Modelling of open loop systems

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* work performed as part of MSc thesis at University of Leeds

** numerical modelling carried out under contract for Environment Agency

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Listen carefully

I have a shameful secret…

…I have a small peccadillo…

….I have a hidden vice….

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$$s = \frac{Q}{4.\pi.T} W(u)$$

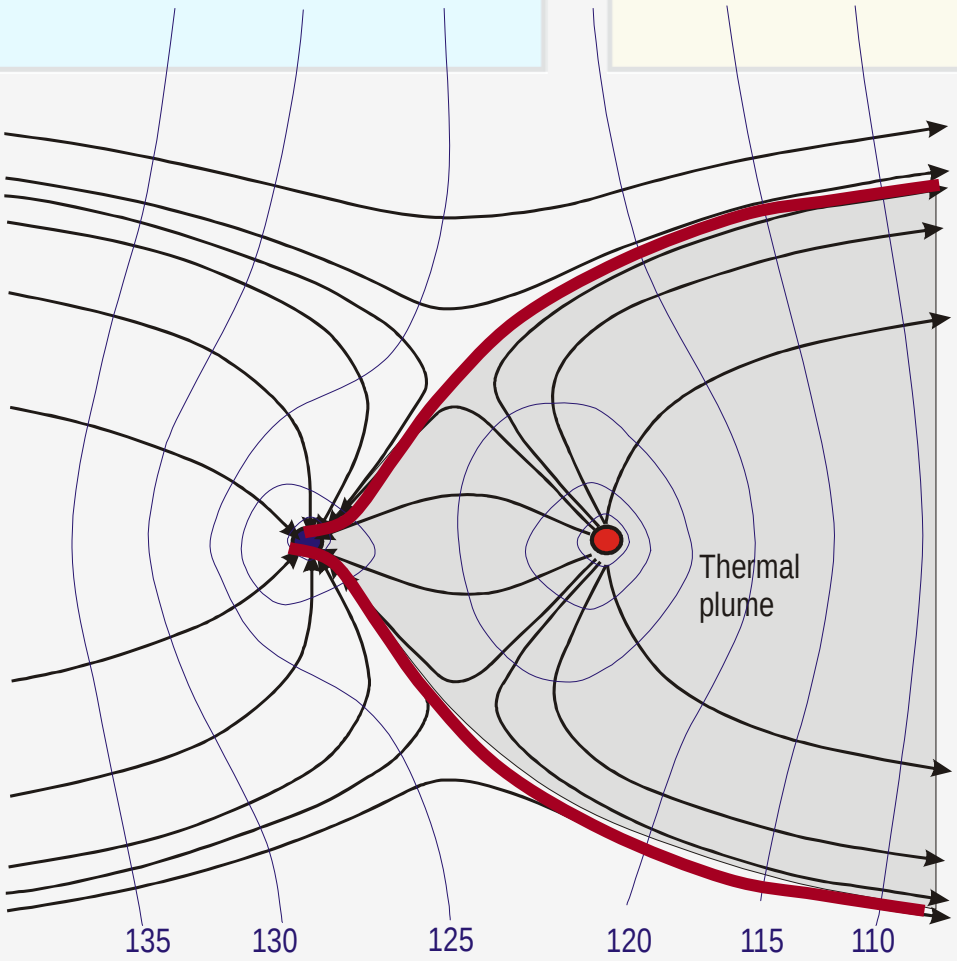
I like mathematics !

…in particular, I like equations and analytical models

$$W(u) = -0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + \frac{u^5}{5.5!} - .....$$

…but…why use analytical equations when we have so many fancy numerical models?

$$\Psi = \frac{Q}{2\pi m}\left(\tan^{-1}\left(\frac{y}{x-d}\right) - \tan^{-1}\left(\frac{y}{x+d}\right)\right) - (yU_x - xU_y)$$



Just as we assign contours of equal head an *equipotential value,*

We can assign each streamline (crossing the equipotentials as right angles) a stream potential value (stream function in complex number space).

We can find the critical streamline that delineates the thermal plume

Well separation L = 2d
U = Darcy velocity
m = aquifer thickness
(assumes wells are fully penetrating and located at coordinates (-d,0) and (d,0)

$$\Psi = \frac{Q}{2\pi m}\left(\tan^{-1}\left(\frac{y}{x-d}\right) - \tan^{-1}\left(\frac{y}{x+d}\right)\right) - (yU_x - xU_y)$$

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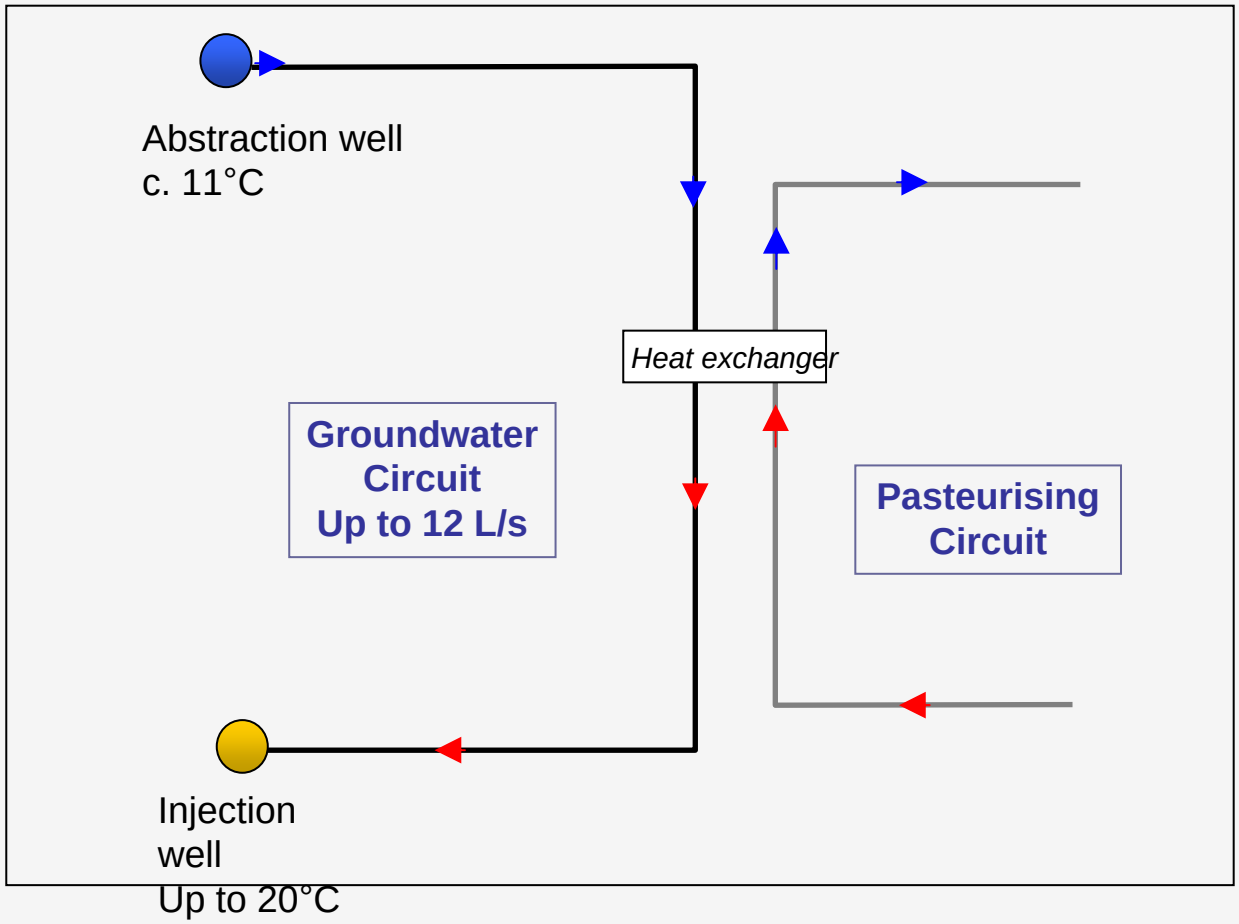
Selby doublet cooling scheme



Hazelwood Foods in North Yorkshire use groundwater from the Sherwood Sandstone for passive industrial cooling

Operating since 1998 (10 years at time of study)

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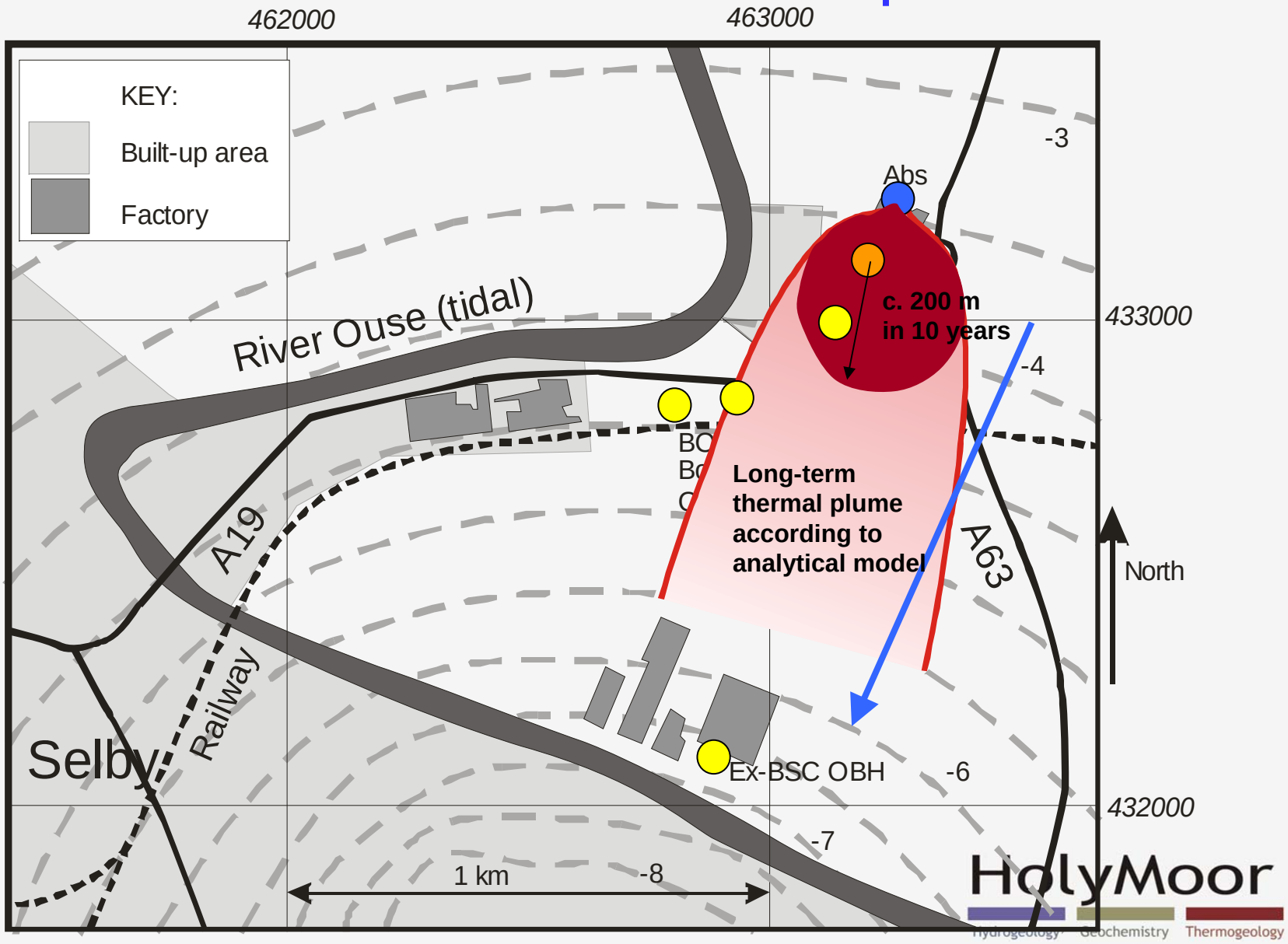
Schematic site map



2-D Numerical model

Simple model created in SHEMAT

Model simulated 10 years, using a single source of heat injection

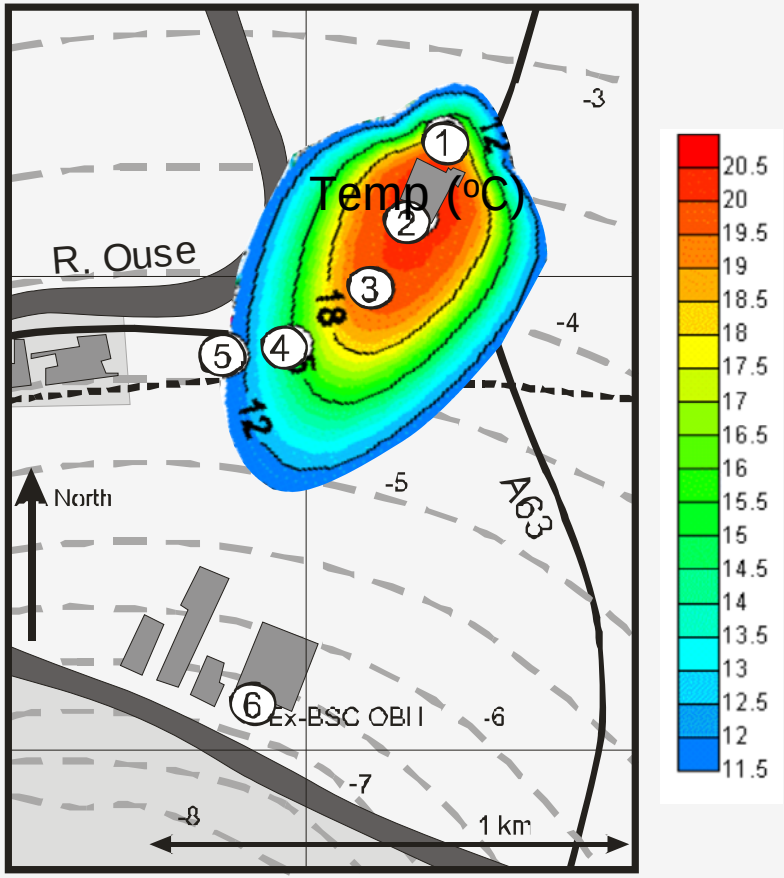
Time = 10 years

K= 11m/d

SHEMAT cell size = 50x50m

Dispersion observed

– Real? Numerical?



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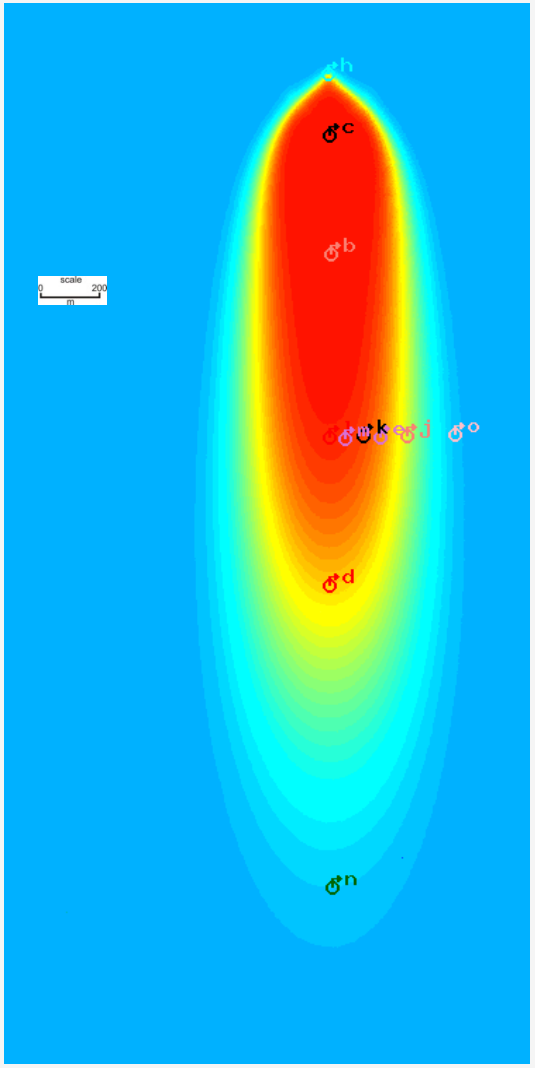
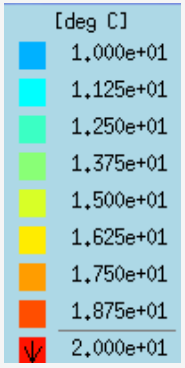
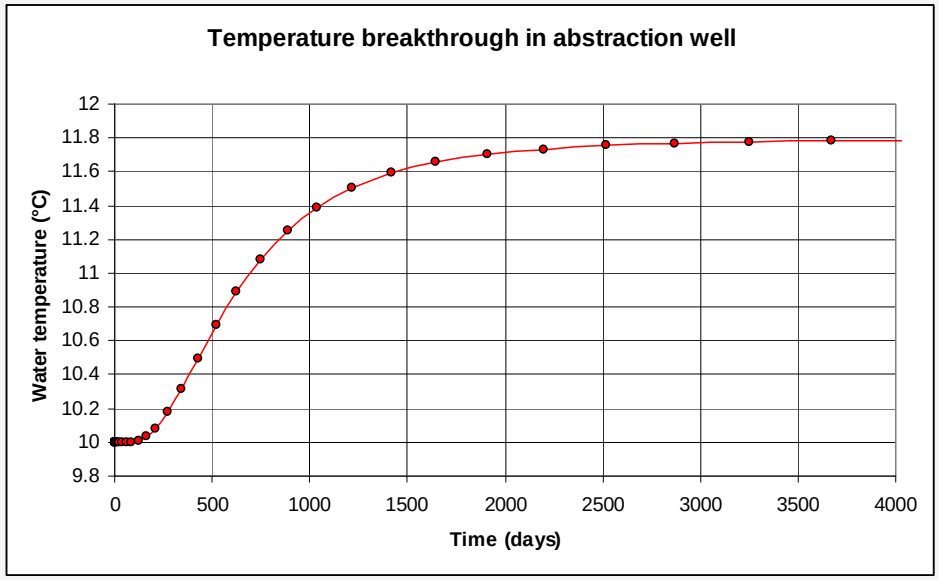
Generic modelling of thermal plumes







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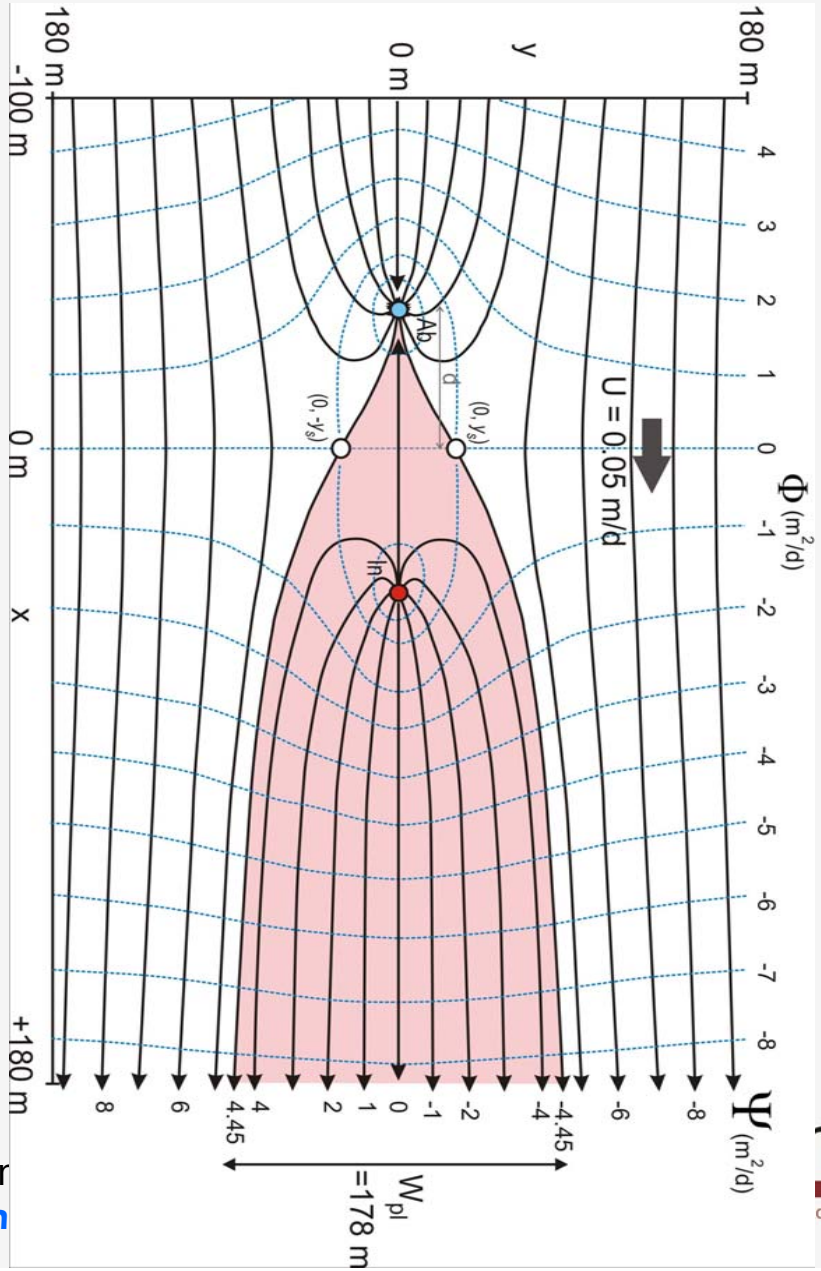
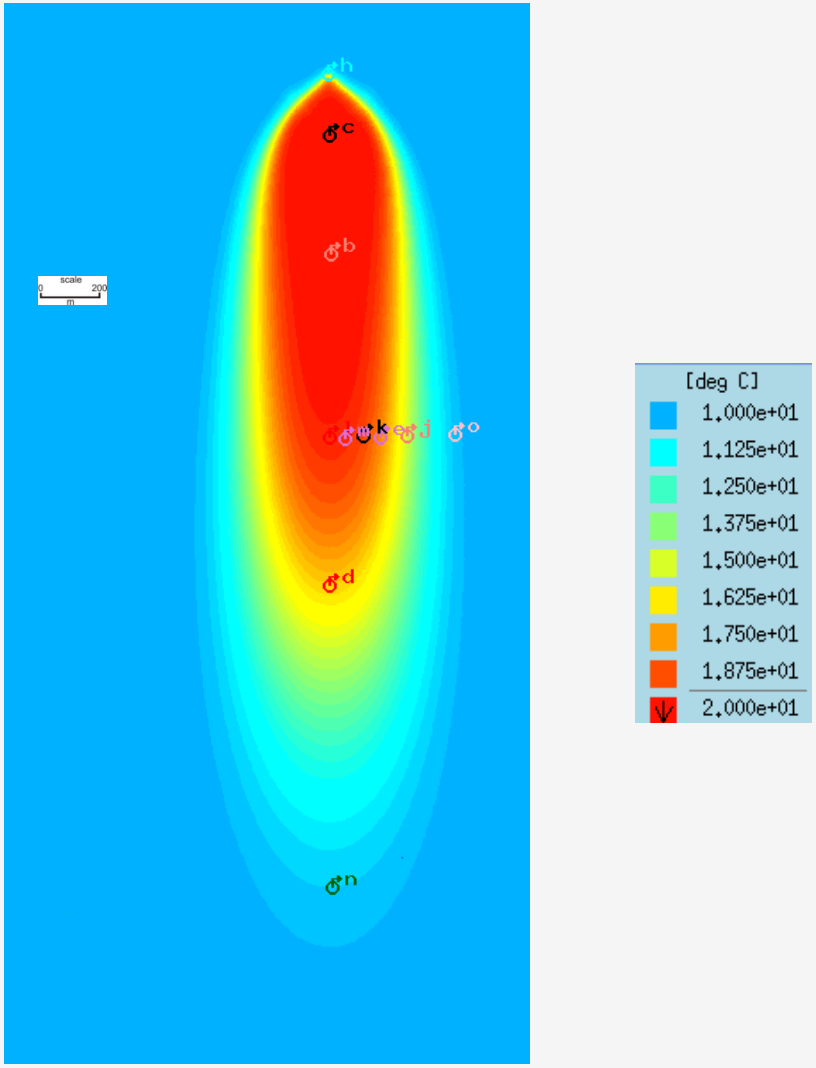
Comparison with analytical models

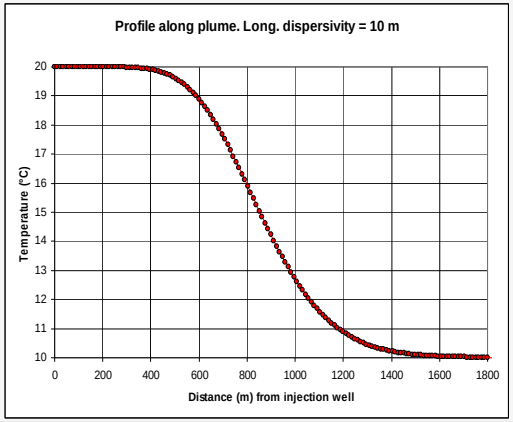
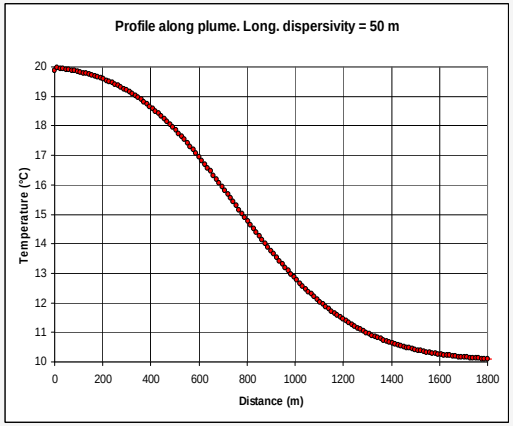




Generic modelling of thermal plumes

Parameter	FEFLOW® Model	Analytical model
Single well		
Plume length (L_{pl}) – from reinjection well	935 m	824 m
Plume width (W_{pl})	298 m	333 m
Time to breakthrough in OBH (500 m d/s)	3552 days	4435 days
Well Doublet (*2d* = 100 m)		
Plume length (L_{pl}) – from reinjection well	854 m	824 m
Plume width (W_{pl})	255 m	266 m
Time to breakthrough (15°C) in OBH ***i*** (500 m d/s)	4030 days	4435
First breakthrough in Abstraction well		457 days
Time to breakthrough (50%) in Abstraction well	628 days	
Equilibrium temp. in abstraction well	11.79°C	12.0°C

Generic modelling of thermal plumes

	FEFLOW model. Longitudinal profile of plume after 20 years	1-D Ogata-Banks Advective Dispersive Analytical Model. Longitudinal profile of plume after 20 years
$\beta_L = 10$ m $\beta_T = 1$ m		
$\beta_L = 50$ m $\beta_T = 5$ m		

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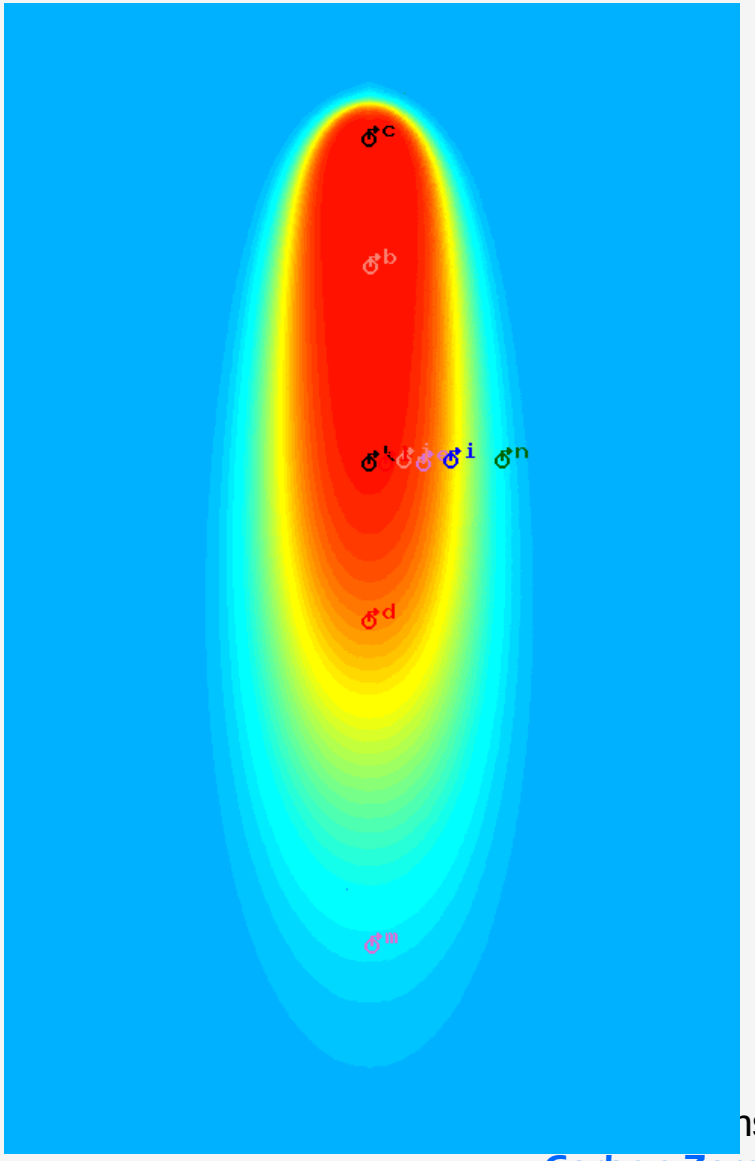
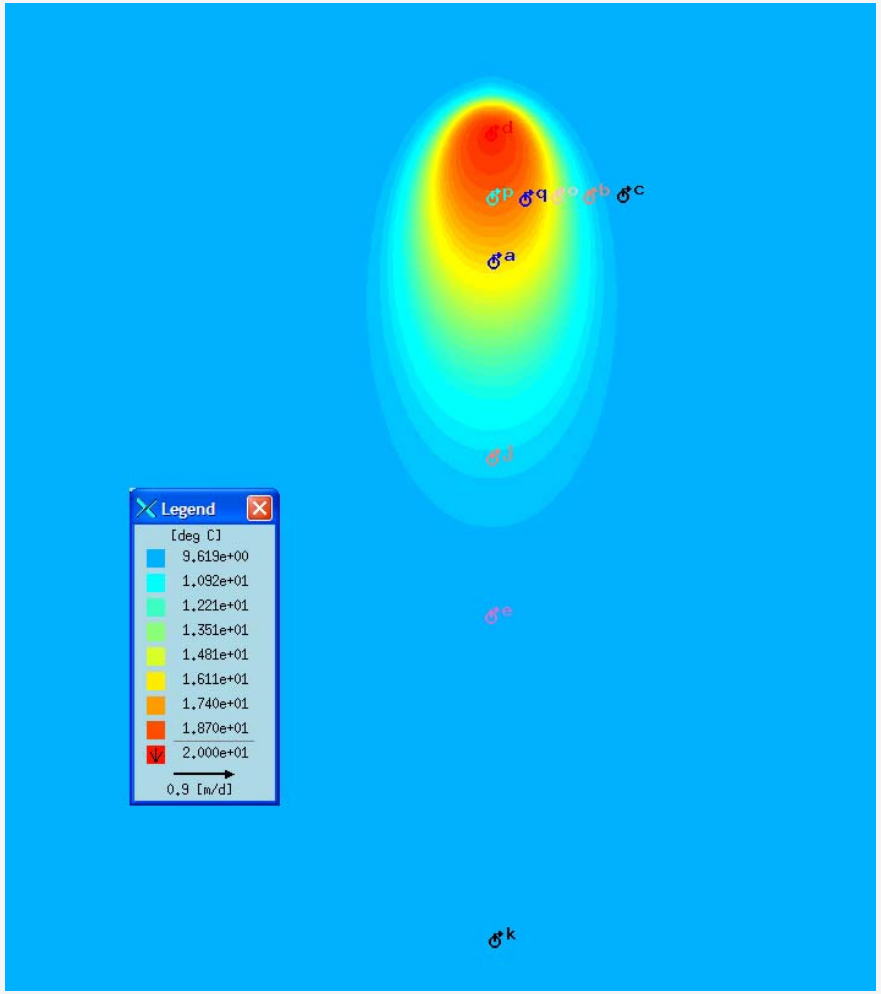
2D versus 3D models





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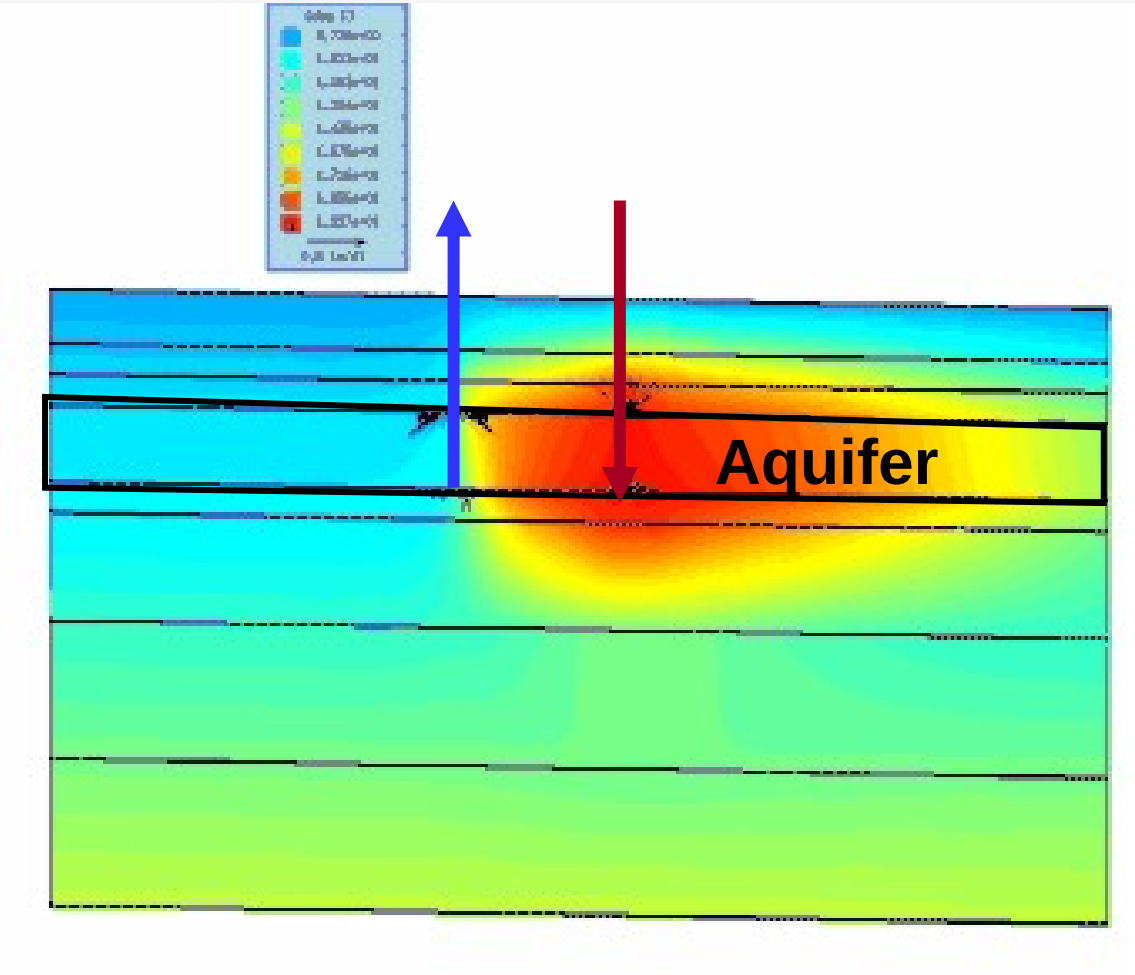
Here's where a 3-D numerical model may be of use !



FEFLOW (for example) can simulate the 3rd dimension

Heat may be lost by vertical conduction into overlying and underlying strata

(left) Example of FEFLOW modelling work performed by Carbon Zero Consulting and Holymoor Consultancy for the Environment Agency on generic well-doublet systems

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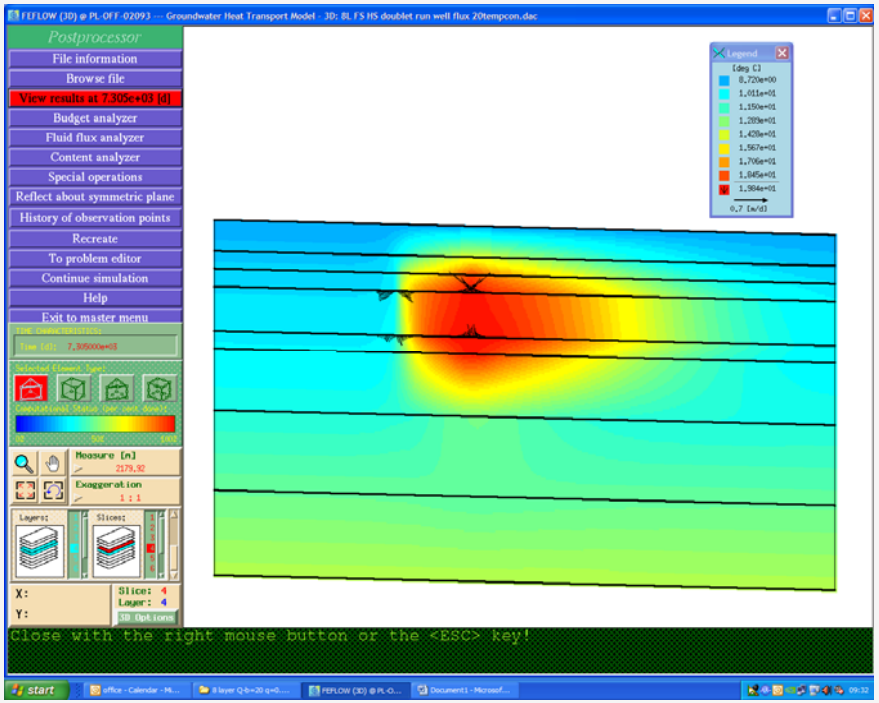
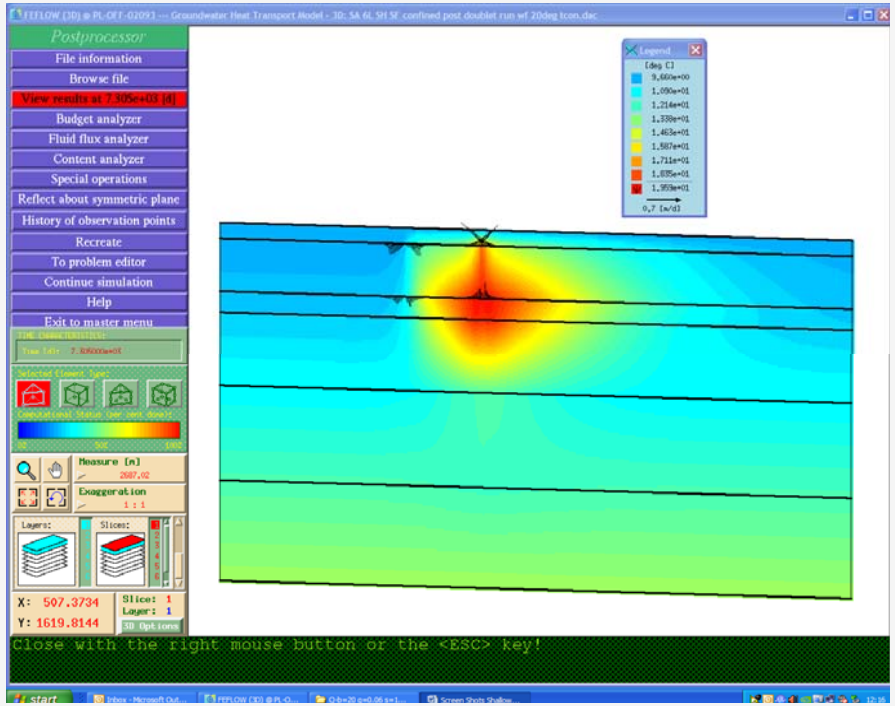
Generic modelling of thermal plumes





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CONCLUSIONS

- Let's reopen the analytical toolbox that was developed in the 1920s to 1980s (before numerical models turned our brains to wet cardboard)
- Analytical tools provide rapid and accurate means of first assessment of thermogeological risk
- In this case, 2-D equations are conservative (they ignore vertical heat conduction)
- Fire up the numerical models only at a later "tier" of risk assessment, when you feel you have a good understanding of the analytical solutions
- Remember – both analytical and numerical models typically assume porous media, Darcian flow and instantaneous thermal equilibrium…

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