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

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## Abstract

This study investigated the thermal regime of shallow groundwater in the Turin area (NW Italy), where the large energy demand has motivated a new interest for renewable sources, such as the use of ground-source heat pumps (GSHPs) for domestic heating and cooling. The vertical variability of the groundwater temperature between the ground surface and 10-20 m was detected: deeper temperatures were higher than shallow temperatures in spring, while a decrease with depth occurred in autumn. These variations are connected with the heating and cooling cycles of the ground surface due to seasonal temperature oscillation. Variations below the seasonal oscillation are likely to be connected with the presence of advective heat transport due to the groundwater flow, according to the hydraulic features of a shallow aquifer. Temperature values mostly ranged between 12°C and 14°C in rural areas, while below Turin city, the values were between 14°C and 16°C. This groundwater warming is attributed to a widespread urban heat island phenomenon linked to warmer land surface temperatures in Turin city. Sparse warm outliers are connected with point heat sources and site-specific conditions of land and subsurface use, which may cause the aquifer temperature to rise. A relatively stable temperature below the seasonal fluctuation zone combined with high productivity and legislated limits for deeper groundwater use represent favourable conditions for a large-scale diffusion of groundwater

heat pumps (GWHPs) within the shallow aquifer. Moreover, this heat surplus should be regarded as a resource for future geothermal installations.

## 1. Introduction

Italy still largely depends on non-renewable fossil fuels, despite its global energy goals for 2020. In particular, NW Italy is a highly populated and industrialized area where large conurbations (Turin, Milan) present critical issues for the large energy demand. Geothermal energy, one of the most promising renewable worldwide sources, has had limited development in the country in terms of electricity generation in recent years. Medium to high enthalpy geothermal sources accounted for 1.8% of the national gross energy generation in 2005 (European Commission 2007), and the total contribution to the final energy consumption, excluding geothermal heat pump applications, decreased from 213 to 130 ktoe/year (toe=tonne of oil equivalents) in the period of 2009-2014 (European Commission 2015). High and medium enthalpy geothermal sources for electricity generation have had limited development in NW Italy, hence, alternative green sources should be used. Furthermore, domestic heating and cooling needs, which could possibly be provided by low enthalpy heat, represent a relevant fraction of fossil fuels consumption in the northernmost regions. For these reasons, low temperature geothermal reservoirs are being increasingly regarded as promising thermal energy supplies. Recently, geothermal systems have doubled their contribution to the final consumption of renewable energy in Italy from 39 to 71 ktoe/year, but this amount still represents a small part of the national demand of 10,000 ktoe/year for thermal energy (European Commission 2015). Geothermal systems operation is based on the heat exchange between the soil and the groundwater and a heat pump. This procedure requires knowledge of many thermal and hydraulic properties, including the undisturbed subsurface temperature, thermal conductivity, groundwater occurrence, local flow direction, groundwater level depth, and recharge conditions (Stauffer et al. 2013). The undisturbed temperature is a crucial parameter because it represents

54 the base thermal energy level that can be extracted/injected by a geothermal heat pump. In a

55 closed-loop system (GSHPs, ground-source heat pump), the heat-carrier fluid circulating into the

56 vertical heat exchanger acquires the undisturbed temperature of the subsurface, whereas an

57 open-loop system (GWHP or groundwater heat pump) operates via a direct exchange between

58 the groundwater and the heat pump; hence, the aquifer temperature is the same as the inlet

59 temperature.

60 In NW Italy, the availability of shallow groundwater resources in the Po Plain makes the area

61 very promising for the large-scale dissemination of geothermal heat pumps, for example, for use

62 in district heating (Sparacino et al. 2007; Beretta et al. 2014) and space heating (Baccino et al.

63 2010). Furthermore, large cities are typical cases because previous studies indicate that a heat

64 surplus is expected to occur beneath an urban area (Ferguson & Woodbury 2004; Zhu et al.

65 2010; Menberg et al. 2013).

66 The Turin area still lacks a city-scale thermal aquifer characterization despite recent advances in

67 geothermal applications. The present study is concerned with the temperatures of the shallow

68 groundwater in the Turin area. Data were collected in both urban and rural areas adjacent to the

69 city, and their distribution was related to both regional and local factors, for example, the

70 climatic regime, land use, and aquifer recharge and discharge. The effect of anthropogenic

71 warming was reported and some preliminary considerations about the future dissemination of

72 GSHPs in the Turin area have been expressed according to the survey results.

73

## 2. Temperature model

75 The shallow underground temperature regime is mostly determined by the air temperature. The

76 unsaturated zone is the first part of the subsurface to be reached by an external input. The

77 temperature of this zone can be described using a 1D heat diffusion model for a semi-infinite

78 solid if approximations are made, i.e., a homogeneous medium with no vertical water movement.

79 Water input due to infiltration from the ground surface can be considered negligible in a heat

80　transfer process because it is of short duration in well-drained sites (Taylor & Stefan 2009). The

81　solution to the diffusion model, provided by Banks (2008), among others, consists of

82　temperature variations with time and space around the average ground temperature $T_m$. This

83　value represents the topmost boundary value, and it is transient because the air temperature is

84　subject to daily and seasonal variation. $T_m$ is difficult to determine since it depends on the way

85　the air temperature is transmitted in the topmost soil. The $T_m$ is generally higher than the air

86　temperature (Stauffer et al. 2013), but measurements of this parameter are very infrequent;

87　hence, the air temperature is commonly used as the approximate temperature at the ground

88　surface. The subsurface temperature variations mainly depend on the amplitude of the

89　temperature oscillation at the ground surface, which depends on the local climate and land cover

90　conditions. Furthermore, an exponential term gives the decay of temperature fluctuation with

91　depth, and a cosine term provides the cyclicity of the increasing time lag with depth. In general,

92　these variations show that more oscillation penetrates into the ground during longer

93　temperature cycles, but the amplitude is gradually damped with depth by the heat dissipation

94　within the geologic medium. For instance, Silliman and Booth (1993) reported that the

95　amplitude of the temperature is not significantly affected by diurnal fluctuations at the ground

96　surface below 1.5 metres.

97　The depth interval affected by external temperature oscillations can be designated as the

98　"surficial zone", and it precedes the so-called "geothermal zone" in which a constant increase in

99　temperature occurs due to the geothermal gradient (Anderson 2005).

100　Physical processes become more complex when surface seasonal inputs reach the shallow

101　groundwater and a 2-layer model better describes the temperature distribution (Taylor & Stefan

102　2009). The thermal conductivity is enhanced because the pores and fractures are now filled,

103　replacing air and giving continuity to the geologic medium. At the same time, the high heat

104　capacity of the water causes a reduction of the heat diffusivity. In aquifers with high

105　permeability, the flow velocity of the water in the porous medium, the inertial effects and

106 eventual turbulence increase the apparent thermal diffusivity until it is orders of magnitude

107 greater than the molecular thermal diffusivity (Taylor & Stephan 2009). This phenomenon

108 results in an increased rate of heat transport due to the hydrodynamic effects of the horizontal

109 and vertical water movements. Such phenomena lead to temperature distortions below the

110 surficial zone and above the geothermal zone. Alterations in the thermal regime can be traced by

111 borehole temperature measurements in recharge and discharge sectors as concave or convex

112 profiles, respectively (Taniguchi 1999; Anderson 2005). Multi-temporal borehole measurements

113 in very shallow aquifers are useful to assess cyclical temperature variations. Generally, these

114 observations lead to flower-shaped profiles followed by constant temperature values. Taniguchi

115 (1993), among others, provides type-curves for assessing the recharge and discharge regime

116 depending on whether it has an elongated or compressed shape. The constant temperature

117 below the surficial zone with seasonal oscillations is usually 1 to 2°C higher than the average

118 annual temperature at the ground surface (Anderson 2005).

119 However, the groundwater temperature can be assumed as relatively constant throughout the

120 year in comparison with the seasonal air oscillations typically recorded in a medium temperate

121 climate of Europe. Consequently, most part of aquifers can be used as low enthalpy geothermal

122 reservoirs, compensating for the daily and seasonal delay between need and supply of heat and

123 cold (Rybach & Eugster 2010).

124 The amplitude of the temperature oscillation in aquifers strictly depends on the local climate

125 and land use, as previously shown. The shallow groundwater is thus necessarily affected by

126 anthropogenic factors at various scales. The most evident thermal footprints occur beneath

127 urban areas because local climate conditions, land use changes and artificial heat sources are

128 concentrated there. Temperature increases of several degrees have been recorded in the urban

129 subsurface all over the world, including in Asian megacities (Taniguchi et al. 2007; Zhu e al.

130 2010) as well as German (Menberg et al. 2013) and Finnish cities (Arola & Korkka-Niemi 2014).

131 The primary cause has been identified as the replacement of natural land cover by artificial

5

surfaces and heat loss from buildings. The magnitude of the temperature increase due to
anthropogenic land use varies depending on the type and density of the heat source. For
instance, Taylor and Stefan (2009) observed increments of up to 3°C linked to isolated roads.
Menberg et al. (2013) expressed the urban heat island intensity as the difference between rural
and urban areas, finding values between 1.9°C and 2.4°C in some German cities. However,
warmer temperatures indicated by borehole measurements have also been linked to global
warming (Taniguchi et al. 2007, Bayer et al. 2016). A specific analysis of past climate signals is
required to distinguish the two overlapping phenomena.

A synthetic scheme has been reported (Fig. 1) to summarize those anthropogenic heat sources
that are expected to occur in the investigated area to discuss them along with the results. The
idea of a schematic conceptual model of heat sources that affect the groundwater temperature in
an urban area was first contributed by Menberg et al. (2013) and further elaborated by Benz et
al. (2015). Since the Turin area includes both rural and urban sectors, the sketch includes the
most representative heat sources for both land use types. Point, linear and areal sources can be
distinguished using geometrical criteria. In rural areas (left side of Fig. 1), natural land use
prevails, even though some anthropogenic sources with both areal and linear geometry can be
found, such as irrigation and canals (1). In this case, the input can be either colder or warmer
depending on the type of water source (river, aquifer, etc.) and on the cultivation. Point sources
are those elements that have small dimensions, for example, sewage systems (2) and isolated
buildings or roads in remote areas (3), landfills (4), industrial sites (5), and wells for thermal
wastewater reinjection such as geothermal wells (6). Linear sources include many types of
underground infrastructures such as sewage systems or district heating networks (7) and
railway and road tunnels (8). Benz et al. (2015) provide evidence that sewage systems play a
dual role in higher ground and groundwater temperatures, as exemplified by the heat loss from
pipe walls and warm water leakage from damaged pipes. Areal sources are large built-up areas
(9), where the previously mentioned point and linear sources (roads, buildings, sewage systems,

6

158 etc.) occur at high density and extension and, for instance, heat losses derived from elevated

159 ground surface temperatures caused by interconnected asphalt and paved surfaces.

160

## 3. Study area

### 3.1. Climatic context

163 The area investigated is located in NW Italy and includes both the narrow sector of the western

164 Po Plain between the Western Alps (W) and Turin Hill (E) and the internal plain sector of the

165 Ivrea Morainic Amphitheatre (Fig. 2). At the regional level, the climate is determined by an

166 orographic component rather than by latitude because of the presence of the Alps and the small

167 latitudinal development of the region (Agenzia Regionale per la Protezione Ambientale 2007).

168 Air temperatures show a regular decrease with elevation and are sporadically changed by local

169 conditions such as urban areas or valley floors. In plain areas, the average annual temperature is

170 between 10°C and 12.5°C, with higher average monthly values in autumn than in spring.

171 Temperatures are also subject to the effects of global climate change. An analysis of a historical

172 climate series (Cortemiglia 1999) shows an increase of 0.8°C per century in the plain areas of the

173 Piedmont region. The average annual value increased from 12.5°C to 13.7°C during the periods

174 of 1870-2010 and 1971-2010 (Garzena et al. 2014). Furthermore, in the Turin area, the air

175 temperatures in the city were higher than in surrounding rural area throughout the 20th

176 century because of an urban heat island phenomenon (Oke 1995, Voogt 2004). Such a rise in

177 temperature over the last 150 years is likely to be caused by the vigorous expansion of the city.

178 The increase in the number of inhabitants and vehicles in Turin city are among the largest and

179 are responsible for the urban air warming according to Garzena et al. (2014).

180

### 3.2. Geological and hydrogeological context

182 A synthetic geo-hydrological map (Fig. 2) depicts the main lithological features of the area,

183 which include the metamorphic rocks of Western Alps (1), Tertiary marine and transitional

7

184 deposits (2), and Quaternary glacial deposits (3) that form morainic amphitheatres at the outlets

185 of main Alpine valleys. The metamorphic rocks and Tertiary deposits merge underneath the Po

186 Plain sediments, forming a weakly permeable bedrock. Transitional to marine units deposited in

187 the Pliocene and early Pleistocene are found above the bedrock and consist of silty-clayey levels

188 interbedded with sands and gravels. The Po Plain was formed by Quaternary outwash and

189 fluvial units (4) consisting of heterogeneous sediments, mainly sands and gravels with

190 subordinated silty and clayey levels (Festa et al. 2009; Forno et al. 2009; Irace et al. 2009). The

191 oldest sediments are discontinuously distributed and include highly weathered soils, while the

192 youngest sediments are ubiquitous and less altered. The distribution of the Quaternary units is

193 linked with the morphology of the Po Plain, which has been conventionally divided into two

194 sectors known as the high and the low plains. The high plain is located at the uppermost

195 elevations near the Alps and was formed by the oldest sediments (middle Pleistocene), while the

196 low plain is located topographically at lower elevations and comprises late Quaternary and

197 Holocene deposits.

198 From a hydrogeological point of view, the sediments of the Po Plain represent a continuous

199 highly permeable porous medium that hosts many groundwater systems. Conventionally, one

200 shallow and various deep aquifers have been described (Bortolami et al. 1988; Bove et al. 2005;

201 De Luca et al. 2014). The deeper aquifers are hosted in the sandy intercalations of transitional

202 and marine deposits found below the continental units. They are multi-layered, and their

203 groundwater circulation is confined to the sandy levels. The recharge of the deep aquifers occurs

204 in the high plain sectors, where the units outcrop or the low permeable intercalations have

205 limited spatial continuity and thickness. Early Pleistocene sediments with low permeability

206 vertically separate the deep and the shallow groundwater systems. The shallow aquifer is hosted

207 in late Pleistocene and Holocene units and it is mostly unconfined. The shallow aquifer is

208 supplied by the infiltration of rainfall and secondarily by rivers in the high plain sectors. The low

209 plain sectors are generally discharge areas and the Po River represents the main regional

8

210  discharge axis for the groundwater flow (Debernardi et al. 2008; Lasagna et al. 2016a, b). The

211  regional flow is thus directed from the Alps towards SE-E-NE (Fig. 3). The water table generally

212  follows the topographic surface trend, and its depth varies between 1 and 50 metres, with

213  minima in the high plain sectors. The hydraulic gradient varies between 0.1 and 3% with higher

214  values in high plain sectors.

215

### 3.3. Geothermal context

217  The geothermal manifestations in the Piedmont region are limited to sporadic cases of

218  hydrothermal circuits with local significance in the SE (Acqui Terme, see for example Pasquale et

219  al. 2011) and the SW Piedmont (Vinadio and Valdieri, see Perello et al. 2001 and Baietto et al.

220  2008). The most promising and easily accessible reservoir of low enthalpy heat is currently

221  represented by the Po Plain (Lo Russo et al. 2015). Both shallow and deep aquifers may be

222  exploited within the typical depths of low enthalpy geothermal systems, according to the

223  previously described lithostratigraphic setting. Closed systems cross both the shallow and the

224  deep aquifers, while open systems are mostly associated with shallow aquifers. The use of deep

225  aquifers is protected by regional regulations, which restrict deep groundwater withdrawal only

226  for human consumption and limit drillings that cross two aquifers. Hence, the focus of the many

227  geothermal investigations has been on the shallow aquifer. Recent studies (Stringari et al. 2010)

228  assessed the shallow aquifer temperatures in the Po Plain at regional scale. The average annual

229  the groundwater temperature is approximately 14°C, but lateral variability reaches several

230  degrees Celsius. A positive temperature gradient occurs from the SW to the NE Piedmont along

231  the regional groundwater flow direction and locally from the high plain to the low plain sectors.

232  Such lateral temperature variations have been attributed to both regional climatic trends and

233  hydrogeological features, including the heat conduction from the ground surface in

234  progressively warmer climatic conditions and the thermal equilibration of colder rainfall waters

9

235 infiltrating recharge areas (high plain) with warmer subsurface along the groundwater flow

236 path towards the Po River.

237

## 4. Methods

239 One of the most common techniques in thermal groundwater characterization at both shallow

240 and deep depths (Taniguchi 1993; Taniguchi et al. 1999) is the downhole thermal log. It can be

241 performed by automatic acquisition or manually, for example, by thermal resistances equipped

242 with wires of the proper length (Barbero et al. 2016). In this study, the groundwater

243 temperatures were collected in two surveys, one performed in spring and one performed in

244 autumn, that consisted of downhole thermal logs performed manually. Temperature values were

245 recorded throughout the entire water column by an electronic water level metre equipped with

246 a thermometer (0.01 m and 0.1°C sensitivity). In the spring survey, 40 monitoring points were

247 used, and 30 wells were used in the autumn survey; most of them were managed by the regional

248 Environmental Protection Agency (ARPA). Since Turin city lacks ARPA monitoring wells,

249 supplementary points owned by private authorities were included in the measurements (Table

250 1). The depths of the wells ranged between 8 and 50 metres and were screened exclusively in

251 the shallow aquifer. The following two classes of land use were distinguished: rural and city. The

252 city type included the wells within the municipal boundaries of Turin, and the rural type

253 encompassed the remaining areas.

**Table 1** Information about monitoring the well design, site features and the groundwater temperature data. The latter are divided into S (the spring survey) and A (the autumn survey). (*Well top temperatures are meant to be the first useful measurement, namely 1 m below the groundwater level.)

| Code | Land use | Elevation | Depth | Screens penetrating the whole water column | Groundwater level | | Saturated thickness | | Well top temperature* | | Well bottom temperature | | Temperature difference within water column (Ttop - Tbottom) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | S | A | S | A | S | A | S | A | S | A |
| | | (m a.s.l.) | (m b.g.l.) | | (m b.g.l.) | (m b.g.l.) | (m) | (m) | (°C) | (°C) | (°C) | (°C) | (°C) | (°C) |
| Arpa P43 | rural | 229 | 23 | No | 3.56 | 3.98 | 19.44 | 19.02 | 13.5 | 14.2 | 12 | 13.1 | 1.6 | 2.9 |
| Arpa P42 | rural | 254 | 25 | No | 5.50 | 6.65 | 19.5 | 18.35 | 13.5 | 13.5 | 12.3 | 12.3 | 1.7 | 2.1 |
| Arpa P45 | rural | 384 | 42 | No | 23.57 | | 18.43 | | 13.5 | | 13.4 | | 0.2 | |
| Arpa P24 | rural | 301 | 35 | Yes | 24.05 | 22.95 | 10.95 | 12.05 | 14.0 | 14.1 | 13.6 | 13.7 | 0.6 | 0.6 |
| Arpa P38 | rural | 259 | 50 | Yes | 47.22 | | 2.78 | | 13.2 | | 13.2 | | 0 | |
| Arpa P20 | rural | 237 | 20 | No | 2.38 | 3.01 | 17.62 | 16.99 | 13.7 | 16.0 | 14.4 | 14.5 | -1.7 | 4.2 |
| Arpa TF2 | rural | 233 | 15 | No | 5.70 | | 9.3 | | 13.7 | | 13.6 | | 0.1 | |
| Arpa P16 | rural | 238 | 25 | No | 5.45 | | 19.55 | | 15.3 | | 14.8 | | 0.6 | |
| Arpa PZ-SL6 | rural | 279 | 20 | No | 4.75 | 5.14 | 15.25 | 14.86 | 13.2 | 18.5 | 13.4 | 18.3 | -0.3 | 0.35 |
| Arpa P15 | rural | 299 | 30 | Yes | 22.67 | | 7.33 | | 12.4 | | 12.3 | | 0.1 | |

11

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arpa P3 | rural | 196 | 30 | No | 7.29 | | 22.71 | | 13.6 | 13.3 | 13.3 | | 0.4 | |
| Arpa PZ-SL3/1 | rural | 330 | 20 | Yes | 8.52 | 8.89 | 11.48 | 11.11 | 13.2 | 13.3 | 13.1 | 13 | 0.8 | 0.6 |
| Arpa P18 | rural | 275 | 30 | No | 25.87 | 25.91 | 4.13 | 4.09 | 13.8 | 13.9 | 13.7 | 13.8 | 0.1 | 0.1 |
| Arpa PZ-SL5/3 | rural | 274 | 20 | No | 13.57 | 15.07 | 6.43 | 4.93 | 13.8 | 14.1 | 13.8 | 14.15 | 0.1 | -0.05 |
| Arpa P19 | rural | 226 | 35 | No | 3.87 | 4.20 | 31.13 | 30.80 | 16.4 | 17.1 | 17.9 | 18 | -2.4 | -0.7 |
| Arpa PZ-SL1 | rural | 441 | 15 | No | 3.26 | | 11.74 | | 10.3 | | 12.3 | | -3.3 | |
| Arpa PZ-SL7/1 | rural | 252 | 20 | No | 3.36 | | 16.64 | | 12.8 | | 13.6 | | -2.4 | |
| PZC1 | rural | 225 | 30 | Yes | 4.49 | 4.87 | 25.51 | 25.13 | 15.2 | 16.4 | 15 | 14.9 | 0.1 | 2.3 |
| PZ10 | rural | 247 | 8 | Not known | 0.95 | 1.20 | 7.05 | 6.80 | 12.0 | 15.4 | 13.7 | 14 | -2.9 | 2.2 |
| Orbassano P1 | rural | 262 | 23.5 | Not known | 11.04 | 11.68 | 12.46 | 11.82 | 14.5 | 14.4 | 13.9 | 14 | 0.9 | 0.5 |
| Arpa P10 | rural | 274 | 25 | Yes | 14.16 | 12.15 | 10.84 | 12.85 | 13.1 | 14.3 | 12.7 | 14 | 0.7 | 0.4 |
| Arpa P22 | rural | 238 | 15 | No | 0.00 | 1.12 | 15 | 13.88 | 14.7 | 14.7 | 14.7 | 14.6 | -3.1 | 5.4 |
| Arpa P21 | rural | 266 | 20 | No | 2.67 | 3.65 | 17.33 | 16.35 | 12.3 | 15.3 | 13 | 13.5 | -1.7 | 3.1 |
| Arpa P37 | rural | 208 | 22.5 | Yes | 19.39 | | 3.11 | | 12.1 | | 12.2 | | -0.1 | |
| Arpa PZ-SL4 | rural | 319 | 20 | No | 1.41 | | 18.59 | | 13.0 | | 13.9 | | -1.8 | |
| Arpa P17 | rural | 258 | 14 | No | 1.12 | 1.95 | 12.88 | 12.05 | 13.3 | 15.9 | 13.3 | 13.3 | -2.7 | 4.8 |
| Arpa P44 | rural | 232 | 25 | No | 7.50 | 7.82 | 17.5 | 17.18 | 13.6 | 13.4 | 13.4 | 13.4 | 0.3 | -0.1 |
| S nuovo | city | 223 | 13 | Not known | 5.51 | 4.86 | 7.49 | 8.14 | 14.8 | 16.6 | 15.5 | 15.2 | -1.4 | 2.5 |
| PZ N1 | city | 224 | 15 | Not known | 6.36 | 6.60 | 8.64 | 8.40 | 15.7 | 15.7 | 15.8 | 15.7 | -0.2 | -0.1 |
| Arpa SI2 | city | 218 | 20 | Yes | 7.66 | 7.92 | 12.34 | 12.08 | 15.7 | 15.6 | 15.8 | 15.2 | -0.3 | 0.5 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PZ B3 | city | 257 | 35 | Not known | 26.31 | 26.55 | 8.69 | 8.45 | 15.1 | 14.9 | 15 | 14.9 | 0.1 | 0.05 |
| GTT PM2 | city | 270 | 40 | Yes | 33.79 | 33.91 | 6.21 | 6.09 | 14.3 | 14.2 | 14.2 | 14.2 | 0.1 | 0.1 |
| PZ34 | city | 240 | 40 | No | 17.42 | | 22.58 | | 19.7 | | 15.5 | | 7.8 | |
| PZ50 | city | 265 | 40 | Yes | 18.21 | 18.39 | 21.79 | 21.61 | 14.7 | 14.7 | 14.5 | 14.5 | 0.4 | 0.5 |
| Arpa P26 | city | 247 | 42 | No | 21.49 | 21.80 | 20.71 | 20.40 | 14.9 | 14.9 | 14.8 | 14.9 | 0.2 | 0 |
| PZ55 | city | 270 | 45 | Yes | 38.22 | 38.34 | 6.78 | 6.66 | 14.2 | 14.2 | 14.1 | 14 | 0.1 | 0.2 |
| Arpa P30 | rural | 263 | 35 | No | 15.72 | 16.47 | 19.28 | 18.53 | 14.5 | 14.3 | 14.5 | 14.25 | 0 | 0.05 |
| Arpa SI5 | rural | 177 | 20 | Yes | 9.65 | | 10.35 | | 14.6 | | 14.4 | | 0.3 | |
| Arpa PZ-SL2 | rural | 380 | 20 | No | 2.95 | | 17.05 | | 9.0 | | 9.2 | | -0.4 | |
| Villarbasse P1 | rural | 337 | 14 | Not known | 10.18 | 10.64 | 3.82 | 3.36 | 12.8 | 12.7 | 12.7 | 12.6 | 0.1 | 0.2 |
| Arpa P7 | rural | 246 | 15 | No | 2.05 | 2.38 | 12.95 | 12.62 | 12.3 | 13.1 | 12.8 | 12.8 | -1.4 | 2.8 |
| Arpa P34 | rural | 218 | 20 | No | 3.12 | 4.08 | 16.88 | 15.92 | 11.3 | 13.9 | 12.2 | 15.7 | -2 | 1.6 |
| | | | | | | | | | | | | | | |
| Mean | | | 25.53 | | | | | | | | 13.8 | 14.4 | | |
| City mean | | | | | | | | | | | 15.0 | 14.8 | | |
| Rural mean | | | | | | | | | | | 13.4 | 14.2 | | |

13

## 5. Results and discussion

The vertical distribution of the groundwater temperatures assessed by the thermal logs shows lower values in the shallow portions and a gradual increase in the spring measurements (Fig. 3). Conversely the values are higher in the first few metres and decrease with depth in autumn (Fig. 4). This vertical temperature variability is compatible with the heating and cooling cycles of the ground temperatures due to seasonal variation. According to the previously described heat transfer processes, the external daily and seasonal fluctuations are damped in the subsurface by the heat dissipation occurring in the unsaturated zone and in the shallow portions of aquifers. In the shallow wells, the temperature variations disappear within 10-20 metres below the ground surface. In the deeper wells (<20 m), the temperature variations are smaller. In the shallow wells, the attenuation occurs in the aquifer, enhanced by the groundwater flow. In the deeper boreholes, the inputs from the ground surface are dissipated into the unsaturated zone above the groundwater table. This phenomenon was confirmed by the good correlation between the depth to the groundwater and the temperature difference along the water column (Fig. 5). The plot also shows that the decrease in the temperature difference is particularly rapid at <10 m the groundwater level depth.

In both the spring and autumn logs, the deeper portions of the aquifer show small temperature oscillations and a constant value ranging between 12°C and 15°C is reached in most wells, which is compatible with the presence of the groundwater flow in the aquifer, as reported in Taniguchi's (1993) shallow borehole thermal logs. Recent studies on the groundwater temperatures in the Piedmont Po Plain (Stringari et al. 2010; Barbero et al. 2016) suggest that in the shallow alluvial aquifer, a homoeothermic surface to distinguish where the groundwater temperatures are constant in time should be defined, that is, where the daily and seasonal oscillations are no longer evident. The homoeothermic volume is the aquifer volume below the homoeothermic surface and above the geothermal zone in which the geothermal gradient causes a temperature rise. The homoeothermic surface for the whole Piedmont Po Plain ranges

14

27 between 20 and 25 metres b.g.l. according to Barbero et al. (2014), and this range is compatible

28 with the analysis of the thermal logs reported in this study (Fig. 3 and Fig. 4).

29 The vertical variations in the aquifer were considered before extracting a single temperature

30 value for each well. For this purpose, the well bottom measurements were considered as

31 representative of the aquifer temperature. The values were between 9.2°C and 17.9°C in spring

32 and between 12.3°C and 18.3°C in autumn (Table 1). The well top measurement of each log was

33 used to compute the difference along the entire water column (Table 1). Negative values (i.e.,

34 colder temperatures in the uppermost part of the aquifer) correspond to the spring logs

35 according to the shape of thermal logs described above. Conversely, the values are mostly

36 positive in the autumn logs because shallow temperatures are warmer. The overall temperature

37 variation range in the monitored wells in both surveys is between -2.9°C and +5.4°C (excluding

38 one outlier in the spring survey, which will be clarified later).

39 The bottom temperature measurements extracted from thermal logs were plotted on maps to

40 distinguish lateral variations of the aquifer temperature excluding the seasonal temperature

41 variations. The spring temperature values (Fig. 7) mostly lay in the interval of 12°C-14°C in rural

42 areas. Some cold outliers below this range were found N of Turin city in the high plain sectors

43 close to the Alps. In Turin city, the aquifer temperatures were generally higher (14°C-16°C),

44 while the three easternmost wells had intermediate values (14°C-15°C). In the autumn survey

45 (Fig. 8), the spatial distribution was approximately the same, with occasional warmer values.

46 The average values across the investigated area were 13.8°C and 14.4°C in spring and autumn,

47 respectively, and reflected minor variations between the two surveys. These temperatures were

48 very close to the average annual air temperatures recorded in the Piedmont Po Plain, according

49 to the aforementioned climatic features. Temperatures gradually increased from the high plain

50 sectors close to the Alps towards the Po River, which matched the main groundwater flow

51 direction. Colder aquifer temperatures in the high plain sectors reflected the colder top soil

52 temperatures occurring in the sectors close to the Alps well, due to the cooling of the air with an

15

53 increase in the topographic elevation. This effect was confirmed by the correlation between the

54 groundwater temperatures and the well elevation (Fig. 6). This groundwater warming along the

55 flow path was found by several basin-wide studies. Stringari et al. (2010) found this trend in the

56 Piedmont Po Plain, as described in section 3.2. Burns et al. (2016) found a similar increase in the

57 land surface and the groundwater temperatures along the Eastern Snake River Plain aquifer (SE

58 Idaho, US). The same authors also reported that the thickness of the unsaturated zone had the

59 primary effect of insulating the aquifer from the land surface. A similar observation is also valid

60 for the Turin Po Plain in the present study: wells with a deeper groundwater level have

61 narrower temperature oscillations (Fig. 5; Fig. 7; Fig. 8). Cooler groundwater in the high plain

62 sectors may also be partially determined by inputs from surface hydrology; in the high plain

63 sectors, the rivers and streams generally feed the aquifer, while in the discharge areas, the

64 aquifer is drained by the rivers. The different hydrogeological role of the respective recharge

65 and discharge areas of the high and low plain sectors of the Turin Po Plain is not still clear. The

66 role of recharge and discharge sectors was reported to have major importance in determining

67 the shape of the thermal logs of the shallow aquifer in the Nagaoka area by Taniguchi (1993). In

68 the present study, such a distinction would benefit from a comparison of the temperature logs

69 derived from the two distinct hydrogeological areas.

70 The high concentration of warm temperatures below Turin city is likely linked to the presence of

71 the large urbanized area. A rough estimate of the intensity of the groundwater warming below

72 the city was made by comparing the urban and rural bottom well (i.e., undisturbed)

73 temperatures (Table 1). The results showed warmer average temperatures in the city

74 monitoring wells of +1.6°C and +0.6°C in spring and autumn measurements, respectively. The

75 difference between the two surveys may be affected by extrinsic factors, such as the smaller

76 number of points considered in the second survey. More than one phenomenon acting

77 simultaneously in the urban areas may cause groundwater warming, i.e., global warming and the

78 urban heat island effect. In Turin city, an urban heat island effect in the air (see Paragraph 3.1)

16

79 likely affected the temperature of the shallow aquifer. The magnitude of the urban air warming

80 during recent decades was similar to the warming in the aquifer. In addition, a long climate

81 series analysis indicates that global climate change exists (see Paragraph 3). Unfortunately,

82 deeper borehole temperatures are not available to distinguish past climate signals in the

83 groundwater; it can only be stated that further studies should take into account its recent

84 transitory behaviour. Indeed, Garzena et al. (2014) found that during 1992-2009, the urban heat

85 island decreased in intensity, as evidenced by the relatively constant average annual air

86 temperature in Turin city; however, it increased in rural areas. Another type of heat source with

87 a linear geometry is expected to have an effect on a city scale: old and largely damaged

88 wastewater networks are distributed across the subsurface of Turin, and extensive leakage is

89 expected to be found.

90 Most wells have been drilled close to roads, squares and buildings. Paved and asphalt surfaces

91 modify the porosity and reflectivity of the natural soil, causing an enhancement of heat

92 accumulation at the ground surface (Taylor & Stefan 2009), while buildings increase the

93 temperature of the surrounding subsurface via their foundations, basements or underground

94 car boxes (Menberg et al. 2013). Local warming due to artificial land use is thus expected to

95 contribute in both rural and urban areas. However, the longer history and larger size of Turin

96 city make this phenomenon much more intense with respect to the surrounding urban centres.

97 Sporadic outliers have been found that can scarcely be explained by the previously mentioned

98 phenomena. Positive local temperature anomalies are generally related to single point heat

99 sources, for example, industrial districts, power stations, and landfills, that can affect a small

100 subsurface volume. One of these points lies outside Turin city in the S sector (La Loggia) and has

101 a high temperature (>17°C). This anomalous warming is likely linked to the presence of an

102 industrial district that may be responsible for an abnormal heat flux from the buildings due to

103 the huge volumes of warm air inside and/or to industrial exothermic processes. Another outlier

104 is represented by a well in Turin city which showed anomalous temperatures (up to 23°C) in the

spring thermal log (Fig. 3). This anomaly is easily explained by the presence of a geothermal

system working in heat injection mode. Two outliers in the towns of Volpiano and Caselle

showed marked differences between the two surveys (3°C to 5°C, respectively). Such values

indicate that the seasonal effect was probably not completely excluded. Without prior

knowledge of localized heat sources, the limited depth of the groundwater and the presence of

large paved parking areas next to the monitoring point might have amplified the heat

accumulation during the warm months. Furthermore, the points at the southern boundary of

Turin city show higher temperatures (14°C-15°C range) compared with the points at the

northern side of the city. One of these points is located close to the town of Moncalieri. Since this

well is used for monitoring a polluted site, the exothermic decomposition of organic compounds

may have affected the temperatures of the subsoil and aquifer. This monitoring point should be

further investigated to better understand how the anthropogenic factors in the area, mainly at

the contaminated site and secondarily of the paved surfaces, may affect the thermal regime.

## 6. Conclusions

The scenario outlined shows that the regional climatic trend largely influences the thermal

regime of the shallow aquifer in the Turin area. A seasonal oscillation can be clearly recognized,

and it is rapidly damped in the shallow portions of subsurface. In addition, other factors also

play an important role, such as the recharge conditions and anthropogenic contributions. The

latter could be distinguished in the thermal regime of the shallow aquifer either as a diffuse

temperature increase due to Turin city or as local differences linked to local heat sources, such

as polluted sites, industrial districts, or geothermal systems.

However, the current thermal trend of the shallow aquifer in the Turin area shows a relatively

stable temperature, since the seasonal oscillations only affect the shallow portion of the aquifer.

This phenomenon, combined with high productivity, contributes to the creation of favourable

conditions for large-scale diffusion in the shallow aquifer for heat pumps coupled with the

18

groundwater (GWHPs). At present, the installation of GWHPs is limited; however, an increasing demand for domestic heating and cooling by means of this technology may lead to a rise in conflicts. The findings of this study would then represent a contribution for the future sustainable development of GWHPs in the Turin area. For instance, the heat surplus identified in the urban area could be used as a resource for building/district heating. This strategy should be accompanied by further efforts to gain new knowledge about the thermal features of shallow aquifers as affected by both local and regional factors, for instance, by extending the monitoring network to the Turin subsurface. New temperature data to better support site-specific interpretations may be collected and, once combined with hydraulic parameters such as saturated thickness, transmissivity and storage, could be used to compute the potential for GWHP exploitation in a sector such as an urban area. However, such large-scale characterization should not exclude a detailed site-specific assessment of hydrogeological and thermal properties for new installations.

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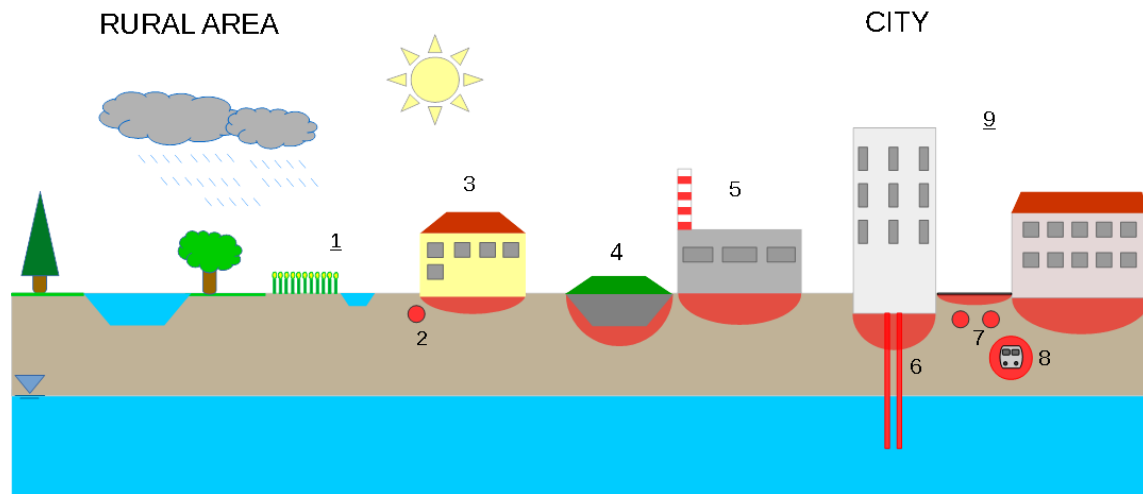
**Fig. 1** The ground surface anthropogenic inputs that affect the temperature in shallow aquifers in rural

and urban areas. Areal sources are distinguished by an underlined number.

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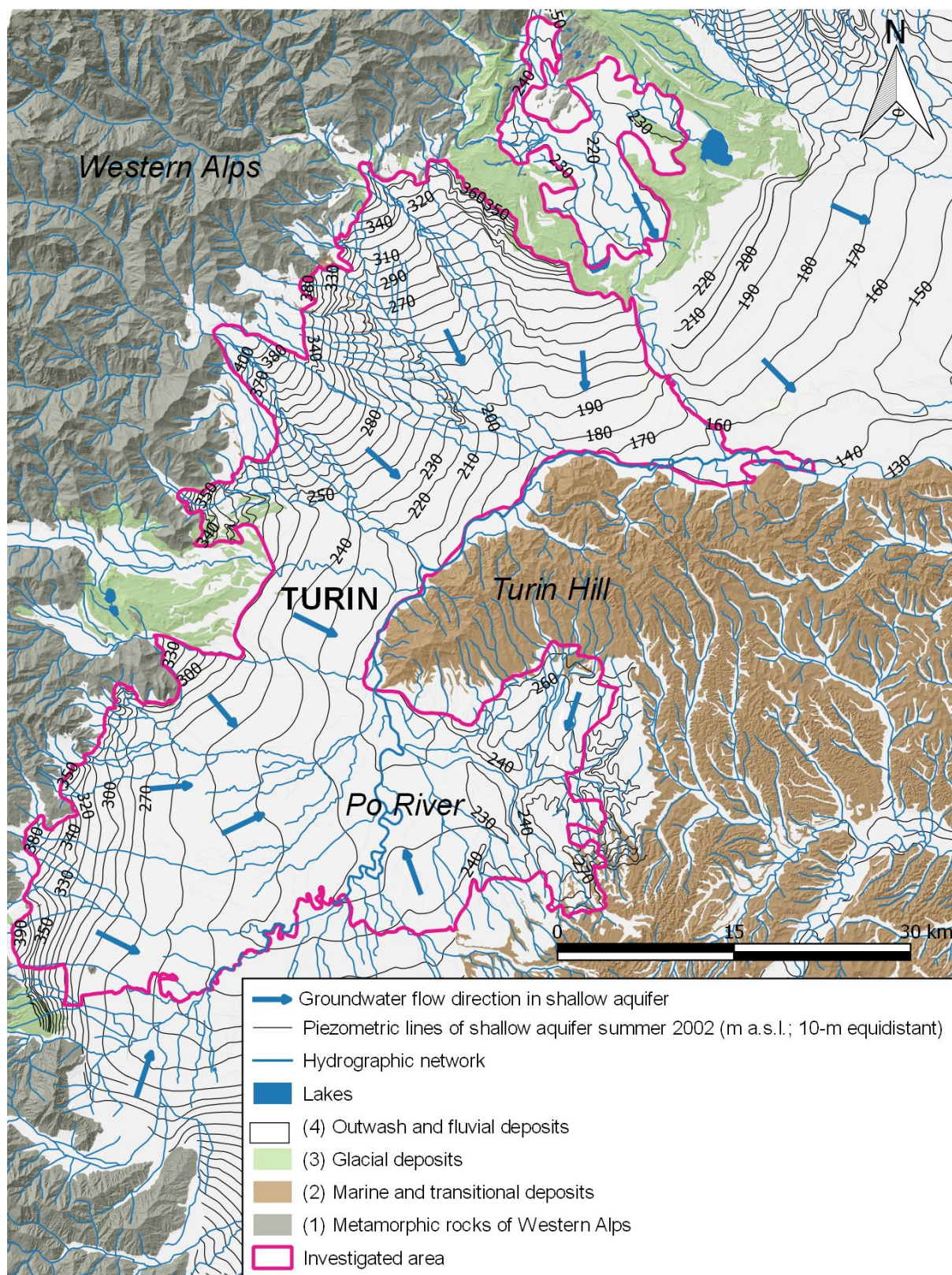
**Fig. 2** Geo-hydrological map of the area investigated.

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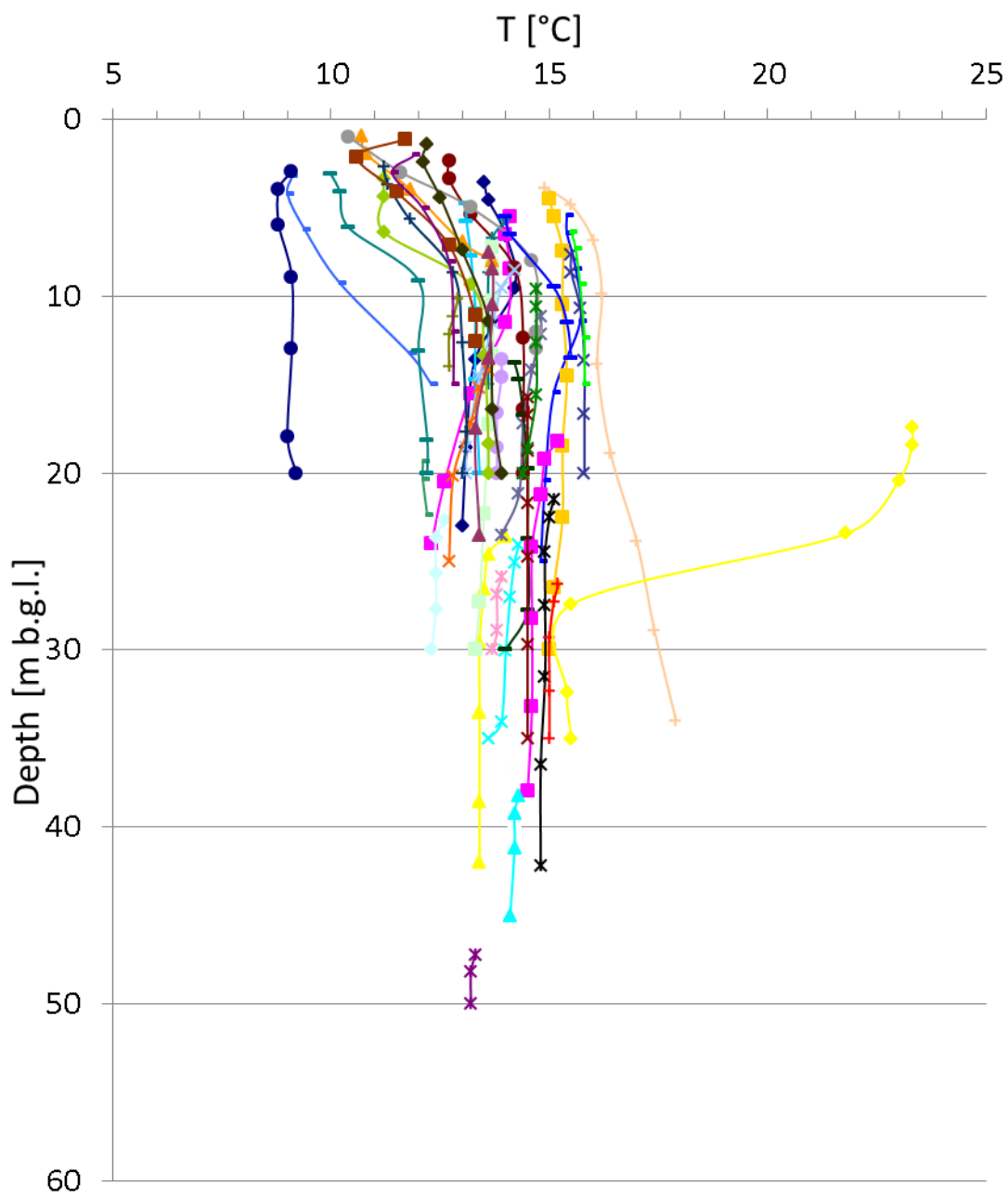


**Fig. 3** Temperature logs recorded in the spring of 2014.

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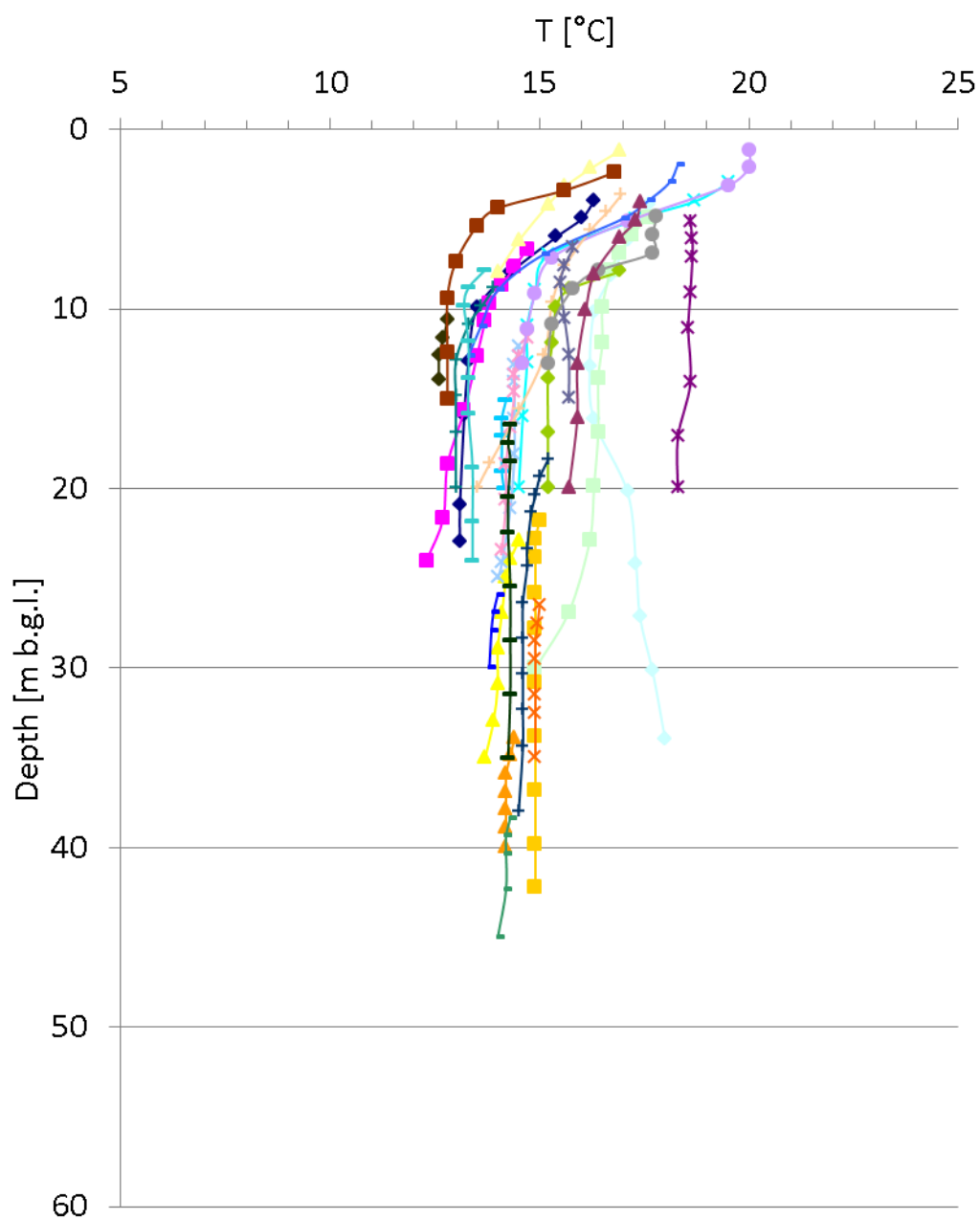


**Fig. 4** Temperature logs recorded in the autumn of 2014.

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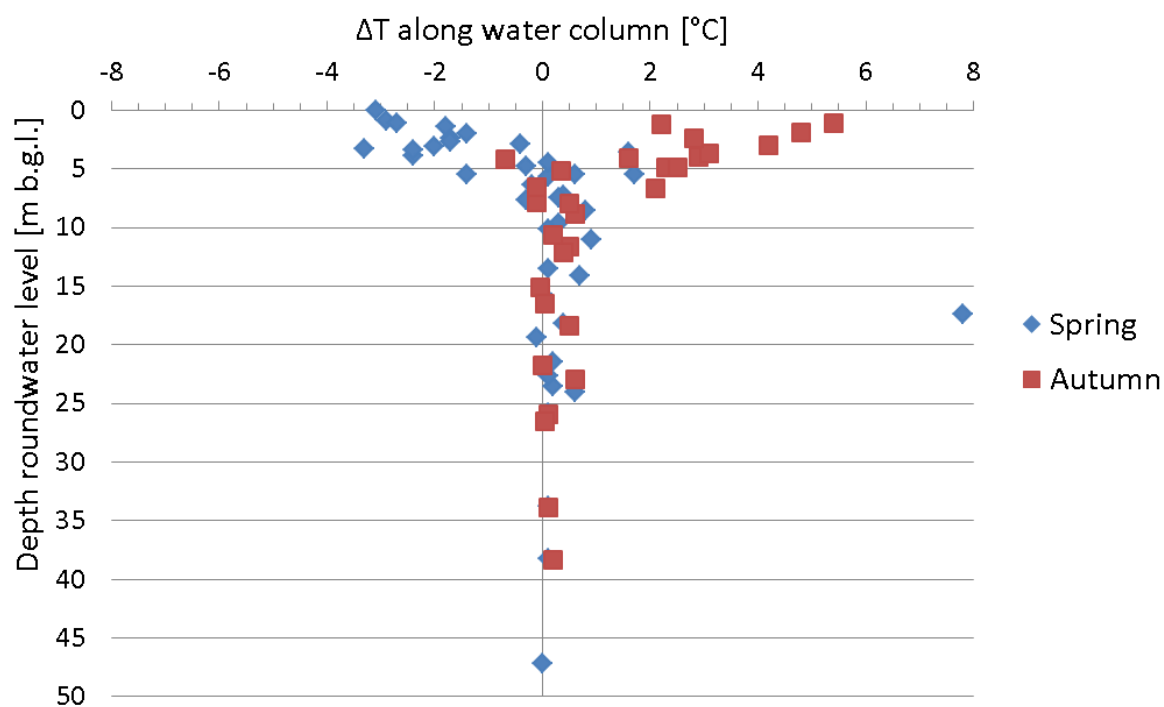
**Fig. 5** The groundwater temperature correlation with temperature difference along water columns in the
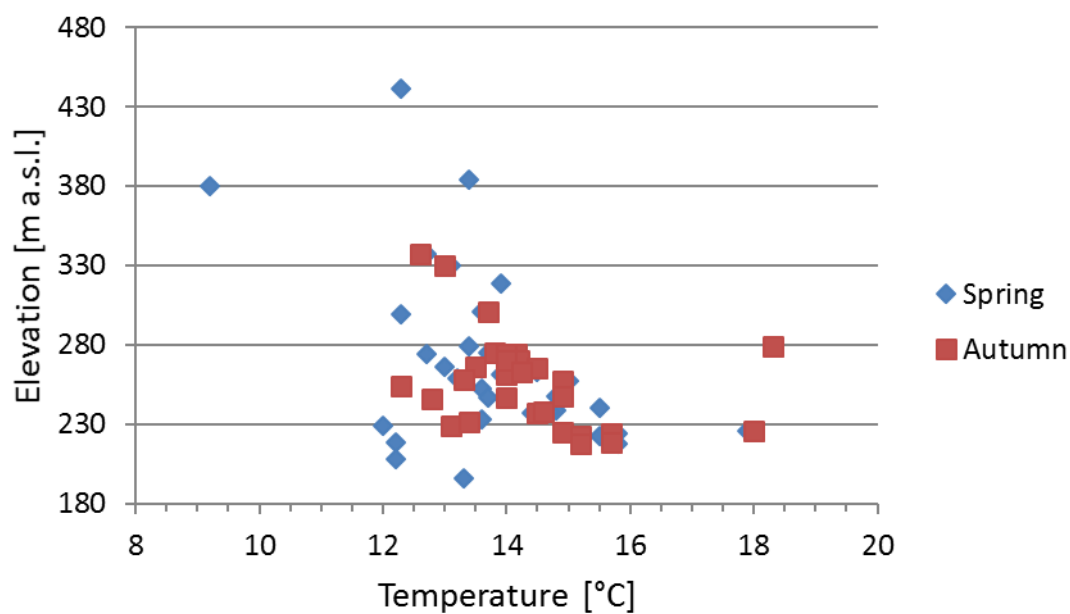
wells.

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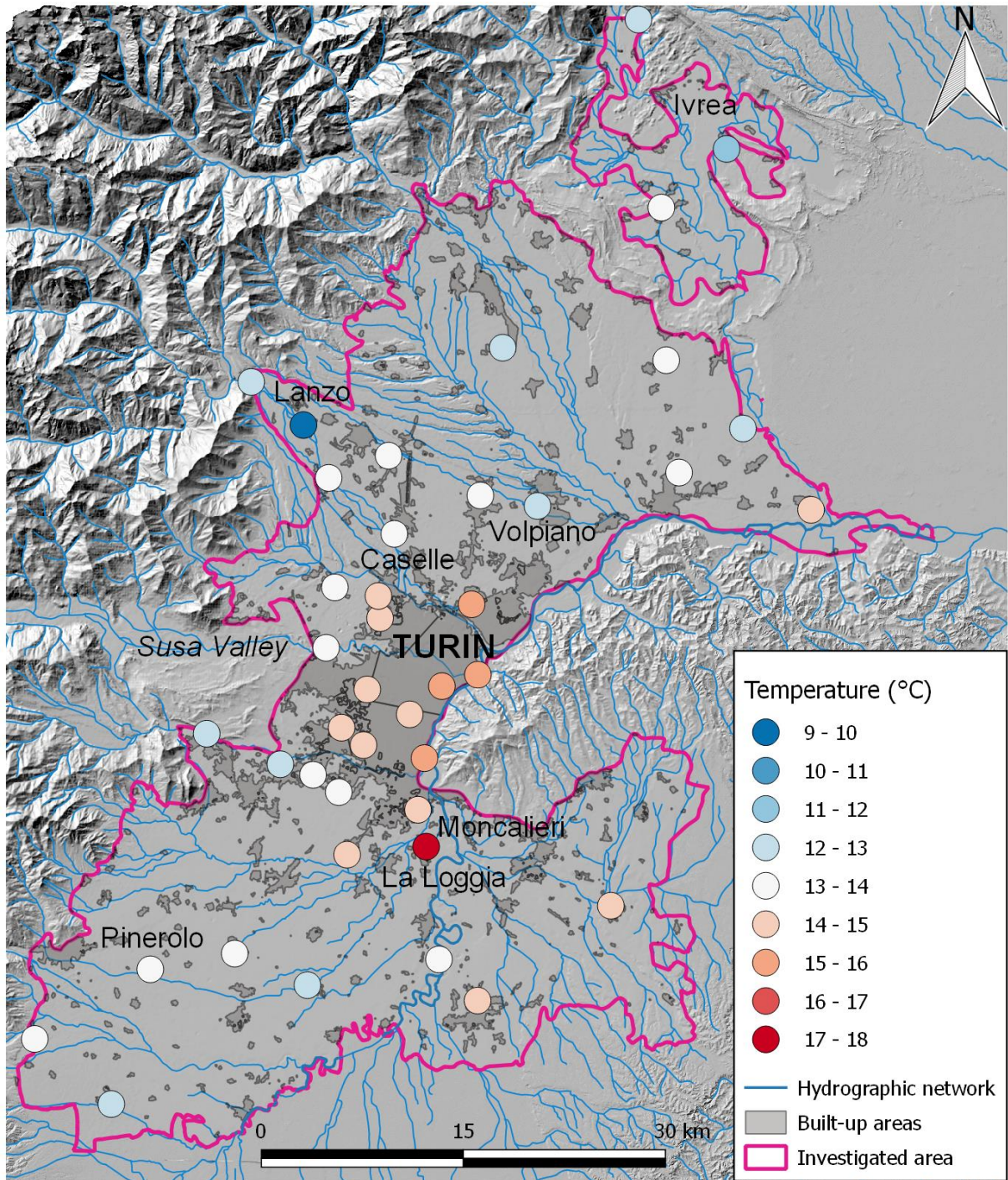328    **Fig. 6** The groundwater temperature correlation with well elevation.

**Fig. 7** Temperatures in the shallow aquifer in the spring of 2014. The plotted values refer to the well
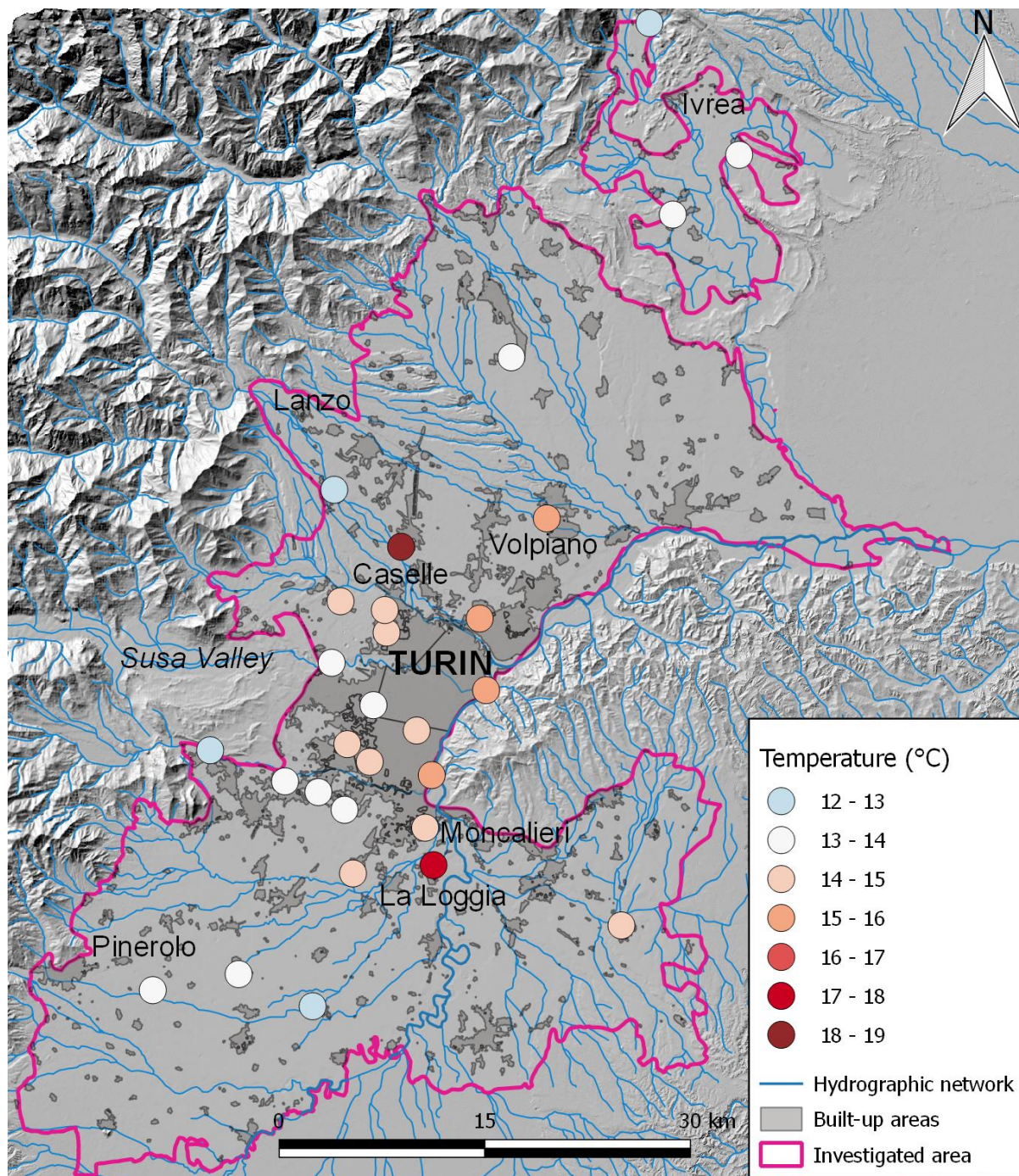
bottom temperatures.

**Fig. 8** Temperatures in the shallow aquifer in the autumn of 2014. The plotted values refer to the well

bottom temperatures.