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Groundwater hydrodynamic behaviours based on water table levels to identify natural and anthropic controlling factors in the Piedmont Plain (Italy)

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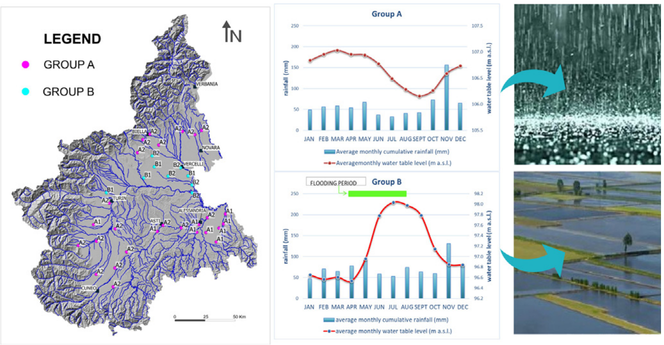
HIGHLIGHTS

- Analysis of water table highlights two main hydrodynamic groundwater table behaviours.
- Water table in Piedmont plain is influenced by rainfall and paddy fields irrigation.
- The study emphasizes the dependence of water table level on climate change.
- Highest rainfall in 2009–2017 is reflected on high water table compared to 2002–2008.
- Water table levels highlight a recent change in irrigation methods for paddy fields.

GRAPHICAL ABSTRACT



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ABSTRACT

Water table level monitoring and analysis are among the tools available to identify variations in the quantitative state of groundwater. Moreover, these levels highlight the response of groundwater to climate change and other global change drivers, including land use changes.

In this study, water table level (37 monitoring wells) and rainfall (30 rain gauges) data analyses were performed in an alluvial unconfined aquifer in the Piedmont Plain (NW Italy) for the 2002–2017 period. The aim of this study was to identify possible trends in the time series and classify the groundwater hydrodynamic behaviours, as well as their spatial distributions and the main drivers of change in the plain. Moreover, two different sub-periods (2002–2008 and 2009–2017), which were identified with a change point analysis, were analysed to highlight possible variations in the groundwater hydrodynamic behaviours.

The results of this study highlighted the lack of a trend in the rainfall time series, while a trend was detected for the water table. To explain this inconsistency, water table behaviours were analysed during the year, highlighting different groundwater hydrodynamic behaviours. Over time, the groundwater hydrodynamic behaviour generally showed the dependence of the water table level on rainfall occurrence. This correlation was also underscored by analysing the standardised anomalies of rainfall and groundwater levels. A different behaviour was observed in the paddy field areas, where the main driver of water level modification is the agricultural technique of rice cultivation. Furthermore, a reduction in the maximum water table level period was observed in 2009–2017 in

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this area. More specifically, the high water table period passes from 4 to 3 months, which could be the result of changes in irrigation methods.
In this study, by analysing the present resource status, a first step is made to obtain future insights into flow dynamics and trends in storage.

1. Introduction

Prior to large-scale anthropogenic activities (pre-1950), human impacts on groundwater (GW) systems in terms of modification, abstraction and pollution was minimal compared to the available resources (IAH, 2016). A significant increase in water needs has been recorded in the last century, resulting in an intensification of water withdrawal for the domestic, agricultural and industrial sectors (FAO, 2016). Moreover, it is acknowledged that climate change also influences GW systems, both directly through variations in recharge rates and indirectly through changes in GW use (Taylor et al., 2012).

The assessment of GW hydrodynamic behaviour is an essential starting point for highlighting the response of GW to natural and anthropic factors. Indeed, GW behaviour is a spatiotemporally complex and sensitive function of climate regimes, local geology and soil, topography, vegetation, surface-water hydrology, coastal flooding, and land use activities (Aureli and Taniguchi, 2006; Holman, 2006; McMahon et al., 2006; Green et al., 2007; Trenberth et al., 2007; Radfar et al., 2013).

The natural long-term fluctuations in GW levels depend on climate variability (Hanson and Dettinger, 2005; Anderson and Kustas, 2008; Gurdak et al., 2009) and on natural processes linked to climate variability, such as GW recharge, discharge, storage, and sea level fluctuations (Dong et al., 2012; Pholkern et al., 2018; Taminskas et al., 2018). GW recharge depends on the distribution, amount and timing of precipitation, evapotranspiration, losses from watercourses, snow cover thickness, snowmelt characteristics, land use, land cover and air temperature. Air temperature is the main factor that regulates snowmelt, evapotranspiration and anthropogenic water demand. For example, warmer winter temperatures can reduce the amount of ground frost and allow more water to infiltrate into the ground, resulting in increased GW recharge (Kløve et al., 2014). Recharge is affected by forecasted changes in precipitation patterns (Sharif and Singh, 1999). Different studies have revealed that fluctuations in GW levels are a direct response to seasonal precipitation (Ducci and Tranfaglia, 2008; Hiscock et al., 2012; Lutz et al., 2015; Lasagna et al., 2019a). Moreover, changes in the magnitude and timing of GW recharge and a shift in seasonal mean and annual GW levels were identified, depending on changes in the distribution of rainfall (Liu, 2011) and snow melt (Jyrkama and Sykes, 2007; Okkonen and Klove, 2010), as being due to climate change impacts.

Land use and urbanisation may amplify or hide GW responses to climate variability. Thus, in addition to climate variability, human impacts must be considered. Urbanisation can increase GW withdrawal due to enhanced human consumption (Taylor et al., 2012; Lasagna et al., 2014; De Luca et al., 2018; Lasagna et al., 2019b), leading to a piezometric level lowering. On the other hand, the presence of rice cultivation, irrigation and afforestation can increase recharge (De Luca et al., 2005; Chaves et al., 2012; Gning et al., 2017), thus influencing GW levels.

The GW hydrodynamic behaviour in space and time reflects climate variations and other global change drivers, including population growth, urbanisation and land use change (Taylor et al., 2012; Kløve et al., 2014; Taniguchi and Hiyama, 2014).

Accordingly, the aim of this paper is to classify and describe the GW table hydrodynamic behaviours, their spatial distribution and the controlling factors in the Piedmont Plain (NW Italy).

In particular, the Piedmont Plain is the westernmost part of the Po Plain and represents the largest and most important GW reservoir in the Piedmont region (Debernardi et al., 2008). This area has a strong agricultural vocation, with rice, maize and other cereal cultivations. More than half of the land and volume of rice production in Italy is in the Piedmont Plain (Unioncamere Piemonte, 2019).

The most recent climatic studies and models in the Mediterranean area suggest that future rainfall decreases, temperature increases and piezometric levels decrease (Polemio and Casarano, 2008; Chaouche et al., 2010; AllEnvi, 2016). In the Piedmont Plain, long time series studies of rainfall (reference period from 1939 to 2011) show a rainfall trend identifying both positive and negative slopes, depending on the area of the plain analysed. Moreover, a decrease in the amount of precipitation was highlighted (Acquaotta and Fratianni, 2013; Baronetti et al., 2018). Accordingly, there is widespread concern about the possibility of a progressive lowering of the water table level, which is also due to the increase in temperature (IPCC, 2007; Garzena et al., 2018) and the subsequent decrease in recharge, as well as the increase in the water demand and withdrawals. A decrease in the water table level may have serious environmental, economic and social consequences for both urban and rural communities.

Consequently, piezometric time series of the shallow unconfined aquifer, mainly consisting of coarse gravel and sand of fluvial or fluvioglacial origin, were analysed in this study to identify possible alterations in the quantitative state of GW in the plain. More specifically, the aim of this study is to identify the main change drivers and to advance the understanding of how GW systems are likely to respond to current pressures, especially those created by major land use and climate variability in the study area.

Water table levels recorded in monitoring wells and rainfall time series observed in rain gauges were analysed to recognise possible trends and to identify the hydrodynamic behaviours of the GW, their spatial distribution and rainfall regime. Moreover, water table levels and rainfall were analysed in two different time intervals (2002–2008 and 2009–2017) to highlight possible variations in the GW hydrodynamic behaviour and emphasize the dependence of the water table level on climate variability and land use modifications.

This study represents a first step aimed at achieving one of the IAH (International Association of Hydrogeologists) priority actions for global change and GW (IAH, 2016), which is stated as follows: “Investigation and long-term monitoring of groundwater systems are needed to establish their present resource status and flow dynamics and to confirm current trends in storage and quality changes”.

2. Study area

The Piedmont region, located in northwestern Italy, covers an area of approximately 25,400 km^2. This region includes mountains over approximately 43% of its territory and hills over 30% of the area. The plain, which represents the study area, covers 27% of the regional territory. The Piedmont Plain is the westernmost part of the Po Plain and is the most important GW reservoir of the region because of its size, the features of its deposits and the possibility of recharge (Debernardi et al., 2008; De Luca et al., 2014). The Piemonte Plain is surrounded by the Alps in the northern and western areas, and it is surrounded by the BTP (*Bacino Terziario Piemontese*) Hills in the southern and eastern sectors.

The hydrogeological conceptual model of the Piedmont Plain (Fig. 1) consists of superimposed hydrogeological units represented (from top to bottom) by a fluvial deposit unit; a glacial deposit and morainic hill

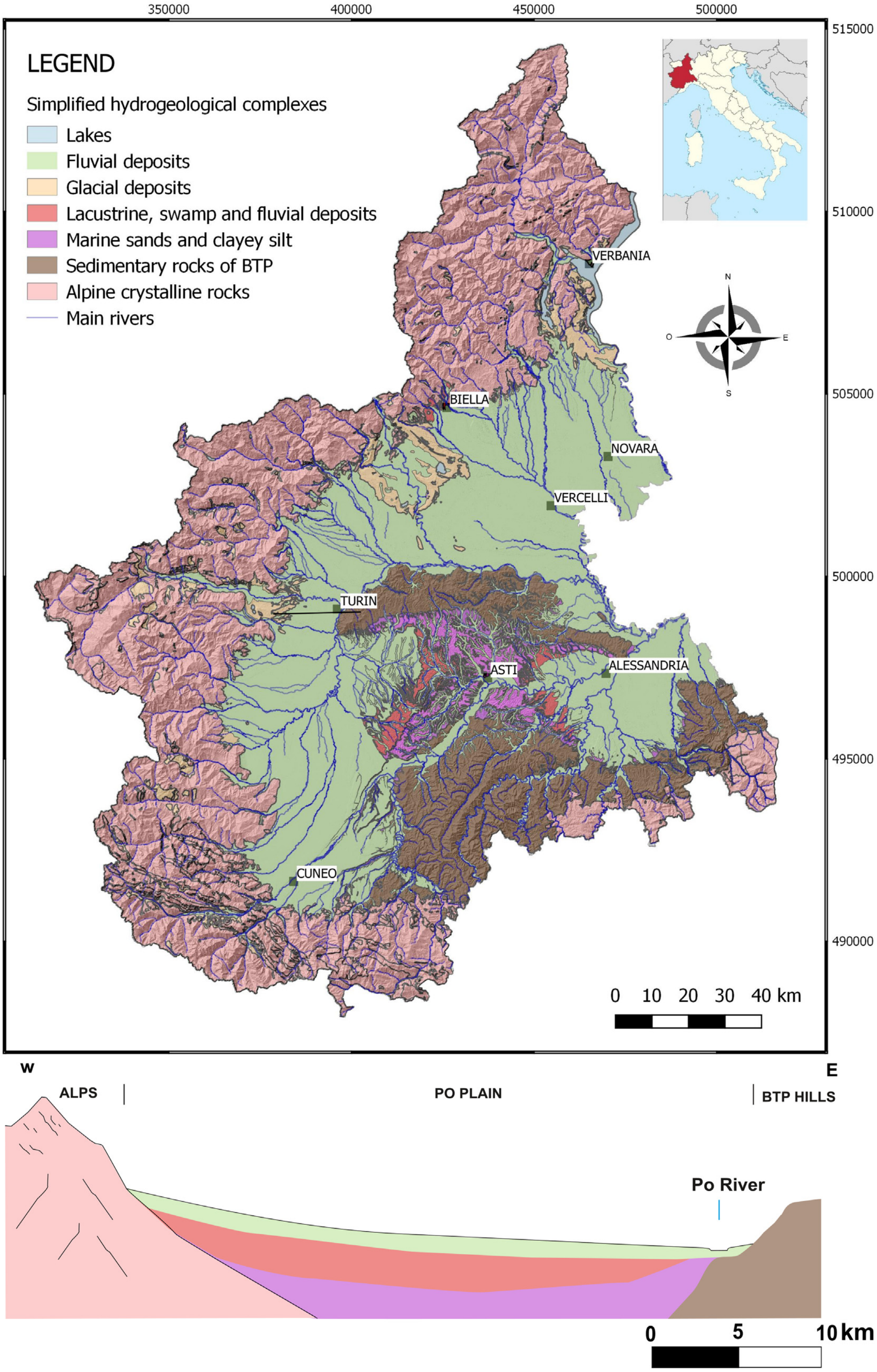


Fig. 1. Simplified hydrogeological map of the Piedmont region (NW Italy) (modified from http://www.geoportale.piemonte.it/). The cross section has a W-E orientation that passes through Turin city.

unit; a lacustrine, swamp and fluvial sediments unit; a marine sand and clayey silt unit; sedimentary rocks of the BTP unit; and an alpine crystalline rock unit (Bortolami et al., 1976; Bove et al., 2005; Castagna et al., 2015a, 2015b; Lasagna et al., 2016a; Piana et al., 2017; Forno et al., 2018; Lasagna et al., 2018; Martinelli et al., 2018; De Luca et al., 2019a; De Luca et al., 2020).

The fluvial deposit unit (Lower Pleistocene-Holocene) is composed of coarse gravel and sand of fluvial or fluvioglacial origin, with subordinate silty-clay intercalations. The grain size is variable and normally decreases from the mountains to the low plains. This unit has a thickness that generally ranges between 20 and 50 m, and the unit hosts a shallow unconfined aquifer. The productive levels cover approximately 75% of the unit.

The glacial deposit and morainic hill unit (Pleistocene) comprises heterogenic glacial deposits, such as silt and clay with sand, cobbles and blocks. The average thickness of the unit is approximately 80 m, with only 15% productive levels.

The unit comprising lacustrine, swamp and fluvial sediments (also called the Villafranchian series) (Upper Pliocene-Lower Pleistocene) consists of fluvial-lacustrine deposits characterised by alternations of silty-clayey and gravelly sandy horizons. This unit forms a multilayered, confined and semi-confined aquifer system, which is found irregularly beneath the Piedmont plain. The average thickness of this unit is 100 m, and the productive levels are 40%.

The marine sand and clayey silt unit (Pliocene) is represented by sediments with fine grain size (Lugagnano Clay) and fine sands (Asti sands). The average thickness is 100 m, with 35% productive levels. Important confined aquifers are present in these sand levels.

The sedimentary rocks of the BTP unit consist of fine-grained pre-Pliocene marine deposits (marls, conglomerate, sandy arenaceous formations and evaporitic deposits). These sediments, locally permeable by fissuration, have a notably low permeability and do not contain any significant aquifers.

Finally, the alpine crystalline rock unit consists of magmatic and metamorphic rocks. The alpine rocks are mostly impermeable or slightly permeable due to fissuration.

In this paper, the analysis of groundwater levels in an unconfined aquifer is reported. The unconfined aquifer has a high hydraulic conductivity that ranges between $5*10^{-3}$ and $5*10^{-4}$ m/s.

Recharge areas of the unconfined aquifer are mainly due to rainfall infiltration. Subordinately, rivers contribute to recharge in the high plain sectors, where streams lose water to the ground-water system. The low plain sectors are generally discharge areas, and the Po River represents the main regional discharge axis for groundwater flow (Lasagna et al., 2016b).

Turin city is the capital of the Piedmont region and located in the plain. This city is the fourth largest Italian municipality by population and is part of a large metropolitan area of approximately 2300 km^2 that contains nearly 2,000,000 inhabitants (Bartaletti, 2009). Turin city is the third largest economically productive complex in the country.

The Piedmont plain has a strong agricultural vocation (www.arpa.piemonte.it/reporting/rsa_2008/agricolt2008). Most of the Piedmont Plain is covered by arable lands (Fig. 2) that are characterised by cultivated land parcels under rainfed agricultural use for annually harvested non-permanent crops, which are normally under a crop rotation system. Fields with sporadic sprinkler irrigation systems that use non-permanent devices to support dominant rainfed cultivation are included (https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html). Cereals and legumes represent the main crops. Arable lands cover approximately 24% of the regional territory. A large part of the Vercelli and Novara plains is characterised by cultivated land parcels prepared for rice production, which consist of periodically flooded flat surfaces with irrigation channels (5% of the Piedmont territory). Vineyards and fruit trees are uniquely located on the hills of the Asti and Cuneo provinces and subordinately in the high plain areas (14% of the regional territory).

In the Piedmont, GW provides approximately 85% of the drinking water supply for the entire region (Arpa Piemonte, 2019). Industrial needs are almost completely satisfied by GW, which originates from the shallow unconfined aquifer and the semiconfined and confined aquifers. Regarding agricultural use, some water for crop irrigation (especially maize and rice) comes from surface water. Where surface water resources have scarce availability (e.g., some agricultural areas of the southern Piedmont in the Alessandria and Cuneo plains), a significant number of wells were drilled in the plain aquifers. Finally, GW greatly contributes to the feeding of surface water rivers (rivers and lakes).

The Piedmont region is located at the head of the Po Valley and is limited on three sides by mountain chains. This geography defines local circulations that favour the presence of microclimates.

The average annual cumulative precipitation over the 1957–2009 period on the Piedmont shows values higher than 1600 mm/year in the northern part of the region and quantities of less than 720 mm/year in the Alessandria Plain in the southeastern sector of the region (http://rsaonline.arpa.piemonte.it/meteoclima50/clima_ed_indicatori.htm).

The annual distribution of precipitation in the Piedmont Plain is characterised by a bimodal trend, with 2 maxima (spring and autumn) and 2 minima (winter and summer). The position of the main maximum, the secondary maximum and the main minimum indicate that the pluviometric rates are of the continental type (prealpine or subalpine) (Biancotti et al., 1998; Acquaotta and Fratianni, 2013; Baronetti et al., 2018).

In the Piedmont Plain, the minimum and maximum average monthly temperature for the 1958–2009 period indicates that July is the hottest month (Tmax = 28.5 °C and Tmin = 17.7 °C) and January is the coldest month (Tmax = 5, 7 °C and Tmin = −0.8 °C). The spatial distribution of annual average temperatures over the 1957–2009 period shows that on the Piedmont Plain, the highest average temperature values are in the eastern and southern parts of the plain.

The analysis of the annual average temperature anomalies in the Piedmont, which were calculated from 1958 to 2015, shows a trend reversal over the past twenty years, with an estimated total increase in temperature of approximately 1.2 °C in 50 years (http://rsaonline.arpa.piemonte.it/meteoclima50/clima_ed_indicatori.htm). The data indicate that this increase is mainly concentrated in the winter, spring and summer months and that the years after 1985 show a more marked average increase in temperature.

3. Methods

The studied piezometric time series are from monitoring wells in the automatic monitoring network of the shallow aquifer in the Piedmont region (De Luca et al., 2019b). More specifically, the water table levels in 37 piezometers, which are homogeneously distributed in the shallow unconfined aquifer of the Piedmont Plain, were analysed (Fig. 3). The piezometers belong to the ARPA (Regional Agency for the Protection of the Environment) Piedmont monitoring network, and data are available on the web (http://www.regione.piemonte.it/monitgis/jsp/cartografia/mappa.do). The typical depth of the piezometers ranges from approximately 30 to 50 m, and the screens are in the unconfined aquifer.

Rainfall time series from 30 rain gauges managed by ARPA Piedmont were also studied (Fig. 3).

The monitoring period for both the water table level and rainfall is 2002–2017. The groundwater monitoring network in the Piedmont Plain has been active since 2000, but the piezometers were drilled in different time steps. Consequently, data elaboration was performed on a shorter period (starting in 2002) to analyse data with a high completeness index (CI). The completeness index represents the ratio of the number of daily piezometric data out of the total number of data in the measuring period (ISPRA, 2013), according to the following equation:

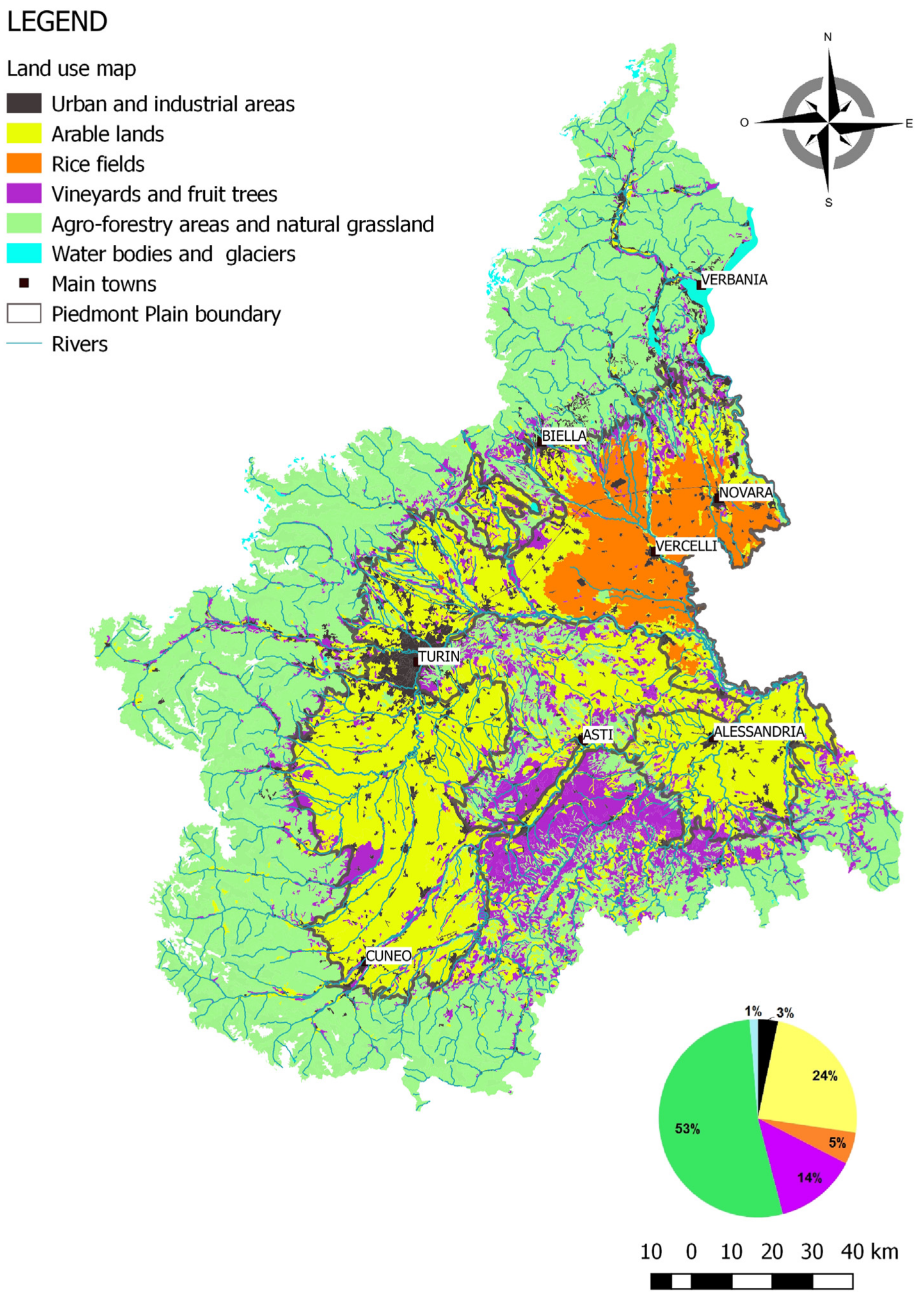


Fig. 2. Land use map of the Piedmont region (modified from Corine Land Cover, http://groupware.sinanet.isprambiente.it/uso-copertura-e-consumo-di-suolo/library/copertura-del-suolo/corine-land-cover) and land use percentage compared to the regional territory.

$$CI = (\text{number of available piezometric data} / \text{maximum number of data in the considered interval}) * 100.$$

The piezometric time series of the monitoring wells are characterised by a CI greater than 85%. The rainfall time series has a CI equal to 100%. The water table levels collected for each piezometer were measured at the hours of 6 a.m., 12 a.m., 6 p.m. and 12 p.m. during the day, and the average daily piezometric level was calculated. An example of daily time series for two typical piezometers is illustrated in Supplementary material 1 to highlight the actual intra and interannual variations.

Daily piezometric data and daily rainfall data were aggregated at the monthly time step (monthly piezometric level and cumulative monthly rainfall).

First, a trend analysis was performed for 10 groundwater level time series, which are referred to as representative piezometers in the Piedmont Plain, and for 10 rainfall time series for the interval period of 2002–2017. To quantify the time series data trend, the Mann-Kendall test was used. The Mann-Kendall test (Mann, 1945; Kendall, 1975) is widely used in the field of water resources and in climatic studies (Wu et al. 2008; Jain and Kumar 2012; Patle et al. 2015). To assess the significance of the trend test, the null hypothesis Ho (where the variable does not possess a trend) is tested against the alternative hypothesis H1 (where the variable has a trend). When the null hypothesis H0 is not rejectable, the data do not present a significant trend; when the null hypothesis is rejected at the 5% significance level, the data present a significant trend.

Second, the average 2002–2017 monthly piezometric level and average cumulative 2002–2017 monthly rainfall were computed to identify

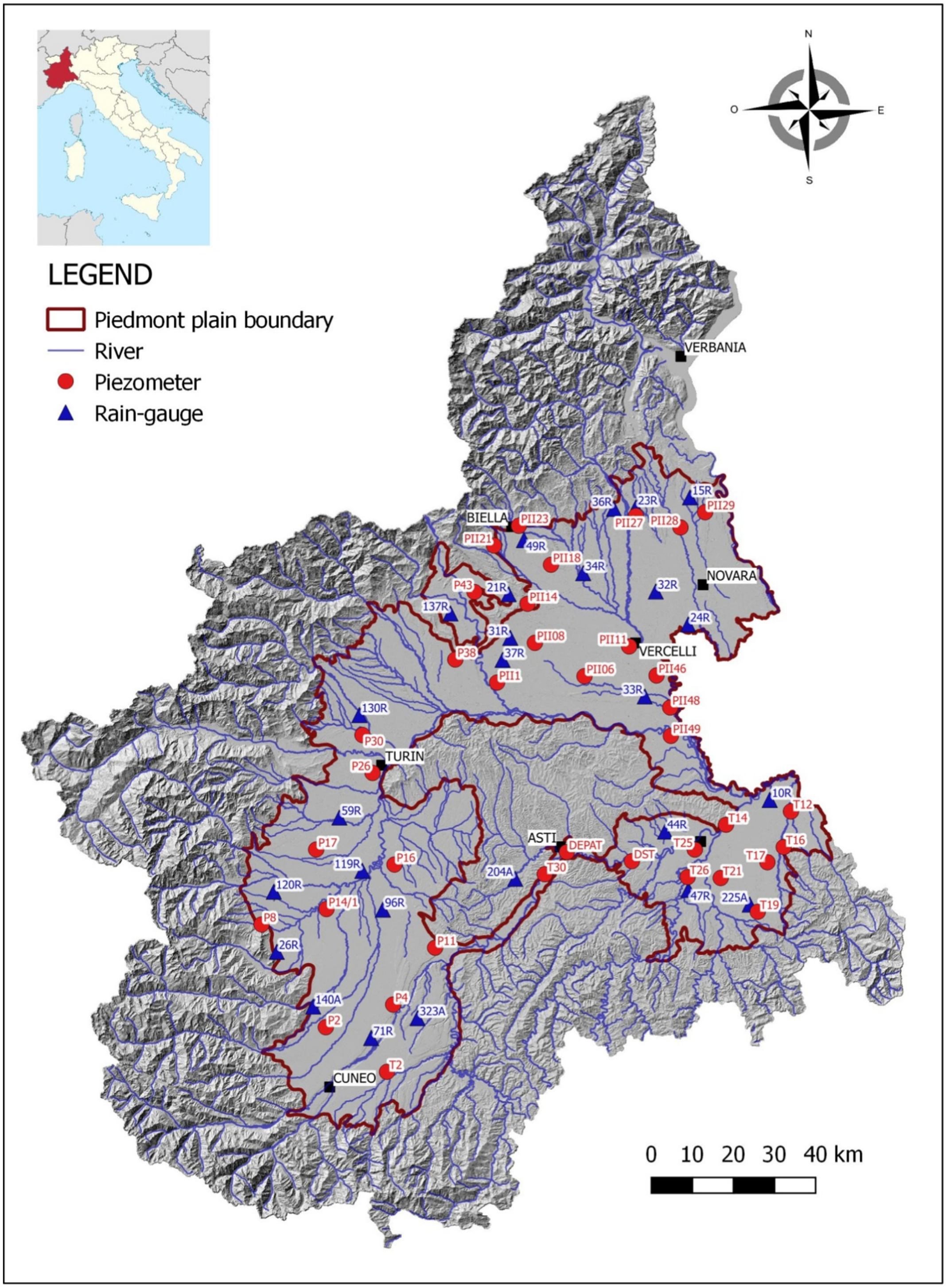


Fig. 3. Location map of monitoring wells and rain gauge networks.

the hydrodynamic behaviours of the GW, their spatial distribution and rainfall regime. Both the average monthly piezometric levels and the average cumulative monthly rainfall from 2002 to 2017 were plotted versus time (from January to December). Then, the hydrodynamic behaviours of the GW table, which provides a qualitative description of water table levels during the year, were classified based on two main criteria: the presence of maxima and minima and the time position of the maxima and minima during the year. The different monitoring wells, characterised by different types of hydrodynamic GW table behaviours, were plotted on a map to evaluate their spatial distribution. A comparison between their location and land use (i.e., agricultural practices) was also made. Finally, a comparison between the average monthly piezometric levels in 2002–2017 and the rainfall regime was performed by comparing the positions of the maxima and minima for the piezometric and pluviometric series. This analysis permitted us to determine whether the GW level changes were correlated with precipitation.

To confirm the possible relationship between rainfall and water table level, the standardised anomalies of the cumulative annual rainfall and mean annual GW levels for the 2002–2017 period were analysed. The standardised anomalies are a dimensionless measure of distance between a data value and its mean. These anomalies are calculated by

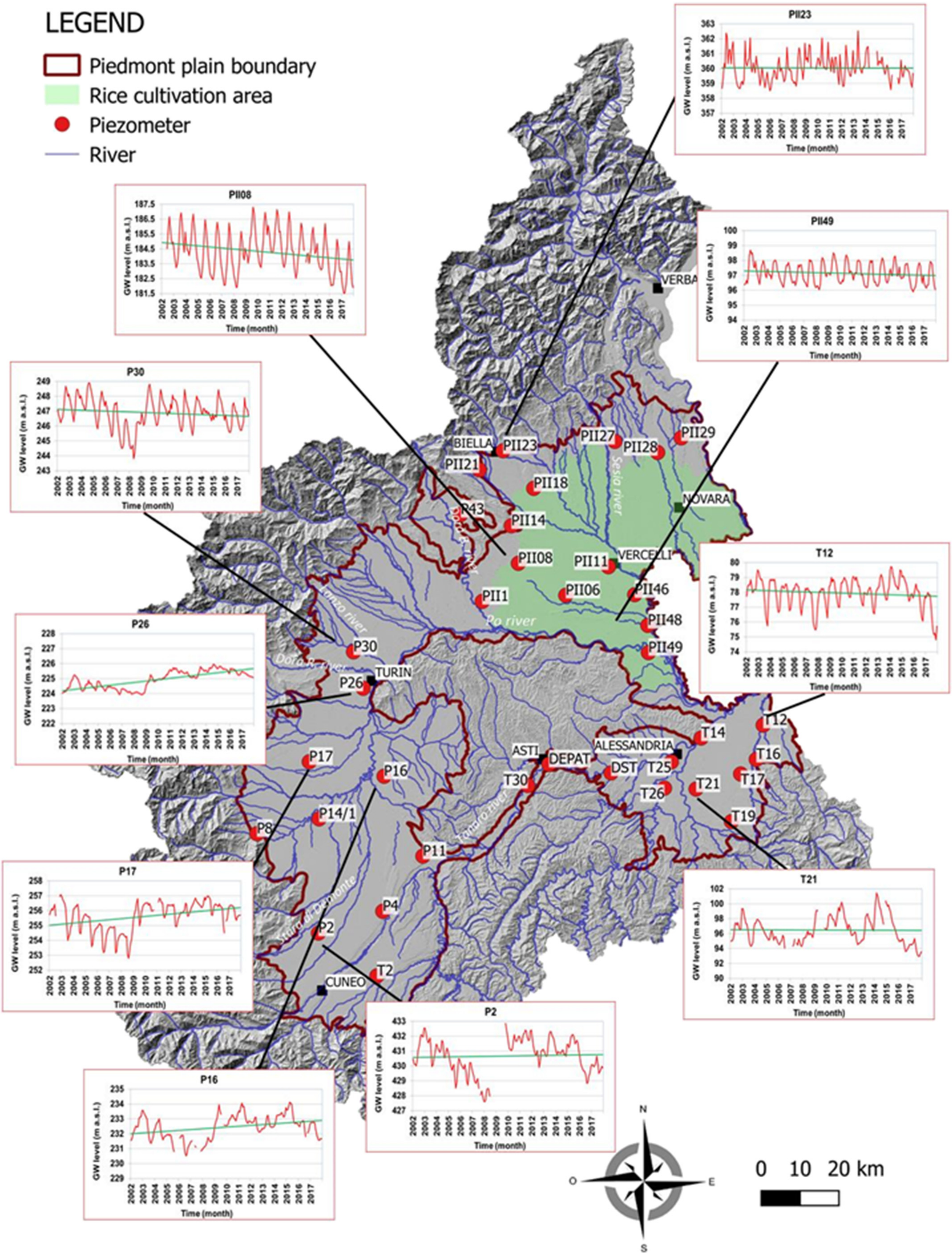


Fig. 4. Spatial distribution of the groundwater table trend computed for the 2002–2017 period. Some examples of different trends are displayed on the map.

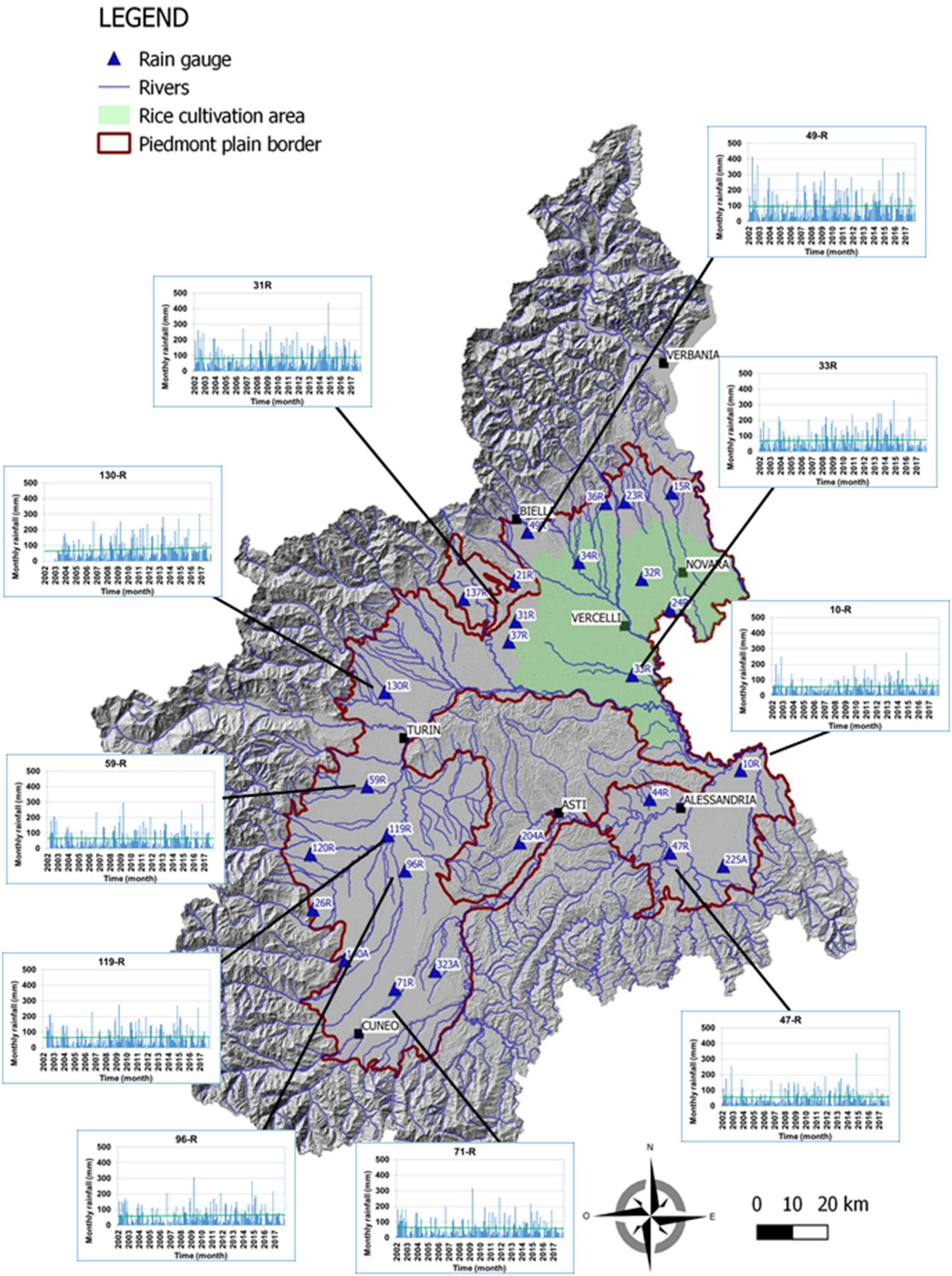


Fig. 5. Spatial distribution of monthly rainfall computed for the 2002–2017 period. Some examples of different trends are displayed on the map.

subtracting the mean from the observed data and then dividing by the standard deviation. These measurements permitted easier discernment between normal and unusual values. Standardised anomalies were largely used for climatic studies (Gagnon et al., 2001; Kennedy et al., 2015; Montazerolghaem et al., 2016). In this study, the normalisation procedure was performed according to the equation $A = (Xi - Mi) / \sigma i$, in which A refers to the resulting anomalies. The terms Xi, Mi, and σi refer to the observed value, the long-term mean value, and the standard deviation, respectively. More specifically, Xi and Mi correspond to cumulative annual rainfall and mean cumulative annual rainfall for the 2002–2017 period in the rainfall standardised anomalies. These variables refer to the mean annual GW level and mean annual GW level for the 2002–2017 period in the GW level anomalies. The standardised anomalies of rainfall and GW level were compared to facilitate the identification of wet and dry years, as well as the GW level variation tendency.

Finally, an analysis was conducted to observe the correlation between rainfall and GW level at the monthly level. More specifically, for the time series referring to rainfall and water table levels, the cumulative monthly rainfall was calculated in correspondence with the period between the minimum and the maximum water table levels (generally between January and April–May for group A and between April and July–August for group B). The cumulative rainfall (in mm) was calculated for each year in the 2002–2017 period. Moreover, the corresponding water level rise was calculated (in m). Finally, correlation plots were used to investigate the dependence between the water level rise and the rainfall in each analysed year, and the coefficients of determination and correlation were evaluated.

Finally, a change point analysis (CPA) was performed. The CPA is a statistical analysis for the identification of sudden changes (change points) in a time series. The CPA has been used in the field of meteorology to analyse changes in air temperature and seasonal rainfall (Tomozeiu et al., 2000; Reeves et al., 2007), carbon dioxide concentration (Costa et al., 2016), in studies of financial markets (Andreou and Ghysels, 2002), and for GW resource analysis (Zarenistanak et al., 2014; Yeh et al., 2016; Shih et al., 2019). In this study, a CPA was applied to search for potential significant changes in the monthly groundwater levels and cumulative monthly rainfall time series collected in piezometers and rain gauges of the Piedmont Plain. More specifically, the analysis was performed by ordering the data according to time; then, data were tested by the statistical non-parametric Pettitt test (Pettitt, 1979). Subsequently, the identified change points were used to divide the piezometric level and rainfall time series in the given subperiods. An analysis of GW hydrodynamic behaviour over time during the different subperiods was performed using average monthly piezometric levels. Moreover, the average cumulative annual rainfall was also calculated in the different subperiods for all rain gauges, and a comparison was performed between the subperiods.

Finally, a comparison was conducted between the GW hydrodynamic behaviour and rainfall regime in the analysed sub-periods to identify where rainfall influences the water table level regime.

4. Results and discussion

4.1. GW and rainfall trends in the Piedmont Plain

Table 1

Results of the Mann-Kendall tests (tau and p-value) of groundwater level trend analysis for the 2002–2017 period. Tau varies between −1 and +1 and indicates the sign and magnitude of the trend. The p-value measures the level of significance of the statistical test. H0 is the null hypothesis: when the null hypothesis H0 is not rejectable, the data do not present a significant trend; when the null hypothesis is rejected at the level of significance of 5%, the data present a significant trend.

Piezometer	Mann-Kendall test - groundwater level trends for 2002–2017		
	Tau	p-Value	Test results
T21	−0,043	0,397	Hypothesis H0 not rejectable
T12	−0,084	0,085	Hypothesis H0 not rejectable
P2	−0,058	0,253	Hypothesis H0 not rejectable
P16	0,181	0,000	*Hypothesis H0 rejectable*
P17	0,211	0,000	*Hypothesis H0 rejectable*
P26	0,462	0,000	*Hypothesis H0 rejectable*
P30	−0,120	0,013	*Hypothesis H0 rejectable*
PII08	−0,162	0,001	*Hypothesis H0 rejectable*
PII23	0,020	0,697	Hypothesis H0 not rejectable
PII49	−0,095	0,049	*Hypothesis H0 rejectable*

Trend analyses highlighted the presence of an upward trend in 30% of the GW level time series (variation between 3.6 cm/year and 11 cm/year in the piezometers) and a downward trend in 30% of the GW level time series (variation between 2.9 cm/year and 7.3 cm/year) during the 2002–2017 period (Fig. 4). No trend was observed in 40% of the analysed piezometers over the entire period. Rainfall generally showed no trend (Fig. 5). The results of the trend analyses for the groundwater level time series and the rainfall time series are shown in Tables 1 and 2, respectively. The tables show the results (tau and p-value) of the nonparametric Mann-Kendall test. The spatial distribution of the GW level trend shows a negative trend in the southern Vercelli and northern Turin plains and a positive trend in the southern Turin and Cuneo Plains. No trend was observed in the southern Cuneo, Alessandria and Biella Plains.

Positive or negative trends in GW levels have been observed in many regions worldwide. Negative trends were observed in Bangladesh (Rahman et al., 2016), the Indian subcontinent (Rodell et al., 2009; Tiwari et al., 2009; Thakur and Thomas, 2011; Singh and Kasana, 2017), North Africa (Lutz et al., 2015), in Turkey (Apaydin, 2009) and the USA (Zwilling et al., 1989). Additionally, in southern Italy, a great decreasing piezometric trend was observed in Apulia and in Campania (Polemio and Casarano, 2008; Polemio, 2016; Ducci and Polemio, 2018). The main reasons are generally due to two different causes: extensive groundwater withdrawal and a decreasing trend in rainfall.

An increasing GW level trend was observed in the Illumeden Basin of sub-Saharan Africa (Favreau et al., 2012) due to a change in land use (land clearing). In northern Italy (Milan area), a gradual increase in piezometric levels since 1979 was observed, and this increase is strictly connected to the reduction in groundwater withdrawals (Bonomi, 1999). Moreover, groundwater level trends in shallow aquifers can be strictly connected to rainfall, as demonstrated in Asian megadeltas, where GW levels are highly seasonal as a result of intensive precipitation during the annual monsoon

Table 2

Results of the Mann-Kendall tests (tau and p-value) of rainfall time series trend analysis for the 2002–2017 period. Tau varies between −1 and +1 and indicates the sign and magnitude (strength) of the trend, and p-value measures the level of significance of the statistical test. H0 is the null hypothesis: when the null hypothesis H0 is not rejectable, the data do not present a significant trend at the 5% significance level.

Rain gauge	Mann-Kendall test - rainfall time series trends of 2002–2017		
	Tau	p-Value	Test results
59R	−0,005	0,913	Hypothesis H0 not rejectable
96R	0,053	0,271	Hypothesis H0 not rejectable
119R	0,019	0,704	Hypothesis H0 not rejectable
130R	0,078	0,120	Hypothesis H0 not rejectable
31R	0,034	0,480	Hypothesis H0 not rejectable
49R	0,035	0,471	Hypothesis H0 not rejectable
33R	0,003	0,952	Hypothesis H0 not rejectable
10R	0,035	0,473	Hypothesis H0 not rejectable
225A	−0,014	0,781	Hypothesis H0 not rejectable
140A	0,072	0,148	Hypothesis H0 not rejectable

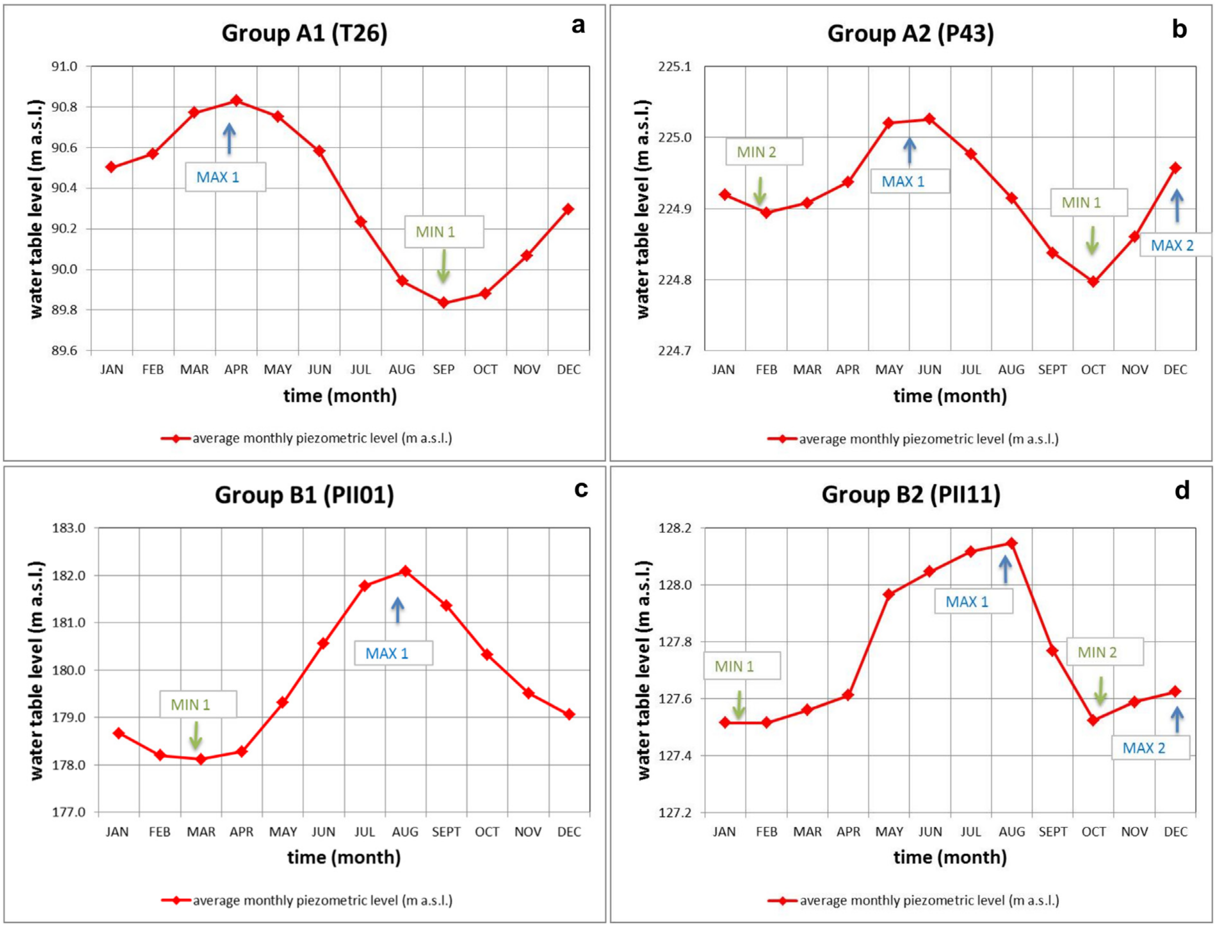


Fig. 6. Example of the hydrodynamic behaviours of subgroups A1 (monitoring well T26 in panel a), A2 (monitoring well P43 in panel b), B1 (monitoring well PII01 in panel c) and B2 (monitoring well PII1 in panel d) for the Piedmont Plain.

season (Klump et al., 2006; Mukherjee et al., 2007; Larsen et al., 2008; Norrman et al., 2008; Berg et al., 2008).

The trend distributions, both positive and negative, in the Piedmont Plain GW levels and the lack of a rainfall trend indicate that rainfall is not the only cause of the rise or decline in GW levels.

4.2. Hydrodynamic GW table behaviours and rainfall regimes in the Piedmont Plain

Two main groups of GW hydrodynamic behaviours based on the water table levels were classified in the Piedmont Plain, considering the presence of 1 or more than 1 maximum and minimum and their time position during the year (Fig. 6):

(1) Group A is characterised by the presence of a main maximum in spring and a main minimum at the end of summer – start of autumn and sometimes a secondary maximum and minimum; and
(2) Group B is represented by a main maximum in summer and a main minimum at the end of winter - start of spring and sometimes a secondary maximum and minimum.

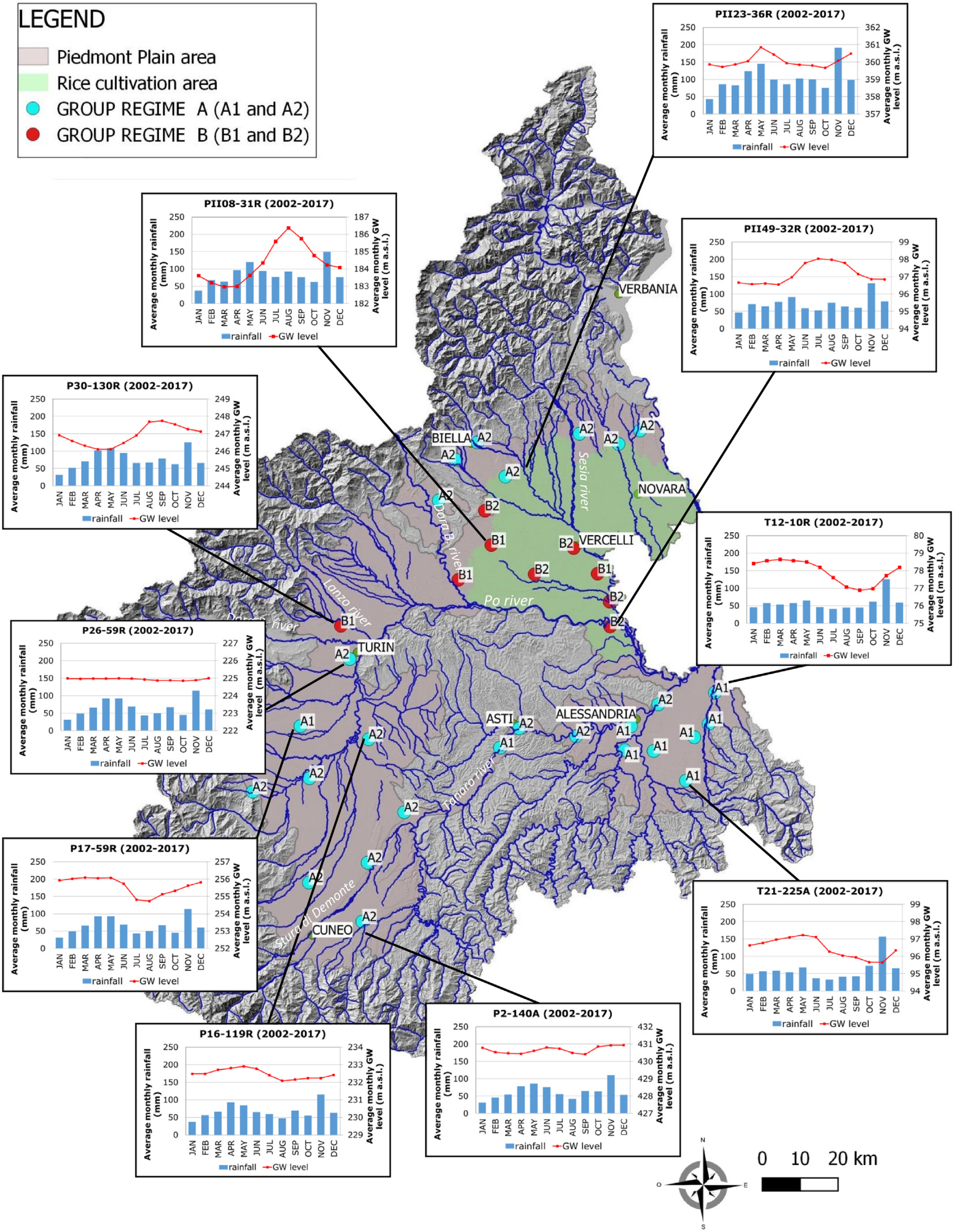
Moreover, some subgroups (A1, A2, B1 and B2) of piezometric regimes were recognised, according to the number and time position of the minimum and maximum piezometric levels in the year. More specifically,

- Subgroup A1 = 1 main maximum in spring and 1 main minimum in summer-start of autumn;
- Subgroup A2 = 1 main maximum in spring and 1 main minimum in summer-start of autumn, with a secondary maximum in December and a secondary minimum in February;
- Subgroup B1 = 1 main maximum in summer and 1 main minimum at the end of winter-start of spring; and
- Subgroup B2 = 1 main maximum in summer and 1 main minimum at the end of winter-start of spring, with a secondary maximum in December and a secondary minimum in October–November.

For clarity, one piezometer was selected in each group to illustrate the general behaviour (Fig. 6).

The rainfall pattern in the Piedmont Plain shows a main isolated maximum in November, a secondary maximum in spring and usually a main minimum in January and a secondary minimum in summer (Fig. 7). The amount of annual average rainfall varies from minimal

Fig. 7. Spatial distribution of different subgroups of GW hydrodynamic behaviours. Some examples of the different subgroups are displayed in the graphs with the corresponding average cumulative monthly rainfall (analysed during the 2002–2017 period). Rice fields in the Vercelli and Novara plains are described by a green area (referred to year 2012, modified from http://groupware.sinanet.isprambiente.it/uso-copertura-e-consumo-di-suolo/library/copertura-del-suolo/corine-land-cover). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)


LEGEND
Piedmont Plain area
Rice cultivation area
GROUP REGIME A (A1 and A2)
GROUP REGIME B (B1 and B2)
PII23-36R (2002-2017)
PII08-31R (2002-2017)
PII49-32R (2002-2017)
P30-130R (2002-2017)
T12-10R (2002-2017)
P26-59R (2002-2017)
P17-59R (2002-2017)
T21-225A (2002-2017)
P2-140A (2002-2017)
P16-119R (2002-2017)
Average monthly rainfall (mm)
Average monthly GW level (m a.s.l.)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
rainfall
GW level
VERBANIA
BIELLA
NOVARA
VERCELLI
TURIN
ASTI
ALESSANDRIA
CUNEO
Sesia river
Dora B. river
Po river
Lanzo river
Dora R. river
Tanaro river
Stura di Demonte
A1
A2
B1
B2
N
O
E
S
0 10 20 km

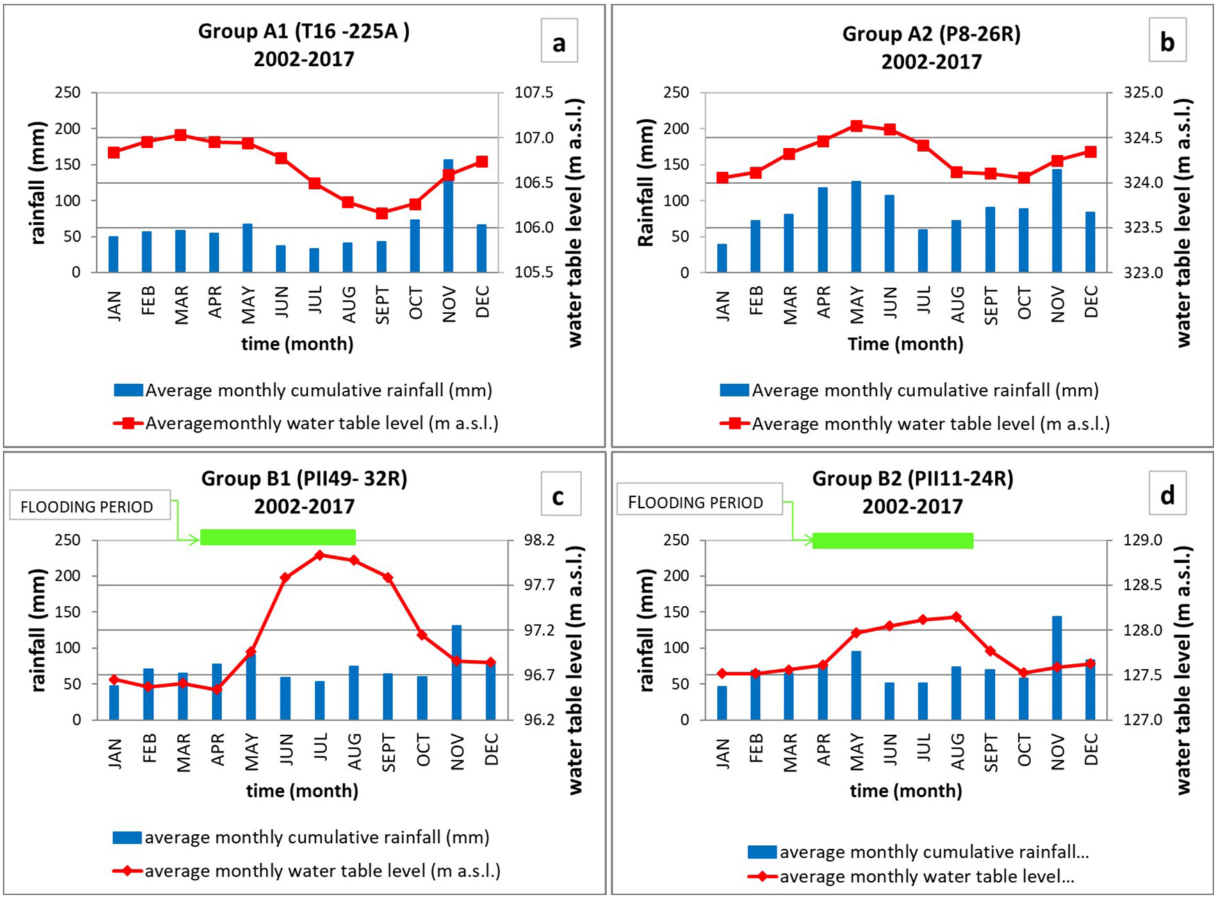


Fig. 8. Comparison between the average monthly water table level and average cumulative rainfall (analysed period is 2002–2017) for monitoring wells of groups A and B (monitoring well T16 and rain gauge 225A as an example of subgroup A1 in panel a; monitoring well P8 and rain gauge 26R as an example of subgroup A2 in panel b; monitoring well TII49 and rain gauge 32R as an example of subgroup B1 in panel c; and monitoring well PII11 and rain gauge 24R as an example of subgroup B2 in panel d). An indication of the flooding period in the rice area is also shown.

values of 500–800 mm/y in the southern part of the Piedmont Plain (Asti and Alessandria Plains), medium values between 550 and 900 mm/y in the central part of the Piedmont Plain (Cuneo and southern Turin Plains), and maximal values between 750 and 1200 mm/y in the northern part of the Piedmont Plain (Novara, Vercelli and Biella Plains).

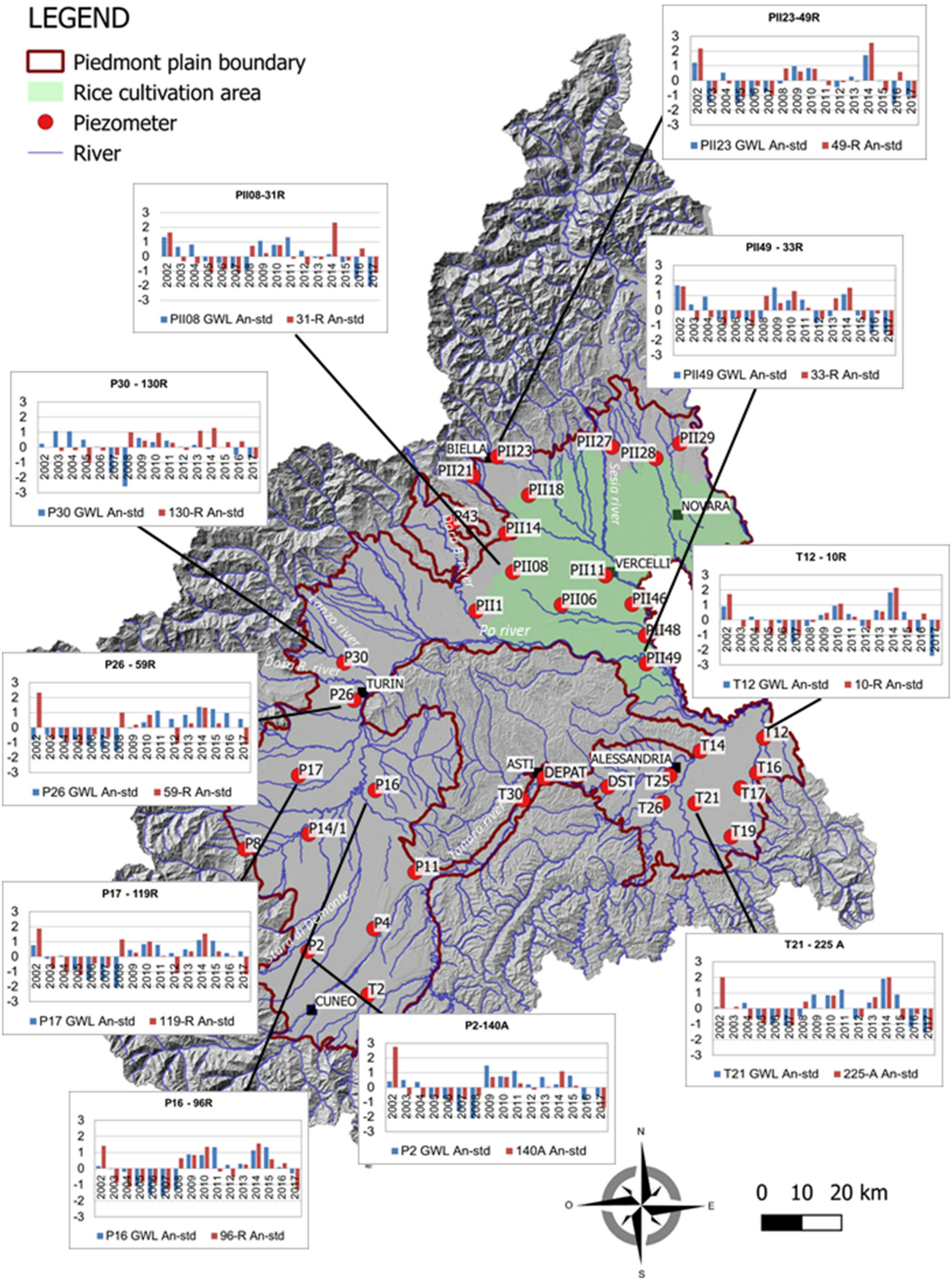
Analysing the distribution of the different hydrodynamic behaviours on a regional scale, it is possible to observe that most monitoring wells belonging to Group B are located within paddy fields in the Novara and Vercelli Plains (Fig. 7). Monitoring wells of Group A are distributed in the rest of the Piedmont Plain.

A comparison of different groups of hydrodynamic behaviours with the rainfall regime highlights the relationship between the rainfall and water table level. In general, the monitoring wells with hydrodynamic behaviour A show a water table level trend similar to the rainfall trend, and often, an approximately 1 month delay in the response is observed (Fig. 8a and b). Lag times between groundwater-level response times to rainfall are primarily attributed to lithological controls on the transmission of rain-fed recharge and thickness of the unsaturated zone (Kotchoni et al., 2019). Similar lag times (less than 17 days) were observed in a sedimentary aquifer in Benin (Kotchoni et al., 2019). A lack of correlation between the precipitation amounts and the GW level was reported in Eastern Romania due to the lithological constitutions of geological formations (mostly loess deposits). According to the author (Dragusin, 2015), the precipitation recharge period could be longer than 1 year in this region, and this phenomenon explains the lack of correlation.

Almost all the piezometric series with the GW hydrodynamic behaviour in group A show an absolute maximum in spring, corresponding to a rainfall secondary maximum, and an absolute minimum at the end of summer-early autumn, corresponding to a rainfall minimum. Some piezometric series show a secondary maximum in December that is related to the maximum rainfall in November.

Monitoring wells in group B show the opposite behaviour with respect to the rainfall regime, especially in the spring-summer period, where the maximum in the piezometric level is recorded in correspondence to the rainfall minimum (Fig. 8c and d). The generally different GW behaviour of group B with respect to the rainfall regime could be explained by land use. Indeed, in paddy fields, where the monitoring wells of group B are located, the submersion irrigation method is used. This method involves permanent flooding of the rice fields, which provides optimal thermal conditions for rice

Fig. 9. Standardised anomalies for cumulative annual rainfall (in red) and mean annual GW levels (in blue) for the 2002–2017 period in ten locations of the Piedmont Plain. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)


LEGEND
Piedmont plain boundary
Rice cultivation area
Piezometer
River
PII23-49R
PII23 GWL An-std
49-R An-std
PII08-31R
PII08 GWL An-std
31-R An-std
PII49 - 33R
PII49 GWL An-std
33-R An-std
P30 - 130R
P30 GWL An-std
130-R An-std
T12 - 10R
T12 GWL An-std
10-R An-std
P26 - 59R
P26 GWL An-std
59-R An-std
P17 - 119R
P17 GWL An-std
119-R An-std
T21 - 225 A
T21 GWL An-std
225-A An-std
P2-140A
P2 GWL An-std
140A An-std
P16 - 96R
P16 GWL An-std
96-R An-std
3
2
1
0
-1
-2
-3
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
BIELLA
PII23
PII27
PII28
PII29
PII21
PII18
Sesia river
NOVARA
P43
Dora B. river
PII14
PII08
PII11
VERCELLI
PII1
PII06
PII46
Po river
PII48
PII49
Stura di Lanzo river
P30
Dora R. river
TURIN
P26
T12
T14
ASTI
DEPAT
ALESSANDRIA
T16
P17
P16
T30
DST
T25
T26
T21
T17
P14/1
Tanaro river
T19
P8
P11
P4
Stura di Demonte
P2
T2
CUNEO
N
O
E
S
0 10 20 km

growth and helps to control weeds. The water obtained from rivers in the northern part of the study area is distributed through a network of channels managed by local irrigation authorities (*Consorzi d'irrigazione*). Flooding starts in early April in the northern part of the rice district (closer to the irrigation sources) and reaches the southern part around the end of April. Rice is sown in water, and submersion lasts until August, which is when the paddies are left to gradually dry (Romani, 2008).

The GW hydrodynamic behaviour is directly influenced by paddy field flooding, and the effects of the irrigation water infiltration into the subsoil are evident in Fig. 8c and d. In particular, the piezometric level rise is generally observed in the second half of April, even during the driest years. The water table level generally shows a gradual rise until August, with a GW delay with respect to the start of flooding that is generally less than one month. When the water is removed from the rice paddies at the end of August, due to the interruption of the continuous and direct artificial water supply, the water table level tends to fall.

The effect of submersion irrigation on the water table level was observed in all the monitoring wells located in the rice area. Short and intense rainfall events during summer are obliterated by this anthropic activity. The lowering of the water table continues until March, when it is possible to observe the absolute minimum. In the A2 and B2 subgroups, abundant November rainfall is the cause of a water table maximum, which generally registers in December.

The standardised anomalies of cumulative annual rainfall and mean annual GW levels for the 2002–2017 period permitted us to observe a relationship between rainfall and water table level at the yearly scale. The standardised anomalies relating to rainfall and GW level generally show the same sign (negative or positive) with respect to the corresponding reference value in nearly all the Piedmont Plain (Fig. 9). A positive standardised anomaly, corresponding to a wet period with a high GW level, was observed in 2002, 2009–2011, and 2013–2014. A negative standardised anomaly, consistent with a dry period with a low GW level, was registered in 2003–2008 and 2017. The year 2015 shows a positive standardised anomaly for rainfall and GW level in the Turin and Cuneo Plains. A negative standardised anomaly was registered in the same year in the Vercelli, Biella and Alessandria Plains. A different sign for the standardised anomaly relating to rainfall and GW level was observed locally in 2012 and 2016. The general consistency between rainfall and GW level tendencies indicates a direct relationship between these parameters at the yearly scale.

The analysis conducted at a monthly level permitted us to observe a more precise relationship between GW level and rainfall. More specifically, correlation plots showed an overall positive correlation at most of the piezometers located in the Piedmont Plain. However, a lower correlation was observed in correspondence with the wells located in the rice paddy area. As an example, correlation plots for piezometers T16 and PII49 (whose GW hydrodynamic behaviours are described in Fig. 8) are reported in Fig. 10. Piezometer T16 is located in the Alessandria Plain. The coefficient of determination R^2 was 0.71. This value supports a good correlation between the analysed parameters (correlation coefficient $r = 0.84$). In contrast, in piezometer PII49, which is placed in the centre of the rice area in the Vercelli Plain, the coefficient of determination R^2 was 0.16, and the correlation coefficient r was 0.40. Consequently, it is possible to conclude that groundwater level and rainfall are poorly correlated at the seasonal scale, despite the general consistency between the rainfall and GW level tendencies obtained by analyses at the yearly scale. In the rice area, the water table rise in the summer period is probably not only due to rainfall infiltration but is more markedly related to flooding of the rice fields.

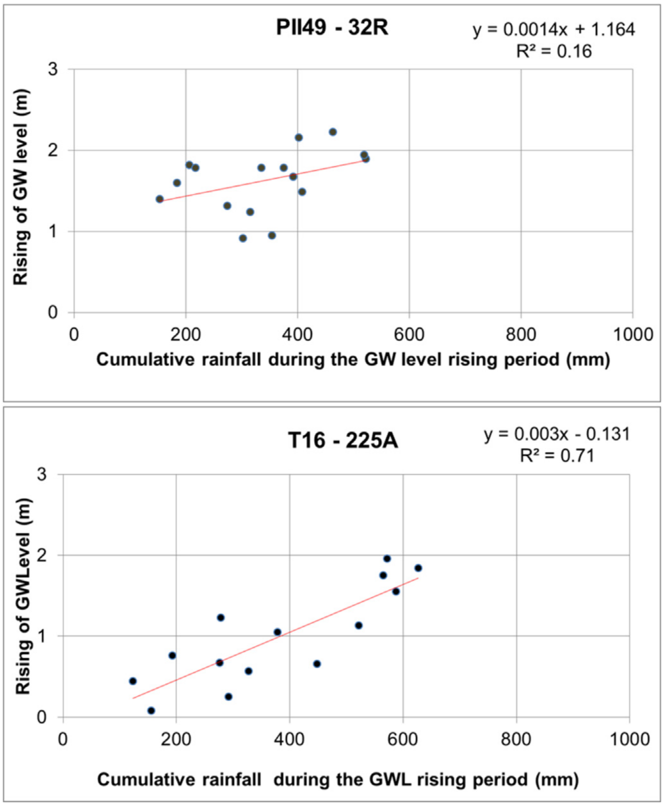


Fig. 10. Correlation plots between the cumulative monthly rainfall (calculated in the period between the minimum and maximum water table levels) and the corresponding water level rise for piezometer T16 and rain gauge 225A (Alessandria Plain) and piezometer PII49 and rain gauge 32R (Vercelli Plain).

These results are consistent with previous studies on paddy rice fields. More specifically, recharge of aquifers due to the flooding of rice fields was observed by Guerra et al. (1998), Tuong (1999), Cabangon and Tuong (2000), Bouman et al. (2001), and Belder et al. (2004). Adarsh and Thomas (2019) reported that in rice cultivation areas, 60% of the irrigation water is used by the plants and the remaining 40% of water filters through the soil to recharge the aquifer below. Iwasaki et al. (2013) compared the groundwater level in paddy fields during irrigation and non-irrigation periods and observed groundwater levels of approximately 5 m higher during the irrigation period than during the non-irrigation period, highlighting the significant contribution of paddy irrigation water to groundwater recharge.

4.3. CPA

The CPA highlighted a change point in nearly all the analysed groundwater level time series in the 2008–2009 period. More specifically, a change point was observed in more than 80% of the analysed piezometers. This change point corresponds to passage from a strong lowering to a sudden and considerable rise in the groundwater level (Fig. 11). The 2008 change point was also detected in 88% of the rainfall time series for the Piedmont Plain, confirming the strong relationship between rainfall and GW level. According to the change point spatial distribution, it is possible to identify two areas of the plain that are characterised by a temporally defined rainfall change point. The central-northern sector of the plain (Vercelli and Novara Plains, Turin Plain and the northern Cuneo Plain) shows a change point in March 2008. The southern sector of the plain (Alessandria and southern areas of the Cuneo Plain) shows a change point in

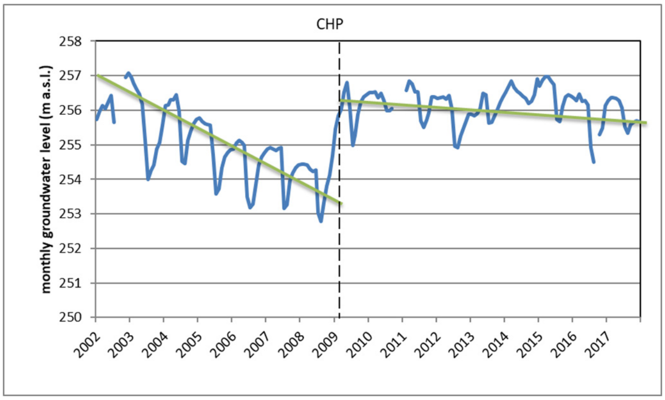


Fig. 11. Example of change points in the groundwater level time series and trend line (gray line) for 2008–2009 of the two identified subperiods.

October 2008. The results of the CPA are shown in Supplementary material 2 (Tables 1 and 2) for the piezometric and pluviometric series, respectively.

The comparison between the 2008 change point of piezometric level (chp P) and rainfall (chp R) time series shows a delay. The delay is detected in the groundwater level series and varies from approximately 0 to 6 months depending on the monitoring point. In a few piezometers, the change points detected in the piezometric series showed a delay of over 1 year compared to the rainfall change points.

The magnitude of the delays between the piezometric and pluviometric change points could provide indications of aquifer recharge by rainfall. Minor delays (0–3 months) could indicate recharge of the aquifer mainly due to rain (Alessandria Plain). High delays (over 3–6 months) could indicate that the change in level also depends on other factors, such as irrigation.

The CPA permitted us to divide the analysis period (2002–2017) into two subperiods of 2002–2008 and 2009–2017, which were used for further elaborations.

4.4. Variations in hydrodynamic behaviours over time

The analysis of the average 2002–2008 and 2009–2017 monthly piezometric levels highlighted some notable results related to a) the changes in the magnitudes of the average annual and monthly piezometric levels; b) the change in the period amplitude of high piezometric levels; and c) the time shifting of the GW level maxima.

4.4.1. Changes in magnitudes of the average monthly piezometric levels

In most of the monitoring wells, it was observed that the most recent period (2009–2017) is characterised by higher average monthly piezometric levels compared to those in the previous period of 2002–2008. More specifically, 31% of the analysed monitoring wells show a higher water table level in the 2009–2017 sub-period for all months (Fig. 12a); 47% of the wells indicate a higher water table level in the 2009–2017 sub-period but only in some months (Fig. 12b); and 22% of the wells display no or little variations in the water table level in the two sub-periods (Fig. 12c). These last monitoring wells are all located in the rice cultivation area. Therefore, irrigation of the paddy rice not only influences the hydrodynamic behaviour of the GW but also the possible variations in the water table levels over time.

The analysis of rainfall in the two sub-periods highlights the highest cumulative rainfall values in the sub-period of 2009–2017 in nearly all of the analysed rain gauges (Supplementary material 3, Fig. 13). More specifically, the average annual cumulative rainfall in the Piedmont Plain during the 2002–2017 period is 950 mm/yr. By analysing the subperiods, the average annual cumulative rainfall for 2002–2008 is 869 mm/yr, while the average annual cumulative rainfall for 2009–2017 is 971 mm/yr.

Because no variations were registered or reported in non-rice areas in terms of irrigation method or other anthropic activities, the highest rainfall amount could explain most of the average increase in the piezometric levels.

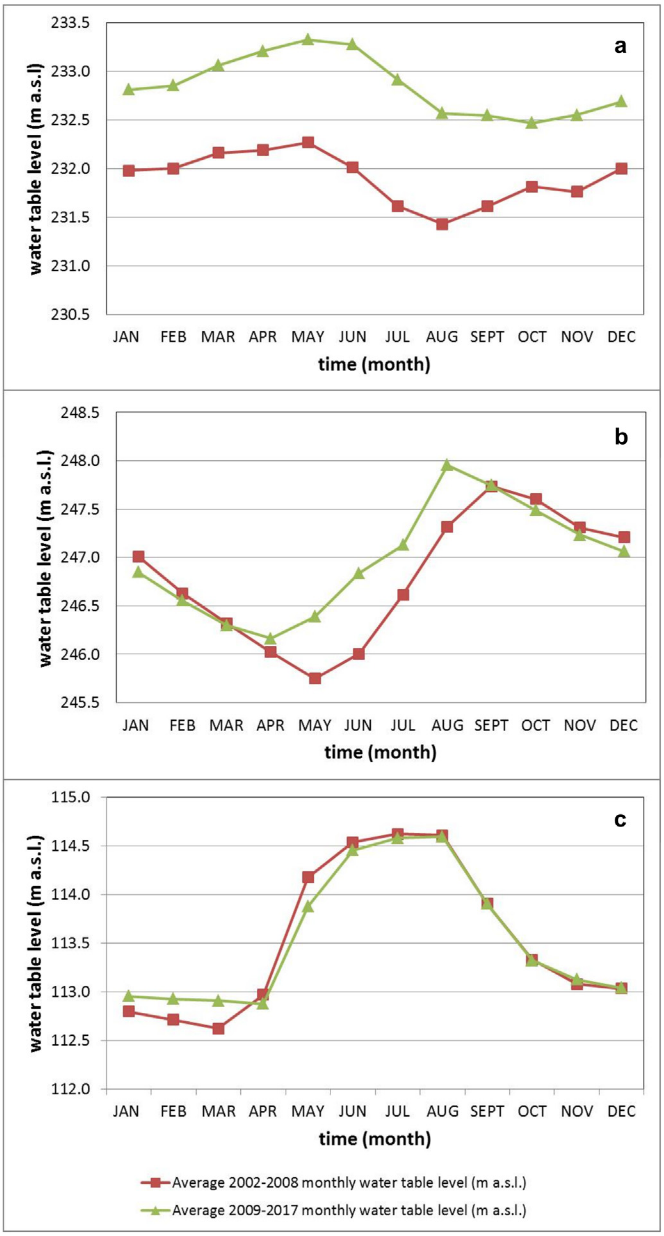


Fig. 12. Examples of changes in average monthly water table levels between the subperiods of 2002–2008 and 2009–2017: a) monitoring well P16, variations in all months; b) monitoring well P30, variations in some months; and c) monitoring well PII46, few variations in water table levels during both sub-periods.

4.4.2. Change in the period amplitude of the high piezometric levels

In some piezometric series belonging to Group B and located in the paddy rice of the lower Vercelli plain (e.g., monitoring wells PII46, PII48 and PII49), a reduction was observed in the period of

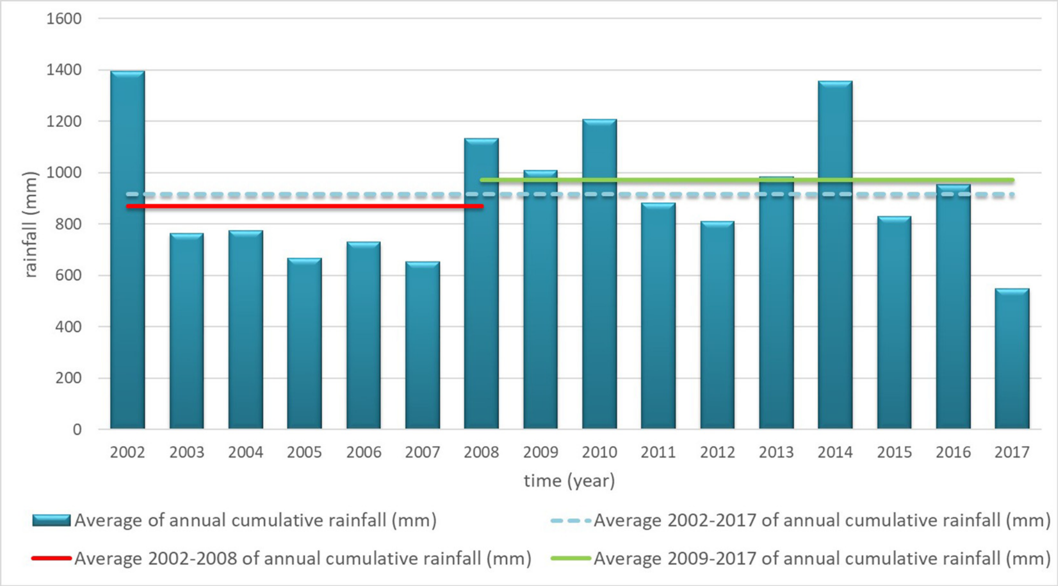


Fig. 13. Average annual cumulative rainfall of rain gauges analysed in the Piedmont Plain (light blue dashed line is the 2002–2017 average annual cumulative rainfall; red line is the 2002–2008 average annual cumulative rainfall; and green line is the 2009–2017 average annual cumulative rainfall). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

high water table levels. In particular, the period of high water table levels decreases from 4 to 3 months. An example is shown in Fig. 14.

This change in the amplitude of the period of high piezometric levels is connected to the modification of the agricultural technique of rice cultivation. In the traditional rice cultivation technique, the flooding of paddy fields starts in April and ends in September (Fig. 14a). The flooding of the rice fields helps to raise and maintain high water table levels of the underlying aquifer throughout the flooding period.

Recently, the dry direct-seeded rice technique with delayed flooding has replaced the traditional technique in some areas of the Piedmont Plain. Dry direct-seeded rice is an alternative cropping technique that avoids three basic operations, namely, puddling (a process where soil is compacted to reduce water seepage), transplanting and maintaining standing water (Joshi et al., 2013). Therefore, the technique requires less water and labour than classical transplanted-flooded rice (Liu et al., 2015). In particular, the dry direct-seeded rice technique has developed in more than 30–40% of the rice paddies in the low Vercelli Plain (https://www.risoitaliano.eu/). In the dry direct-seeded rice technique, water is introduced when the seedlings have already grown, which is almost one month later (May) than in the traditional technique. The flooding of the rice fields takes place for a shorter period, causing a corresponding reduced period of raised piezometric level (Fig. 14b).

4.4.3. Time shift in the GW level maxima

The comparison between the average monthly piezometric levels in the sub-periods of 2002–2008 and 2009–2017 highlighted a shift in the main spring maximum in more than 65% of the monitoring wells of group A. More specifically, an advance of 1–2 months in the main spring maximum was highlighted for the sub-period of 2008–2017 (Fig. 15), which generally occurred from June to May. The comparison of the average monthly cumulative rainfall and average monthly water table level highlighted that in most cases, this time shift seems to be related to the change in the rainfall regime.

5. Conclusions

Monitoring and analysis of water table levels are among the best tools available to identify possible variations in the quantitative state of groundwater. Moreover, levels can highlight the response of groundwater to climate change and other global change drivers, including land use changes, urbanisation and population growth.

The analysis of water table levels and rainfall was performed in the Piedmont Plain, which is an alluvial plain in NW Italy. The study highlighted the lack of a trend for the rainfall time series, while a trend (positive or negative) was detected for the water table in the plain. To explain this inconsistency, hydrodynamic GW table behaviours during the year were analysed. Different hydrodynamic GW table behaviours (namely, Group A and Group B), especially those behaviours that depend on natural factors and anthropic causes, were identified in the plain. Group A is particularly linked to rainfall and its variations during the year. Group B, which shows the opposite behaviour with respect to the rainfall regime, is especially connected to land use and mainly the presence of paddy fields. More specifically, the paddy field is an important artificial ecosystem, and the presence of the irrigation canal network that is used for field flooding ensures the maintenance of water on the surface for some months during the summer. The effect of this irrigation on the water table levels was observed in all the monitoring wells located in the rice area.

The dependency between GW level and irrigation in rice areas is also emphasized by the correlation plots between the cumulative monthly rainfall (calculated in the period between the minimum and maximum water tables) and the corresponding water level rise.

Moreover, the study of the GW hydrodynamic behaviours over time (2002–2008 and 2009–2017 periods, identified with a change point analysis) highlighted the dependence of the water table level on climate variability. Particularly, it was observed that the most recent period (2009–2017) is characterised by higher average monthly piezometric levels compared to the previous period of 2002–2008. The highest rainfall could explain most of the average

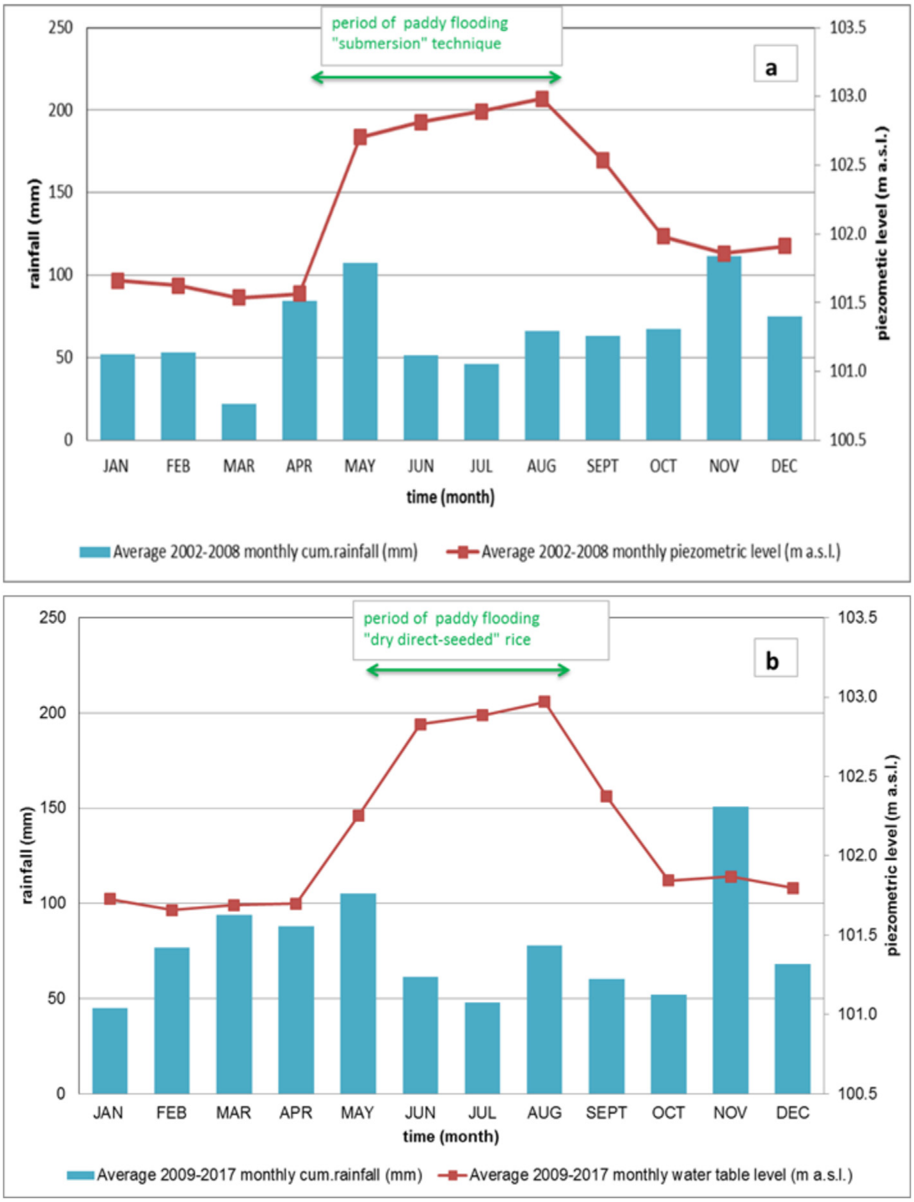


Fig. 14. Comparison of the average monthly piezometric levels between the sub-periods of 2002–2008 (panel a) and 2009–2017 (panel b) for a well located in the rice cultivation area (data are from monitoring well PII48 and rain gauge 33R).

increase in the piezometric levels. The higher water table level can be present during the whole year (31% of the analysed monitoring wells), in some months only (47%) or never (22%). The monitoring wells that display little or no variation in the water table level in the two subperiods are all located in the rice cultivation area. Therefore, paddy rice irrigation not only influences the hydrodynamic behaviour of the GW but also the time variations in the water table levels.

In the most recent sub-period (2009–2017), a reduction in the high water table level period from 4 to 3 months was observed in some piezometric series of Group B. This change is likely due to the changing agricultural technique of rice cultivation from the submersion technique to the dry direct-seeded technique with delayed flooding. Thus, this analysis also permitted the identification of the location where a change in the irrigation technique has occurred.

Finally, more than 65% of the monitoring wells in group A showed a 1–2 month advance in the main spring maximum for the sub-period of 2008–2017, which seems to be related to the change in the rainfall regime.

A key outcome of this study is identification of the paramount role of water table level investigation and fluctuation analysis, especially under land use modifications and from a climate change perspective.

The conceptual framework created for the Piedmont Plain shallow aquifer and the correlation with anthropic and natural factors were very promising and could be adopted to study similar alluvial plain areas.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.137051.

CRediT authorship contribution statement

Manuela Lasagna: Conceptualization, Methodology, Validation, Writing - original draft. **Susanna Mancini:** Conceptualization, Methodology, Formal analysis, Writing - original draft. **Domenico Antonio De Luca:** Supervision.

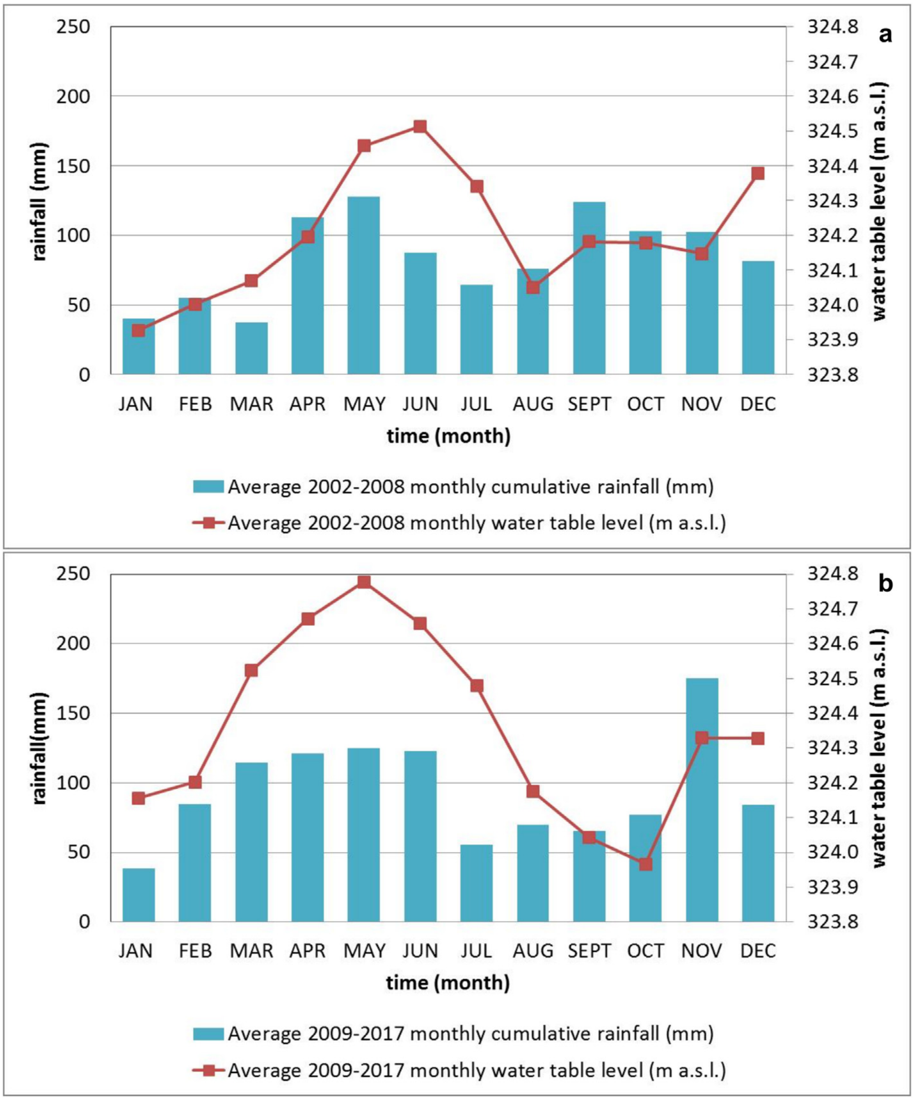


Fig. 15. Comparison of average monthly piezometric levels between two sub-periods: a) 2002–2008 and b) 2009–2017 (monitoring well P8 – rain gauge 26R). An advance of 1 month was observed in the main spring maximum for the water table level in the sub-period of 2009–2017.

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