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Influence of Ground-source Heat Pumps on groundwater

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ABSTRACT

Differently to the deep, high enthalpy geothermal resources exploitation, the widespread use of low grade, shallow geothermal systems for heating and/or cooling has not come along with a proportional development of conceptual and numerical understanding of the impacts of these systems on groundwater. Environmental agencies' requirements often neglect the particularity of the hydrogeological systems and consequently, adverse situations such as increase of temperature of water may occur in aquifers but also in the heat pump extraction wells themselves. This latter should be of particular concern yet reduces the long-term efficiency of these systems.

A state-of-the-art on the existing regulation at different countries where groundwater geothermal systems are implemented is briefly presented, putting special attention on some of the key regulated issues that concern the resources.

The paper presents a two-phase methodological approach, followed to fulfil the Catalan Water Agency requirements. First, analytical expressions are proposed and the direct equations are solved to obtain a preliminary assessment of the thermal impact. Second, we simulate explicitly the impact of groundwater heat pumps with numerical methods that can take the particularities of the aquifer into account. Codes that can handle the coupled heat and flow problem are preferred, but in fact, most codes that solve for groundwater flow and solute transport can be used in the methodology.

The methodology is applied to a study case where interferences with groundwater wells and underground constructions like concrete walls and tunnels are analyzed. In general terms, the study shows the feasibility of the system and that the thermal plume is mostly controlled by the amount of water involved and the difference in temperatures between these waters.

1. INTRODUCTION AND FRAMEWORK

Today's major environmental challenge is global warming. Society and governments had received the message that the scientific community has proclaimed all through the last years that *an improvement of energy efficiency and a responsible energy usage reduces green-house gas (GHG) emissions that contribute to climate change* and several key actions are focused on this.

Within this context, heating, cooling or air conditioning of houses and facilities represent one of the major percentages in the total energy consumption. Among the several conventional systems for these purposes, the most widely extended systems are based on the utilization of fossils compounds –such as carbon, gas oil or natural gas- which increases the GHG emissions.

An alternative to conventional systems that permits improving energy efficiency in climate control, are the so called geothermal heat pumps or ground-source heat pumps. Ground-source heat pump systems (GSHP) are one of the 'new' energy technologies that has shown rapid increase worldwide in usage over the past years. These systems offer substantial benefits to consumers and utilities in energy savings. Additionally, a framework of grants is available within many countries to individuals, organisations and companies wishing to install GSHP technology, since geothermal energy is considered a renewable energy source.

This paper is not devoted to proclaim the energy efficiency and effectiveness of the system; since there are a lot of publications focused on this (Pratsch 1990, Pratsch 1992 or Lienau et al. 2000 among many others), but particularly it will be centred on the influence of GSHP on groundwater, specifically in those systems in which thermal exchange is produced in groundwater.

When using a Groundwater Heat Pump (GWHP) system, also named open loop, for heating, and especially for cooling, water is injected back into the aquifer at different temperature from the original one. These differences in water temperatures can produce abnormal effects in the aquifer's temperatures. In fact, temperatures at different aquifers at some European cities where an intensive use of groundwater for these purposes exists, has increase beyond 25 ºC, having presently little notion on the environmental impacts produced on the resources, and consequently, on the associated ecosystems.

Frequently, regulators requirements' do not take, neither the particularities of the GWHP, nor the hydrogeological systems' into account, thus lacking of a robust regulation established worldwide. Hence, the little knowledge on the influence of GWHP in terms of thermal, biological or chemical impacts on the aquifers do not foster regulation in protected areas or vulnerable aquifers.

GSHP systems had been implemented in many countries along the last decades, especially in the EEUU, Canada, Japan and some of the northern European countries, but its implementation is incipient or relatively 'new' in many other countries. This is the case of Catalonia in Spain, where high energy demand buildings, such as for example hotels are focusing their interest in this technology.

With the aim of protecting the groundwater resources, the Catalan Water Agency (CWA) by means of its Hydraulic Public Domain Department requires to any potential usage of groundwater for building climate control a thermal and hydrogeological study of feasibility of the system.

With this end, ENVIROS has established a two-phase study to fulfil the requirements of the CWA. This methodology has been applied to some cases of study, one of which will be shown in the presented paper. Simultaneously, ENVIROS has been committed by the agency to perform an elaboration of a good practice guideline concerning climate control using groundwater to be followed by constructors, architects, engineering and environmental consultants.

The guide will address to the following objectives: (1) to review the state of water agencies' regulation worldwide; (2) to assess if the actual studies devoted to estimate the impacts on groundwater and infrastructures have enough technical rigor (3) to evaluate the effectiveness of simple analytical approaches to be applied for an easy estimation of thermal impact; (4) to compare analytical solutions with those produced by means of numerical approaches; and (5) to compare the solutions produced by some of the most conventional groundwater flow and transport numerical codes and to test their applicability to assess thermal impacts.

This project is still on-going and only some of the above mentioned issues will be briefly discussed along this paper.

2. BRIEF STATE-OF-THE-ART ON REGULATION OF GWHP SYSTEMS

Despite the high development and efficiency of the geothermal heat pumps and its implementation worldwide, only some estates of EEUU, Sweden or France have a relatively unambiguous legal framework within Some other countries such us Switzerland or Austria are presently developing its own regulation and some others such us Greece, Romania or Germany are focussing their efforts in terms of regulation on closed loop systems in which thermal exchange does not involves groundwater.

In general terms, regulation on GWHP systems constraints a series of key issues of concern for the resources. These are mainly: (1) the difference in temperature between extracted and injected water or thermal range (Δt), (2) additives utilisation, (3) typology of the involved aquifers and (4) protected areas to open loop systems.

The thermal range (Δt) represents the difference between the temperatures of injected and extracted withdrawals. Some guidelines and recommendations are given regarding Δt. While some countries, as for example Canada or Austria, regulate and recommend 5ºC for Δt others like France or Germany regulate 11 and 0.5 ºC respectively. On the other hand, a country with a well established regulation framework, as Sweden, does not have any constraint on the Δt produced to groundwater.

Additives are forbidden in Canada, Sweden, Switzerland and Holland, while in some countries, such as France or Denmark, can be used presenting feasibility studies.

Thermo-hydraulic short circuiting between different aquifers is not allowed for most of the regulations found, and usually, the systems concentrate on the worst quality aquifers in cities,.

At many locations, areas where a drinking water well or mineral water companies exists, implementation of open loop systems is strictly forbidden. Additionally, other particular cases such Japan where water extraction is associated to land subsidence also forbid open loop systems, thus having a knock-on effect on a major implementation and development of closed loop technologies. Other regulation coincide with natural parks (as for example in France) or contaminated areas (Sweden or EEUU).

At countries where no regulation is currently in force, such as for example UK, Denmark, Holland or Spain each particular case is treated specifically and a hydro-geo-thermal study of aquifer vulnerability and impact on the resources is often required by the regulating agencies.

3. METHODOLOGY APPLIED TO ASSESS THERMAL IMPACT

Until the guideline will be finished or any robust regulation will exist, CWA requirements can be fulfilled by organisations and companies wishing to install GWHP systems by means of hydro -and thermo- geological studies to be checked and approved by their corresponding technicians.

ENVIROS had been committed in the last years by several companies, usually hotel chains and other large buildings where open loops can have better energy savings and full costs of implementation than closed loops. Among the tasks performed throughout these projects can be found: the feasibility of the proposed system; the dimension of injection and extraction wells and their optimal location to avoid thermal and hydraulic interferences and the assessment of the thermal impact expected to fit CWA requirements.

With this end, a two-phase approach methodology based on both analytical expressions and numerical modelling techniques had been well established to reach the previous objectives.

The starting phase of the study is devoted to a preliminary assessment of the feasibility of the system; in terms of both accomplish and fulfil water –and energy- demands and to analytically estimate if the heat plume could be dissipated downwards. A second numerical approach phase is devoted to tune locations; to fix a more exactly water and energy demands throughout operating times; and to more accurately estimate expected impacts on singular features.

This paper will deal with two topics within the overall standard project: how to estimate the expected impacts with both analytical solutions and numerical techniques.

3.1 Preliminary evaluation of the expected impact by using analytical expressions

Major development of technologies and conceptualisation is purely associated to closed loop systems since these are the more implemented everywhere. Consequently, scientific literature has growth in parallel to development, and while there are an important amount of papers focused on closed loop systems, only a few can be found concerning GWHP. Some examples on closed loops geothermal impacts can be found at Diao et al. (2004); Fujii et al. (2005) or Gehlin et al. (2003).

This fact could be explained by the intrinsic characteristics of the system that requires an associated hidrogeologic study for the design (and impact) and a frequently extensive bureaucratic and administrative documentation to be presented at the corresponding regulating agency (Berntsson, 2002; Rafferty, 2003).

Heat transport had been tackled in terms of media characterisation (Anderson, 2005) and heat -or cold- storage (Chevalier, 1999; Dwyer and Eckstein, 1987) but only few articles tackle thermal impacts of these systems. An example on this last is Ferguson and Woodbury (2006), where importance on design of open loop systems is put evidence in a hydraulic system where 4 different GWHP systems interfere between them, affecting their operating ratios.

Prior to the description of 2 analytical expressions to assess thermal impact it is necessary to describe how the heat can be transported in aquifers. With this end, the next subsection shortly describes controlling processes and parameters.

Energy (heat) transport in aquifers

Energy is transported in the water-solid matrix system by groundwater flow, and by thermal conduction from higher to lower temperatures through both the fluid and solid. As the true, not average, velocity field is usually too complex to be measured in real systems, an additional transport mechanism approximating the effects of mixing of different temperatures of groundwater moving both faster and slower than the average velocity, (v) is hypothesized. This mechanism is called energy dispersion, and tends to approximate, the description of these mixing process.

In this way, the energy transport balance equation follows the expression:

$$\rho''c''\frac{\partial T}{\partial t} = \nabla\left((\lambda + D\rho_w c_w)\nabla T\right) - \left(q\rho_w c_w \nabla T\right) - \left(q_R T_R\right) \quad (3.1)$$

where ρ'' is the aquifer density (Kg m^{-3}); c'' is the aquifer specific heat (J Kg^{-1} K^{-1}); ρ_w is water density (Kg m^{-3}); c_w the fluid specific heat (J Kg^{-1} K^{-1}); T is the temperature (ºK); t is time (s); λ is the aquifer (bulk) thermal conductivity (J s^{-1} m^{-1} K^{-1}); D is the dispersion (m^2 s^{-1}); q is the Darcy's flux (m^3/s); q_R is an injected/extracted flow rate (m^3/s); and T_R is the injected/extracted temperature of the injected/extracted fluid (ºK).

The time derivative (left-hand side of equation 3.1) expresses the total change in energy stored in both the solid matrix and fluid per unit total volume. On the right hand side, the first term can be understood as divided into two; the term involving bulk thermal conductivity (λ) expresses heat conduction contributions to local stored energy; and the term involving the dispersivity tensor (D) approximately expresses the contribution of irregular flows and mixing, which are not accounted for by average energy advection. The term involving q expresses contributions to locally stored energy from average-uniform flowing fluid (average energy advection). The term involving q_R accounts for the energy added by a fluid source with temperature, T_R.

Additional sink/source terms can be added to this expression to account for energy production in the fluid and solid, respectively, due for example to chemical (endothermic) reactions.

Aquifer calorific capacity can be expressed as the sum of specific heat from both water and soil (G. de Marsily, 1986):

$$\rho''c'' = \left(\phi\rho_w c_w\right) + \left((1-\phi)\rho_s c_s\right) \quad (3.2)$$

where ρ_s is the solid density (Kg m^{-3}); c_s is the solid specific heat (J Kg^{-1} K^{-1}); and ϕ is porosity.

Thermal conductivity of the aquifer can be expressed as the sum of water and solid thermal conductivities following the expression:

$$\lambda = \left(\phi\lambda_w\right) + \left((1-\phi)\lambda_S\right) \quad (3.3)$$

where λ_w and λ_S represent thermal conductivities for both water and solid (J s^{-1} m^{-1} K^{-1}) respectively.

Substituting equations 3.2 and 3.3 into equation 3.1 results in:

$$\phi\left(1 + \frac{(1-\phi)\left(\frac{\rho_s c_s}{\rho_w c_w}\right)}{\phi}\right)\frac{\partial T}{\partial t} = \nabla\left(\left(\alpha q + \frac{\lambda}{\rho_w c_w}\right)\nabla T\right) - \left(q\nabla T\right) - \left(q_R T_R\right) \quad (3.4)$$

$$D = \alpha q + \frac{\lambda}{\rho_w c_w} \quad (3.5)$$

$$R = 1 + \frac{(1-\phi)\left(\frac{\rho_s c_s}{\rho_w c_w}\right)}{\phi} \quad (3.6)$$

D [L^2·T^{-1}] represents the dissipation coefficient and R [-] is the retardation coefficient.

Walton (1979) lists a series of analytical solutions available to perform the solute and energy transport equation in an aquifer. Among these equations and with the end of a preliminarily assessment of the thermal impact of a system, 2 different analytical approximations can be selected for these purposes: (1) heat transport in a semi-infinite 1D column and (2) radial heat transport from an injection well.

Heat transport in a semi-infinite 1D

This expression states that in a semi-infinite 1D column, with a boundary condition of constant heat flux at x=0, equivalent to a heat injection, the shortest pathway in a dipole test will follow the following initial and boundary conditions:

$t \le 0,\ x > 0,\ T = 0$

$t > 0,\ x = 0, \qquad [T_0 - T]v = -D\frac{\partial T}{\partial x} \quad (3.7)$

$t > 0,\ x > 0,\ T = 0$

The solution of Gershon and Nir (1969) (also detailed in Bear; 1972) follows:

$$\frac{T(x,t)}{T_0} = \frac{1}{2}erfc\left\{\frac{Rx - vt}{\sqrt{4RDt}}\right\} - \frac{1}{2}\exp\left(-\frac{vx}{D}\right)erfc\left\{\frac{Rx + vt}{\sqrt{4RDt}}\right\}\left(1 + \frac{Rx + vt}{\left(\frac{RD}{v}\right)}\right) + $$
$$+ \sqrt{\frac{v^2 t}{\pi RD}}\exp\left(-\frac{vx}{D} - \frac{(Rx + vt)^2}{4RDt}\right) \quad (3.8)$$

where $T(x,t)$ [T] is the temperature at a distance x from the boundary domain and at a time t; T_0 [T] is the prescribed temperature -thermal range (Δt) of the system-; x [L] is the observation distance; v [L·T^{-1}] is the average velocity (Darcy's velocity times the porosity) and $erfc$ is the complementary error function.

A standard temperature solution for a semi-infinite media for a given thermal range in a GWHP system can be showed in Figure 1. This solution follows a sigmoid.

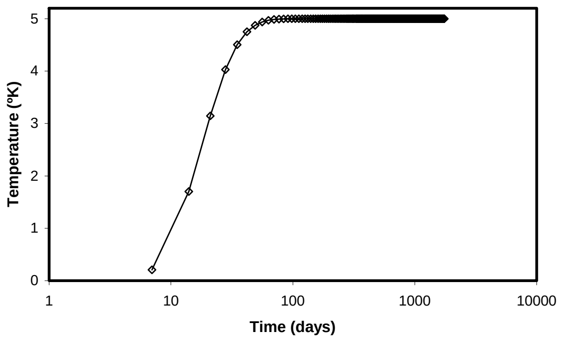

Figure 1: Standard energy transport 1D solution for a semi-infinite media and a thermal range (Δt=5ºK).

radial heat transport from an injection well

Another useful analytical equation that can be potentially utilised to assess thermal impact is the solution expressed on Gelhar and Collins (1971). The expression is a modification of the conventional radial flow equation for a fully penetrating injection well in a confined aquifer. Fluid is injected at a rate of Q_{tot}, with a temperature of T*, into an aquifer initially at a temperature of T_0.

Radial flow propagation from the injected well follows the expression:

$$\left(\frac{T-T_0}{T^*-T_0}\right)=\frac{1}{2}erfc\left\{\frac{r^2-\left(r^*\right)^2}{2\left[\left(\frac{4}{3}\alpha_L\right)\left(r^*\right)^3+\left(\frac{\lambda}{A_T}\right)\left(r^*\right)^4\right]^{\frac{1}{2}}}\right\} \qquad (3.9)$$

where:

$$A_T=\left(\frac{\phi\rho_w c_w}{\gamma}\right)\frac{Q_{TOT}}{2\pi\phi b\rho_w} \qquad (3.10)$$

$$r^*=\left(2A_T t\right)^{\frac{1}{2}} \qquad (3.11)$$

and where the rest of the terms had been defined in previous equations.

The above energy solution may be obtained from the solute solution by retarding the velocity of transport to represent energy storage in the solid grains of the aquifer material in the storage term of the analytical solution.

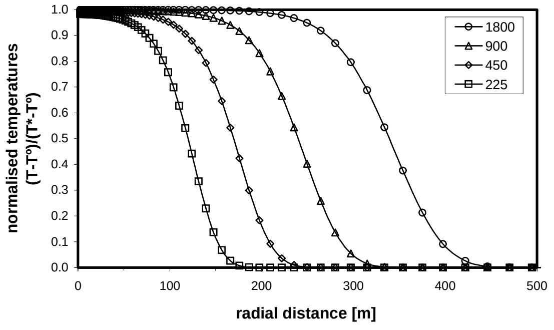

Figure 2: Standard analytical solution for radial energy transport (modified from Gelhar and Collins, 1971) for different time steps (1800, 900, 450 and 225) where 1 time step represents 4021 s.

These solutions become *worst case* scenarios that not contemplate all the existing features and singularities of the aquifers. In the case of the first one approach, since the equation is one-dimensional, no temperature losses within other geological materials in the vicinity of the aquifer (top, bottom and laterally), or atmosphere are considered, and as heat injection remains constant, the estimated impact solution represents the highest and worst limit for the solution. Furthermore, the solution produces valuable information on the heat behaviour, as can aport an estimation for the steady state of the heat plume in aquifer natural conditions.

Concerning the second analytical expression, no dissipation on top and bottom layers of the aquifer is taken into account and also represents a conservative approximation. On the other hand, analytical solutions represent potent tools for benchmarking of the solutions that numerical codes compute, playing an important role on the testing and validation of the reliability of the numerical techniques.

3.2 Assessment of the expected impact by using numerical techniques

Analytical expressions can not permit to represent all the ‘real’ existing heterogeneities in aquifers. For those cases that preliminary –first- evaluation does not clearly discard the implementation of this technology, a numerical conceptualisation will allow tuning well locations and fixing water flowrates and associated temperatures to fulfil energy demands through operating time. Thus, benefits in the system designs are clearly a key point.

Another key point to take into account, lie in that numerical models will permit to include within its discretisation, key infrastructures potentially to be affected, other existing GSHP systems or drinking wells, as well as, the heat plume dissipation itself, consequently, assessing in a more accurate manner the thermal impact of the geothermal system.

Numerical models to be preferred applied are those solving the coupled flow and energy equations, but in fact, most codes that permit solving groundwater flow and solute transport can be used, applying an easy analogy between some of the key parameters of the solute and energy transport.

In the next section, a case of study where ENVIROS had applied the presented methodology is briefly described. Only those issues concerning numerical modelling will be described, since prior information was devoted to conceptualization of the problem and site characterisation tasks.

4. ASSESSMENT OF THE THERMAL IMPACT IN A CASE OF STUDY

The case of study is located in l’Hospitalet del Llobregat, a nearest village in the southeast part of the Barcelona city. Concerning the hydrogeology, the area is located within the Llobregat alluvial multilayer aquifer, which corresponds to the Delta area of the Llobregat River (Figure 3).

Synthesizing, this multilayer aquifer is formed by two sand and gravel quaternary aquifers separated by an aquitard (clay and silt materials with a low hydraulic conductivity) placed over a marl host material (Agència, 2004). The thickness of the superficial aquifer ranges from 10 to 20 meters, and in general terms its behaviour matches with an unconfined aquifer. Its exploitation has decrease through the last years, since its quality has a parallel decrease due to some contamination episodes, as well as it is affected by salt water intrusion.

The principal -deep- aquifer has thicknesses ranging from 4 to 20 meters and a confined behaviour. It is exploited for drinking water purposes and plays an important role on the water management context of the Barcelona area, and consequently of the Catalonian region.

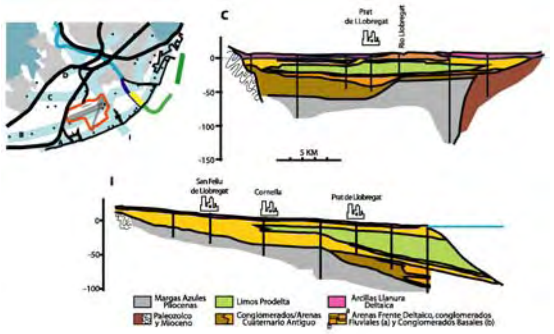

Figure 3: Simplified geological framework of the studied area (Agència, 2004).

Within above hydrogeological context a hotel chains wishing to have presence in this particular area, started bureaucratic and administrative documentation at CWA with the end of implementing an open loop geothermal system for cooling space, basically. If the proposed GWHP system is feasible, this will be placed in the superficial aquifer, as a first requirement of the CWA.

With the end to give advice and helping implementers in the GWHP design tasks, as well as to satisfy CWA requirements, ENVIROS was committed by the company to perform some parts of the overall project.

Prior tasks devoted to geological, hydrogeological and geotechnical characterization will not be object of this paper that will focused their efforts on the description of the second numerical modelling phase undertaken to assess thermal impact and feasibility of the GWHP technology.

A great number of boreholes (Figure 4) were available from the characterization phase. However, boreholes' diameters differed between them, and not all permitted to produce expected water demands. Consequently they were not being introduced in the model to optimizing mesh size.

The selected domain represents an area of 1500x1500 meters in the vicinity of the hotel plot and can be discretised in a finite element mesh (FEM) where computations will be finally done. The model represents this domain by means of a quasi-3D finite element mesh (a plan view of the FEM is showed in Figure 5).

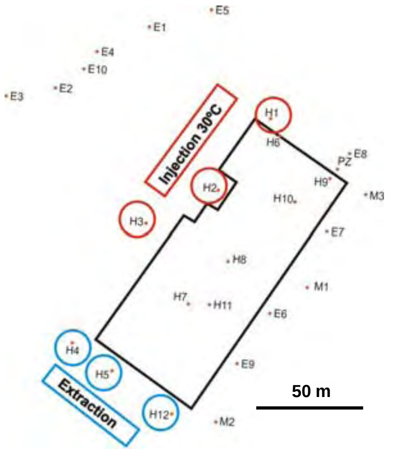

Figure 4: Well points in the vicinity of the hotel. The figure shows a configuration of 3 dipoles (extraction/injection wells) and some of the existing monitoring points.

Mesh refinement around well points had been performed in order to avoid any numerical problems due to high thermal and hydraulic gradients.

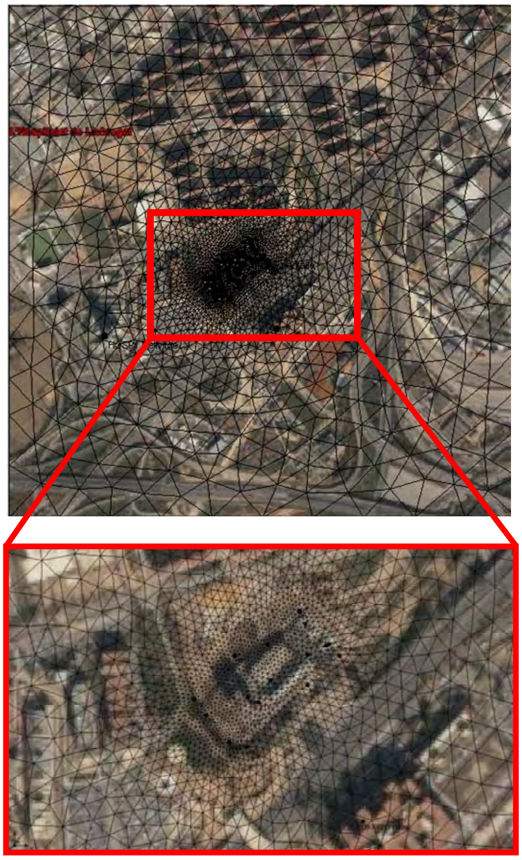

Figure 5: Discretisation of the area. The figure shows a plan view of the finite element mesh within the domain (up) and a detail of the mesh refinement in the vicinity of the hotel (down).

The domain was selected in such a way that boundary conditions to be applied did not affect results. In this way, lateral (E and W) boundaries were prescribed as no flux boundaries, since flux had a clearly S-N component, where the north coincided with the down gradient direction. In order to respect this flow direction, N and S boundaries

Three-dimensionality was modelled by means of 1D finite elements in order to represent heat dissipation through the atmosphere and through the underlying aquitard. 2D models are not suitable to represent these heat transport 'realities', and consequently sub-estimate heat dissipation in the third dimension, converting quasi-3D or fully 3D models into the most rigorous approach.

Following this, top and bottom were also selected as no flux boundary conditions, as top coincides with topography and no flux though the underlying aquifer was assumed.

Concerning energy transport boundary conditions, water entering S boundary entered in the system at 15 ºC, while the injected water in the wells injection was done at 30 ºC. Additionally, heat can be dissipated through the atmosphere and aquifer.

The system was supposed initially at a temperature of 15ºC and the corresponding head levels at each node according the existing piezometer field were fixed.

In order to perform the computations, a FE numerical code was selected. As mention, a conventional code that solves groundwater flow and solute transport can be used, applying an easy analogy between some of the key parameters of the solute and energy transport. TRANSIN code (Medina et al., 1996) was selected for the modelling of the coupled transient flow and transport equations.

Time discretisation was selected in order to avoid numerical problems associated to Courant and Peclet numbers. Also, the total simulation time was selected in such a way that the system arise a steady heat transport state. Finally, 20 years of simulation were computed.

Energy demands –and consequently water demands- is one of the key points in the overall design of a system. A tight collaboration and feedback between climate engineers and hydrogeologists must exist and is extremely necessary in order to success. Thermal ranges to be applicable to groundwater can be combined with different flowrates of the extraction wells in order to satisfy the energy demand, but it is indispensable to have in mind the available resources and the downward impact. Numerical simulations (modelling scenarios) play an important role to optimize the system.

In the case of study, water demands (Figure 6) were considered the controlling factor, as the accumulating flow-rate expected to be in a year raised to 0.4 hm^3, thus leading to important impacts.

The model also considered nearest infrastructures and wells to be potentially affected.

After a calibration phase of the main controlling parameters, a series of modelling scenarios were selected to check different well configurations, volumes and thermal ranges.

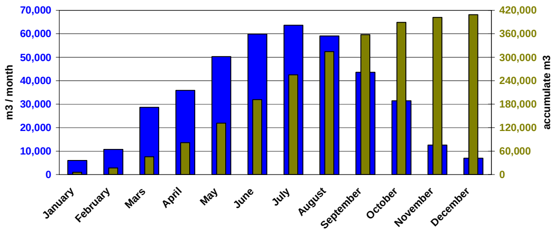

Figure 6: Water demand through a year. The left axis shows needed flowrates to fulfil energy demand, and the right axis shows the accumulating demand along the year.

Modelling results showed that at the higher extracted volumes (July and August) the hydraulic affection on the vicinity was not negligible. In terms of drawdowns (well influence perimeter) the affected area –some centimetres- arise to 500 meters (Figure 7), while in the well extraction area exceeded 1 meter. In spite of, the system did not affect any of the singular features considerably.

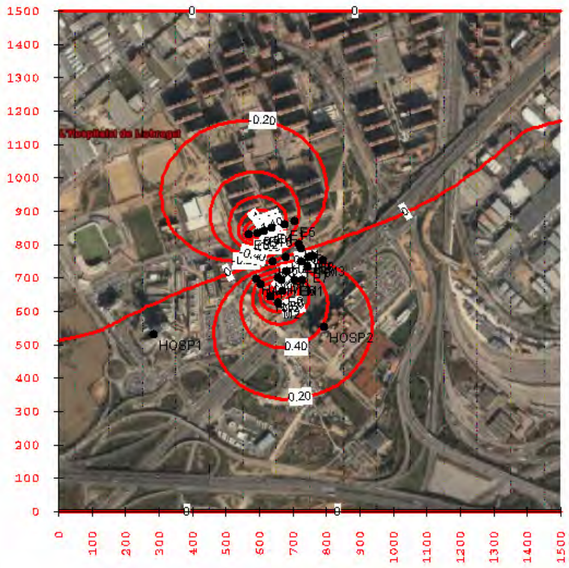

Figure 7: Hydraulic impacts of the system. The figure shows the drawdowns in the area after 180 days of simulation (values in meters).

Concerning thermal plumes, the affected area clearly exceeded 500 meters (some few degrees). Extraction wells were also affected putting in evidence that efficiency of the system was compromised by the presented configuration.

Not only the effectiveness and efficiency of the system was putted in evidence with the expected energy demands but also CWA requirements in terms of expected impacts were surpassed.

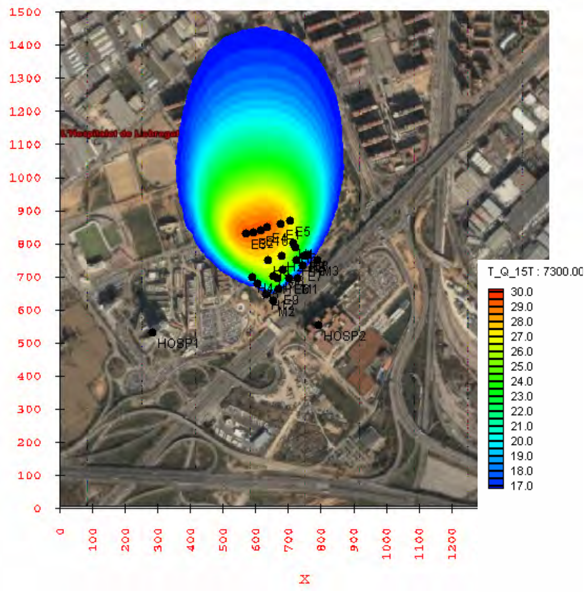

Figure 8: Thermal impact of the system. Steady heat plume in the aquifer achieved at 10 years of simulation (values in ºC). The thermal range produced to groundwater is 15 ºC.

Additionally, a sensitivity analyses on the most relevant parameters was made with particular emphasis on the abstraction/injection water yields and their corresponding temperature difference. The analysis showed that the impacts in groundwater, in terms of temperature plume, were relatively insensitive to the thermal properties of the rock, and to some of the most relevant for solute transport such as dispersivity, while the mentioned temperature difference and flowrates involved were deemed crucial in the propagation of the perturbation.

5. CONCLUSIONS

A brief state-of-the-art on the existing regulation at different countries where groundwater geothermal systems are implemented is presented. As shown, much can be done in terms of regulation and recommendations. The paper has centred efforts on thermal impacts of open loop systems in groundwaters but also closed loops can affect on the resources.

The paper has presented a two-phase approach methodology to assess thermal impact based on both analytical and numerical approaches.

Analytical expressions can be useful tools to preliminary assess the thermal impact in aquifers but they usually become worst case scenarios because do not contemplate all the existing features and singularities of the aquifers. Furthermore, they can produce valuable information to reject a proposed system.

On the other hand, numerical models can match environmental agencies' requirements, as well as design demands of implementers, yet can test the long-term efficiency of these systems. Codes that can handle the coupled heat and flow problem are preferred to model heat transport, but also codes that solve groundwater flow and solute transport can be used using a simple analogy between solute and energy parameters.

Only the thermal impact of GWHP was tackled and other plausible impacts, such us biological growing or chemical impacts are still areas of little knowledge.

The methodology was applied to a study case where interferences with groundwater wells and underground constructions like concrete walls and tunnels were analyzed. The numerical model has shown that can be a potent tool to approach thermal impact and designing a GWHP system and test its efficiency.

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