Geothermics 70 (2017) 281–294

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Monitoring, utilization and sustainable development of a low-temperature geothermal resource: A case study of the Euganean Geothermal Field (NE, Italy)

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ARTICLE INFO

Keywords:
Sustainable management
Geothermal resource monitoring
Overexploitation
Potentiometric level decline
Anthropic impact
Po plain foredeep

ABSTRACT

The Euganean Geothermal Field (EGF) and its thermal water (temperature from 63 °C to 87 °C) represent an important environmental and economic resource for the Veneto Region (NE Italy). Approximately 14.7×10^6 m^3 of hot water were exploited in 2015 through 142 boreholes from rocky aquifers located at different depths. The water is mainly used for balneotherapy feeding approximately 240 pools. Hundreds of thousands of tourists visit the spa facilities of the EGF every year, producing a huge income for the regional economy. The Euganean thermal resource suffered a significant anthropic impact during the 20th century related to the development of the local tourism industry. Hydrogeological data and information about the utilization of the resource spanning the century are analyzed to evaluate this impact with the aim of assessing the sustainable utilization of the thermal resource. In particular, the potentiometric levels of the thermal aquifers are affected by seasonal variations (i.e., decreases during the spring and autumn, recoveries during the winter and summer) induced by the different flow rates related to the tourist seasons. Similarly, the historical reconstruction of the level shows a decrease during the initial and middle parts of the 20th century followed by a gradual recovery up to the present. The reduction of the level was related to the growth of the tourism industry attested by the increase in exploitation, wells, mining claims and tourists. The limitation of the flow rate and its continuous monitoring have produced the observed recovery since the 1990s. The performed reconstruction suggests that the present flow rate (approximately 14×10^6 m^3/y) produces an acceptable drawdown preserving the Euganean thermal resource for future generations and maintaining a constant income for the regional economy. This work attests that thermal resources for balneotherapeutic purposes could be affected by overexploitation and depletion. Therefore, their sustainable utilization has to be achieved through specific management policies, preserving their important environmental and socio-economic values.

1. Introduction

The renewable and sustainable usage of natural resources is one of the main tasks of the 21st century. The European Commission noted the importance of using natural renewable resources to reduce greenhouse gas emissions and comply with the Kyoto Protocol (European Parliament, 2009). Thermal water is a well-established example of a renewable resource that should be used while achieving its sustainable development. Several authors discussed the renewability and sustainability of geothermal resources (e.g., Burnell et al., 2016; Mongillo and Axelsson, 2010; Rybach and Mongillo, 2006; Shortall et al., 2015). Renewability describes the ability of a system to replace an amount of removed resource on a fixed time scale (Stefansson, 2000), and it depends mainly on the geological and hydrogeological features of the regional system. Sustainability refers to the development of a resource in such a way that meets the needs of the present without compromising the ability of future generations to meet their own needs (Axelsson, 2010). A sustainable flow rate with an acceptable drawdown depends mostly on: i) the local hydraulic properties of the reservoir (i.e., transmissivity, hydraulic conductivity and storativity); ii) how the resource is exploited including the mode of utilization and the possible technological advances in its exploration/extraction; iii) the social,

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http://dx.doi.org/10.1016/j.geothermics.2017.07.002
Received 11 January 2017; Received in revised form 29 June 2017; Accepted 3 July 2017
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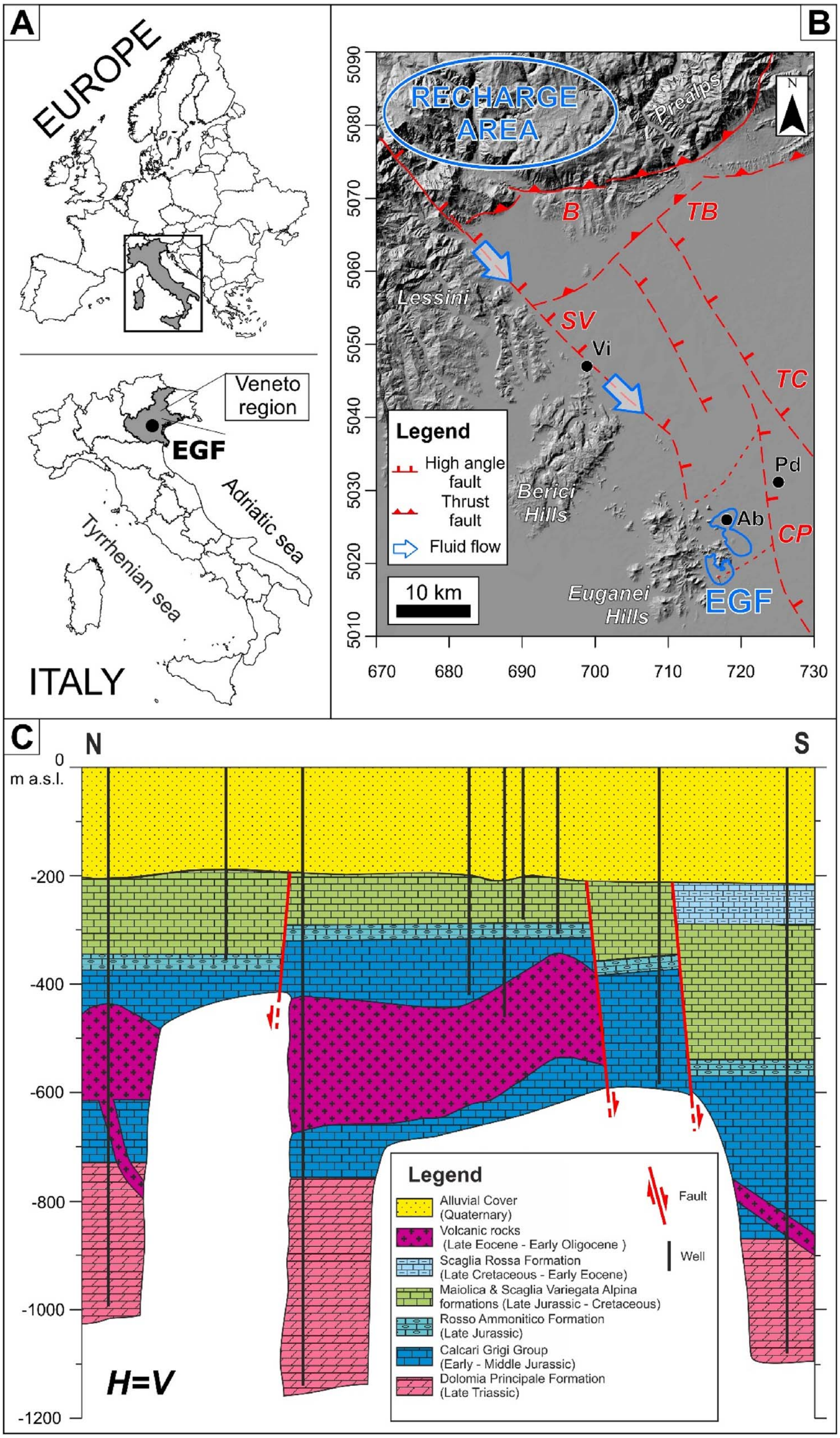

Fig. 1. (A) The Euganean Geothermal Field (EGF) is located in the central part of the Veneto Region (NE Italy). (B) Schematic structural sketch of the central Veneto. The regional faults fragmenting the subsurface (B: Bassano thrust; TB: Thiene-Bassano thrust; SV: Schio-Vicenza fault; CP: Conselve-Pomposa fault; TC: Travettore-Codevigo fault) and the principal features of the Euganean Geothermal System are shown (i.e., recharge area in the Veneto Prealps, preferential flow path along the Schio-Vicenza fault, outflow area corresponding to the EGF). The main cities (Vi: Vicenza; Pd: Padua; Ab: Abano Terme) are also reported. Map coordinates are UTM (zone 32N) system using WGS84 datum. (C) Cross-section of the EGF subsurface (trace in Fig. 3) showing the Mesozoic to Cenozoic bedrock fragmented by the network of faults. The horizontal scale corresponds to the vertical scale.

economic and environmental impacts of its utilization. The sustainable exploitation of thermal resources can be evaluated using mathematical models (e.g., O'Sullivan et al., 2010; Sarak et al., 2005; Scott et al., 2016), but they have to be supported by exhaustive datasets on the status of the thermal resource and on its utilization.

The Euganean thermal water is one of the most important and economically profitable water-dominated, low-enthalpy, geothermal resources in Italy and in the entirety of southern Europe. The related Euganean Geothermal Field (EGF) extends on a plain band of 25 km^2 to the SW of the city of Padua in the central part of the Veneto Region

(Fig. 1a, b). The EGF covers the municipalities of Abano Terme, Montegrotto Terme, Battaglia Terme and Galzignano Terme, and it is divided to 138 mining claims for the utilization of the thermal water. The Euganean thermal water has been used for therapeutic purposes since the Roman period (Ghedini, 2011). The first spa facilities, built in the 19th century, were fed by the naturally rising water of thermal springs. The increasing demand for hot water, related to the development of the local tourism industry, was met by drilling boreholes that exploited the thermal groundwater. The first thermal well of the EGF was drilled in 1873 reaching a depth of 107 m (Mameli and Carretta, 1954). The well was located close to a thermal spring, and the water was naturally flowing at 72 °C. This drilling represented the first step to induce the intensive utilization of the Euganean thermal resource. Approximately 600 wells have been drilled, and 142 wells were active in 2015 exploiting 14.7×10^6 m^3 of hot water with temperatures between 63 °C and 87 °C. The thermal water is used mainly for balneotherapy and recreational purposes, feeding approximately 240 pools, and secondarily to heat the spa facilities and few greenhouses for floriculture and aquaculture. A huge number of tourists visit the hotels of the EGF every year, producing an income of 300 million € (Consorzio Terme Euganee, 2016).

The uncontrolled utilization of the thermal resource caused a rapid decline in the middle of the 20th century drying thermal springs and shallow wells. A local network to monitor both the potentiometric levels of the thermal aquifers and the pumping rates of the thermal wells has been developed since the 1970s. The dataset derived from the monitoring activities is presented in this paper, and it is discussed in relation to the utilization of the thermal resource. Sporadic level measurements and complementary data complete the reconstruction of the potentiometric level and the extraction before their continuous monitoring. This reconstruction also employs a linear mathematical relationship to predict the original potentiometric level of the thermal aquifer. The results give a comprehensive picture of the utilization of the Euganean thermal resource in the last century. In particular, the sustainability of the exploitation is evaluated with the aim of preserving this important environmental, renewable, profitable resource.

2. Geological and hydrogeological setting

The EGF is the outflow area of the Euganean Geothermal System (EGS) that extends in the central part of Veneto for approximately 100 km (Pola et al., 2015b). The thermal water is of meteoric origin, as suggested by its stable isotope compositions (Gherardi et al., 2000; Norton and Panichi, 1978). The recharge area is located to the north of the EGS in the Veneto Prealps (Fig. 1b). The parent meteoric water infiltrates due to the high secondary permeability of the outcropping rocks and flows to the south in a Mesozoic carbonate and dolomite reservoir reaching a depth of approximately 3 km. The fluid flow is enhanced by the high permeable damage zone of the Schio-Vicenza fault (Pola et al., 2013; Zampieri et al., 2009). This fault is part of a regional system of NW–SE to NNW–SSE trending, NE-dipping, high-angle faults that extends for approximately 120 km beneath the central Veneto alluvial plain (Fig. 1b; Pola et al., 2014b). The fault system has been active since the Mesozoic accommodating a maximum throw of approximately 1.5 km with a scissor movement. In the area to the south of Padua, the thermal water intercepts a network of fractures associated with an interaction zone between the Schio-Vicenza and the Conselve-Pomposa faults. This structural setting is favorable for the rising of deep fluids as observed in worldwide geothermal fields (e.g., Faulds et al., 2013). The concentration of the stress within the interaction zone produces a localized high secondary permeability, maintaining the aperture of the fractures. The regional crustal heat flow (70–80 mW/m^2; Pasquale et al., 2014), the fluid convection driven by the local high permeability and the anomalous radiogenic heat released by the volcanic bodies of the Euganean area warm the water to approximately 100 °C at 1000 m in depth. The pattern of fractures deforming the EGF subsurface parallels the fissures (main directions: NNE-SSW, ESE-WNW, NW-SE) observed on the Montirone travertine mound in Abano Terme (Pola et al., 2014a; Zampieri et al., 2010). The thermal water rises quickly through the open fractures to the surface as suggested by the analyses of Ra and Rn isotopes (Mayer et al., 2015). ^3H and ^{14}C analyses of the water, as well as U-series and stable isotope analyses on the travertine, evidence that the residence time of the thermal water is probably in the range of several thousand years (Boaretto et al., 2003; Gherardi et al., 2000; Pola et al., 2011, 2014a).

The geological and hydrogeological setting of the EGF has been reconstructed since the 1990s using stratigraphic logs of the thermal wells, some of which reach a depth of 1000 m (Antonelli et al., 1993). The stratigraphic sequence beneath the Quaternary alluvial cover (maximum thickness 200 m) is composed of Mesozoic and Cenozoic sedimentary formations locally intruded by Cenozoic volcanic rocks (Fig. 1c). The sedimentary units are Triassic to Eocene limestones, dolostones and mudstones that usually constitute the stratigraphic succession of western Veneto Region (Antonelli et al., 1990). The volcanic rocks are Late Eocene − Early Oligocene trachyte and rhyolite (secondarily, basalt and latite). They crop out in the nearby Euganei Hills and are ascribable to the Paleogene magmatism of Northeastern Italy (Bartoli et al., 2015; Macera et al., 2003). The bedrock of the EGF is fragmented into a mosaic of blocks located at different depths by the network of faults related to the interaction zone. A vertical displacement in the range of a few tens of meters can be inferred from the stratigraphic logs (Fig. 1c).

The thermal aquifers are located in highly permeable horizons at different depths within the alluvial cover and the rocky formations of the bedrock. Most wells exploit the thermal water from 300–600 m deep aquifer hosted in fractured horizons within the Maiolica Formation (Late Jurassic − Early Cretaceous). This aquifer is the most thoroughly investigated, and transmissivity and temperature maps are available (Fabbri, 1997, 2001; Fabbri and Trevisani, 2005). The thermal water can also be locally found in the shallow sandy layers of the Quaternary alluvial cover and in the 800–1000 m deep fractured beds of the Calcari Grigi Group and Dolomia Principale Formation (Early − Middle Jurassic and Late Triassic, respectively). The shallower sandy aquifers were exploited until the 1970s, while the deeper rocky aquifer is moderately exploited. The extracted thermal water is characterized by temperatures from 63 °C to 87 °C, near-neutral pH from 6.3 to 7.4, and salinity values up to 6 g/l. The constituents are primarily Cl^- and Na^+ (70 wt%; Fig. 2) and secondarily SO_4^{2-}, Ca^{2+}, Mg^{2+},

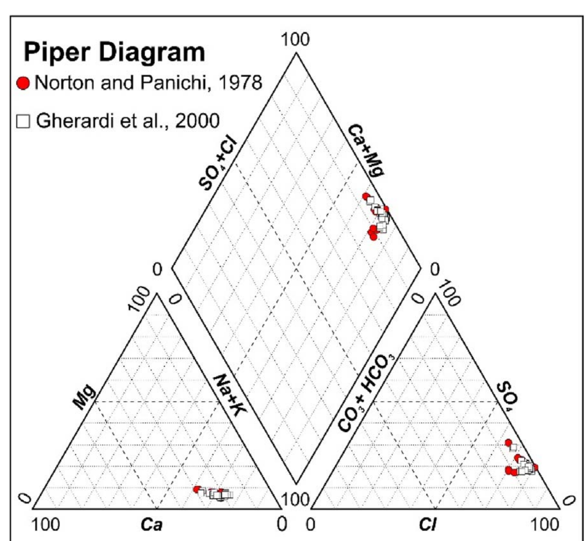

Fig. 2. Piper diagram of the chemical analyses on the Euganean thermal water (circle: Norton and Panichi, 1978; square: Gherardi et al., 2000) suggesting that the facies of the water is sodium-chloride.

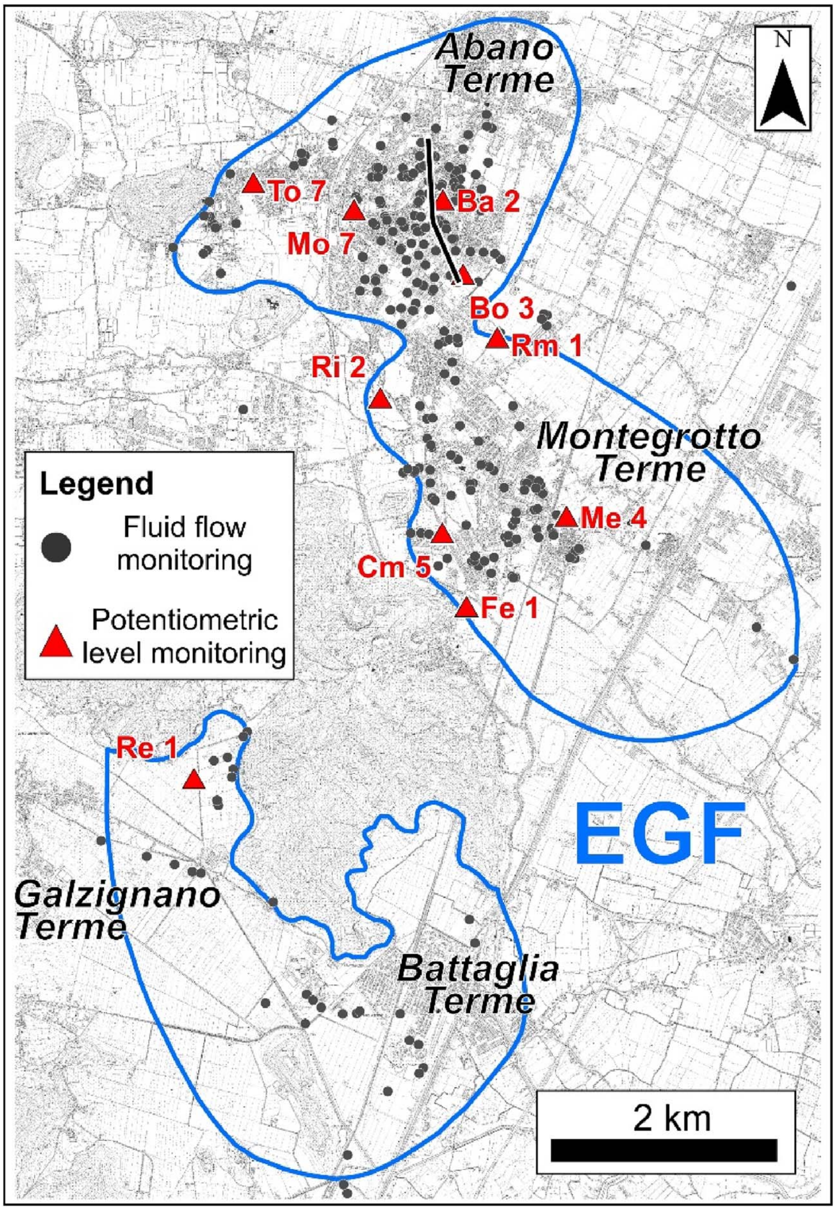

Fig. 3. Distribution of wells equipped with flow meters (gray dots) or used for the continuous monitoring of the potentiometric level (red triangles; see Table 1 for the acronyms). The main towns of the EGF are also reported.

Fig. 3. Distribuzione di pozzi dotati di flussometri (punti grigi) o utilizzato per il monitoraggio continuo del livello potenziometrico (triangoli rossi; vedere la Tabella 1 per gli acronimi). Le principali città del FEG
sono anche riportati.

HCO_3^- and SiO_2 (Gherardi et al., 2000; Norton and Panichi, 1978). The stable isotope compositions ($\delta^{18}O$ from −11.5‰ V-SMOW to −10.1‰ V-SMOW and δD from −84.8‰ V-SMOW to −71.5‰ V-SMOW) fit the global meteoric water line, but they are more negative than the local meteoric water suggesting an infiltration height of approximately 1500 m a.s.l. The absent or very low ^{3}H content and the high salinity point out the long residence time of the water.

3. Methods

A monitoring network has been developed to record the potentiometric level of the thermal aquifer and the flow rate from the active wells since the 1970s. The first instruments for the continuous monitoring of the level were installed within the inactive wells Molino 7 of Abano Terme, and Fonte Colli Euganei 1 and Mezzavia 4 of Montegrotto Terme in 1975. The network was progressively enlarged to obtain the actual configuration comprising 10 inactive wells (Fig. 3; Table 1). The depth of the monitored wells ranges from 237 m to 600 m, and the loggers measure the water level of fractured horizons located at depths from 225 m to 600 m within the Maiolica Formation (Table 1). The monitoring of the status of the Euganean thermal resource was extended to the aquifers hosted in the sandy layers of the Quaternary alluvial cover. Their potentiometric levels have been monitored using 3 piezometers since 1990. The piezometers were drilled in Abano Terme together with an exploration well (Antonelli et al., 1993), approximately 250 m toward the south of the Barillari 2 well (Fig. 3). They are screened at depths of 13 m, 58 m and 136 m, where the water temperatures are 26 °C, 48 °C and 78 °C, respectively. In addition, the actively exploited wells of the EGF have been equipped with flow meters to monitor the utilization of the thermal resource since 1977. The potentiometric levels are hourly measured, while the exploited volumes are acquired monthly.

The control of the extraction on the water level was evaluated over different temporal windows. First, daily average level measurements were compared with the monthly exploitation over the time scale of one year. Subsequently, the longest time series of the monitoring wells (Table 1) were analyzed, and the yearly means of the water level were compared with the yearly flow rates. The long-term analysis was extended back in time with auxiliary data before the development of the monitoring network (i.e., discontinuous potentiometric level measurements, qualitative hydrogeological data, number of mining claims per year, number of drilled wells per year, number of nights spent in the spa

Table 1
Wells constituting the monitoring network of the potentiometric level in the EGF. The coordinates East and North are UTM zone 32N (WGS84 datum). Their location is shown in Fig. 3.

Well	Municipality	Monitored from	East *m*	North *m*	Height *m a.s.l.*	Depth *m*	Fracture depth *m*
Barillari 2 (Ba2)	Abano Terme	1980	718165	5025925	10.60	237	225; 235
Bonato 3 (Bo3)	Abano Terme	2014	718346	5025258	10.47	326	245; 307
Molino 7 (Mo7)	Abano Terme	1975	717371	5025835	10.64	351	320
Rigati 2 (Ri2)	Abano Terme	1982	717606	5024154	10.25	484	280; 320
Toson 7 (To7)	Abano Terme	2014	716469	5026078	11.25	602	535; 600
Regazzoni 1 (Re1)	Galzignano Terme	1984	715939	5020749	3.25	261	259–261
Commodore 5 (Cm5)	Montegrotto Terme	2014	718160	5022945	9.48	260	240; 255
Fonte Colli Euganei 1 (Fe1)	Montegrotto Terme	1975	718378	5022288	10.01	403	391–403
Mezzavia 4 (Me4)	Montegrotto Terme	1975	719271	5023094	9.49	410	270
Romana 1 (Rm1)	Montegrotto Terme	2014	718652	5024693	10.53	400	240; 285

accommodations, and tourist arrivals).

In addition, the monthly averages of the water levels and the monthly extraction were used to perform a regression analysis using R code (R Core Team, 2016). This relationship predicted the potentiometric level or the pumping rates before the development of the monitoring network. In particular, the natural potentiometric level was calculated by using historical data on the flow rates of the thermal springs. The results completed the analysis of the water level, yielding an insight into the utilization of the Euganean thermal resource in the last century.

4. Results

4.1. Analysis of seasonal variations of the potentiometric level

The data recorded by the monitoring network show seasonal variations of the potentiometric level. The data collected in 2011–2012 are used as an example to describe this peculiar annual regime (Fig. 4). It is characterized by three minima (one absolute and two relative) and three maxima (one absolute and two relative). The minima occur at the beginning of winter (January), at the beginning of spring (March) and at the middle of autumn (November), while the maxima occur at the middle of winter (February), during the summer and at the end of autumn (November or December). The absolute minimum is currently represented by the wintry minimum, but it coincided alternately with the spring or autumn minimum before the 2000s.The absolute maximum always occurs during the summer. These seasonal variations also affect the potentiometric levels of the shallower sandy thermal aquifers and the deeper rocky one. In particular, the levels of piezometers P58 and P136 (screen depths of 58 m and 136 m, respectively) show a recovery during the spring up to the maximum values during the summer, followed by a decrease during the autumn and winter (Fig. 4b). Their trends are comparable with the regime observed in the Barillari 2 well, although the magnitude of the level variations is smaller in the piezometers than in the thermal well. Piezometer P13 monitoring the shallow unconfined aquifer does not show this regime, and the annual fluctuation is approximately 0.5 m. On the other hand, the potentiometric level of the deeper aquifer hosted in the Calcari Grigi Group and Dolomia Principale Formation is discontinuously monitored. Its regime shows a moderate variation (Pola et al., 2016), but it corresponds to the thermal aquifer hosted in the Maiolica Formation.

The observed seasonal variations of the potentiometric level can be related to the different pumping rates during the year (Fig. 4a), and in turn to the main usages of the thermal water (i.e., balneotherapy and warming of the hotels). The high extraction and the increase of tourist arrivals in the spa facilities produce the level decreases in the spring and autumn, while the drops in both the exploitation and tourist arrivals cause the recoveries during February and the summer. In addition, the higher pumping rates during the wintry months can also be ascribed to the utilization of the thermal water for heating.

The obtained results show that the potentiometric levels of all Euganean thermal aquifers have comparable annual regimes induced by the exploitation. Therefore, the human activity in the EGF strictly impacts the thermal aquifer layers that are hydraulically connected (Masetti et al., 2015; Pola et al., 2015a).

4.2. Variations of the potentiometric level during the last century

4.2.1. Variation of the potentiometric level before 1975

Data on the potentiometric level of the Euganean thermal aquifer before its continuous monitoring are lacking or discontinuous. However, auxiliary information can be used to infer its trend qualitatively. Historically, several thermal springs occurred in the EGF and in the nearby Euganei Hills (e.g., Mandruzzato, 1789). They numbered 38 at the beginning of the 20th century (i.e., 8 in Abano Terme, 22 in Montegrotto Terme and 8 in Battaglia Terme; Mameli and Carretta, 1954) with a total flow rate of $0.74 \times 10^6\ m^3/y$ (i.e., $0.37 \times 10^6\ m^3/y$ of the springs in Abano Terme, $0.37 \times 10^6\ m^3/y$ of the springs in Montegrotto Terme and Battaglia Terme; Vinaj, 1906). Their distribution did not change in the subsequent censuses of 1920, 1929 (Fig. 5a) and 1932, but the census of 1953 evidenced a slight reduction of the springs to 32 (1 in Abano Terme, 22 in Montegrotto Terme and 9 in Battaglia Terme and Galzignano Terme). This decrease mainly affected the field of Abano Terme, and it reflected a drop in the potentiometric level related to the increasing exploitation through the wells. As a matter of fact, the flow rate in Abano Terme grew from $2.62 \times 10^6\ m^3/y$ in 1929 to $4.04 \times 10^6\ m^3/y$ in 1953. Similarly, the flow rates in the Montegrotto Terme and Battaglia Terme fields increased from $1.7 \times 10^6\ m^3/y$ and $0.5 \times 10^6\ m^3/y$, respectively, in 1929 to $2.21 \times 10^6\ m^3/y$ and $0.63 \times 10^6\ m^3/y$, respectively, in 1953. These rapid changes can be ascribed to an increase in the number of wells and the development of the tourism industry (Section 4.4).

The potentiometric level suffered a sharp drop during the 1960s and the 1970s. The decrease of the 1960s is clearly shown by Fig. 5b, which displays the mining claims with artesian wells in 1959 and 1965. The area covered by “artesian mining claims” was $3.1\ km^2$ in 1959, compared with $4.7\ km^2$ for all claims, and this number was reduced to $2.3\ km^2$ in 1965. The predominant altitude of the areas, representing roughly the potentiometric level of the thermal aquifer, decreased as well from 10–11 m a.s.l. in 1959 to 9–10 m a.s.l. in 1965. This reduction occurred mainly in Abano Terme field, while Montegrotto Terme suffered a higher impact at the beginning of the 1970s (Fig. 5c). 26 thermal wells were active in Montegrotto Terme in 1953, and all were artesian. The number of wells increased to 40 in 1965 of which 31 were artesian, representing a reduction of 22%. The decrease continued, going from 26 artesian wells of 55 wells in 1972 (reduction of 51%) to 2 artesian wells of 60 wells in 1974 (reduction of 97%) and finally to 0 artesian wells in 1975.

The rapid decline of the thermal resource demanded a regular measurement of the thermal aquifer potentiometric level. Its level in Abano Terme was monitored monthly in 19 wells from August 1970 to December 1975. The data showed a constant decrease of approximately

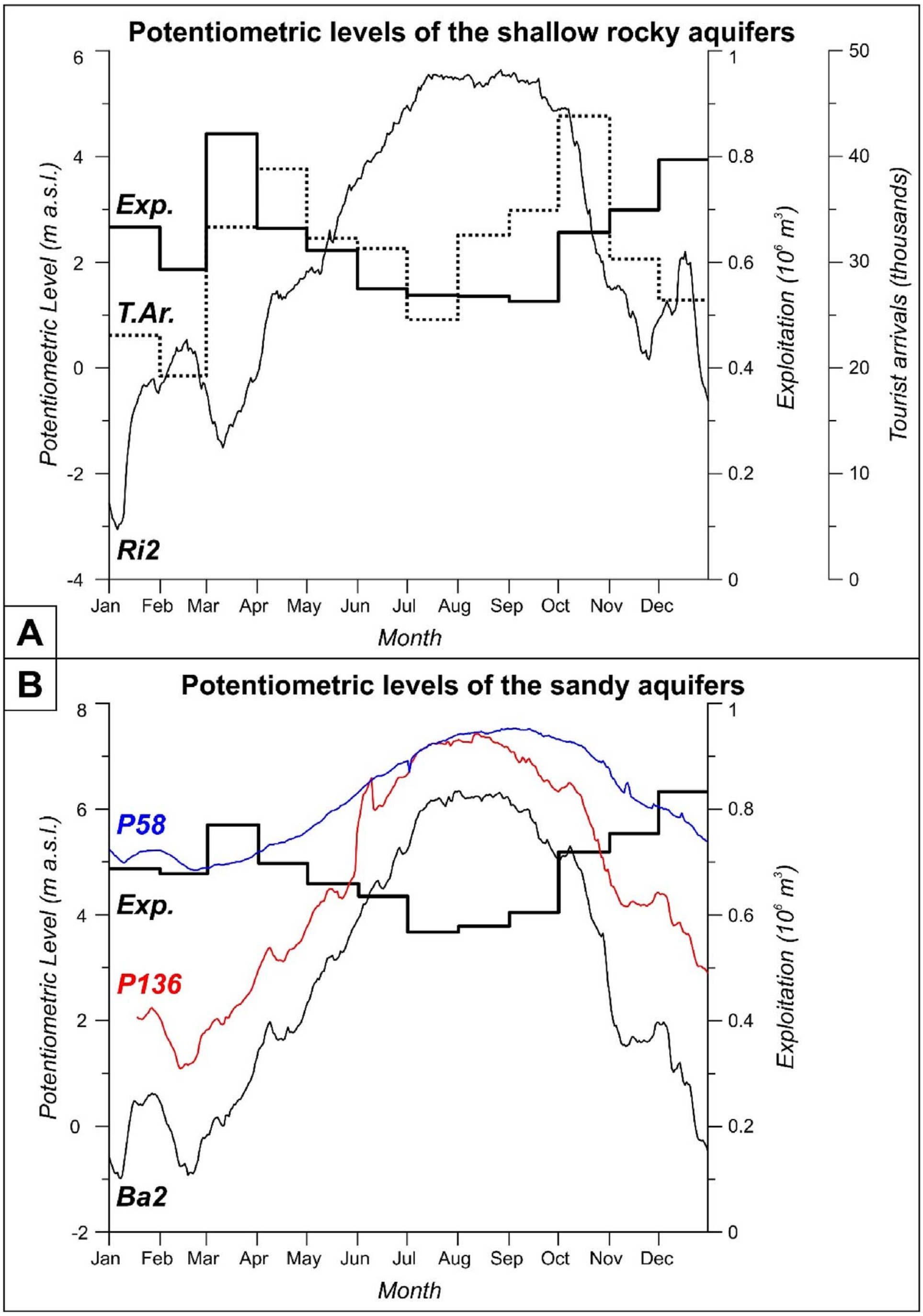

Fig. 4. Annual trends of the potentiometric level in the thermal aquifers of the EGF (A: year 2011; B: year 2012). The trend is comparable in both the 300–600 m deep rocky aquifers (Ri2 in A and Ba2 in B) and the shallow sandy aquifers of the alluvial cover (P58 and P136 in B). The observed seasonal variations can be associated with different exploitations (Exp.) and in turn to the different rates of incoming tourists (T.Ar.).

2.5 m per year (Fig. 5d). In addition, a test was conducted in the field from November 1974 to February 1975. A drastic reduction of the flow rates produced a recovery of the potentiometric level from −17.41 m a.s.l. to −1.97 m a.s.l., but the subsequent restart of the exploitation caused the level to decrease sharply to its previous value. Similarly, measurements of the potentiometric level in the area of Montegrotto Terme were conducted every 6 months on 20 wells from the summer of 1973 to the summer of 1975. A decrease in the level was again observed with a total decay of approximately 3 m in 2 years. The level dropped under the ground level, and the last thermal spring located in Montegrotto Terme dried in 1970.

4.2.2. Variations of the potentiometric level after 1975

The sharp decline of the potentiometric level suffered by the thermal aquifers during the 1960s and the first half of the 1970s evidenced the importance of the continuous monitoring of the level and the exploitation. In this section, the recorded potentiometric levels are presented as annual means, and they are compared with the total annual volume of exploited thermal water in the relevant thermal areas.

The exploitation in the EGF generally reduced from the 1977 to present (Fig. 6). The drop was approximately 35% in the thermal fields of Abano Terme and Battaglia Terme and Galzignano Terme, up to 60% in the Montegrotto Terme field. In particular, sharp decreases occurred at the end of the 1970s in Montegrotto Terme (3.1×10^6 m^3 in 3 years) and from 1989 to 1993 in both Abano Terme and Montegrotto Terme (2×10^6 m^3 and 1.5×10^6 m^3, respectively, in 5 years). The exploited annual volume in 2015 was 8.7×10^6 m^3, 4.3×10^6 m^3 and 1.7×10^6 m^3 in Abano Terme, Montegrotto Terme and Battaglia Terme and Galzignano Terme fields, respectively.

The time series of the potentiometric levels monitored by the wells

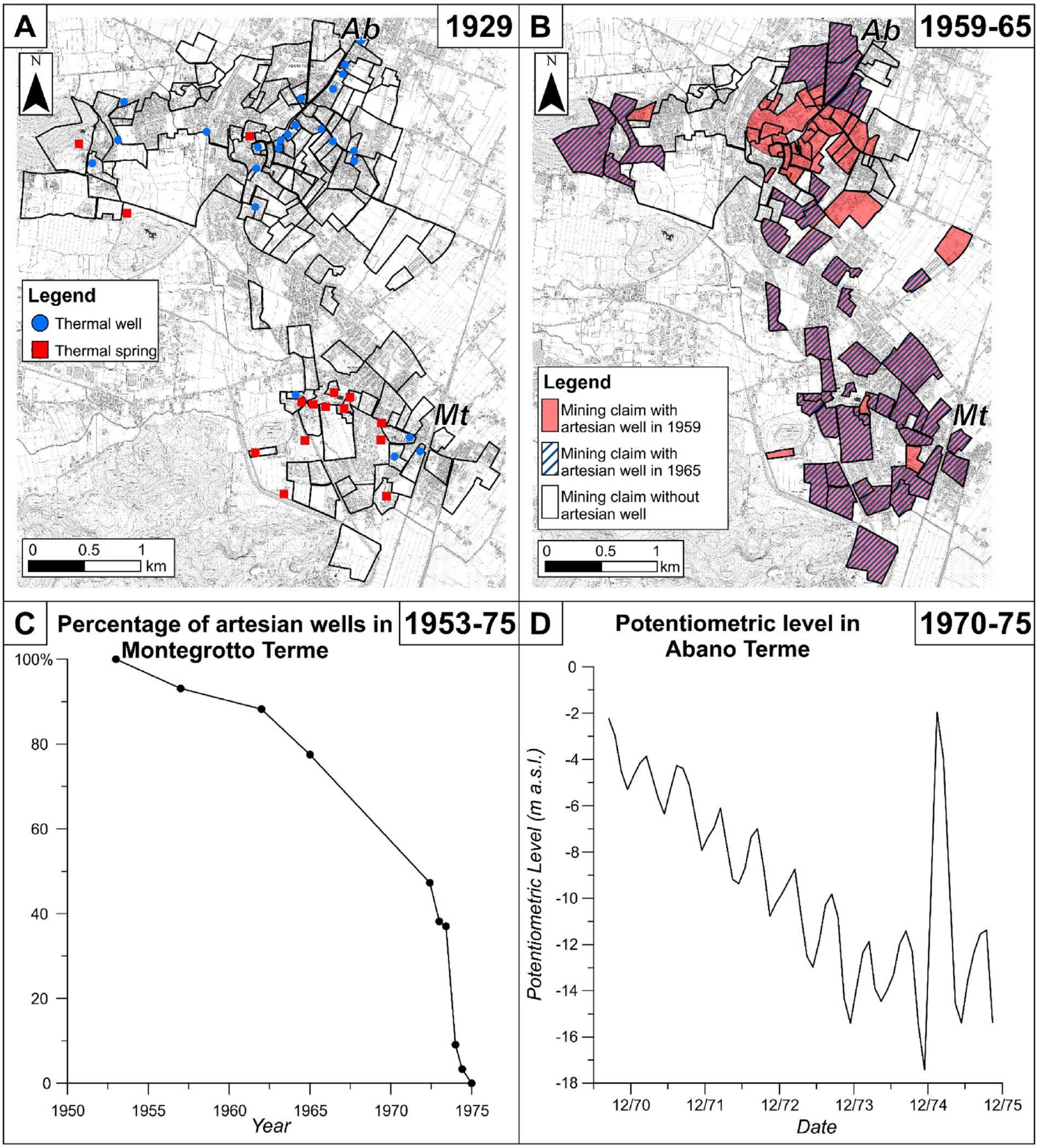

Fig. 5. Historical data used to qualitatively assess the potentiometric level of the thermal aquifers in the Abano Terme (Ab) and Montegrotto Terme (Mt) fields before 1975. (A) Natural springs and wells in 1929 (modified from Corpo Reale delle Miniere, 1931). (B) Mining claims with artesian wells in the period 1959–1965. (C) Percentage of artesian wells in the Montegrotto Terme field from 1953 to 1975. (D) First continuous monitoring of the potentiometric level in the Abano Terme field attesting a reduction of approximately 2.5 m per year. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

showed different trends from 1975 to 2015. The levels in the Molino 7 and Barillari 2 wells clearly increased during the investigated period (Fig. 6a). The annual means were quite constant from 1975 to 1985 fluctuating around −5 m a.s.l. and −14.5 m a.s.l., respectively. The water level slightly increased in the second half of the 1980s, but the highest rate of recovery occurred from 1991 to 1993. In particular, the annual mean potentiometric level raised from −3.6 m a.s.l. (year 1991) to −0.7 m a.s.l. (year 1993) in the Molino 7 well and from −14.2 m a.s.l. (year 1991) to −6.8 m a.s.l. (year 1993) in the Barillari 2 well. Their recovery trends continued gradually up to 2015 (Fig. 6a). The magnitudes were comparable with that observed in 1991-93 (i.e., approximately 6 m and 10 m in the Molino 7 and Barillari 2 wells, respectively), although they occurred over a longer period.

The time series of the Rigati 2 well showed a moderate recovery of the potentiometric level (Fig. 6a), but its general trend was different from the Molino 7 and Barillari 2 wells. The level was approximately 0.5 m a.s.l. in the first half of the 1980s, while the second half of the 1980s was lacking. It slightly increased from 1.9 m a.s.l. in 1992 to 3.1 in 1997, while a reduction occurred in the first half of the 2000s reaching a minimum of −0.18 m a.s.l. in 2005 (Fig. 6a). Subsequently, the water level recovered up to a mean annual value of 4.05 m a.s.l. in 2015. Similarly, the time series of the potentiometric level monitored by the Fonte Colli Euganei 1 and Mezzavia 4 wells in Montegrotto Terme (Fig. 6b) have shown a stable increasing trend from 2005 to

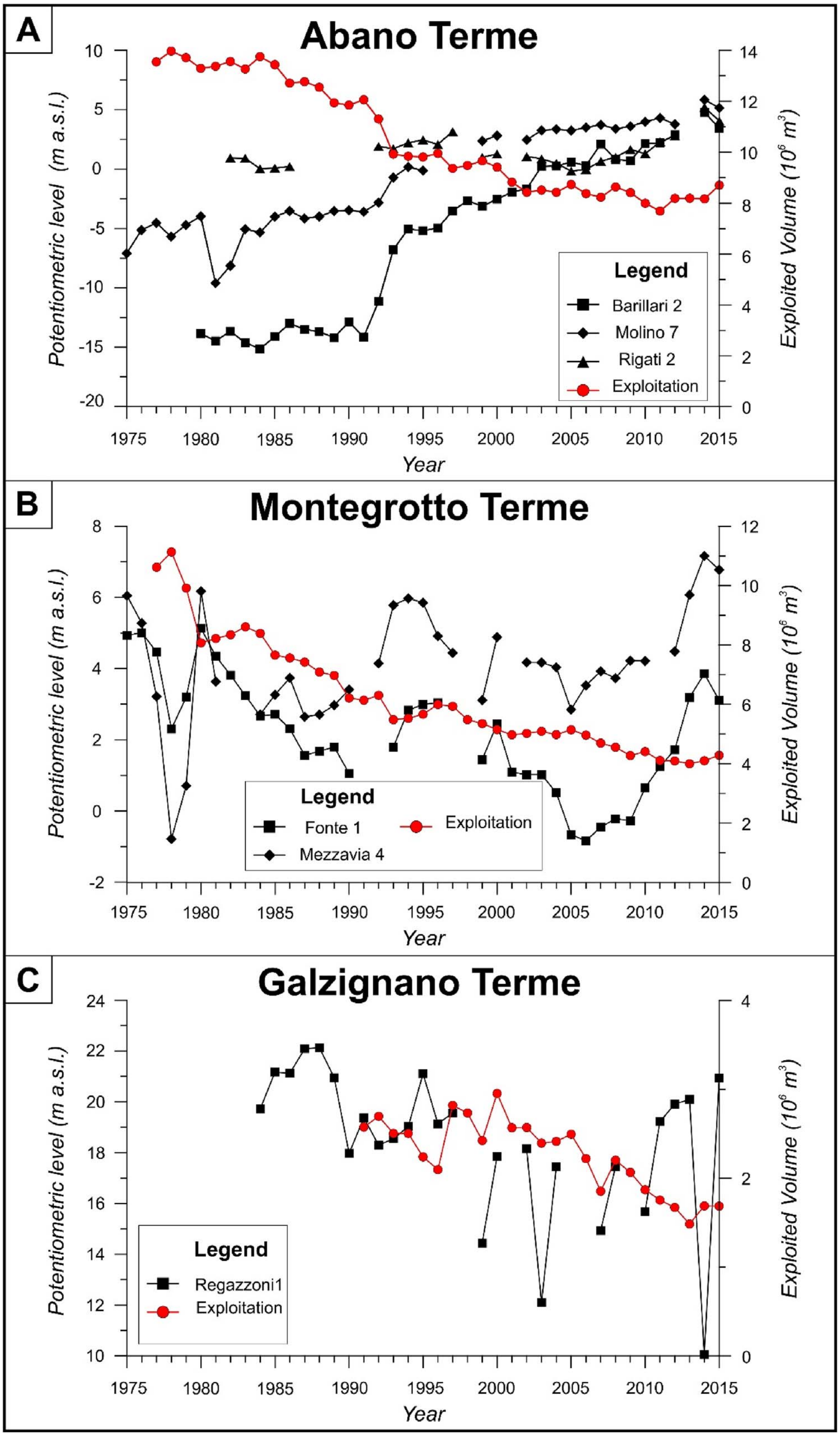

Fig. 6. Annual mean potentiometric level measured in the wells of the monitoring network since 1975 (Table 1; Fig. 3). The time series are grouped for the different areas of the EGF (A: Abano Terme; B: Montegrotto Terme; C: Battaglia Terme and Galzignano Terme), and they are compared with the total annual extracted water volume.

2015, but both drops and recoveries occurred before. The second half of the 1970s was affected by a rapid decline and a recovery, while the first part of the 1980s attested a decrease in the water level followed by a stability or a slight reduction (Fig. 6b). The annual mean potentiometric level increased in the first part of the 1990s (approximately 2 m in both Fonte Colli Euganei 1 and Mezzavia 4 wells), while the second half of the decade showed a comparable reduction of the water level until 2005–06. As observed in the time series of the Rigati 2 well, a new recovery occurred up to annual mean values of 3.1 m a.s.l. and 6.8 m a.s.l. in the Fonte Colli Euganei 1 and Mezzavia 4 wells, respectively (year 2015).

Conversely, the time series of the annual mean potentiometric level recorded by the Regazzoni 1 well did not show a clear trend (Fig. 6c). The level wavered between 18 and 22 m a.s.l., although negative peaks were observed. These peaks occurred suddenly, and they are usually accompanied by a lack of data.

The comprehensive analysis of the described time series (Fig. 6) showed a decrease of the exploitation in the EGF. This decrease was constant, although a higher rate occurred at the beginning of the 1990s. The expected response should be a recovery of the potentiometric level, but the observed trends in the monitored wells were variable. In particular, the time series of the Barillari 2 and Molino 7 wells clearly showed the expected rises of the level, with higher rates in 1991-93. However, the time series of the Rigati 2, Mezzavia 4 and Fonte Colli Euganei 1 wells showed small variations of the water level, with a recovery from the second half of the 2000s. The potentiometric level of the Regazzoni 1 well was also dissimilar, recording generally comparable values since the installation of the data logger. The observed different trends could be explained by taking into account the distance of the wells from the centers of the towns. In fact, the city centers are the oldest parts of the towns, with historical spa facilities, old boreholes, the highest density of wells and a long-lasting utilization of the thermal resource. Molino 7 and Barillari 2 are located in this area. On the other hand, the wells Rigati 2 in Abano Terme, Fonte Colli Euganei 1 and Mezzavia 4 in Montegrotto Terme and Regazzoni 1 in Galzignano Terme are located outside of the main exploited areas. These areas are investigated by few boreholes and do not have important spa facilities (Fig. 3). Therefore, the recorded water levels are probably less affected by the variation of the flow rates.

4.3. Assessment of potentiometric level through a flow rate − level relationship

The potentiometric levels of the Barillari 2 well were selected among others to calculate the relationship between the level and the flow rate (Fig. 7a). The analysis of the dataset recorded by the monitoring network showed some gaps in the time series related to temporary malfunctions of the loggers. The time series of the Barillari 2 well was the most continuous and showed a clear connection with the exploitation in the Abano Terme field. The monthly mean of the potentiometric level was employed to develop the model, with the aim of using the most detailed dataset of the level in relation to the smallest available interval of exploitation (i.e., total monthly exploitation). The results show a high inverse correlation between the monthly average potentiometric level and the flow rate (Pearson correlation coefficient $R = -0.91$). However, a discrepancy between the beginnings of the two time series was depicted (i.e., March 1980 for Barillari 2 and January 1977 for the exploitation). Therefore, a mean potentiometric level was calculated for the period 1977–1980 using available level values from the wells near Barillari 2. The new time series spans from 1977 to 2015, representing a general potentiometric level in the central, most exploited, part of Abano Terme. Similar to the time series of the Barillari 2 well, this dataset shows a good inverse correlation between the potentiometric level and the flow rate (Pearson correlation coefficient $R = -0.9$). Therefore, a linear relationship between the potentiometric level and flow rate is developed. The monthly flow rate represents the predictor variable, while the monthly average potentiometric level is the response variable. The resulting linear relationship is:

$$L = 23.72 - 3.43e^{-5} \times Q \tag{1}$$

where L represents the potentiometric level (m a.s.l.) and Q represents the flow rate (m^3/month). The residuals of the linear regression confirm a good relationship between the two variables, showing a normal distribution of residuals (Fig. 7b, c), and the whole dataset is within the prevision interval of regression (Fig. 7d).

The linear regression is employed to estimate the potentiometric level or the exploitation in the Abano Terme field using the flow rates from the literature or unpublished level data, respectively. The calculated potentiometric level suffered a drop of 24 m in approximately 60 years, related to an increase in the flow rate of $8.7 \times 10^6\ m^3/y$ (Table 2). As a matter of fact, the natural flow rate of the spring was $0.37 \times 10^6\ m^3/y$ at the beginning of the 20th century (Vinaj, 1906), producing a potentiometric level of 22.7 m a.s.l. The exploitation increased to $2.62 \times 10^6\ m^3/y$ in 1929 due to the development of the local tourism industry (Corpo Reale delle Miniere, 1931). The rise in the flow rate resulted in a decrease of the level reaching 16.2 m a.s.l. The calculated representative level of Abano Terme is slightly higher than the height of Montirone Hill (max. height = 16 m a.s.l.), in agreement with the occurrence of thermal springs in the early decades of the 20th century. The drop in the level continued in the 1950s and 1960s, decreasing from 12.5 m a.s.l. in 1953 to −1.1 m a.s.l. in 1969 (Fig. 7e). Contemporaneously, the exploitation increased from $5.77 \times 10^6\ m^3/y$ to $9 \times 10^6\ m^3/y$, producing the observed decrease.

4.4. Development of the thermal area and utilization of the hydrothermal resource

The Euganean thermal resource encountered intense overexploitation during the 20th century. In this section, a qualitative analysis of the utilization of the thermal resource is performed using data on the mining claims, the drilled boreholes and the tourism in the spa facilities from 1900 to present (Fig. 8). This analysis focuses on the northern part of the EGF, roughly corresponding to the municipality of Abano Terme, which suffered the highest anthropic impact. The datasets integrates the performed quantitative reconstruction of the potentiometric level and the exploitation. The result is a comprehensive analysis of the utilization of the Euganean thermal resource during the 20th century (Fig. 9).

The Italian law “Regio Decreto n. 1443, 29 July 1927” (R.D. 1443/1927) regulated the extraction of mineral and thermal waters through the introduction of mining claims. The first mining claims of the EGF were established in 1930 within the Abano Terme field and their number progressively enlarged up to the present-day amount of 76 mining claims (138 in the EGF). The highest growth occurred during the 1950s and 1960s increasing from 31 to 62 (Fig. 8a). Although the mining claims were authorized at the beginning of the 1930s, the forced utilization of the thermal water through the boreholes started before. The number of drilled wells progressively increased (Fig. 8b) with a trend that is almost comparable to that of the mining claims. The decades from the 1950s to 1970s recorded an intense exploration of the subsurface, and the 1960s saw the highest growth, with 102 new wells. The drilled wells in Abano Terme are 377(588 in the EGF). The mining claims or the number of wells drilled per year partially describes the utilization of the Euganean thermal resource that is mostly controlled by the therapeutic and recreational tourism. Data on tourist arrivals and overnight stays in the spa facilities of the EGF have been collected since 1938 and 1947, respectively, and they were used to calculate the average length of stay (i.e., overnight stays divided by tourist arrivals). The whole EGF was considered in this case to obtain a comprehensive analysis of the tourism industry. The tourist arrivals have increased from 30 thousand in 1938 to 730 thousand in 2015, and the initial number of 0.3 million overnight stays in 1947 grew to a quite stable value of 3–3.5 million of stays recorded from the 1980s to the present (Fig. 8c). Similarly, the average length of a stay in the spa facilities increased from approximately 10 days in the 1940s to approximately 11.5 days in the first part of the 1970s. Subsequently, it decreased, reaching 4 days in 2015 (Fig. 8c). The change in the type of tourism from therapeutic to recreational could explain the observed decrease in the average length of stay, in turn affecting the exploitation.

The described datasets were integrated with the performed reconstruction of the potentiometric level (Fig. 9) to demonstrate the magnitude of the anthropic impact on the Euganean thermal resource

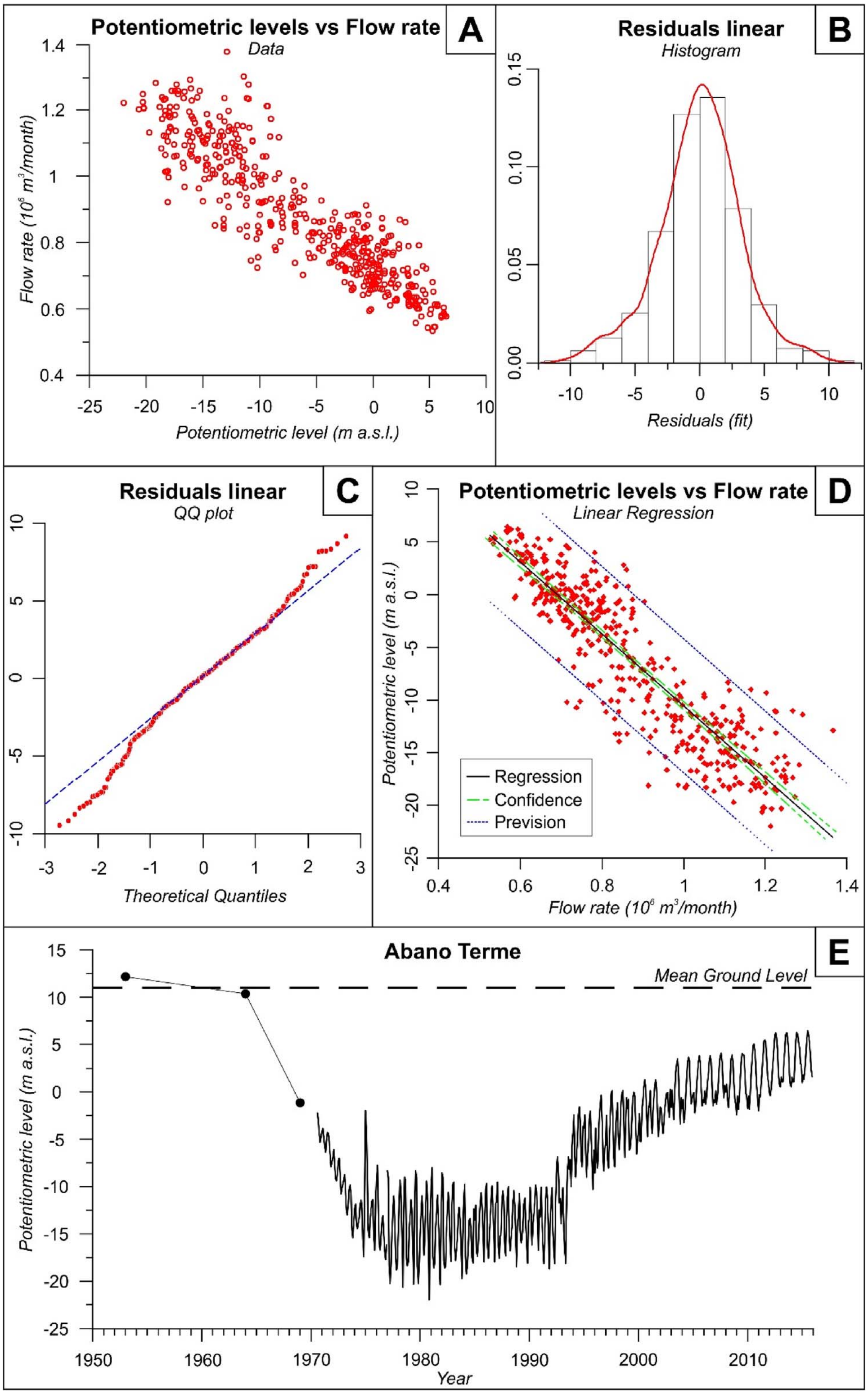

Fig. 7. (A) Dataset of the monthly average potentiometric level and the monthly flow rate used to calculate the linear regression. (B) Histogram showing the normal distribution of the residuals of the linear regression. (C) QQ plot of the residuals showing a good fit with the linear distribution of the theoretical quantiles. (D) Linear regression (black line) calculated using the dataset of Fig. 7a (red diamonds). The confidence (dashed green lines) and the prevision (dotted blue lines) intervals are reported. (E) Representative potentiometric level of the thermal aquifer in Abano Terme. The diagram collects the levels calculated by the linear regression (black circles) and the average monthly level of Abano Terme calculated using 19 wells from 1970 to 1976 (Fig. 5d), wells close to the Barillari 2 well from 1977 to 1980 and the dataset of the Barillari 2 well from 1980 to 2015 (Fig. 6a). The mean height of the ground in Abano Terme (11 m a.s.l.; horizontal black dashed line) is also shown evidencing a decrease in the water level under the ground at the beginning of the 1960s. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and its past, unsustainable utilization. The estimated potentiometric level of the thermal aquifer was 22.7 m a.s.l. at the beginning of the 20th century, producing an outflow of 0.4×10^6 m^3/y from the main springs of the Abano Terme field (Table 2; Fig. 9). This original potentiometric level is in agreement with the mean value recorded by the Regazzoni 1 well sited outside the most exploited areas of the EGF, representing a good constraint for the performed estimation. The forced extraction of the thermal water through the boreholes increased the outflow resulting in a progressive decrease of the potentiometric level. A higher anthropic impact on the Euganean thermal resource occurred from the 1950s to the 1970s, as attested to by the sharp increases in mining claims, boreholes, overnight stays and exploitation (Table 2; Fig. 8). The potentiometric level in Abano Terme dropped up to 1977 when the representative level attested to a minimum value of −15 m a.s.l. (Fig. 9). The unsustainable utilization of the thermal resource in the middle part of the century could seriously compromise its future availability. In addition, it caused several issues for both the owners of the spa facilities and the local population. The shallow wells and the

Table 2
Potentiometric levels of the Euganean thermal aquifer and flow rates calculated using the linear regression in Eq. (1). The data obtained from the literature are reported in a regular font, while the calculated values are in bold.

Year	Level *m a.s.l.*	Flow Rate $10^6 \times m^3$/month	$10^6 \times m^3$/y	Reference
1906	**22.67**	0.03	0.37	Vinaj (1906)
1929	**16.22**	0.22	2.62	Corpo Reale delle Miniere (1931)
1953	**12.16**	0.34	4.04	Mameli and Carretta (1954)
1964	10.35	**0.48**	5.77	Unpublished data
1969	−1.14	**0.75**	9.04	Unpublished data

thermal springs dried up. Deeper boreholes had to be drilled to obtain the requested flow rate of thermal water at a sufficient temperature, increasing the costs of drilling and exploitation. Subsidence problems also occurred, as attested to by the collapse of a drilling rig in 1965 (Calvino, 1967). In addition, geodetic surveys have been performed since 1959 showing a land lowering of few centimeters per year (Strozzi et al., 1999). Therefore, the regional stakeholders limited the exploitation and controlled the status of the thermal resource through a monitoring network. The regulation of the flow rate, its control through the monitoring network and the crisis of the local tourism industry led to a decrease in the exploitation in the last 40 years (Fig. 6). The result was a general recovery of the potentiometric level up to 3.4 m a.s.l. in 2015 (annual mean potentiometric level of the Barillari 2 well). In particular, the highest increase occurred from 1991 to 1993 with a growth in the annual mean potentiometric level recorded by the Barillari 2 well of 7.4 m (Fig. 6a). A decrease in the subsidence was observed in the same period (Strozzi et al., 1999), and it stopped at the beginning of the 2000s.

However, the growth of the potentiometric level has recently been facing a new issue. The potentiometric level varies during the year due to the different flow rates and reaches its maximum value during summer when the exploitation is low. Locally, the level of the water table moves upward to the ground level, and a few wells become artesian, flowing out water at high temperature. Therefore, it is necessary to maintain a minimum flow rate during periods of low number of incoming tourists to prevent the uncontrolled and potentially dangerous outflow of hot water from the wells.

5. Concluding remarks

In this paper, the utilization of the local thermal water in the Euganean Geothermal Field (EGF) is studied to assess the anthropic impact on this important, economically valuable environmental resource during the 20th century. Good management policies are well-established in thermal fields for energy production (e.g., Lopez et al., 2010; Monterrosa and López, 2010), but the literature is lacking information on the sustainable utilization of thermal water for tourism purposes.

The EGF (NE Italy) is one of the most important thermal fields for balneotherapy in Europe. The long-lasting utilization of the thermal resource, as well as the huge amount of data (i.e., hydrogeological data, flow rates, information about the utilization of the thermal resource and tourism data), represents a probable unique case study. The analyses of the collected time series highlight the strict connection between the potentiometric levels of the Euganean thermal aquifers and the extraction at different time scales. A regression analysis with a linear function supported this result. Regular seasonal variations of their levels are observed during one year. This trend is ascribable to different monthly pumping rates and in turn to the balneotherapeutic tourist seasons, reflected by the tourist arrivals. Similarly, the variable anthropic pressure on the Euganean thermal resource affected its status during the 20th century. The development of the tourism industry and the increasing demand of thermal water dropped the annual mean potentiometric level from 12 m above the ground level at the beginning of the 20th century to 26 m below ground level in the 1970s. This overexploitation caused a serious environmental impact drying the thermal springs of the EGF and producing subsidence problems. The

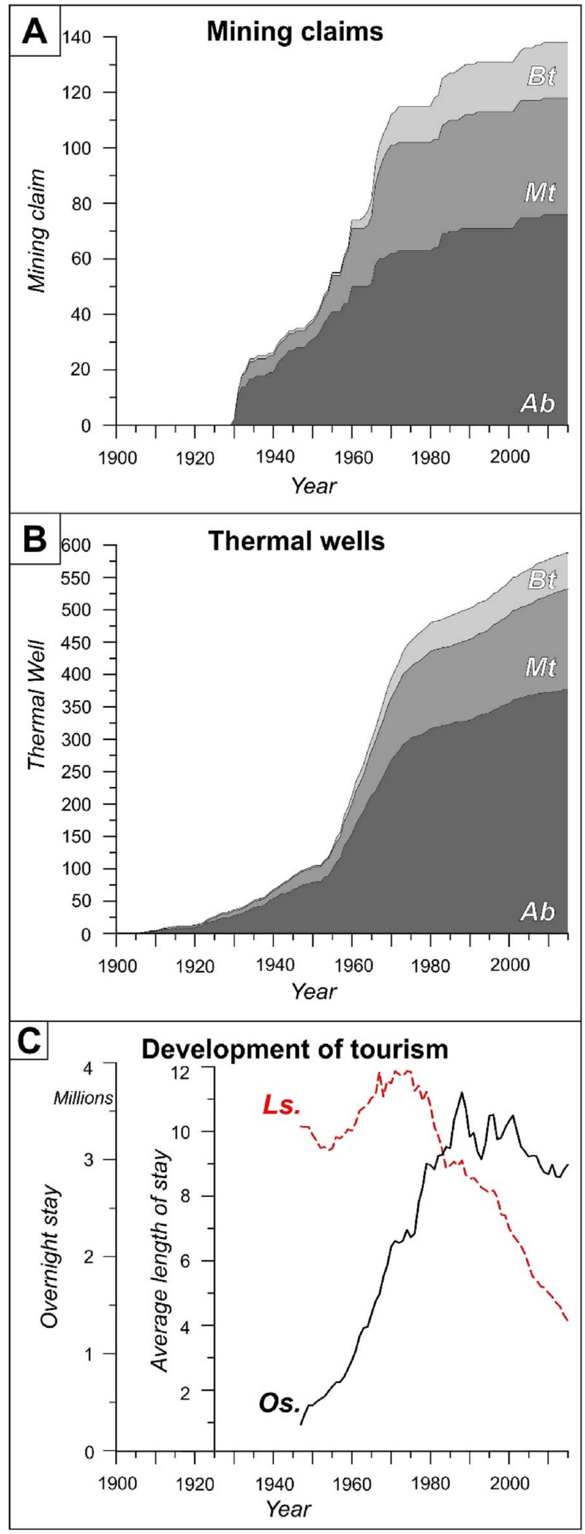

Fig. 8. (A, B) Cumulative graphs of the mining claims (A) and the drilled wells (B) in the different zones of the EGF (Ab: Abano Terme; Mt: Montegrotto Terme; Bt: Battaglia Terme and Galzignano Terme). (C) Overnight stays (Os: black line) and average length of stay (Ls: red dashed line) in the spa facilities of the EGF.

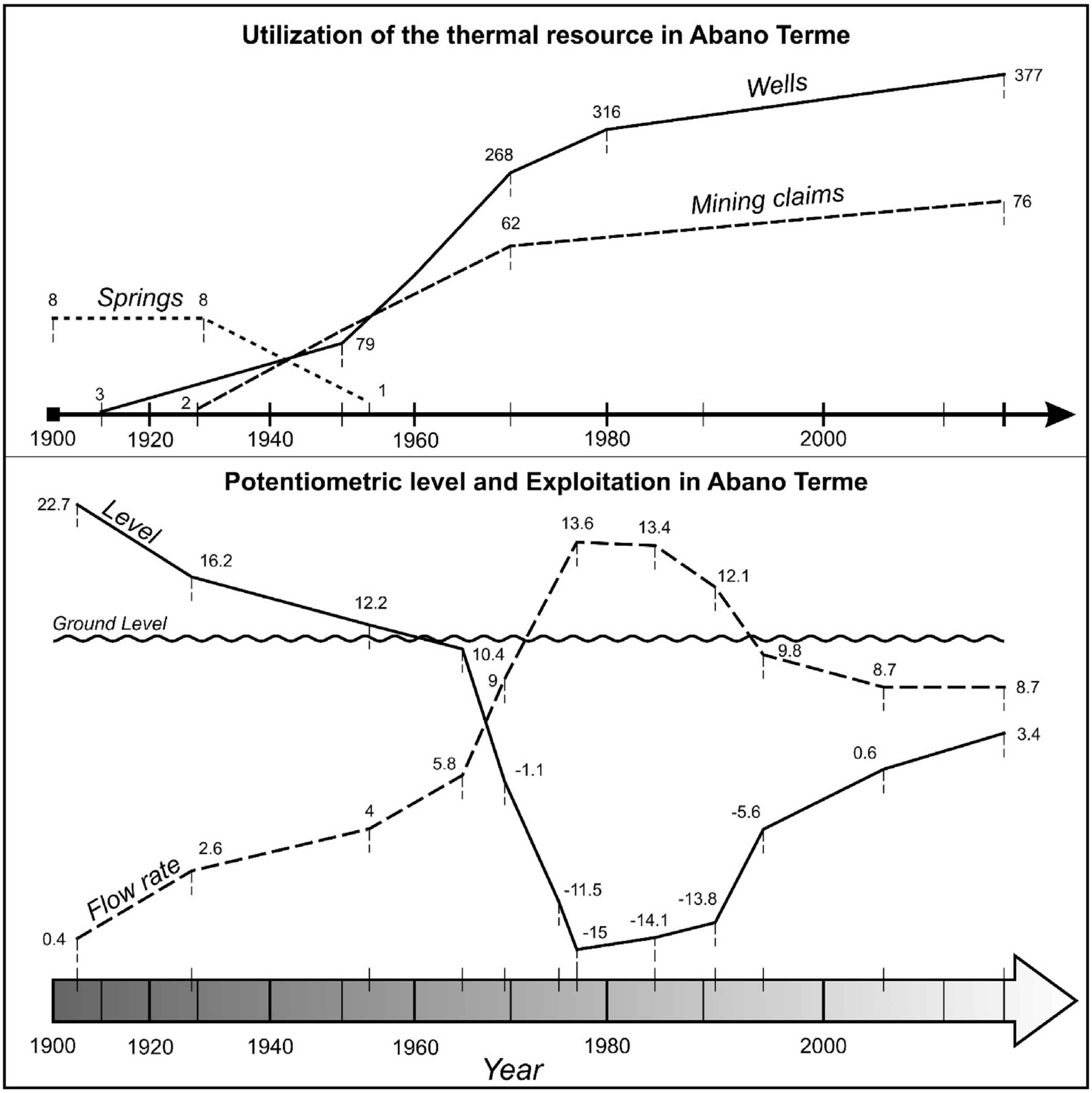

Fig. 9. Historical reconstruction of the status and the utilization of the thermal resource in Abano Terme. The potentiometric level (unit of measurement: m a.s.l.) shows an abrupt decrease in the decades of the 1960s and 1970s, corresponding to an increase in the flow rate (unit of measurement: 10^6 m^3/y). In particular, the level dropped under the ground level (approximately 11 m a.s.l. in Abano Terme) drying all thermal springs. The observed variation in the potentiometric level is ascribable to a variable anthropic pressure on the thermal resource during the 20th century, as shown by the increases in mining claims and drilled wells.

subsequent recovery of the level attested a decrease of the extraction related to the limitation of the flow rates and their continuous monitoring. The quite constant flow rate of the last few years (approximately 14×10^6 m^3/y) produced a stable potentiometric level (8 m below the ground level) and a general drawdown in the most exploited area of the EGF from few meters to a few tens of meters. This range is acceptable considering the lateral variations of the transmissivity in the Euganean thermal aquifer. Therefore, the ongoing exploitation seems sustainable for the utilization of the Euganean thermal resource. This rate of extraction permits to preserve the current, profitable, economic status of the Euganean thermal area and its related social impact on the central Veneto. These aspects, as well as the conservation of the environmental status, are crucial in the decision of a sustainable utilization. A considerable increase in the flow rate could cause a higher drawdown depleting the resource for the future generations. On the other hand, a high reduction of the extraction could produce a general recovery of potentiometric levels above the ground level producing public safety issues. The uncontrolled outflow of thermal water from abandoned or untapped wells is currently sporadic, but a higher potentiometric level could sprawl this issue in a wider area or over a longer period.

The status of the thermal resource has to be monitored regularly improving the actual continuous pointy monitoring with a regular areal one. In addition, the monitoring should consider also the physical and chemical features of the thermal water, as well as the potentiometric level of the thermal aquifer. As a matter of fact, few cases of chemical and temperature changes related to overexploitation are reported in the literature (Rman, 2014). The comparison of historical and recent chemical analyses on the Euganean thermal water shows a small variation of its water solute contents (Gherardi et al., 2000). The Euganean thermal resource did not suffer a deterioration of its chemical qualitative state due to the past overexploitation. The sustainable management of the Euganean thermal resource should consider the hydrogeological setting of the EGF and a more homogenous distribution of the pumping sites over the thermal area. In particular, the areas with high transmissivity or with low amount of wells should be the target for future detailed studies and explorations improving the conceptual model of the EGF and the data for the management of the resource.

Further analysis on the renewable component of the system could be speculative. As a matter of fact, the performed regression model predicts the potentiometric level produced by a given flow rate, but it is not able to reproduce the dynamics of the thermal system. More sophisticated lumped models (Sarak et al., 2005), artificial neural networks (Choong and El-Shafie, 2014) or numerical models (Buday et al., 2015; O'Sullivan et al., 2010; Scott et al., 2016) could take into account the local hydrogeological setting of the thermal system. However, they require reliable datasets on production and reservoir parameters to reproduce the behavior of the system induced by the exploitation. This paper provided a comprehensive dataset that should be used as reference for a numerical analysis supporting the assessment of the renewability and the sustainable utilization of the thermal resource.

The stakeholders have to consider carefully the sustainable utilization of thermal resources for balneotherapeutic purposes. The monitoring of the thermal resource status through continuous measurements of the exploited flow rates and of the thermal aquifer potentiometric level is the key to the good management of the reservoir. A long-lasting, comprehensive reconstruction of the suffered anthropic impact should be included in the analysis of the thermal resource status, enforcing the emphasis on its opportune sustainable utilization.

Acknowledgements

This researcher was funded by the hydrothermal district of Euganean Geothermal Field (B.I.O.C.E.) within the project "Hydrogeological model of Euganean Geothermal System (EGS)", grant to P. Fabbri. The authors would like to thank the Veneto Region Environmental Agency (ARPAV) for the data support and B.I.O.C.E. for the technical support and fruitful discussions. We are grateful to the two anonymous reviewers for the revisions of the manuscript and the helpful comments.

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