

Geothermal heat pumps for sustainable farm climatization and field irrigation

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In intensive breeding farms, maintaining an adequate indoor thermal environment and air quality is crucial in order to establish healthy conditions and increase productivity. In the EU, fossil fuels and electricity are the main energy sources adopted for this purpose, yet introducing renewable energy sources and efficient Heating Ventilating Air Conditioning systems would reduce energy consumption and improve sustainability.

Another environmental concern in agricultural production is related to the intensive use of fertilizers, causing nitrate contamination in surface water and groundwater. Therefore, innovative strategies to reduce fertilizers and simultaneously reduce primary energy consumption are worthy of investigation.

This paper addresses both issues, studying the application of geothermal heat pumps in the agro-zootechnical sector, where they are rarely applied and thus their potential needs to be verified. The study considers systems based on the closed loop configuration, i.e. Ground Source Heat Pumps (GSHP), and on the open loop configuration, i.e. Groundwater Heat Pumps (GWHP).

Firstly, a pilot GSHP system for a piglet stable in Northern Italy is presented. Thanks to the use of both ground source and thermal recovery of air ventilation, the system achieves an appreciable reduction in both primary energy consumption and running costs, compared with a more traditional system typically adopted in this kind of farm.

Secondly, the feasibility of an innovative concept of a GWHP combined with the irrigation system is studied through numerical modelling. The area of the piglet stable is represented in a flow and heat transport model; groundwater used by the heat pump is re-injected up-gradient during the cold season, while it is used for irrigation during the warm season. The system would provide energy-efficient climatization to the farm stables and, at the same time, promote the reuse of nitrogen in cultivated fields as a result of groundwater recirculation through irrigation.

Keywords: Geothermal energy, Heat pump, Climatization, Piglet farm, Numerical modelling, Groundwater

1. Introduction

According to the Eurostat database (Eurostat, 2017), in 2014 in the European Union energy consumption by agriculture made up 2.8% of the final energy consumption, with the highest share in the Netherlands (7.2%) and Poland (5.6%). In all probability these figures are underestimated (Gołaszewski et al., 2012), since they account only for the so-called direct energy uses in agriculture, namely related to electricity and fuel consumption. Out of the total primary energy consumption in agriculture in the EU, the proportion of direct energy used is estimated at 61% (Meyer-Aurich et al.,

2013), although it may largely vary for the specific activity. Considering pig production in Italy, according to the IPPC document (The European Commission, 2003), fossil fuels and electricity represent up to 74% of the total energy consumption, depending on the farm size.

Improving energy efficiency in agricultural production is important for reducing energy consumption, dependency on fossil energy input, energy related costs and greenhouse gas emissions. Energy efficiency measures have been proposed, impacting on the levels of crop production, greenhouse production, animal housing and system approaches (Meyer-Aurich et al., 2013).

Among the measures aimed at reducing indirect energy consumption, the efficient management of fertilizers is expected to contribute to a large extent. Elevated levels of nutrients in both surface water and groundwater as a result of the leaching of

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Nomenclature

ACH	Air changes per hour
AHU	Air handling unit
BHE	Borehole heat exchanger
COP	Coefficient of performance
EDZC	Experimental didactic zootechnical centre
EER	Energy efficiency ratio
GSHP	Ground source heat pump
GWHP	Groundwater heat pump
HVAC	Heating ventilating and air conditioning

excess fertilizers in agricultural regions have been acknowledged for decades (Thorburn et al., 2003; Zhang et al., 1996). In recent years, however, the magnitude of the phenomenon has increased in scale, resulting in one of the most common contamination problems worldwide (Baily et al., 2011; Buvaneshwari et al., 2017; Duwig et al., 2003; Kim et al., 2015; Rudolph et al., 2015), investigated by several authors and through different approaches (Carucci et al., 2012; Caschetto et al., 2017; Sorichetta et al., 2012; Stevenazzi et al., 2015).

In Europe, the Council Directive (Consiglio delle comunità europee, 1991) aims to prevent nitrates from polluting surface water and groundwater, and promotes the use of good farming practices. In general, any strategy allowing a reduction in the use of fertilizers in agriculture would have a positive impact on both indirect energy consumption and pollution in aquifers.

As far as direct energy consumption is concerned, interventions on animal housing are needed, aimed at reducing the energy demand of stables, increasing the efficiency of climatization systems and introducing renewable energy sources. Enhancement of indoor air quality (both in terms of thermo-hygrometric conditions and pollution) is also required to improve animal wellbeing and bolster production (Fabrizio et al., 2015). The climatization and ventilation systems currently installed are mostly based on fossil fuels or electricity from the grid, making livestock production a contributor to climate change (Rojas-Downing et al., 2017). Geothermal heat pump systems potentially represent an improvement both in energy consumption and indoor air quality; their applicability to the sector is eased by the fact that agro-zootechnical farms already withdraw groundwater from wells, or have the space to host them.

Geothermal heat pump systems can be classified into Ground Source Heat Pump (GSHP) and Groundwater Heat Pump (GWHP) systems (Kavanaugh and Rafferty, 1997). In the first case, the heat pump extracts heat from the ground by means of a closed water loop consisting in several Borehole Heat Exchangers (BHEs). In the second case, the heat pump operates on an open water loop circuit, where groundwater is extracted from a well and re-injected into another well after heat exchange. The advantage in both cases is the exploitation of a heat source (the ground or groundwater) whose temperature is unperturbed all year round (e.g. between 13 and 17 °C in Milan (Davoglio and Ghezzi, 2014)), resulting in high energy efficiency and low running costs (Farabi-Asl et al., 2018; Lee et al., 2010; Lo Russo et al., 2009; Pulat et al., 2009; Yang et al., 2009). In both cases, the heat pump operation can be inverted in the warm season, so that the heat pump provides cooling to a building by injecting heat into the ground or the aquifer.

While geothermal heat pumps are commonly installed in residential, public and commercial buildings (Allaerts et al., 2016; Zhou et al., 2016), their use in agriculture is mostly limited to greenhouse heating (Huang and Mauerhofer, 2016; Noorollahi et al., 2016), aquaculture pond heating and crop and food drying (Erbay and Hepbasli, 2016; Lund and Boyd, 2016). The possibility to adopt geothermal heat pump systems in animal farms was investigated

only recently by some authors (Borge-Diez et al., 2015; Islam et al., 2016; Wang et al., 2012). Wang et al. (2012) performed an economic comparison among different systems for a typical swine farm in Beijing, China. They concluded that considering the cooling effect obtained without increasing indoor relative humidity, as well as the energy saving in the heating period and the avoided air pollution from PM 2.5, the GSHP system is likely to be preferred in the upcoming future. Islam et al. (2016) experimentally investigated the performance of a GSHP and a conventional electrical heating system in a nursery pig house in Korea. GSHP provided a 46% reduction of energy consumption, and CO₂ and other noxious gas emissions were significantly lowered.

From the analysis of the state of the art, the necessity arises to verify the possibilities of implementing low-temperature geothermal solutions in the agro-zoo-technical sector. Geothermal heat pumps are rarely adopted in farms and, compared to conventional building applications, design for farms has to address specific issues: high ventilation requirements, deriving from the necessity to remove noxious emissions by the animals, and relatively high indoor temperature requirements, necessary in the first life stages of the animals. The possibility to improve the indoor thermo-hygrometric conditions and air quality as well as animal wellbeing can be foreseen, yet it needs to be proved. At the same time, application to the agro-zoo-technical sector opens the way to innovative strategies combining the traditional irrigation uses of groundwater with less common climatization uses. In order to demonstrate the potential for low-temperature geothermal solutions in this new field, the EcoZoo project was promoted by the Lombardy Region. The project, concerning both GSHP and GWHP, consisted of two parts:

- design, installation and monitoring of a pilot GSHP system for heating and cooling a typical piglet room. The aim was to adapt the GSHP system design to animal housing applications and to verify energy performance and possible savings compared with more conventional solutions typically adopted in farms;
- development of a new concept of a GWHP system integrated with the irrigation system of a farm. The objective was to assess the possibility to optimise the use of groundwater in farms, by coupling thermal and irrigation uses through a proper designing of the wells. At the same time, a further aim was to reduce pollution by agricultural inputs in groundwater by adopting a smart groundwater management strategy. The feasibility of this innovative system was numerically studied, assuming the well-known hydrogeological conditions of the Experimental Didactic Zootechnical Centre (EDZC) site, as well as the energy demand for heating and cooling of the entire Campus building dedicated to animal housing.

2. Case study

2.1. Location

The case study for both parts of the research is a portion of the EDZC in the Lodi Campus of the Università degli Studi di Milano. The EDZC is located in the South Western part of Lodi, in an area where many agricultural and breeding farms are present (see Fig. S1 in the Supplementary Material).

The pilot GSHP system was installed in the post-weaning piglet room, located in one of the sheds of the EDZC (Fig. 1) dedicated to experimental research on breeding (Savoini et al., 2002). At the same time, for the concept of the innovative GWHP system, it was assumed that the latter system would satisfy the heating and cooling demand of the entire shed, as shown in Fig. 1c.

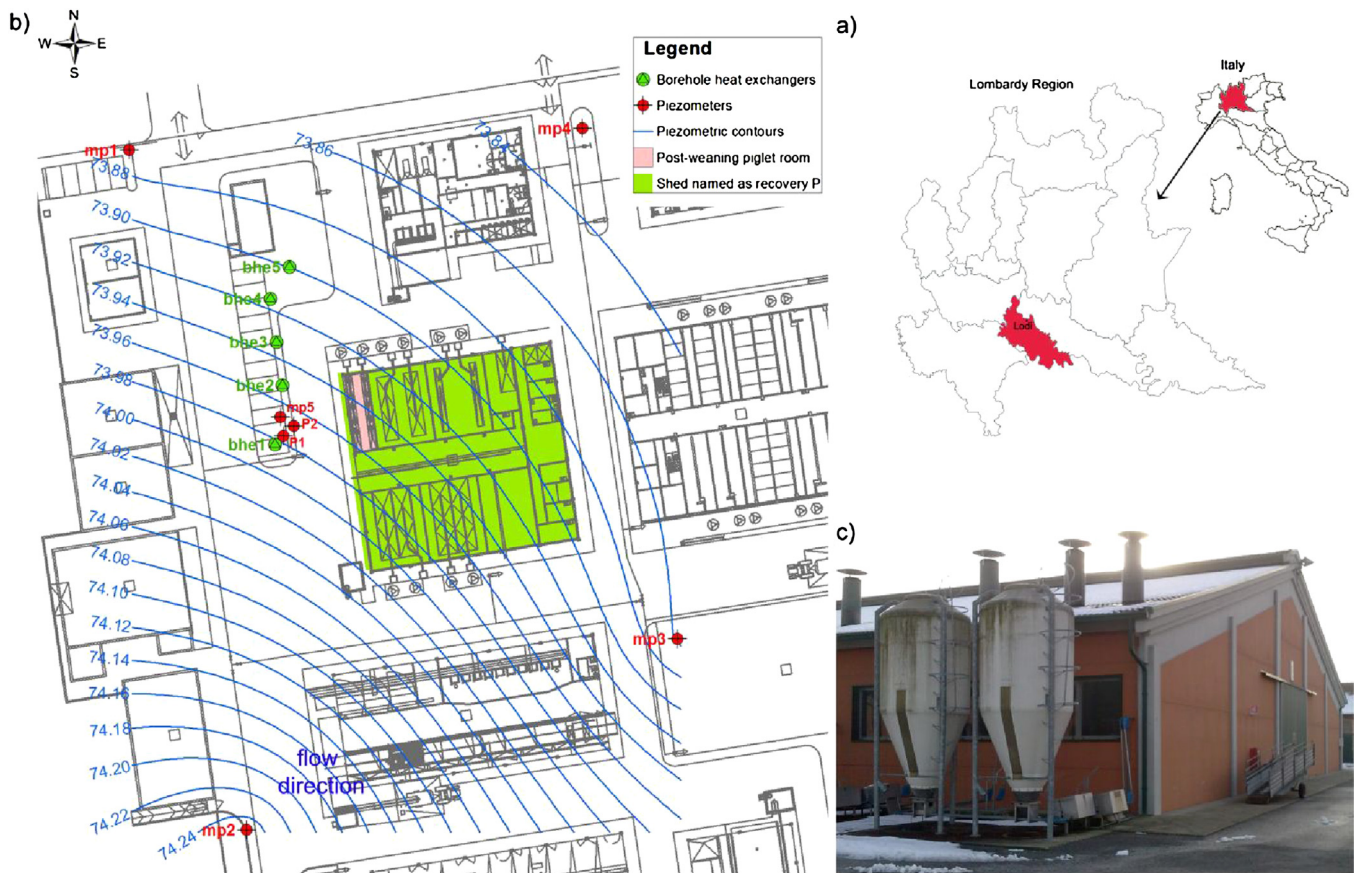


Fig. 1. (a) Location of the Lombardy Region and the city of Lodi in Italy; (b) Case study area in the EDZC: the shed (green and in the center of the image), the post-weaning piglet room (pink and included in the shed), the BHE, the micro-piezometers and the water table at local scale; (c) a picture of the shed from the outside. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Hydrogeological characteristics

The hydrogeological characteristics of the area were then investigated, both analysing literature and performing specific surveys on site, with a dual purpose. The first aim was to design the layout of the BHEs for the pilot system, drawing the maximum advantage from the groundwater flow: it is well known that locating the BHEs orthogonally to the preferential direction of the groundwater flow enhances the heat exchange and thus increases the total efficiency of the system. The second purpose was to create an accurate model of the aquifer to be used in the numerical simulations for the development of the innovative concept of a GWHP system.

2.2.1. Soil lithozone

Based on literature (Alberti et al., 2016; Bersezio et al., 2007; Mele et al., 2012), two lithozones were identified in this area at regional scale: a shallow aquifer extended to a depth varying from 40 to 70 m, composed of gravel and prevalent sands, with few levels of clay lacking continuity; a deep aquifer, with sandy or gravelly levels having the frequent presence of clay and silty lenses. From literature and from stratigraphies of some wells located in the area of the Lodi Campus, the separation between the shallow and the deep aquifers was estimated to be about 60 m below surface level. In order to verify and supplement information concerning the litho-stratigraphic and hydrogeological characteristics of aquifers, a geognostic survey was carried out on site. The drilling technique (in rotation with a continuous core sampling) allowed the extraction of cores and made it possible to draw the stratigraphic sequence of the subsoil up to the expected depth for BHE, i.e. 60 m from ground level. As shown in Fig. 2, a sequence of silty

sand and sandy silt was revealed in the first 18 m, followed by nearly 10 m of coarse sand and gravel. A local level of clayey silt layer was found between 30.5 m and 33 m from the surface, followed by coarse and medium sand layers, with an irregular presence of gravel or pebbles up to the end of the hole.

Field tests, such as one pumping test and four pneumatic slug tests, were performed to investigate the hydraulic parameters of the aquifer. The results (Table S1 and S2 in Supplementary Material) made it possible to infer an equivalent value of aquifer permeability nearly equal to 10^{-4} m/s (Antelmi, 2016), revealing that the hydraulic response of the system was dominated by sandy layers; these are mainly present in the lower part of the aquifer and their hydraulic conductivity is an order of magnitude greater than the lithology of the first 10 m of the aquifer.

2.2.2. Water table

As far as the groundwater flow direction is concerned, the water table from literature showed a SSW – NNE direction in the University area. In order to effectively position the BHEs while avoiding the superposition of the thermal plumes, it was also necessary to identify the water table at the local scale and to determine the groundwater flow direction with great accuracy. A piezometric monitoring network was set up, comprising both existing wells and four newly drilled network wells and four newly drilled micro-piezometers (named mp1, mp2, mp3 and mp4, see Fig. 1b). Five BHEs and some additional monitoring wells (namely the micro-piezometer mp5 and two piezometers, named P1 and P2) immediately down-gradient were subsequently placed (Fig. 1a). The water table at the site scale confirmed the direction

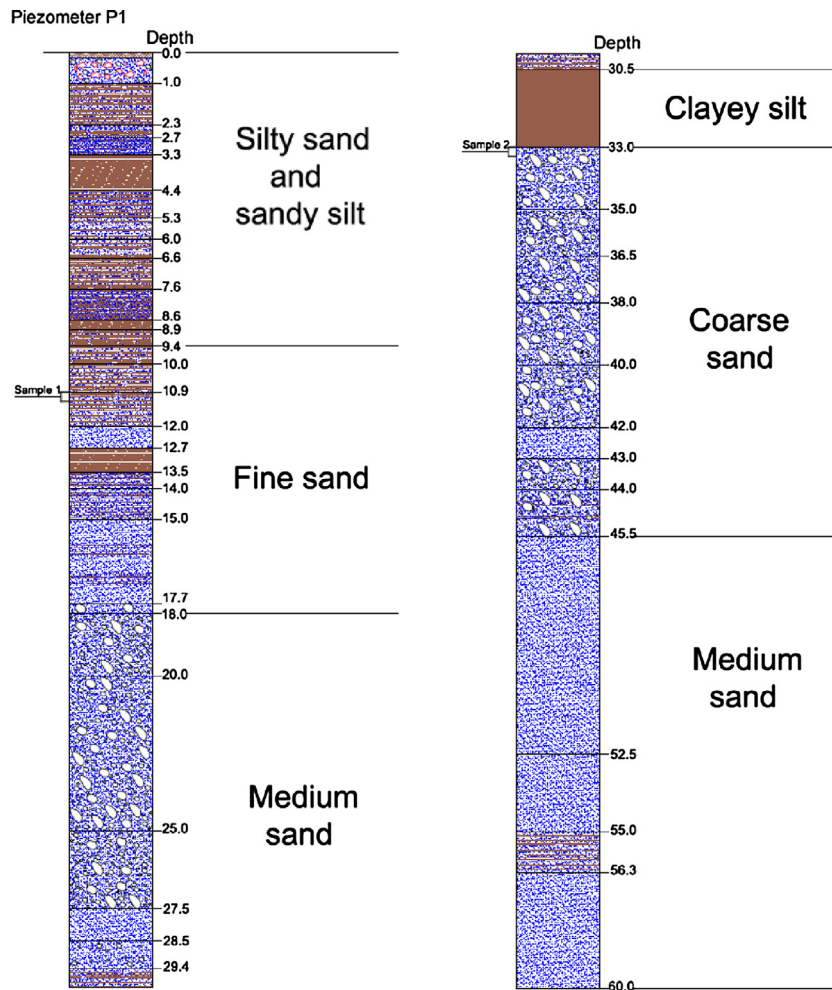


Fig. 2. Stratigraphic log 0–60 m of the underground at the Centre site for the piezometer P1.

of the groundwater flow achieved at Lodi scale, that is SSW – NNE as mentioned above (Fig. 1a).

3. Ground source heat pump system application

3.1. System description

The pilot system was designed to provide heating, cooling and ventilation to the post-weaning piglet room of the EDZC. The piglet room (Fig. 3) is 43 m² large, 3.3 m high and can host up to 100 piglets, located in two rows each made up of 12 boxes. Although small, the mentioned animal housing conditions can be considered representative of the typical pig farms in the area. Usually, the piglets arrive at the EDZC when they weigh about 6 kg and leave the room after 6–8 weeks when they weigh about 34 kg. The comfort temperature required decreases as the piglets grow, being usually around 30 °C at the beginning of their stay at the EDZC and generally decreasing by 1 °C every week. At the same time, a large ventilation rate of about 1000 m³/h is required, corresponding to 8 Air Changes per Hour (ACH), in order to remove the pollutants emitted by the animals.

Before the EcoZoo project, a 16 kW fan gas burner (at the centre in Fig. 3) and two fans for the air suction installed in the piglet room provided the necessary heating and ventilation in winter. In winter the combustion occurred inside the room, whereas during summer no cooling system was available but some mitigation was obtained by running the fans at maximum velocity.

Since the ventilation rate requirements are very large, as usually occurs in animal housing, the GSHP system was designed to be an air conditioning system, equipped with heat recovery from the exhaust air in order to reduce energy consumption. The system layout is shown in Fig. 4. The heating and cooling generator is a reversible GSHP (heating capacity 14.4 kW at 40/45 °C on the supply side and 3/0 °C on the ground side; cooling capacity 15.9 kW at 10/15 °C on the supply side and 30/35 °C on the ground side). The warm/cold water produced by the heat pump was stored in a 300 l water tank supplying the heating/cooling coil of an Air Handling Unit (AHU) with a nominal ventilation flow rate of 1200 m³/h. The heat recovery heat exchanger in the AHU had a nominal efficiency equal to 78%.

The GSHP was coupled to 5 BHEs with a single U-pipe 60 m deep in the ground, being distanced 5–6 m from each other. As already mentioned in Section 2, the BHE layout (Fig. 1a) was chosen, within the constraints expressed by the EDZC, in order to minimise thermal interference among neighbouring boreholes by taking advantage of the effect of the groundwater flow (Angelotti et al., 2014).

3.2. Data acquisition system

In order to verify the thermo-hygrometric conditions achieved in the piglet room, so influencing animal wellbeing, and to measure the energy performance of the GSHP system, a monitoring system was installed based on an NI cDAQ data acquisition system and



Fig. 3. The piglet room (left), the pre-existing gas burner (centre) and the new GSHP system (right).

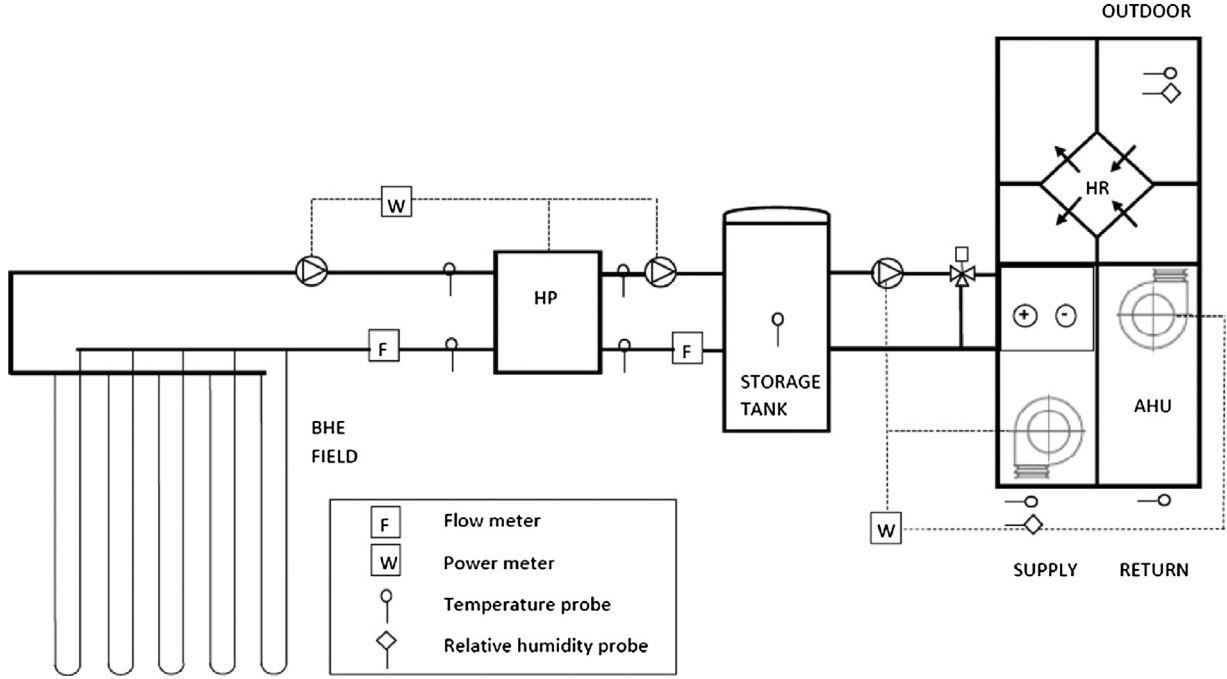


Fig. 4. The pilot GSHP system installed in the piglet room in the EDZC. Monitoring probes are shown.

LabView. Several probes were installed (Fig. 4) to measure: water temperature and flow rate at the heat pump inlet/outlet on the ground and supply sides; air temperature and relative humidity in several points of the AHU unit and in the piglet room; air flow rate in the AHU and power consumption by the heat pump and by the AHU (parameters listed in Table S3 of the Supplementary Material).

During a typical monitoring campaign, data are acquired every minute. From the measured data it is possible to calculate the thermal power produced by the heat pump as:

$$\dot{Q}_{th, hp} = \dot{m}_{w,s} c_{p,w} (T_{w,s,in} - T_{w,s,out}) \quad (1)$$

where $\dot{m}_{w,s}$ is the mass flow rate in the supply loop of the heat pump, $c_{p,w}$ is the specific heat capacity of water, $T_{w,s,in}$ and $T_{w,s,out}$ are the water temperature at the inlet and outlet of the storage tank respectively. In a similar way the thermal power produced by the AHU can be calculated as:

$$\dot{Q}_{th, AHU} = \dot{m}_{a,s} c_{p,a} (T_{a,sup} - T_{a,ext}) \quad (2)$$

where $\dot{m}_{a,s}$ is the supply air mass flow rate, $c_{p,a}$ is the specific heat capacity of the air, $T_{a,sup}$ and $T_{a,ext}$ are the air supply temperature and the external air temperature respectively.

3.3. Monitoring campaign

A monitoring campaign was carried out for a month in 2016, namely from October 26th to November 25th. During that period,

50 piglets were hosted in the EDZC post-weaning room. The request from the veterinary research team, for this special experimentation, was to maintain 30 °C at the beginning of the experimental period and gradually reach 28 °C at the end. The operation of the AHU and the thermo-hygrometric conditions in the piglet room in a representative week of the campaign are shown in Fig. 5. Considering the thermostat dead band as equal to 1 °C, the system was able to maintain the temperature set point, which, as shown in the graph, was varied from 29 °C to 28.5 °C in the late afternoon of the 14th day from the beginning of the campaign. The two indoor air probes installed in Boxes 5 and 16 provided very similar data, suggesting that temperature conditions were almost uniform in the room. Furthermore, it can be seen that the indoor relative humidity was generally kept below 55%, well below the limit of 70% recommended by the International Commission of Agricultural Engineering (Dolz et al., 2015).

In Fig. 6 the electrical power consumed and the thermal power produced by the heat pump and the AHU are shown for a typical day, from 6 a.m. to 2 p.m. While electrical power is directly measured by the power meters installed, thermal power is calculated from measured flow rates and temperature difference according to Eqs. (1) and (2). The fans of the AHU are always on, since they constantly provide the required ventilation rate, thus the electrical power consumption of the AHU is constant and equal to 0.5 kW. In turn, the heat pump switches off whenever the water temperature at the storage tank outlet rises above the set point, equal to 48.5 °C,

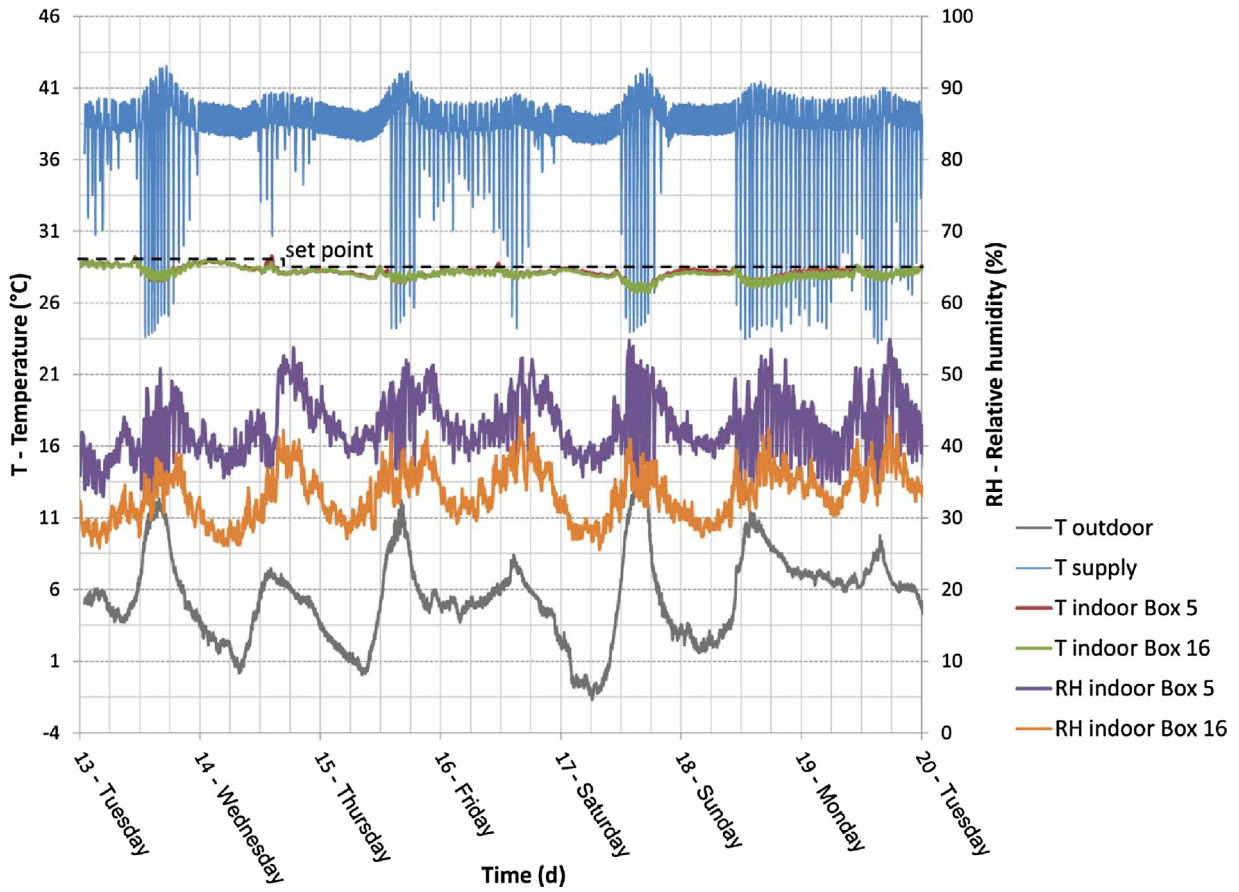


Fig. 5. Monitoring campaign on the GSHP system: temperature (T) on the left axis and relative humidity (RH) on the right axis during a representative week.

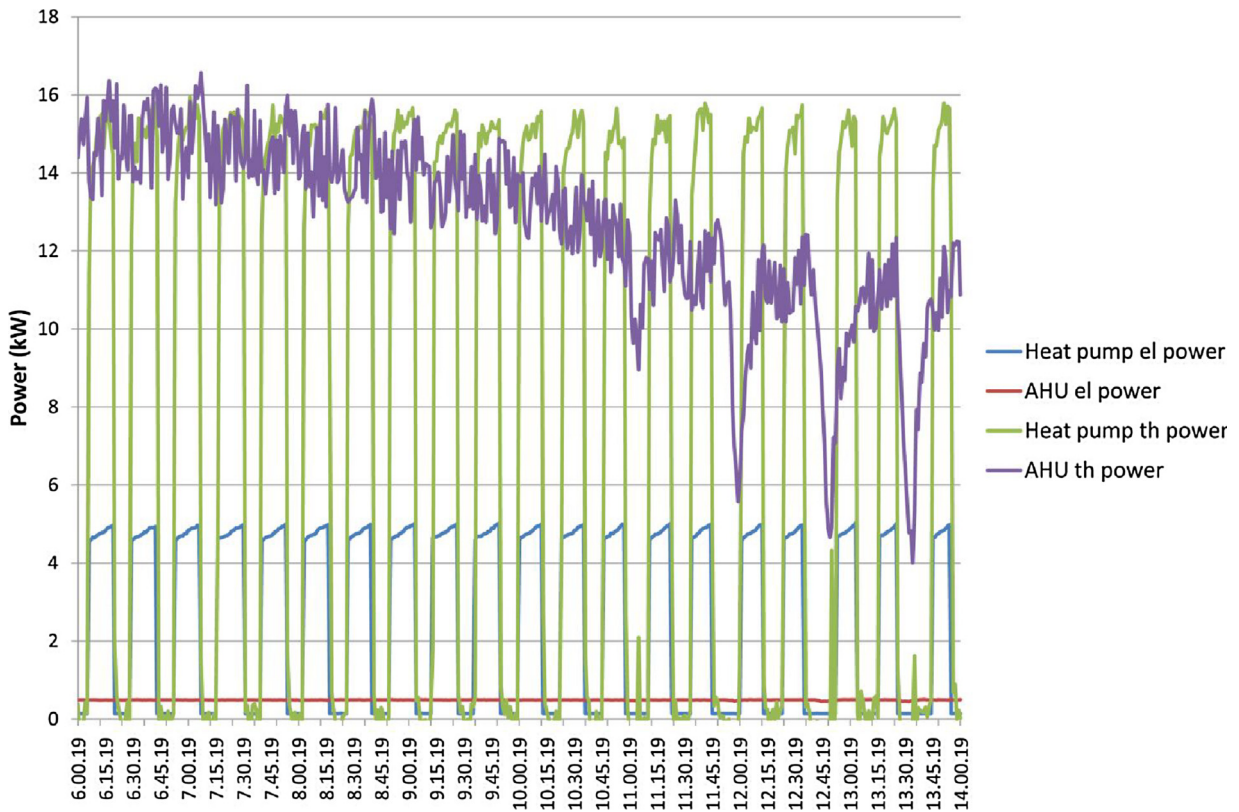


Fig. 6. Monitoring campaign on the GSHP system: heat pump and AHU electrical and thermal power from 6 a.m. to 2 p.m. of a representative day.

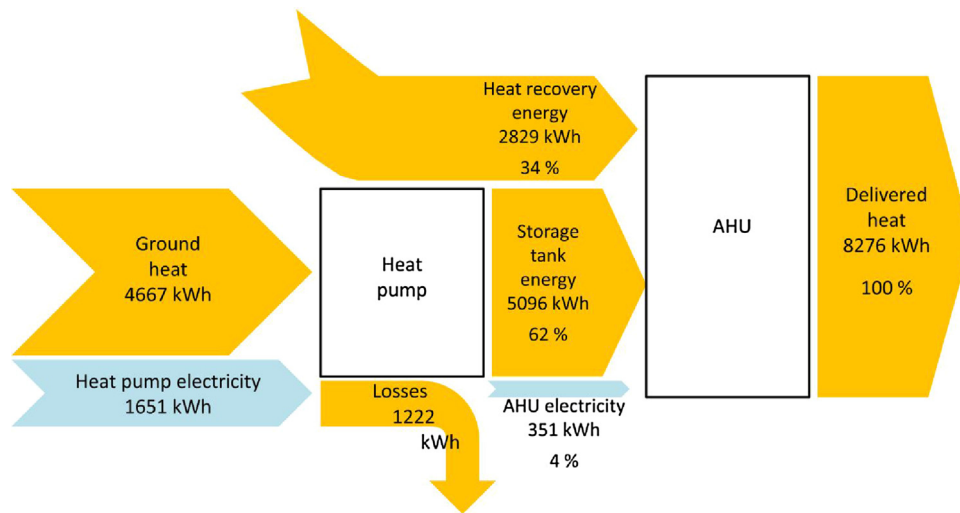


Fig. 7. Monthly energy balance for the pilot GSHP system, derived from the monitoring campaign.

then the electrical power falls to zero. When the heat pump is on the absorbed electrical power is in the range of 4.6–4.9 kW and the supplied thermal power is about 15 kW.

Starting from the measured data, the monthly energy balance of the EcoZoo GSHP system was performed and is shown in Fig. 7. The average heat pump COP, calculated as the heat produced by the heat pump (5096 kWh) over the electricity consumption (1651 kWh), was found to be 3.1. This value is coherent with the relatively high water temperature level on the supply side (around 50 °C) required by the heating coil in the AHU. However the overall system efficiency, namely the ratio of the heat delivered by the AHU (8276 kWh) over the total electricity consumed by the heat pump and the AHU (2002 kWh), was found to be 4.1. Therefore, although the heat pump COP was penalized by the medium temperature heat production and the system was handling a very high ventilation rate, the overall system operated with a high energy efficiency, also thanks to the presence of the heat recovery heat exchanger. The heat recovery energy is not measured directly, but can be approximately estimated as the difference between the heat delivered by the AHU and the sum of the heat produced by the heat pump plus the electricity consumed by the AHU. Although this is a rough estimation disregarding any thermal losses, it allows to highlight the relevant role played by the heat recovery unit, accounting for 34% of the heat delivered to the piglet room.

3.4. Comparison with the reference HVAC system

The energy performance of the EcoZoo GSHP system measured during the monitoring campaign in 2016 can be compared with that of a traditional Heating Ventilating and Air Conditioning (HVAC) system. The gas burner fan system originally installed in the piglet room was chosen as a reference system, being quite common in the zoo-technical farms operating in the area. Since the gas burner is placed inside the room, a 100% efficiency in converting gas energy into useful heat was assumed. According to the data sheets the fans consume 180 W. In the comparison the two systems are assumed to provide the same heat and the same ventilation air changes. The primary energy conversion factors adopted were 1.05 and 2.42 for gas and electricity respectively, according to the current Italian regulation (Decreto Interministeriale 26/06/15, 2015). As summarized in Table 1, the EcoZoo system consumes 46% less primary energy than the traditional system. Considering the energy costs for non-domestic consumers in 2014 (as reported by Autorità per l'Energia Elettrica il Gas e il Sistema Idrico (AEEG), 2015), namely 0.31 €/kWh

for electricity and 0.79 €/m³ for gas, the EcoZoo system gave a 14% saving in energy costs compared to the traditional system. The smaller cost savings compared to the primary energy savings were clearly due to the high ratio between the electricity and gas costs of the Italian market. In those countries where the cost of electricity is significantly lower, cost savings become consequently larger.

In conclusion, the monitoring campaign performed at the EDZC shows that GSHP systems can be effectively adopted for animal housing. By coupling a GSHP with an AHU incorporating a heat recovery system, the high ventilation rates required to remove indoor emissions and guarantee animal wellbeing are provided with a high overall energy efficiency. Compared to the conventional systems typically adopted in animal housing, the system configuration proposed allows significant savings in both primary energy consumption and in energy cost.

4. Groundwater heat pump system development

4.1. System concept

Among low temperature geothermal systems, open loop systems are currently considered more efficient and cheaper than closed loop systems. Therefore, the concept and feasibility of an innovative open loop system combined with irrigation is here assessed and discussed.

Indeed, usually in farms there is at least one well used by the owners for specific functions, such as human or animal water supply, field irrigation or farm stable washing. Additional wells could possibly be added in operating of GWHP system, to be used either as extraction or injection wells. The concept of the geothermal open loop system presented here concerns the coupled use of water extracted from wells for both the thermal uses of the farm and irrigation. The eco-friendly idea is based on three items:

- during the warm season (summer), groundwater is used for cooling farm stables by means of the GWHP, and subsequently to irrigate fields up-gradient of the extraction wells;
- during the cold season (winter), groundwater is used by the same heat pump to provide heating to the animal housing stables, and then it is re-injected up-gradient into the ground;
- finally, the extraction wells, if rationally positioned, could be used as a sort of hydraulic barrier to prevent or decrease nitrate pollution down-gradient of the agricultural fields. In this way, less surface water would be used for irrigation practices and lower

Table 1
Comparison between the energy performance of the EcoZoo GSHP and of the reference system.

System	Delivered heat (kWh)	Electricity (kWh)	Fuel energy (kWh)	Primary energy (kWh)
EcoZoo GSHP	8276	2002	–	4845
Reference		132	8690	9009

pollution from fertilizers and pesticides should be detected in the shallow aquifer.

The proposed system operation according to the season is briefly summarized in Table 2 and Fig. 8.

As far as the location of the extraction and injection wells is concerned, it has to be remarked that usually, in open loop heat pump systems, extraction wells are located hydraulically up-gradient with respect to the injection ones in order to avoid thermal interference (Casasso and Sethi, 2015). On the contrary, in the innovative GWHP application proposed here, extraction wells have to be positioned on a line perpendicular to the preferential direction of the groundwater flow and down-gradient in order to act as hydraulic barrier for nitrates. Consequently, the injection and extraction wells have to be drilled at an appropriate distance with the aim to prevent the cold water re-injected during winter operation from reaching the extraction wells too soon, decreasing the system energy efficiency.

A validation of this concept was achieved through a numerical model. The implementation of the flow and transport numerical model was preceded by the conceptual model, based on the information gathered from the area of interest of the EDZC, as reported in Section 2. Specifically, we assumed that the groundwater flow present under crop fields – to be used by a hypothetical farm – could be extracted down-gradient of the fields through a series of wells 30 m deep. We assumed that the water could be extracted at a temperature equal to 15.5 °C, approximately constant all year round, corresponding to the yearly average temperature of Lodi's aquifer (Antelmi, 2016). The heat pump would provide winter and summer air-conditioning to the entire building dedicated to breeding (green building in Fig. 1a), whose peak heating load was roughly estimated to be ten times the piglet room load, namely 170 kW.

4.2. Numerical model

The numerical model was developed through MODFLOW (Harbaugh et al., 2000) and MT3DMS (Zheng and Wang, 1999) codes. MODFLOW is a code that numerically solves the groundwater flow equations in a three-dimensional porous medium, using the finite differences method. The code, developed by the U.S. Geological Survey, is one of the most worldwide used codes in hydrogeology and it can work coupled with many other USGS codes (e.g. MODPATH, SEAWAT, MT3DMS, RT3D, etc.). MODFLOW includes a set of commands necessary to simulate and solve different site-specific mathematical models and to solve the equations of the groundwater flow it needs a horizontal and vertical discretization of the domain into unitary or homogeneous elements, to apply the set of numerical equations. MT3DMS is a modular three-dimensional multispecies code for the simulation of the fate and transport of contaminants in groundwater systems. MT3DMS can be used to simulate concentration changes of miscible contaminants or heat transport (Thorne et al., 2006; Angelotti et al., 2014; Alberti et al., 2017) in groundwater considering advection, dispersion, diffusion and some basic chemical reactions, with various types of boundary conditions and external sources or sinks.

As shown in Fig. 9, the modelling domain is a square area of 4.5 km² with a number of cells equal to 291600. In the centre of this large domain, a study area of 200 m × 200 m was defined, where the geothermal open loop system – consisting of 8 down-gradient

wells, 2 up-gradient wells – and the heat pump were located. The modelling domain was substantially widened beyond the study area in order to adequately distance boundary conditions, inferred by hydraulic heads measurements (see Fig. S1 in the Supplementary Material). In the domain, the grid size varied from a maximum of 100 m to a minimum of 1 m in the study area.

Along the vertical direction, a homogeneous aquifer approximately 30 m deep was implemented. This is the upper part of the regional shallow aquifer, locally separated from the deeper portion by a clayey layer at 30 m. Therefore, considering the stratigraphy (Fig. 2), the vertical domain was divided into 4 layers, each representing a given lithology identified in the aquifer: sandy silt (layer 1, 9.4 m thick), fine sand (layer 2, 8.3 m), medium sand (layer 3, 12.8 m) and clayey silt (layer 4, 3.5 m). The hydrogeological properties adopted for each layer are shown in Table S4 of the Supplementary Material. Hydraulic conductivities (K_x, K_y and K_z), storage coefficient (S_s) for confined aquifer or specific yield for unconfined aquifer and porosity values were assigned both on the experimental data (stratigraphy analysis, flow pumping test, slug tests) and on a flow model specifically built to simulate the pumping test carried out in Lodi (Marocchi, 2015). In the model, the difference between observed and simulated hydraulic heads was minimized with a trial and error approach. The advection term is variable along the layers, in fact the Darcy velocity, depending on hydraulic conductivity and porosity, varies from 10⁻¹¹ m/s for the clayey layer to 10⁻⁷ m/s for the sandy layers, producing an averaged Darcy velocity of the aquifer equal to 1.6 · 10⁻⁷ m/s. Other hydrogeological properties, such as bulk density, distribution coefficient, thermal diffusion or thermal dispersivity were assigned starting from the Thermal Response Test carried out in Lodi and subsequently calibrated through trial and error method (Antelmi, 2016). The bulk density (ρ_b) was calculated for each layer, depending on the density of each material (ρ) and porosity (θ) of the same layer, as:

$$\rho_b = (1 - \theta) \rho \quad (3)$$

The distribution coefficient, depending on the specific heat capacity of water and soil, was calculated as:

$$K_d = \frac{c_{p,s}}{\rho_w c_{p,w}} \quad (4)$$

while the thermal diffusion coefficients, depending on the thermal conductivities of each layer, were calculated as:

$$D^* = \frac{\theta \lambda_w + (1 - \theta) \lambda_s}{\theta \rho_w c_{p,w}} \quad (5)$$

where θ is the porosity, λ_w and λ_s are the thermal conductivities of water and soil, $c_{p,w}$ and $c_{p,s}$ are the specific heat capacities of water and soil, and ρ_w is the density of water (Alberti et al., 2017). Thermal dispersivities along longitudinal, transverse and vertical directions were constant and uniform into the model (respectively equal to 0.5, 0.5 and 0.05 m) everywhere (Gelhar et al., 1992; Martone, 2014). In fact, the model is almost insensitive to this parameter as the heat transport is mainly driven by thermal diffusion. The hydrogeological properties values adopted for each layer are shown in Table S4 of the Supplementary Material.

Two boundary conditions were assigned to the West and East boundaries of the model: they were two hydraulic constant heads (respectively 78 m and 69.6 m a.s.l.) inferred from the piezometric

Table 2
GWHP system operation according to the season.

Season	Duration (days)	Extraction wells	Injection wells	GWHP	Fields irrigation
winter	120	ON	ON	ON, heating	OFF
intermediate	61	OFF	OFF	OFF	OFF
summer	138	ON	OFF	ON, cooling	ON
intermediate	46	OFF	OFF	OFF	OFF

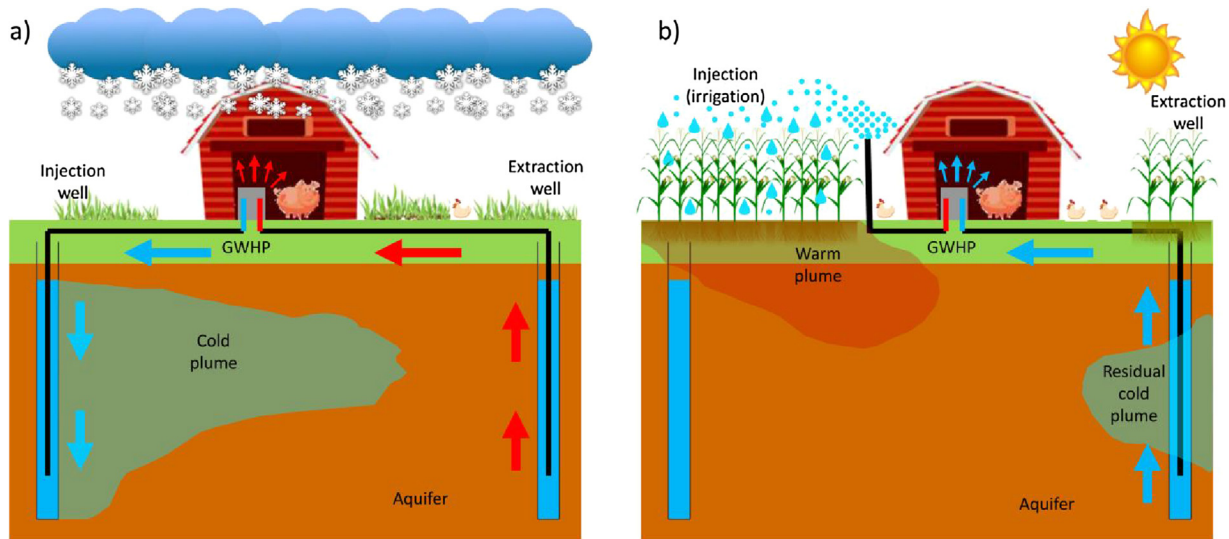


Fig. 8. GWHP system operation in the winter season producing a cold plume in the aquifer; (a) and in the summer season producing a warm plume in the aquifer (b).

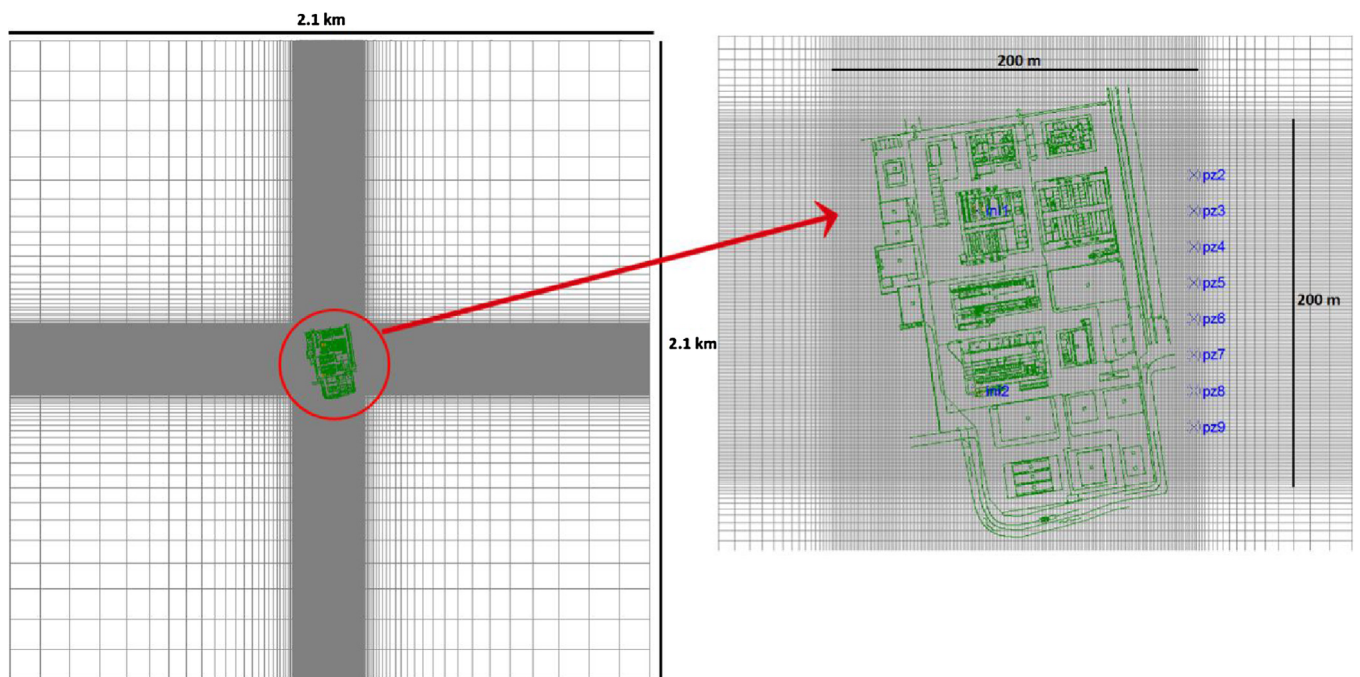


Fig. 9. Plan view of the model domain (left), including grid cell size refinement in the study area (right), EDZC area (green) in the center of the model and wells on the right (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

measurement, and the hydraulic gradient was 0.4%. The temperature at both boundaries, reproducing the unperturbed temperature of the aquifer, was set constant at the value of 15.5 °C. This was also assumed as the uniform initial temperature in the domain.

4.3. Numerical simulations – results and discussion

Numerical simulations were carried out in order to assess the influence of two design parameters: the water flow rate to be extracted and the distance between extraction and injection wells.

For a first estimation of the water flow rate, some energy considerations were carried out. If the GWHP COP is set equal to 4 and the peak thermal load of the hypothetical building is 170 kW, the heat pump has to absorb 128 kW from the groundwater. By assuming a typical water temperature difference equal to 5 °C between the inlet and the outlet of the heat pump evaporator, the total water flow rate to be extracted from the aquifer was estimated in 61/s. This flow rate was then adopted in numerical simulations and the capability of the 8 extraction wells to work as a hydraulic barrier was assessed.

It was found that by extracting a total flow rate of 61/s (i.e. 0.75 l/s per well), a large part of the re-injected water was captured by the extraction wells during winter and summer. Fig. 10 shows a simulated piezometric map (blue lines identify hydraulic heads) in the area of interest for a typical warm season, corresponding to the irrigation period. The distance among extraction wells was previously evaluated analytically (Colombo et al., 2012) to guarantee an overlapping of wells capture areas. During both seasons, the extraction wells were able to capture a great amount of water flowing under crop fields and consequently also a large quantity of nitrates. A water mass balance carried out up-gradient and down-gradient of the 8 extraction wells (corresponding to the unconfined aquifer in the first three layers) confirmed that a percentage from 73.3% to 79.5% of the total groundwater flow was captured by the 8 wells, depending on the season.

Moreover, the capacity to capture nitrates was assessed through a forward particle tracking simulation, which represents the effect of advective transport. Particles (red lines in Fig. 10) were seeded along a line (thickest black line in Fig. 10) in the aquifer, up-gradient of the field irrigated in summer. Then, through the MODPATH code, the path and fate of each single particle (Fig. 10) was calculated, according to the flow field previously calculated by MODFLOW. Fig. 10 shows that in Layer 3 less than 20% of the particles went beyond the hydraulic barrier. In Layer 1 and 2, corresponding to the shallow part of the unconfined aquifer, the percentage of the particles that escaped was even smaller, reducing to 5%. This is a relevant issue because nitrate concentration in groundwater generally decreases along the vertical due to the effects of de-nitrification processes supported by oxide-reductive conditions (Guffanti et al., 2010). Consequently, the designed GWHP system can be considered an efficient approach for limiting nitrate contamination linked to fertilization practices.

Starting from 61/s, additional simulations were performed, increasing the extracted pumping rate so as to increase the number of particles captured. It was found that by extracting 121/s, it would be possible to completely capture the total aquifer flow rate in the first three layers (more than 98% of water captured by 8 wells and less than 1% of particles beyond the hydraulic barrier). This flow rate corresponds to 1.51/s per well, which, being lower than the maximum rate of about 41/s per well suggested by Basta and Minchio (Basta and Minchio, 2007), prevents the transport of fine materials that could damage the heat exchanger. However, with this flow rate the heat pump thermal power would exceed the peak thermal load previously evaluated by factor 2. In this case, the excess thermal power could be used for the climatization of the adjacent building.

The second parameter investigated was the distance between the injection and the extraction wells. Actually, this distance impacts on the temperature of the pumped groundwater and consequently on the GWHP energy efficiency. The heating mode energy efficiency (COP) decreases as the groundwater temperature decreases. As such, the distance should be large enough to prevent the cold water re-injected up-gradient during winter from reaching the pumping wells. At the same time, the cooling mode energy efficiency (EER) increases as the groundwater temperature decreases. The distance should then be small enough to exploit the winter cold plume during summer operation. Therefore, the wells should not

be placed neither too close to each other, nor too distant. For this purpose, a numerical simulation of a typical yearly operation of the open loop geothermal system was carried out, according to the four periods reported in Table 2.

On the basis of traditional and innovative irrigation practices in Lombardy (Alberti et al., 2016; Gandolfi, 2003; Masseroni et al., 2017), the flow rate of 0.421/s/ha is the seasonal average water demand for maize crops. Therefore, the 61/s extracted from the aquifer are adequate to irrigate an area of about 10 ha, being the field dimension considered in the following simulations. The groundwater flow model running in unsteady state conditions gave, as outputs, four different head distributions for each simulated period. After this, the flow fields of the groundwater system were used to run the heat transport model. During the cold season, the water temperature implemented as input into the re-injection wells was equal to 10 °C, i.e. 5.5 °C lower than the unperturbed aquifer temperature (15.5 °C). Differently during the warm season, the temperature of the water supplied to the agricultural fields for irrigation was equal to 21 °C.

Starting from a minimum value of 60 m derived from literature (Kavanaugh and Rafferty, 1997), the distance between the injection and the extraction wells was increased to up to 100 m. Fig. 11 shows the temperature of the extracted water as a function of time for different distances between the extraction and the injection wells. The temperature values are averaged for the eight pumping wells, in relation to the amount of water extracted from each layer; therefore, the temperature curves are not available during the intermediate periods (Table 2) because the wells are not in use. Considering, for instance, a distance of 70 m, the water extracted has a temperature equal to the unperturbed aquifer temperature approximately for the first 80 days. Subsequently, the temperature starts to decrease because of the influence of the cold water injected up-gradient, reaching 15 °C at the end of the first period (Fig. 11, point A) when the heat pump is turned off. During the second period, the cold thermal plume proceeds according to a groundwater velocity no longer affected by the presence of injecting/pumping wells, resulting in a water temperature equal to 14.0 °C at the beginning of the summer operation (Fig. 11, point B). This temperature, being lower than the unperturbed one, would increase heat pump energy efficiency. During the warm season, the average temperature of the water extracted decreases to a minimum of 13.4 °C (Fig. 11, point C), but then starts to increase as the effect of the cold plume weakens and simultaneously warm water from irrigation enters the aquifer.

If the distance is increased to 100 m, the cold plume does not interfere in any negative way with the winter operation of the heat pump. Conversely, the positive influence on the summer operation is less relevant, since the minimum temperature is reached only at the end of summer.

The temperature distribution can be observed also through a plan view of the isothermal curves in the model domain. Fig. 12 shows the thermal plume in layer 3, in each of the 4 periods during the first year of operation, resulting from the 70 m distance configuration between the injecting and the pumping wells. In particular, since layers 1 and 2 have a lower hydraulic conductivity than layer 3 (Table S4 of the Supplementary Material), they produce a shorter cold thermal plume than said layer, in which a higher Darcy velocity results in a very extended plume. As 95% of the water extracted from the hydraulic barrier comes from layer 3, and only the remaining 5% from layers 1 and 2, the plume in layer 3 is considered to be more representative of the actual temperature of the aquifer. The cold thermal plume arrives at the pumping wells at the end of the winter (Fig. 12a), because of the increased hydraulic gradient produced between the injection and the extraction wells; in the second period (Fig. 12b) the injection wells are turned off and the cold plume moves forward, because of the natural groundwater flow.

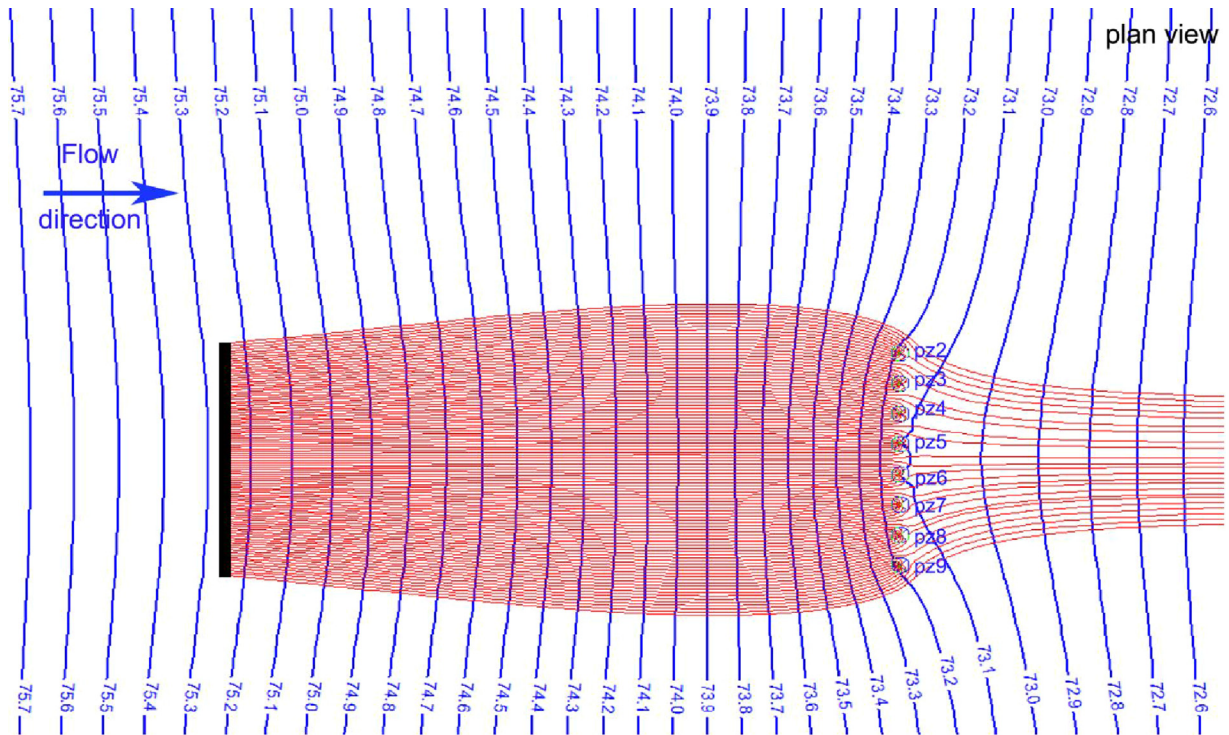


Fig. 10. Zoom of the model domain showing hydraulic head distribution (blue lines) and contaminant particle path lines (red lines) flowing under crop field and captured from the 8 extraction wells in layer 3 (during warm season); the thickest black line on the left represents the starting point of the particles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

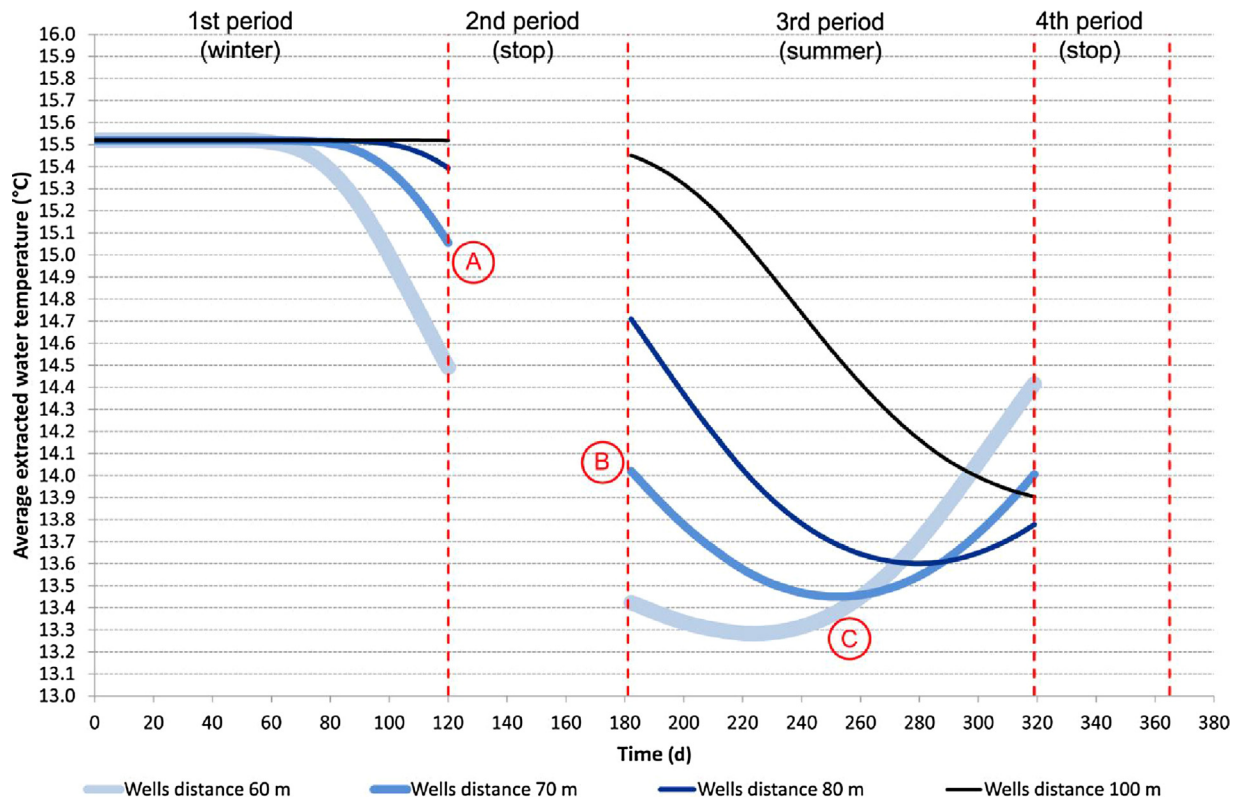


Fig. 11. Average temperature of the water extracted from the 8 wells versus time, for different well distance values. The simulation starts on November 1st and A, B and C are the points discussed in the text. During the 2nd and 4th period data are not available as the wells are not in use.

In the third period, the cold plume still moves forward, although it assumes a radial symmetry because of the warm water injected as

irrigation (Fig. 12c). Lastly, it goes beyond the eight pumping wells, after the fourth period (Fig. 12d).

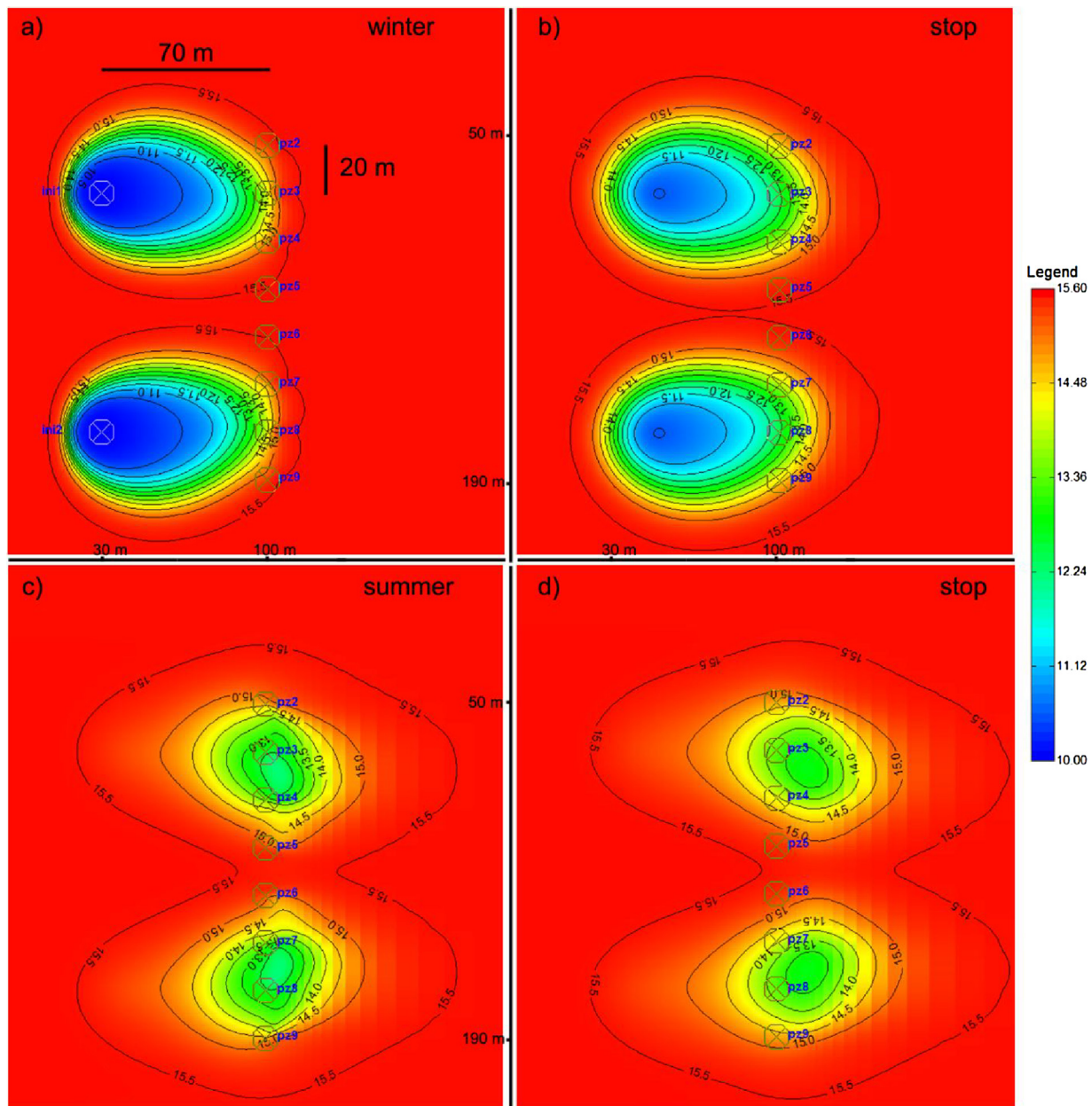


Fig. 12. Plan view of thermal plumes at the end of the first (a), second (b), third (c) and fourth (d) operation periods at layer n. 3 (model zoom showed); the 2 injection wells are drawn only in the first period simulated.

The results of the numerical simulations presented here demonstrate the feasibility of the innovative GWHP system concept. They show that through a proper configuration of the extraction and injection wells, the system can act as a hydraulic barrier towards nitrates, potentially improving the environmental conditions of the aquifer. At the same time, the results show that the distance between the injection and the extraction wells has an impact on the development and interaction of the cold and warm plumes generated by the integrated GWHP-irrigation system. Therefore, the yearly energy efficiency of the GWHP system depends on this key parameter.

5. Conclusions

This study applied some alternatives to conventional climatization in farms based on geothermal sources with the aim to improve temperature and ventilation control, while assessing the potential

use of groundwater extraction wells for irrigation and the prevention of nitrate diffusion. The monitoring campaign on the pilot GSHP, installed in a piglet stable in Northern Italy, shows a 46% reduction in primary energy consumption and a 14% decrease in operating energy costs compared to a traditional gas fuelled heating system. The experimental results show that the specific needs of the animals in terms of thermo-hygrometric conditions and ventilation rates can be satisfied. GSHPs integrated with a heat recovery system are thus a promising option for energy-efficient heating and ventilation of breeding farms, avoiding combustion in stables and providing summer cooling in addition.

As far as the new strategy for the optimised use of groundwater is concerned, the concept case of the GWHP system coupled to 8 extraction wells and 2 injection wells is considered, and the yearly operation of the integrated system according to a seasonal schedule is numerically simulated. The influence of the extracted groundwater flow rate and of the distance between the extraction and

the injection wells on the overall behaviour is investigated, with a focus on system efficiency and control of nitrate diffusion. The numerical investigation demonstrates the feasibility of the application of the GWHP combined with irrigation, showing the potential for reducing nitrate diffusion as well as primary energy consumption. Nevertheless, the prosecution of the research will need field experimentation to collect data on nitrate concentrations, water temperature and GWHP performance. This information will allow to calibrate a nitrate advective-dispersive transport model and estimate a contaminant mass balance, both useful to fully demonstrate the efficacy of the system in controlling nitrate diffusion. Furthermore, in case of a real application of the concept presented above, the system design should be optimised by adopting a detailed dynamic energy simulation, including the heat pump operation and the building.

In a context where concurring purposes are to be attained, a detailed hydrogeological survey coupled with numerical modelling proved to be essential for exploring and designing effective strategies for more sustainable agriculture and breeding.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.agwat.2017.10.009>.

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