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Shallow groundwater temperature in the Turin area (NW Italy): vertical distribution and anthropogenic effects

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(Article begins on next page)

1 **Urban groundwater warming in Turin area (NW Italy)**

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6
7 **ABSTRACT**

8 This study investigated the thermal regime of shallow groundwater in the Turin area (NW
9 Italy), where the large energy demand has driven a new interest for ground-source heat
10 pumps (GSHPs). The strongest vertical variability of groundwater temperature is found
11 within 10-20 m below ground surface. In spring, deeper temperatures are higher than
12 shallow temperatures, while in autumn the trend is reversed. These variations are
13 connected with the heating and cooling cycles of the ground surface due to seasonal air
14 temperature oscillation, propagating into the aquifer.

15 The areal temperature distribution shows an increase from the foothill sectors close to the
16 Alps towards the central Po Plain, driven by the progressive warming along the flow path.
17 In the Turin city aquifer temperatures are 0.6 ÷ 1.6 °C higher than rural sectors. This
18 groundwater warming is linked to the urban heat island effect, mainly driven by the typical
19 artificial land use. Sparse warmer outliers (16-20 °C) are in some cases connected to
20 documented point heat sources, such as GSHP systems, industrial districts and landfills.

22 KEY WORDS: groundwater temperature; seasonal oscillation; anthropogenic heat sources;
23 ground-source heat pumps

24 **INTRODUCTION**

25 As many other countries in Europe, Italy is trying to reduce its dependence to non-
26 renewable fossil fuels. NW Italy is one of the most densely populated and industrialized
27 areas and concerns are rising for the great thermal energy demand, especially in its large
28 conurbations (Turin, Milan). Among the renewable sources, low temperature reservoirs are
29 being increasingly regarded worldwide as promising thermal energy suppliers via the use
30 of heat pumps. A similar trend has been characterizing Italy in the last decades: geothermal
31 heat pumps have doubled their contribution to the final consumption of renewable energies
32 (EC, 2015).

33 In NW Italy the Po Plain is a very promising area for the large-scale dissemination of
34 geothermal heat pumps: the relatively thick alluvial body forming the plain hosts many
35 productive groundwater systems, making possible the installations of geothermal heat
36 pumps in the above mentioned cities (Sparacino et al., 2007; Baccino et al., 2010; Beretta
37 et al., 2014; Alberti et al., 2017; Emmi et al., 2017; Piga et al., 2017).

38 The Turin area is located in such a favourable geological context, but it still lacks a city-
39 scale thermal characterization of aquifers. The present study thus investigated the
40 temperatures of the shallow groundwater in the Turin area, considering both the urban and
41 the rural areas adjacent to the city. Another reason to study the Turin case is that several
42 studies, carried out in many cities worldwide, reveal an over-heating of urban shallow
43 aquifers (Ferguson and Woodbury, 2004; Zhu et al., 2010; Menberg et al., 2013; Benz et
44 al., 2015).

STUDY AREA

47

48 The area investigated is located in Piedmont Region (NW Italy) and includes both the
49 narrow sector of the western Po Plain between the Western Alps (W) and Turin Hill (E)
50 and the internal plain sector of the Ivrea Morainic Amphitheatre. The regional climate is
51 driven by the orographic component (ARPA 2007): air temperatures show a regular
52 decrease with elevation in western direction towards the alpine chain and can be changed
53 by local conditions, such as urban areas. The average annual temperature of Piedmont Po
54 Plain ranges between 10°C and 12.5°C, with higher average monthly values in autumn
55 than in spring (Table 1).

56

57 Table 1

58

59 From a hydrogeological point of view, the Quaternary alluvial sediments of the Po Plain
60 represent a continuous highly permeable porous medium that hosts many groundwater
61 systems. Conventionally, one shallow and various deep aquifers have been described in
62 Piedmont Region (Bortolami et al., 1988; Bove et al., 2005; De Luca et al., 2014; Lasagna
63 and De Luca, 2017). The shallow aquifer, hosted in late Pleistocene and Holocene units, is
64 mostly unconfined and supplied by the infiltration of rainfall and secondarily by rivers in
65 the high plain sectors. Due to the mainly sandy–gravelly texture, many quarry activities are
66 exploiting this complex (De Luca et al. 2007; Castagna et al. 2015a, 2015b). The
67 maximum aquifer thickness is 50 m and the water table generally has depths between 1 and
68 50 metres below ground level, with minima located in the high plain sectors. In most of the
69 wells (78%) the water table depth is found between 1 and 20 metres b.g.l. (Bucci et al.,

70 2017). The low plain sectors, far from the Alpine chain, are generally discharge areas and
71 the Po River represents the main regional discharge axis for the groundwater flow
72 (Debernardi et al., 2008; Lasagna et al., 2016a, 2016b).

73

74

75 TEMPERATURE MODEL AND METHODS

76

77 The shallow subsurface temperature is mainly controlled by the temperature at the ground
78 surface, which strictly depends on the local climate and on the land use conditions. The
79 temperature temporal oscillation in the unsaturated zone, solved by a 1D heat diffusion
80 model for a semi-infinite medium characterized by homogeneous properties and negligible
81 vertical water movements (Banks, 2008; Taylor and Stephan, 2009), consists of an
82 oscillating temperature around the average annual ground temperature. The fluctuations
83 undergo a decay and an increasing time lag with depth. This means that longer temperature
84 cycles -decades, centuries- are, the more they penetrate the subsurface, whereas the short
85 cycles -days, months- but their amplitude is increasingly damped and lagged by the heat
86 dissipation within the geologic medium. The heat transfer processes become more complex
87 when the ground temperature inputs reach the groundwater: the flow of the water in the
88 porous medium, the inertial effects and eventual turbulence enlarge the apparent thermal
89 diffusivity until it reaches several orders of magnitude greater than the molecular thermal
90 diffusivity (Taylor & Stephan 2009). This means an increased rate of heat transport due to
91 hydrodynamic effects that are highlighted by distortions in borehole temperature logs.
92 The aquifer depth interval affected by temperature oscillations, known as the “surficial
93 zone”, is generally 10 to 20 m deep; it is followed by the so-called “geothermal zone”, in

which the geothermal gradient drives a constant increase in temperature (Anderson 2005). However, previous works in NW Po Plain alluvial aquifers (e.i. Barbero et al., 2016) revealed a “homoeothermic zone” with no temperature oscillations in time. The temperature below the surficial zone is usually 1 to 2 °C higher than the average annual temperature at the ground surface (Anderson 2005).

The mean annual average temperatures and the amplitude of temperature oscillations in the vadose zone and in the aquifers strictly depend also on the local land use: variations in reflectance and porosity of soil are able to influence the transmission of solar radiation and water infiltration. Consequently, temperatures are affected by anthropogenic elements found at ground surface: buildings, roads, paved surfaces and so on. The temperature rise varies depending on the type of element: for example, Taylor and Stefan (2009) observed increments of up to 3°C linked to isolated roads. The most evident thermal footprints occur beneath urban areas: Menberg et al. (2013) estimate a temperature difference between rural and urban areas equal to +1.9 °C to +2.4 °C in some German cities. Warmer temperatures below cities are also linked to the global warming (Taniguchi et al., 2007; Bayer et al., 2016).

Thermal logs, the typical survey method for aquifer temperature detection (Taniguchi, 1993; Pasquale et al., 2011), were carried out throughout the water column of around 50 observation wells of Turin area, all wells are screened in the shallow aquifer. Temperature acquisition interval was 1 to 5 m (depth-wise increase) and an electronic water level metre equipped with a thermometer (± 0.1 °C accuracy) was used. For assessing possible city-related effects, temperatures were collected in rural and urban (Turin city) sectors. A multi-temporal approach was used to detect the seasonal fluctuations. The largest part of the wells was surveyed in 2014 in a spring-autumn survey. In 2016 further observation points were added with measurement frequency equal to 1 month. The depths of monitored wells

119 have the following ranges: <10 m (2.4%), 10 to 20 m (42.9%) and >20 m (54.7%).

120 According to the afore mentioned temperature model and to air temperatures, the
121 maximum expected groundwater temperature below the surficial zone with climatic
122 variations is between 12 and 14.5 °C in the Turin plain.

123

124 RESULTS AND DISCUSSION

125

126 The most evident feature of the temperature profiles measured in the observation wells of
127 the area investigated is the vertical variability in the shallow portion of the aquifer,
128 according to the afore mentioned models. The temperature delta along the water column of
129 the well, obtained by the difference between top and bottom well temperature, indicates the
130 warming/cooling of very shallow groundwater; as expected, the temperature variation
131 along the well water column diminishes significantly with the depth of groundwater level
132 (Fig. 1). This trend is season-driven: in spring deep values are higher than the shallow ones
133 ($\Delta T < 0$), while in autumn a decrease of temperature with depth occurs ($\Delta T > 0$). Such depth
134 and time variations are connected to the heating and cooling seasonal cycles of ground
135 surface temperatures, propagating into the shallow portion of the aquifer. Furthermore, the
136 seasonal amplitude reduction with increasing depths means that the vadose zone plays a
137 major role in damping the oscillations, according to similar studies by Burns et al. (2016).

138

139 Figure 1

140

141 Underneath the seasonal oscillation zone, groundwater temperatures are approximately
142 constant in most wells, according to Barbero et al. (2016): in Fig. 1, below 10 m the
143 residual changes (less than ± 1 °C) can be connected to other processes, such as advective

144 heat transport within the aquifer. Deviations from constant temperature in the thermal
145 profiles can be read as either upward or downward water movements, in recharge and
146 discharge areas, or as lithological heterogeneities in areas with nearly horizontal flow. The
147 groundwater temperature in Turin plain, averaged on spring and autumn values extracted
148 from Bucci et al. (2017), is 14.1 °C, that is within the expected temperature range (see
149 previous paragraph).

150 Lateral variations of aquifer temperature in autumn 2014 are displayed by plotting the
151 bottom well temperatures, not affected by seasonal oscillations (Fig. 2), that were
152 measured at the average depth of 25 m. There is a gradual groundwater warming from high
153 plain sectors close to the Alps towards the Po River. This feature is consistent with the
154 main groundwater flow direction, meaning that colder aquifer temperatures of recharge
155 areas -due to colder air temperatures in high plain sectors- warm up during their pathway.
156 The second most evident feature is the high concentration of warm temperatures below the
157 Turin city: compared to rural values, the urban aquifer is 14-16 °C and rural aquifer is 12-
158 14 °C. More precisely, the urban warming intensity can be calculated with the difference
159 between the average temperatures in the city area and rural area: in the Turin case in 2014
160 it is +1.6 °C in spring and +0.6 °C in autumn. This feature is likely linked to the
161 groundwater warming caused by the large urbanized area of Turin: the extensive cover of
162 roads and buildings warms up the land surface and then this heat is transferred to the
163 underlying aquifer.

164

165 Figure 2

166

167 Sporadic high temperatures (>16 °C) have local significance and may be related to point
168 heat sources. In the case of La Loggia observation well (Fig. 2), located few kilometres

169 south of the Turin city, groundwater reaches a temperature of around 17 °C. In this case the
170 groundwater heating is likely linked to the presence of an industrial district that may be
171 responsible of intense heat fluxes due to the huge volumes of warm indoor air and/or to
172 industrial exothermic processes. Other outliers are: a well in Turin city close to an open-
173 loop geothermal system working in heat injection mode, which displayed temperatures up
174 to 23 °C -not in figure- and the Caselle T.se observation well (N of Turin), which showed a
175 high maximum temperature in autumn (18.6 °C) and a marked difference with the spring
176 value (13.4 °C). Without any further knowledge on heat sources in the surroundings and
177 lithological variations at the site, such behaviour may be related to a significant seasonal
178 effect on groundwater: the small groundwater table depth (< 5 m) and the limited well
179 depth (20 m) make the groundwater at that site largely influenced by the seasonal
180 oscillations, even at the bottom of the observation well, where the plotted measurement
181 was taken. Furthermore, the land use of both sites is constituted by large paved parking
182 areas that might have amplified the heat accumulation during summer, with consequent
183 high temperatures in autumn.

184 Fig. 3 and 4 show the typical urban thermal logs from the 2016 survey and their evolution
185 in time. The 4 monitoring points (green dots in Fig. 2) were grouped in 3 sites: PZC1 and
186 PZE6 (Site 1), are in the same site, a former illegal landfill; PZ3 A is in Turin city
187 neighbourhood with early urbanization (Site 2); PZ34 is located in an industrial waste
188 landfill (Site 3). Site 1 and 3 have less dense urbanization. The strongest vertical variability
189 is evident in the wells of Site 1 with shallow water table depth, whereas in Site 2 and 3 the
190 groundwater temperatures are approximately constant in depth because the water table is
191 below 20 m b.g.l., where the seasonal effects are supposed not to influence the
192 groundwater temperatures. The huge differences between PZC1 and PZE6 of Site 1 are
193 mainly due to the position with respect to the landfill (PZC1 is downstream, PZE6 is

194 upstream) and, secondarily, to the land use: PZC1 is drilled few centimetres far from an
195 asphalted road, while PZE6 is some meters far from an unpaved road and around 10 m far
196 from buildings. Overall, groundwater in PZC1 is overheated by the heat transported from
197 the polluted sector, where exothermic reactions of organic matter degradation likely occur
198 (the site has methane burners), and by the asphalted road that, according to previous
199 studies (i.e. Taylor & Stefan, 2009), can increment the temperatures up to 3 to 4 °C.

200

201 Figure 3

202 Figure 4

203

204 **CONCLUSIONS**

205

206 The climatic component has a major influence on the shallow aquifer temperatures in
207 Turin area, creating vertical temperature heterogeneities up to 10 m depth. Seasonal
208 thermal variations are more effectively damped as long as the vadose zone is thicker. Other
209 factors play an important role at regional level, such as recharge conditions and altitude of
210 infiltration waters: the high plain sector has colder waters, compared to the low plain
211 sectors. Anthropogenic heat sources were also recognized: a diffuse temperature increase
212 below the Turin city was indeed detected that ranges between 0.6 and 1.6 °C season-wise.
213 At the same time, warmer outliers linked to local heat sources (polluted sites, industrial
214 districts, geothermal systems) and/or site-specific conditions were also detected. For
215 instance, S to Turin a contaminated site constitutes an interesting case study of pollution-
216 driven groundwater warming. Other outliers need further surveys for better comprehension
217 of the measured temperature values.
218 Concerning the geothermal applications, the groundwater temperatures of shallow aquifer

219 can be assumed as relatively constant throughout the year if compared with the wider
220 seasonal air oscillation recorded in a medium temperate climate of continental Europe. The
221 thermal features of shallow aquifer, combined with the high productivity and the legal
222 protection of deeper aquifers, contributes to create favourable conditions for the large-scale
223 diffusion of groundwater-coupled heat pumps (GWHPs).

224

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226

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230

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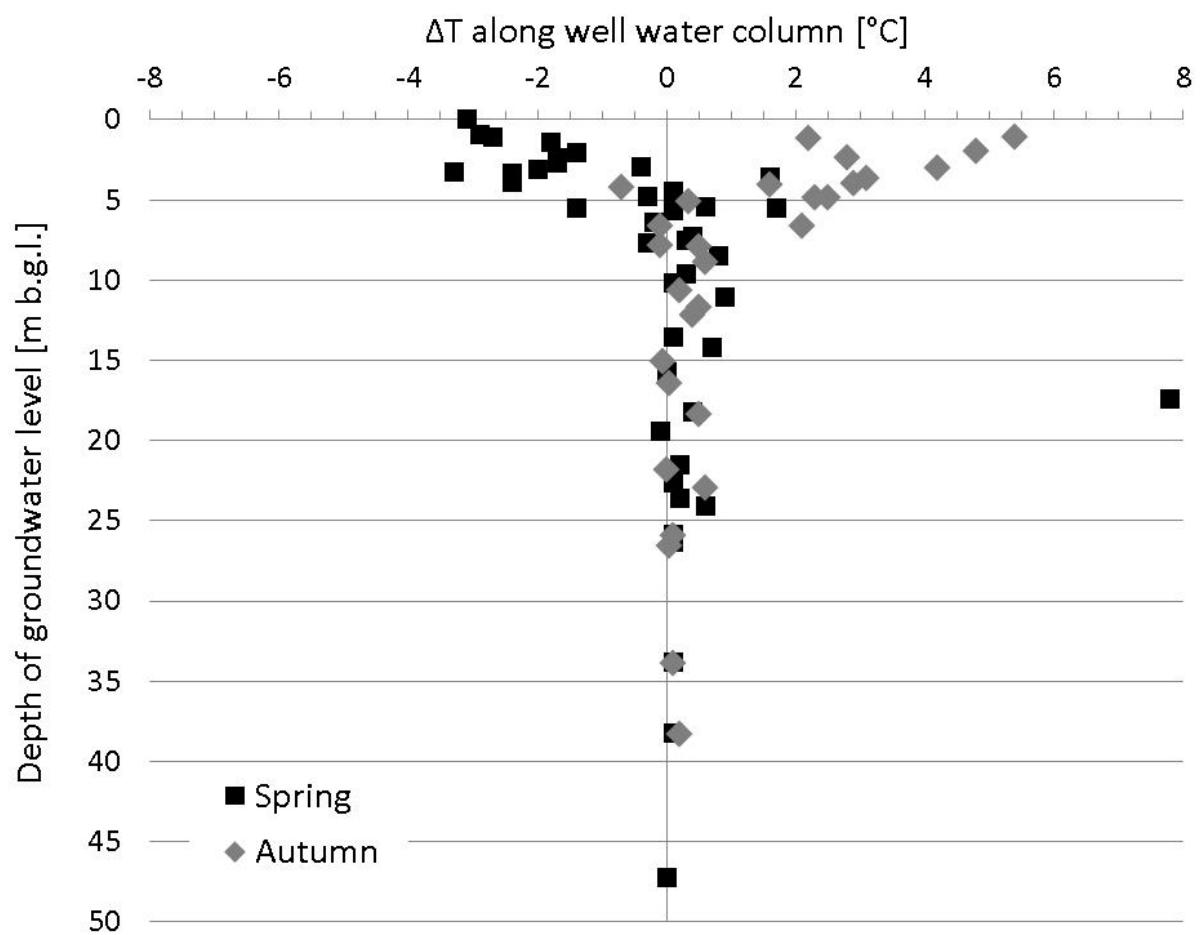
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Fig. 1 – Correlation between groundwater temperatures and temperature difference along
water column of the monitored wells in 2014

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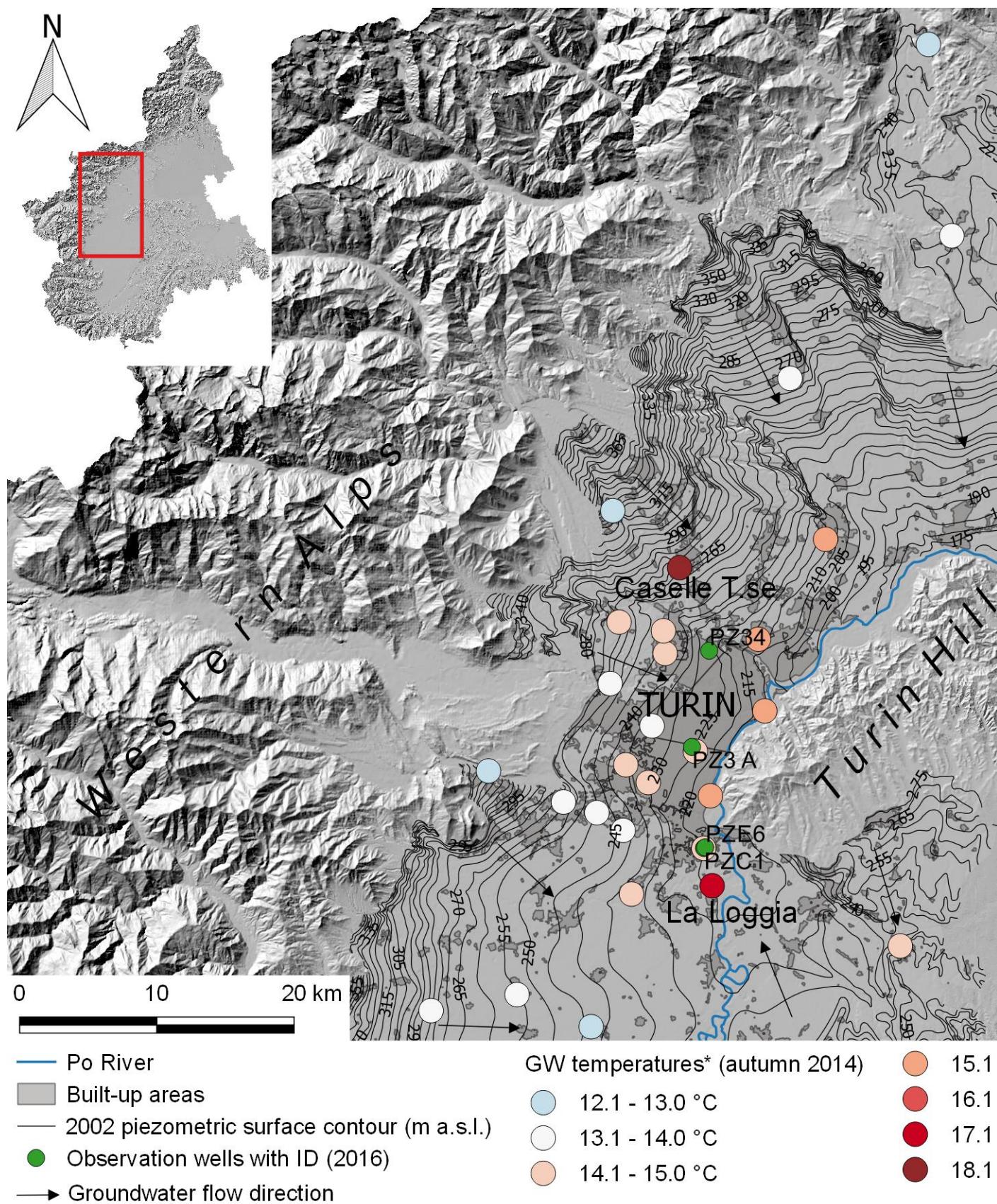
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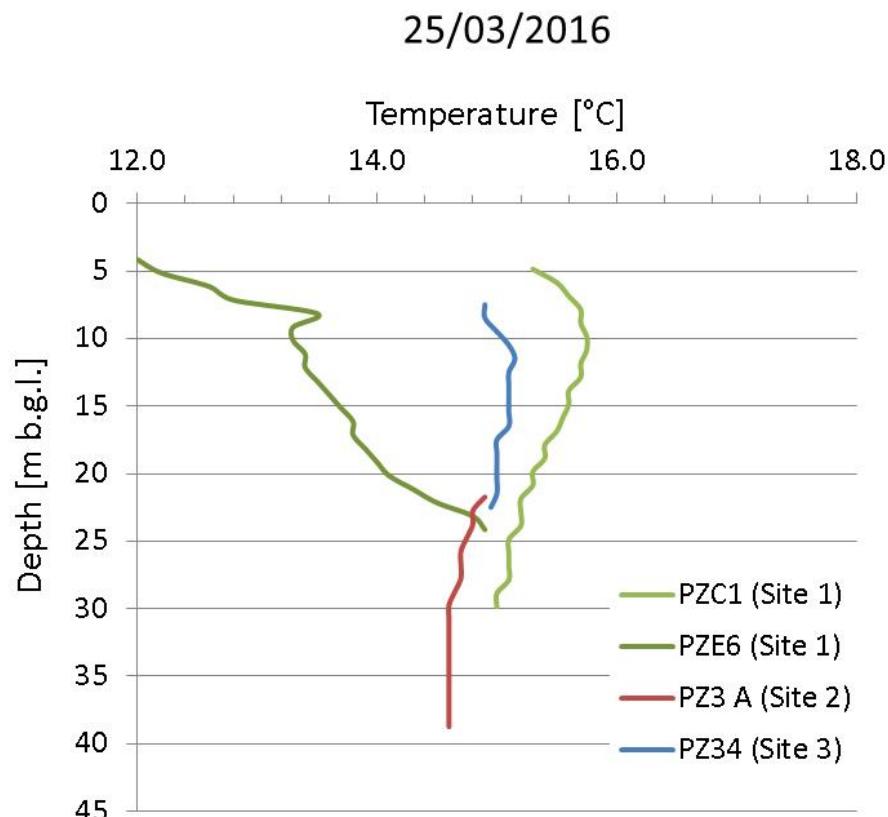
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343 Fig. 2 – Temperatures of the shallow aquifer in autumn of 2014. *The values refer to the
344 well bottom temperatures
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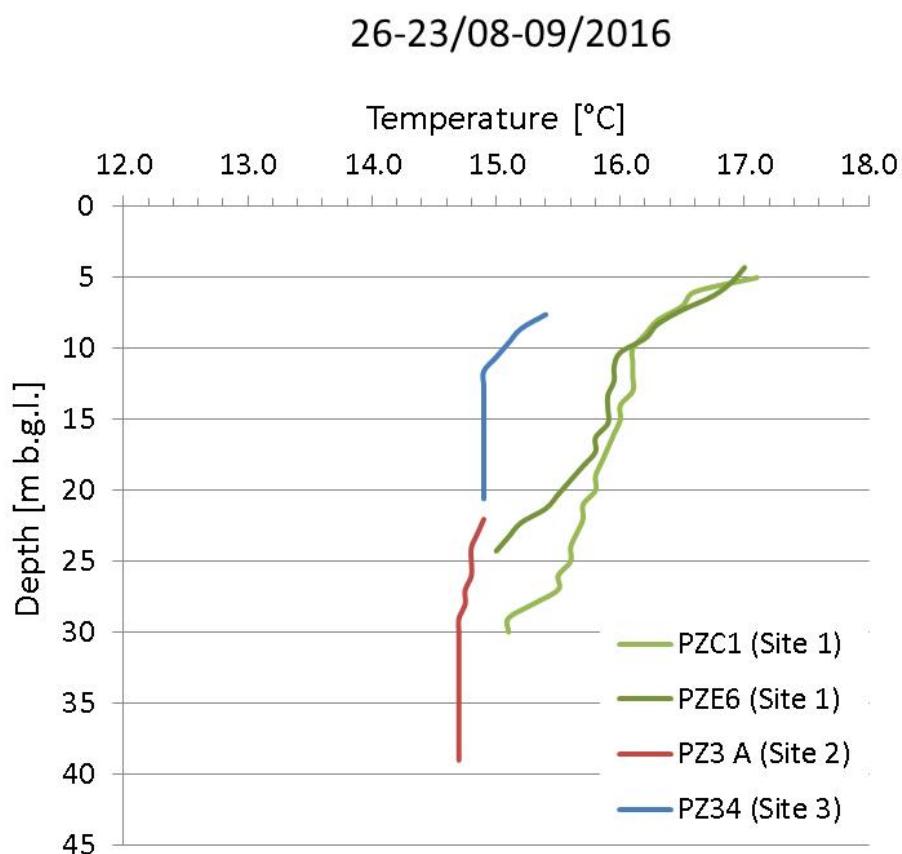


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349 Fig. 3 – Groundwater temperatures at 3 urban sites in spring of 2016
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355 Fig. 4 – Groundwater temperatures at 3 urban sites in autumn of 2016

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