CSIRO
AUSTRALIA

FLOWTHRU

AN INTERACTIVE PROGRAM FOR CALCULATING GROUNDWATER FLOW REGIMES NEAR SHALLOW SURFACE WATER BODIES

Version 1.0

By L.R. Townley, A.D. Barr and S.P. Nield

TECHNICAL MEMORANDUM 92/1
February 1992

Division of Water Resources

FlowThru

AN INTERACTIVE PROGRAM FOR CALCULATING GROUNDWATER FLOW REGIMES NEAR SHALLAOW SURFACE WATER BODIES

Version 1.0

By Lloyd R. Townley and Anthony D. Barr

CSIRO Division of Water Resources, Private Bag, PO Wembley, WA 6014

and

Simon P. Nield

Mackie Martin and Associates, PO Box 654, Nedlands, WA 6009

Technical Memorandum 92/1
February 1992
CSIRO
Institute of Natural Resources and Environment
Division of Water Resources

ISBN 0 643 05302 6

Publications enquiries to:

Divisional Editor
CSIRO Division of Water Resources
GPO Box 1666
Canberra ACT 2601 Australia
ph. (06) 246 5717
fax (06) 246 5800

ABSTRACT

FlowThru provides a general framework for classifying groundwater flow patterns near elongated surface water bodies. The program recognises a large number of distinct flow regimes (seventeen flow-through, eleven discharge and eleven recharge flow regimes) which can occur under different regional flow and recharge conditions. Although developed with shallow lakes in mind, the program can also be applied to wetlands, rivers, streams, canals, channels and drains. The main uses of the program are (i) for determining the depths of groundwater capture zones near shallow water bodies (analogous to the problem of wellhead protection), and (ii) is an educational tool, to allow users to visualise flow patterns near surface water bodies.

Installation and Execution

FlowThru is presently available for 80386 PCs with 80387 coprocessors and Macintosh computers. To install the program, copy all files into a directory or folder. If files have been compressed using an archiving utility, follow the instructions in the ***read.me*** file supplied. To run the program, give the command `flowthru`.

Conditions

FlowThru is distributed on the understanding that each copy will be used on only one computer.

Warranty

This software is supplied "as is" without warranty of any kind. In no event will the authors or their organisations be liable for damages resulting from any defect in the software or manual. All reasonable care has been taken to ensure that **FlowThru** operates as described in this manual. It is each user's responsibility to verify the applicability of **FlowThru** to a field site of interest, and to check the results for consistency.

Range of Pre-Calculated Solutions

Only a limited number of finite element solutions are supplied with **FlowThru**. Additional solutions for different geometries (including water bodies which are too deep to be assumed of negligible depth), different bed resistances and layered conductivities can be supplied on request.

Contact Address

For further information, please contact:

CSIRO Division of Water Resources
Private Bag
PO WEMBLEY
Western Australia 6014

Telephone: +61-9-387-0200
Fax: +61-9-387-8211

Copyright

TABLE OF CONTENTS

1. INTRODUCTION

Types of water bodies

FlowThru displays groundwater flow patterns in an aquifer near a surface water body. Although written originally with shallow lakes in mind, the program also applies to wetlands, rivers, streams, canals and channels.

FlowThru is based on a two-dimensional vertical section through water bodies which are long in the direction perpendicular to the direction of regional groundwater flow (Figure 1). Depending on the directions of flow at lateral boundaries, **FlowThru** is relevant to flow-through lakes (Figure 1a), to rivers or channels receiving water from both sides (Figure 1b), or to channels or elongated pits which provide recharge to the regional aquifer (Figure 1c).

Computational method

FlowThru is not a numerical groundwater model, but rather, combines and displays a set of precomputed solutions. These solutions were obtained using the linear triangular finite element model, AQUIFEM-N [Townley, 1992]. The solutions are provided as a set of unformatted files.

Display options

Numerous display options are possible. The user can choose to work in either non-dimensional or physical variables, to view equipotentials, streamlines and/or dividing streamlines, and to view or hide spatial distributions of piezometric head on specified flux boundaries. The spatial distribution of seepage through the bottom of the surface water body can be displayed and written to an output file. Graphical output can also be saved as files suitable for HP plotters and laser printers and PostScript laser printers.

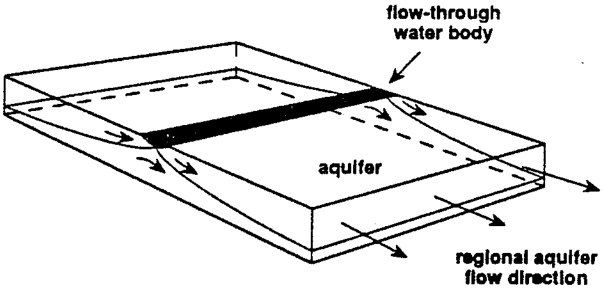


FIGURE 1a : Flow near a long flow-through water body.

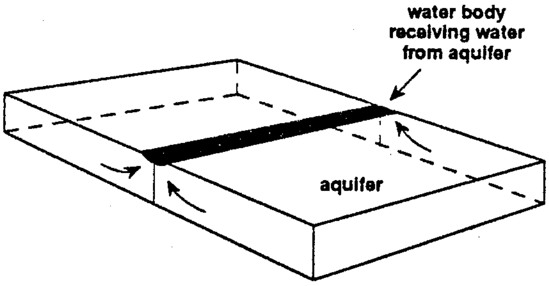


FIGURE 1b: Flow towards a long water body from both sides.

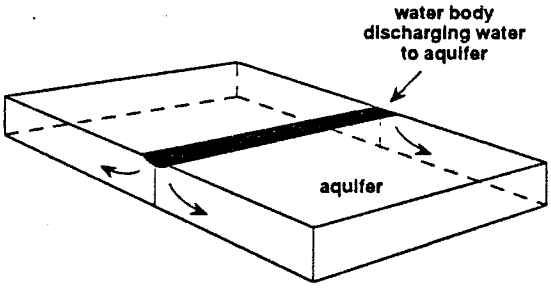


FIGURE 1c : Flow away from a long water body in both directions.

Further reading

FlowThru can be considered as a companion to papers by Nield and Townley [1992a, 1992b], which provide a general framework for classifying groundwater flow patterns near elongated surface water bodies. Work is proceeding on extending these results to three-dimensional flow near flow-through lakes (Figure 2).

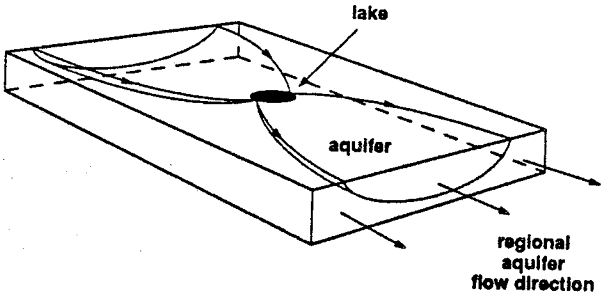


FIGURE 2 : Three dimensional flow near a circular flow-through lake.

2. ASSUMPTIONS

Long water bodies

FlowThru displays groundwater flow patterns in a two-dimensional vertical section near a shallow surface water body. This representation is only valid if the vertical section is aligned with the direction of regional groundwater flow and if the surface water body is long in the direction perpendicular to that section. The model therefore applies to rivers or canals in valleys with negligible along-valley slope, and to elongated lakes and recharge basins.

FlowThru is not intended for application to non-elongated water bodies. But preliminary results indicate that **FlowThru** applies reasonably well to a vertical section through the diameter of large circular water bodies.

Shallow water bodies

FlowThru assumes that water bodies are shallow relative to the thickness of the aquifer. The model represents the water body as a layer of constant head lying at the top surface of the aquifer. **FlowThru**'s standard solutions should not be used to simulate a lake or river channel which penetrates deeply into the aquifer, although additional solutions can be provided on request (see page 2). Flow patterns near water bodies with circular and elliptical bottom topography are presented by Townley and Davidson [1988].

Lateral boundaries

FlowThru fixes the lateral boundaries of the modelled domain at a distance of twice the aquifer thickness from the edge of the water body (in an isotropic or equivalent isotropic coordinate system). Flow at the lateral boundaries is assumed to be uniform over the thickness of the aquifer. This assumption has been found to be valid when the distance from the water body to an upgradient groundwater divide is about ten times the aquifer thickness, in equivalent isotropic coordinates [Barr and Townley, 1992].

Aquifer properties

FlowThru assumes that the aquifer is homogeneous with spatially uniform horizontal and vertical hydraulic conductivities. The resistance of low conductivity bottom sediments can also be taken into account.

Water table slope

FlowThru simulates flow in a rectangular domain with a horizontal upper surface. This is an approximation to real situations with a sloping water table as the upper boundary. But since water table slopes are generally small, the approximation is very good.

3. DEFINITION OF VARIABLES

Geometry and boundary fluxes

Figures 3 and 4 define the geometry and boundary fluxes for the rectangular domain assumed by **FlowThru**. The piezometric head in the surface water body is arbitrarily set to zero. Figure 5 shows the conceptualisation of bottom resistance in terms of an equivalent layer of depth D and conductivity K_z . Vertical resistance to flow through this layer is the same as through a region with spatially varying vertical conductivity $K_{zs}(z)$. D can be calculated as [Nield and Townley, 1992a]:

$$D = \int_{-B}^{0} \left[\frac{K_z}{K_{zs}(z)} - 1 \right] dz$$

Anisotropy

Although the pre-calculated results used by **FlowThru** have been obtained using isotropic conductivities, they can also be applied to anisotropic situations by appropriate scaling of the geometry [Nield and Townley, 1992a]. A physical anisotropic domain is converted to an equivalent isotropic domain by shrinking all horizontal coordinates by a factor of $(K_x/K_z)^{1/2}$. If the user specifies unequal K_x and K_z, **FlowThru** computes the correct scaling, identifies the closest possible solutions available, and informs the user about any approximation that has been made.

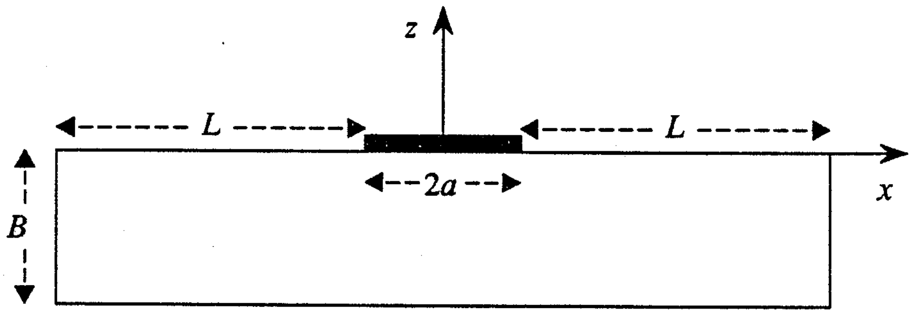


FIGURE 3 : Geometry of the modelled domain.

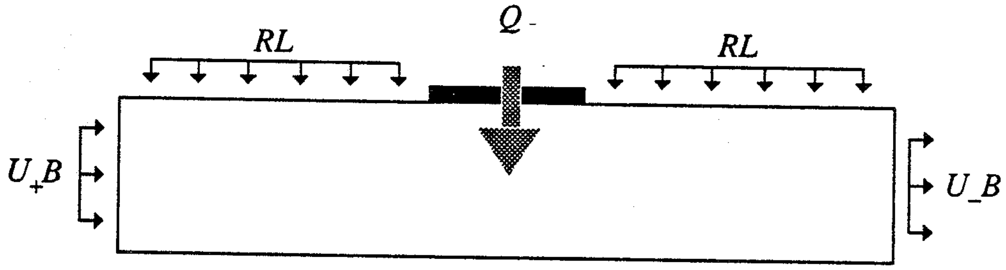
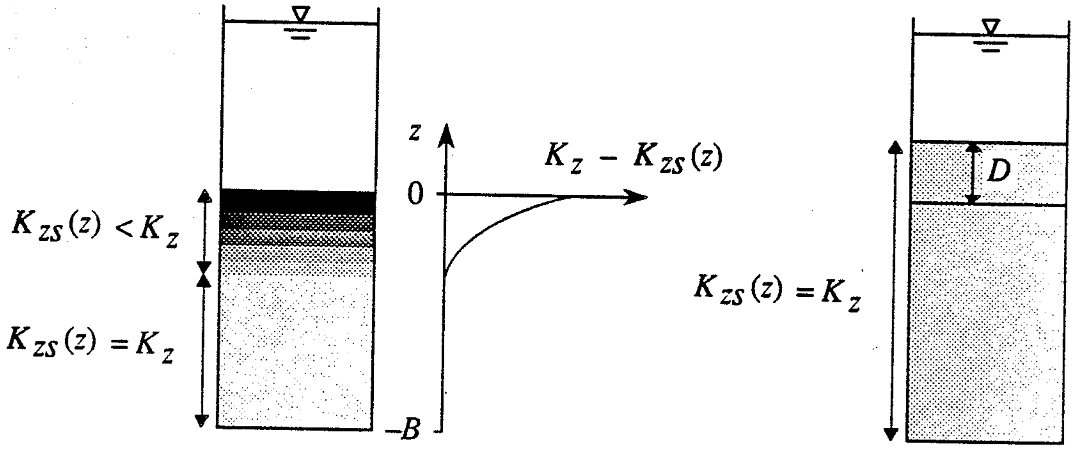


FIGURE 4 : Fluxes through the boundaries of the modelled domain.



(a) (b)

FIGURE 5 : Definition of the equivalent sediment depth *D*:
(a) True distribution of vertical conductivity
(b) Equivalent model distribution of vertical conductivity.

The following list defines the parameters used by **FlowThru**:

a	water body half-length, in the direction of regional aquifer flow [L]
B	aquifer thickness [L]
D	equivalent sediment depth (depth of aquifer material with the same resistance to vertical flow as the bottom sediment) [L]
K_x	horizontal hydraulic conductivity [LT^{-1}]
K_z	vertical hydraulic conductivity [LT^{-1}]
K	hydraulic conductivity of an equivalent isotropic aquifer, equal to $(K_xK_z)^{1/2}$ [LT^{-1}]
$K_{zS}(z)$	depth-dependent hydraulic conductivity of sediments below the water body [LT^{-1}]
L	distance from the edges of the water body to the vertical boundaries of the model domain [L]
Q	net flux per unit width from the water body into the aquifer [L^2T^{-1}]
R	downwards flux per unit area across the phreatic surface (recharge flux) [LT^{-1}]
U_+	flux per unit area into the domain through the left-hand boundary [LT^{-1}]
U_-	flux per unit area out of the domain through the right-hand boundary [LT^{-1}]
Ø	piezometric head in the aquifer [L]
Ψ	streamfunction in the aquifer [L^2T^{-1}]

Important non-dimensional ratios used by **FlowThru** include $2a/B$, D/B, L/B, K_x/K_z, U_-/U_+, RL/U_+B, $KØ/U_+B$ and Ψ/U_+B.

4. HOW TO USE FLOWTHRU

Menu structure

FlowThru is an interactive menu-driven program with two levels of menus. Menu items are selected by typing a single character which corresponds to the desired choice, followed by Enter or Return. The primary menu is shown in Figure 6.

Physical versus non-dimensional units

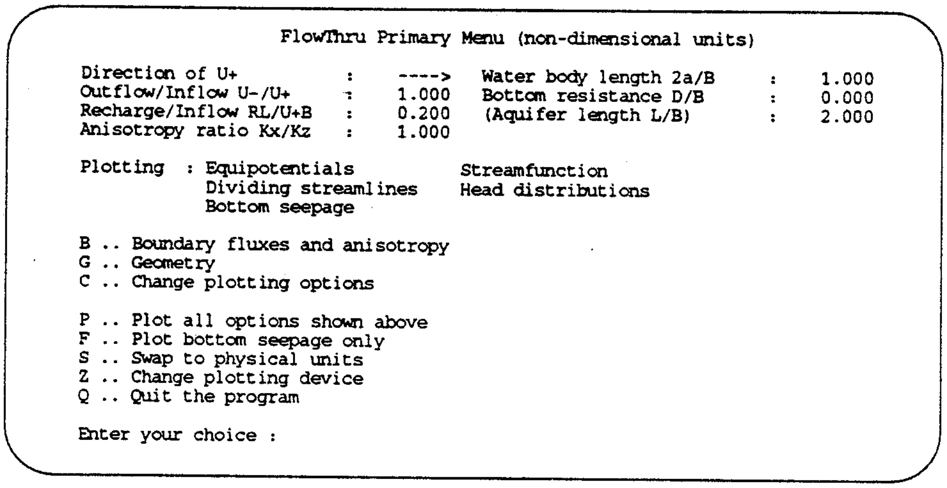
FlowThru uses either non-dimensional ratios or parameters measured in physical units. The option **S** allows swapping between these different sets of units.

Boundary fluxes

FlowThru requires three user-specified boundary flux parameters, which are modified using a sub-menu under option **B**. In physical units, the three fluxes are the inflow into the aquifer region from the left boundary (U_+), the outflow from the aquifer region to the right boundary (U_-), and the recharge to the top surface on either side of the water body (R). Using non-dimensional ratios, the first parameter indicates whether flow enters (+1.0) or leaves (–1.0) the left boundary, and the remaining parameters represent U_-/U_+ and RL/U_+B. Since subscripts are not available, `U+`, `U-` and `U+B` should be interpreted to represent U_+, U_- and U_+B in both text and graphical output. Option **B** also allows the user to change aquifer properties. In physical units, the user supplies K_x and K_z. In non-dimensional units, the user provides the anisotropy ratio K_x/K_z.

Aquifer geometry

Aquifer geometry is modified using a sub-menu under option **G**. In physical units, the user supplies values of $2a$, B and D. In non-dimensional units, geometry is defined by $2a/B$ and D/B. Since **FlowThru** assumes that $L = 2B$ in an equivalent isotropic domain, the value of L or L/B is computed and displayed.



```
                    FlowThru Primary Menu (non-dimensional units)

Direction of U+          :   ---->  Water body length 2a/B     :   1.000
Outflow/Inflow U-/U+     :   1.000  Bottom resistance D/B      :   0.000
Recharge/Inflow RL/U+B   :   0.200  (Aquifer length L/B)       :   2.000
Anisotropy ratio Kx/Kz   :   1.000

Plotting  : Equipotentials         Streamfunction
            Dividing streamlines   Head distributions
            Bottom seepage

B .. Boundary fluxes and anisotropy
G .. Geometry
C .. Change plotting options

P .. Plot all options shown above
F .. Plot bottom seepage only
S .. Swap to physical units
Z .. Change plotting device
Q .. Quit the program

Enter your choice :
```

FIGURE 6 : Primary Menu of FlowThru (using non-dimensional units)

Display options

Option **C** provides a sub-menu which allows the user to change (i.e. toggle on and off) the types of information to be displayed on the screen. Possible options are to display the dividing streamline, contours of streamfunction and equipotentials within the aquifer, the head distributions along the sides and the top of the aquifer, and the seepage distribution through the bottom of the water body. The default is to display all these options.

Plotting options

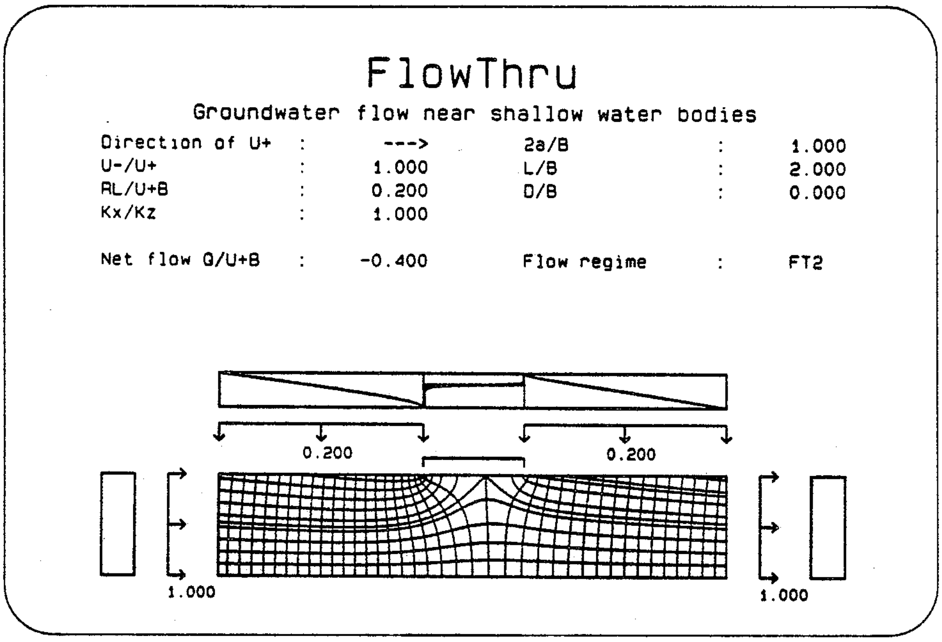
Option **P** on the primary menu plots the selected results to the current plotting device. Option **F** plots the bottom seepage distribution at a much larger scale. Option **Z** option allows the user to change the current plotting device.

Quitting

Option **Q** exits **FlowThru**.

5. EXPLANATION OF GRAPHICAL RESULTS

An example plot produced by option **P** is shown in Figure 7. This plot has all the graphical options selected.



```
                          FlowThru
        Groundwater flow near shallow water bodies
Direction of U+  :     --->         2a/B          :      1.000
U-/U+            :     1.000        L/B           :      2.000
RL/U+B           :     0.200        D/B           :      0.000
Kx/Kz            :     1.000

Net flow Q/U+B   :    -0.400        Flow regime   :      FT2
```

FIGURE 7 : Example of the graphical display with option P.

Text

The top half of the plotting surface displays the user-defined parameters. **FlowThru** also identifies and displays the amount of water flowing into the aquifer from the water body (*Q* in physical units, or Q/U_+B as a non-dimensional ratio) and the type of flow regime in the aquifer [see Nield and Townley, 1992a]. The classification of flow regimes is discussed in Section 6.

The bottom half of the graphical display has the following features:

Flow net

The large rectangle represents the aquifer domain and contains the dividing streamline, and contours of streamfunction and equipotentials. If physical units are used, Ψ and $\varnothing$ are displayed in their usual units.

When non-dimensional ratios are used, streamfunction is plotted as $\Psi/U_{+}B$ and equipotentials are plotted as $K\varnothing/U_{+}B$ where $K = (K_x K_z)^{1/2}$. Contour intervals are chosen so that there are ten streamtubes between the minimum and maximum values of streamfunction. Streamfunction is arbitrarily set to zero along the bottom of the domain. The contour interval for equipotentials is chosen such that $\Delta\varnothing = \Delta\Psi/K$ in physical units or $\Delta(K\varnothing/U_{+}B) = \Delta(\Psi/U_{+}B)$ in non-dimensional units. The three sides of a rectangle located immediately above the aquifer show the location of the water body. Arrows show the direction of flows through the sides and top of the aquifer.

Piezometric heads on boundaries

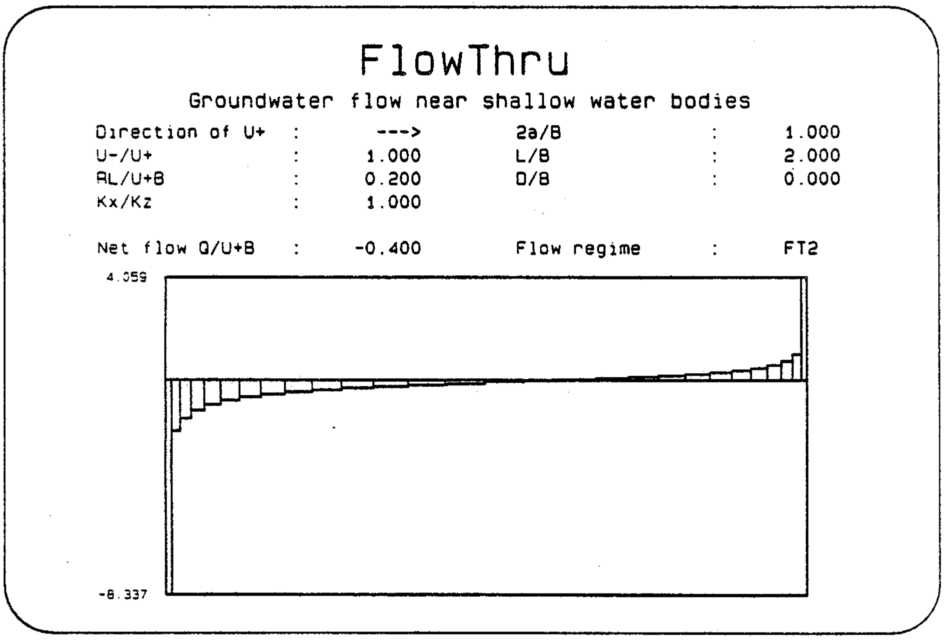
Rectangular boxes at the sides of the aquifer show the calculated distributions of piezometric head along these prescribed flux boundaries. Boxes along the top of the aquifer also show head distributions, which can be interpreted as water table elevations. Head values are scaled so that maximum and minimum values of head and a zero reference axis all fit within the box. Ideally, the end head boxes should appear as empty rectangles, i.e. there should be no apparent deviation from a hydrostatic distribution of heads. In the top head boxes, the head at the edges of the water body is zero when D is zero (i.e. the water table elevation is equal to the water level in the water body) and near zero when D is non-zero.

Seepage distribution

The rectangular box over the water body shows the seepage flux distribution through the bed of the water body. Fluxes are scaled so that maximum and minimum values of seepage, as well as a horizontal axis identifying zero flux, all fit within the height of the box. Fluxes out of and into the aquifer are plotted below and above the axis, respectively.

Enlarged seepage distribution

Figure 8 shows an example plot produced with option F. The spatial distribution of seepage flux is now enlarged. The distribution is piecewise constant between nodes in the finite element grid, in order to be perfectly consistent with the methods of computation.



```
                         FlowThru
        Groundwater flow near shallow water bodies
Direction of U+  :     --->       2a/B          :      1.000
U-/U+            :     1.000      L/B           :      2.000
AL/U+B           :     0.200      D/B           :      0.000
Kx/Kz            :     1.000

Net flow Q/U+B   :    -0.400      Flow regime   :      FT2
```

FIGURE 8 : Example of the graphical display with option F.

6. CLASSIFICATION OF FLOW REGIMES

Recharge, discharge and flow-through regimes

Nield and Townley [1992a] identify eleven types of recharge and discharge regimes (in which the surface water body recharges water or receives water from the aquifer over the whole of its bottom) and seventeen types of flow-through regimes (in which the water body recharges water to and receives water from the aquifer in different parts of its bottom). These regimes are shown schematically in Figure 9.

Figure 9 shows idealised patterns with four types of dividing streamlines. The first three types separate regions which interact with the lake from those which do not. The majority of these pass through a stagnation point on the bottom of the water body (e.g., regime FT1), or through a point on the top surface away from the water body (regimes R1 and D1); some pass through one end of the water body when seepage between the water body and the aquifer is in the same direction as R (e.g., regimes R2 and D2); and others pass through an internal stagnation point (e.g., regimes R3 and D3). The fourth kind of dividing streamline passes through a stagnation point on the bottom of the aquifer (e.g., regimes R5 and D5).

Stagnation points

FlowThru identifies flow regimes on the basis of the occurrence of maxima and minima of $\emptyset$ and Ψ on the boundary of the domain. Flow regimes can then be described in terms of the number and location of stagnation points and dividing streamlines.

Stagnation points can occur in the following locations:

- on the bottom of the water body, in which case there must be a reversal in the direction of vertical flow (exhibited by a local maximum or minimum in Ψ) and the regime must be a flow-through regime;

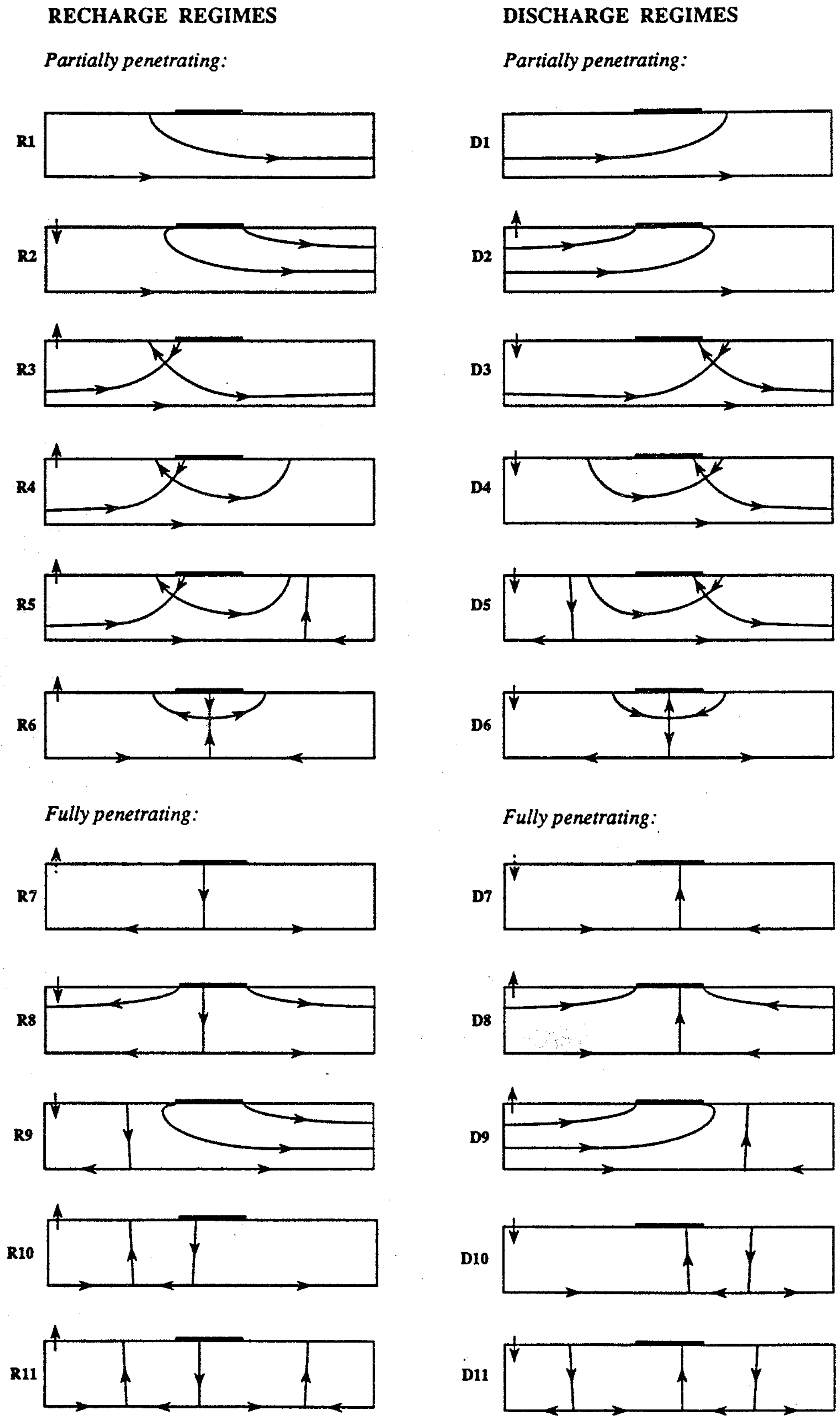
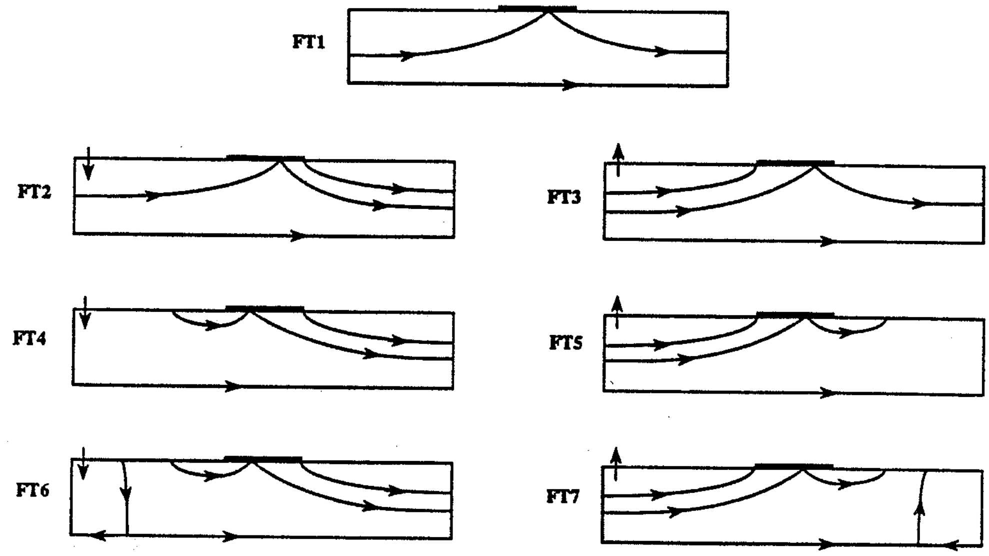


FIGURE 9a : Recharge and discharge regimes

FLOW-THROUGH REGIMES

With no reverse flow regions:



With reverse flow regions:

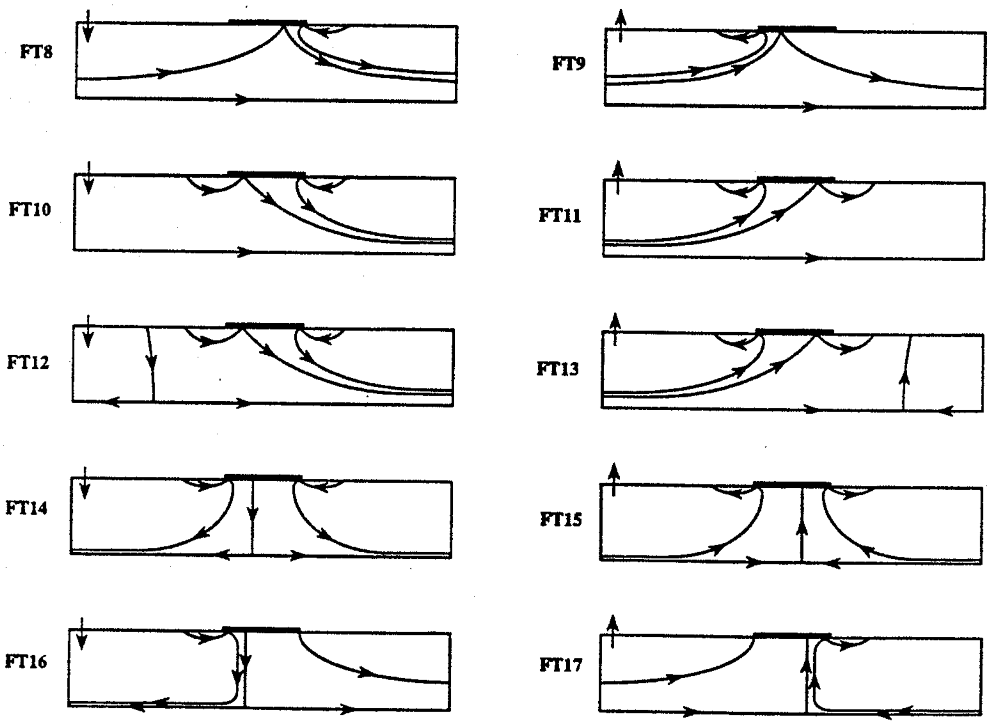


FIGURE 9b : Flow-through regimes

- on the top surface of the aquifer (exhibited by a local maximum or minimum in Ø), but this can only occur when $R = 0$;
- on the bottom of the aquifer (exhibited by a local maximum or minimum in Ø); or
- in the interior of the domain (exhibited by a very flat region in both Ø and Ψ), but this can only occur when $R < 0$ and $Q > 0$, or when $R > 0$ and $Q < 0$.

When D/B is non-zero, flow reversals on the bottom of the water body do not indicate stagnation points because there is still a component of horizontal flow. Such points are therefore described by **FlowThru** as dividing points.

Symmetry

According to the definitions of Nield and Townley [1992a], a flow regime has the same name when viewed from either side of a cross-section. But an asterisk is appended to the name if the regime is not shown explicity in Figure 9. Thus regime R5 is characterised by $R < 0$, an internal stagnation point and a stagnation point on the bottom of the domain. If the internal stagnation point is on the right of the water body, the regime is known as R5*.

FlowThru uses such symmetries to simplify the process of identifying flow regimes. Any situation with $U_+ < 0$ is internally converted to a situation with all flows reversed in direction. Regime D5, for example, is thus identified as R5*, but because U_+ is actually negative, the name R5* is later mapped to D5, the correct result.

Rules and criteria

The identification of flow regimes is quite complex. Table 1 presents simple rules or criteria which are used in **FlowThru** to identify flow regimes.

TABLE 1: Rules for identifying flow regimes

		Regime
No stagnation points:		
$Q > 0, R > 0, U_- > 0$		R2
$Q < 0, R < 0, U_- > 0$		D2
One stagnation point on the water body:		
$R = 0, U_- > 0$		FT1
$R > 0, U_- > 0$	and both ends of Ψ contour through stagnation point intersect ends of domain	FT2
$R < 0, U_- > 0$	and both ends of Ψ contour through stagnation point intersect ends of domain	FT3
$R > 0, U_- > 0$	and one end of Ψ contour through stagnation point intersects top of aquifer	FT4
$R < 0, U_- > 0$	and one end of Ψ contour through stagnation point intersects top of aquifer	FT5
One stagnation point on the top surface:		
$Q > 0, R = 0$	and stagnation point is to left of water body	R1
$Q < 0, R = 0$	and stagnation point is to right of water body	D1
One stagnation point on the bottom of the aquifer:		
$Q < 0, R \geq 0, U_- \leq 0$	and Ψ contour through stagnation point intersects the water body	D7
$Q < 0, R < 0, U_- < 0$	and Ψ contour through stagnation point intersects the water body	D8
$Q < 0, R < 0, U_- < 0$	and Ψ contour through stagnation point intersects the top surface of the aquifer	D9
When $U_+ < 0$, these rules lead to the identification of regimes R7, R8 and R9, respectively		
One internal stagnation point:		
$Q > 0, R < 0, U_- > 0$	and Ψ contours through stagnation point intersect the top of the aquifer only once	R3
$Q > 0, R < 0, U_- \geq 0$	and Ψ contours through stagnation point intersect the top of the aquifer twice	R4
$Q < 0, R > 0, U_- > 0$	and Ψ contours through stagnation point intersect the top of the aquifer only once	D3
$Q < 0, R > 0, U_- > 0$	and Ψ contours through stagnation point intersect the top of the aquifer only once	D3

Two stagnation points on the water body:

		Regime
$R > 0, U_- > 0$	and Ψ contours through one stagnation point intersect both ends of the domain	FT8
$R < 0, U_- > 0$	and Ψ contours through one stagnation point intersect both ends of the domain	FT9
$R > 0, U_- > 0$	and Ψ contours through both stagnation points intersect the top of the aquifer	FT10
$R < 0, U_- > 0$	and Ψ contours through both stagnation points intersect the top of the aquifer	FT11

One stagnation point on the water body and one on the bottom of the aquifer:

$R < 0, U_- < 0$	Ψ contour through stagnation point on the bottom of the aquifer intersects the top of the aquifer	FT7
$R < 0, U_- < 0$	Ψ contour through stagnation point on the bottom of the aquifer intersects the water body	FT17

When $U_+ < 0$, these rules lead to the identification of regimes FT6 and FT16, respectively

One internal stagnation point and one on the bottom of the aquifer:

$Q > 0, R < 0, U_- < 0$	and Ψ contour through stagnation point on the bottom of the aquifer intersects the top of the aquifer	R5
$Q > 0, R < 0, U_- < 0$	and Ψ contour through stagnation point on the bottom of the aquifer intersects the water body	R6

When $U_+ < 0$, these rules lead to the identification of regimes D5 and D6, respectively

Two stagnation points on the bottom of the aquifer:

$Q > 0, R < 0, U_- \geq 0$		R10
$Q < 0, R > 0, U_- > 0$		D10

Two stagnation points on the water body and one on the bottom of the aquifer:

$R < 0, U_- < 0$	and Ψ contour through stagnation point on the bottom of the aquifer intersects the top of the aquifer	FT13
$R < 0, U_- < 0$	and Ψ contour through stagnation point on the bottom of the aquifer intersects the water body	FT15

When $U_+ < 0$, these rules lead to the identification of regime FT12 and FT14, respectively

Three stagnation points on the bottom of the aquifer:

$Q > 0, R < 0, U_- < 0$		R11

When $U_+ < 0$, this rule leads to the identification of regime D11

7. EXPLANATION OF OUTPUT FILES

FlowThru produces a number of output files. All output files overwrite files of the same name created in previous runs of **FlowThru**.

flowthru.prt

This file contains a sequence of header records (defining the current choice of parameters), followed by a formal description of the corresponding flow regime. New information is added to the file every time a plot is displayed. Careful study of the results, which are presented differently depending on the use of physical or non-dimensional units, can allow the user to determine features such as the thickness of a capture zone. Figure 10 shows an extract from ***flowthru.prt*** for the case illustrated in Figure 7.

flowthru.flx

This file contains seepage values through the bottom of the water body. Header information is provided to allow easy identification of each set of fluxes. Results are presented in two columns, containing the x-coordinate on the bottom of the water body and the seepage flux per unit length (positive downwards, $[LT^{-1}]$). The columns are separated by a tab (ASCII 9) to facilitate further processing with a spreadsheet package or other software. If the user is working with non-dimensional ratios, seepage is scaled relative to U_+B, and x is given as x/a, i.e. ranging from –1.0 to 1.0. If physical units are being used, seepage is in the same units as U_+, U_- and R, and x ranges from $-a$ to a. Figure 11 shows an extract from ***flowthru.flx*** for the case illustrated in Figures 7 and 8.

plotnn.hpg

If an HP plotter is selected as the output device, this file contains graphics commands in Hewlett Packard Graphics Language (HPGL), which can be sent to an HPGL-compatible plotter or printer. The field ***nn*** starts at 01 and is incremented by 1 for each subsequent plot. The files ***flowthru.prt*** and ***flowthru.flx*** identify the names of ***.hpg*** files, as they are created.

plotnn.ps

If a PostScript printer is selected as the output device, this file contains PostScript graphics commands which can be sent to a PostScript printer. The field ***nn*** starts at 01 and is incremented by 1 for each subsequent plot. The files ***flowthru.prt*** and ***flowthru.flx*** identify the names of ***.ps*** files as they are created.

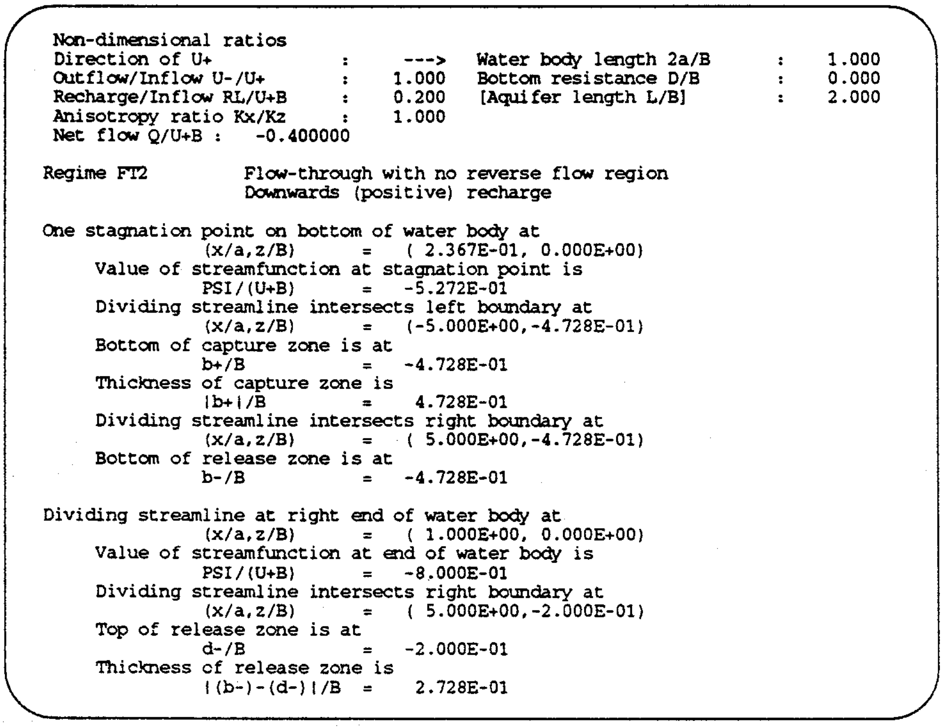
Sending .hpg and .ps files to output devices

The method of sending plot files to a hardcopy output device depends on the type of computer being used.

On PCs, ***.hpg*** files can be sent to an HPGL-compatible plotter using the batch file ***sendhp.bat***, which is supplied with **FlowThru**.

To send ***.hpg*** or ***.ps*** files from PCs to a properly configured printer, simply use the DOS `print` command.

On Macintosh computers, ***.ps*** files can be printed using the utility program **SendPS**, which is supplied with **FlowThru**.



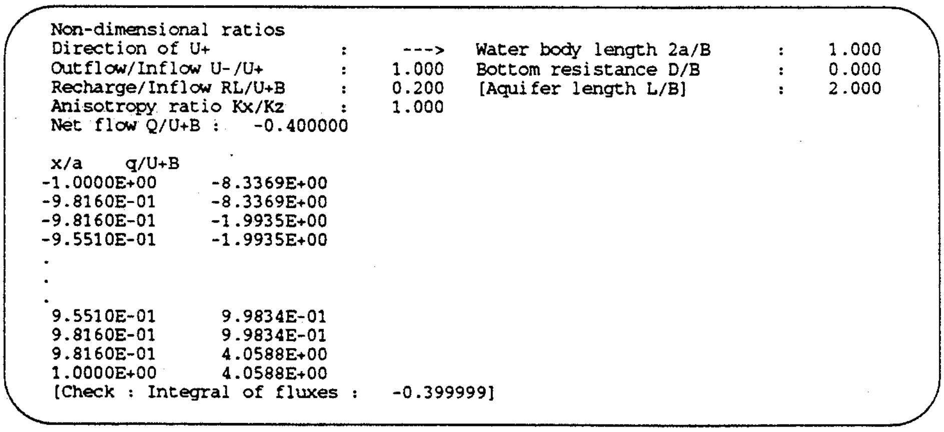
```
 Non-dimensional ratios
 Direction of U+            :     --->  Water body length 2a/B     :    1.000
 Outflow/Inflow U-/U+       :    1.000  Bottom resistance D/B      :    0.000
 Recharge/Inflow RL/U+B     :    0.200  [Aquifer length L/B]       :    2.000
 Anisotropy ratio Kx/Kz     :    1.000
 Net flow Q/U+B :    -0.400000

Regime FT2          Flow-through with no reverse flow region
                    Downwards (positive) recharge

One stagnation point on bottom of water body at
               (x/a,z/B)       =    ( 2.367E-01, 0.000E+00)
     Value of streamfunction at stagnation point is
               PSI/(U+B)       =    -5.272E-01
     Dividing streamline intersects left boundary at
               (x/a,z/B)       =    (-5.000E+00,-4.728E-01)
     Bottom of capture zone is at
               b+/B            =    -4.728E-01
     Thickness of capture zone is
               |b+|/B          =     4.728E-01
     Dividing streamline intersects right boundary at
               (x/a,z/B)       =    ( 5.000E+00,-4.728E-01)
     Bottom of release zone is at
               b-/B            =    -4.728E-01

Dividing streamline at right end of water body at
               (x/a,z/B)       =    ( 1.000E+00, 0.000E+00)
     Value of streamfunction at end of water body is
               PSI/(U+B)       =    -8.000E-01
     Dividing streamline intersects right boundary at
               (x/a,z/B)       =    ( 5.000E+00,-2.000E-01)
     Top of release zone is at
               d-/B            =    -2.000E-01
     Thickness of release zone is
               |(b-)-(d-)|/B  =     2.728E-01
```

FIGURE 10 : Extract from *flowthru.prt* for the case illustrated in Figure 7.



```
 Non-dimensional ratios
 Direction of U+            :     --->  Water body length 2a/B     :    1.000
 Outflow/Inflow U-/U+       :    1.000  Bottom resistance D/B      :    0.000
 Recharge/Inflow RL/U+B     :    0.200  [Aquifer length L/B]       :    2.000
 Anisotropy ratio Kx/Kz     :    1.000
 Net flow Q/U+B :    -0.400000

 x/a      q/U+B
-1.0000E+00     -8.3369E+00
-9.8160E-01     -8.3369E+00
-9.8160E-01     -1.9935E+00
-9.5510E-01     -1.9935E+00
 .
 .
 .
 9.5510E-01      9.9834E-01
 9.8160E-01      9.9834E-01
 9.8160E-01      4.0588E+00
 1.0000E+00      4.0588E+00
 [Check : Integral of fluxes :    -0.399999]
```

FIGURE 11 : Extract from *flowthru.flx* for the case illustrated in Figures 7 and 8.

8. EXPLANATION OF DATA FILES

FlowThru needs a number of data files, but few of these files need to be modified by the user. The following information is supplied only to satisfy the user's curiosity.

xxx_yyyy.z

FlowThru is supplied with sets of pre-calculated finite element solutions for different values of $2a/B$ and D/B. These files have names of the form ***xxx_yyyy.z***, where ***xxx*** is 10 times the value of $2a/B$ (filled with preceding zeroes if necessary), ***yyyy*** is 100 times the value of D/B (filled with preceding zeroes if necessary) and ***z*** is a single character (*a*, *b* or *c*) corresponding to pre-calculated inflow, outflow and recharge solutions, respectively. These files are unformatted files produced by AQUIFEM-N [Townley, 1992].

xxx.grd

This file contains the finite element grid for each value of $2a/B$. The format of the grid file is that used by AQUIFEM-N [Townley, 1992].

xxx.crn

This file contains information related to the corners of the grid for different values of $2a/B$.

ftdata.dat

This file contains a list of all available values of $2a/B$ and D/B. If the user attempts to use values of $2a/B$ and D/B that are not available, **FlowThru** chooses the closest values of $2a/B$ and D/B available.

plot.def

This file provides default parameters for the available plotting devices. Its format is documented by Townley [1992], but should not need to be modified.

9. REFERENCES

Nield, S.P., Effects of recharge and lake linings on lake-aquifer interaction. Master of Engineering Science Thesis, Department of Civil Engineering, University of Western Australia, 1990.

Nield, S.P. and Townley, L.R., A framework for quantitative analysis of surface water - groundwater interaction, 1: Flow geometry in a vertical section. Accepted for *Water Resources Research*, 1992a.

Nield, S.P. and Townley, L.R., A framework for quantitative analysis of surface water - groundwater interaction, 2: Spatial distributions of bottom seepage in a vertical section. Accepted for *Water Resources Research*, 1992b.

Townley, L.R. and Davidson, M.R.(1989). Definition of a capture zone for shallow water table lakes, *Journal of Hydrology*, 104, 53-76, 1988.

Townley, L.R., AQUIFEM-N: A Multi-Layered Finite Element Aquifer Flow Model: User's Manual and Description, CSIRO Division of Water Resources, Perth, Western Australia, 1992.

Barr, A.D. and Townley, L.R., The effects of downgradient boundary conditions on predictions of groundwater flow in a vertical section near shallow surface water bodies. CSIRO Division of Water Resources, Perth, Western Australia, 1992.