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Reservoir Management of Simultaneous Heat and Cold Production from Shallow Aquifers

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ABSTRACT

As there is an increasing need, in Paris and its suburbs, for cooling, shallow ground water sources are targeted to provide sufficient flow rates in order to provide cool to offices, commercial and tertiary activity buildings. Water reinjection, abusive use of superficial ground water for cooling purposes, could lead to a short term increase of the aquifer temperature. Hence, sustainable use of the thermal energy stored in shallow seated aquifers requires to balance the amount of heat reinjected in the aquifer during the cooling season by injecting cooled water during the heating season. Inversion of fluid circulation in the geothermal loop (groundwater wells share seasonally both production and injection functions) results in seasonal heat and cold storage, thus upgrading heat pump performance.

Two projects are presented. In the first one the well spacing is so short that theoretical thermal breakthrough and shtort circuiting for a single doublet occur in less than a month. Therefore, a quadruplet scheme, extracting heat and cold from two aquifers was contemplated in order to accommodate with the thermal breakthrough issue. The second one addresses the energy supply of two district heating and cooling grids from a highly productive shallow aquifer source. The need of continuous and simultaneous heat and cold suggests the use of high capacity, high efficiency heat pumps, able to produce hot water and chilled water at 80°C and 5°C respectively. Ground water is used, particularly during summer, when heat and cold requirements are not balanced and the peak load for space cooling may reach 22 MW_{th}. Such ground water based designs should secure the development of large, environmentally compatible, district heating and cooling scheme, thus avoiding atmospheric cooling systems whose utilization is restricted in urban areas.

1. INTRODUCTION

Whereas the deepest and hottest aquifers are targeted as energy sources for heating purposes, shallow superficial aquifers have been used for decades, providing low constant temperature water, available for cooling, particularly in industrial processes. Ground water, when used, was most of the time disposed in the sewage network, when existing, or in the closest straight forwards river. In urban areas, the cooling needs have changed since dwellings, offices and tertiary buildings have replaced the former factories. In most cases, the reinjection of the water in the source aquifer is now favored, thus: (i) avoiding the cost of surface water disposal and (ii) securing mass conservation of the aquifer resource. If not thermally counterbalanced, the injection of warm water in the aquifer will lead to a local warming of the underground, ending up with the thermal breakthrough at the producing well. Because the volume and specific capacity of the aquifers are finite, the extraction of heat, at a rate greater than the local heat flow density, leads to the exhaustion of the resource. If the aquifer is used for heating purpose as well as cooling, it is possible to balance the extracted annual heat and cold quantities, and thus avoid the fatal thermal breakthrough issue.

2. STUDTY 1: SHORT SPACING DOUBLET

This first case deals with a project with severe building constraints. Located downtown Paris, the six storey block footprint is a 2314 m^2 area. The doublet is to be drilled in the central area, demolished in order to excavate two levels of underground car parks prior to reconstruction. The distance between the wells will not exceed 41 meters.

Figure 1: Building view downtown Paris.

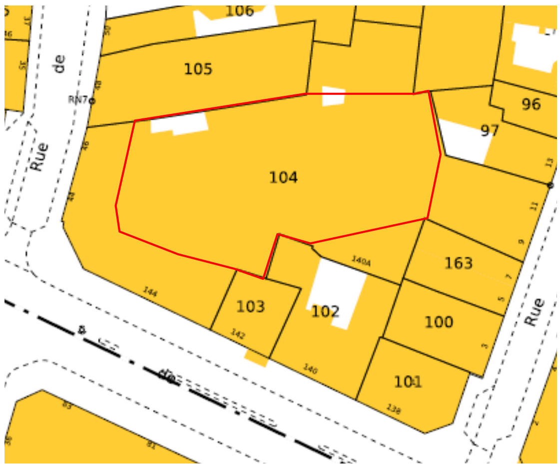


Figure 2: Building view (block 104 2314 m^2 footprint). Due to restricted car park space, delimited in red, the maximum well spacing is limited to 41 m.

2.1 Overview

2.1.1 Thermal Needs

Dedicated to house 4 000 m^2 of offices and 2 000 m^2 of shops, the thermal needs of the building amount at 858 and 472 kW, at peak heating and cooling demands. The lack of data on expected consumptions leads us to produce assumptions on daily heat pump and chiller uses estimated 12 (winter heating) and 10 hrs/day (summer cooling) respectively. Figure 3 shows nominal underground power (calculated from heat pumps and chillers efficiency) and variations of time use during the heating and cooling seasons. Sanitary hot water impact is negligible and is not concerned by the present geothermal design.

2.1.2 Ground Water Resource

Two shallow aquifers are available. The first, seated between 25 and 45 m depth, consists of an unconsolidated silica sand. The second, between 65 and 85 m depth, is a fractured chalk unit. The temperatures of these two aquifers are around 14°C and 16°C. Thus, reinjection at 5°C during heating season and 30°C during cooling season leads to a maximum flow rate of 80 m^3/hr of ground water to reach the expected power levels.

2.2. Production Design

First estimates for a conventional doublet (one production well and one injection well) in a 20 m thick aquifer shows that thermal breakthrough occur in less than a month at 80 m^3/hr constant flow rate. Moreover the productivity of each aquifer does not allow extracting the flow rate needed to meet the designed requirements.

Hence, the following mining scheme was proposed: one doublet per aquifer, with seasonal inversion in order to cope with the thermal breakthrough issue. The exploitation of two overlying aquifers allows drilling two wells close to each other. Whenever well doublet spacing stands at ca 40 m, two wells tapping different aquifers can be drilled from 3 m distant surface location (Figure 4).

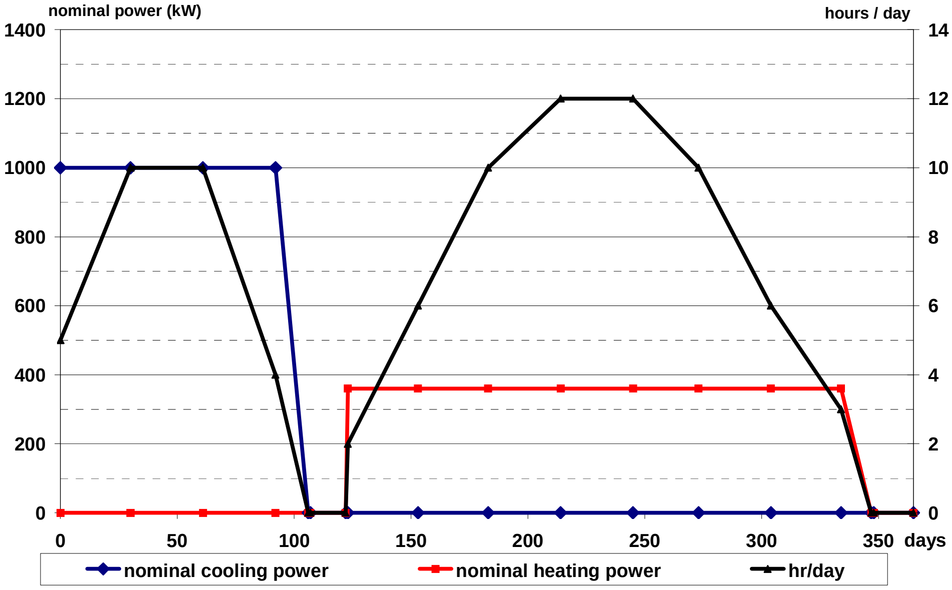


Figure 3: Ground water cooling (heat pumps) and heating (chillers) installed capacities (kW_{th}) and operating times (hrs/day).

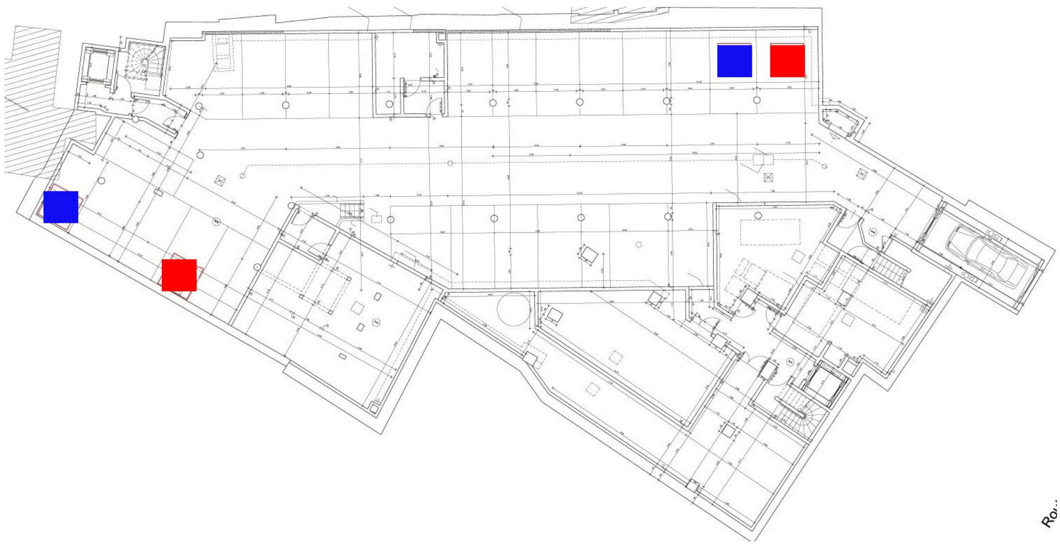


Figure 4: Well head locations inside the building R-2 level. Chalk (deep aquifer) and sand (shallow aquifer) targeted doublets are marked red and blue respectively.

2.3 Aquifer Simulation

In order to validate the mining scheme, numerical simulation of 10 years of heat and cold production has been run, using, the TOUGH2 eos 1 numerical simulator.

2.3.1 Grid

The grid includes 8120 cells distributed on 14 layers. Horizontal cell sizes vary between 5x5 m^2 and 20x20 m^2 (Figure 5). Vertically, each reservoir reduces to a 20 m thick single layer. They are separated by 4 layers of equal thickness. Starting from ground level, the grid extends to 200 m in order to account for vertical heatl transfers.

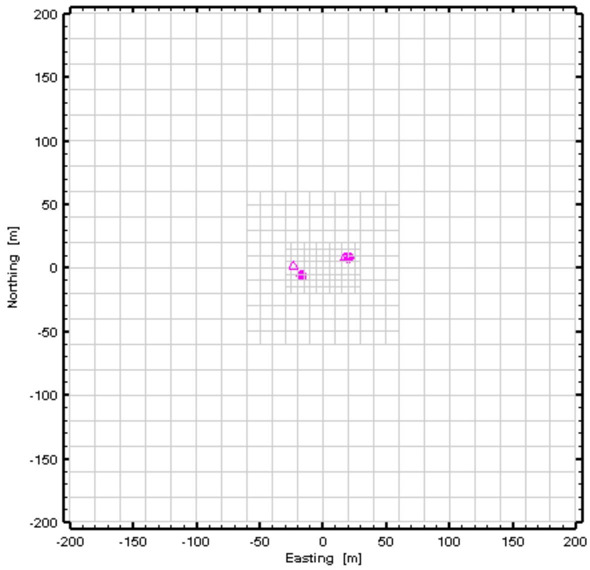


Figure 5: Horizontal reservoir simulation grid. Square cell sizes varies from 20 m (outer) to 5 m (inner).

2.3.2 Initial and Boundary Conditions

The initial temperature distribution derives from the geothermal gradient (Figure 6) and a constant temperature boundary condition is assigned to top and bottom layers, whereas a zero flow condition applies to grid vertical boundaries.

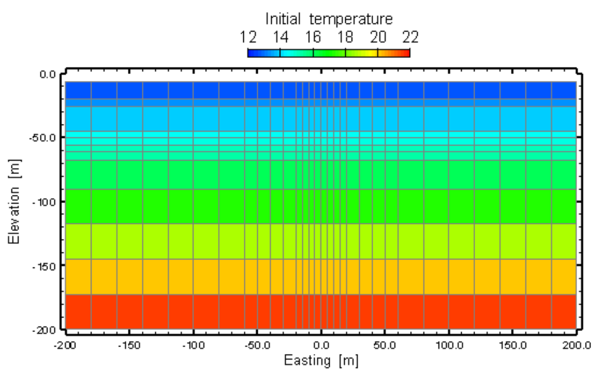


Figure 6: Vertical space discretisation and initial temperature distribution Top and bottom layer temperature boundary conditions are assigned constant.

2.3.3 Results

With respect to the temperature distribution in the chalk aquifer (Figure 7) layer, noteworthy is that the hot plume extend at the end of summer is larger than its cold counterpart at the end of winter. This relates to the beginning of doublet production, when the first simulated season is summer. Last but not least, the thermal breakthrough is avoided.

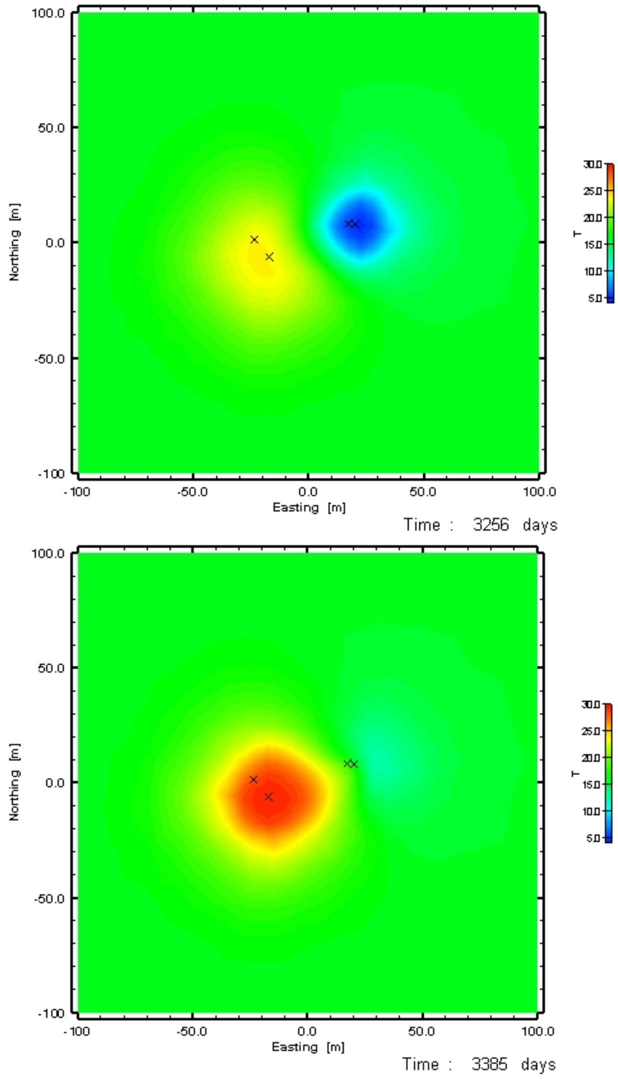


Figure 7: Temperature distribution in the chalk aquifer at the end of the 9th winter (top map) and at the end of the 10th summer (bottom map). Note that the hot plume (red and yellow color sequence) almost reaches the cold well still not causing any thermal breakthrough.

Figure 8 shows the extent of the thermal influence of the doublets on impervious intermediate shale layers.

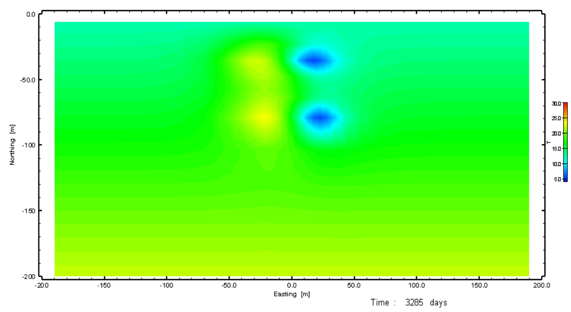


Figure 8: Slice view (Y=0) of the reservoir, showing the extents of hot and cold plumes.

Simulation outputs show how seasonal inversion of the geothermal loop improves the doublet efficiency. First, delta T is much greater than anticipated. Regarding well temperature in the deep chalk aquifer (see Figure 9) except the first year, delta T starts from 23 °C at the seasons starts and never decreases below 12.5°C. As a consequence, the average flow rates required to match the expected cooling and heating power ratings are smaller, i.e. 53 m^3/h, against the previously calculated 80 m^3/h, equally shared between the two aquifers (see Figure 10).

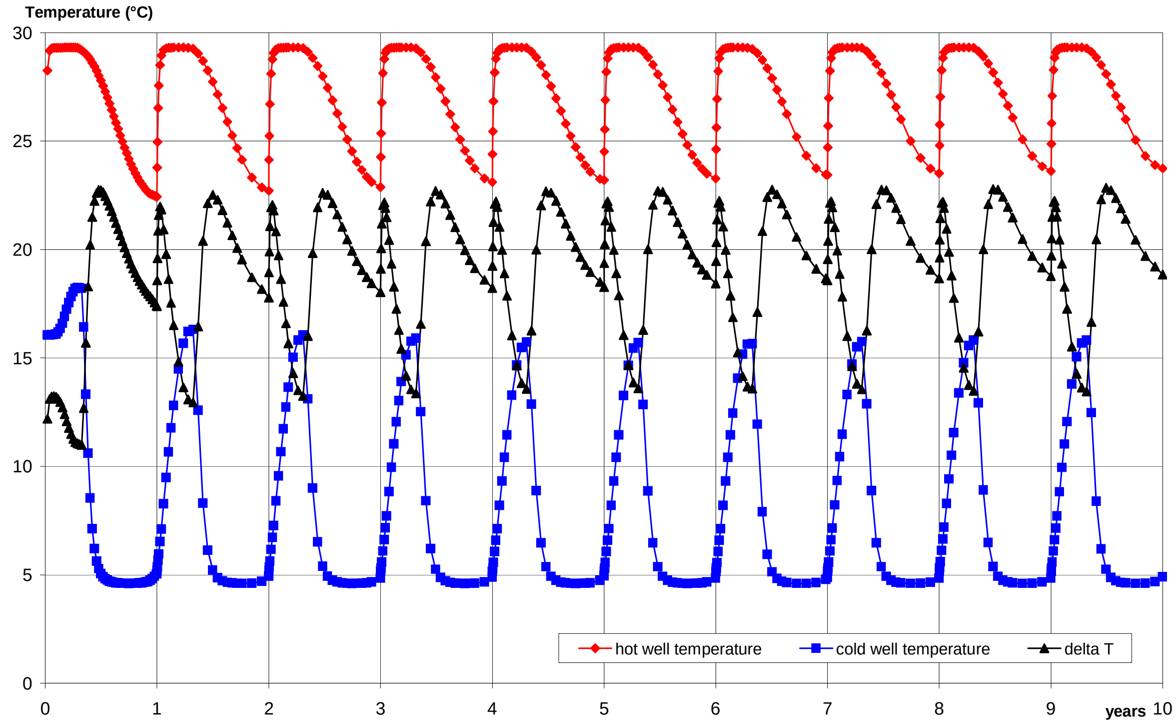


Figure 9: Temperature changes within the deep seated doublet. Hot and cold well temperature are dotted in red and blue and the temperature differential is in black.

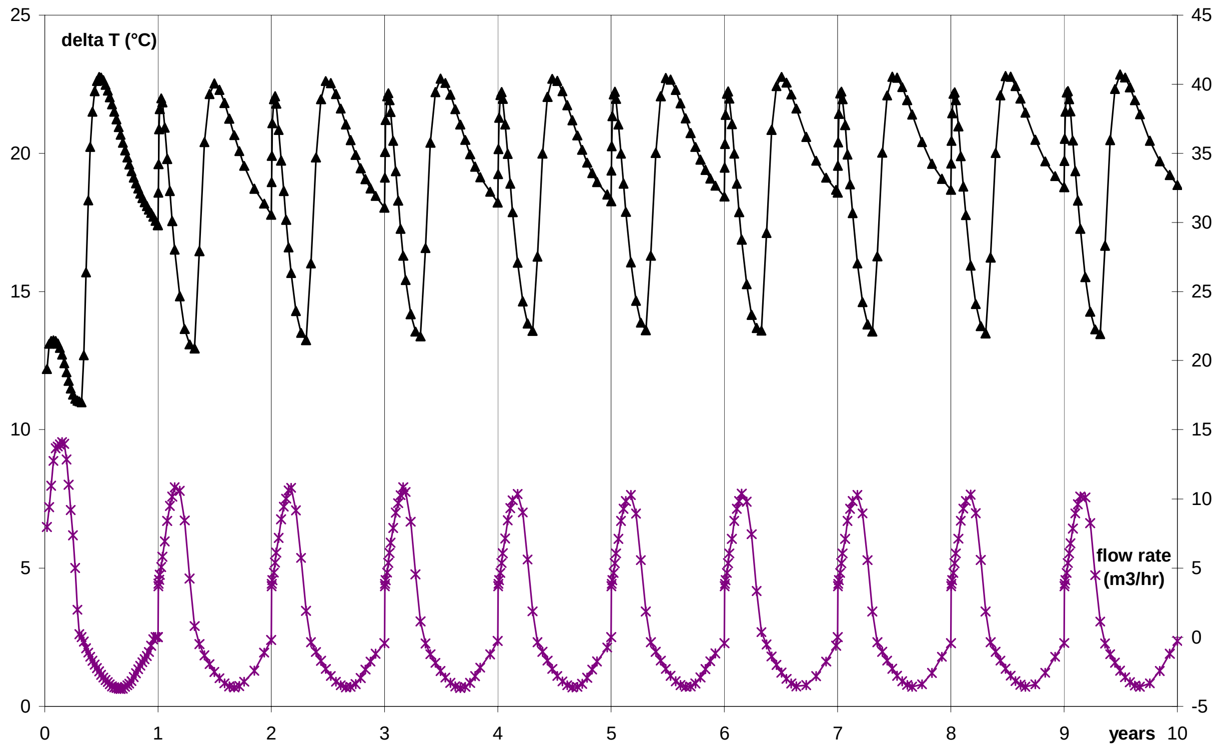


Figure 10: Average flow rate and temperature differential variations of the deep doublet (chalk reservoir). Note the significant decrease in maximum flow rates from 40 m^3/h (design) to 26.4 m^3/h (11m^3/h * 24 / 10) actual peak figures, as the result of delta T (hot vs cold plumes temperature differential) increases.

2.4 Conclusion

Thanks to a balanced energy ratio between heat and cold injected annually in the two aquifers, and the seasonal inversion of the injection and production wells, it is possible to provide space heating and cooling to a six floor building. The use of the aquifers for heating or cooling alone would have led to very short thermal breakthroughs and premature aquifer cooling or heating. Therefore, aquifer energy storage was sought as the best means for meeting project design features, an objective which could be achieved, thanks to relevant aquifer heat and mass transfer simulation.

3. STUDY 2: SIMULTANEOUS HEAT AND COLD PRODUCTION

The Renault car manufacturer dismantled his historical plant site in Boulogne-Billancourt in 1992. The industrial wasteland of, approximately 415 000 m^2 in area is presently hosting new buildings, connected to two district heating and cooling grids. Buildings began to rise in 2008 and the final planning program should be completed in 2020.

Figure 11: Aereal view of the Boulogne Billancourt site in 1970. In red are delineated the perimeter of the car plant dismantled in the 90’s. Left is the Ile Seguin, right is the Trapèze area.

3.1 Overview

3.1.1 Thermal Needs

The two district grid facilities will be used 365 days per year, supplying power for space heating (67.7 MW_{th}), sanitary hot water (5.4 MW_{th}), and space cooling, up to 22.8 MW_{th} in summer, but also even 2.2 MW_{th} cooling power during winter.

Table 1: Heating and cooling grid key figures (in 2020)

	Cooling	Heating
Temperature (in/out)	4.5°C/14°C	105°C/65°C
Maximum thermal power in 2020	22.8 MW_{th}	73.1 MW_{th}
Minimum thermal power in 2020	2.2 MW_{th}	5.4 MW_{th}
Energy consumption	40 616 MWh_{th}	135 563 MWh_{th}

The heat and cold needs are strongly unbalanced. While the district cooling grid is limited to the former factory zone, district heating will extend downtown Boulogne-Billancourt to the West, delivering heat at high temperature (105°C) to existing with conventional heaters, generally old dwellings (see Figure 12).

These simultaneous needs led to the selection of combined heat pumps/chillers (HPC) production units able to supply at the same time hot and chilled water at 80°C and 4°C, condenser and evaporator temperatures respectively. In summer mode, the condenser temperature will decrease at 30°C in order to use ground water for the evacuation of evacuating excess heat.

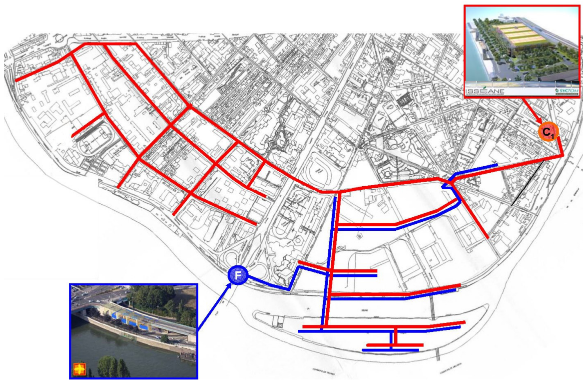


Figure 12: Grid extents and heat and cold plant location (source IDEX) .

3.1.2 Ground Water Resource

The geological context is locally favorable. The former plant used to pump more than 5 000 000 m^3/year of ground water from a shallow aquifer. The reservoir consists of a 300 m thick chalk, eroded and saturated at its top by the river. Accessible below 10 m of alluvia, the chalk is highly productive in its first 20 m, allowing well deliverabilities under 4 m drawdowns.

3.1.3 Complementary Sources

Regarding the strong imbalance between the amounts of heat and cold demands, added to a peak supply to heat the water from 80°C to 105°C, a city waste incinerator will provide additional power, in order to achieve the 73.1 MW_{th} load required the coldest days of the year.

Taking advantage of the nearby Seine River, a chilled water unit will produce a 6 MW_{th} cold load from 1 000 m^3/h river water.

The advantage of this two subsidiary heating and cooling sources is the ability to regulate the amount of energy extracted seasonally from the aquifer, so that the heat injected in summer will equal the heat extracted in winter.

3.2 Production Design

The table 2 describes the heating and cooling equipments used either as base or peak load, and the contribution of groundwater. *HPC* means simultaneous production of hot water at 80°C and chilled water at 4°C. *Chiller* means production of chilled water at 4°C at a condensing 30°C temperature)

In order to accomodate with the progressive increase of the thermal needs until 2020 and in order to manage two different condensing temperatures (80°C – the district heating – 32°C – surplus heat to be injected in the aquifer), three HPCs need to be set up online with the chiller unit using river water. The characteristics of these units are described in tables 3 and 4. (powers are expressed in kW_{th}, bold characters address district heating/cooling grid supplies).

3.3 Energy Balance

In order to secure a global balance of energy within the aquifer, the quantity of heat injected in the aquifer during the cooling cycle will equal the quantity of heat extracted from the aquifer during the heating season (see table 5).

Table 2: Hot and cold base and peak load supply. Equipment types.

	Winter	Summer
Heating	**Base load**: HPC **Peak load**: incinerator	**Total load**: HPC
Cooling	**Total load**: HPC	**Base load**: HPC **Peak load 1**: chiller on ground water **Peak load 2**: chiller on river water
Ground water	Surplus of chilled water from HPC	Surplus of warm water from chiller

Table 3: Summer power design features

Device n°	**1**	**2**	**3**	**4**
Function	HPC	Chiller	Chiller	Chiller
Hot source	District heating water	Ground Water (Island)	Ground Water (Trapèze)	River
Hot source temp.	65°C	14°C	14°C	23 - 27°C
Cold source	Cooling district water			
Cold source temp	14°C			
Heating power	**5 045**	7 900	7 900	6 800
Cooling power	**3 250**	**6 600**	**6 600**	**6 000**
COP	**4.72** (Heat + cold)	**4.83**	**4.83**	**4.35**

Table 4: Winter power design features

Device n°	**1**	**2**	**3**	**4**
Function	HPC	HPC	HPC	-
Hot source	District heating water			-
Hot source temp.	65°C			-
Cold source	District cooling water	Ground water (Island)	Ground water (Trapèze)	-
Cold source temp.	14°C	14°C	14°C	-
Heating power	**3 500**	**6 027**	**6 027**	-
Cooling power	**2 200**	3 900	3 900	-
COP	**4.39** (Heat + cold)	**2.73**	**2.73**	**-**

Table 5: Annual energy budget

Total hot water production	135 563 MWh
HPC hot water production	62 117 MWh (45.8 %)
Additional hot water production from incinerator	73 446 MWh (54.2 %)
Total chilled production	40 616 MWh
HPC chilled water production	23 333 MWh (57.4 %)
Chillers production	17 283 MWh (42.6 %)
Chilled water injected in the aquifer (winter)	17 081 MWh
Aquifer injected warm water (summer)	17 081 MWh
River injected warm water	3 784 MWh

The monthly amounts are plotted on Figure 13 graphic display. The plain bars represent the effective hot (positive) and chilled (negative) water quantities supplied monthly. Hatched symbols represent the quantities of energy injected in the aquifer and in the river.

3.4 Aquifer Simulation

In order to assess the feasibility of this heat and cold production regarding the ground water resource and related mass and heat transfers, numerical simulations have been run, using the TOUGH2 eos1 code.

3.4.1 Grid, Initial and Boundary Conditions

At this early stage, a single layer reservoir, with constant, uniform pressure boundary conditions was modeled, neglecting any assumed aquifer regional flow and vertical thermal conduction whatsoever. Figure 14 shows the 1747 cells grid used to model the reservoir. The initial temperature distribution is a 14°C in the whole aquifer. Zero flow is assigned at model frontiers.

Four years of exploitation were simulated, injecting and extracting alternatively 17 GWh_{th} during 20 weeks (cooling season) and 32 weeks (heating season). The waste heating/cooling waters are pumped back into the aquifer at 30°C/5°C.

Two mining schemes are simulated. The first scheme calls for six producing wells and ten injection wells. Water is extracted all year long in the producing wells, located north of the Trapèze and west of the island respectively. When warmed or cooled, groundwater is injected in the wells located south of the Trapèze and east of the island. The second scheme depicts the impact of seasonal inversion within well functions (either production or injection) which results in two hot well clusters on one side and two cold well clusters on the other.

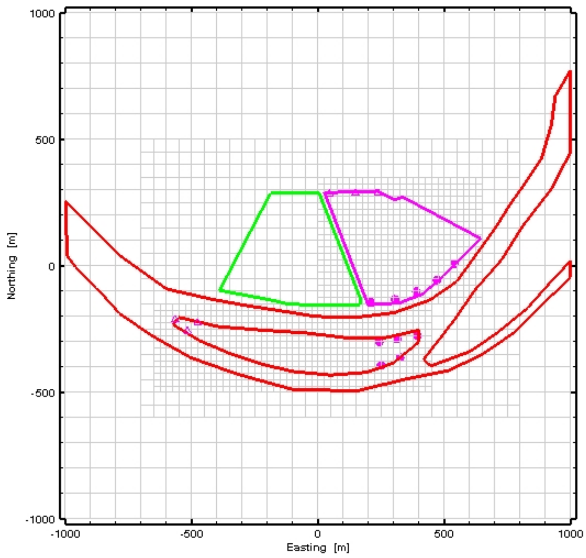


Figure 14: Shallow aquifer reservoir discretisation grid. Wells are located on two zones, within the Seguin Island, and in the eastern Trapèze. Mesh size vary from 25x25 m^2 between the wells to 100x100 m^2 in the outer domain.

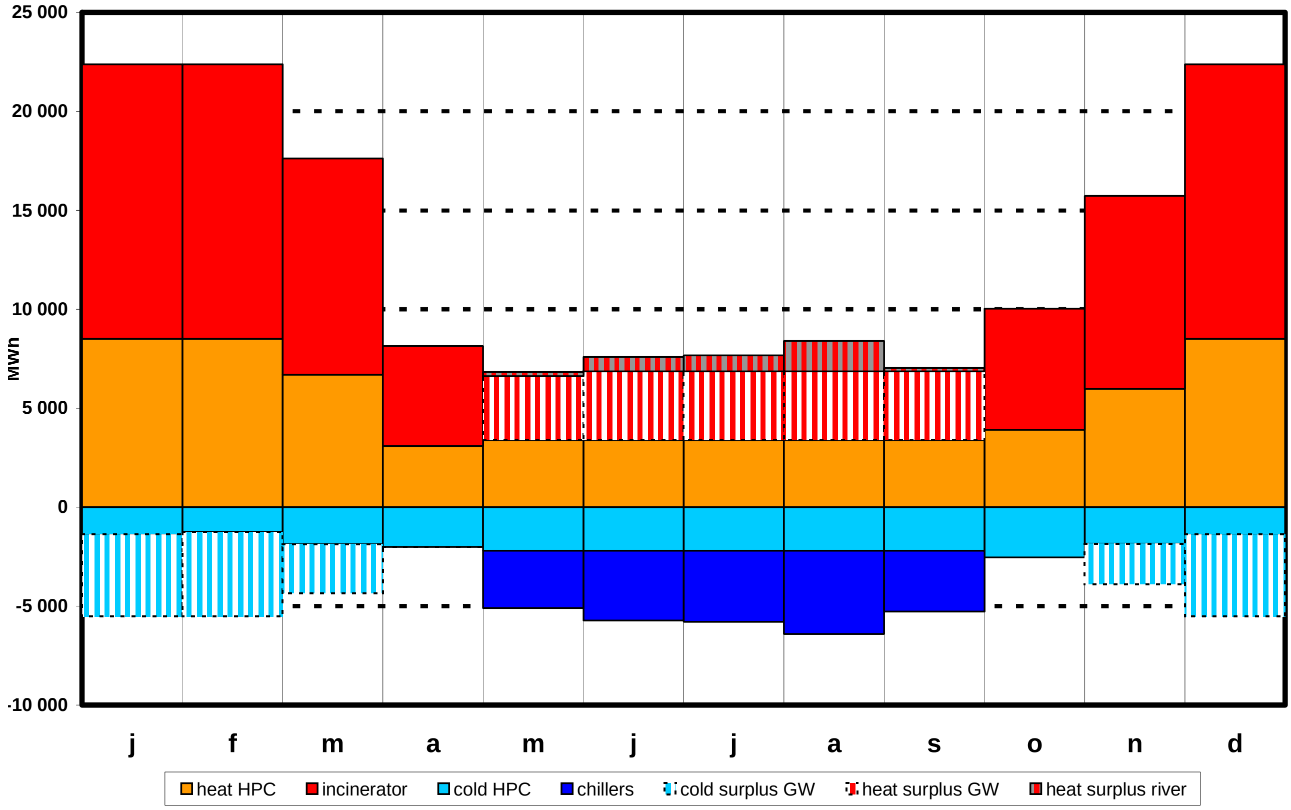


Figure 13: Graphic display of annual energy balance. Hatched colour symbols address the excess water wasted either to the aquifer (chilled water turquoise, warm water red/white hatched) or to the river (red/grey hatched).

3.4.2 Results

Temperature distributions within the reservoir after four years are plotted in Figure 15, which displays the state of chilled water injection during the fourth winter after system start up. Average production and injection well head temperatures are elsewhere plotted in Figure 16, according to the two candidate strategies (assigned production and injection wells *vs* seasonally inversed production and injection wells).

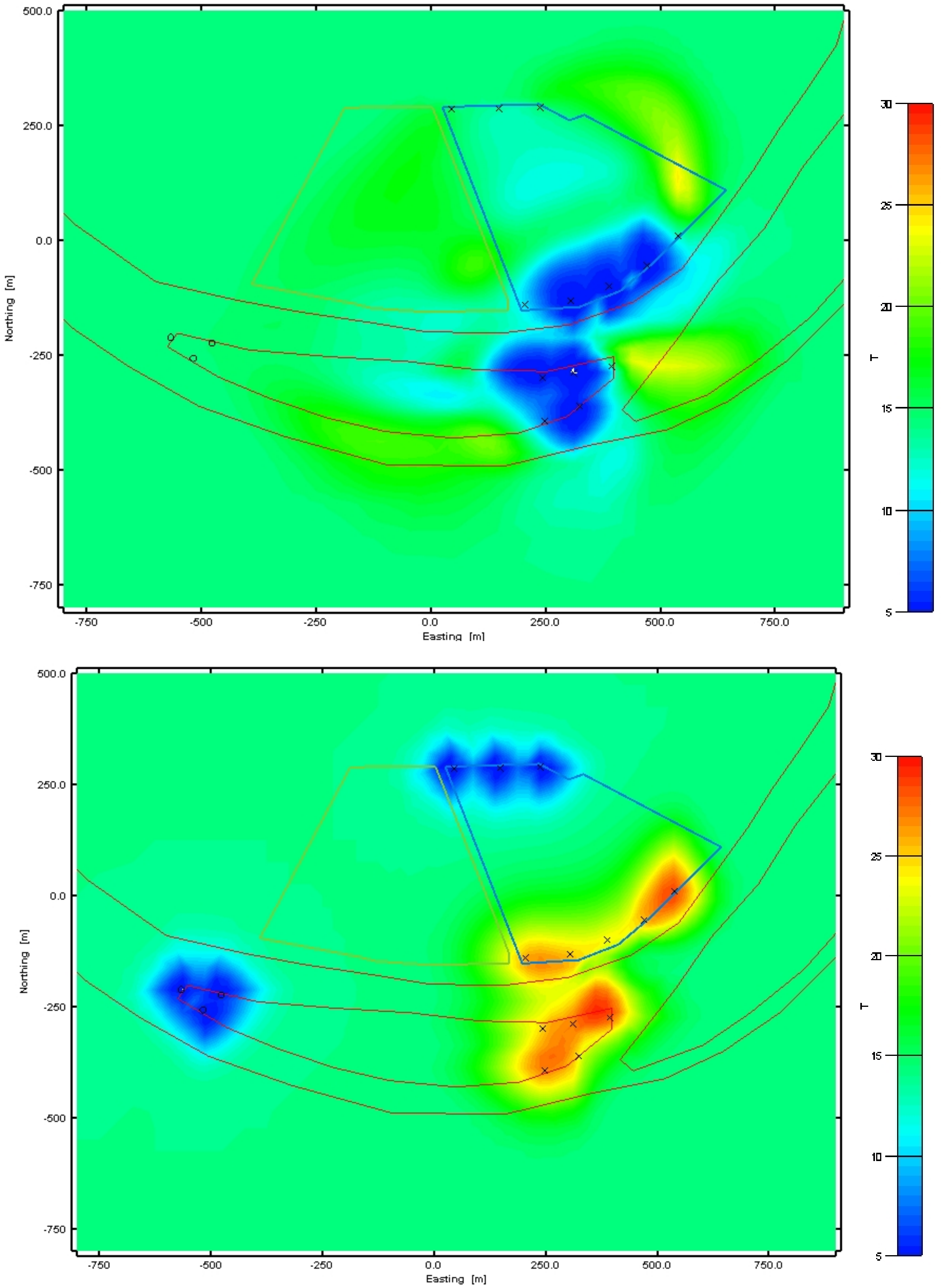


Figure 15: Aquifer temperature patterns further to four year production/injection alternating sequences without (top) and with well seasonal inversion (bottom). Note that in the first case (top) got and cold plumes do mix and reach production wells, whereas in the second one (bottom) they grow and decrease without mixing.

Scheme 1: Successive hot and cold plumes mix in the aquifer before they reach the production wells. As the quantities of heat and cold injected in the aquifer are the same, the temperature at production wells after the thermal breakthrough stays close to the initial aquifer temperature. Thus it allows extracting heat and cold for more than two years, theoretically endlessly, from ground water at sub-constant temperature.

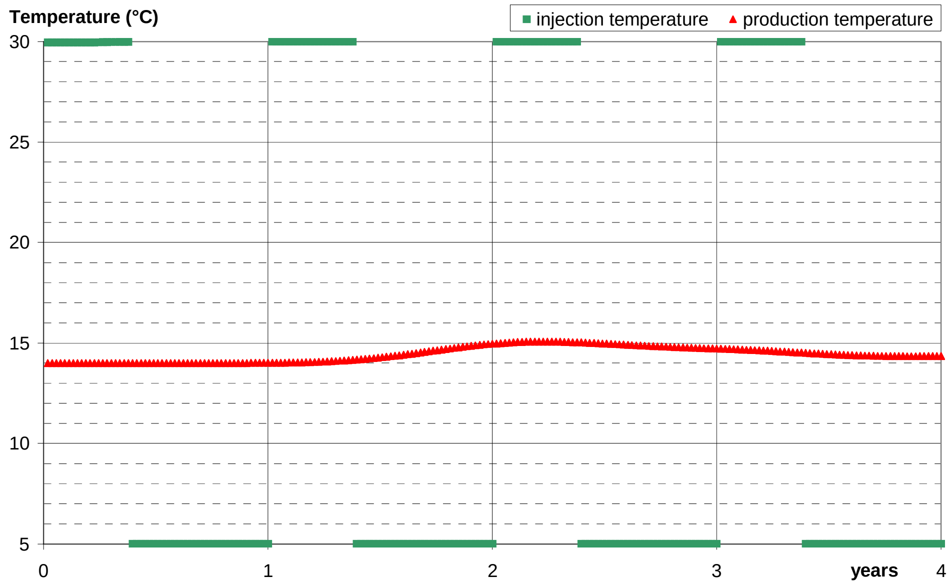
Scheme 2: Seasonal inversion of the mining scheme, by exchanging production and injection well leads to the development of hot and cold bubbles around the well clusters. As the bubbles are growing, their stability is improving (see Figure 16). The more stable the bubble temperature, the smaller the flow rates required to reach the targeted power.

3.5 Conclusion

The use of high capacity heat pumps/chillers, able to supply at the same time hot and chilled water, will be a premiere in France, at this size of district heating and cooling grids. 57% of the chilled water produced is directly supplied from simultaneous production of hot water, achieving a global COP of 4.7. Taking advantage from a well surveyed known dependable shallow aquifer alongside presence of a nearby river, up to 22.8 MW_{th} of chilled water will be produced with efficiency significantly better than with individual air cooled devices.

By adjusting the hot water production in winter, in order to balance the quantities of heat and cold injected in the aquifer, heat pumps will produce 46 % of the total hot water demand.

Seasonal inversion of geothermal loops clearly results in heat and cold storage in the aquifer. Year after year, the increasing stability of the storages, visualized in Figure 16, will improve the efficiency of the system by reducing the flow rates required to meet grid demand.



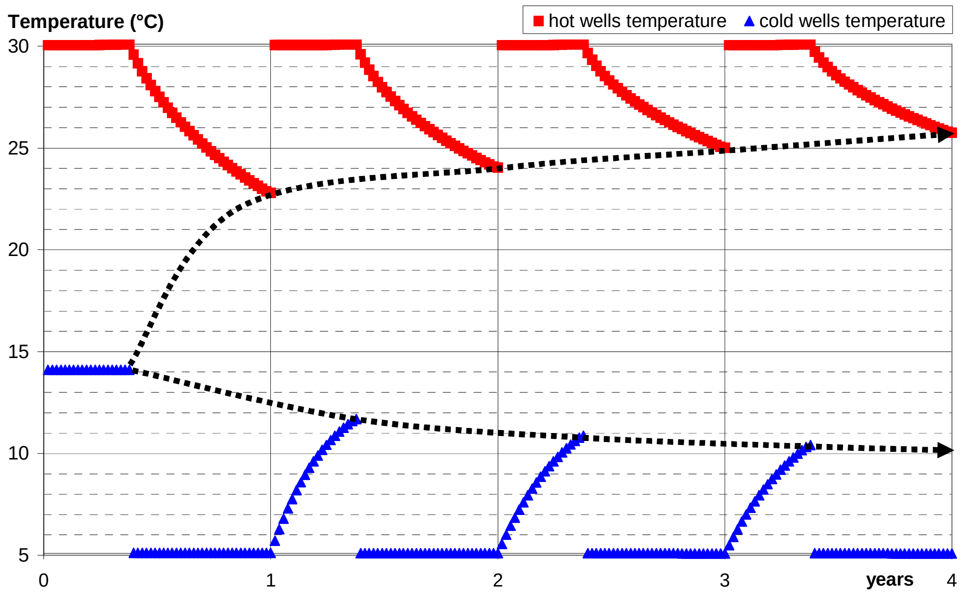


Figure 16: Temperatures evolution at production and injection wells. On the top, without seasonal inversion, as the hot and cold plumes mix in the reservoir, the temperature at production wells does not show a significant breakthrough, variations being damped through the reservoir. At the bottom, we can see how the hot and cold bubbles are growing and are stabilizing. Every new year, the production temperature is more stable than the year before.

CONCLUSIONS

It is shown that seasonal inversion of underground geothermal loops can accommodate critical cases, where building space constraints do not allow to space the well far enough to each other. Provided a thoroughly balanced energy extraction/injection scheme be designed, it is possible to cope with thermal breakthrough shortcomings. Moreover, the seasonal storage of warm and chilled water allows improving the global efficiency of the system, by reducing the required groundwater flow rates. Moreover, wherever space limitation does not occur, aquifer thermal energy storage proved to upgrade system efficiency, by reducing significantly the required ground water flow rates, indeed a rewarding outcome when contemplating water injection issues.

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