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Groundwater Protectio
Small Sources

Volume II - Worked Exa

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Statement of Use
This three-part document reviews the methods which have been employed in the UK and elsewhere to define capture zones around groundwater sources, evaluates their applicability to the need to safeguard small sources as part of the NRA's groundwater protection policy and makes selective recommendations on which should be adopted as standard techniques for protection zone delineation. Its primary purposes are to provide a technical guide to the subject, and as a policy development initiative by the NRA Groundwater Centre.

NRA Contractor
These documents were produced under an operational support contract by:
Southern Science Ltd
Vanguard House
Churchill Court
Manor Royal
Crawley
West Sussex RH10 2PN Tel: 01293 538444 Fax: 01293 530830

Additional input was provided by:
NRA Groundwater Centre
Sapphire East
550 Streetsbrook Road
Solihull B91 1QT Tel: 0121 711 5885 Fax: 0121 711 5910

NRA Project Leader
The NRA's Project Leader and support staff-member for this operational contract were:
Brian Morris } NRA Groundwater Centre
Paul Armstrong }

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CONTENTS

Volume II : Worked Examples

Symbols and Notation

A_d	Area of t_d (days) travel zone (m^2)
A_R	Source recharge area (m^2)
b	Aquifer thickness (m)
h	groundwater elevation (m)
k	Aquifer permeability (m/d)
n	Aquifer porosity
q	Abstraction rate (m^3/d)
r	Radial distance from well
r_d	Radial distance travelled in t_d days (m)
r_o	Radius of influence of a well
r_R	Radius of recharge area A_R (m)
r_w	Radius of well or borehole (m)
R_c	Rainfall recharge (m/a)
T	Aquifer transmissivity (m^2/d)
t	Time (days)
t_d	Travel time (days)
t^*	Non-dimensional time
v	velocity (m/d)
V_d	Aquifer volume dewatered in t_d days (m^3)
w	Non-dimensional coordinate
x	Coordinate parallel to hydraulic gradient
x_d	Distance travelled in t_d days (m)
x_L	Distance of null point from well (m)
y	Coordinate orthogonal to hydraulic gradient
y_{max}	Maximum half-width of steady-state capture zone
z	Non-dimensional coordinate
Δ	Hydraulic Gradient
π	3.142

1 INTRODUCTION

1.1 This document, comprising a collection of Worked Examples, is Volume II of the report on small source protection zone delineation. Volume I of the series contains a review of available methodologies and existing practice, while Volume III contains a selection of predefined WHPA capture zone approximations.

1.2 The mathematical techniques which are available for capture zone delineation are described in some detail in Volume I, together with recommendations for use in determining such zones around small sources. For the purposes of this study, small sources are assumed to be those abstracting less than 250 m^3/d, although the techniques are equally valid at higher rates.

1.3 Numerical models, eg FLOWPATH and MODFLOW+MODPATH, are used extensively for capture zone delineation, but such methods tend not to be applicable for delineating the zones around small sources because of the spatial resolution required, and perhaps more importantly, because of the frequent lack of data defining the characteristics of the aquifer blocks in which such sources are often located. In such circumstances, perhaps more appropriate are the analytical (and semi-analytical) methods detailed in Volume I, which enable approximate capture zones to be defined based on limited data sets.

1.4 For completeness, Tables 4.2, 4.3 & 4.4 from Volume 1 are reproduced in this report as Tables 1, 2 & 3. Table 1 gives the recommended techniques for delineating capture zones around small sources, while Table 2 provides guidance on problems which may be encountered when carrying out such procedures. Table 3 describes the applicability of the various techniques to differing aquifer flow conditions.

1.5 Detailed case studies on actual sources are presented in Volume I. But in this Volume, the series of worked examples are based on idealized scenarios to illustrate the use of the recommended methodologies.

1.6 Ultimately, the recommended methods only provide approximations to the "correct" solution, and properly documented local knowledge may be just as useful. In any event, the techniques should not be used in isolation, for the purpose of such modelling is to "provide insight and not numbers". It is no substitute for informed professional judgement, but rather should be used to provide a framework upon which to test ideas about the flow characteristics in the vicinity of specific sources.

Table 1 Recommended techniques for adoption to delineate small source protection zones

No	Description	Report Section	Report Page	Ease or Speed of application	Comments
1	HYDROGEOLOGICAL MAPPING	-	-	2	Groups wells into hydrogeological domains/aquifer types enabling classification of behaviour; must apply in all case at paper map level and be used in conjunction with other methods to ensure results make geological sense
2	ARBITRARY FIXED RADIUS CIRCLES (AFRCs)	3.5-3.6	18	1	A default 50 m radius zone ($AFRC_{50}$) is possibly the only option for either very small sources or those for which further effort is not justified. Other AFRCs not defensible.
3	CALCULATED CIRCULAR ZONES BASED ON RECHARGE & ABSTRACTION (+EFFECTIVE POROSITY & THICKNESS FOR TOTZs)	3.16-3.20	23-27	2	Easy to apply; is clearer when applied to groups of similar q & R_t. Arithmetically valid approach. Where no aquifer parameters available could be used with 50 m default AFRC. Problematic if actual daily rates >> annual q/365. Only suitable for TOTZs if no hydraulic gradient available. Underlying concept easy to grasp by non-specialists
4	CATCHMENT ZONES BASED ON CAPTURE ZONE HYDRAULICS	3.21-3.24	25-28	2	Useful starting point where some aquifer parameters, including hydraulic gradient, are known. No TOTZs or upgradient catchment curtailment available.
5	STANDARD SIMPLE SHAPES BASED ON IDEALISED REPRESENTATION OF LOCAL CONDITIONS	3.25-3.33	29-35	1	Previous UK variants may be difficult/inappropriate to apply to small abstraction rates because of extreme variation in shape factor. WHPA-MWCAP code produces EPA hybrid version and has been used by NRA-GC to compile compendium of standard shapes based on parameter values typical of aquifers in England & Wales. These succeed & replace previous SWA,TWA, NRA Southwestern & NRA Thames approaches.
6	SEMI-ANALYTICAL MODELLING WITH WHPA	3.40-3.46	39-45	2	MWCAP module can be used as interactive code where data are adequate to provide non-idealised parameter values. Otherwise use pre-drawn capture zones (see technique 5 above)
7	NUMERICAL MODELLING WITH FLOWPATH, MODFLOW	3.47	45-50	3	Generally only justified where numerous small sources occur across a small area or in vicinity of large sources already being modelled.

Note : The reference to "Report Section and Page" in the table above refers to Volume I

Table 2 Guidance on practical problems which may be encountered when zoning small sources

No	Description of limitation encountered in application of recommended techniques	Ease or rapidity of application.	Comments/policy advice to aid compliance with recommended techniques
1	SOURCE SO SMALL, NO CALCULATED ZONES CAN ECONOMICALLY BE APPLIED	-	Public health aspects of small sources too important to neglect protection as many used for potable supply. $AFRC_{50}$ can always be applied as minimum measure eg for sources < 20 m^3/d.
2	NO PRACTICAL INNER ZONE CAN BE DRAWN .	1	Inner (50 day) Zone for low abstraction rates eg less than 20 m^3/d may be impracticably small in some groundwater settings., In such cases apply $AFRC_{50}$ as minimum 50 day zone
3	NO PRACTICAL OUTER ZONE CAN BE DRAWN EITHER	1	Where Outer (400 day) Zone is also impracticably small and less than 50 m radius in any direction apply $AFRC_{50}$ as minimum 400 day zone following precautionary principle.
4	400 DAY ZONE IS < 25% OF TCZ	2	Where area of Outer Zone ($A_{400}=q*t_d/bn$) at 400 days is less than 25% of TCZ area ($A_s=365q/R_e$), choose value of t_d required to produce 25% area by substituting back into equation ($t_d=bn*0.25/R_e$)
5	PREVIOUS ATTEMPT AT ZONING SOURCE EXISTS	1/2	Check method & verify (i) that it is one of the recommended techniques described in Table 1, (ii) that it is appropriate to the hydrogeological setting, water use, size of abstraction/flow and methods being applied to other sources in same aquifer unit. If not, apply one of recommended techniques in Table 3

Table 3 Applicability of zone delineation techniques to aquifer flow conditions

Aquifer flow conditions	Ample data available	Poor data availability
Intergranular flow dominant	e.g q, k, b, n, Re ($q > 20\ m^3/d$) WHPA MWCAP techniques 5 or 6 supplemented by local knowledge & mapping Technique 4 if data array incomplete	e.g. q, Re ($q > 20\ m^3/d$) Techniques 1,2 & 3
Fissure flow dominant but aquifer approximates to darcian conditions	No satisfactory methods yet available but use of methods for intergranular flow supplemented by local knowledge may provide an approximation	
Non-darcian conditions or Poorly documented aquifers	q & location plus field data, tracer studies or mapping available : Technique 1 Professional judgement supplemented by local knowledge or fixed 50 m radius zone for zone 1 Combined zone II & TCZ across all or part or the outcrop	Only q and location available Fixed 50 m radius for zone 1 Combined zone II & TCZ across all or part of outcrop*

2 WORKED EXAMPLES

Example 1	Circular source catchment zone
Example 2	Circular time of travel zones
Example 3	Source in a uniform flow field
Example 4	Approximate or Hybrid time of travel zones
Example 5	Bear & Jacobs model : isochrons
Example 6	WHPA model
Example 7	ABARM model
Example 8	FLOWPATH model

Example 1 Circular source capture zones

Parameter	
q (m^3/d)	100
k (m/d)	*
b (m)	*
n	*
Δ	*
Recharge (mm/a)	250

Assume that flow within the aquifer is intergranular, with only Q, (annual abstraction), and R_e (annual recharge or effective rainfall) known.

Then the only capture zone that can be specified is the source catchment zone of area A_R defined as

$$A_R = \frac{Q}{R_e}$$

If the catchment is assumed to be circular, (and in the absence of either estimates of the hydraulic gradient or of geological information to the contrary no other assumption is likely to be valid), the radius r_R is given by:

$$r_R = \sqrt{\frac{Q}{\pi R_e}}$$

Using the data from the table above, and noting the units :

$$r_R = \sqrt{\frac{365.100.1000}{250\pi}} = 216\ m$$

Thus the estimated radius of the circular source catchment zone is 216 m.

The radius r_d of a circular *Outer protection zone* of area equal to 25% of the source catchment area A_R may be deduced from the relationship $r_d = r_R/2$, from which $r_d = 108$ m.

Example 2 Circular time of travel zones

Parameter	
q (m^3/d)	100
k (m/d)	*
b (m)	50
n	*
Δ	*
Recharge (mm/a)	250

If the aquifer thickness b (m) is known together with the abstraction rate q (m^3/d), then circular *time of travel* zones based on t_d (d) days pumping, may be derived.

In t_d days, the volume pumped is

$$V_d = qt_d$$

which may be equated to the volume of a cylinder of aquifer of radius r_d surrounding the source from which the water is obtained :

$$V_d = \pi r_d^2 b$$

from which r_d may be determined as

$$r_d = \sqrt{(\frac{qt_d}{\pi b})}$$

Using the data in the table, when $t_d = 50$ days : $r_d = \surd(100.50/50\pi) = 5.6$ m which is significantly less than the recommended minimum radius of 50 m.

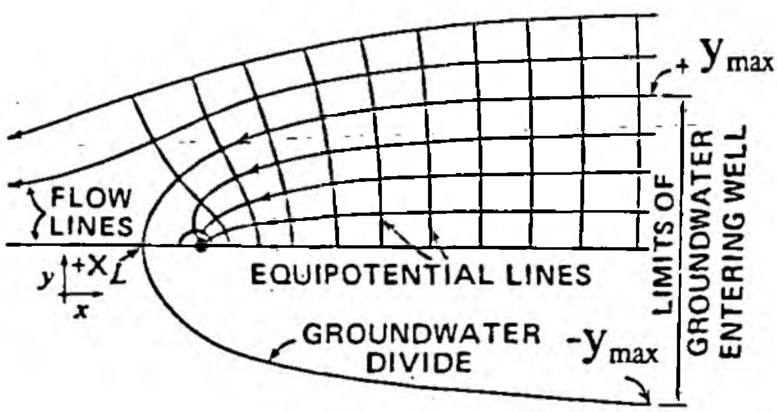
A similar calculation for $t_d = 400$ days, yields $r_d = \surd(100.400/50\pi)$, from which $r_d = 16$ m. This is also less than the minimum recommended 50 m radius *Inner protection zone* , and a circular *Outer protection zone* based on 25% of the recharge area is recommended (see Example 1).

Example 3 Source in a uniform flow field

Parameter	
q (m^3/d)	100
k (m/d)	10
b (m)	50
n	0.1
Δ	0.001
Recharge (mm/a)	250

Under a uniform hydraulic gradient Δ, the capture zone around a source abstracting q (m^3/d) extends a distance x_L down gradient from the source and has a maximum up- gradient width $2y_{max}$ where[1] :

$$x_L = \frac{q}{2\pi \Delta kb}, \quad y_{max} = \pm \frac{q}{2\Delta kb}$$



By substitution using the data in the table above, x_L = 32 m, and $y_{max} = \pi x_L$ = 100 m. The up- gradient width is therefore $2y_{max}$ = 200 m.

The calculated value of x_L is less than 50 m which is the minimum recommended radius for a circular *Inner protection zone.*

[1]Todd D K, Groundwater Hydrology, Wiley

The equation describing the capture zone boundary (labelled as the "Groundwater Divide" on the figure on page 10) is :

$$\frac{y}{x} = \tan(\frac{y}{x_L})$$

which has no limit in the up- gradient direction.

An approximate up- gradient capture zone with an area equal to the recharge area A_d ($=q/R_e$) can, however, be constructed geometrically (assuming that R_e is known - see Example 1) by representing the zone as a trapezium of average width y_{av} and length x_{max} where

$$y_{av} = y_0 + y_{max}$$

with y_0 equal to the half- width of the capture zone at x = 0, i.e y_0 is the half- width of the zone along the line orthogonal to the direction of regional flow passing through the source.

The up- gradient distance x_{max} is calculated as:

$$x_{max} = \frac{A_d}{y_0 + y_{max}}$$

Using the data above, y_0 = 50 m, y_{max} = 100 m and from Example 1, A_d = 146000 m^2 from which x_{max} = 146000/(50 + 100) = 973 m.

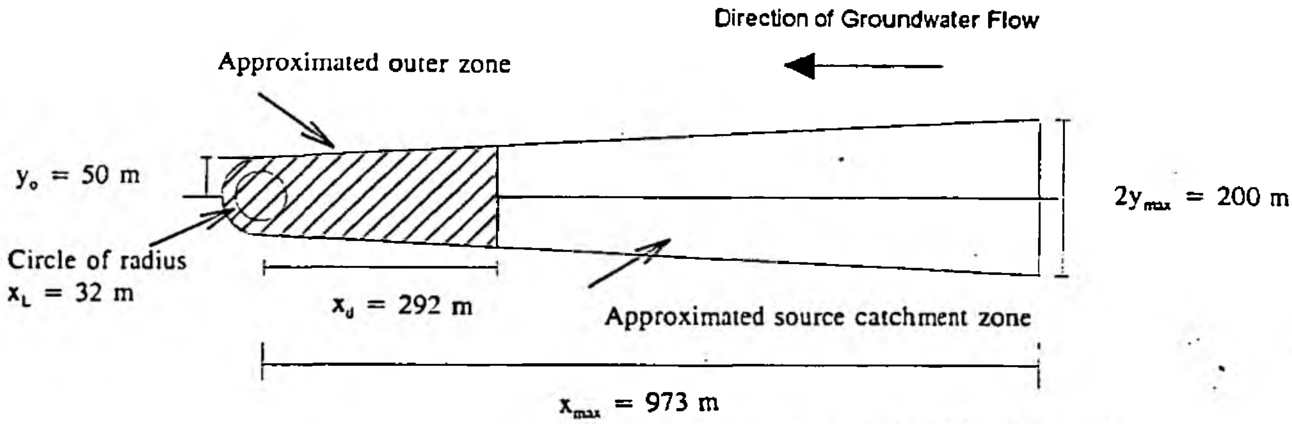
This approximation ignores the area of capture zone down- gradient of the source, but in this example it is small relative to A_d.

Similarly, an approximation to the *outer* zone may also be derived assuming it is represented as a trapezium with an area equal to 25% of A_d. In order to define a maximum up- gradient distance, the maximum width of this trapezium is assumed to be y_{av}, (see above) from which the up- gradient extent of the zone x_d can be approximated by :

$$x_d = \frac{A_d}{2(2y_0 + y_{av})}$$

By substitution, x_d = 146000/(2(100+150)) = 292 m.

The capture zones constructed using the approximations described above are illustrated on page 12.


Direction of Groundwater Flow
Approximated outer zone
y_o = 50 m
Circle of radius
x_L = 32 m
x_d = 292 m
Approximated source catchment zone
$2y_{max}$ = 200 m
x_{max} = 973 m

Example 4 Approximate or Hybrid time of travel zones

Parameter	
q (m^3/d)	100
k (m/d)	10
b (m)	50
n	0.1
Δ	0.001
Recharge (mm/a)	*

An equation relating the travel time t from any point directly up- gradient from a pumping source to the distance x from the source was derived by Jacob & Bear[2].

Defining the following non- dimensional quantities z & t^* by the relationships:

$$z = \frac{2\pi kb\Delta x}{q}, \qquad t^* = \frac{2b\pi(k\Delta)^2 t}{nq} \tag{A}$$

then x and t are related in terms of z and t* by the equation:

$$t^* = z - \ln(1+z) \tag{B}$$

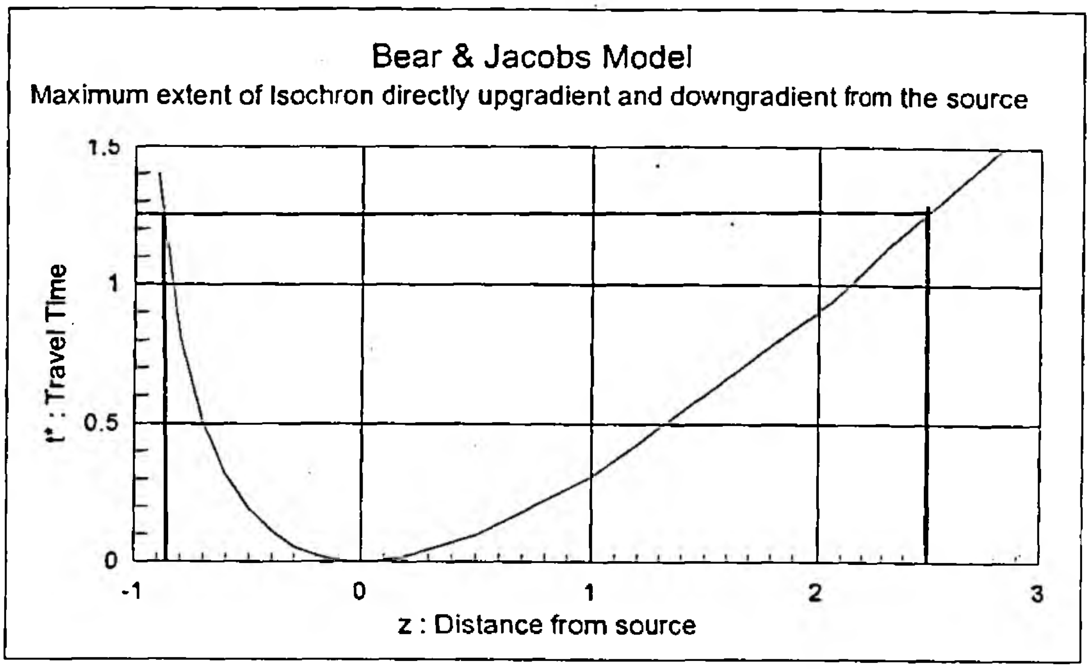
This equation, for z in the range : $-1 < z < 3$ is illustrated below.

As an example of the use of this equation :

Determine the travel time from a point 500 m directly up- gradient from a source operating under the conditions given in the above table :

From (A), when x = 500 m, z = 5π, and by substitution into (B), t^*= 12.89
The corresponding travel time t can be deduced from (A) as t = 4103 days.

[2]Bear J & Jacobs M., (1965), On the movement of water bodies injected into aquifers. J. Hydrology, 3, 37 - 57



The inverse problem of finding x when t is specified is more difficult, and an accurate solution of this problem requires a numerical procedure. However, the example below illustrates the use of the graph to obtain an approximate solution, and this can be readily extended or expanded, to allow interpolation to greater degrees of accuracy if required.

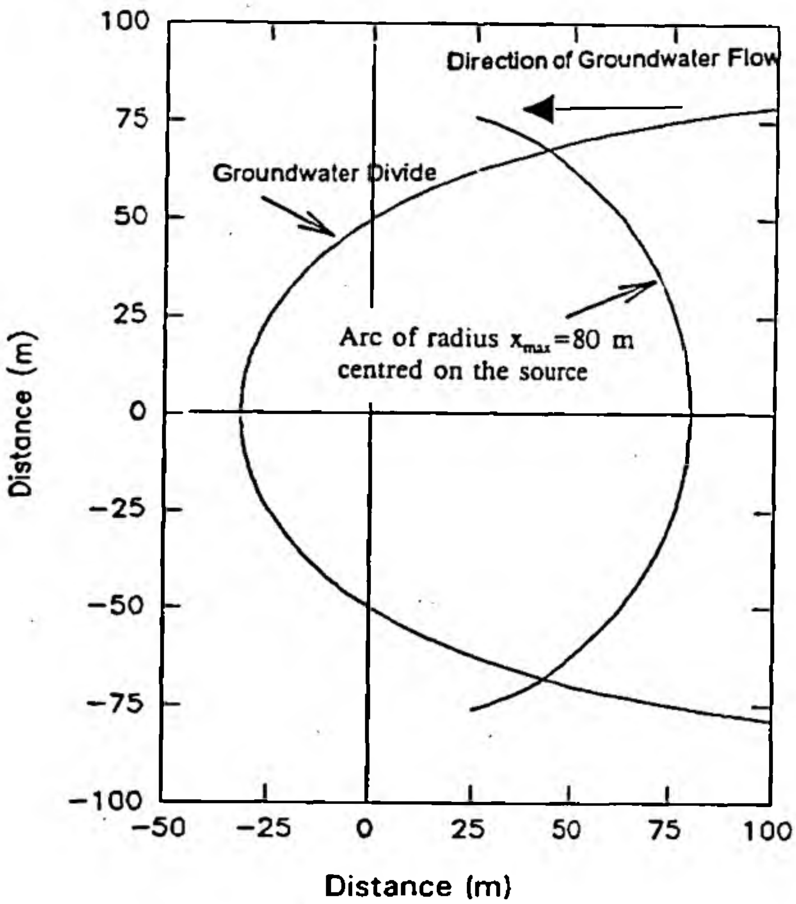
Determine the up- gradient (x_{max}) and down- gradient (x_{min}) points from which to reach the source in 400 days

Using (A), when t_d = 400 days, t* = 1.26.

The graph shows there are two solutions to the equation : one up- gradient (z_{max} =2.5) and the other down- gradient (z_{min} = -0.87) of the source.

Using the relationships in (A) yields x_{max} = 80 m and x_{min} = -28 m.

An approximate or hybrid *time of travel* zone may be constructed geometrically using the capture zone boundary but bounded up- gradient of the source by an arc of radius x_{max}, centred on the source. The diagram below illustrates this method of construction.



Example 5 Bear & Jacobs Model : Isochrons

Parameter	
q (m^3/d)	100
k (m/d)	10
b (m)	50
n	0.1
Δ	0.001
Recharge (mm/a)	*

The loci of all points in an aquifer from which water takes exactly t_d days to reach a borehole forms a curve, called an *Isochron*, and the region bounded by this curve is called the t_d *time of travel* zone. For an aquifer of infinite extent, Bear & Jacobs[2] derived the equation for these curves as:

$$e^{-z}\left(\cos w + \frac{z \sin w}{w}\right) = e^{-t^*} \tag{C}$$

with the non- dimensional variables z, w and t^* defined as:

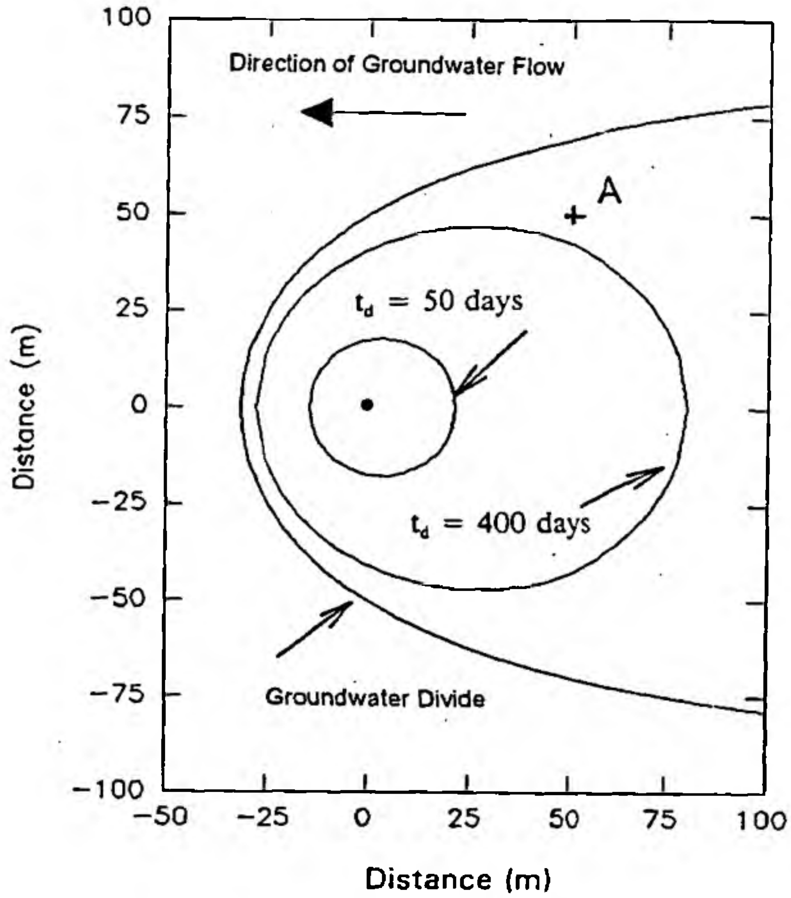
$$z = \frac{2\pi k\Delta bx}{q}, \quad w = \frac{2\pi k\Delta by}{q}, \quad t^* = \frac{2b\pi(k\Delta)^2 t}{nq} \tag{D}$$

The travel time t_d from any point (x_d,y_d) in the flow field to the source can be readily deduced from the relationships in (C) and (D) as follows :

Calculate the travel time from a point 50 m up- gradient but off-set by 50 m from the x- axis (labelled A in the figure).

Using the data from the table above in (D) with x = y =50 m yields z = w = $\pi/2$.
By substitution into (C), $t^* = \pi/2$. Therefore, by substitution into (D), t = 500 days.

The calculations outlined above can be readily performed using spreadsheets, but the converse problem of determining the coordinates of the isochron for specified travel times requires numerical solutions of (A). Such computations are beyond the scope of this text, but the figure below illustrates the resulting 50 day and 400 day isochrons for this particular problem.


Direction of Groundwater Flow
A
t_d = 50 days
t_d = 400 days
Groundwater Divide
Distance (m)
Distance (m)
100
75
50
25
0
−25
−50
−75
−100
−50
−25
0
25
50
75
100

Example 6 WHPA Model

Parameter	
q (m^3/d)	100
k (m/d)	10
b (m)	50
n	0.1
Δ	0.001
Recharge (mm/a)	*

The WHPA model, developed for the United States Environmental Protection Agency, is the recommended model (see Table 3) for delineating capture zones in aquifers for which the assumptions of darcian flow are valid at the catchment scale. It should be clear, however, from the previous examples that a model is not necessary to delineate the capture zones around small sources, because of the ready availability of simple formulae from which the basic dimensions of the capture zones can be determined, and because the resulting calculated size relative to that of the default protection zones (minimum of 50 m radius for the *inner zone*s and 25% of the recharge area for the *outer zones)* is often smaller.

Nevertheless this example is included to illustrate the data requirements and resulting outputs from the WHPA model when used to delineate 50 day, 400 day and boundary catchments and to enable comparisons to be made with the zones delineated in Examples 1 to 5. The underlying theory of the WHPA model has been covered in earlier examples, but the reader is referred to the *User Manual* for a more complete presentation.

The WHPA model has 4 modules, of which two (RESSQC & MWCAP) are recommended for use in delineating capture zones for small sources. The reader is referred to the *User Manual* for details of the GPTRAC & MONTEC modules, whose range of applicability is beyond the scope of this document.

Inputs to the model are via a series of screens as illustrated in Table 4 (RESSQC) & Table 5 (MWCAP). The values given in these tables were those used to derive the results illustrated below which were obtained with version v2.2 of the model[3].

[3] WHPA, (1993), Wellhead Protection Area Code, US EPA Office of Groundwater Protection. Guiger N & T Franz, (1991), Development and application of a wellhead protection area delineation computer program. Water Science & Technology, 24(11), 51 - 62.

Table 4 RESSQC - Input parameters

Screen	Parameter	Value
1	Run title	
	Units (0 = imperial, 1=metric)	1
	Minimum x- coordinate (m)	-50.0
	Maximum x- coordinate (m)	100.0
	Minimum y- coordinate (m)	-100.0
	Maximum y- coordinate (m)	100.0
	Maximum spatial step (m)	1.0
2	No of pumping wells	1
	No of recharge wells	0
	Delineate capture zones around pumping wells (1), or recharge wells (2)	1
	Transmissivity (m^2/d)	500.0
	Aquifer thickness (m)	50.0
	Aquifer porosity - ($\geq$ 0.01)	0.1
	Hydraulic gradient	0.001
	Angle of ambient flow (degrees)	180.0
3	x- coordinate of pumping well	0.0
	y- coordinate of pumping well	0.0
	pumping rate (m^3/d)	100.0
	Well radius (m)	0.3
	Number of pathlines (default =20)	40
	Pathline plotting interval	1
4	Time period for simulation (days)	400.0
	No of capture zones	2
	Capture zone : Time#1 (days)	50.0
	Capture zone : Time#2 (days)	400.0
5	No of reverse pathlines - in addition to those released at the source	0

RESSQC *Delineates time related capture zones around sources in homogeneous aquifers of infinite areal extent and uniform groundwater flow.*

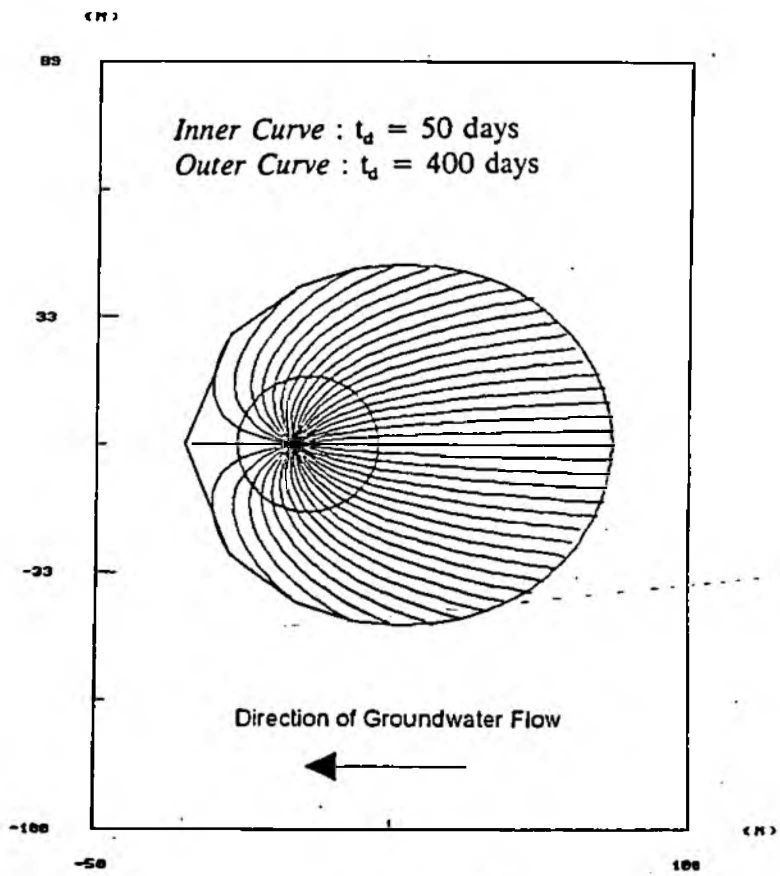
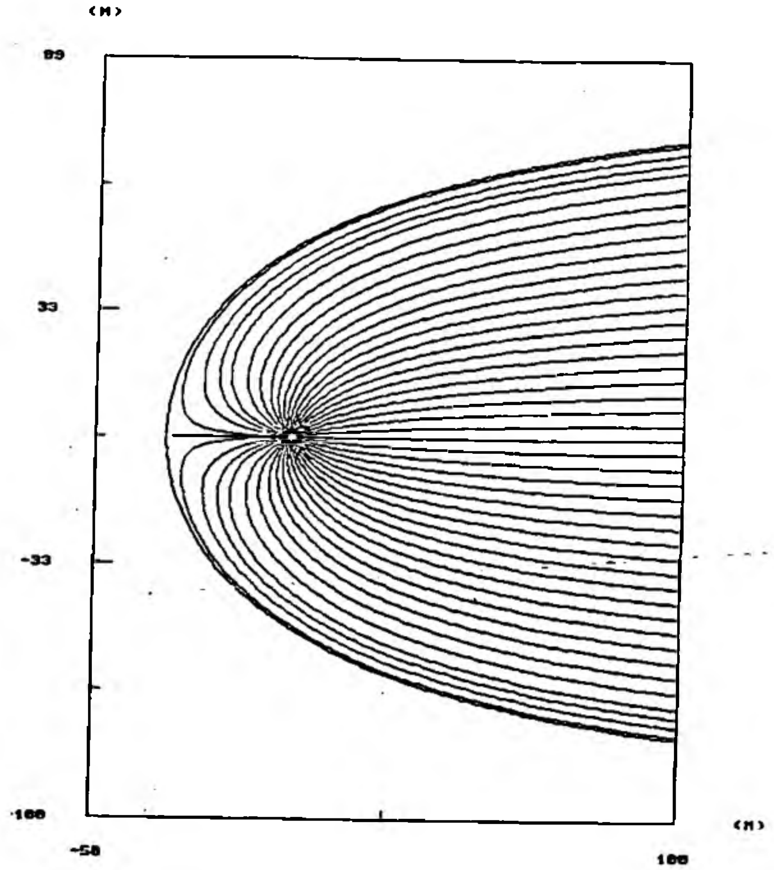


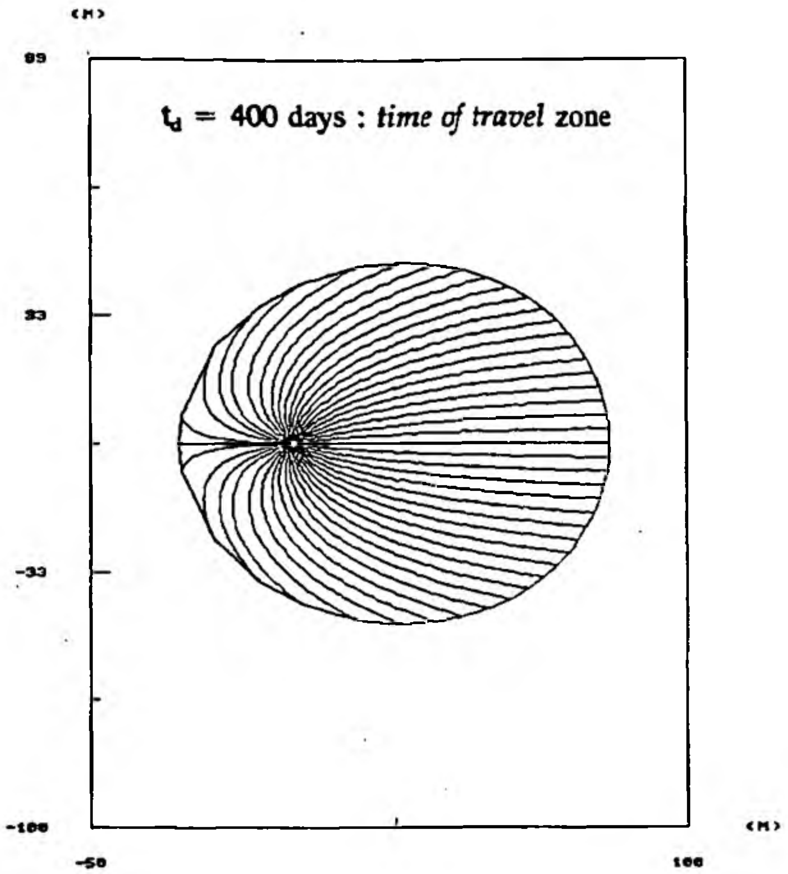
Table 5 MWCAP - Input parameters

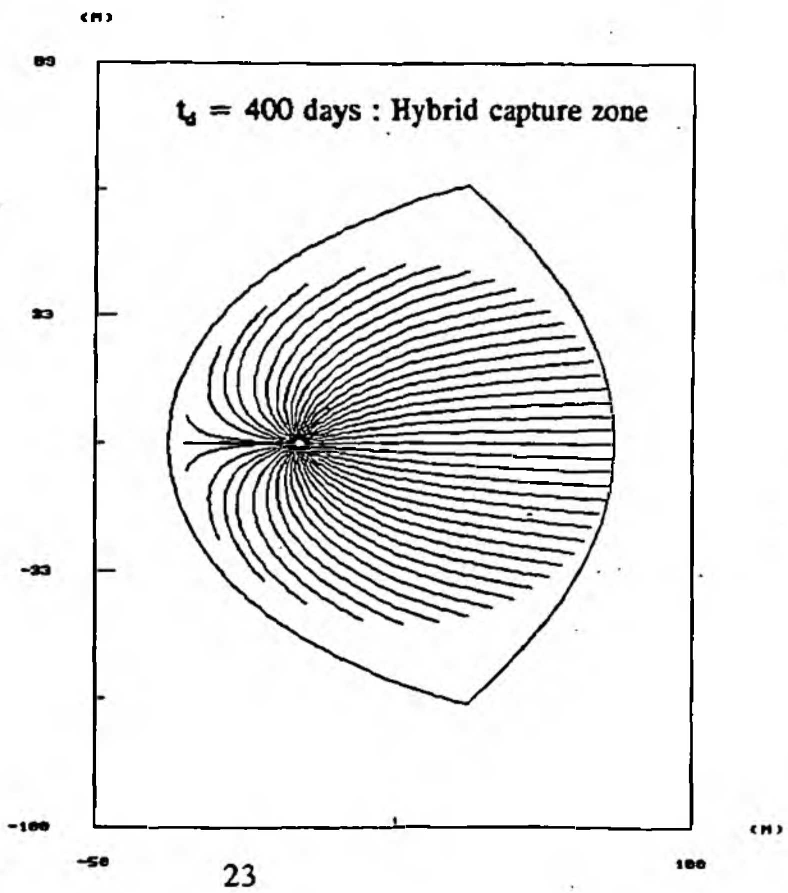
Screen	Parameter	Value
1	Rub title	
	Units (0 = metric, 1 = imperial)	0
	No of wells	1
	Minimum x- coordinate (m)	-50.0
	Maximum x- coordinate (m)	100.0
	Minimum y- coordinate (m)	-100.0
	Maximum y- coordinate (m)	100.0
	Maximum spatial step length (m)	1.0
	Perform head calculations (1 = yes, 0 = no)	1
2	No of grid columns	15
	No of grid rows	20
	x- coordinate of reference head (m)	-50.0
	y- coordinate of reference head (m)	0.0
	Reference head (m)	0.0
3	x- coordinate of well (m)	0.0
	y- coordinate of well (m)	0.0
	Discharge rate (m^3/d)	100.0
	Transmissivity (m^2/d)	500.0
	Aquifer gradient	0.001
	Angle of ambient flow (degrees)	180.0
	Aquifer porosity ($\geq$ 0.01)	0.1
	Aquifer thickness (m)	50.0
4	Boundary type (0= no boundary, 1=stream, 2 = barrier)	0
5	capture zone options : 0 = steady state, 1 = hybrid, 2 = time related	see figures
	No of pathlines (default = 0)	40

MWCAP *Delineates steady- state, time related and hybrid capture zones for sources in homogeneous aquifers with steady and uniform ambient groundwater flow.*



Steady- state capture zone


(M)
89
33
-33
-100
-50
100
(M)
t_d = 400 days : *time of travel* zone

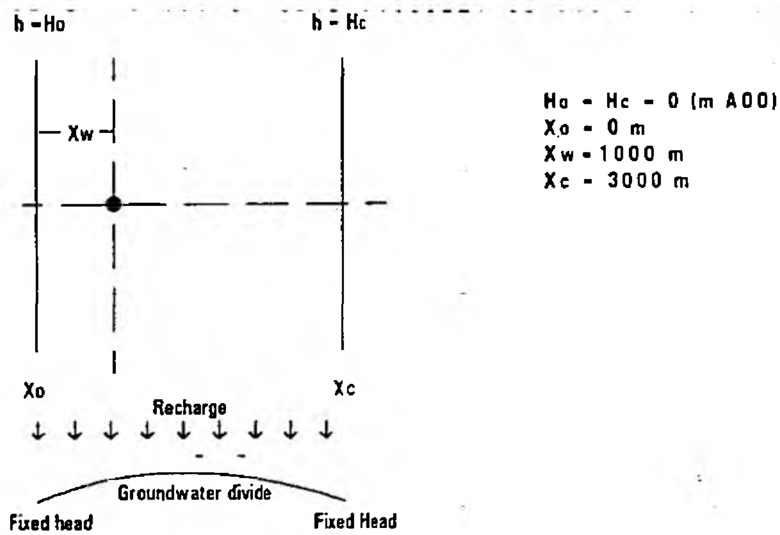

(M)
89
33
-33
-100
-50
100
(M)
t_d = 400 days : Hybrid capture zone

Example 7 ABARM Model

Parameter	
q (m³/d)	100
k (m/d)	10
b (m)	50
n	0.1
Δ	*
Recharge (mm/a)	250

Lerner[4] proposed a semi- analytical model incorporating recharge and aquifer boundaries which overcomes the limitations of the infinite areal extent assumption of the Bear & Jacobs model. For full details of this model, the reader is referred to the original publication (see footnote). But a simple example, using the data in the table above, is included here to illustrate the effects of recharge and a groundwater divide on the source capture zone.

The notation used in the derivation of the theory is defined in the figure below:



[4]Lerner D N, A semi- analytical model for borehole catchments and time of travel zones which incorporates recharge and aquifer boundaries. Quarterly Journal of Engineering Geology, (1992), 25, 137-144.

At any point in the aquifer, the flow velocity is assumed to comprise two components:

- the regional velocity, due to recharge which is parallel to the x-axis
- a radial component due to the abstraction

Assuming a uniform areal recharge R_e, the regional velocity component v_x is given by:

$$v_x = \frac{R_e}{bn}(x - \frac{L}{2}) \qquad \text{(E)}$$

where L is the distance (Xc - Xo) between the two fixed boundaries.

Assume that the abstraction is located at the point $(x_w,0)$, and define the new variables :x^+, x^- and $y^-$by

$$x^+ = \frac{\pi}{L}(x + x_w - L), \quad x^- = \frac{\pi}{L}(x - x_w), \quad y^- = \frac{\pi}{L}y \qquad \text{(F)}$$

then the velocity components v_{xw} and v_{yw} at the point (x,y) due to abstraction are:

$$v_{xw} = \frac{q}{4bLn}\left(\frac{\sin x^-}{\cosh y^- - \cos x^-} + \frac{\sin x^+}{\cosh y^- + \cos x^+}\right) \qquad \text{(G)}$$

$$v_{yw} = \frac{q}{4bLn}\left(\frac{1}{\cosh y^- + \cos x^+} + \frac{1}{\cosh y^- - \cos x^-}\right)\sinh y^- \qquad \text{(H)}$$

where cosh and sinh are hyperbolic sine and cosine functions.

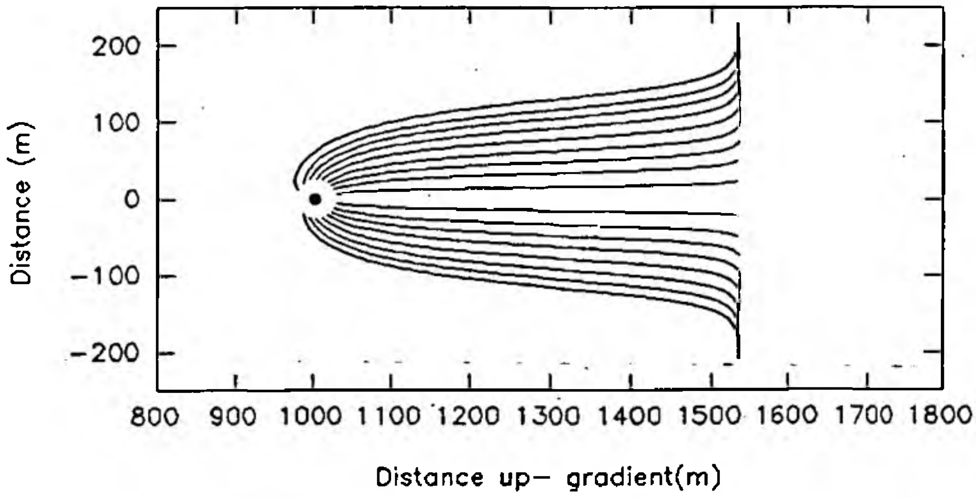
At the point (x,y), the total velocity components (V_X,V_Y) are given by summing regional and radial components together : $V_X = v_x + v_{xw}$ and $V_Y = v_{yw}$, and the paths of particles are given as the solution of the equations:

$$\frac{dx}{dt} = V_X \, , \; \frac{dy}{dt} = V_Y \qquad \text{(I)}$$

which may be obtained via numerical integration techniques. Given an initial particle position (x,y) at time t the position at time (t+dt) is obtained from the solution of (I). Repeating the procedure gives a series of positions along a pathline.

The capture zone illustrated below was obtained by reverse tracking over a 50,000 day period from a series of points initially uniformly distributed on a circle centred on the source.

ABARM Output



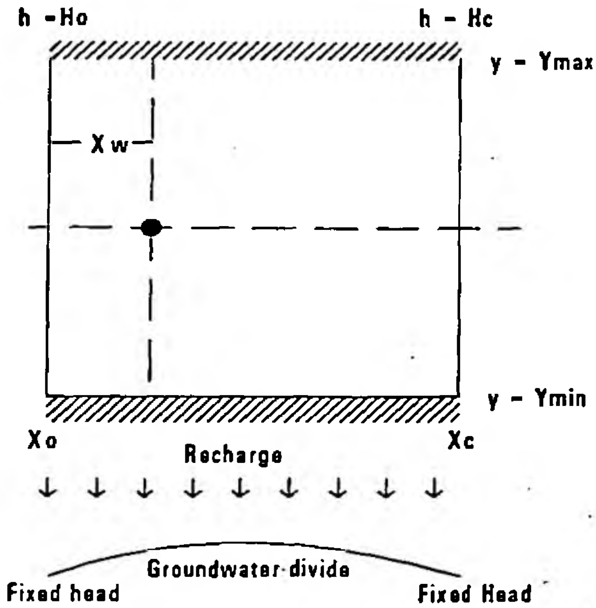
Example 8 FLOWPATH Model

Parameter	
q (m^3/d)	100.0
k (m/d)	10.0
b (m)	50.0
n	0.1
Δ	*
Recharge (mm/a)	250

For a source abstracting from a point close to a groundwater divide, the assumption of an open- ended up- gradient capture zone is unrealistic, and a more hydrogeologically acceptable model is required. The ABARM model example, described earlier enables capture zones to be delineated in such circumstances, but the computational complexity, and the unavailability of the model as a *commercial* package, has tended to limit its use to date.

Groundwater divides, and recharge which the basic capture zone models cannot account for, may be accommodated in numerical models. But one of the problems of using such models to delineate capture zones around small sources is the spatial scale of the problem and the associated grid size required to resolve detail across the flow field. Nevertheless, it is possible to construct numerical models to solve such problems, and the results of applying FLOWPATH to the test problem are given below for comparison with the earlier results.

Determine 50 day and 400 day time of travel zones, and the catchment around a source located 0.5 km from a groundwater divide.



Ho - Hc - 0 (m AOD)
Xo - 0 m
Xw - 1000 m
Xc - 3000 m
Ymin - 0 m
Ymax - 500 m

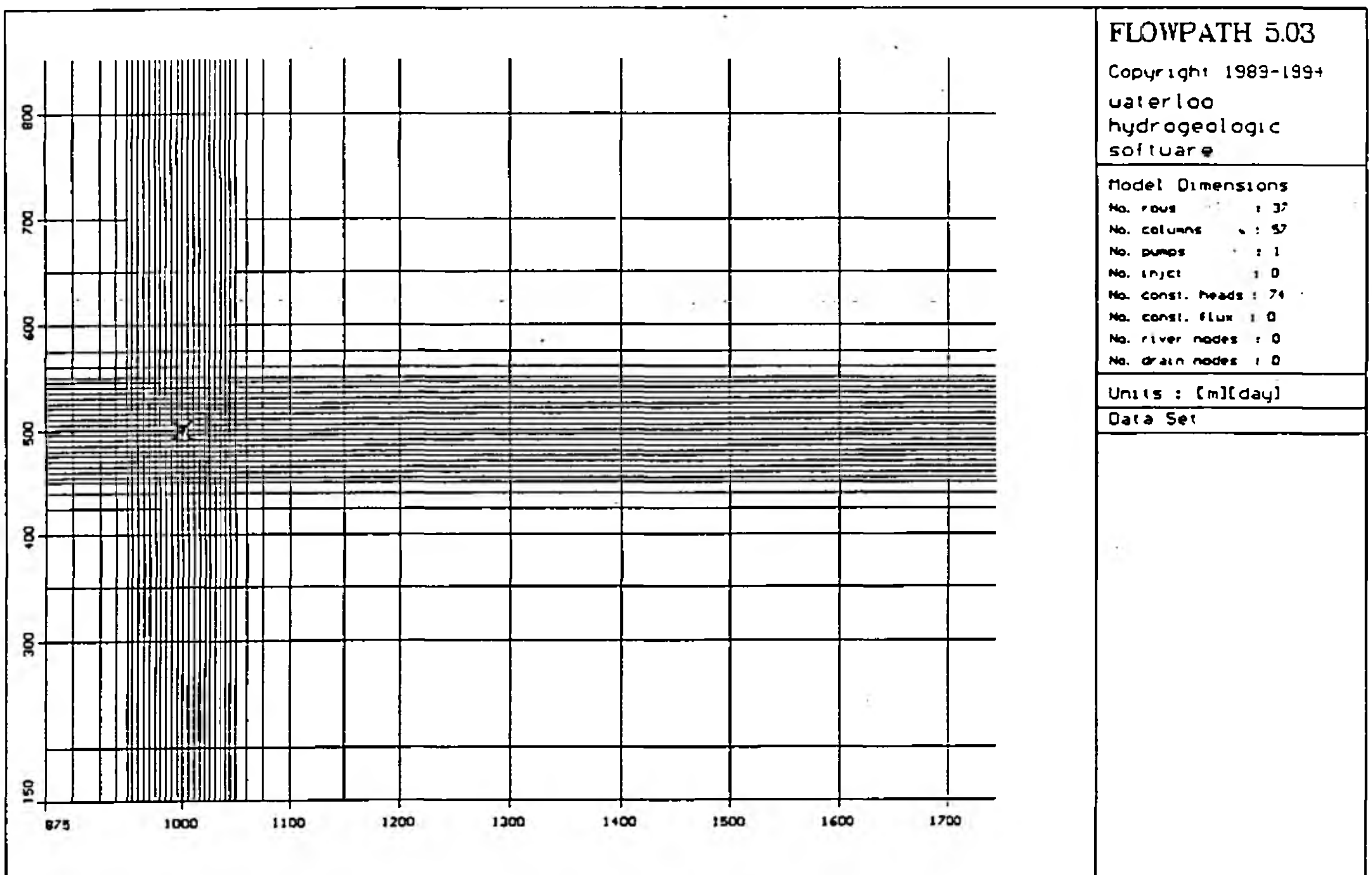
Represent the aquifer as in Example 7 with constant head boundaries to the east and west of the groundwater divide, but with the addition of no- flow boundaries to the north and south of the source. The location of these boundaries should be such as to avoid constraining the flow and therefore several locations may need to be examined before their influence can be discounted.

An arbitrary 100 m grid was established across the flow domain, reducing to 5 m in the vicinity of the source - see figure below. The extent of the fine mesh was varied as the solution progressed to examine the sensitivity of the resulting capture zones.

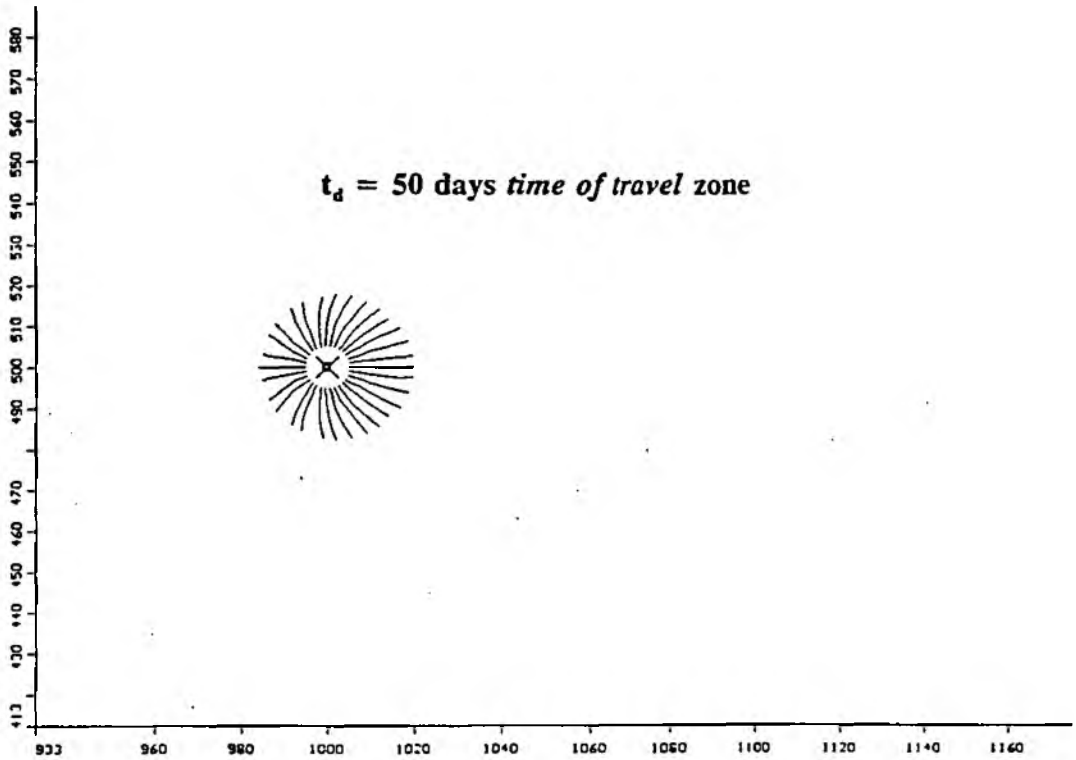
FLOWPATH model results are illustrated in two forms :

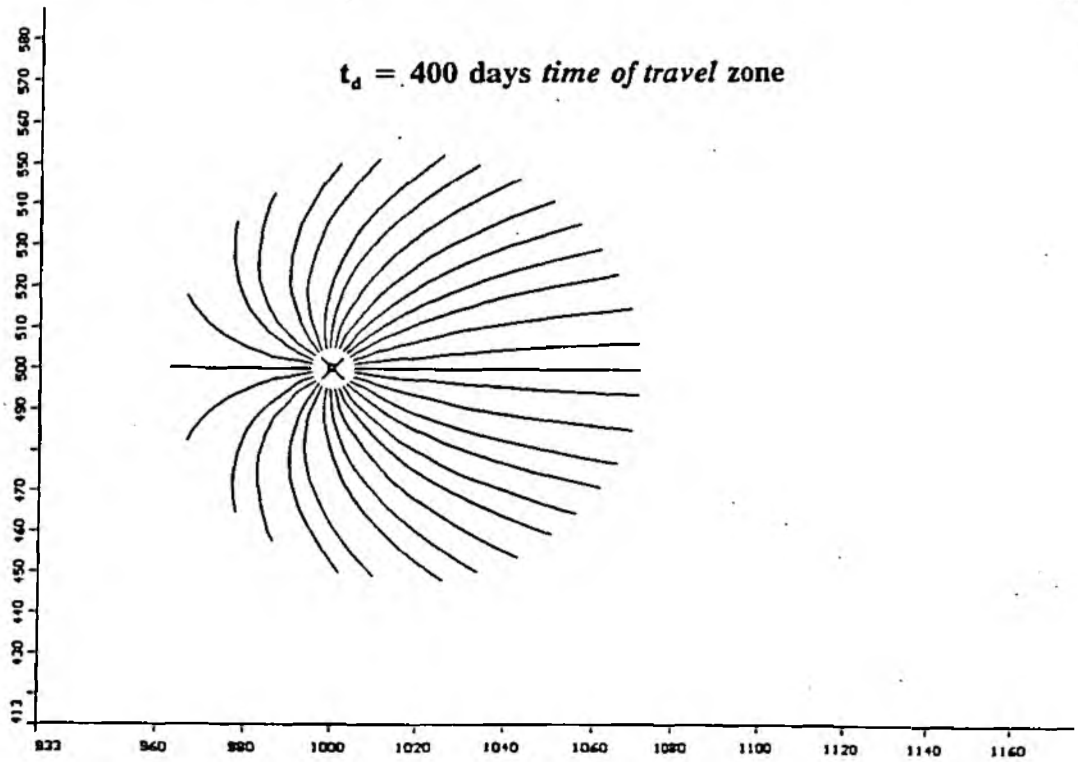
- actual model output
- CAD output

to illustrate the use of the model, and to facilitate comparison with the results derived earlier.

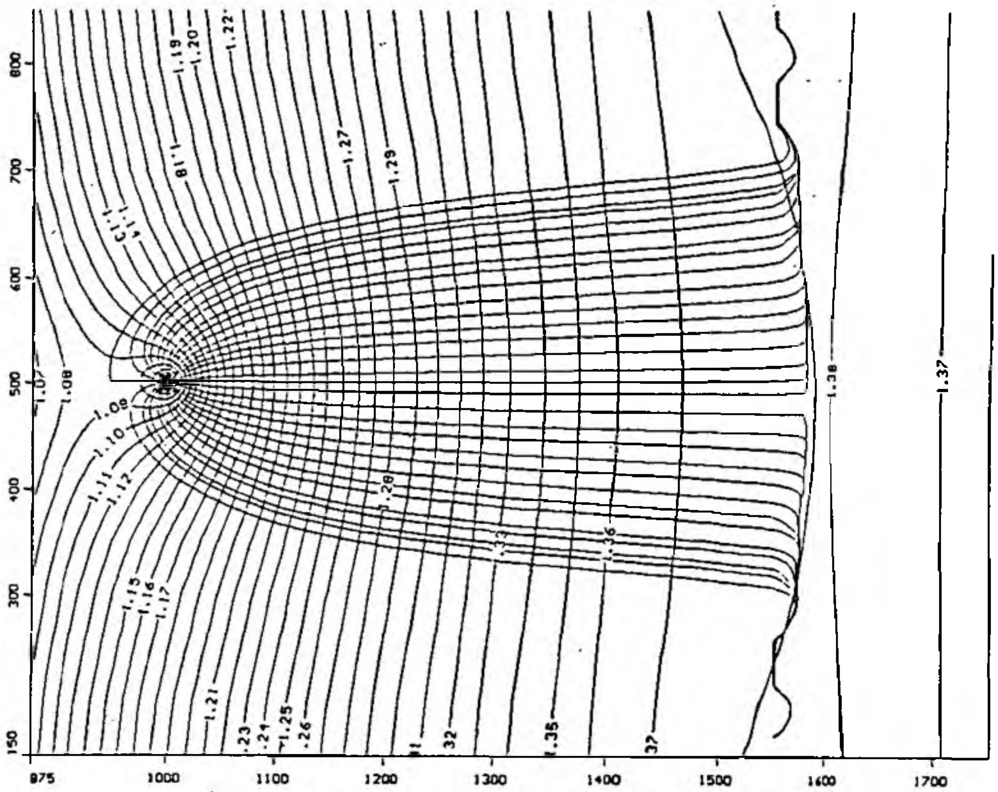


Computational Grid


t_d = 50 days *time of travel* zone

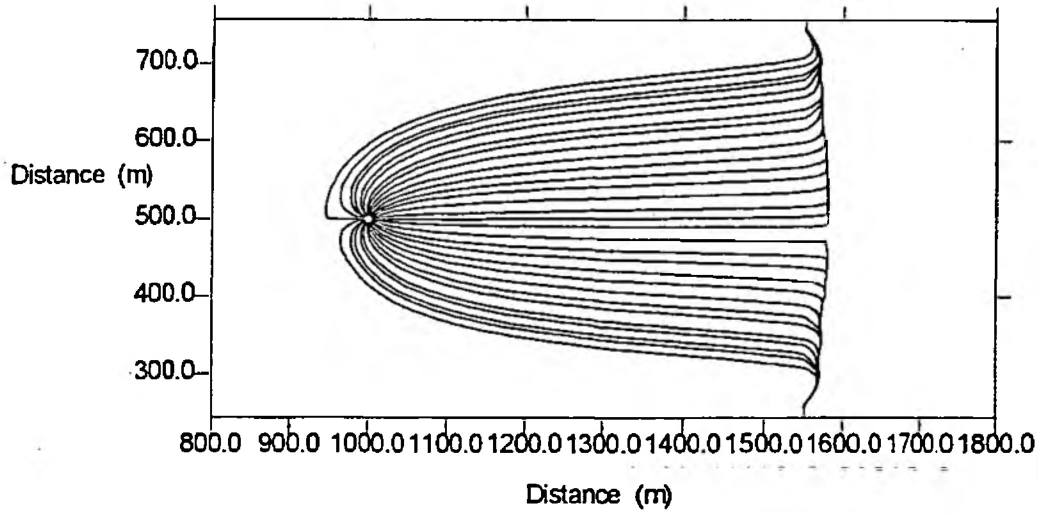

t_d = 400 days *time of travel* zone

FLOWPATH Output

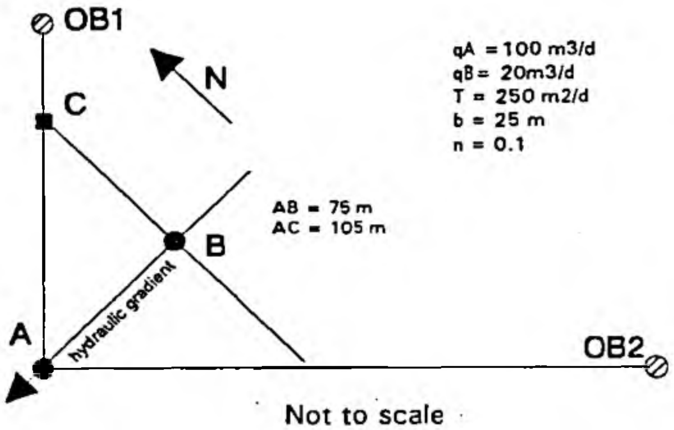


Groundwater contours and source catchment zone

CAD Output



3 CASE STUDY



Not to scale

The figure above shows the relative location of 2 boreholes A & B, distance 75 m apart. A represents an existing source, which is licensed to abstract 100 m^3/d, while B is a proposed source which is intended to supply the domestic needs of the property on which it is located. Both A & B penetrate the full thickness of the aquifer which is estimated to be 25- 30 m. Drift deposits, although present, are no more than 1 m thick and are considered to be relatively permeable in the vicinity of both wells.

Records show that Source A was test pumped for 12 hours many years ago, when a maximum drawdown of 40 cm was recorded but aquifer parameters were not determined. There was approximately 25 m of water in the hole, and the pump was positioned 5 m above the base of the aquifer (20 m below the water table). Time drawdown data are not available for this well, nor were any measurements made in boreholes nearby.

Drawdown Calculations

Determine the likely impact of source B on Source A

Source B is intended to supply the domestic needs of several cottages.

Estimated consumption : 5 - 10 m^3/d

Estimated regional aquifer parameters : T = 250 m^2/d, S = 10%

The long term effects of abstraction may be calculated assuming source B is pumped continuously for 400 days without recharge, at the minimum rate necessary for licensing, i.e. 20 m^3/d, (Groundwater Investigation Consents - A Handbook for Water Resources Staff : NRA Internal publication).

The drawdown Δh after time t, at a distance r from a source pumping at a rate q is given by the Theis formula:

$$\Delta h = \frac{q}{4\pi T} W(u)$$

where

$$u = \frac{r^2 S}{4Tt}$$

and T is the transmissivity, S is the storativity, and W(u) is the "Theis Well Function" or Exponential Integral Function[5].

By substitution

$$u = \frac{75*75*0.1}{4*250*400}$$

from which u = $1.41*10^{-3}$, and from *Annex 3.1*, (Kruseman & de Ridder), W(u) = 5.99

Therefore, the drawdown at B caused by source A, denoted as Δh_{BA} is given as

$$\Delta h_{BA} = \frac{100}{4*\pi*250} W(u) = 0.19\ m$$

and the drawdown at A caused by source B ($q_B = 0.2*q_A$) amounts to approximately 0.04 m.

The impact of B on A is small and it is unlikely to cause water levels to drop below the level of the pumps in A or even seriously affect the yield of A. Therefore it probably represents an acceptable development.

Capture Zone Hydraulics

The residents of the cottages have expressed concern over the possibility of pollution of their source B arising from farming activities in the vicinity. In particular, there is a slurry silo (designated C on the figure) some 105 m northeast of A. Research has suggested that the silo was initially designed to the appropriate British Standards, but it is now many years old and corrosion of the walls is suspected.

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[5]Kruseman G P & de Ridder N A, (1991), Analysis and evaluation of pumping test data. Publication 47, International Institute for Land Reclamation & Improvement, Wageningen.

Delineate the capture zones of each source and determine the likelihood of effluent from the silo reaching source B.

The MAFF "Code of Good Agricultural Practice for the Protection of Water" recommends that storage facilities be designed in accordance with the appropriate British Standards and the NRA "Groundwater Protection Policy" recommends that such facilities should not be constructed within 50 days travel time of a source unless adequate measures have been taken to minimise the risk of pollution.

Assume that when the silo C was constructed, its design was such that the pollution risk in relation to source A was considered to be acceptable.

Calculations show that Silo C is 75 m north of source B and is therefore beyond the minimum 50 m radius recommended in the MAFF code. However, C lies within the cone of depression of both A & B.

Source A is not pumped continuously, but fills a reservoir after water levels fall to a preset limit. Measurements of the water level in A, taken some 6 hours after the cessation of pumping, recorded 40.5 m OD, when the level in a borehole 2000 m northeast of A, (OB1), was 41.9 m OD.

Along the line passing through A & B, the component of the hydraulic gradient as determined from the measurements in A & OB1 is

$$\Delta_{Aob1} = \frac{(41.9-40.5)}{2000\cos(45)} = 0.001$$

The water level in a new borehole (OB2) , 4000 m southeast of A, sunk after OB1 was abandoned and the above measurements were taken, gives the level as 43.8 m when the levels in A were 41.0, from which the component of the hydraulic gradient along the line AB as:.

$$\Delta_{Aob2} = \frac{(43.8-41.0)}{4000\cos(45)} = 0.001$$

Thus Δ, the hydraulic gradient along the line AB is approximately 0.001

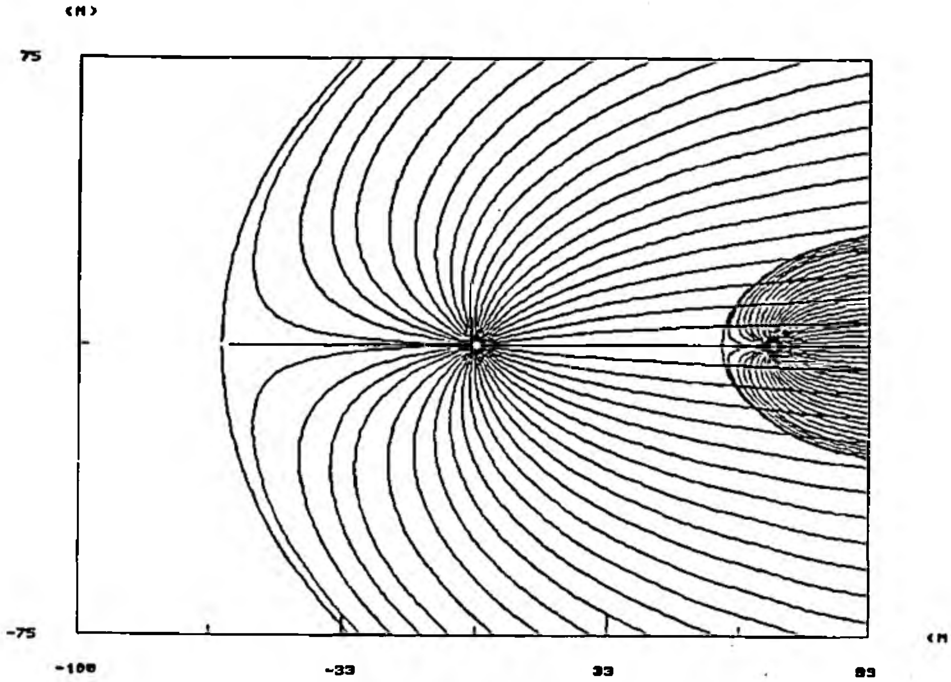
There are insufficient data on which to determine the location of any groundwater divides. It is therefore assumed that the Bear & Jacobs capture zone model is the appropriate model to use in the vicinity of these two sources, and that WHPA is available.

Using the MWCAP option, the source capture zones for A & B, together with the 400 day *time of travel* zone around A have been determined and these are illustrated below.

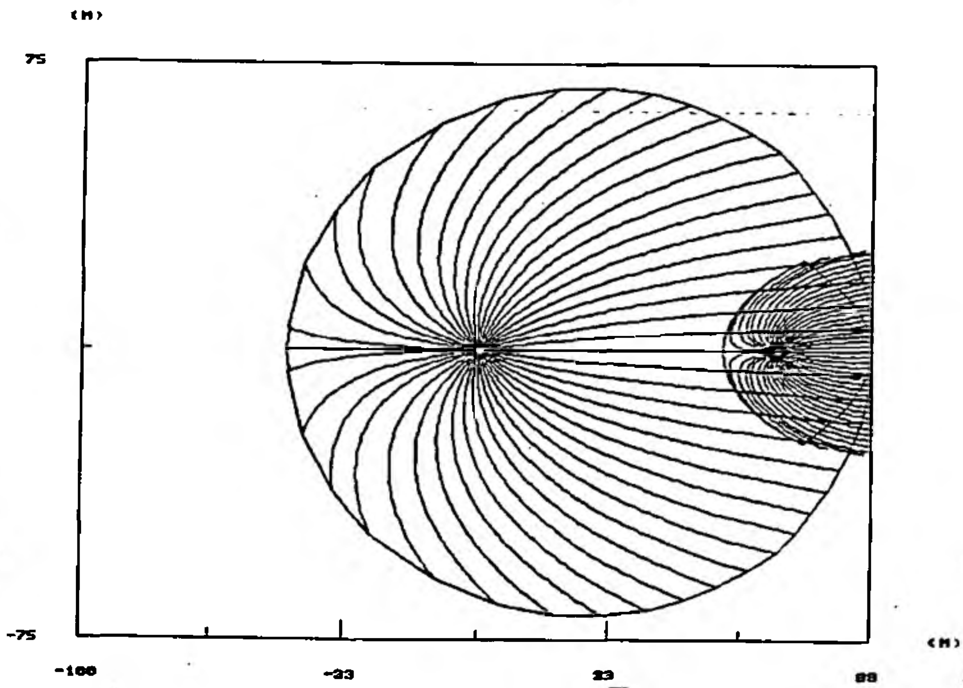
These results show that C is not within the capture zone of B, even though it is within the cone of depression. C is within the capture zone of source A, but the travel time is greater than 400 days.

If the areal recharge is 250 mm/a, then the radius of a circular catchment zone around A would be 216 m, and the radius of the corresponding "25% rule" zone would be 108 m. Thus C is at the limit of the *outer protection zone* of source A.

WHPA MWCAP Option



Steady State Capture zones around Sources A & B



t_d = 400 days *time of travel* zone around Source A
and
Steady State capture zone around Source B

Small Source Protection Zone Delineation - Vol II :Worked Examples
National Rivers Authority

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