

# Chapter 64

## Assessment of Smart Heating and Cooling System Based on Thermal Use of Shallow Aquifer



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**Abstract** All metropolis across the world are facing the challenges of the growing energy demand and the need to reduce the CO<sub>2</sub> emissions. In order to match the two constraints, urban environments should diversify energy sources and maximize local opportunities offered by renewable resources. Within this context, water resources and especially groundwater represent potential alternatives that could provide an efficient answer to the development needs. Nice Côte d'Azur Metropolis gathers around 540,000 inhabitants with more than 350,000 for the city of Nice. Within a national strategic project, the metropolis is currently developing a new urban environment located within the low valley of the Var river and has decided to establish a multi-energy Smart Grid solution. The innovative technological approach is based on: storage of heat, production of cold and electricity, and also a cooling offer for individuals, resulting from the recovery of energy used to air-condition commercial buildings. The chosen solution is based on thermal use of the shallow unconfined aquifer located with the Var floodplain. The network is using surface geothermal energy from the alluvial aquifer. By 2029, it will cover the heating (7.2 GWh per year), air conditioning (15.5 GWh per year) and domestic hot water (7.5 GWh per year) needs of 520,000 m<sup>2</sup> of housing, hotels and additional residential facilities, shops, services and offices served by 1.6 km of geothermal network, 5.6 km of hot and cold networks and 94 sub-stations. The Nice Méridia area will thus be supplied by 82% renewable and recovered energy for heating and 78% for cooling. The development of the geothermal solution requests to pump and to reinject important volumes within the unconfined aquifer. In order to assess the potential impact of the solution on the existing uses (drinking water supply pumping stations), a 3D modelling approach has been deployed over the full groundwater resource of the Var valley. The model, built with FEFLOW solution, validated with field observation, can reproduce the

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behavior of the aquifer (flow dynamic and thermal). The results have demonstrated the efficiency of the 3D modelling approach and the possibility to use the geothermal resource without significant impact on the aquifer. The thermal use of the shallow unconfined aquifer represents a promising solution that could be duplicated in other locations where similar aquifers are present.

**Keywords** Geothermia · Smart energy grid · Heating and cooling network · Shallow unconfined aquifer · 3D groundwater modelling · Impact assessment · FEFLOW

## 64.1 Introduction

All metropolis cities across the world are facing the challenges of the growing energy demand and the need to reduce the CO<sub>2</sub> emissions. In order to match the two constraints, urban environments should diversify energy sources and maximize local opportunities offered by renewable resources. Within this context, water resources and especially groundwaters represent potential alternatives that could provide an efficient answer to the development needs. The geothermal concept is a commonly used solution since decades for modern urban environments. However, most of the time, the chosen technology mobilizes hot water resources pumped in deep aquifers. The high temperatures—sometimes above 100 °C—allow to provide heating services to vast complex of buildings and public facilities. This technology maximizes the benefit of the deep hot water resources.

With the recent development of efficient energy storing units and improvement of thermic performances of construction material, the possibility to use water resources with a lower temperature has appeared and becomes today an operational solution in several cases. In favorable conditions, shallow aquifer could be mobilized to produce thermal resources for energy production. Obviously, the interest of the approach is reinforced by the limited cost of investment compare to deep aquifers that required stronger and costly infrastructures for wells drilling operations and maintenance.

The Nice Côte d'Azur Metropolis, France, gathers around 540,000 inhabitants with more than 350,000 for the city of Nice, 5th largest city in France. Within a national strategic project, the metropolis is currently developing a new urban environment located within the low valley of the Var river. The new area will welcome more than 40,000 new inhabitants. In order reduce impact on environment and to control energy consumption, the Nice Côte d'Azur Metropolis has decided to mobilize only renewable resources and to develop a strategy for energy production on the shallow aquifer located immediately below the new urban development, within the Var low valley. In order to ensure the feasibility of this approach and in addition to the energetic efficiency, it is essential to ensure that the new pumping and reinjection activities will not affect the current uses of the aquifer that is used as one of the main resources for water supply of the population.

## 64.2 The Energy Production Strategy

As part of its legal commitment to reducing CO<sub>2</sub> emissions, the Nice Côte d'Azur Metropolis has outlined a roadmap for significant increases in the use of renewable energies and has decided to mobilize only those resources for new urban extensions and especially for the development taking place within the low Var valley under the Eco valley National Interest Operation (OIN Eco-Vallée—<http://www.ecovallee-cotedazur.com>). The Nice Côte d'Azur metropolis has chosen IDEX to create and operate its future renewable heating and cooling network intended to meet all the thermal needs of the Nice Meridia area, a development operation of 24 hectares led by the Nice Éco-Vallée Public Planning Establishment (EPA) under a PPP agreement with IDEX company (<https://www.idex.fr>).

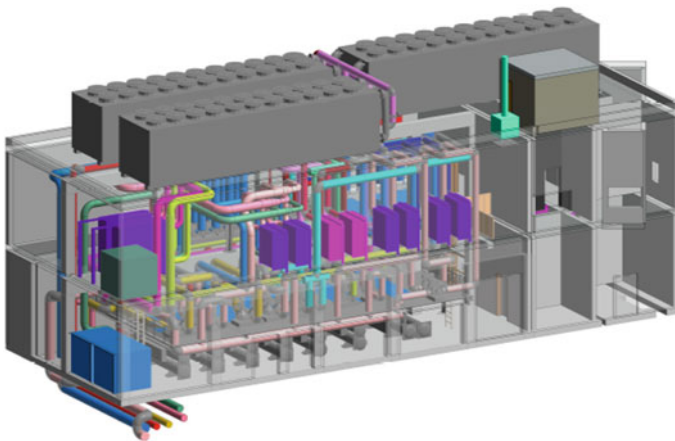
In order to optimize the consumption of all the energies of the future eco-district (heating, cooling and electricity), the operator must combine it with a multi-energy Smart Grid solution. The innovative technological approach is based on storage of heat, production of cold and electricity, and also a cooling offer for individuals, resulting from the recovery of energy used to air-condition commercial buildings.

The chosen solution is based on thermal use of the shallow unconfined aquifer located with the Var floodplain. The network is using surface geothermal energy from the alluvial aquifer. By 2029, it will cover the heating (7.2 GWh per year), air conditioning (15.5 GWh per year) and domestic hot water (7.5 GWh per year) needs of 520,000 m<sup>2</sup> of housing, hotels and additional residential facilities, shops, services and offices served by 1.6 km of geothermal network, 5.6 km of hot and cold networks and 94 sub-stations. The Nice Meridia area will thus be supplied by 82% renewable and recovered energy for heating and 78% for cooling. To this end, a 200 m<sup>2</sup> production and storage plant will be built. Depending on the temperature levels, five thermo-fridge pumps are drawing on alluvium from the Var (12 wells: 4 for extracting and 8 for reinjection at 480 m<sup>3</sup>/h) to heat all the buildings in winter (with a power of 6.5 MW) or cool buildings hosting tertiary activities in summer (with a power of 5.7 MW). Part of the energy needed to operate these thermo-fridge pumps will come from the production of local photovoltaic electricity. By choosing this heating and cooling network, the Metropolis will avoid the emission of nearly 80,000 tons of CO<sub>2</sub> over the duration of the contract. The investment cost for the creation of distribution infrastructure and production facilities amounts to € 18.8 millions and is supported by grants from ADEME and the SUD region (Figs. 64.1 and 64.2).

The innovative solution has been assessed and optimized regarding extraction and reinjection points with a 3D hydrogeological model [1, 2]. The main objectives were to assess potential impacts of pumping and reinjection activities on the aquifer that is currently used for water supply purposes. The modeling results have demonstrated both the interest of the approach and feasibility regarding the other water uses.



**Fig. 64.1** Heating and cooling network with extraction and reinjection points for the new Meridia district (Source MNCA & IDEX)



**Fig. 64.2** Production plant for heating and cooling networks in Meridia district (Source IDEX)

### 64.3 Modelling strategy

In order to assess the impact of the pumping and the reinjection activities, the model has been developed to simulate the current state of the unconfined aquifer and its dynamic with the planned activities. Following calibration and validation phases, the model is assumed to provide a realistic view of the behavior of the groundwater under various hydrological conditions and for different scenarios.

The modelling strategy has been elaborated and implemented with the 3D groundwater model established within the AquaVar project [1, 2]. The 3D groundwater

model for the low Var valley is built with the FEFLOW modelling system. The model has been calibrated and validated over years through its current application in real time and in numerous detailed analysis conducted within various projects taking place within the Var low valley.

3D physically based hydraulic model is the most appropriate methodology to study the physical processes and to ensure an efficient groundwater management within a final exploitation phase. However, the model-based operational tool requests a structured methodology for data integration and validation. The sequential steps for the development of the assessing tool are:

- to develop a hydraulic model of the groundwater flow of the lower Var valley using FEFLOW modeling system;
- to calibrate the unmeasured parameters according to a sensitivity analysis;
- to evaluate the impacts of the pumping and reinjection activities weirs on the groundwater table.

### 64.3.1 3D Model Conception and Extension

The chosen approach is based on the use of the AquaVar model [1, 2] that is covering the full low Var valley and to increase its accuracy in the interest area by densifying the mesh resolution. The approach ensures relevant boundary conditions and allow to provide a global overview of the physical processes in the full extension of the low Valley (Fig. 64.3).

The modelled domain is the total area of the hydrogeological catchment that is delimited by geological faults and the scope of permeable geological layers. Within this range, all the precipitated water contributes to recharge the unconfined aquifer in the valley. For the original model covering the full extent of the low valley, three types of mesh are used to discretize the computational domain: 25 m for the riverbed

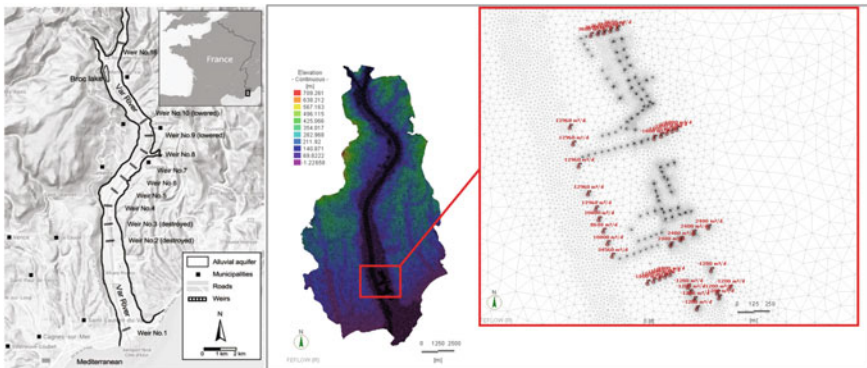


Fig. 64.3 Low Var valley extension (left) [DU, 2018] and extension of the 3D model with specific interest area for the planned geothermal project

and pumping stations where the water exchanges are the most intensive, 50 m for the alluvial aquifer and 100 m for the rest model domain. For considering the pumping and reinjection activities, a fourth type of mesh has been implemented in order to reproduce properly the unconfined aquifer: 0.1 m for the elements within a radius of 75 m around each pumping and reinjection station. The mesh is smoothed so that no obtuse angles are created. The northern boundary of the model is set at the weir No. 16 where the data of a piezometer are used as upstream boundary conditions. The southern boundary is the Mediterranean Sea. Knowing that the alluvial aquifer is connected to the sea water [3, 4], the sea level is used as the downstream boundary condition. The model covers an area of 146.45 km<sup>2</sup>, with a river length of 22.4 km. Vertically, the model contains the layers of recent alluvium, alluvial terraces, Pliocene conglomerate, Pliocene marls, impermeable layer from Miocene to Cretaceous, and the Jurassic limestone. Even though the model focuses on the flow in the first three layers where the unconfined aquifer exists, it is important to include the other layers to reduce the bottom boundary influence on the top layers. As a key material property, the hydraulic conductivity is a decisive input data of the model. In reality, the recent alluvium, alluvial terraces, conglomerate, marl are homogeneous in different flow directions, while in the limestone, the flow direction depends on the fissures. Since there is only a small section of the valley where the limestone contacts directly the alluvium, it could be acceptable to assume that the flow in the limestone is also homogeneous in order to simplify the model.

### 64.3.2 Groundwater Flow and Thermal Simulation

FEFLOW solves the 3D groundwater flow equations in porous media with finite element method. The code has been validated by a numerous case studies [5, 6] and applied for research and engineering projects [7–9]. The governing equations are fluid mass conservation equation and the Darcy equation [5]:

$$S_s \cdot s(h) \frac{\partial h}{\partial t} + \varepsilon \frac{\partial s(h)}{\partial t} + \nabla q = Q \quad (64.1)$$

$$q = -K_r(s)K(\nabla\psi_g + \chi e) \quad (64.2)$$

where  $\psi_g = h + z$  is the hydraulic head (m),  $z$  is the elevation (m),  $h$  is the pressure head (m),  $s(h)$  is the saturation ( $s = 1$  if medium is saturated),  $q$  is the Darcy flux vector (m/s),  $Q$  is the specific mass supply (m/s),  $S_s = \varepsilon_y + (1 - \varepsilon)Y$  is the specific storage due to fluid and medium compressibility,  $\varepsilon$  is the porosity,  $\gamma$  is the fluid compressibility,  $Y$  is the coefficient of skeleton compressibility,  $K_r(s)$  is the relative hydraulic conductivity ( $0 < K_r < 1$ ,  $K_r = 1$  if saturated at  $s = 1$ ),  $K$  is the hydraulic conductivity for the saturated medium,  $\chi$  is the buoyancy coefficient including fluid density effects,  $e$  is the gravitational unit vector.

For the simulation of the reinjection activities, the formulation used for thermal conditions simulation is implemented. For the fluid phase  $f$  and the rigid solid phase  $s$  the individual energy conservation equations are in the following forms:

$$\frac{\partial}{\partial t}(\varepsilon_f \rho^f E^f) + \frac{\partial}{\partial x_i}(\varepsilon_f \rho^f v_i^f E^f) - \frac{\partial}{\partial x_i} \left[ \left( \lambda_{ij}^{cond f} + \lambda_{ij}^{disp f} \right) \frac{\partial T^f}{\partial x_i} \right] = \varepsilon_f \rho^f Q_T^f \quad (64.3)$$

$$\frac{\partial}{\partial t}(\varepsilon_s \rho^s E^s) - \frac{\partial}{\partial x_i} \left[ \left( \lambda_{ij}^{cond s} \right) \frac{\partial T^s}{\partial x_i} \right] = \varepsilon_s \rho^s Q_T^s \quad (64.4)$$

Assuming a thermal equilibrium between the phases  $f$  and  $s$ , it holds:

$$(T^\alpha - T) = 0 \quad \text{for } \alpha = s, f$$

where  $T$  is the system temperature. Moreover, it is assumed the state of internal energy  $E^\alpha$  of the phases should be primarily a function of temperature:

$$dE^\alpha = \frac{\partial E^\alpha}{\partial \rho^\alpha} d\rho^\alpha + \sum_k \frac{\partial E^\alpha}{\partial C_k^\alpha} dC_k^\alpha + \frac{\partial E^\alpha}{\partial T^\alpha} dT^\alpha \approx C^\alpha dT^\alpha_\varepsilon \quad (64.5)$$

for  $\alpha = s, f$ .

with the heat capacity  $C^\alpha = \frac{\partial E^\alpha}{\partial T^\alpha}$  of  $\alpha$  - phase.

Accordingly, the heat transport Eqs. (64.3) and (64.4) can be combined (added). As a result, energy equations for each phase need not be considered. Rather the total energy conservation equation is preferred. After summation of Eqs. (64.3) and (64.4), it yields:

$$\frac{\partial}{\partial t}[\varepsilon \rho^f E^f + (1 - \varepsilon) \rho^s E^s] + \frac{\partial}{\partial x_i}(\rho^f q_i^f E^f) - \frac{\partial}{\partial x_i} \left[ \lambda_{ij} \frac{\partial T}{\partial x_i} \right] = Q_T \quad (64.6)$$

In forming the above total energy conservation Eq. (64.4) the following thermodynamic and heat supply expressions, respectively, naturally result:

$$\lambda_{ij} = \left[ \lambda_{ij}^{cond f} + \lambda_{ij}^{cond s} + \lambda_{ij}^{disp f} \right] \quad (64.7)$$

$$\lambda_{ij} = [\epsilon\lambda^f + (1 - \epsilon)\lambda^s]\delta_{ij} + \rho^f c^f \left[ \alpha_T V_q^f \delta_{ij} + (\alpha_L - \alpha_T) \frac{q_i^f q_j^f}{V_q^f} \right] \quad (64.8)$$

$$Q_T = \epsilon\rho^f Q_T^f + (1 - \epsilon)\rho^s Q_T^s \quad (64.9)$$

where  $V_q^f = \sqrt{q_i^f q_j^f}$  designates the absolute Darcy flux.

## 64.4 Simulation Protocole and Results

The smart grid is designed for the production of hot water during the winter period and cool water during the summer time in order to answer to needs of the inhabitants of the new Meridia residential area. In a first phase, 4 pumping stations are planned and will extract from the unconfined aquifer located around 15 m below the ground surface, 100 m<sup>3</sup>/h for each which represents 9600 m<sup>3</sup>/day. The 10 reinjection stations are located downstream the pumping stations in order to avoid affecting the pumped volumes and operate with a rate of 50 m<sup>3</sup>/h. Obviously, the extracted volume is significant and may potentially affect the groundwater resource and impact other uses such as the drinking water supply pumping stations located within the downstream area.

The aquifer is characterized with a constant temperature over the year with 15 °C. In order to simulate the impact of the geothermal project, the year has been defined in two periods for the production of hot or cool water according to the seasonal climatic situation:

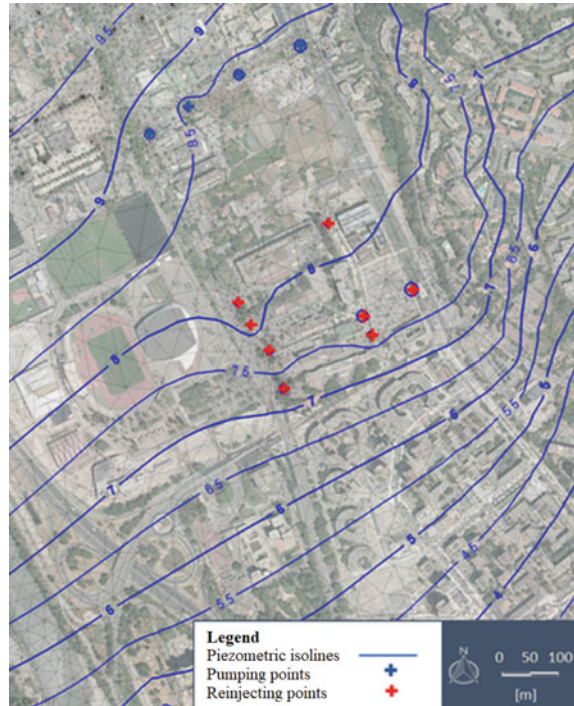
- from 15th of April to 15th of October, the water is used for cooling purpose and the reinjection temperature is up to 23 °C;
- from 15th of October to 15th of April, the water is used for heating purpose and the reinjection temperature is down to 7 °C (Fig. 64.4).

At the initial stage, the model was validated with observed data. This step was achieved previously within the context of the AquaVar model's development and the simulation results have demonstrated that the model can perfectly reproduce the dynamic of the unconfined aquifer. The validation period has been conducted over a period of 4 years—2009 to 2012—that includes a major flood event and one of the most severe droughts in 2012 (50 years return period). Despite those important variations observed within the Var river discharges, the aquifer is only affected by a 0.5 m annual fluctuation. This specific situation can be explained in one hand by the massive dimension of the aquifer and in the other hand by the very high transmissivity—up to 0.3 m<sup>2</sup>/s—of the hosting geological layer mainly composed with coarse fluvial sediments.

The volumes from the pumping and reinjection stations have been integrated within the densified model and a new piezometric mapping has been produced (Fig. 64.2). The validity of the model for the pumping and reinjection stations has



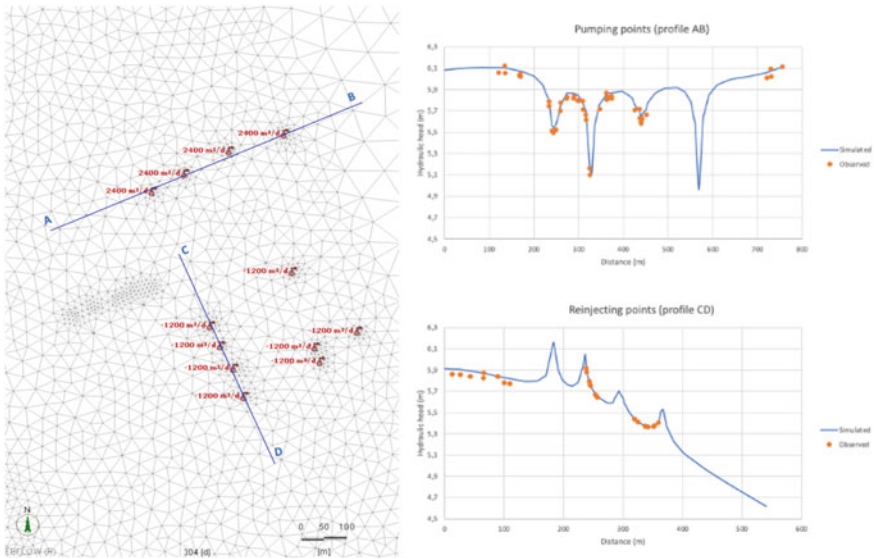
**Fig. 64.4** Piezometric map for the unconfined aquifer affected by pumping and reinjection stations



been obtained from field tests achieved by the technical services of Nice Côte d'Azur Metropolis in 2019. The 3D model can perfectly reproduce the aquifer behavior as long as the mesh size is reduced to 0.1 m. As expected and due to the magnitude of the extracted volumes, the aquifer is lowered around the pumping stations and elevated at the reinjection points. However, the effect has a limited spatial extension due to the characteristic of the aquifer and of the geological layer (Fig. 64.5).

Simulations were carried out also to assess the potential impact for the reinjection of volumes. Those volumes are characterized by a different temperature—7 °C or 23 °C—and can potentially affect the aquifer. In order to minimize the potential risks, the local regulation regarding aquifers and reinjections imposes a maximum temperature shift of 8 °C. The simulations have been running over a period of 4 years in order to assess the potential cumulative effects that can generate the development of long-term increase of the temperature of the aquifer. In fact the reinjection of cold water has a potential minor effect as the regulation for water uses is mainly addressing the high temperatures.

The obtained results demonstrate that the reinjection volumes will generate an increase of the aquifer's temperature during the summer period. However, this increase is very limited in space as demonstrated on Fig. 64.6. Even after several months, the heat effect remains limited to few meters around the reinjection stations and obviously do not affect the pumping stations that are located downstream and



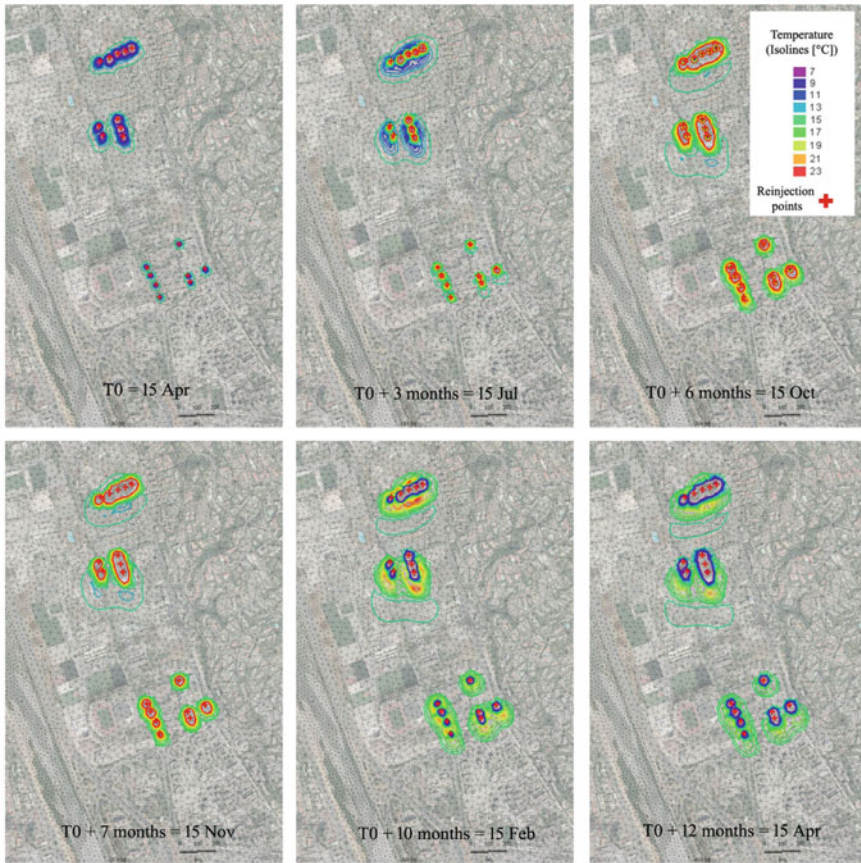
**Fig. 64.5** Validation of the 3D with field data collected in 2019 for pumping and reinjection activities

used for drinking water supply. At the same time, no cumulative effect can be identified over time and the impact of the thermal exploitation looks minimal.

## 64.5 Conclusions

The multi-energy smart grid planned for the new urban development of Nice Meridia area is based on the use of the shallow unconfined aquifer located within the Var valley. The constant temperature of the aquifer located close to the ground surface allows to produce water volumes that could be used for cooling during summer and heating during winter. The innovative solution ensures a high level of performance but requests important pumping volumes from the groundwater resource. In addition to the pumping operations, the extracted volumes must be reinjected within the aquifer. The reinjections' locations have to be optimized in order to limit the extension of the network but also to avoid affecting to existing water uses and moreover do not affect the global quality of the aquifer by altering the thermal characteristics.

The modeling strategy based on a 3D model covering the full extend of the aquifer with a very high resolution at the level of the pumping and reinjection stations was able to provide a global overview of the groundwater flows in current and future situation. The validity of the model has been demonstrated with field data. In addition, the model was also able simulate the thermal impact of reinjection stations. Due to the high transmissivity of the unconfined aquifer, the thermal characteristics of the



**Fig. 64.6** Evolution of the aquifer temperature over 12 months and with the reinjection volumes for summer and winter periods

groundwater are not significantly affected and do not disturb the current uses located in the downstream area. The technical solution represents a very efficient alternative and could be easily duplicated under the condition of similar characteristics for the aquifer.

Within the specific context of the low Var valley and its superficial alluvial aquifer, the innovative solution based on the thermal characteristics appears very efficient and associated to a negligible impact on the groundwater resource. The 3D model has demonstrated its capacity to assess the project and it will be used during the exploitation phase in real-time mode, within a Decision Support System [10, 11], in order to monitor the effect of reinjections and to anticipate a potential malfunctioning.

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