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The Impact of Climate Change on Groundwater Temperature of the Piedmont Po Plain (NW Italy)

Elena Egidio , Susanna Mancini , Domenico Antonio De Luca and Manuela Lasagna *

Earth Sciences Department, University of Turin, 10125 Turin, Italy
* Correspondence: manuela.lasagna@unito.it

Abstract: This paper represents the first regional-scale investigation in the Piedmont Po plain about the relationship between groundwater temperature (GWT) and climate variability. The understanding of relationships between air temperature (AT) and GWT is really important, especially in the context of global climate change. The aim of this investigation is to study the relationship between GWT and AT over a 10-year time period (from 2010 to 2019) to analyse how these two parameters interrelate and to evaluate possible trends. To carry out this study, basic statistic interpolations were performed on both parameters to facilitate comparison. Both AT and GWT showed an increase over the observed decade with a more pronounced growth of the AT; this allow to state that GWT is more resilient to climate change than AT. However, some areas in the Piedmont plain showed a behaviour that partially deviated from the standard trend observe for the majority of the region. These areas were influenced by particular anthropic factors (for example the paddy fields in the Novara plain) or natural elements (as the monitoring wells in the "Canavese" area, located downstream of melting glaciers, or the wells located close to the Tanaro River). Moreover, this study wanted to stress the importance of the knowledge of the localization in wells of the instruments for the GWT measurement, to have the most accurate and comparable data. It was proved that as the depth increased, the maximum and minimum peaks of the GWT shifted in time respect to the maximum and minimum peaks of the AT, and, in addition, the GWT fluctuation in the bottom part of the aquifer was milder than the fluctuation observed in the most superficial part. Further investigations will be conducted in future in Piedmont plain areas with different behavior, in order to better understand their dynamics and the factors that may influence GWT and how they are affected by climate change.

Keywords: groundwater temperature; trend; climate change; Po plain

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1. Introduction

In the 20th century the number of towns and cities dependent from groundwater (GW) was continuously increasing [1] and GW has become an essential resource to support the constant development of mankind [1,2]. Groundwater withdrawals in 2010 are estimated to have reached 900 km^3/y and, in varying proportions by country, 36% was used for water-supply, 42% for agricultural purposes and 24% for industrial use [1]. Although, actually, only few countries publish water use data on a regular basis by sector [3].

In literature, it's recognized that a global climate change is taking place [4] and this could affect the hydrologic cycle [5–9], leading to an increase in temperatures and a variation in precipitation regime, also affecting GW all over the world [10–18]. Moreover, it is reported that the period 2015–2019 was the warmest period ever registered globally [19,20]. Consequently, the understanding of how GW are influenced by climate change [21,22] is becoming more and more important. Indeed, GW can mitigate periods of drought because larger aquifers are potentially less stressed by climate variability than surface water [23], and so they reduce the risk of temporary water shortage [2,24,25].

It is also known that GW temperature (GWT) responds rapidly to climate variations [26–28], and especially the shallow aquifers are influenced by the air and ground surface temperatures, that are directly linked to different land uses and climate change [28,29]. These factors make the aquifers (especially the shallow ones) and the GW-dependent ecosystems vulnerable to future climate scenarios [6,11]. Moreover, it is also highlighted how the variations of GWT really affects the ecosystems in GW dominated wetlands [14].

In Italy there are only few studies conducted on this topic. One of them [30] analyses an unconfined aquifer in the Campanian plain (Southern Italy) and shows a clear correlation between the mean minimum air temperature (AT) and the mean minimum GWT. Also, in a recent study it was observed that the temperature of Alpine springs of the NW Alps of the Piedmont region increased in the last decade in relation to climate change [31].

The aim of this study is to evaluate how the climate change affects the GWTs in Piedmont Po plain (NW Italy). The importance of GW in Piedmont plain is linked to the fact that about 85% of the total GW extracted is used for human consumption [32]. The analysis was conducted by the evaluation and comparison through a statistical approach of the AT and the GWT for a period of 10 years (from 2010 to 2019). Trend analyses were carried out on the two studied parameters (AT and GWT) in order to observe how they behave individually and also to be able to analyse the relationships that exist between them.

A study of AT trends over the past 60 years has already been carried out in the study area [33], which showed an increasing trend. With this work, the aim is to deepen this study and also compared data with the GWT trend.

Moreover, the study stresses the importance of a correct location of the instruments for the GWT measure, to have accurate and comparable data.

2. Study Area

2.1. Geological and Hydrogeological Setting

Piedmont is located in the north-western Italy and covers an area of almost 25,000 km^2. The Piedmont Po plain represents the 27% of the whole region and is bordered by the Alps to the north and east, and the Apennines to the south [34]. Because it is bounded on three sides by mountain ranges, the Piedmont Po plain is the meeting point for continental currents from the Po Valley, moisture from the Mediterranean Sea and Atlantic currents from the NW that interact with the Alpine foothills. These characteristics favour the presence of different microclimates that make this territory unique [35].

From a geological point of view, the Piedmont Po plain consists, from top to bottom (Figure 1), by Quaternary Alluvial deposits (lower Pleistocene-Holocene), that host a shallow unconfined aquifer, the Villafranchiano transitional deposits (late Pliocene-early Pleistocene), that host a multi-layered aquifer and Pliocenic marine deposits (Pliocene), hosting a confined aquifer [34,36]. For these features and its size the Piedmont Po plain is considered the most important GW reservoir of the Piedmont region [34,37,38].

More details of the hydrogeological setting of the study area can be found in [34].

This study was conducted on the shallow unconfined aquifer, hosted in the Quaternary alluvial deposits, which has a thickness between 20 and 50 m and is characterised by high hydraulic conductivity ($K = 5 \times 10^{-3}/5 \times 10^{-4}$ m/s). This aquifer consists of coarse gravels and sands of fluvial or fluvioglacial origin, with minor intercalations of silty clay [34]. These fluvial deposits are connected to the ancient river courses of Po and Tanaro [39]. At the base of the shallow aquifer locally thick and continuous layers of silt or clay rich deposits are present, that represent the separation between the shallow aquifer and the deep aquifers [40].

2.2. GW Thermal Model of the Piedmont Plain

The GW thermal conceptual model of the shallow aquifer of the Piedmont Po plain has been conceptualized based on previous researches [26,31,34,41].

The annual distribution of GWT in the shallow aquifer is usually characterised by a maximum in autumn and a minimum in spring [26,41]. This behaviour reflects with a short time delay the AT distribution [26] that shows a mean maximum in July (28.5 °C) and a mean minimum in January (−0.8 °C) over the period 1958–2009 [42].

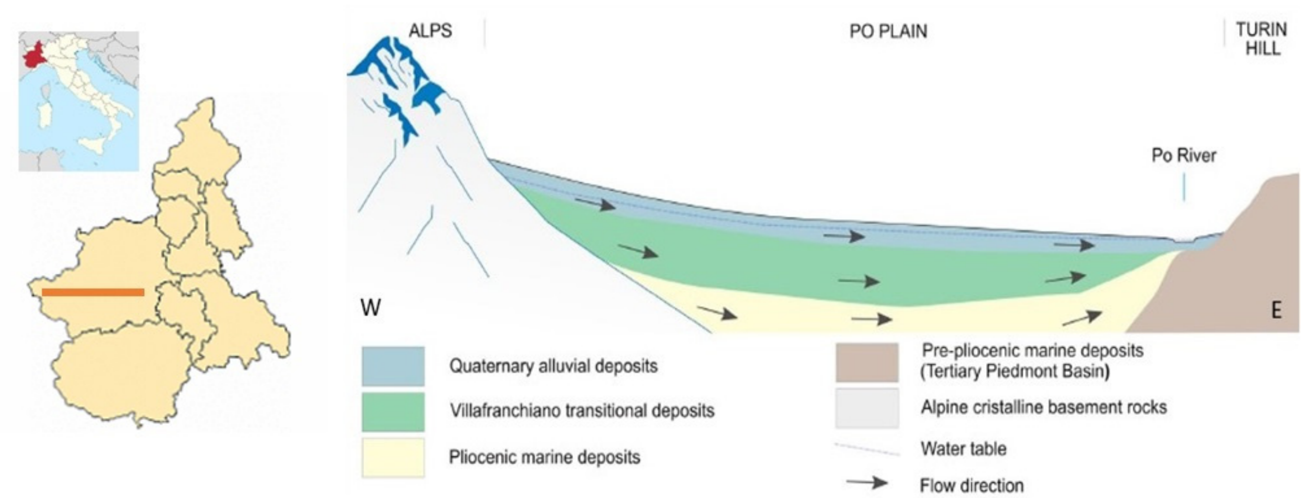

Figure 1. Sketch of a W-E cross-section of the hydrogeological complexes of the Po Plain (modified from [34]). The red line highlights the localization of the cross-section.

Moreover, GWT varied in depth, depending of the analysed season [43,44]. This variation occurs up to a surface called 'constant temperature surface' located at a depth of about 25 m from the earth surface. Then GWT remains constant between 25 and 50 m. At a depth of 50 m there is a second surface called 'geothermal constant temperature surface' from which GWT tends to increase due to the geothermal potential. In addition, as the depth increases, the maximum and minimum peaks of the GWT shift, moving respectively from autumn to winter and from spring to summer. [26,28]. Moreover, a statistical elaboration [26] in a small portion of the study area of this paper highlights that with increasing depth in aquifer, the amplitude of GWT fluctuation (difference between annual GWT mean maximum and annual GWT mean minimum) is milder than the fluctuation observed in the shallowest part of the aquifer.

3. Materials and Methods

For this research, 41 monitoring wells in the shallow aquifer and 20 weather stations were selected throughout the Piedmont Po plain area (Figure 2).

The monitoring wells are equipped with the GW data logger OTT Orpheus Mini (OTT Hydromet GmbH, Loveland, CO, USA) for the measure of the water table and the GWT (resolution temperature: 0.1 °C; accuracy temperature: ±0.5 °C), positioned between 7 and 20 m from the topographic surface. All of the monitoring wells are screened in the shallow aquifer of the Piedmont Po plain. The GWTs in the 41 monitoring wells have been downloaded from the GREASE database of Regione Piemonte [45]. The most of the GWTs data start from January 2010 and end in December 2019, and consequently the decade 2010–2019 was analysed. Only for 6 of the 41 monitoring wells the observed period is reduced to the interval 2013–2019 as the database only contains data for this time interval.

The same time period has been analysed for the weather stations. The data of the AT are available from the MeteoWeb app [46]. The studied 20 weather stations have been selected in order to cover uniformly the territory of the Piedmont Po plain as best as possible.

The available GWT data are from measurements taken 3 times a day (8 a.m., 4 p.m., 12 p.m.); the AT data, on the other hand, are single daily measurements. For both, it was decided to use the monthly mean value and the annual mean value for data processing.

The data from the weather stations are complete and present measurements for all months of the studied period; instead, the GWT data are not always complete since some wells show periods in which measurements are not present. Consequently, the completeness index (CI) [47] of each well was calculated in the observed period (2010–2019 or 2013–2019), according to the equation:

$$CI = \frac{number\ of\ available\ GWT\ data}{maximum\ number\ of\ data\ in\ the\ considered\ interval} \times 100$$

Only wells with CI $\geq$ 75% were selected for the study.

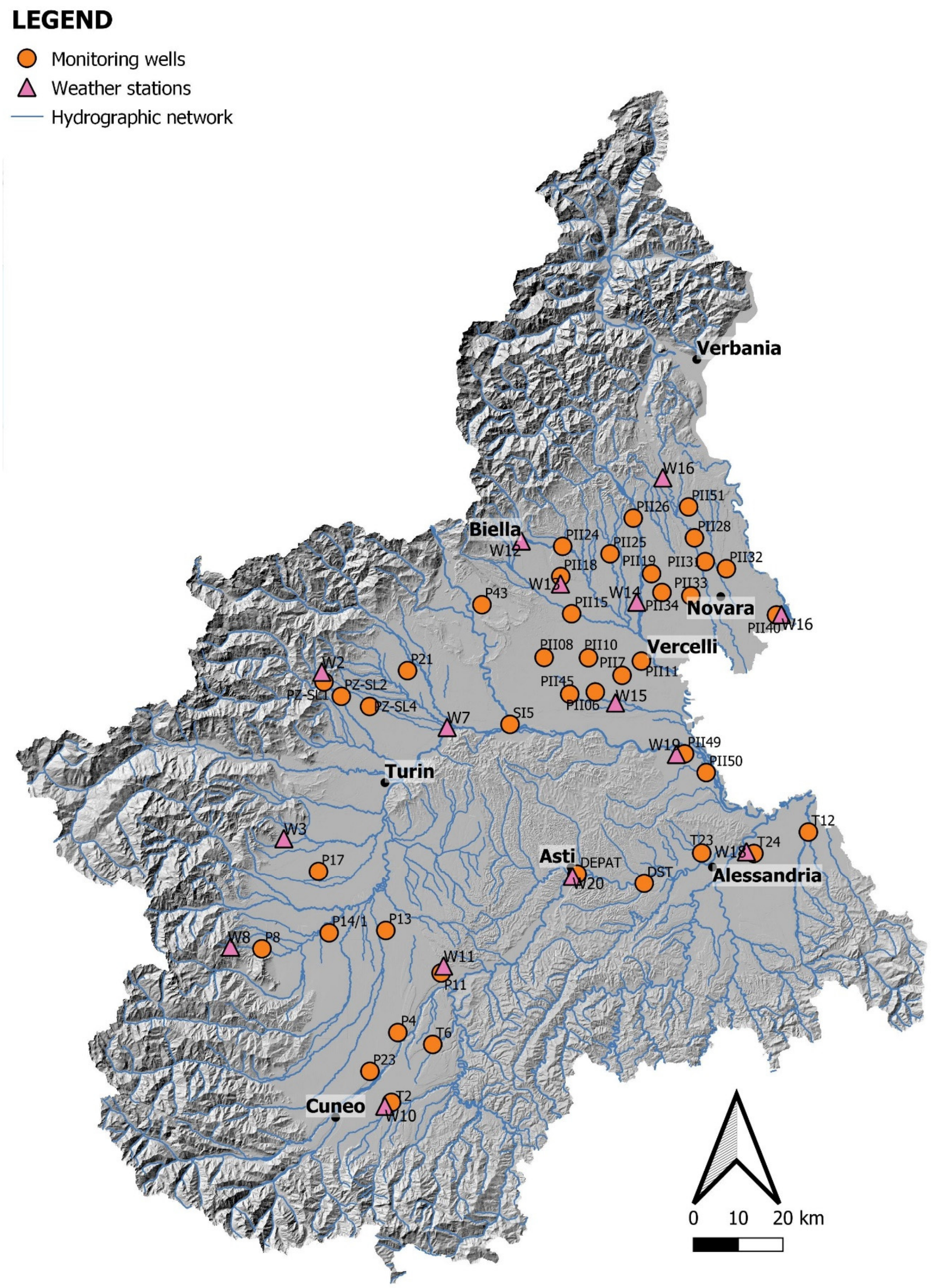

Figure 2. Map of the Piedmont region with the localization of the 41 monitoring wells and the 20 weather stations used for the study.

At first, temperature data and their variation over the observed time period were plotted for both GWT and AT data. These graphs were then studied to observe the maximum and minimum temperature peaks and the seasonal trends.

To correlate the GWT and AT data, the Voronoi polygon method [48,49] was used on the QGis software (version 3.16 Hannover). The Voronoi polygons were centered on weather stations, to match the monitoring wells to the weather stations and to better understand the relationship between GWT and AT.

Subsequently the GWT and AT data were both studied with basic statistical analysis (mean, maxima, minima) to make a statistical assessment of temporal variations in temperature data. These statistics were also processed in order to observe the annual GWT variability measured by subtracting the data referred to day that registered the absolute minimum GWT from the data referred to day that registered the absolute maximum GWT of each year.

After, the non-parametric methods of the Mann-Kendall [50,51] and Theil-Sen [52] were used to assess the trends and the slopes of the monthly mean of GWT and AT. These tests, calculated on the ProUCL 5.1 software (United States Environmental Protection Agency, Washington, DC, USA) [53], were chosen because they both allow non-parametric analysis and they are largely used in study in the field of water resource and climate [54–56].

4. Results and Discussion

4.1. Qualitative Analysis

During the qualitative analysis conducted on the GWT time-plots, three families of wells were recognised, concerning the period of maximum and minimum temperature peaks (Figure 3). The first family, in red in the Figure 3a, has a maximum temperature peak in autumn (September–October) and a minimum in spring (March) (behaviour 1) (Figure 3b). The second group, in green in the Figure 3a, has a maximum in winter (December–January) and a minimum in summer (July) (behaviour 2) (Figure 3c). A third group, in blue in Figure 3a, was also identified, characterising only 3 wells, in which there is a variable behaviour that cannot be categorised into either of the two families described above (behaviour 3). More specifically, two of these wells (T23, T6) cyclically have a maximum peak in winter and a minimum in spring; the third (P23) has a maximum in spring and a minimum in winter.

As far as AT is concerned, it has been observed that for all the analysed weather stations there is a summer maximum (mainly in July) and a winter minimum (mainly in January) as expected (Figure 4).

4.2. Statistical Analysis

To make a statistical assessment of temperature data for both GWT and AT, it was calculated the monthly mean, the monthly absolute maximum, the monthly absolute minimum and the standard error. The results, averaged over all the years observed, are shown in Tables 1 and 2 respectively.

The regional distribution of mean monthly GWTs and ATs varied respectively between 12.3 and 17.3 °C and between 7.7 and 14.0 °C.

The regional distribution of monthly absolute maxima varied between 14.0 and 22.0 °C for GWT and between 12.4 and 20.1 °C for AT.

The regional distribution of monthly absolute minima varied between 6.8 and 15.6 °C for GWT and between 4.0 and 10.2 °C for AT.

As far as GWTs are concerned, the maximum temperatures are recorded in the provinces of Turin and Vercelli, as shown in Table 1; with regard to ATs, as is to be expected, the maximum temperatures are recorded in the larger urban centres within the study area.

4.3. Non Parametric Test Analysis

Mann-Kendall and Theil-Sen methods allowed to quantify the time series data trend and to better understand how the temperature (both AT and GWT) vary in the observed time period (Tables 3 and 4).

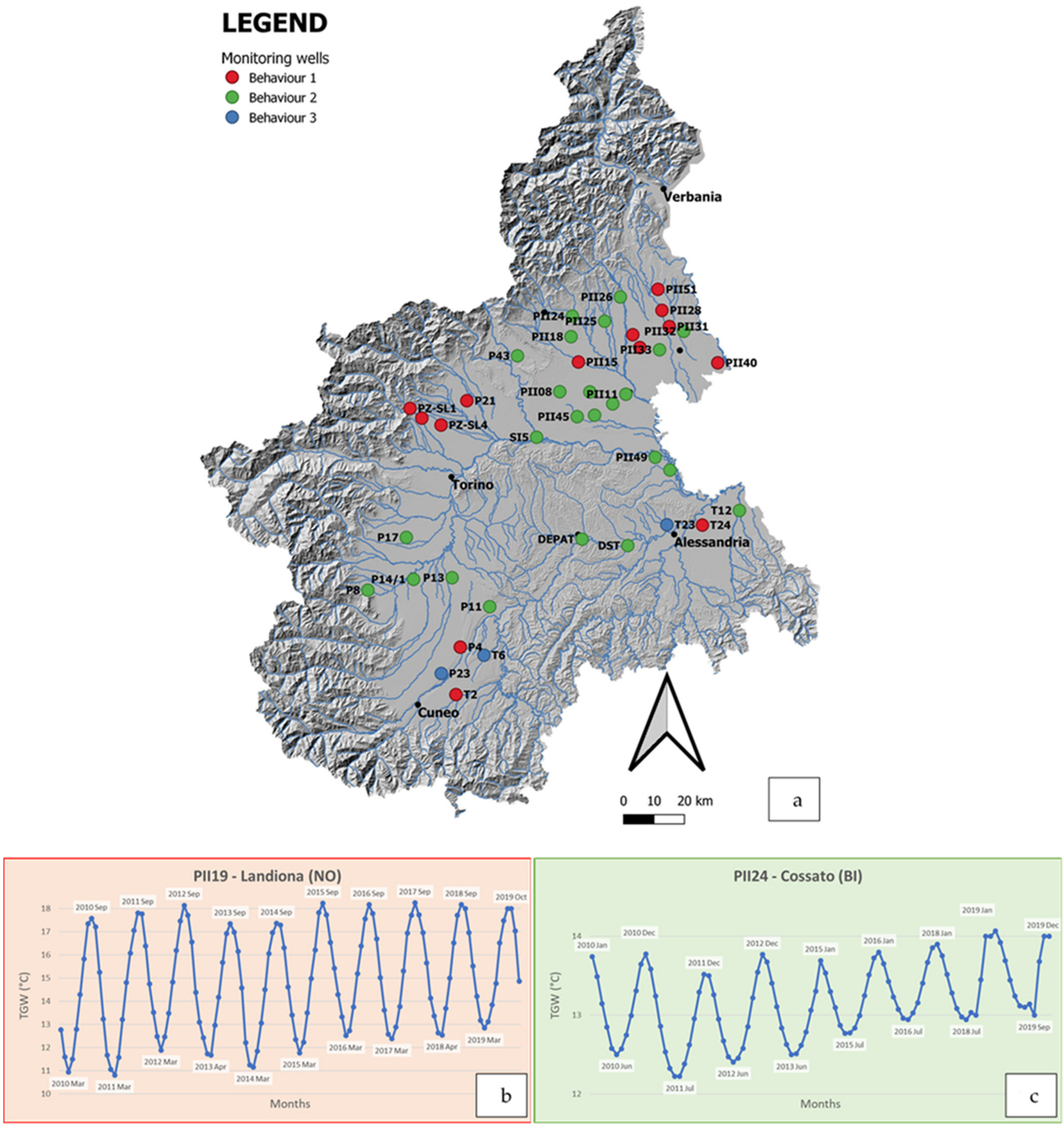

Figure 3. Maximum and minimum GWT peak behaviours throughout the whole Piedmont Po plain. (**a**): distribution of the monitoring wells highlighting different behaviours. (**b**): example of behaviour 1 (maximum in autumn and minimum in spring). (**c**): example of behaviour 2 (maximum in winter and minimum in summer).

Table 1. Summary of monthly mean statistical data for GWT (mean, mean absolute maximum, mean absolute minimum and standard error) for the observed monitoring wells.

Well—Location	Observation Period	Mean GWT (°C)	Absolute Maximum GWT (°C)	Absolute Minimum GWT (°C)	Standard Error
DEPAT—Asti	2010–2019	15.4	16.9	13.9	0.08
PII18—Massazza	2010–2019	15.7	17.0	13.9	0.06
PII24—Cossato	2010–2019	13.1	14.1	12.1	0.05
PII19—Landiona	2010–2019	14.8	19.0	10.5	0.21
PII28—Momo	2010–2019	14.3	18.0	12.3	0.09
PII31—Caltignaga	2010–2019	15.6	20.0	12.0	0.21
PII32—Cameri	2010–2019	16.5	18.0	14.9	0.08
PII33—San Pietro Mosezzo	2010–2019	14.1	15.0	13.7	0.03
PII34—Biandrate	2010–2019	14.4	18.8	9.3	0.23
PII40—Cerano	2010–2019	16.2	19.0	13.7	0.08
PII51—Suno	2010–2019	13.2	16.0	11.0	0.12
P4—Fossano	2010–2019	13.7	17.3	9.4	0.22
P8—Barge	2010–2019	13.2	14.5	12.4	0.04
P11—Bra	2010–2019	15.6	16.3	15.0	0.03
P13—Racconigi	2010–2019	13.9	16.0	12.8	0.07
P14/1—Moretta	2010–2019	14.1	15.0	13.6	0.02
P23—Fossano	2010–2019	13.5	14.0	13.0	0.02
T2—Morozzo	2010–2019	12.6	15.2	9.2	0.13
T6—Bene Vagienna	2010–2019	15.1	16.3	11.8	0.06
DST—Masio	2010–2019	13.2	15.0	9.2	0.04
PII49—Frassineto Po	2010–2019	17.3	19.2	15.6	0.08
PII50—Valmacca	2013–2019	13.9	14.2	13.5	0.02
T12—Castelnuovo Scrivia	2010–2019	13.8	14.6	13.2	0.03
T23—Alessandria	2010–2019	14.1	15.2	12.8	0.04
T24—Alessandria	2010–2019	13.7	16.6	10.8	0.14
PII06—Ronsecco	2010–2019	14.6	18.9	13.2	0.07
PII7—Lignana	2013–2019	14.0	15.2	10.7	0.09
PII08—Bianzè	2010–2019	13.7	14.4	12.8	0.04
PII10—Salasco	2010–2019	14.4	15.0	14.0	0.03
PII11—Vercelli	2010–2019	16.0	18.0	12.8	0.08
PII15—Carisio	2010–2019	14.5	17.0	12.7	0.11
PII25—Rovasenda	2013–2019	14.2	16.1	13.3	0.04
PII26—Gattinara	2010–2019	13.2	22.0	12.2	0.06
PII45—Trino	2010–2019	16.0	17.3	13.4	0.05
P17—Scalenghe	2013–2019	13.3	14.0	12.9	0.03
P21—Rivarolo Canavese	2010–2019	13.2	15.0	11.4	0.09
P43—Albiano d'Ivrea	2010–2019	13.3	14.0	12.5	0.04
PZ-SL1—Lanzo Torinese	2010–2019	12.3	15.4	6.8	0.17
PZ-SL2—Villanova Canavese	2013–2019	13.0	17.0	8.4	0.25
PZ-SL4—S. Maurizio Canavese	2013–2019	14.1	17.0	10.3	0.18
SI5—Verolengo	2010–2019	14.1	15.7	13.6	0.02

Table 2. Summary of statistical data for AT (mean, mean absolute maximum, mean absolute minimum and standard error) for the observed weather stations.

Weather Station	Location	Monthly Mean AT (°C)	Monthly Mean Absolute Maximum AT (°C)	Monthly Mean Absolute Minimum AT (°C)	Standard Error
W1	Forno Alpi Graie	7.7	12.4	4.0	0.60
W2	Lanzo	11.7	17.6	7.0	0.79
W3	Cumiana	13.4	19.6	8.0	0.86
W4	Venaria	12.7	18.9	7.4	0.92
W5	Bauducchi	12.9	19.5	7.3	0.70
W6	Santena	12.6	19.0	7.1	0.70

Table 2. *Cont.*

Weather Station	Location	Monthly Mean AT (°C)	Monthly Mean Absolute Maximum AT (°C)	Monthly Mean Absolute Minimum AT (°C)	Standard Error
W7	Brandizzo	13.0	18.8	7.9	0.68
W8	Barge	10.4	13.3	7.7	0.65
W9	Dronero	11.8	16.8	7.5	0.70
W10	Morozzo	12.1	18.0	7.0	0.72
W11	Bra	13.5	20.1	8.7	0.74
W12	Biella	14.0	18.7	10.2	0.71
W13	Massazza	12.7	18.7	7.4	0.80
W14	Albano Vercellese	12.6	19.4	7.2	0.88
W15	Tricerro	13.4	19.0	8.6	0.76
W16	Borgomanero	12.7	19.0	7.5	0.74
W17	Cerano	13.9	19.3	8.9	0.76
W18	Alessandria Lobbi	13.3	19.5	7.9	0.77
W19	Casale Monferrato	13.9	19.2	9.4	0.88
W20	Asti Tanaro	13.1	19.0	8.0	0.77

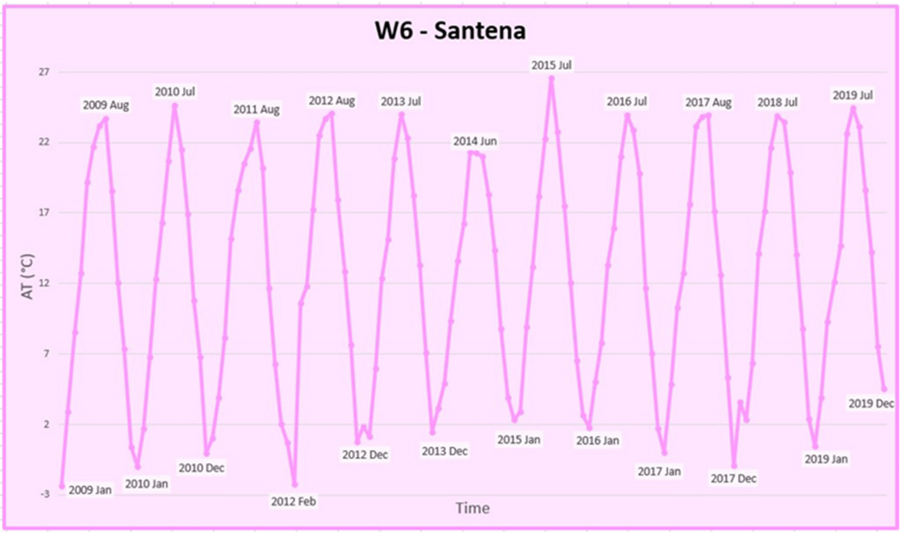

Figure 4. Example of maximum and minimum AT peak behaviour observed in the weather stations.

Table 3. Nonparametric test analysis results for AT.

Weather Station	Theil-Sen Trend Line Slope—AT Mean (2010–2019) (°C/Month)	Theil-Sen Trend Line Slope—AT Mean (2013–2019) (°C/Month)	Total AT Mean Increase over the Observed Period (°C in 10 Years)	Total AT Mean Increase over the Observed Period (°C in 7 Years)
W2	0.014	0.017	1.716	1.462
W3		0.017		1.428
W4		0.022		1.882
W7	0.017		2.088	
W8	0.018		2.172	
W10	0.017		2.064	
W11	0.015		1.848	
W12	0.016		1.908	
W13	0.015		1.788	
W14	0.017	0.021	2.041	1.739
W15	0.018	0.021	2.124	1.697
W16	0.015		1.812	
W17	0.016		1.884	
W18	0.0171		2.052	
W19	0.017	0.021	2.076	1.697
W20	0.016		1.932	

Table 4. Non-parametric tests analysis results about GWT.

Well	Theil-Sen Trend Line Slope—GWT Mean (°C/Month)	Theil-Sen Trend Line Slope—GWT Max (°C/Month)	Theil-Sen Trend Line Slope—GWT Min (°C/Month)	Total GWT Mean Increase over the Observed Period (°C)	Total GWT Max Increase over the Observed Period (°C)	Total GWT Min Increase over the Observed Period (°C)
DEPAT	0.008	0.009	0.008	1.008	1.068	0.960
PII18	0.008	0.007	0.008	0.948	0.828	0.996
PII24	0.006	0.005	0.006	0.672	0.576	0.684
PII19	0.015	0.013	0.017	1.812	1.572	2.004
PII28	0.006	0.006	0.004	0.696	0.672	0.516
PII31	0.016	0.015	0.015	1.908	1.800	1.824
PII32	0.010	0.010	0.010	1.176	1.248	1.164
PII33	0.008	0.008	0.008	0.984	0.996	0.996
PII34	−0.002	0.000	−0.007	−0.180	0.000	−0.804
PII40	0.008	0.007	0.009	0.960	0.780	1.020
PII51	0.011	0.010	0.010	1.308	1.248	1.200
P4	0.011	0.008	0.013	1.296	0.996	1.500
P8	0.004	0.004	0.003	0.420	0.480	0.396
P11	0.004	0.003	0.003	0.420	0.336	0.396
P13	0.007	0.009	0.006	0.888	1.092	0.756
P14/1	0.004	0.004	0.004	0.456	0.444	0.432
P23	0.004	0.004	0.003	0.432	0.432	0.396
T2	0.008	0.004	0.012	0.960	0.468	1.440
T6	0.006	0.005	0.007	0.756	0.648	0.816
DST	0.006	0.005	0.007	0.732	0.648	0.792
PII49	0.017	0.016	0.018	2.088	1.932	2.112
PII50	0.003	0.003	0.004	0.269	0.218	0.311
T12	0.004	0.004	0.004	0.504	0.480	0.516
T23	0.004	0.005	0.006	0.528	0.588	0.708
T24	0.010	0.008	0.010	1.152	0.996	1.152
PII06	0.005	0.004	0.005	0.648	0.516	0.600
PII7	0.008	0.003	0.006	0.664	0.277	0.521
PII08	0.003	0.001	0.003	0.312	0.168	0.408
PII10	0.000	0.000	0.000	0.024	0.000	0.000
PII11	0.006	0.000	0.010	0.708	0.000	1.176
PII15	0.005	0.005	0.005	0.636	0.624	0.612
PII25	0.005	0.007	0.002	0.378	0.571	0.176
PII26	0.001	0.000	0.000	0.156	0.036	0.036
PII45	−0.003	−0.004	−0.001	−0.336	−0.504	−0.156
P17	0.004	0.004	0.003	0.294	0.328	0.277
P21	0.007	0.006	0.008	0.864	0.768	0.936
P43	0.003	0.002	0.003	0.384	0.288	0.348
PZ-SL1	0.010	0.009	0.011	1.212	1.044	1.368
PZ-SL2	0.008	0.008	0.010	0.680	0.680	0.848
PZ-SL4	−0.005	−0.004	−0.006	−0.386	−0.311	−0.521
SI5	0.000	0.000	0.000	−0.024	0.000	0.000

With regard to AT all the weather stations had shown an increasing trend and, moreover, it is possible to observe a variation in annual mean AT over the period 2010–2019 ranging between 1.7 and 2.2 °C/10 years (Figure 5).

Furthermore, also annual mean GWT generally shows a variation in the period 2010–2019 between −0.3 and 2.1 °C/10 years (Figure 5).

The trends, processed with the ProUCL statistical software, show that, as far as the monthly average GWTs data are concerned, most of the monitoring wells (34) show a statistically significant positive trend with a level of significance 0.05. With regard to the remainder, 6 of these (PII34, PII10, PII26, PZ-SL2, PZ-SL4, SI5) do not have a statistically significant trend, but still show an increase in temperature over time, and only 1 monitoring well (PII45) is characterised by a statistically significant negative trend.

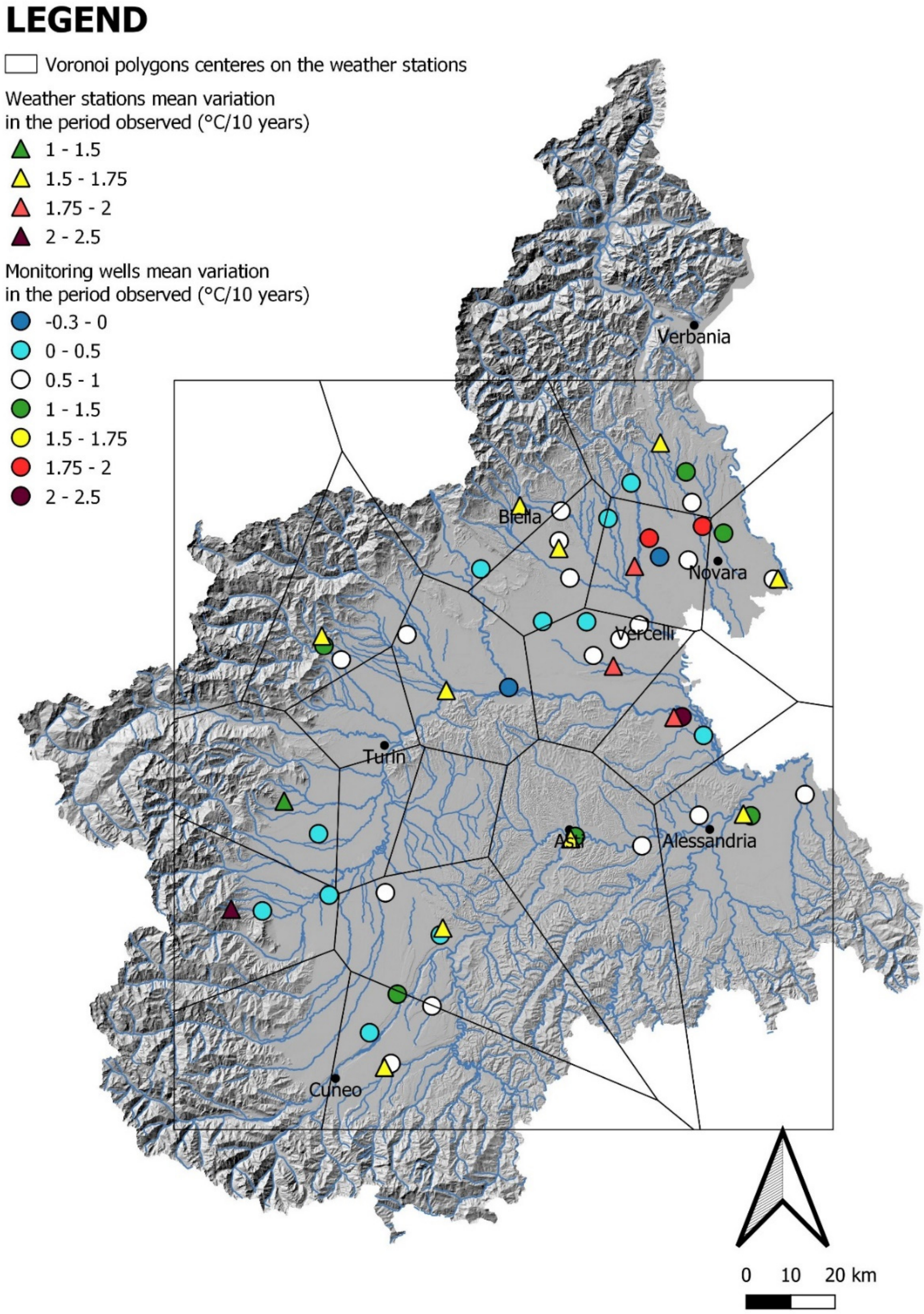

Figure 5. Mean variation of ATs (triangles) and GWTs (rounds) in the entire observed period (2010–2019) and Voronoi polygons, centered on weather station used to match the monitoring wells to the weather stations.

Observing the geographical position of these 7 monitoring wells with no statistically significant positive trend, it is possible to note that they are concentrated within the provinces of Vercelli and Turin. This behaviour is hypothesised to be linked to the particular nature of the two areas. In fact, the first one, the province of Vercelli, is characterised by the presence of a large quantity of rice fields, which therefore, due to the nature of the agricultural method, could have influenced the GWTs data.

As far as the province of Turin is concerned, on the other hand, this behaviour is thought to be linked to the fact that most of the monitoring wells located in the territory are in correspondence with the area called "Canavese" area. These monitoring wells are located downstream to mountain areas with glaciers, so this behavior could be linked with the glacial melting of the Lanzo valley glaciers due to climate change, of which there are several testimonies in the literature [57].

Through the comparison between GWT and AT, using the Voronoi polygons (Figure 5), it was possible to highlight that in most cases (37 on 41, 90% of the analysed couples of temperature data) there is a greater increase in the monthly mean AT than in the monthly mean GWT.

Then, the data of GWT mean increase have been plotted with the GWT mean annual variability for each monitoring wells (Figure 6).

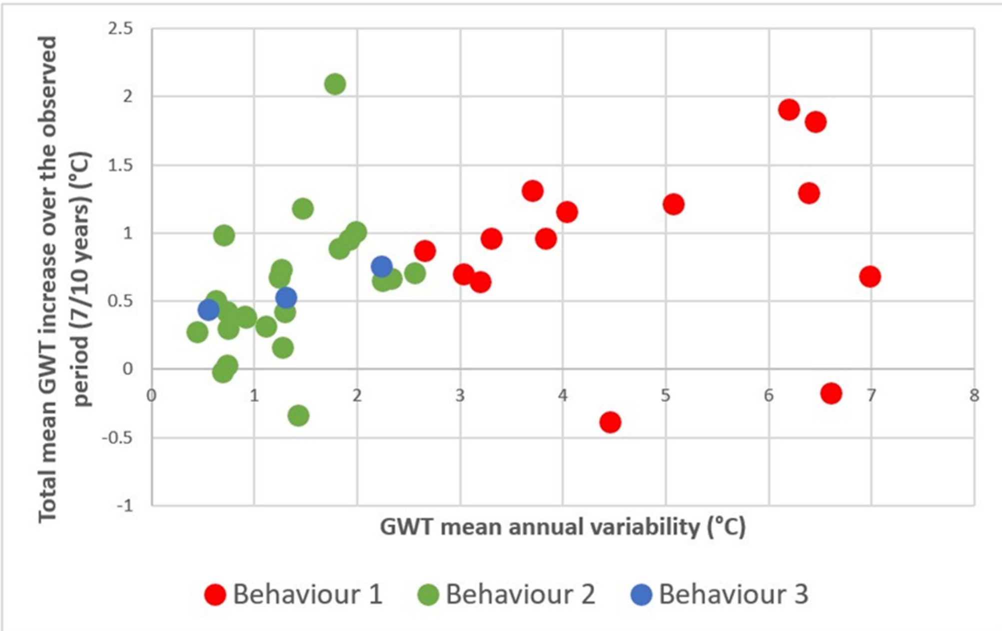

Figure 6. Correlation between mean annual variability of GWT and total GWT mean increase in the period observed.

It is possible to observe that the data related to wells with behaviour 1 (in red), that also have a greater annual GWT variability, generally have higher values of increase in the mean GWT in the observed decade. On the contrary, the data related to wells with behaviour 2 (green) and behaviour 3 (blue) have a lower annual GWT range and also present a lower increase in mean GWT in the decade observed.

These results, added to those observed through qualitative and statistical analysis, allows us to conclude that the observed thermal reply of GW to AT is influenced by the height of the water column above the groundwater temperature measuring instrument and by the GW level depth. In fact, as mentioned in the literature [26,41], the depth at which the temperature of GW is measured affects the observation of GWT seasonal behaviour: the deeper the GWT is measured, the more the maximum temperature peak is shifted in time (compared to atmospheric data) and the lower the annual GWT range as it tends to be less sensitive to atmospheric temperature variations.

To stress the link between GWT and position of the instrument, data relating to the water column above the instrument, the annual mean variability of GWT and the depth of the groundwater level were plotted in the diagram of Figure 7. As hypothesized previously it has been possible to observe that the monitoring wells with a greater column of water above the instrument tend to have a lower annual mean variability.

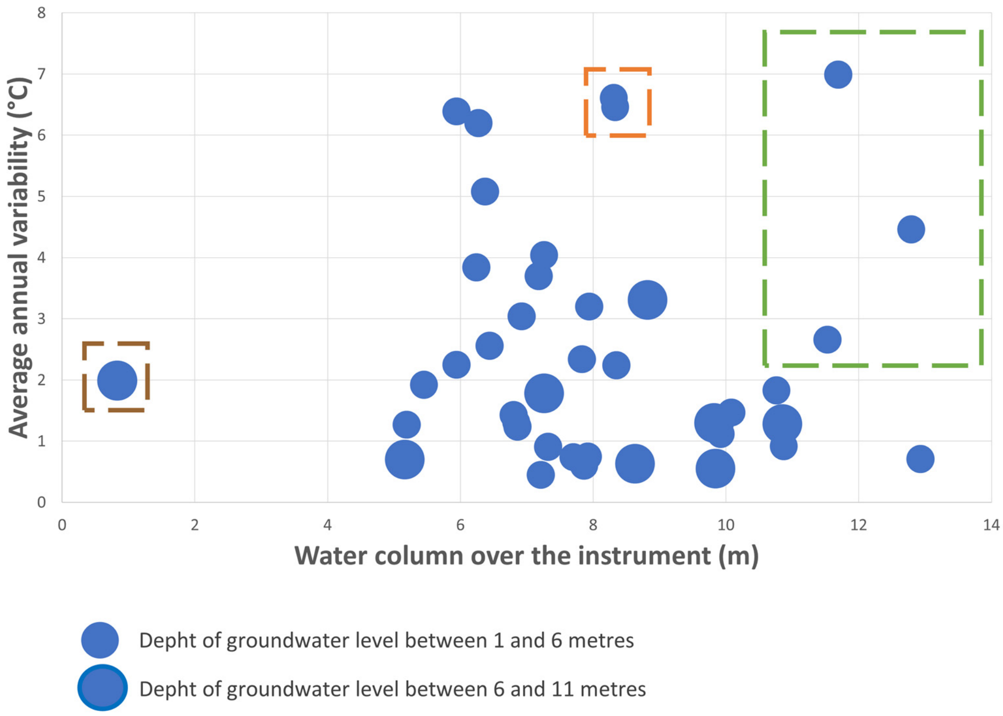

Figure 7. Correlation between GWT mean annual variability and water column over the instrument. The different dimensions of the dot represent the depth of the GW level. The coloured dashed rectangles show three particular cases in which the results deviate from the mean trend: in brown a well located close to a river, in orange wells located in paddy fields area and in green wells located in the downstream of a mountain area.

Moreover, the plot of GWT mean annual variability vs. the groundwater depth shows that a high annual variability is generally typical of wells with low depth to GW (1–6 m). On the contrary, wells with a higher depth to GW (6–11 m) have a lower mean annual variability.

Some wells (a total of six, highlighted by coloured dashed rectangles in Figure 7) have a behaviour that does not match with this description. When analysing these points, it was possible to observe that they are linked to particular situations. In brown is highlighted a well located in the province of Asti (DEPAT) that is a monitoring well drilled close to the Tanaro river and it is probably influenced by the watercourse. In orange there are two monitoring wells located in the province of Novara (PII34 and PII19), within the paddy fields areas. As reported in [54,58], in this area the agricultural technique of rice represents the main driver of water level modification, and consequently physical-chemical parameters of groundwater. Finally, in green, there are three monitoring wells located in the province of Turin, and more specifically in the area called "Canavese" area (PZ-SL2, PZ-SL4 and P21). These are the only monitoring wells in plain located downstream to mountain areas with glaciers. GWT in this area is probably influenced by the glacial melting of the Lanzo valley glaciers due to climate change, of which there are several testimonies in the literature [57].

5. Conclusions

This study represents the first regional-scale investigation in the Piedmont Po plain about the relationship between GWTs and climate variability. Prior to this, only studies concerning the observation of air temperature trends and how them influenced and are influenced by precipitations were carried out [33]. However, the understanding of relationships between AT and GWT is really important, especially in the context of global climate change. This is a fundamental analysis that is part of a global research strand that is already underway around the world (e.g., [14,16,17]) and which certainly needs to be deepened both at the Italian national level, but also at the international level.

The aim of this research was to study the evolution over time of GWT over a period of 10 years (from 2010 to 2019) and the relationship between GWT and AT, to analyse how these two parameters interact with each other, and to evaluate possible trends.

The analysis of 41 wells and 20 weather stations allowed us to highlight the existing positive correlation between AT and GWT.

Mann-Kendall and Theil-Sen tests show that approximately 90% of the 41 GWT data have an increasing trend at the 95% confidence level for mean, minimum and maximum annual GWT. The increasing trend of the GWT reflect the increase in air temperature. Indeed, AT shows an increase in annual mean values in all the analysed weather stations as already reported in previous work in the same study area that had also observed the increasing trend of the AT [33]. Other works also highlighted a positive trend concerning AT in Italy (e.g., in the southern Italian territory [30]).

However, it is evident that the increasing trend for AT is more pronounced than that for GWT. Consequently, it is possible to state that, despite the study area is located in a context of climatic variability, GWT are more resilient to change than AT.

The second objective of this study was to highlight the importance of the knowledge of the location in wells of the instruments for the GWT measure, to have accurate and comparable data.

The results of this study confirmed that GWT varies, depending of the analysed season. In addition, as the depth increases, the maximum and minimum peaks of the GWT shift in time respect to the maximum and minimum peaks of the AT, and the GWT fluctuation is milder than the fluctuation observed in the shallowest part of the aquifer.

Moreover, it was observed that the location in the wells of the instruments for the GWT measure seems to influence the mean annual variability recorded by the instrument. Indeed, the analysis of the water column above the instrument showed that the monitoring wells with a greater column of water tend have a lower annual mean variability. Moreover, a low annual variability is generally typical also of wells with low depth to GW (1–6 m).

Some areas in the Piedmont plain have behaviours that partially deviate from the mean trend (see Figure 7). These areas are influenced by particular anthropic factors (as the paddy fields in the Novara plain) or natural elements (as the monitoring wells in the "Canavese" area, located downstream of melting glaciers, or the wells located close rivers). Further investigations will be conducted in future in these areas of the Piedmont plain in order to better understand their dynamics and the factors that may influence GWT.

At last, although correlations confirm that AT influences GWT, further investigation is needed to better understand how GWT is affected by, for example, different land uses and atmospheric precipitation events. Future insights will also concern a detailed analysis of the factors influencing the more or less evident increase in GWT in relation to AT (e.g., depth of the water table, position of the monitoring well . . .). All this information will permit to obtain a more complete description of all the factors (e.g., [59–61]) affecting the groundwater in the Piedmont plain, that represents the most important GW reservoir of the Piedmont region.

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