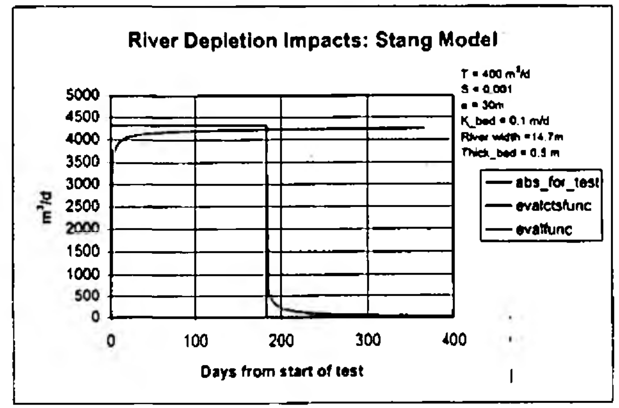
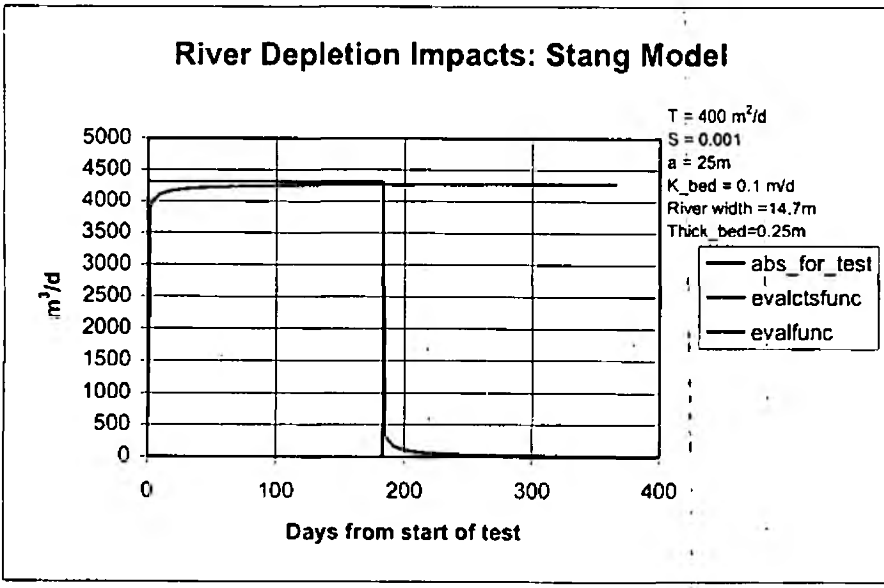
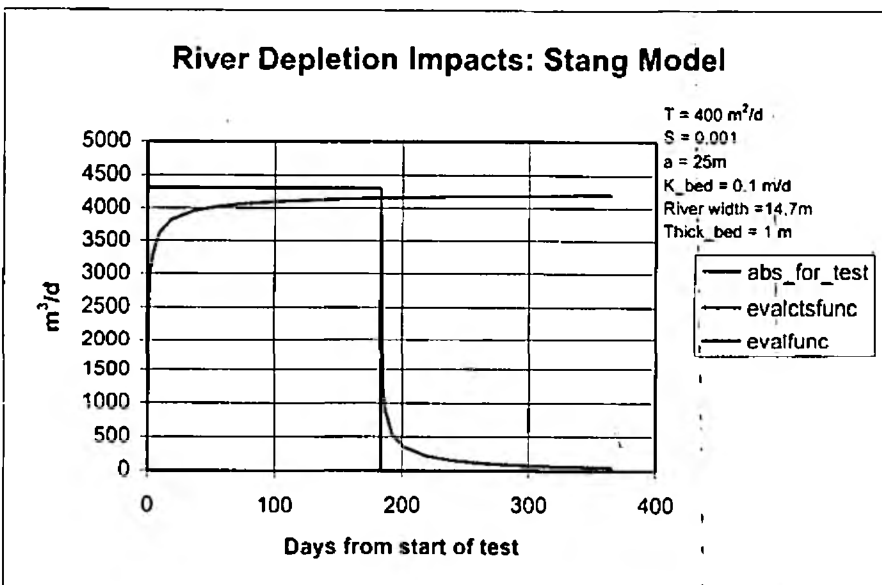
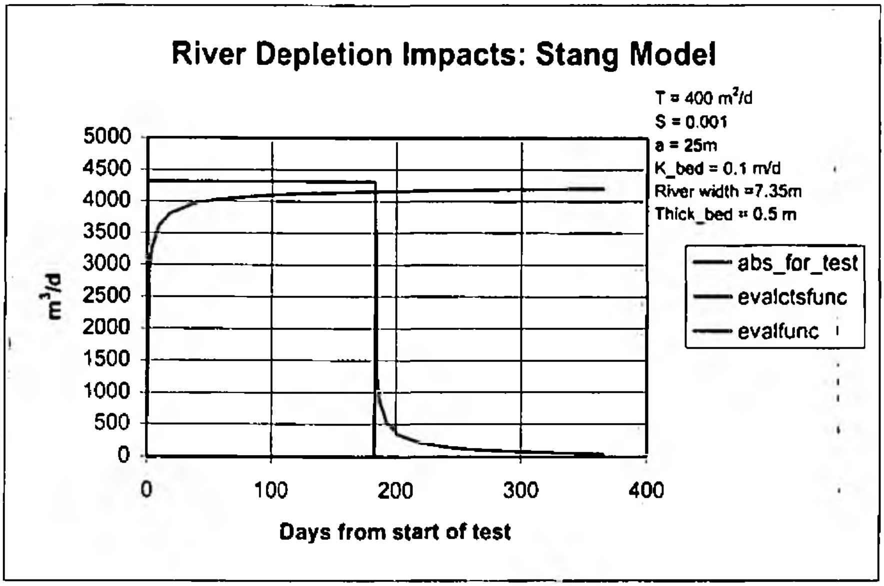

River Depletion Impacts: Stang Model
T = 400 m³/d
S = 0.001
a = 30m
K_bed = 0.1 m/d
River width =14.7m
Thick_bed = 0.5 m
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
m³/d
0
100
200
300
400
Days from start of test
abs_for_test
evalctsfunc
evalfunc

Figure A22





Otterton BH4



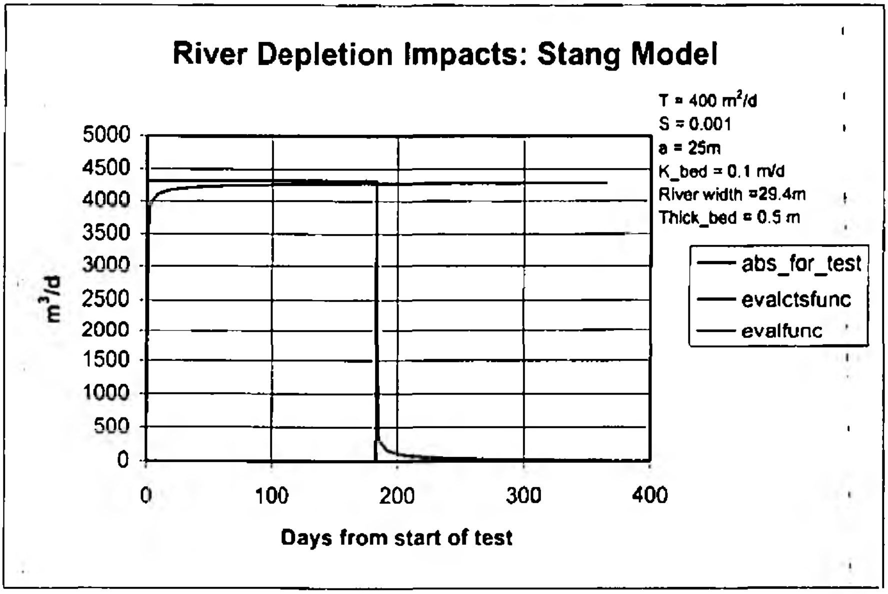
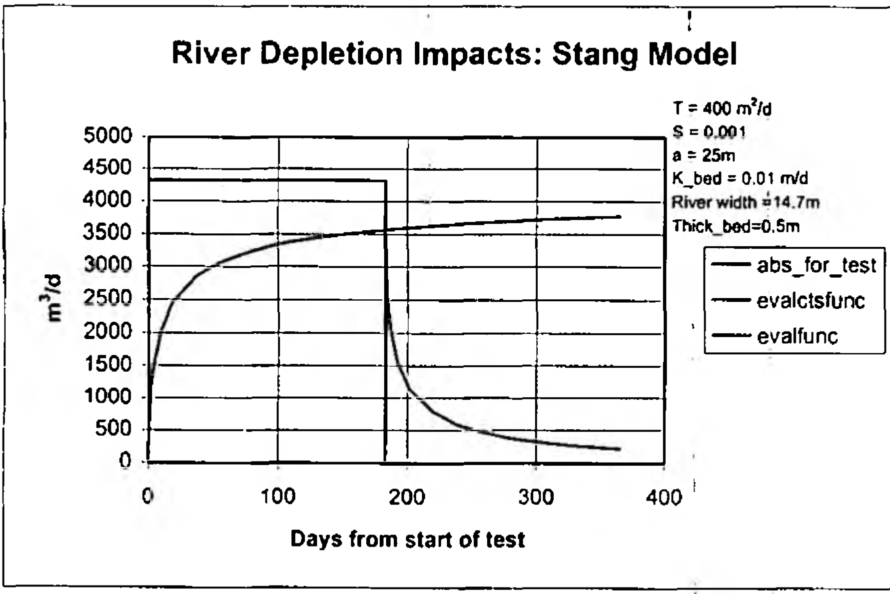
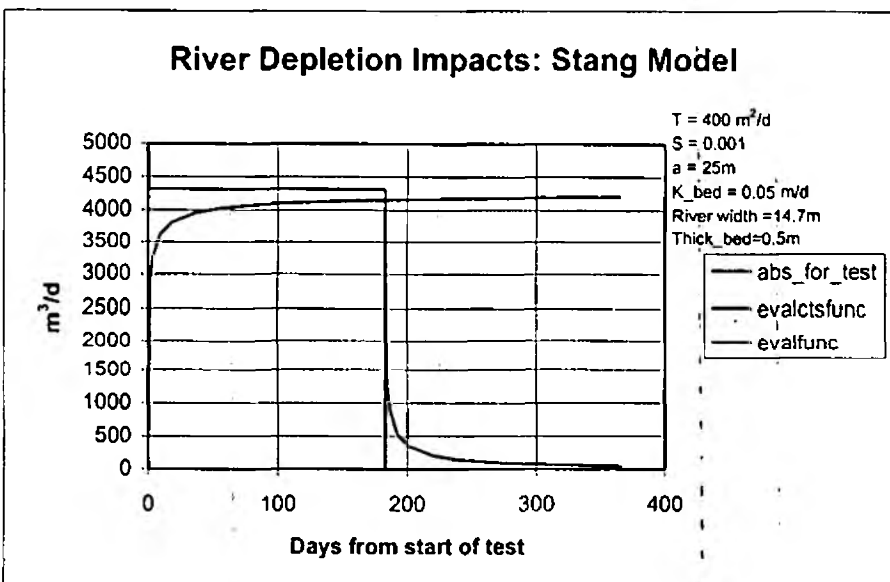


Figure A23

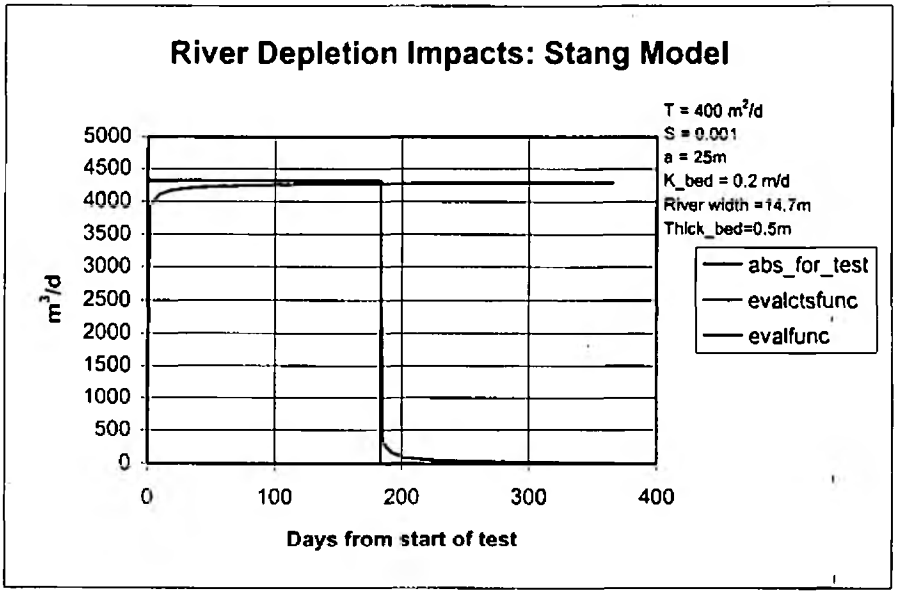
Stang solution

Variations of river width and bed thickness





Otterton BH4



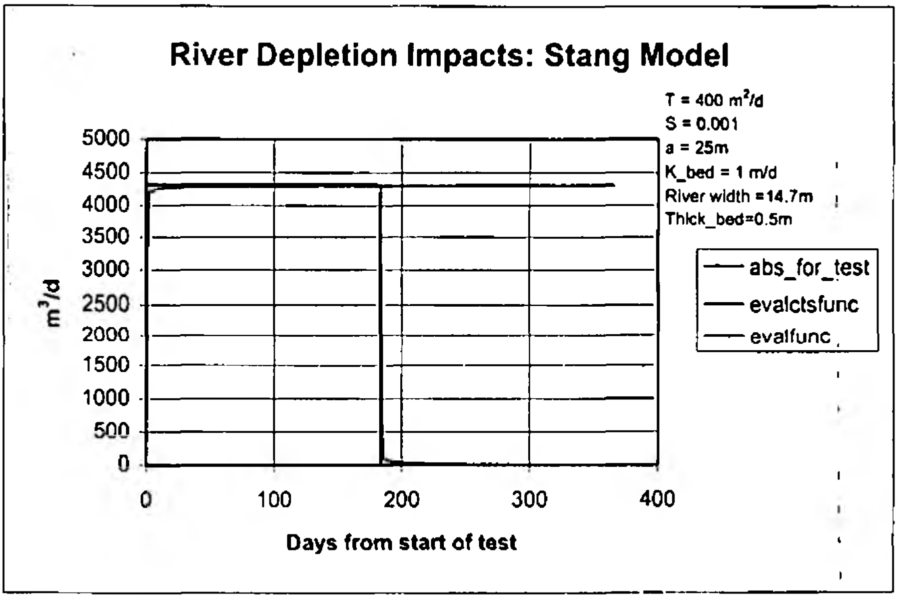


Figure A24

Stang solution

Variations of bed Hydraulic conductivity