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

Published version:

DOI:10.1007/s12665-017-6546-4

Urban groundwater warming in Turin area (NW Italy)

Arianna Bucci ([a]), Diego Barbero ([a]), Manuela Lasagna ([a]), M. Gabriella Forno ([a]),
Domenico Antonio De Luca ([a])

(a) Department of Earth Sciences, University of Turin, via Valperga Caluso, 35, 10125,
Turin, Italy. E-mail: arianna.bucci@unito.it

ABSTRACT

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

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

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

INTRODUCTION

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

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

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

STUDY AREA

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

Table 1

From a hydrogeological point of view, the Quaternary alluvial sediments of the Po Plain represent a continuous highly permeable porous medium that hosts many groundwater systems. Conventionally, one shallow and various deep aquifers have been described in Piedmont Region (Bortolami et al., 1988; Bove et al., 2005; De Luca et al., 2014; Lasagna and De Luca, 2017). The shallow aquifer, hosted in late Pleistocene and Holocene units, is mostly unconfined and supplied by the infiltration of rainfall and secondarily by rivers in the high plain sectors. Due to the mainly sandy–gravelly texture, many quarry activities are exploiting this complex (De Luca et al. 2007; Castagna et al. 2015a, 2015b). The maximum aquifer thickness is 50 m and the water table generally has depths between 1 and 50 metres below ground level, with minima located in the high plain sectors. In most of the wells (78%) the water table depth is found between 1 and 20 metres b.g.l. (Bucci et al., 2017). The low plain sectors, far from the Alpine chain, are generally discharge areas and the Po River represents the main regional discharge axis for the groundwater flow (Debernardi et al., 2008; Lasagna et al., 2016a, 2016b).

TEMPERATURE MODEL AND METHODS

The shallow subsurface temperature is mainly controlled by the temperature at the ground surface, which strictly depends on the local climate and on the land use conditions. The temperature temporal oscillation in the unsaturated zone, solved by a 1D heat diffusion model for a semi-infinite medium characterized by homogeneous properties and negligible vertical water movements (Banks, 2008; Taylor and Stephan, 2009), consists of an oscillating temperature around the average annual ground temperature. The fluctuations undergo a decay and an increasing time lag with depth. This means that longer temperature cycles -decades, centuries- are, the more they penetrate the subsurface, whereas the short cycles -days, months- but their amplitude is increasingly damped and lagged by the heat dissipation within the geologic medium. The heat transfer processes become more complex when the ground temperature inputs reach the groundwater: the flow of the water in the porous medium, the inertial effects and eventual turbulence enlarge the apparent thermal diffusivity until it reaches several orders of magnitude greater than the molecular thermal diffusivity (Taylor & Stephan 2009). This means an increased rate of heat transport due to hydrodynamic effects that are highlighted by distortions in borehole temperature logs.

The aquifer depth interval affected by temperature oscillations, known as the “surficial 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 have the following ranges: <10 m (2.4%), 10 to 20 m (42.9%) and >20 m (54.7%). According to the afore mentioned temperature model and to air temperatures, the maximum expected groundwater temperature below the surficial zone with climatic variations is between 12 and 14.5 °C in the Turin plain.

RESULTS AND DISCUSSION

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

Figure 1

Underneath the seasonal oscillation zone, groundwater temperatures are approximately constant in most wells, according to Barbero et al. (2016): in Fig. 1, below 10 m the residual changes (less than ± 1 °C) can be connected to other processes, such as advective heat transport within the aquifer. Deviations from constant temperature in the thermal profiles can be read as either upward or downward water movements, in recharge and discharge areas, or as lithological heterogeneities in areas with nearly horizontal flow. The groundwater temperature in Turin plain, averaged on spring and autumn values extracted from Bucci et al. (2017), is 14.1 °C, that is within the expected temperature range (see previous paragraph).

Lateral variations of aquifer temperature in autumn 2014 are displayed by plotting the bottom well temperatures, not affected by seasonal oscillations (Fig. 2), that were measured at the average depth of 25 m. There is a gradual groundwater warming from high plain sectors close to the Alps towards the Po River. This feature is consistent with the main groundwater flow direction, meaning that colder aquifer temperatures of recharge areas -due to colder air temperatures in high plain sectors- warm up during their pathway.

The second most evident feature is the high concentration of warm temperatures below the Turin city: compared to rural values, the urban aquifer is 14-16 °C and rural aquifer is 12-14 °C. More precisely, the urban warming intensity can be calculated with the difference between the average temperatures in the city area and rural area: in the Turin case in 2014 it is +1.6 °C in spring and +0.6 °C in autumn. This feature is likely linked to the groundwater warming caused by the large urbanized area of Turin: the extensive cover of roads and buildings warms up the land surface and then this heat is transferred to the underlying aquifer.

Figure 2

Sporadic high temperatures (>16 °C) have local significance and may be related to point heat sources. In the case of La Loggia observation well (Fig. 2), located few kilometres south of the Turin city, groundwater reaches a temperature of around 17 °C. In this case the groundwater heating is likely linked to the presence of an industrial district that may be responsible of intense heat fluxes due to the huge volumes of warm indoor air and/or to industrial exothermic processes. Other outliers are: a well in Turin city close to an open-loop geothermal system working in heat injection mode, which displayed temperatures up to 23 °C -not in figure- and the Caselle T.se observation well (N of Turin), which showed a high maximum temperature in autumn (18.6 °C) and a marked difference with the spring value (13.4 °C). Without any further knowledge on heat sources in the surroundings and lithological variations at the site, such behaviour may be related to a significant seasonal effect on groundwater: the small groundwater table depth (< 5 m) and the limited well depth (20 m) make the groundwater at that site largely influenced by the seasonal oscillations, even at the bottom of the observation well, where the plotted measurement was taken. Furthermore, the land use of both sites is constituted by large paved parking areas that might have amplified the heat accumulation during summer, with consequent high temperatures in autumn.

Fig. 3 and 4 show the typical urban thermal logs from the 2016 survey and their evolution in time. The 4 monitoring points (green dots in Fig. 2) were grouped in 3 sites: PZC1 and PZE6 (Site 1), are in the same site, a former illegal landfill; PZ3 A is in Turin city neighbourhood with early urbanization (Site 2); PZ34 is located in an industrial waste landfill (Site 3). Site 1 and 3 have less dense urbanization. The strongest vertical variability is evident in the wells of Site 1 with shallow water table depth, whereas in Site 2 and 3 the groundwater temperatures are approximately constant in depth because the water table is below 20 m b.g.l., where the seasonal effects are supposed not to influence the groundwater temperatures. The huge differences between PZC1 and PZE6 of Site 1 are mainly due to the position with respect to the landfill (PZC1 is downstream, PZE6 is upstream) and, secondarily, to the land use: PZC1 is drilled few centimetres far from an asphalted road, while PZE6 is some meters far from an unpaved road and around 10 m far from buildings. Overall, groundwater in PZC1 is overheated by the heat transported from the polluted sector, where exothermic reactions of organic matter degradation likely occur (the site has methane burners), and by the asphalted road that, according to previous studies (i.e. Taylor & Stefan, 2009), can increment the temperatures up to 3 to 4 °C.

Figure 3

Figure 4

CONCLUSIONS

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

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

ACKNOWLEDGMENTS

Most of the groundwater monitoring points were accessed thanks to the kind support of ARPA Piemonte. The authors are grateful to all the ARPA’s staff, as well as to all the private subjects and individuals who allowed to access the other monitoring wells.

REFERENCES

Alberti L., Antelmi M., Angelotti A., Formentin G. (2017) - Geothermal heat pumps for sustainable farm climatization and field irrigation. Agricultural Water Management 195:187-200.

Anderson M.P. (2005) - Heat as a ground water tracer. Ground Water, 43(6):951-968.

Baccino G., Lo Russo S, Taddia G, Verda V (2010) - Energy and environmental analysis of an open-loop ground-water heat pump system in an Urban area. Thermal Science 14(3):693-706.

ARPA (2007) Il Piemonte nel cambiamento climatico. Osservazioni passate, impatti presenti e strategie future. ARPA (Agenzia Regionale per la Protezione Ambientale) Piemonte, Torino

Balestro G., Spagnolo G., Lucchesi S., Fioraso G., Forno M. G., Cadoppi P., Tallone S., Piccardo G. B. & Polino R. (2009) - Foglio 155 “Torino Ovest”della Carta Geologica d'Italia alla scala 1:50.000. APAT, Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici - Dipartimento Difesa del Suolo, Roma.

Banks D. (2008) - An introduction to thermogeology: ground source heating and cooling. Blackwell, Oxford. 526 pp

Barbero D., De Luca D.A., Forno M.G., Lasagna M. (2016). Preliminary results on temperature distribution in the Quaternary fluvial and outwash deposits of the Piedmont Po Plain (NW Italy): a statistical approach. Rend. Online Soc. Geol. It., Vol. 41 (2016), pp. 272-275. doi: 10.3301/ROL.2016.146

Bayer P., Rivera J.A., Schweizer D., Schärli U., Blum P. (2016) - Extracting past atmospheric warming and urban heating effects from borehole temperature profiles. Geothermics 64:289-299.

Benz S.A., Bayer P., Menberg K., Jung S., Blum P. (2015) - Spatial resolution of anthropogenic heat fluxes into urban aquifers, STOTEN 524-525:427-439.

Bortolami G., De Luca D.A., Filippini G. (1988) - Caratteristiche geolitologiche e geoidrologiche della pianura torinese. In: Le acque sotterranee della pianura di Torino. Aspetti e problemi. Provincia di. Torino, M/SLit, Torino.

Bove A., Casaccio D., Destefanis E., De Luca D.A., Lasagna M., Masciocco L., Ossella L., Tonussi M. (2005) - Idrogeologia della pianura piemontese. Regione Piemonte, Torino.

Bucci A., Barbero D., Lasagna M., Forno M.G., De Luca D.A. (2017) - Shallow groundwater temperature in the Turin area (NW Italy): vertical distribution and anthropogenic effects. Environ. Earth Sci. 76:221. doi: 10.1007/s12665-017-6546-4

Burns E.R., Ingebritsen S.E., Manga M., Williams C.F. (2016) - Evaluating geothermal and hydrogeologic controls on regional groundwater temperature distribution. Water Resources Research 52:1328-1344.

Castagna S., Dino G.A., Lasagna M., De Luca D.A. (2015a) - Environmental issues connected to the quarry lakes and chance to reuse fine materials deriving from aggregate treatments. G. Lollino et al. (eds.), Engineering Geology for Society and Territory – Volume 5, Urban Geology, Sustainable Planning and Landscape Exploitation, 71-74. Springer International Publishing Switzerland 2015. doi: 10.1007/978-3-319-09048-1_13.

Castagna S.E.D., De Luca D.A., Lasagna M. (2015b) - Eutrophication of Piedmont quarry lakes (north-western Italy): hydrogeological factors, evaluation of trophic levels and management strategies. J. Env. Assmt. Pol. Mgmt 17:4 (December 2015) (21 pages), Imperial College Press. doi: 10.1142/S1464333215500362

De Luca D.A., Destefanis E., Forno M.G., Lasagna M., Masciocco L (2014) - The genesis and the hydrogeological features of the Turin Po Plain fontanili, typical lowland springs in Northern Italy. Bull. Eng. Geol. Environ. (2014) 73:409-427. doi 10.1007/s10064-013-0527.

De Luca D.A., Lasagna M., Morelli di Popolo e Ticineto A. (2007) - Installation of a vertical slurry wall around an Italian quarry lake: complications arising and simulation of the effects on groundwater flow. Environ. Geol. 53:177–189.

Debernardi L., De Luca D.A., Lasagna M. (2008) - Correlation between nitrate concentration in groundwater and parameter affecting aquifer intrinsic vulnerability. Environ. Geol. 55:539-558. doi: 10.1007/s00254-007-1006-1.

EC European Commission (2015) - Italy's Third Progress Report under Directive 2009/28/EC. Available at http://ec.europa.eu/energy/node/70. Accessed 13 April 2016

Ferguson G., Woodbury A.D. (2004) - Subsurface heat flow in an urban environment. J. Geophys. Res. 109:B02402.

Forno M. G., Lucchesi S. (2014) - La successione pliocenico-quaternaria su cui è edificata la Città di Torino e il suo significato per l'utilizzo del territorio. Geologia dell'Ambiente, suppl. 1, 3-10.

Emmi G., Zarrella A., De Carli M., Moretto S., Galgaro A., Cultrera M., Di Tuccio M., Bernardi A. (2017) - Ground source heat pump systems in historical buildings: two Italian case studies. Energy Procedia 133:183-194.

Lasagna M., De Luca D.A. (2017) - Evaluation of sources and fate of nitrates in the western Po Plain groundwater (Italy) using nitrogen and boron isotopes. Environ Sci Pollut Res (2017). doi: 10.1007/s11356-017-0792-6.

Lasagna M., De Luca D.A., Franchino E. (2016a) - Nitrate contamination of groundwater in the western Po Plain (Italy): the effects of groundwater and surface water interactions. Environ. Earth Sci. 75:240. doi 10.1007/s12665-015-5039-6.

Lasagna M., De Luca D.A., Franchino E. (2016b) - The role of physical and biological processes in aquifers and their importance on groundwater vulnerability to nitrate pollution. Environ. Earth Sci. 75:961. doi: 10.1007/s12665-016-5768-1.

Menberg K., Bayer P., Zosseder K., Rumohr S., Blum P. (2013) - Subsurface urban heat islands in German cities. Sci. Total Environ. 442:123-133. doi: 10.1016/j.scitotenv.2012.10.0437.

Pasquale V., Verdoya M., Chiozzi P. (2011) - Groundwater flow analysis using different geothermal constraints: the case study of Acqui Terme area, northwestern Italy. J. Volc. Geotherm. Res. 199:38-46. doi:10.1016/j.jvolgeores.2010.10.003.

Piga B., Casasso A., Pace F., Godio A., Sethi R.(2017) - Thermal Impact Assessment of Groundwater Heat Pumps (GWHPs): Rigorous vs. Simplified Models. Energies 10:1385-1403.

Sparacino M., Camussi M., Colombo M., Carella R., Sommaruga C (2007) - The world's largest geothermal district heating using ground water under construction in Milan (Italy)- AEM unified heat pump project. In: Proc. European Geothermal Congress, Unterhaching, Germany.

Taniguchi M. (1993) - Evaluation of vertical groundwater fluxes and thermal properties of aquifers based on transient temperature-depth profiles. Water Resour. Res. 29(7):2021–2026.

Taniguchi M., Uemura T., Jago-on K. (2007) - Combined effects of urbanization and global warming on subsurface temperature in four Asian cities. Vadose Zone J. 6:591-596. doi:10.2136/vzj2006.0094

Taylor C.A., Stefan H.G. (2009) - Shallow groundwater temperature response to climate change and urbanization. J. Hydrol. 375 601-612. doi: 10.1016/j.jhydrol.2009.07.009.

Zhu K., Blum P., Ferguson G., Balke K.D., Bayer P. (2010) - The geothermal potential of urban heat islands. Environ. Res. Lett. 5:044002. doi:10.1088/1748-9326/5/4/044002.

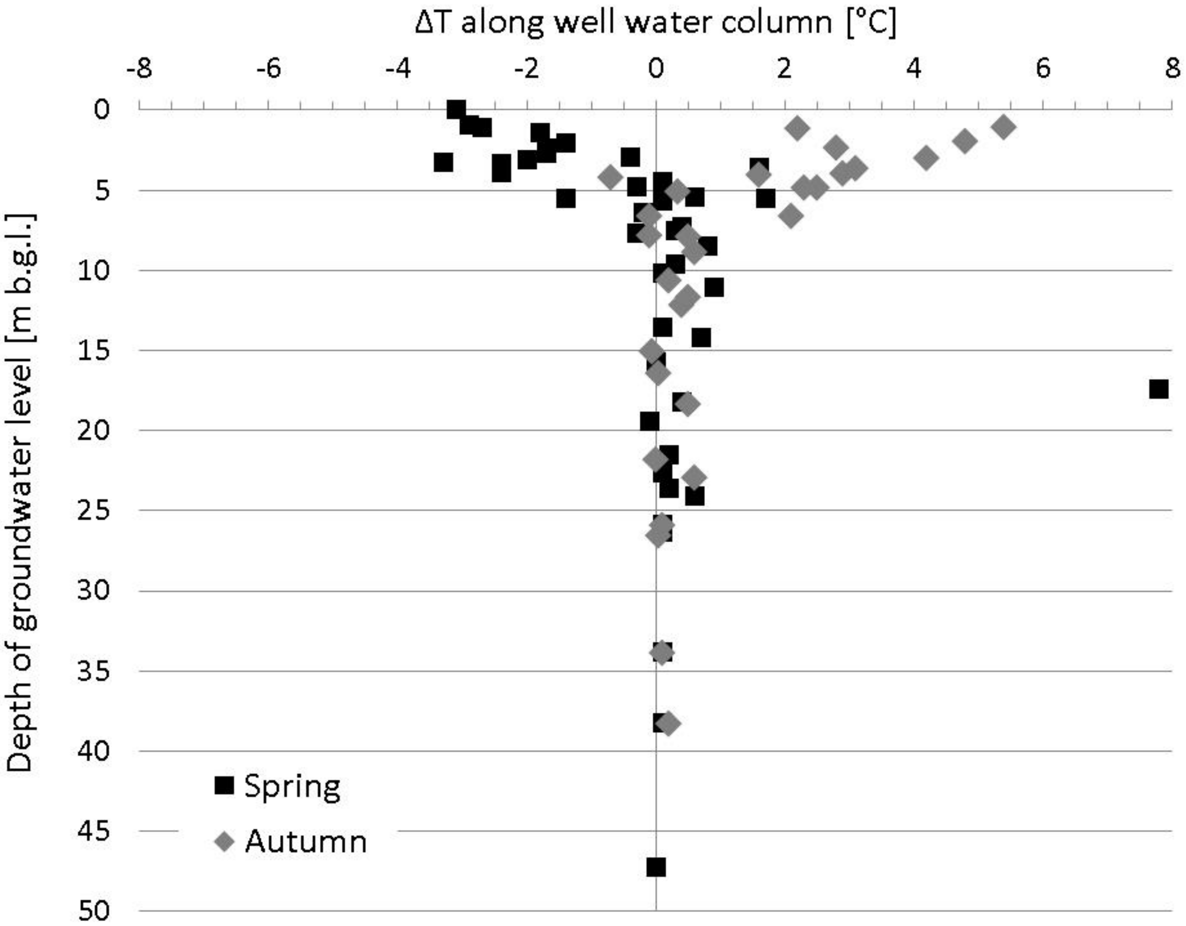

Fig. 1 – Correlation between groundwater temperatures and temperature difference along water column of the monitored wells in 2014

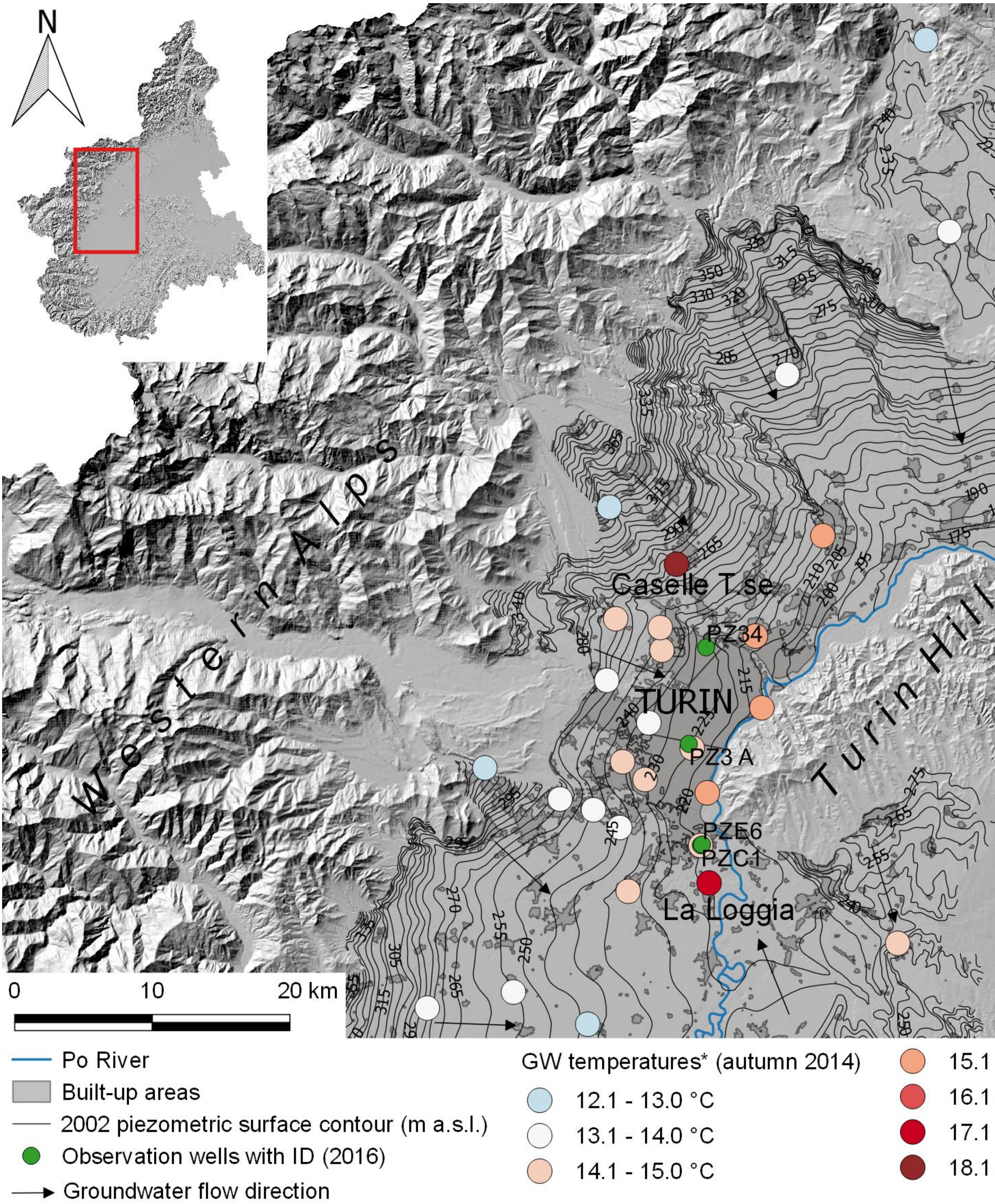
N
Western Alps
Turin Hill
Caselle T.se
TURIN
La Loggia
PZ34
PZ3 A
PZE6
PZC1
0
10
20 km
Po River
Built-up areas
2002 piezometric surface contour (m a.s.l.)
Observation wells with ID (2016)
Groundwater flow direction
GW temperatures* (autumn 2014)
12.1 - 13.0 °C
13.1 - 14.0 °C
14.1 - 15.0 °C
15.1
16.1
17.1
18.1

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

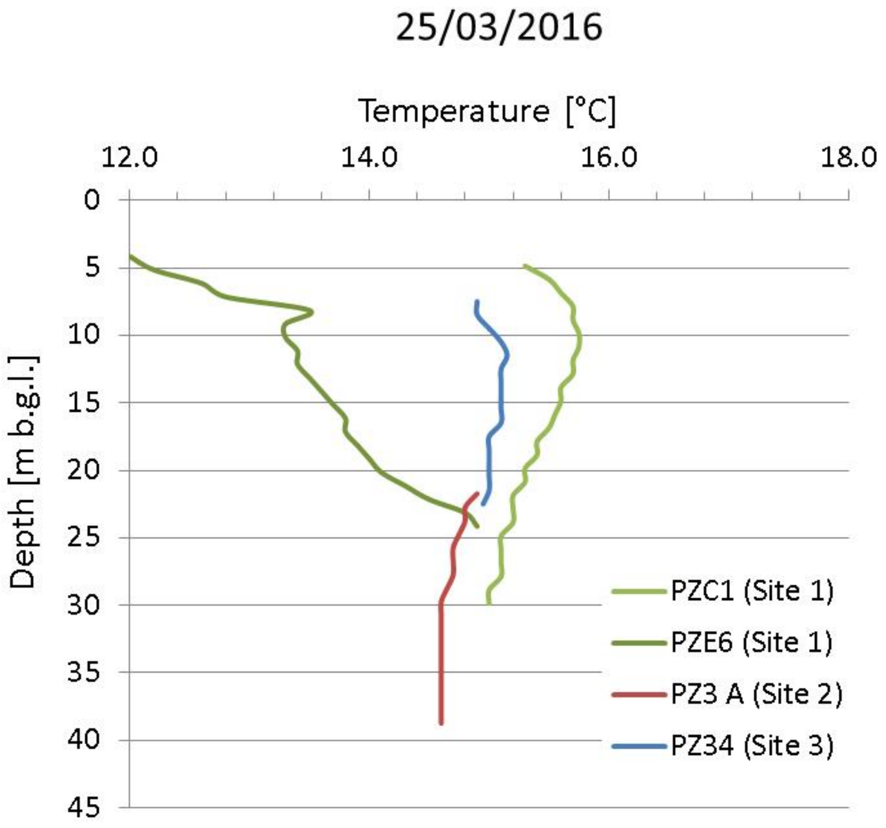

Fig. 3 – Groundwater temperatures at 3 urban sites in spring of 2016

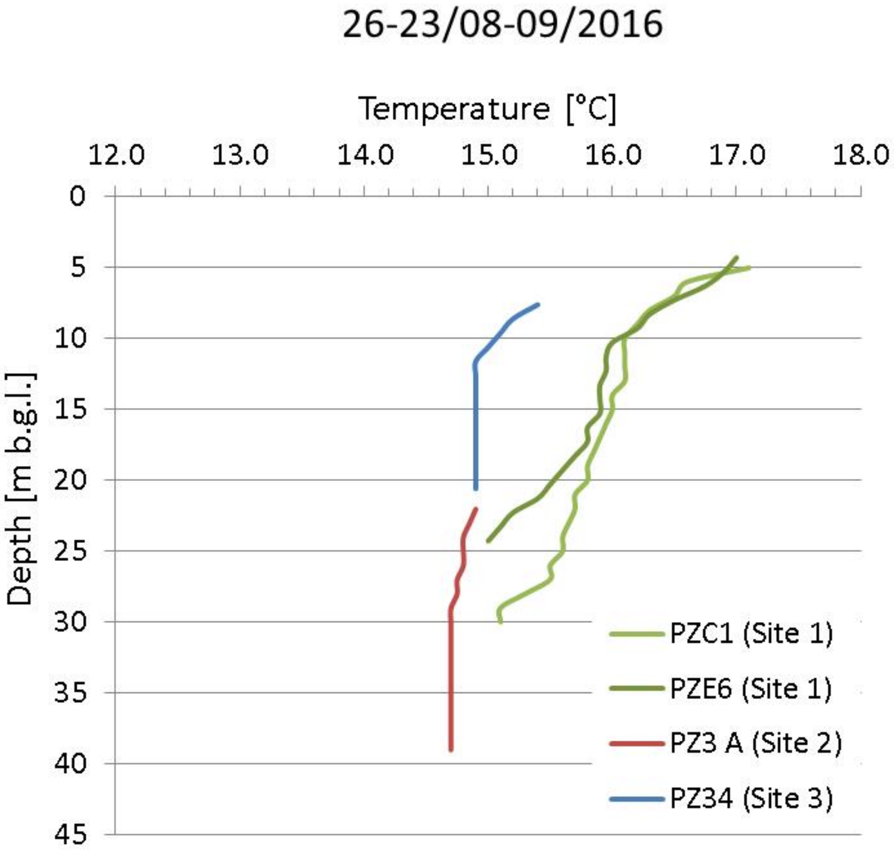

Fig. 4 – Groundwater temperatures at 3 urban sites in autumn of 2016