Thermogeological assessment of open-loop well-doublet schemes: a review and synthesis of analytical approaches

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Abstract Use of well doublets for groundwater-sourced heating or cooling typically results in a “thermal plume” of cool or warm reinjected groundwater. Such a plume may be regarded either as a potential anthropogenic geothermal resource or as pollution, depending on downstream aquifer usage. A thermal plume may pose an external risk to downstream users and environmental receptors or an internal risk to the sustainability of the well doublet, due to the phenomenon of thermal feedback. A three-tier assessment of the risk of thermal feedback is proposed, based on: (1) consideration of well separation and yield; (2) analytical modelling of heat migration in a doublet to ascertain breakthrough time and post-breakthrough temperature evolution and (3) numerical modelling of complex scenarios.

Keywords Heat transport · Analytical solutions · Cooling · Well doublet · Groundwater flow

Introduction

The objective of this paper is to re-acquaint a new generation of hydrogeologists with the pioneering analyses of the performance of well-doublet ground source heat schemes by early researchers (Gringarten and Sauty 1975; Tsang et al. 1977) and to synthesise these into a tiered approach to thermogeological risk assessment of the sustainability of such schemes.

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The ground (or groundwater) has been widely used as a heat source or sink for space heating and cooling for many decades. The ground source heat pump (GSHP) was patented by Heinrich Zoelly in 1912 (Ball et al. 1983; Spitler 2005; Kelley 2006). Even before the GSHP became widespread, groundwater from shallow confined aquifers below Shanghai, China, is reported to have been abstracted and used for cooling workshops and factories. This led to over-abstraction and serious ground subsidence until, in the 1960s, the authorities strictly limited shallow consumptive abstraction. Moreover, they commenced re-injecting cold surplus winter surface water into deeper aquifer horizons in an attempt to create a sustainable resource of groundwater “coolth” (Luxiang and Manfang 1984; Volker and Henry 1988). Groundwater was also a popular solution for space cooling in Brooklyn and Long Island, USA in the 1920s and 1930s: so popular, in fact, that there began to be fears that the large scale abstraction of groundwater would deplete the aquifer resource. Authorities then began to insist that the warmer waste water should be somehow re-injected to the aquifer, leading to new fears of regional thermal groundwater “pollution” (Kazmann and Whitehead 1980).

Ground source heating and cooling systems are widespread in the US and Canada and certain European nations (particularly Switzerland, Germany and Scandinavia). Elsewhere in Europe (e.g. UK, Ireland and the Mediterranean) they are regarded as an emerging technology. In large cities, groundwater-based heating and (especially) cooling schemes are being planned by engineers, sometimes with minimal hydrogeological input. In London, UK, for example, the demand for ground source cooling has been huge, thanks to the local authority’s insistence on a certain percentage of renewable energy being incorporated into sizable new developments. Initially, given the perceived surplus of groundwater in the London Chalk aquifer (the groundwater levels had been regionally rising for some decades, due to post-industrial decline in abstraction), most such schemes proposed discharging the abstracted water directly to the River Thames (Ampofo et al. 2004). More recently, the Environment Agency (EA) has noted that groundwater levels beneath London have tended to stabilise, or even decline, in some areas. New consumptive groundwater abstraction licenses have thus been restricted in some parts of London (EA 2006). The EA has thus increasingly

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favoured reinjection of "thermally used" water to the aquifer as a means of conserving water resources. In a repeat of the American experience (Kazmann and Whitehead 1980) from the 1920s–1930s, there is increasing concern over the sustainability of such abstraction-reinjection "well doublet" schemes and their impact on the aquifer's thermal budget (Fry and Kelly 2008).

Groundwater-based heating and cooling using a "well doublet"

A typical well-doublet scheme for heating or cooling typically comprises three elements:

1. An abstraction well, from which water is abstracted at a rate Q and a temperature θ_{gwabs}
2. A heat-transfer system (a heat exchanger or a heat pump), which either extracts heat from, or rejects heat to, the groundwater flux
3. One (or more) re-injection well(s), at a distance L from the abstraction well, where water is re-injected at a rate Q and temperature θ_{gwinj}. For space-cooling schemes, $\theta_{\mathrm{gwinj}} > \theta_{\mathrm{gwabs}}$ and for heating schemes $\theta_{\mathrm{gwinj}} < \theta_{\mathrm{gwabs}}$. The amount of heat rejected to, or extracted from, the water is approximated by:

$$\text{Heat rejected} = Q\left(\theta_{gwinj} - \theta_{gwabs}\right)S_{VCwat} \quad (1)$$

where S_{VCwat} = the volumetric heat capacity of water = ca. 4,180 J L^{-1} K^{-1}

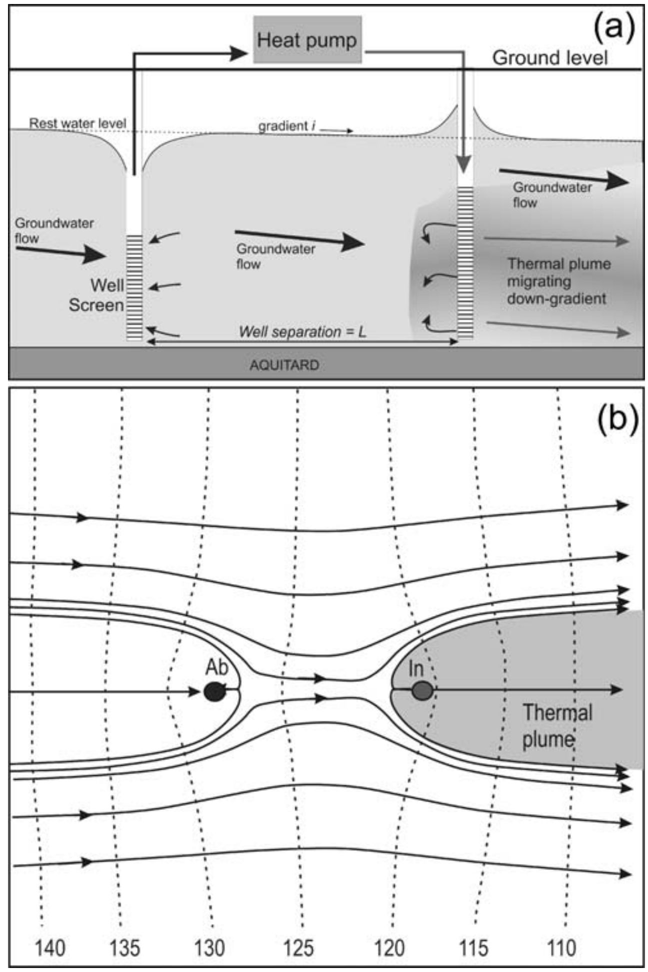

Fig. 1 **a** Section and **b** plan of a well-doublet system for cooling where no hydraulic feedback occurs (modified after Banks 2008). *Arrows* show groundwater flow lines and *dashed contours* are arbitrarily numbered equipotentials. *Ab* abstraction; *In* injection

Risk of failure of thermal well-doublet systems

Let us consider a well-doublet cooling scheme, where naturally cold groundwater is abstracted and warmed water is re-injected to the aquifer. Ideally (Fig. 1), the injection well would be located down the hydraulic gradient from the abstraction well, in the hope that natural groundwater flow would carry the rejected warm water away from the scheme in a "thermal plume", to become "somebody else's problem". The risk to "somebody else" (other aquifer users and environmentally sensitive features) can be considered an "external" risk. Although potentially important, this risk will not be considered further here. There is, however, also a potential "internal" risk to the sustainability of the system. It can be shown theoretically (Lippmann and Tsang 1980; Clyde and Madabhushi 1983; Banks 2007, 2008) that the neat scenario in Fig. 1 will only happen if L (the well separation) is relatively large and if Q is relatively small. In fact, the thermal plume will only fully disappear down-gradient if:

$$L > \frac{2Q}{T.\pi.i} \quad (2)$$

Where T = aquifer transmissivity and i = regional natural hydraulic gradient (this criterion is derived from Eq. (4), below).

If the just described relation is not true, there is a risk that a proportion of the discharged warm water will flow back (against the regional hydraulic gradient) to the abstraction well (Fig. 2). The temperature of the abstracted water will thereafter rise over time, towards a value described by Gringarten and Sauty (1975). At best, this gradually compromises the efficiency of the cooling scheme and at worst it can result in system failure or environmental non-compliance. In other words, far from being a "renewable" cooling source, the system can eventually become unsustainable. In practice, the value of L required to ensure that there is zero risk of thermal feedback is usually unrealistically large for many densely inhabited urban areas (for example, hydrogeologically typical values of T=100 m^2/day, i=0.01, Q=432 m^3/day (5 L/s) require a well separation of 275 m for no hydraulic feedback).

Ferguson and Woodbury (2005) document a case from Winnipeg, Canada, where an open-loop well-doublet

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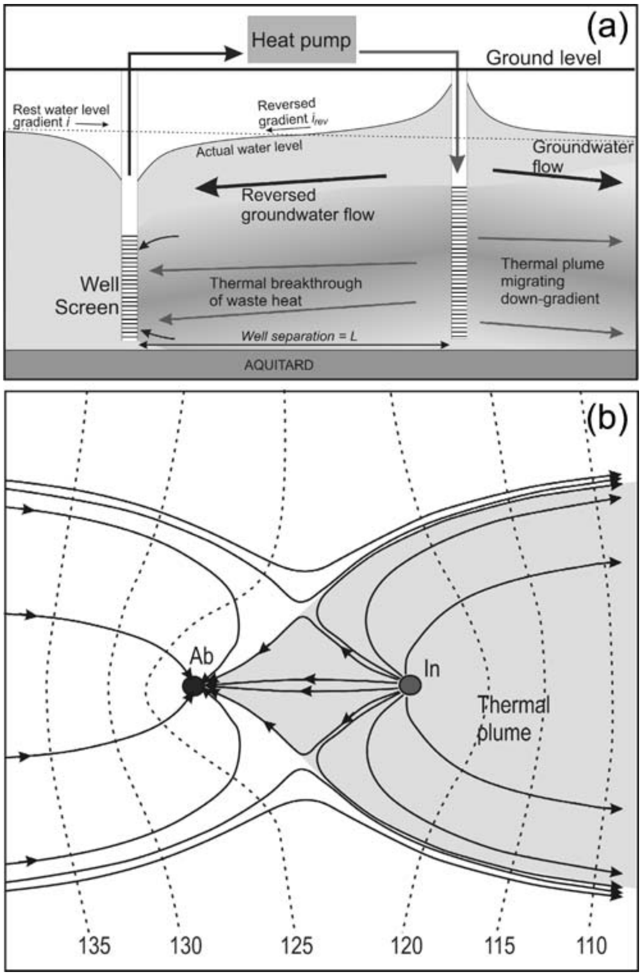

Fig. 2 **a** Section and **b** plan of a well-doublet system for cooling where flow rate (Q) is large enough and the well separation (L) small enough for feedback to occur (modified after Banks 2008). *Arrows* show groundwater flow lines and *dashed contours* are arbitrarily numbered equipotentials. *Ab* abstraction; *In* injection

scheme in a carbonate aquifer almost immediately experienced significant thermal "feedback" following commissioning and a rapid rise in the abstracted water temperature. On the other hand, Todd (2008) describes a scheme in the Sherwood Sandstone of Yorkshire, UK, which has been functioning satisfactorily (although a potential risk of feedback is present), with only minimal rises in the abstracted water temperature, for almost 10 years.

It thus appears that Eq. (2) alone is insufficient as the basis for a risk assessment of such doublet schemes. A more refined methodology is required that enables one to assess the likely timing and magnitude of thermal feedback within a proposed open-loop well-doublet scheme.

Risk of hydraulic feedback

The mathematical analysis of the risk of hydraulic feedback between the re-injection and abstraction wells has been known for several decades. For the case where the natural hydraulic gradient (i)=0, the time (t_{hyd}) taken for groundwater flow along the shortest path between an injection and abstraction well (neglecting dispersion) has been shown from geometric considerations (Hoopes and Harleman 1967; Grove 1971; Güven et al. 1986) to be:

$$t_{hyd} = \pi n_e D \frac{L^2}{3Q} \tag{3}$$

Where n_e = effective porosity and D = effective aquifer thickness.

If i is non-zero and the re-injection well is situated directly down the hydraulic gradient from the abstraction well, Lippmann and Tsang (1980) state that:

$$t_{hyd} = \frac{Ln_e}{Ki}\left[1 + \frac{4\alpha}{\sqrt{-1-4\alpha}}\tan^{-1}\left(\frac{1}{\sqrt{-1-4\alpha}}\right)\right] \tag{4}$$

where:

$\alpha = \frac{Q}{2\pi KDiL} = \frac{Q}{2\pi TiL}$ and K = hydraulic conductivity. i is deemed a negative number and hence α is also negative. Note that, if Eq. (2) is true, no solution exists for t_{hyd} and feedback does not occur.

Risk of thermal feedback

Once the hydraulic travel time from the injection to abstraction well has been calculated, it might appear that this is also the thermal travel time. This is not the case, however: as warm groundwater flows through a cool aquifer matrix, heat is absorbed from the groundwater into the matrix until a thermal equilibrium is attained. This has the effect of retarding the heat travel front (in the same way that sorbed contaminants are retarded by a retardation factor R_f). De Marsily (1986) contends that, if the groundwater flows through a porous medium and contact between water and mineral grains is intimate, then thermal equilibrium is effectively instantaneous (<1 min for grains of <1 mm diameter and 2 h for 10-cm pebbles) and the mineral and groundwater phases in the aquifer at any point can be characterised by a single temperature θ. Let us compare the formulae for one-dimensional advective/dispersive transport of a sorbed chemical solute (Eq. 5; Domenico and Schwartz 1990) and of heat (Eq. 6; De Marsily 1986):

$$\frac{D_x}{R_f}\frac{d^2C}{dx^2} - \frac{1}{R_f}\frac{d(v_xC)}{dx} = \frac{dC}{dt} \tag{5}$$

D_x is a dispersion coefficient, v_x is the linear velocity of groundwater flow and C is solute concentration.

$$\frac{\lambda^*}{S_{VCaq}}\frac{d^2\theta}{dx^2} - \frac{S_{VCwat}.n_e}{S_{VCaq}}\frac{d(v_x\theta)}{dx} = \frac{d\theta}{dt} \tag{6}$$

λ^* is an "effective" thermal conductivity that also takes into account a hydrodynamic dispersion effect, S_{VCaq} is the volumetric heat capacity of the saturated aquifer.

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The parameter $\frac{S_{VCaq}}{n_e S_{VCwat}}$ is thus analogous to R_f and a thermal retardation factor R_{th} (Bodvarsson 1972) can be defined:

$$R_{th} = \frac{v_{hyd}}{v_{the}} = \frac{S_{VCaq}}{n_e S_{VCwat}} \tag{7}$$

where v_{the} is the velocity of a thermal front and v_{hyd} is the hydraulic velocity (of a water molecule). Thus, it is possible to rewrite Eqs. (3) and (4) in terms of thermal breakthrough time t_{the} (Gringarten 1978; Clyde and Madabhushi 1983; Banks 2008):

$$t_{the} = \pi D \frac{S_{VCaq} L^2}{3 S_{VCwat} Q} \; for \; i = 0 \tag{8}$$

$$t_{the} = \frac{S_{VCaq} L}{S_{VCwat} K i} \times \left[1 + \frac{4\alpha}{\sqrt{-1-4\alpha}} \tan^{-1}\left(\frac{1}{\sqrt{-1-4\alpha}}\right)\right] for \; i < 0 \tag{9}$$

Note that the analyses outlined above also work in exactly the same way if chilled water from a heating scheme is being re-injecting, instead of warm water from a cooling scheme.

Can open-loop well-doublet schemes be sustainable?

Having performed a thermogeological risk assessment, it may become evident that the open-loop well-doublet system has a finite operational life before thermal breakthrough becomes too large. However, in an aquifer with a high porosity and a well separation of several hundred metres, the time to thermal breakthrough may be many years. This alone may be enough to render the ground source heating or cooling scheme economically viable (Todd 2008). Moreover, even after thermal breakthrough has occurred, temperatures may not rise so quickly as to render the scheme unworkable immediately. Several years or decades may elapse before the abstracted water becomes unfeasibly warm (if at all). Indeed, Tsang et al. (1977) and Lippmann and Tsang (1980) offer a formula for how the temperature of the abstracted water increases with time following thermal breakthrough, assuming that i=0.

$$\frac{\theta_{gwabs} - \theta_{gwinj}}{\theta_o - \theta_{gwinj}} = 0.338 \exp\left(-0.0023 \frac{t}{t_{the}}\right) + 0.337 \exp\left(-0.1093 \frac{t}{t_{the}}\right) + 1.368 \exp\left(-1.3343 \frac{t}{t_{the}}\right) \tag{10}$$

Where t ($>t_{the}$) = time since scheme started, θ_o = initial temperature of aquifer water, θ_{gwinj} = re-injection temperature (assumed to be constant) and θ_{gwabs} = temperature of abstracted water (which changes with time following thermal breakthrough at time $t = t_{the}$). Hoopes and Harleman (1967) and Güven et al. (1986) provide an alternative, purely geometric model (Fig. 3, which assumes no vertical conduction of heat) yielding a more rapid evolution of abstraction temperature than the Lippmann/Tsang/Witherspoon equation. The discrepancy appears to be most likely due to the latter model (Eq. 10), assuming a degree of vertical conductive heat loss via cap- and bedrock (although Tsang et al. 1977 do not provide details of the parameterisation of vertical heat loss). Note also that, if θ_{gwinj} increases in parallel with θ_{gwabs} (due to a constant temperature differential across the building heat exchanger), the temperature rise will be steeper than predicted in Fig. 3.

Thus, although an open loop well-doublet scheme may not be indefinitely sustainable, its lifetime may be long enough to be economically worthwhile. Gringarten (1978) summarises various strategies for prolonging the life of such abstraction/re-injection schemes and notes that a chequerboard arrangement of alternating abstraction and injection wells is amongst the most efficient ways of exploiting the heat resource of a given volume of aquifer.

Limitations on application of analysis

Equations 2, 8, and 9 (and the models in Fig. 3) are simple enough to be programmed into a computer spreadsheet. In order to judge the reliability of the assessment, one must, however, be aware of the underlying assumptions (Banks 2008), namely:

1. That groundwater flow is laminar and Darcian and can adequately be simulated using homogeneous, saturated porous medium assumptions
2. That dispersion effects (hydrodynamic dispersion and conductive thermal diffusion) are not considered (In reality, some thermal breakthrough will inevitably occur ahead of the calculated mean travel time)
3. That thermal equilibration between groundwater and aquifer matrix is instantaneous
4. That (except for Eq. 10) conductive heat losses into overlying or underlying strata are negligible
5. That the recharge well is located immediately down-gradient of the abstraction well

The equations are thus likely to work best for granular, porous-medium aquifers such as alluvial sands and gravels or porous sandstones. If flow is via fractures, then macro-scale dispersion along fracture pathways of greatly differing transmissivity is likely to be significant, leading to earlier than expected thermal breakthrough. Furthermore, if flow is through a few widely spaced fractures, separated by large volumes of matrix, thermal equilibration between water and matrix will not be instantaneous. This, too, may lead to significant overestimation of travel

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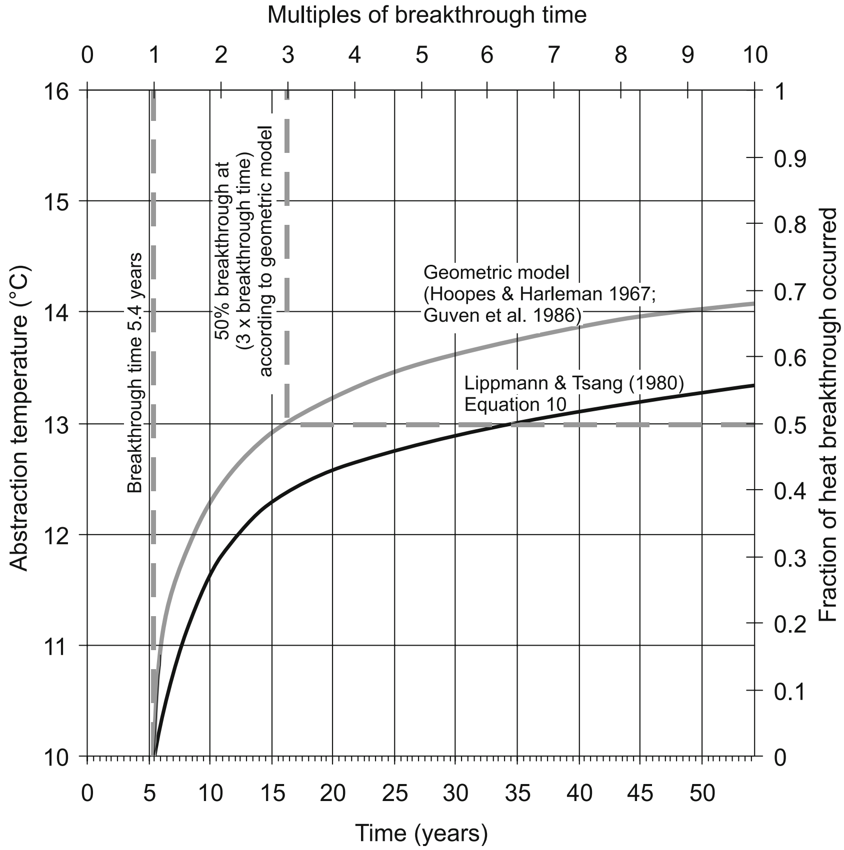

Fig. 3 The predicted temperature evolution in an abstraction well of an open-oop well-doublet system, where the breakthrough time is calculated at 5.43 years, the initial groundwater temperature is 10°C and the constant injection temperature is 16°C. i=0

times. These equations are thus likely to be poorly applicable in fissured and fractured aquifers such as the chalk, many limestones and crystalline bedrock, and should probably only be used for defining best/worst case envelopes. Some progress is, however, being made towards simulating heat migration in fractured and heterogeneous aquifers by, *inter alia*, Shook (2001a, b) and Law et al. (2007).

As regards assumption 2, Hoopes and Harleman (1967) demonstrate that dispersion can be considered in more complex analytical models, while Gringarten and Sauty (1975) and Gringarten (1978) offer techniques to account for vertical conductive losses (assumption 4) and other well geometries (assumption 5).

Seasonally reversible schemes

Probably the best strategy for the sustainable operation of an open-loop well-doublet scheme is to use it (via a reversible heat pump system) alternately for heating in the winter and cooling in the summer. Thus, given a well doublet comprising wells A and B, one could envisage two modes of reversible operation:

Mode 1.
- Winter: Well A used for abstraction. Heat extracted from water. Well B used for recharge of chilled water.
- Summer: Well A used for abstraction. Heat rejected to water from cooling system. Well B used for recharge of warm water.

Here, if the annual heating and cooling loads are well balanced and t_{the} is several years, then, by the time breakthrough occurs, the annual heat signals should have largely evened themselves out and little net temperature change of the abstracted water would be expected.

Mode 2.
- Winter: Well A used for abstraction. Heat extracted from water. Well B used for recharge of chilled water.
- Summer: Well B used for re-abstraction of cold water previously injected during winter. Heat rejected to cold water from cooling system. Well A used for recharge of warm water.
- Next Winter: Well A used for abstraction of previous summer's warm water. Heat extracted from water. Well B used for recharge of chilled water.

Mode 2 with dedicated "hot" and "cold" wells is often called an "aquifer thermal energy storage" (ATES) scheme (Bakema and Snijders 1998; Andersson 1998; Vos 2007). Here, in the heating season, "waste" heat is recovered from the summer: the abstracted water is effectively "pre-

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heated" and the heat pump will operate more efficiently. In the cooling season, "pre-chilled" water is being abstracted and the cooling system operates more efficiently. Furthermore, provided that the seasonal water fluxes and seasonal heating and cooling loads are approximately balanced, sustainable operation is ensured by a well separation that corresponds to a value of t_{the} greater than a single heating or cooling season (i.e. greater than around 6 months). This approach lies behind the well separations recommended by Kazmann and Whitehead (1980).

The disadvantage of mode 2 is that the roles of the wells are seasonally reversed. In aquifers such as the UK Chalk, where unscreened wells can be used, this *may* not be a major problem. In unlithified aquifers, requiring well screens and gravel packs, the construction of recharge wells may differ substantially from abstraction wells, and their roles may not be automatically reversible.

More complex than analytical models can handle?

Clearly, it is possible to reach a stage of complexity that the simple analytical models outlined in this paper cannot handle. For example:

– The recharge well may not be directly down-gradient from the abstraction well
– Heating/cooling loads and re-injection temperatures may vary in a complex manner through the year
– The scheme may comprise multiple abstraction and re-injection wells
– The aquifer may be heterogeneous or may have complex boundary conditions
– The abstraction may occur at a different elevation from re-injection (i.e. three-dimensionality)

In such cases, one may resort to some form of numerical modelling. Several models are available that simulate groundwater flow, solute transport and heat transport. These include:

– SHEMAT (Simulator for HEat and MAss Transport) described by Clauser (2003).
– HST3D (Heat and Solute Transport in three-dimensional ground-water flow systems); a finite difference code produced by the US Geological Survey (Kipp 1997).
– FEFLOW (finite element subsurface FLOW system); a commercial finite element programme

Conclusions

The involvement of hydrogeologists in thermogeological problems is likely to increase, due to the rapid uptake of ground source heat pump and passive cooling technologies. A common type of problem to be tackled is a risk assessment of the open-loop well-doublet system. It is common belief amongst engineers and environmental activists that, because such schemes may represent low-carbon heating/cooling alternatives, they are automatically "sustainable". In fact, this is not necessarily the case: the phenomenon of thermal feedback may place a limit on the usable lifetime of the scheme, ranging from (in the worst case) only months or years to (in the best case) many decades. A risk assessment may consist of several tiers of increasing complexity (see Todd 2008 for a recent example of such an assessment):

Tier 1: Assessment of well separation in relation to hydraulic gradient, discharge rate and transmissivity (Eq. 2). Is there a risk of thermal feedback?
Tier 2: Calculation of likely thermal breakthrough times and evolution of temperature of abstracted water following breakthrough. Is "lifetime" adequately long for scheme to be viable? (Eqs. 8–10; Fig. 3).
Tier 3: Numerical modelling of heat transport coupled to groundwater flow.

This type of risk assessment can be performed with most confidence in porous medium-type aquifers (sands, gravels, some sandstones). A significantly lower degree of confidence can be placed in the methodology for fissured and fractured aquifers (such as many limestones and crystalline rocks). In order to improve sustainability (scheme lifetime), the following steps can be taken:

1. Increase well separation
2. Decrease pumping rate (or decrease re-injection rate by running a proportion of the groundwater flux to waste in a sewer or to surface water)
3. Reconsider scheme layout (Gringarten 1978), or re-injection to and abstraction from different horizons in the aquifer
4. Consider the viability of a balanced, seasonally reversible scheme

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References

Ampofo F, Maidment GG, Missenden JF (2004) Review of groundwater cooling systems in London. Appl Therm Eng 26:2055–2062
Andersson O (1998) Heat pump supported ATES applications in Sweden. IEA Heat Pump Centre Newslett 16(2):20–21
Bakema G, Snijders A (1998) ATES and ground-source heat pumps in the Netherlands. IEA Heat Pump Centre Newslett 16(2):15–17
Ball DA, Fischer RD, Talbert SG, Hodgett D, Auer F (1983) State-of-the-art survey of existing knowledge for the design of ground source heat pump systems. Report ORNL/Sub 80-7800/2, Battelle Columbus Laboratories, Columbus, Ohio, 75 pp
Banks D (2007) Thermogeological assessment of open loop well doublet schemes: an analytical approach. Proc. 27th Annual Conference of the Irish Group of the International Association of Hydrogeologists, Tullamore, Ireland, 24–25 April 2007

 DOI 10.1007/s10040-008-0427-6

Banks D (2008) An introduction to thermogeology: ground source heating and cooling. Blackwell, Oxford, 339 pp

Bodvarsson G (1972) Thermal problems in the siting of reinjection wells. Geothermics 1(2):63–66

Clauser C (ed) (2003) Numerical simulation of reactive flow in hot aquifers: SHEMAT and Processing SHEMAT. Springer, Berlin, 332 pp

Clyde CG, Madabhushi GV (1983) Spacing of wells for heat pumps. J Water Resour Plan Manage 109(3):203–212

De Marsily G (1986) Quantitative hydrogeology: groundwater hydrology for engineers. Academic, Orlando, FL, pp 277–283

Domenico PA, Schwartz FW (1990) Physical and chemical hydrogeology. Wiley, New York, 824 pp

EA (2006) Groundwater levels in the Chalk-Basal Sands aquifer of the London Basin: June 2006. Environment Agency (Thames Region), Reading, UK

Ferguson G, Woodbury AD (2005) Thermal sustainability of groundwater-source cooling in Winnipeg, Manitoba. Can Geotech J 42:1290–1301

Fry V, Kelly T (2008) Management of the London Basin Chalk aquifer: status report 2008. Environment Agency report ea/br/e/std/v1, Environment Agency, Bristol, UK

Gringarten AC (1978) Reservoir lifetime and heat recovery factor in geothermal aquifers used for urban heating. Pure Appl Geophys 117(1–2):297–308

Gringarten AC, Sauty JP (1975) A theoretical study of heat extraction from aquifers with uniform regional flow. J Geophys Res 80:4956–4962

Grove DB (1971) US Geological Survey tracer study, Amargosa Desert, Nye County, Nevada, part II: an analysis of the flow field of a discharging-recharging pair of wells. US Geol Surv Rep USGS-474-99, 56 pp

Güven O, Falta RW, Molz FJ, Melville JG (1986) A simplified analysis of two-well tracer tests in stratified aquifers. Ground Water 24(1):63–71

Hoopes JA, Harleman DR (1967) Wastewater recharge and dispersion in porous media. J Hydraul Div ASCE 93/HY5:51–71

Kazmann RG, Whitehead WR (1980) The spacing of heat pump supply and discharge wells. Ground Water Heat Pump J 1 (2):28–31

Kelley I (2006) Ground-source heat pumps deliver both high efficiency and reliability: good news for both contractors and their customers. Wisconsin Perspect Sept.–Oct. 2006, pp 14–16

Kipp KL (1997) Guide to the revised heat and solute transport simulator: HST3D - version 2. US Geol Surv Water-Resour Invest Rep 97-4157, 149 pp

Law R, Nicholson D, Mayo K (2007) Aquifer thermal energy storage in the fractured London Chalk: a thermal injection/withdrawal test and its interpretation. , Paper SGP-TR-183, Proceedings of the 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, CA, 22–24 Jan 2007

Lippmann MJ, Tsang CF (1980) Groundwater use for cooling: associated aquifer temperature changes. Ground Water 18 (5):452–458

Luxiang S, Manfang B (1984) Case History No. 9.2; Shanghai, China. In: Poland JF (ed) Guidebook to studies of land subsidence due to ground-water withdrawal. UNESCO Stud Rep Hydrol 40:155–160

Shook GM (2001a) Predicting thermal velocities in fractured media from tracer tests. Idaho National Laboratory, Idaho Falls, ID, USA. http://geothermal.id.doe.gov/publications/articles/shookgrcpaper01.pdf. Cited December 2008

Shook GM (2001b) Predicting thermal breakthrough in heterogeneous media from tracer tests. Geothermics 30(6):573–589

Spitler JD (2005) Ground source heat pump system research: past, present and future. Int J HVAC&R Res 11(2):165–167

Todd FK (2008) Impact assessment of a warm water discharge in the Sherwood Sandstone at Selby, North Yorkshire. MSc Thesis, University of Leeds, UK, 82 pp

Tsang CF, Lippmann MJ, Witherspoon PA (1977) Production and reinjection in geothermal reservoirs. Trans Geotherm Resour Coun 1:301–303

Volker A, Henry JC (1988) Side effects of water resources management: overviews and case studies. A contribution to IHP Project 11.1.a, prepared by a working group for IHP-III. IAHS Publication 172, IAHS, Wallingford, UK

Vos L (2007) Underground thermal energy storage in the Netherlands. Proc. 27th Annual Conference of the Irish Group of the International Association of Hydrogeologists, Tullamore, Ireland, 24–25 April 2007, pp 4–24