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Application of Aquifer Thermal Energy Storage for heating and cooling of greenhouses in France: a pre-feasibility study.

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ABSTRACT

In the present context of predicted shortage of fossil energies and awareness of environmental preoccupations (greenhouse gases for example), saving energy and converting it to renewable one become priorities. As energy-intensive consumers, greenhouses are directly concerned. That's why Ctifl (Technical Institute for Fruit and Vegetables) would like to develop the concept of "sustainable greenhouses" in France, using renewable energy. In this case, the method which retains the attention is the concept of reversible heating and cooling through Aquifer Thermal Energy Storage (ATES). This technique is already in application in other European countries, especially in the Netherlands, but has never been tested in France for greenhouses. This paper presents the research project actually led by Ctifl and Brgm (French Geological Survey). The objective of this project is to determine the parameters to take into account (and their relative importance), to evaluate the pre-feasibility of this technique on an agricultural site. This was done through numerical modeling of theoretical aquifer. The model used is a finite volumes software developed by Brgm, which can treat both water flow and thermal transfers. A sensitivity analysis is led on several sets of parameters sets, which depend either on exploitation conditions (pumping and injection discharge, distance between wells, etc.), or on aquifer conditions (geometry, thermal and hydraulic characteristics, etc.).

1. INTRODUCTION

In the now urging context of predicted shortage of fossil energies, and with the increasing awareness of environmental preoccupations (greenhouses gas for example), saving energies and converting to renewable ones become priorities. As energy-intensive consumers, greenhouses are directly concerned. In the past few years, the price of fossil energies as gas and fuel has increased in such a way that the annual costs of heating become a larger and larger part of the total exploitation charges of an agricultural site (about 20 to 35%).

That's why the Ctifl (Technical Institute for Fruit and Vegetables) would like to develop the concept of "sustainable greenhouses" in France, promoting the use of renewable energy. In this case, the method which retains the attention is the concept of reversible heating and cooling through Aquifer Thermal Energy Storage (ATES). This technique is already in application in other European countries, especially in the Netherlands. A status beginning of 2005 reports that over 400 projects were operational in the Netherlands, concerning office and commercial buildings, hospitals, housing, industry and agriculture (Snijders (2005)). Other examples of applications can also be mentioned, as the new parliament building in Berlin (Germany), the Sussex hospital in Canada, large scale experiences in Sweden (heating and cooling of commercial buildings) and an experimental greenhouse in Turkey (Turgut *et al.* (2006)).

This paper deals with a pre-feasibility study of Aquifer Thermal Energy Storage, especially in relatively few deep aquifers (10m to 100-150m depth), applied for heating and cooling of greenhouses in France. This study is actually led by Brgm and Ctifl. Its objective is to determine the parameters to take into account (and their relative importance), to evaluate the pre-feasibility of this technique on an agricultural site, for a given range of energetic needs, both for cooling and heating. This study is led through numerical modeling of "theoretical aquifers". Different sets of parameters, depending both on aquifer characteristics and on exploitation conditions, are tested and compared through their effects on ATES efficiency.

2. USING GREENHOUSE AS "SOLAR CAPTOR" – DIMENSIONING THE NECESSARY FLOW RATE FROM AQUIFER

With large glass surfaces, greenhouses act as real "solar captors". The concept of "solar greenhouse" consists in exploiting heat surplus for heating in winter by storing this surplus in aquifer. The objective is to calculate the net energy surplus which is the result of energy inputs (solar radiation) minus the heat losses. The energy balance allows then to deduce the flow rates from the aquifer.

Table 1 shows an example of energy balance for climate conditions in the South of France, with a temperature set point of 17 °C in the greenhouse during the night. The maximum cooling capacity is around 500 W/m² to have a temperature in greenhouse below 28°C during the summer period. The first calculation shows that the maximum flow rate demand from the aquifer is around 260 m^3/h/ha during the cooling period.

Table 1: Energy balance for climate conditions of South of France.

	Winter	Spring	Summer	Autumn	Year
Energy consumption for heating (kWh/m²)	147	87	3	63	300
Energy input Solar radiation (kWh/m²)	187	498	659	498	1607
Maximum flow rate (m^3/h/ha) 1 ha = 10000 m²	118	242	260	80	21 (*)

*: the average number of m^3 per m² per hour during a year

3. PRINCIPLE OF AQUIFER THERMAL ENERGY STORAGE (ATES) USING A REVERSIBLE GEOTHERMAL DOUBLET

The principle of Aquifer Thermal Energy Storage is to take advantage of the thermal capacity of both the geological formations and the water they contain: groundwater is used both as a reservoir and a vector of energy. Geological materials constitute favourable environment for energy storage as they present low thermal conductivities leading to a slow diffusion of energy and moderate thermal losses (Chevalier *et al.* (1997)). The environments of consideration are mainly quite shallow aquifers, lying in few ten meters depth, and where the groundwater temperature remains quite constant over the year (close to the annual mean temperature of the outside air at the site). This low temperature (<30°C) geothermal energy is largely exploited for the heating and cooling of houses, through the use of a geothermal pump (as in the Ile-de-France region for example).

The Aquifer Thermal Energy Storage installation envisaged in the study is based on the use of a geothermal doublet, that means a pair of water wells, one "hot well", and one "cold well". The system is said reversible, as each borehole is used alternatively in pumping or injection according to the season. The principle scheme of a reversible geothermal doublet is shown in Figure 1:

- in cold season, groundwater is pumped from the "warm well", gets cold while heating the greenhouse, and is injected in the "cold well",
- in the hot season the flow is inverted: groundwater is pumped from the "cold well", gets heated while cooling the greenhouse, and is injected in the "warm well".

This use of a reversible geothermal doublet presents some advantages:

- storage of heated and cold water increases the temperature contrasts, and so the efficiency of the system,
- pumped groundwater is re-injected in the same aquifer, limiting the risks of hydraulic overexploitation,
- system is inverted seasonally, limiting the risks of long-term warming or cooling of the aquifer, that could cause both environmental degradations and a drop in efficiency (Bridger and Allen (2005)).

This functioning involves also some counterparts:

- the investments costs are higher than in a non reversible system, as boreholes have to be very carefully designed to function in pumping as well as in injection,
- injection in a borehole is always more difficult than pumping (higher pressure necessary to inject than to pump the same water discharge, clogging risks, etc.). This implies an over-dimensioning of the boreholes (diameters, strainer, etc.) compared to wells acting only for injection.

It should be noted that a particular attention would have to be taken on all the surface installations to avoid any contaminant risks of the re-injected groundwater.

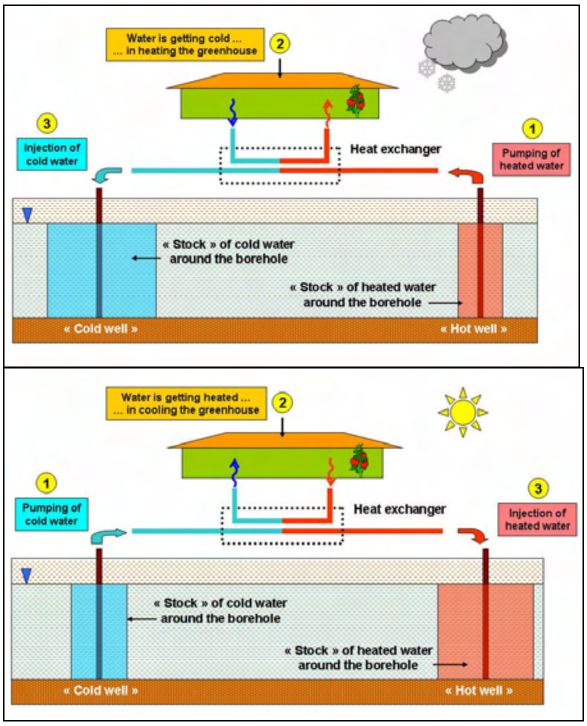

Figure 1: Principle scheme of Aquifer Thermal Energy Storage applied to reversible heating and cooling, through geothermal doublet. Reversible functioning in cold and hot seasons.

4. PROCESSES INVOLVED IN ATES SYSTEM

4.1 Thermal energy transfer in the aquifers

The thermal energy transfer in the aquifers is governed by thermal diffusion, advection, and dispersion. These processes are summarized in Figure 2.

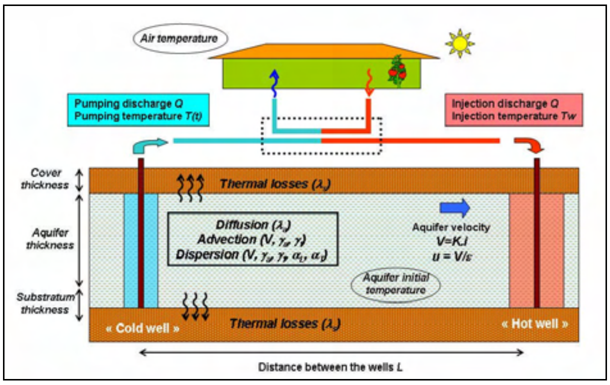

Figure 2: Principle thermal energy transfers

Diffusion is the transfer due to thermal conductivity of the aquifer and its upper and lower limits. Diffusion in one direction is proportional to the thermal conductivity coefficient l_a (expressed in W/m/°C) and to the temperature gradient in that direction. The thermal conductivity of an aquifer depends both on the type of geological material (sand, gravel, etc.), and on its saturation degree by water (or porosity *e.* for confined aquifers). Current values of thermal conductivity of aquifers are given in the range 2.0-2.5 W/m/°C, with porosity between 5% and 20%.

Aquifer acts also with a <u>thermal inertia</u> due to its calorific capacity g_a which represents the heat quantity necessary to increase the temperature of a 1 m^3 volume by 1 °C. Current values of aquifers calorific capacity are given in the litterature in the range: 2.0-2.9.10^6 J/m^3/°C.

Most of the aquifers are subject to a regional natural flow *V* which depends both:

- on the aquifer hydraulic conductivity *K* (in m/s), expressing its aptitude to let the water goes through under the effect of a hydraulic gradient *i*,

- on the value of the hydraulic gradient *i*, which represents the slope of the piezometric surface of the aquifer, and acts as a potential gradient.

$$V = K.i \tag{1}$$

where *V*, *K*, *i* are aquifer Darcy's velocity, hydraulic conductivity, and hydraulic gradient, respectively.

The regional flow *V* can be very low (few meters per year), to relatively large (few meters per day). Current values of hydraulic gradient are usually in the range 0.1 – 10 ‰.

<u>Advection</u> represents the moving of the thermal stock due to the natural flow of the aquifer. To this ensemble movement adds a spreading out of the thermal stock due to spatial heterogeneity of the velocity field. This phenomenon is called <u>dispersion</u>, and leads to an increase of the "global" aquifer thermal conductivity as follows:

$$\begin{aligned} l_L^{global} &= l_a + a_L \cdot g_f \cdot V \\ l_T^{global} &= l_a + a_T \cdot g_f \cdot V \end{aligned} \tag{2}$$

where l_a, g_a, g_f , *V*, a_L, a_T are aquifer thermal conductivity, aquifer calorific capacity, fluid calorific capacity, regional flow of the aquifer (Darcy's velocity), aquifer longitudinal (in the mean flow direction) and transverse (transverse to the mean flow direction) dispersivities, respectively.

4.2 Factors influencing the efficiency of ATES

As shown in Figure 2, different processes control the thermal energy transfer processes in aquifers, and will influence the efficiency of the thermal energy storage:

- ensemble movement and spreading out of the "cold" and "warm" stock around the wells depending of the aquifer velocity field,

- thermal inertia depending on the aquifer calorific capacity,

- thermal losses trough the upper limit depending on the temperature gap between outside air and groundwater, and on the thickness of the cover.

Other factors concerning the exploitation conditions that have to be dimensioned according to the aquifer characteristics (and to other considerations as energetic needs, costs, available space, etc.) to optimise the ATES efficiency:

- pumping and injection discharge *Q*,

- pumping and injection cycles (duration, rest periods, etc.),

- injection temperatures in the cold and in the hot wells,

- distance *L* between the hot and the cold wells (to avoid interference between the heated and cold stocks),

- disposition of the axis of the geothermal doublet towards aquifer flow direction.

5. SENSITIVITY ANALYSIS THROUGH NUMERICAL MODELLING

The objective of the pre-feasibility study was to evaluate and prioritize the effects of different factors that can influence the feasibility and the efficiency of ATES. Some theoretical studies have already been done to determine the influence of physical parameters, and have led to the edition of graphs for dimensionless variables (Sauty (1981)). If these curves can be used to obtain a quick evaluation of feasibility of ATES for a given configuration, they are nevertheless of limited help as they are generally based on oversimplified hypothesis (simple geometry of aquifer, etc.). Numerical modeling is then essential to take into account more complex aquifer geometries, density effects, etc., and to evaluate the evolution of heated and cold groundwater stocks in space and time.

5.1 Model definition

<u>5.1.1 Grid</u>

A numerical study was led with the MARTHE model, a finite-volumes software developed by Brgm that can model both hydrodynamics and thermal transfers.

The model is composed of 10000 cells with varying size, as shown in Figure 3. A finer nested grid is included close to the well to obtain a better definition of the thermal storage.

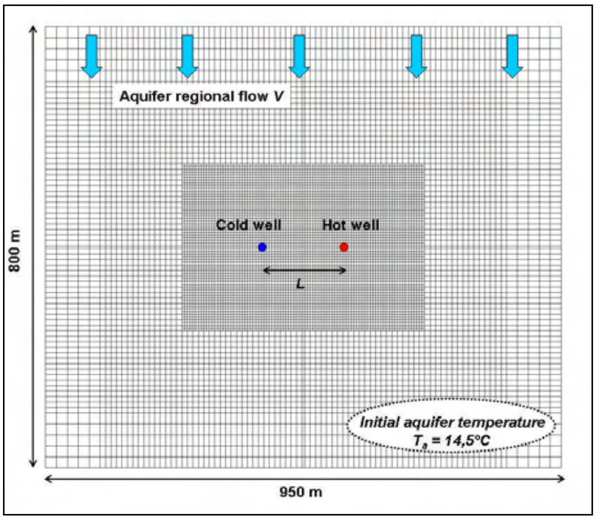

Figure 3: Above view of the model grid

In the simulations presented below, the axis of the geothermal doublet was supposed to be transversal to the regional aquifer flow.

In the vertical direction, the terrain is subdivided into 17 horizontal layers with varying thickness. As shown in Figure 4, outside air temperature is prescribed on the first layer of the cover. The aquifer part is represented by three layers. The vertical water movements due to density phenomenon have been considered as negligible for the considered range of temperature (from 10 to 30°C).

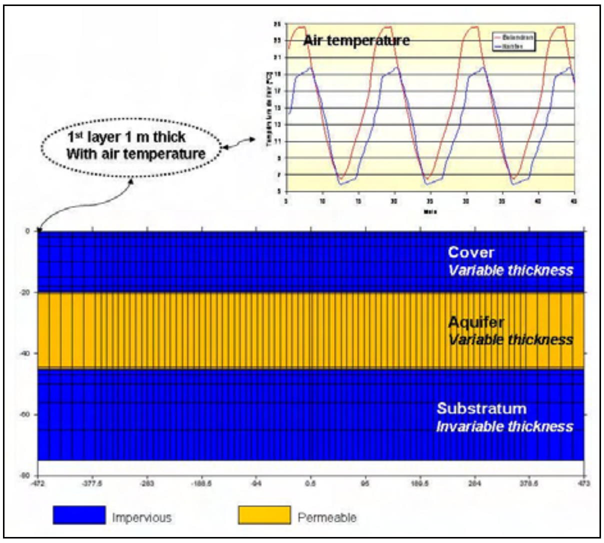

Figure 4: Vertical view of the model grid

5.1.2 Pumping and injection cycles

A first dimensioning of the energy needs for a theoretical greenhouse subjected to the climatic conditions of Nîmes in the South of France has led to the definition of exploitation conditions for the geothermal doublet:

- injection temperature of water in the hot well is constant and equal to 28°C,
- injection temperature of water in the cold well is constant and equal to 10°C,
- groundwater discharge is constant over 24 hours a day in the exploitation phase.

A pumping/injection schedule has also been defined over a one year cycle:

- cooling: pumping of cold water and injection of heated water from June to September (summer),
- rest (no pumping) in October / November,
- heating: pumping of heated water and injection of cold water from December to March (winter),
- rest (no pumping) in April / May.

These exploitation conditions remained the same for all numerical simulations.

5.1.3 Modeling parameters

Simulations were realized with a weekly time step, for 15 yearly cycles (180 months) following the exploitation schedule presented above. The computer CPU time for 15 years of exploitation was about 3 hours on a standard desktop PC.

The initial temperature of the aquifer is 14.5°C (annual mean air temperature).

Table 2 presents the range of parameters that have been tested by modeling.

Table 2: Range of parameters tested by modeling

Parameter	**Unit**	**Range**
Cover thickness	m	5-30
Aquifer thickness	m	10-30
Substratum thickness	m	30
Hydraulic conductivity	m/s	5.10^{-4}–$2.5.10^{-2}$
Porosity	%	5-15
Hydraulic gradient	‰	0-2
Regional flow	m/day	0-8.7
Distance between the wells	m	150-200
Pumping/injection discharge	m^3/h	25-100
Aquifer thermal conductivity	W/m/°C	2.09-2.26
Aquifer calorific capacity	$J/m^3/°C$	$1.84\text{-}2.09.10^{6}$
Longitudinal dispersivity	m	5-7.5
Transverse dispersivity	m	1.7-2.5

5.1.4 Methods to compare simulations

The “basic” principle of a sensitivity analysis is to make the different parameters varying one by one and to compare the obtained simulations results. In this study, several methods have been retained to compare the simulations, in order to evaluate the relative influence of the different parameters on ATES efficiency.

The “global” thermal power that can be furnished by water is proportional to water discharge and temperature following the following equation:

$$P_g = g_f \cdot Q \cdot T \tag{3}$$

where P_g, g_f, Q, T are “global” thermal power, fluid calorific capacity, discharge and temperature, respectively.

The model gives the time evolution of temperatures simulated in the cells containing respectively the hot and the cold wells. As these temperatures will condition the thermal power, the simulations are compared through:

- the temperatures simulated at the end of the 4 months pumping cycle,
- the deviation with the natural aquifer temperature,
- the number of yearly cycles necessary to obtain the stabilization of the temperatures obtained in the hot and cold wells at the end of the 4 months pumping cycle.

The MARTHE model allows also the simulation of the spatial distribution of the temperatures in the aquifer. For the different simulations, these are compared for some key dates of the yearly exploitation cycle (end of pumping cycle, end of rest period, etc.).

In this particular case of thermal storage, the thermal efficiency can be measured through the deviation between the temperature of the stored (and pumped) groundwater and the initial and natural aquifer temperature. We introduce here the notion of “useful” thermal power, that allows to evaluate the surplus of power obtained by storage compared to a “simple” exploitation of groundwater (at constant temperature) without storage.

$$P_u = g_f \cdot Q \cdot \left|T - T^0\right| = P_g \cdot \frac{\left|T - T^0\right|}{T} \tag{4}$$

where P_u, P_g, Q, T, T^0 are global and useful thermal power, groundwater discharge, groundwater temperature at wells, and initial aquifer temperature, respectively.

To compare storage efficiency, a recovery factor is also calculated, for the cold and the hot wells respectively, as the ratio between the quantity of energy pumped during a 4 months cycle, and this injected during the previous season:

$$r = \frac{E_u^{pumped}}{E_u^{stored}} \quad (5)$$

where r, E_u^{pumped}, E_u^{stored} are recovery factor, pumped and stored "useful" thermal quantity of energy, respectively.

The "useful" quantity of energy is defined as the integral of the "useful" thermal power on a 4 months cycle:

$$E_u = \int_0^{4\,months} P_u(t).dt \quad (6)$$

where E_u, and P_u are "useful" thermal energy and thermal power, respectively.

For all the simulations, this recovery factor is calculated for the 15th year of exploitation.

5.2 Simulation results

5.2.1 Influence of aquifer regional flow

Aquifer regional flow is one of the most important parameters that will condition the efficiency of ATES. It will depend on the permeability K, and on the hydraulic gradient, i. The graphs below show the comparison of two simulations with and without aquifer regional flow.

Figure 6 shows comparison of cold and heated groundwater stocks for the first and the 15th years of exploitation, and for different key dates of the yearly cycle. It appears clearly that the thermal storage has increased over the years, leading to an amelioration of the efficiency. The comparison of the first case without regional flow (which, in fact, never happens in reality) and the second one with a flow of 0.86 m/d is eloquent, as it shows the moving and spreading out of the heated and cold water.

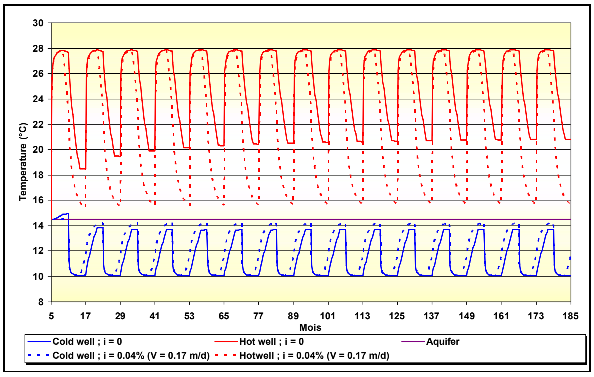

Figure 5: Comparison of the simulated temperatures in the cold and hot wells for *i* = 0 (V = 0), and *i* = 0.4‰ (V = 0.17 m/d) ; Q = 50 m³/h, Aquifer thickness = 25m, Cover thickness = 20m, K = 5.10⁻³ m/s, e = 15%.

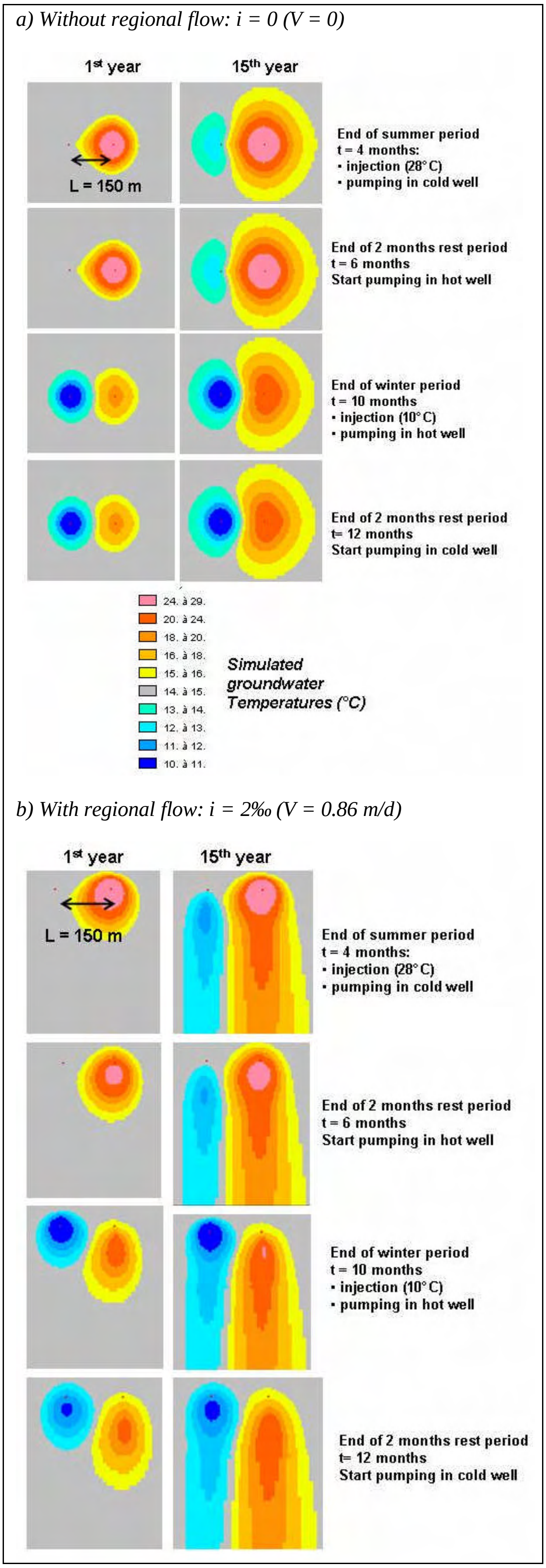

Figure 6: Comparison of spatial spreading of cold and hot stock without (a) and with (b) regional flow *i* = 2‰, V = 0.86 m/d ; other parameters same as in Figure 5.

Figure 5 shows the temperatures simulated in the cells containing the cold and the hot wells. The strong effect of aquifer flow can also be clearly seen, through quicker increase (in the cold well) and decrease (in the hot well), of pumped water temperatures after the end of the 4 months injection period. For the 15th simulation year, the gain in temperature (compared to the natural aquifer temperature) at the end of the 4 months pumping period is:

- in the hot well, +6.3°C and +1.7°C, without and with aquifer flow, respectively,
- in the cold well, +0.8°C and +0.4°C, without and with aquifer flow, respectively.

The influence of natural aquifer flow on the ATES efficiency can be evaluated on the curves of "useful" thermal power, shown below (Figure 7).

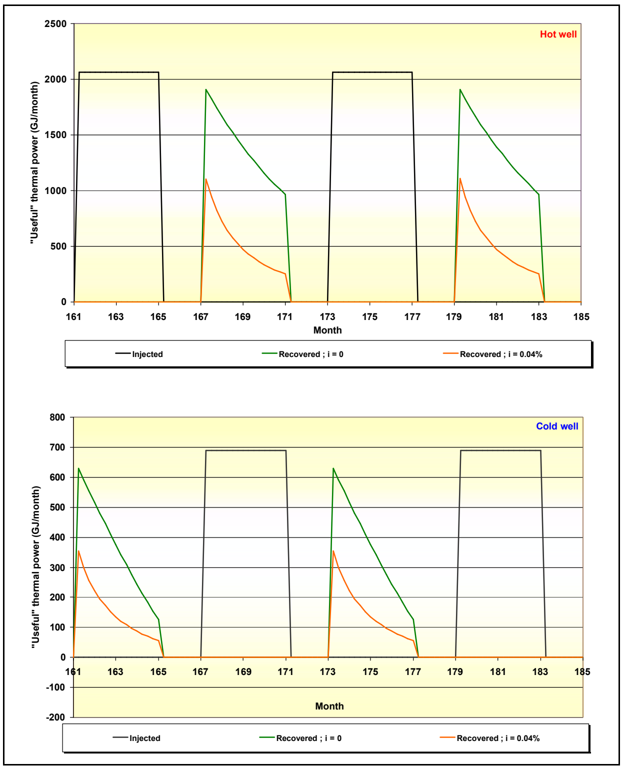

Figure 7: Comparison of simulated "useful" thermal power in the cold and hot wells for *i* = 0 (V = 0), and *i* = 0.4‰ (V = 0.17 m/d) ; other parameters same as in Figure 5.

It appears clearly that the recovered thermal powers are strongly affected by the aquifer flow. Compared to the theoretical case without flow, the recovery factors calculated on the 15th simulation year decrease from 67% to 26% in the hot well, and from 53% to 22% in the cold well.

Table 3: Summary of simulations results for *i* = 0 and *i* = 0.4‰ ; other parameters same as in Figure 5.

Parameters		Hot well		Cold well	
i (‰)	*V* (m/d)	ΔT (°C)	r (%)	ΔT (°C)	r (%)
0	0	+6.3	+67	+0.8	+53
0.4	0.17	+1.7	+26	+0.4	+22

5.2.2 Influence of the cover thickness

Cover thickness will play a role of thermal insulator and reduce the exchange by conduction towards the surface. Figure 8 and Figure 9 show that the results are slightly better in terms of recovered temperatures and "useful" thermal powers for a cover 20m thick compared to 5m.

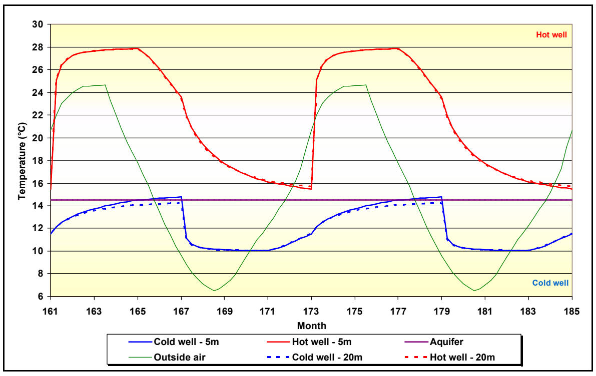

Figure 8: Comparison of the simulated temperatures in the cold and hot wells for cover thickness 5 and 20m ; Q = 50 m^3/h, L = 200m, Aquifer thickness = 25m, Cover thickness = 20m, K = 5.10^{-3} m/s, e = 15%, *i* = 0.4‰.

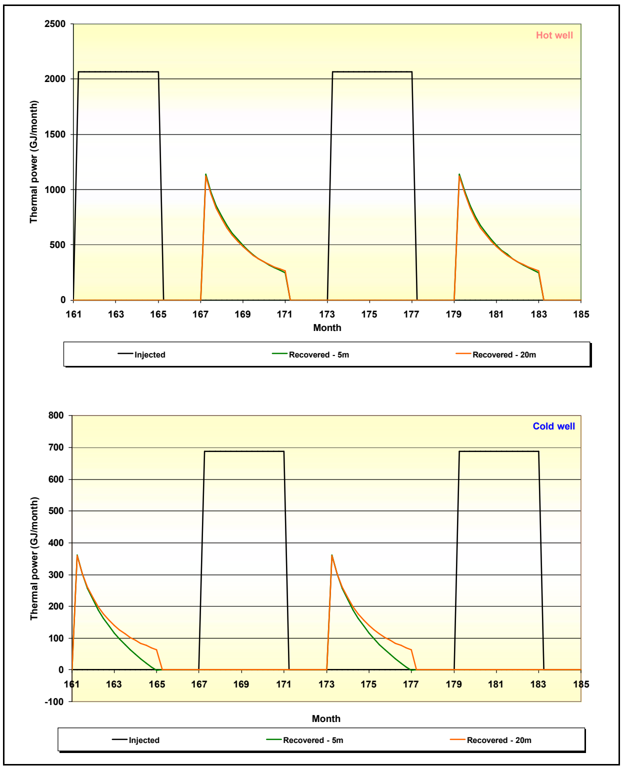

Figure 9: Comparison of simulated "useful" thermal power in the cold and hot wells for cover thickness 5 and 20m ; other parameters same as in Figure 8.

Table 4: Summary of simulations for cover thickness 5 and 20m ; other parameters same as in Figure 8.

Parameters	Hot well		Cold well	
Cover thickness	ΔT (°C)	r (%)	ΔT (°C)	r (%)
5 m	+1.6	+27	+0.0	+19
20 m	+1.7	+26	+0.4	+23

5.2.3 Influence of the distance between the wells

Distance between the two boreholes of the geothermal doublet is also an important parameter to take into account. Figure 10 shows the evolution of simulated temperatures in the hot and cold wells for two distances of 150 and 200m, in a case of a 50 m^3/h exploitation discharge. The interference between the heated and cold groundwater is greater when the boreholes are closer, this is to be seen almost in the temperatures of the pumped waters at the end of the 4 months pumping cycles. The interference is especially marked on the cold well, as shown on the "useful" thermal power (Figure 11). With a 150m distance, the recovered thermal power in the cold well is hardly decreased by the influence of the hot well, where a greater quantity of energy is stored.

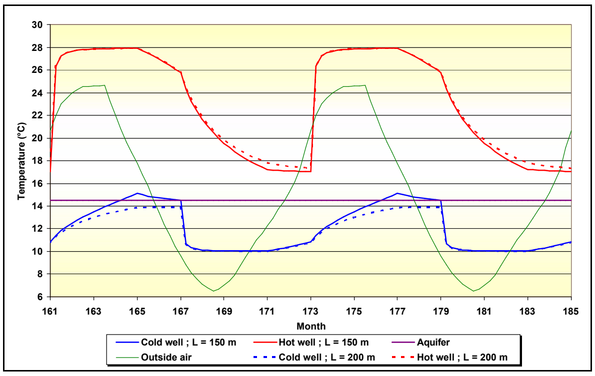

Figure 10: Comparison of the simulated temperatures in the cold and hot wells for L = 150m and 200m, i = 0.4‰; Q = 50 m^3/h, Aquifer thickness = 10m, Cover thickness = 20m, K = 5.10^{-3} m/s, e = 15%.

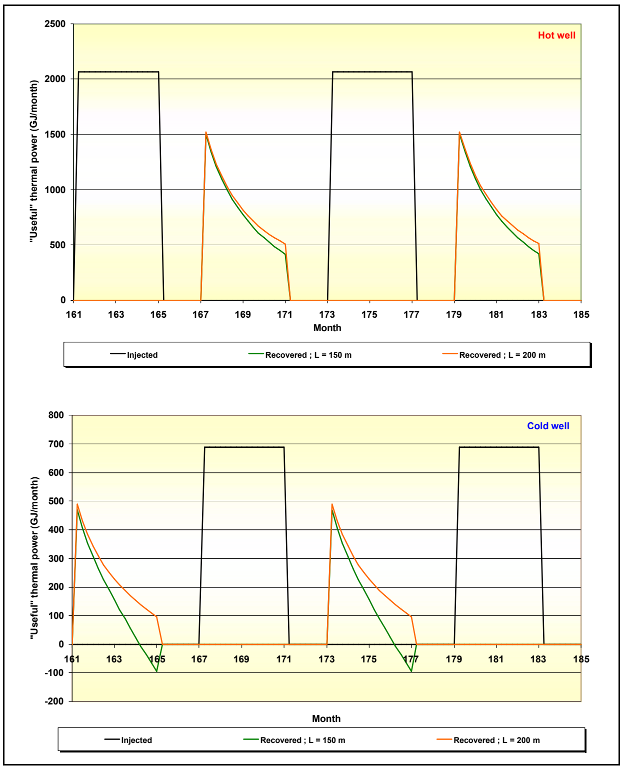

Figure 11: Comparison of simulated "useful" thermal power in the cold and hot wells for L = 150 and 200m ; other parameters same as in Figure 10.

Table 5: Summary of simulations for L = 150 and 200 m ; other parameters same as in Figure 10.

Parameters	Hot well		Cold well	
Distance L (m)	ΔT (°C)	r (%)	ΔT (°C)	r (%)
150	+2.7	40	-0.6(*)	+22
200	+3.3	42	+0.6	+35

*: by choice, a negative value traduces the fact that the temperature of the pumped waters in the cold well is greater than the initial temperature of the aquifer.

In this simulated case with a 50 m^3/h discharge, we can conclude that it is better to install the boreholes on a distance greater than 150m.

The "minimal" distance between boreholes depends on the thermal radius of the stored water, which depends itself both on the aquifer thickness, and on the water discharge. A given distance could be sufficient for a discharge, and not for a greater one.

In real case, a compromise may have to be found between large distances to avoid reciprocal "thermal pollution" of the two stocks, space availability and disposition constraints on the agricultural site, and additional costs of equipments with the distance (piping lengths, greater hydraulic losses leading to larger pipes diameters, etc.).

5.3 Conclusions

The theoretical study led on numerical simulations has shown the variety of factors that influence the efficiency of ATES, dealing with the aquifer characteristics (regional flow, permeability, porosity, thermal parameters), and also with the exploitation conditions (discharge, injection temperatures in the cold and hot wells, pumping and injection cycles, distance between the geothermal doublet).

For this sensitivity analysis, the efficiency of the ATES has been evaluated through:

- the temperature deviation between the pumped groundwater and the aquifer, at the end of the 4 months pumping period and for the 15th year,
- the recovery ratio between the recovered and stored quantity of energy on a 4 months cycle.

For the whole simulations at the hot well:

- the temperature deviation varies from +7.9°C to -0.4°C, with an average of +2.5°C,
- the recovery ratio varies from +74% to -1%, with an average of 36%.

For the whole simulations at the cold well:

- the temperature deviation varies from +2°C to -3.2°C, with an average of +0.08°C,
- the recovery ratio varies from +66% to -7%, with an average of 26%.

Thermal efficiency is on the whole better in the hot well than in the cold one, due to the fact that the stored quantity of energy is greater, and that, in certain cases, the stock of heated water has a strong influence on the cold one.

This sensitivity analysis allowed to evaluate the relative influence of the different parameters on thermal efficiency. The natural flow of the aquifer is the factor that will mostly condition the efficiency of the ATES. The best recovery ratios are those obtained for the “theoretical” (and never observed in the nature …) cases without flow. The distance between the boreholes is also an important parameter.

This sensitivity analysis also allowed to illustrate the complexity of the phenomena that govern the aquifer thermal energy storage. A same parameter can have positive and negative effects on the storage, or can have a positive effect in a given range of values, and a negative one in an other one, depending on the values of the other parameters (as an example, the increase of the exploitation discharge can produce a positive or a negative effect depending on the aquifer thickness and on the distance between the boreholes). This interdependence between the parameters is clearly shown on this sensitivity analysis, where the recovery ratio varies from negative values to very significant ones (+74%). The conclusion to retain is that each site will be a particular case, requiring a detailed dimensioning as a function of its hydrogeological context.

6. ATES SYSTEM DESIGN: CASE TO CASE STUDY

The main component of an ATES system is of course the presence, under the agricultural site, of a suitable aquifer. “Suitable” means here able to produce the required water demand for the project. First question is: how many wells might be needed to meet the demand, bearing in mind peak demand, average demand, and also the fact that a well is often less efficient in injection than in pumping (Bridger and Allen (2005)).

Aquifer characterization for an ATES project requires a case to case study, as hydrogeological conditions can be variable at the local scale. Dimensioning a hydrogeological study for ATES project will hardly depend on the previous knowledge (previous studies, existing nearby water wells, geological maps, etc.), the complexity of the site (type of aquifer, spatial variations of regional flow, etc.), and the size of the ATES system itself. Two phases can be drawn, (i) the pre-feasibility study, which is an indispensable preliminary step, and (ii) the detailed design of the whole ATES system. In these two phases, numerical modeling is a precious tool, to evaluate the capacity of thermal storage of the aquifer, and its evolution in space and time.

In the pre-feasibility step, aquifer characterization is almost done through exploitation of existing data, expertise, and eventually low costs investigations on nearby water wells (pumping tests, piezometric measure, etc.). A first set of numerical simulations can be led with parameters issued from previous studies, and literature review, in order to give some ranges of storage capacity and efficiency.

If the pre-feasibility study leads to a priori favorable conclusions, detailed ATES design can be engaged, with complementary aquifer investigations (drilling of test well, geological logging of boreholes cuttings, pumping test, tracing experiments, geochemical analysis, etc.). New sets of numerical simulations can be led with more accurate parameters issued from the local investigations on the site.

7. CONCLUSIONS AND PERSPECTIVES

Many ATES systems exist all around the world, and have proven to be viable, and energy-efficient technology. Hydrogeological aspects must be considered carefully during the system design to ensure a properly operating system on the long-term (avoid clogging, etc.). To be efficient and viable on the long-term, ATES systems require a really accurate design.

Aquifers at relatively shallow depths (10-100m) are present in large areas in France. ATES could be seen as an interesting perspective for greenhouses farmers willing to reduce their energetic bill and the environmental impacts linked to the consumption of fossil energies. In any case, a case to case study is necessary to evaluate the pre-feasibility on a given site. Numerical modeling appears as a precious tool, from pre-feasibility stage to detailed design.

NOMENCLATURE

Parameter	Symbol	Unit
Hydraulic conductivity	K	m/s
Porosity	ε	%
Hydraulic gradient	i	‰
Regional flow (Darcy velocity)	V	m/j
Longitudinal dispersivity	α_L	m
Transverse dispersivity	α_T	m
Groundwater temperature	$T(t)$	°C
Initial aquifer temperature	T^0	°C
Fluid calorific capacity	γ_f	J/m^3/°C
Aquifer calorific capacity	γ_a	J/m^3/°C
Aquifer thermal conductivity	λ_a	W/m/°C
Distance between the wells	L	m
Pumping/injection discharge	Q	m^3/h
“Global” thermal power	P_g	W
“Useful” thermal power	P_u	W
“Useful” quantity of energy	E_u	J
Recovery factor	r	%

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REFERENCES

Bridger D.W., and Allen D.M.: “Designing Aquifer Thermal Energy Storage Systems”, in *ASHRAE Journal* (2005).

Chevalier S., Gauthier J., and Banton O. : “Evaluation du potentiel géothermique des nappes aquifères avec stockage thermique : revue de littérature et application en deux contextes du Québec.”, *Can. J. Civ. Eng.*, **24**, (1997), 611-620.

Sauty J.P. : “Du comportement thermique des réservoirs aquifères exploités pour le stockage d’eau chaude ou la géothermie basse enthalpie”. Thèse d’état, Grenoble, (1981).

Snijders A.L.: “Aquifer Thermal Energy Storage in the Netherlands, Status beginning of 2005”, IFTech International reference available on: http://www.iftechnology.nl, (2005).

Turgut B. *et al*.: “Aquifer thermal energy storage application in greenhouse climatization”, *Proceedings*, 10th International Conference on Thermal Energy Storage (Ecostock), Stockton (NJ, USA), (June 2006).