Potential recharge areas of deep aquifers: an application to the Vercelli-Biella Plain (NW Italy)

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Abstract

Deep aquifers typically serve as a key source of drinking water due to their good groundwater quality. Then the identification of deep aquifers recharge areas provides the local administration with a management tool to protect groundwater, through the implementation of legislative measures for the control of pollution sources. However, the location and size of recharge areas of deep aquifers are often difficult to define and generally require a large amount of data. The aim of this paper is to propose a method to identify potential recharge, throughflow and discharge areas of deep aquifers on a regional scale, due to their hydrodynamic features. As the proposed method identifies where deep aquifer recharge can occur, but not the recharge rate, delimited areas are defined as "potential". Particularly, the method analyses piezometric level differences between shallow and deep aquifers to understand groundwater flow direction. The areas where groundwater flow is downward are delimited as potential recharge areas of deep aquifers (PRADAs).

The method represents a qualitative approach to the identification of PRADAs, because it permits to narrow down large plain areas extension, highlighting where potentially recharge areas are located. Then PRADAs location and shape can be defined effectively, expanding datasets and furthering analyses (hydrogeological reconstruction, hydraulic connectivity, hydro-chemical and isotopic methods…) in the identified areas.

The hydrogeological setting investigated by this method is representative of many anthropized and groundwater demanding plain around the world that require to be protected. Thus, the method represents a suitable approach for

PRADAs identification in such settings, especially in low income countries, where resource availability for studies and analyses is scarce.

This method was then applied to a plain area of Northwest Italy, and the locations and sizes of potential recharge, throughflow and discharge areas of deep aquifers were identified on a regional scale.

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1. INTRODUCTION

Deep aquifers typically serve as key sources of drinking water because they are generally more productive and have a better groundwater quality. Consequently, specific safety measures must be taken to safeguard the water quality and prevent the development of pollution in such aquifers, also according the EU Water Framework Directive (European Commission, 2000) and the EU Groundwater Directive (European Commission, 2006). In particular, the protection of deep aquifers must involve the dissemination of knowledge on aquifer recharge modes, flow systems and internal dynamics. Hence, their safeguarding must begin with the protection of recharge areas, where the downward movement of groundwater can more quickly transfer some pollutants in deep aquifers and thereby contaminate groundwater supplies.

Because the protection of groundwater resources calls also for the stipulation and implementation of legislative measures, in several European countries, recharge areas of important groundwater basins and aquifers have been delineated and protected. Human activities within these areas, that can cover several hundred square kilometres, are under control and partially restricted by law (Kovalevsky and Vrba 2004). However, the identification and extension of recharge areas of deep aquifers (RADAs) are often difficult to define and generally require a large amount of data (isotopic, stratigraphic…) or hydrogeological models.

The aim of this paper is to propose a simplified method to identify and map potential recharge areas of deep aquifers (PRADAs) at a regional scale. This method makes it possible to determine, according to a precautionary approach, the areas that, due to their hydrodynamic features, can potentially recharge deep aquifers. Particularly, the method analyses the difference of piezometric levels between the shallow and deep aquifers and it considers as PRADAs the areas where groundwater flow is downward. In these areas, indeed, the groundwater flow is directed from the ground surface to deep aquifers through shallow aquifers. The method represents a qualitative approach to the identification of regional potential recharge areas and it is a first approach that, together with stratigraphic and hydrochemical studies, can better define the recharge areas of the deep aquifers.

This method was applied to a plain area of Northwest Italy (Vercelli-Biella Plain in Piedmont Region), and the locations and sizes of potential recharge, throughflow and discharge areas of the deep aquifer were identified on a regional scale.

2. LITERATURE REVIEW

2.1 Regional Groundwater Flow Patterns

According to Freeze and Witherspoon (1967) natural groundwater recharge refers to water that percolates down through the unsaturated zone to the water-table and actually enters the dynamic groundwater flow system. Groundwater discharge is water that is discharged from the dynamic groundwater flow system by means of stream baseflow, springs, seepage areas. A groundwater basin is a three-dimensional closed system that contains the entire flow paths followed by all the water recharging the basin. Toth (1962, 1963) defined a groundwater flow system as a set of flow lines in which any two lines adjacent at one point of the flow region remain adjacent through the whole region and that can be intersected anywhere by an uninterrupted surface across which flow takes place in one direction only. Water moves from the recharge area, where water flow is directed downward, to the discharge area, where it is directed upward. In between them, water passes through an area where water flows move horizontally and laterally (throughflow areas). The driving flow force is the difference in the groundwater head, creating a hydraulic gradient.

Three different types of flow systems can occupy a groundwater basin, namely, local, intermediate and regional systems. In a *local system* of groundwater flow, the recharge area is positioned in a high topographical area, and the discharge area is positioned in a low topographical area. They are located adjacent to one another. Increasing topographic relief levels will tend to increase the depths and intensities of local flow systems. Recharge and discharge areas of *intermediate systems* of groundwater flow do not, respectively, occupy the highest and lowest elevated areas in a basin, and one or more topographic highs and lows may be located between them. A system of groundwater is considered to be *regional* if its recharge area occupies a water divide and its discharge areas lies at the bottom of a basin.

Topography, geology and climate are the major factors for the formation of three sub-flowsystems of gravity-driven flow in a homogenous and isotropic groundwater basin (Zhou and Li 2011). These flow systems can be identified in the field by investigating recharge and discharge areas, changes of groundwater levels with depth, hydrochemistry patterns, environmental isotopes, vegetations and surface water networks (Toth 1970, 1971, 1972).

Whereas Toth (1962, 1963) analysed a homogenous and isotropic groundwater basin, the study of a complex multi-layered aquifer, when anisotropy exists, becomes more difficult. Freeze and Witherspoon (1966, 1967, 1968) were the first to use numerical models to simulate regional groundwater flow in hypothetical nonhomogeneous and anisotropic systems. The factors that affect steady-state regional groundwater flow patterns within a nonhomogeneous, anisotropic basin are: a) depth:lateral extent ratio; (b) water-table configuration; (c) the stratigraphy and resulting subsurface variations in permeability. For example they observed that in presence of a two-layer case in which the upper layer has the larger permeability, the flow pattern resulting is almost identical to that of the homogeneous case (Freeze and Witherspoon 1967). Moreover, the presence of a major valley will tend to concentrate discharge in the valley. Particularly they observed that generally discharge areas are smaller than recharge areas and that in their two-dimensional hypothetical models, occupy between 7 % and 40% of the total length of the basin.

2.2 Shallow and deep aquifers and recharge areas

According to Piedmont Region law 22/1996 (Regione Piemonte, 1996) and subsequent amendments in Piedmont Region law 6/2003 (Regione Piemonte, 2003) groundwater in Piedmont can be divided in shallow aquifer and deep aquifers. The shallow aquifer is the closest to the ground surface; it is directly fed by the infiltration and is in direct connection with the rivers. The deep aquifers are located underneath a shallow aquifer; they are represented by a) confined and semiconfined aquifers, and b) the aquifers hosted in the deep portion of undifferentiated aquifers. In the situation b), the deep aquifers are characterised by a lower flow velocity, longer water residence periods, and a different hydrochemical quality respect to the shallow portion of the undifferentiated aquifer (Lasagna and De Luca 2016, 2019). Moreover, a deep aquifer is characterized by intermediate or regional flow systems, low vulnerability to contamination, and, generally, higher water quality.

In Piedmont, an undifferentiated aquifer is situated locally close to the mountain ranges, and it develops in the plain into a multi-layer system made up of confined or semi-confined aquifers that constitute an important subsurface reservoir.

According to this conceptual model, regional recharge areas of deep aquifers are located along the ground surface where the piezometric level difference between shallow and deep aquifers favours the downward flow of groundwater from the ground surface to deep aquifers through shallow aquifers.

The recharge areas of shallow aquifers (RASAs), but especially of deep aquifers (RADAs) represent portion of territory that must be protected with specific safety measures to prevent the development of pollution in aquifers. This is especially true where the deep aquifers serve as key sources of drinking water, being mostly uncontaminated. For example, in the Po Plain it is very important to protect the quality of the deep aquifers that normally show very high quality standards, also in accordance to the D. Lgs. 152 (2006), Italian implementation of the EU Water Directive, and to the D. Lgs. 30 (2009), implementation of the EU Groundwater Directive.

Fig. 1 describes the location of the RADAs in two hydrogeological conceptual models, concerning the outcrop of the geological unit hosting the deep aquifer.

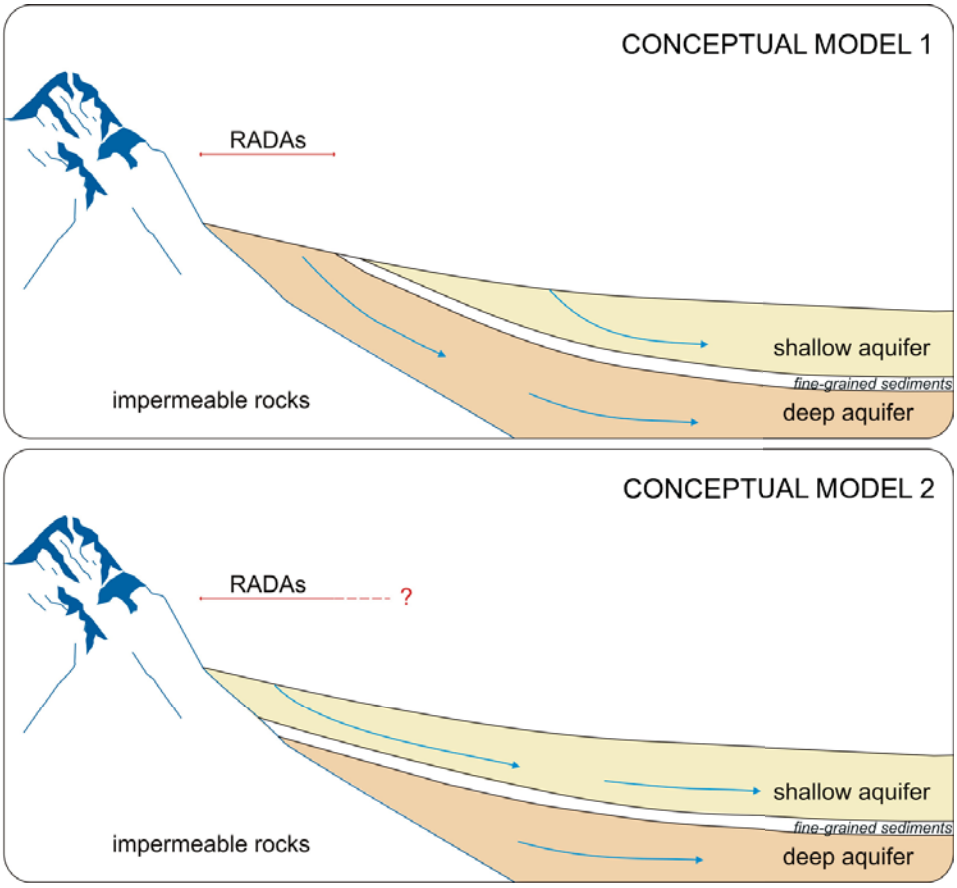

Fig. 1. Locations of RADAs in two different schematic geological settings where geological units hosting deep aquifers outcrop (conceptual model 1) or do not outcrop (conceptual model 2).

In the conceptual model 1 the deep aquifer is hosted in a geological complex that outcrop near the mountains. In this case, the RADAs at a minimum correspond to the outcropping areas, where water infiltrates and recharge the aquifer.

In the conceptual model 2, the RADAs delimitation is more difficult to perform. In this schematic situation the hydrogeological setting is represented by many superimposed hydrogeological unit. The deep aquifer, located in confined and semi-confined hydraulic conditions, is placed under the shallow aquifer and the geological complex hosting it does not outcrop anywhere in the plain. In such cases, the RADAs should be identified at a regional scale in areas close to mountains or hills, with different extension according to the length of the basin. Different approaches for the recharge areas identification are available in literature, according to chemical and isotopic data (Scholl et al. 1996, Sukhija et al. 1996, Dogramaci et al. 2001, Manning and Salomon 2003, Ingram et al. 2007, Blasch and Bryson 2007), chemico-physical parameters (Alfoldi et al. 1985; Taniguchi 1993; Domenico and Schwartz 1998; Anderson 2005; Pasquale et al. 2011; Gisolo et al. 2015; Bucci et al. 2017), geological setting (Regione Emilia-Romagna and ENI-AGIP 1998, Regione Lombardia and ENI-AGIP 2002) and modelling (Bugliosi 1999).

In context as the conceptual model 2 of Fig. 1, geochemical, isotopic and modelling methods have proved to be very useful to identify recharge areas, also in multi-layered aquifer systems. Data collection is an essential part of all these methods. However, when the data collection process results very difficult, e.g for the large size of the study areas or for the lack of financial supports (isotopic analyses can be very expensive), it could be necessary to reach a first delimitation of the areas that potentially represent recharge areas. Indeed, in these areas protective measures can be applied, e.g. limiting soil uses, and thus preserving the deep groundwater quality with a precautionary approach. In the following paragraph, a method for the delimitation of potential recharge areas of deep aquifers (PRADAs) is proposed. This is a first approach that, followed by the stratigraphic and hydrochemical ones, can help to define the recharge areas of the deep aquifers in a preliminary way.

3. MATERIALS AND METHODS

The proposed methodology represents a qualitative approach to the identification of potential recharge (PRADAs), discharge and throughflow areas of deep aquifers in a regional flow system. The method permits to delimit and map the areas that, due to their hydrodynamic features, can potentially recharge deep aquifers. Particularly the method, based on the understanding of the regional groundwater-flow system, evaluate the piezometric level differences between shallow and deep aquifers to determine the main flow direction of groundwater (downward, horizontal or upward flow) and it considers as PRADAs the areas where groundwater flow is downward, and thus directed from the ground surface to deep aquifers through shallow aquifers. This method represent a first approach that, followed by stratigraphic and hydrochemical studies, can help to define the recharge areas of the deep aquifers in a preliminary way. The method involves two steps, which are summarized in the flow chart of Fig. 2.

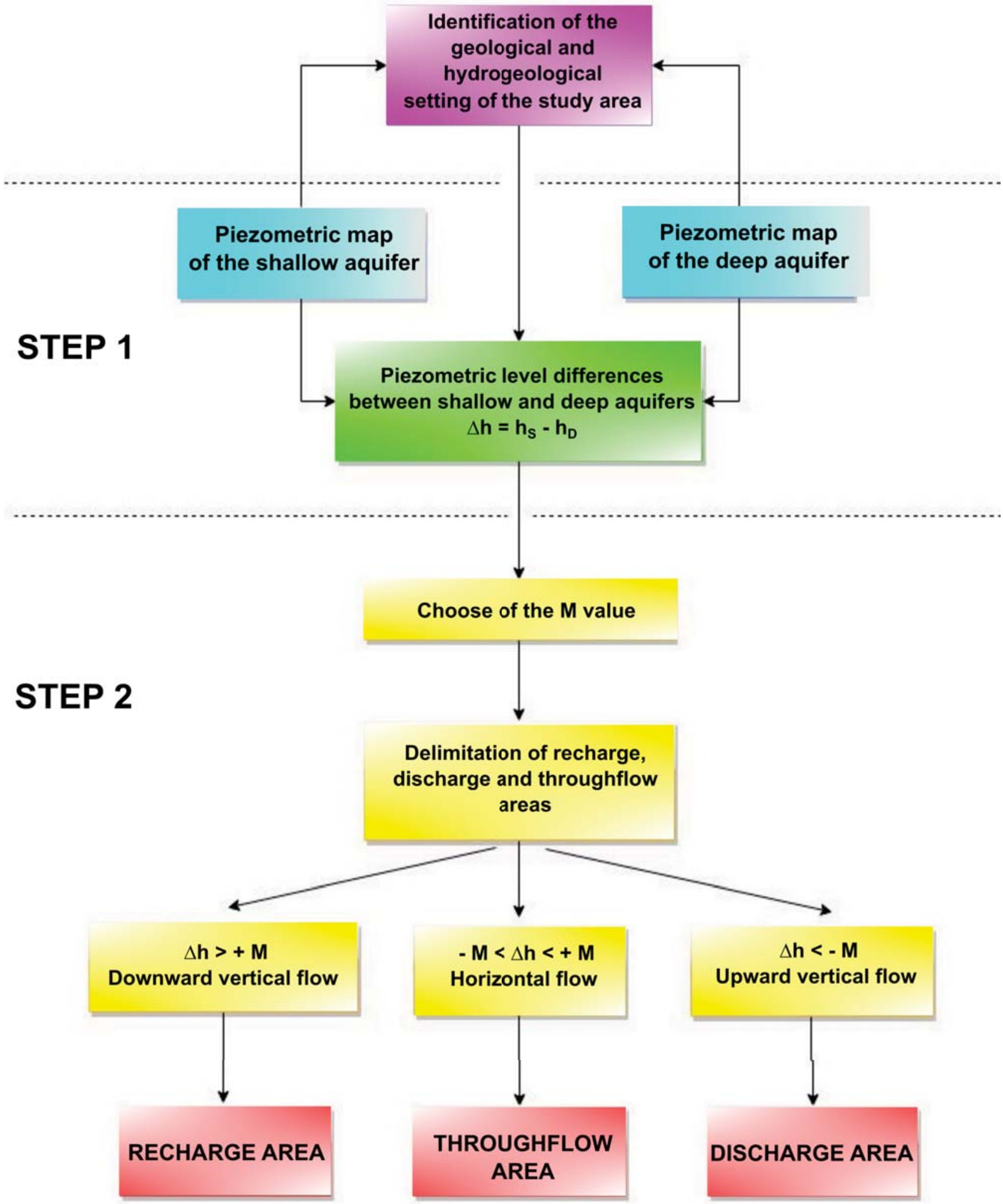

Fig. 2. Flow chart describing the two steps required to identify PRADAs in a study area. h_S: piezometric level of the shallow aquifer; h_D: piezometric level of the deep aquifer. M factor represents the value of piezometric level differences between aquifers (Δh) beyond which the recharge becomes significant.

3.1 Step 1: evaluation of piezometric level differences between shallow and deep aquifers

This step involves firstly the realization of the piezometric maps of the shallow and the deep aquifers. Then the piezometric level differences between aquifers (Δh) should be evaluated. Differences are determined via the point-by-point subtraction of the piezometric level of the shallow aquifer (h_S) and the piezometric level of deep aquifer (h_D) according to eq. 1.

$$\Delta h = h_S - h_D \quad \text{(eq. 1)}$$

The h_S and h_D values represents the average value of the piezometric level of the whole shallow and deep aquifers respectively. Then the Δh values are to be plotted on a map to evaluate their distribution, and areas with the same Δh values must be delimited by contour lines.

3.2 Step 2: delimitation of potential recharge, discharge and throughflow areas

As the piezometric level difference between aquifers influences the upward/downward flow of groundwater in an area, this data can be used to define potential recharge, discharge and throughflow areas of deep aquifers. In particular, the PRADAs are located in areas where the main groundwater flow travels downward. This occurs only when piezometric levels of a shallow aquifer are greater than those of a deep aquifer and thus when Δh values are positive. The method does not consider the effects of artificial discharge (wells and well fields) and abnormal values connected to cones of depression of wells or well fields should be eliminated. Thus only natural potential groundwater recharge and discharge areas are delimited.

After the contouring of Δh values, potential recharge, discharge and throughflow areas must be delimited as follows (Fig. 3):

a) where Δh values are positive, the piezometric level of the shallow aquifer is higher than that of the deep one; main components of water flow are consequently directed downward, and the shallow aquifer potentially recharges the deep aquifer, if the stratigraphic conditions are favourable. All areas characterized by positive Δh values can be contoured and referred to as PRADAs;

b) where Δh values are negative, the piezometric level of the shallow aquifer is lower than that of the deep aquifer; therefore, main water flows are directed upward, and the deep aquifer potentially recharges the shallow one. All areas characterized by negative Δh values can be contoured and referred to as potential discharge areas;

c) where Δh values are zero, no vertical water flows occur because piezometric levels of shallow and deep aquifers are identical. Areas characterized by null Δh values can be referred to as throughflow areas.

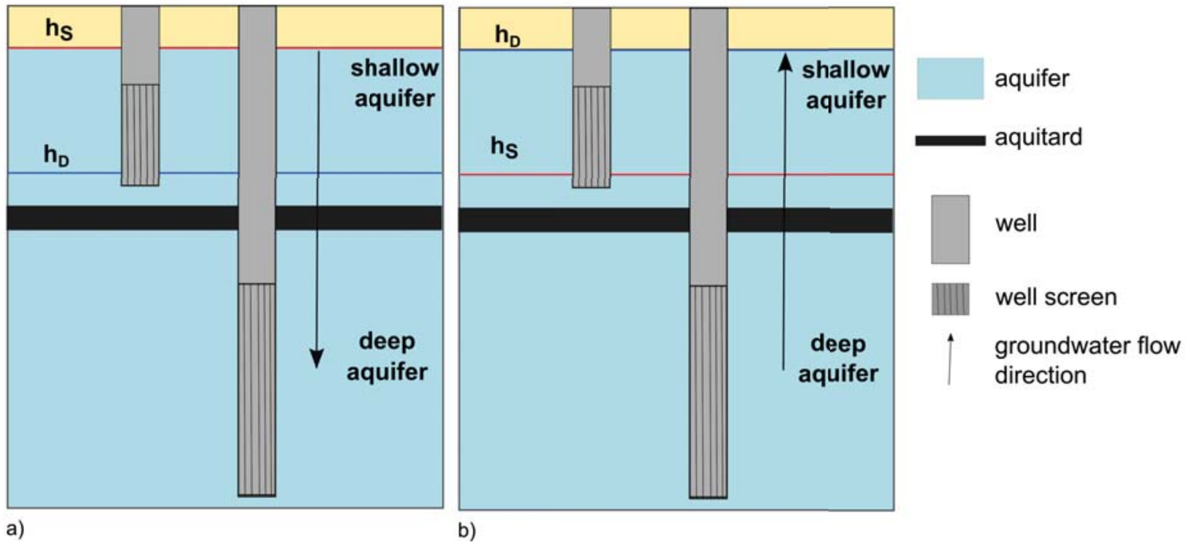

Fig. 3. The positioning of piezometric level of shallow aquifer (h_S) and deep aquifer (h_D) influences the groundwater flow direction. a) Recharge areas are positioned in areas where the h_S is greater than the h_D and thus where groundwater travels downward. b) Discharge areas are positioned in areas where the h_D is greater than the h_S and thus where groundwater travels upward.

However, in some cases recharging flows are not continuous overtime (e.g. areas where there is a recharge only seasonally) or recharge flux is very low. Actually, a very low Δh permits only a low water exchange between aquifers, enable to produce a qualitative deterioration of groundwater. Moreover, the presence of thick fine-grained levels (at least silty-clayey) can prevent high water flux between aquifers.

To avoid the definition of PRADAs in areas with low or no recharge flux, it is possible to introduce in the method a value, defined as M value. M represents the value of piezometric level differences between aquifers (Δh) beyond which the recharge becomes significant, in order to guarantee an important groundwater flux between aquifer. The same is true for the potential drainage areas.

The researcher can decide whether to introduce the M value, and he can select M value on a case-by-case basis, depending on the study purposes and the required precautionary level.

Consequently:

- where the Δh value is greater than +M, a PRADA can be identified;

- where the Δh value ranges between -M and +M, a throughflow area can be identified;
- where the Δh value is lower than –M, a potential discharge area can be identified.

4 EVALUATION OF THE PRADAs IN THE VERCELLI-BIELLA PLAIN

The proposed approach was applied to a plain area of northwestern Italy (Vercelli-Biella Plain in Piedmont Region), and the location and size of potential recharge, throughflow and discharge areas of the deep aquifer were identified on a regional scale. The method was applied according to the steps of Fig. 2.

4.1 Identification of the geological and hydrogeological settings

The Vercelli-Biella Plain is located in the Piedmont Region (Fig. 4). It is bordered by the Po River to the south, by the Sesia River to the east, by the Morainic Amphitheatre of Ivrea to the west and by the reliefs of Biella and Valsesia to the north. The study area forms the northwestern end of the Po Plain, which represents one of the most important aquifers in northern Italy due to its size, deposit features and recharge capacities (Debernardi et al. 2008).

The geomorphology of the study area is influenced by uplift and subsidence phenomena and by glacial and fluvial activities. It is primarily represented by an alluvial plain affected by erosional and depositional cycles that created an E-W piedmont belt of terraces sloping slightly towards the south. In the west, some narrow valleys connect the plain to the hills of the Morainic Amphitheatre of Ivrea. The Vercelli-Biella Plain is also connected to mountain reliefs to the north by fluvio-glacial modelled valleys.

In Biella and the Northern Vercelli Plains, principally Cervo River carved through the plain creating an alluvial terrace that is tens of meters high. The Dora Baltea, the Po and Sesia Rivers travel at the edges of the southern and central Vercelli Plain, lightly carving it. They create a network of artificial channels that drain and irrigate the central area of the Vercelli Plain (Clemente et al. 2015). Part of this network is fed by natural springs of shallow aquifers known as *fontanili* (De Luca et al. 2009; De Luca et al. 2014) located in the northern and central sections of the area.

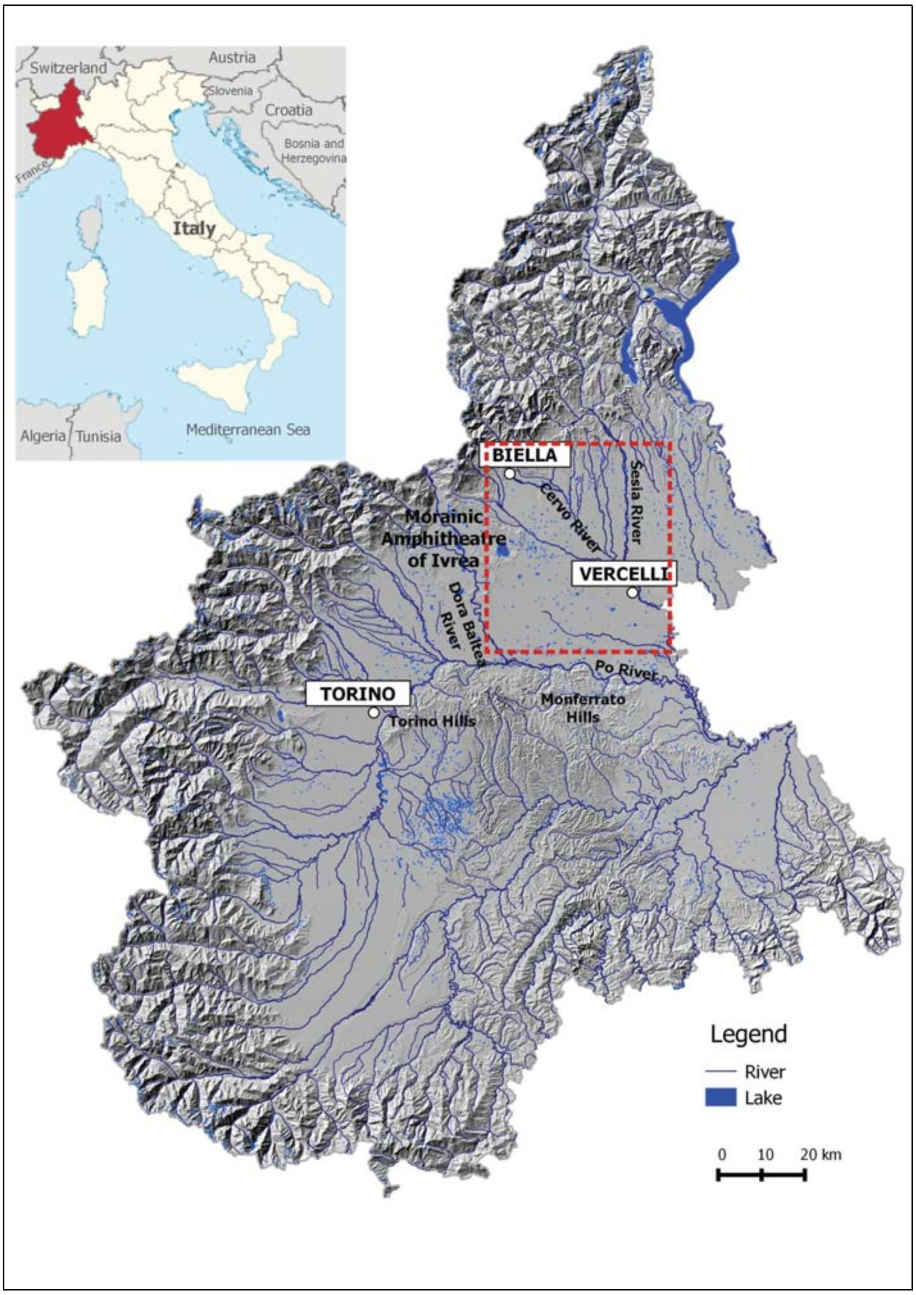

Fig. 4. Location of the study area (dotted square) in the Piedmont Po Plain.

The Vercelli-Biella Plain is characterized by six different geological complexes (Fig. 5). From the bottom to top, they are described as follows (Bortolami et al. 1966; Bonsignore et al. 1969; Bove et al. 2005; De Luca et al. 2006b, 2010):

- "Alpine basement complex": it is composed by polymetamorphic and igneous crystalline rocks and outcrops in the northern section of the study area in correspondence to the mountain front. Fissuration of the bedrock is limited, and thus this complex is considered impermeable.
- "Oligo-Miocene deposit complex": it is composed by marls, clays and sandstones outcropping on the Trino Vercellese plateau and belonging to the Monferrato sedimentary succession (Gelati & Gnaccolini, 1982; Biella et al.,

1997; Forno et al. 2018). The permeability of this complex, with a thickness that is estimated to be greater than thousands of meters, is limited and due to local fissuration.

- "Pliocene marine sediments complex" (Lower-Middle Pliocene): these sediments of marine origin consist of approximately 50 meters of bluish clayey-silty deposits (Lugagnano Clay) at the base of the complex, turning into silty sediment with sandy levels and into silty yellow sand at the top (Asti Sand). Lugagnano Clay has a low permeability and form an aquiclude. Asti Sand present variable degree of permeability and constitute locally important deep aquifers.
- "Multi-layered Villafranchian complex" (Middle Pliocene-Lower Pleistocene): it consists of a thick and laterally continuous sequence of transitional deposits, characterized by coarsely bedded gravel and sand with silty and clay layers. As the Multi-layered Villafranchian complex is characterized by alternations of permeable and impermeable sediment with high thickness and lateral continuity, it hosts an important deep Multi-layered aquifer. The thickness of impermeable levels may allow for the development of confined and semiconfined aquifers. Vertical water exchanges between the shallow and deep aquifers are dependent on the lateral continuity, thickness and permeability of confining layers.
- "Glacial deposits complex" (Pleistocene): it includes the end moraine system of the Ivrea Morainic Amphitheatre, composed by a glacigenic succession with interglacial paleosols and deposits, ranging in age from terminal Early Pleistocene to Late Pleistocene (Gianotti et al., 2015). The permeability of this complex varies depending on the (original) grain size, weathering and argillification of its sediments; glacial and fluvioglacial deposits may host a shallow aquifer and some perched aquifers.
- "Fluvial and outwash deposit complex" (Middle-Upper Pleistocene and Holocene): it is characterized by gravel and sandy gravel with pebbles and boulders, with occasional silty clay sediments in lenses that are several meters thick. Outwash deposits form higher terraces of the study area, and their permeability is dependent on the pedogenesis. The complex has a good permeability, due to the grain size of sediments and their porosity, except for silts and clays that exhibit impermeable or semipermeable hydrogeological behaviours. Owing to its mainly gravelly sandy texture, the complex is often used for quarrying activities (De Luca et al. 2007, 2008; Castagna et al. 2015a, 2015b). The base of this complex, which forms the hypothetical surface that divides the shallow aquifers from the deep aquifers, is situated where the first thick and continuous impermeable layer appears. In this way, the fluvial and outwash complex can range in thickness from 10 to 70 meters.

To determine the thickness and features of the complexes in the Vercelli-Biella Plain, 200 well stratigraphic logs were collected. Then 21 lithostratigraphical cross-sections (11 EW-oriented and 10 NS-oriented) were conducted. Two of these sections are shown in Fig. 6.

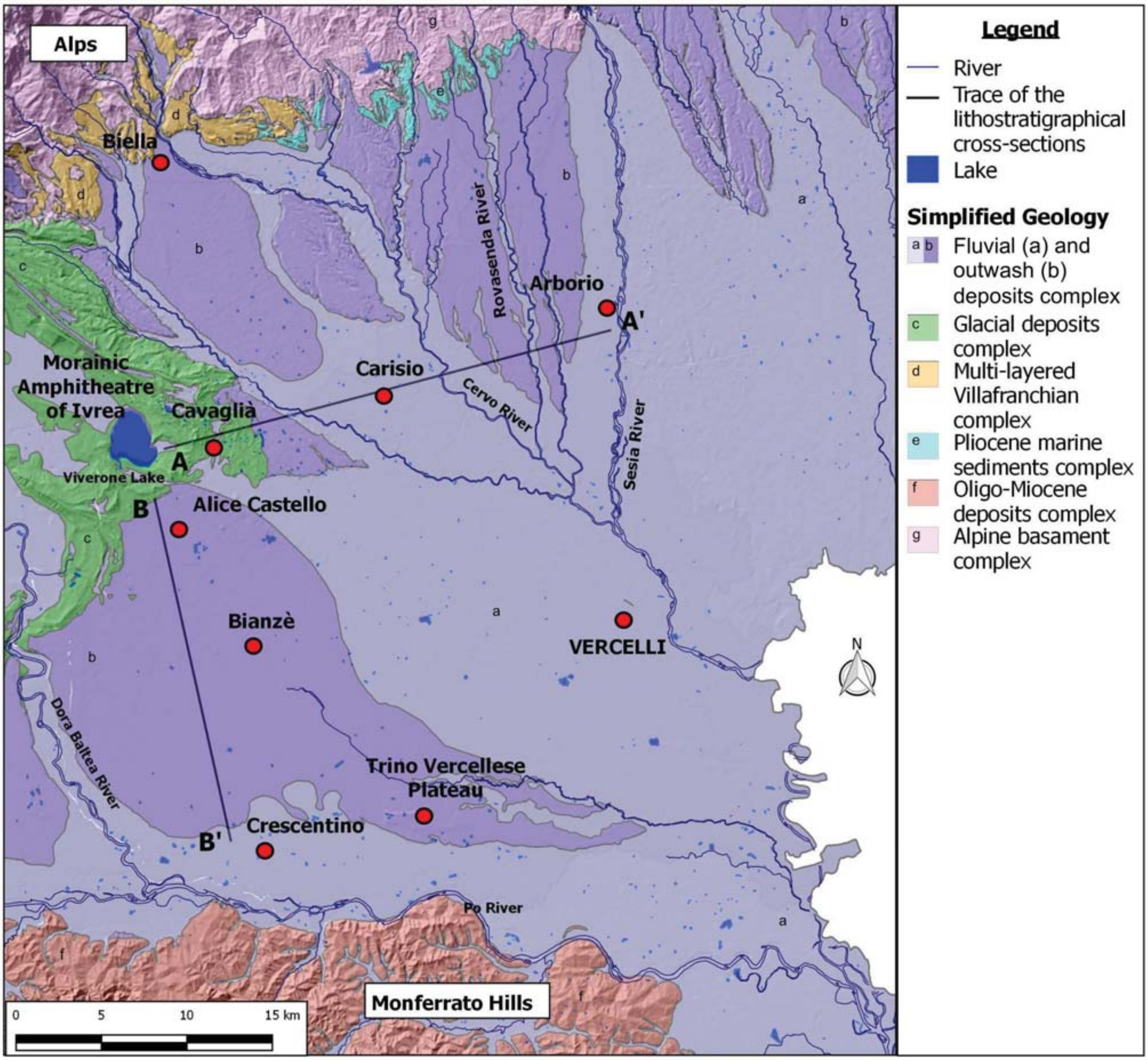

Fig. 5. Simplified geological map of the study area.

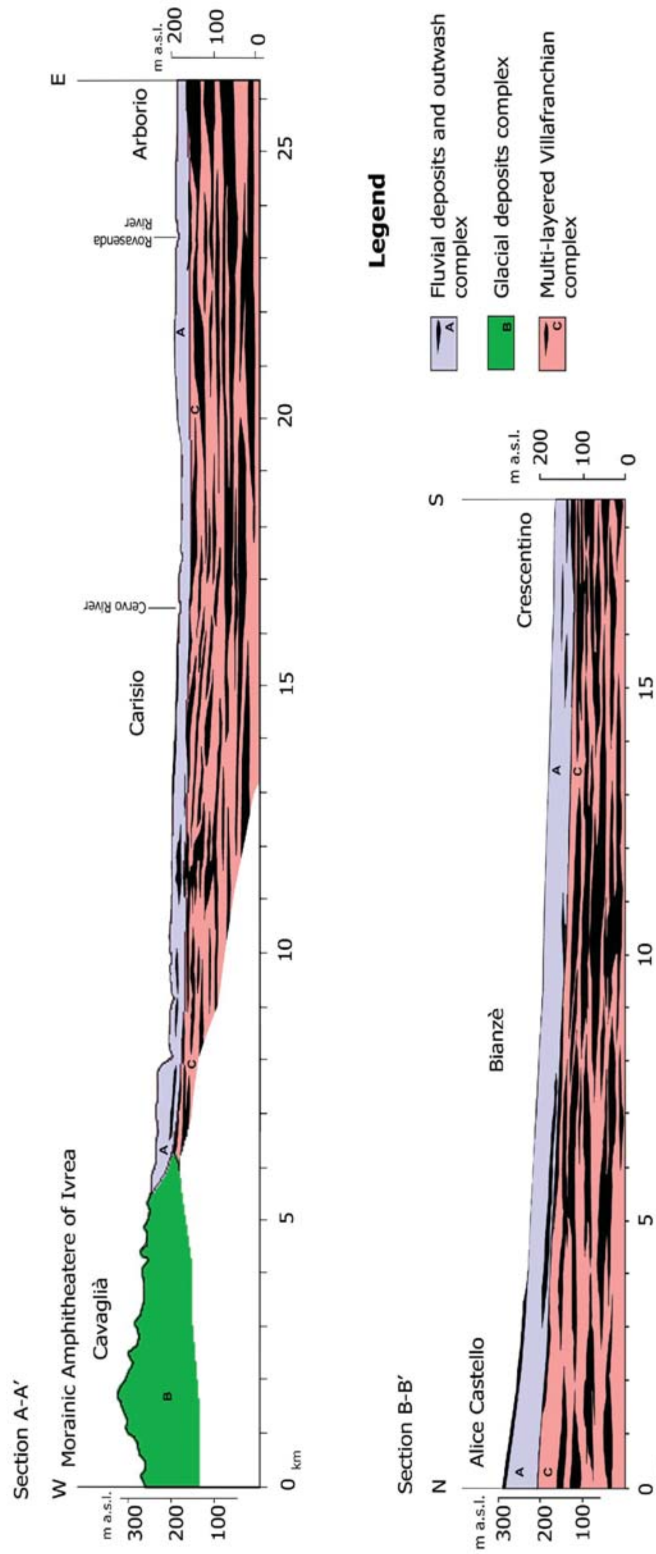

Fig. 6. Lithostratigraphical cross-sections in the study area; low permeability levels (aquitards/aquicludes) are represented in black.

4.1.1 Shallow and deep aquifers in the study area

The shallow aquifer is hosted in fluvial deposits and outwash complexes in the study area. The piezometric map of the shallow aquifer (Fig. 7) was elaborated by interpolating piezometric data on 30 piezometers belonging to the Monitoring Network of the Piedmont Region referred to August 2007. The interpolation was performed using Surfer software (Golden Software, Golden, CO) and the Kriging algorithm. The piezometric map of shallow aquifer was also compared and integrated with a previous map (Bove et al. 2005) regarding the whole Piedmont plain, to enhance the precision of the piezometry.

The piezometric map of the shallow aquifer is considerably influenced by the local topography and by waterway patterns. Piezometric lines are positioned very close together in the NW section of the study area and broaden towards the SE. The hydraulic gradient is greater in the NW section of the study area (ranging between 0.02 and 0.01) than it is in the central and SE zones (roughly 0.005 to 0.002).

The main groundwater flow direction is oriented NW to SE, although in the northern section of the area between the Rovasenda and Sesia rivers, it is oriented N to S.

The Po River is the main drainage line in the plain. Also the Cervo River and at a lesser extent the Sesia River are gaining streams.

The seasonal water table fluctuation is very high in Vercelli Plain due to agricultural practices. Indeed, the plain mainly hosts rice agricultural activities as follows: after fields are prepared and rice is sown, the fields are usually flooded during the second half of April or in early May. Previous studies on the Vercelli Plain revealed increasing water levels for this period that reach 5 m locally. During the second half of May, water levels remain constant until the end of August when water flows out, causing water levels to decrease (De Luca et al. 2006a, 2006b). The deep aquifer, by contrast, shows very limited piezometric level variations throughout the year.

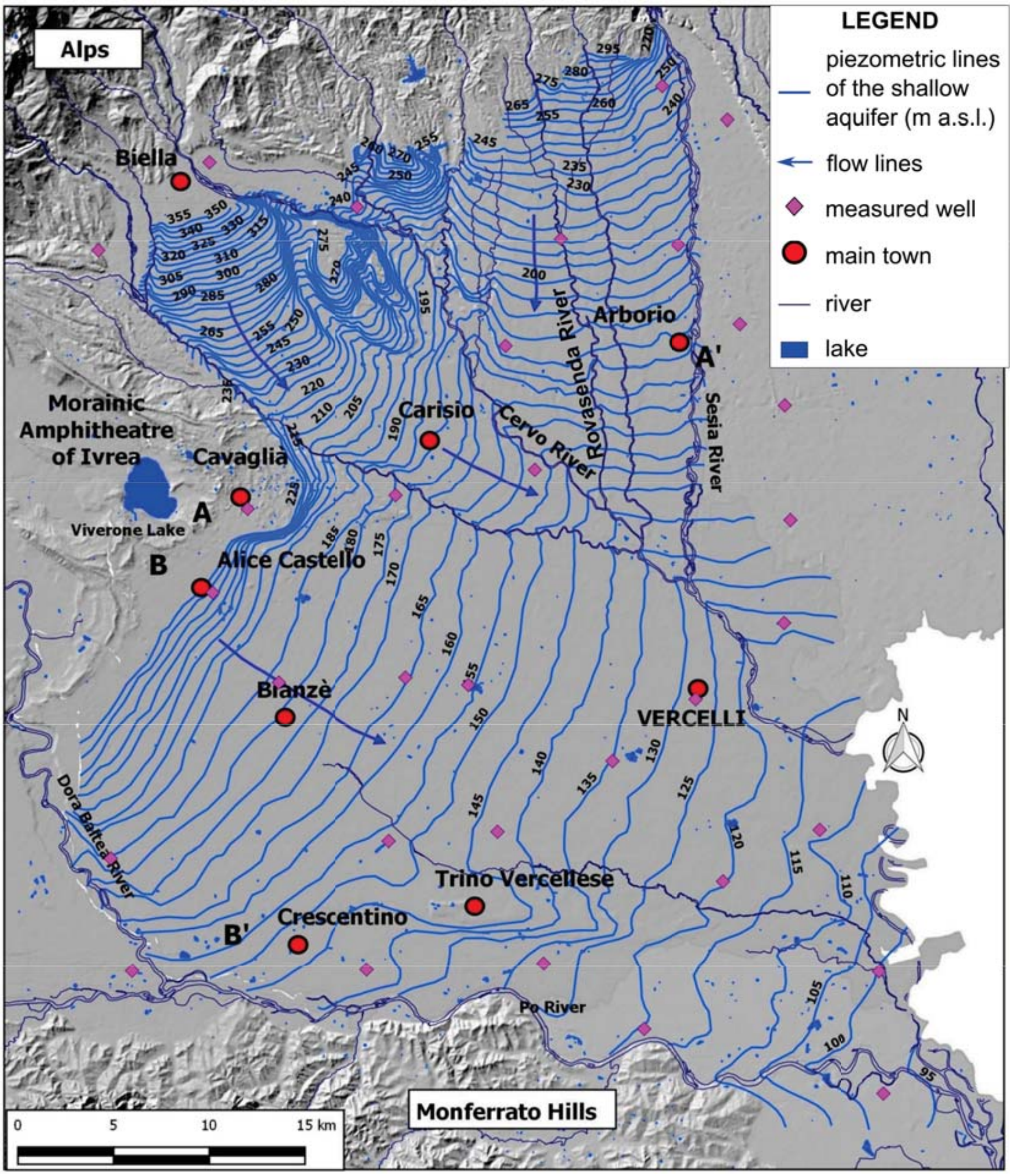

Fig. 7. Piezometric map (m a.s.l.) of the shallow aquifer in the Vercelli-Biella Plain (August 2007).

In the study area, the deep aquifer is hosted in the Multi-layered Villafranchian complex. Indeed, in this zone the Pliocene marine sediments complex, that generally in the Po plain hosts important aquifers, is clayey and so with low permeability. Using pumping test data, the transmissivity of the deep aquifer of the Vercelli-Biella Plain was found to range between 2.00 x 10^{-5} m^2/s and 7.00 x 10^{-2} m^2/s, increasing from the mountain front to the plain (De Luca et al. 2010). The piezometric map of the deep aquifer was defined based on the water levels of 52 deep wells, selected and measured during August 2007. The piezometric levels were measured in wells after the shutdown of the pump and the restoration of static groundwater level, to delete the effects of pumping. Piezometric data were interpolated using Surfer software (Golden Software, Golden, CO) and the Kriging algorithm to generate the piezometric surface of the deep aquifer (Fig. 8). The piezometric map of deep aquifer was also compared and integrated with data from unpublished previous maps regarding the study area, to enhance the precision of the piezometry.

The hydraulic gradient is greater in the NW section of the study area (0.012 to 0.009) than it is in the central and SE zones (roughly 0.005 to 0.002). The flow direction is about NW-SE oriented. However, as for the shallow aquifer, the flow direction in the area between the Rovasenda and Sesia rivers is approximately from N to S.

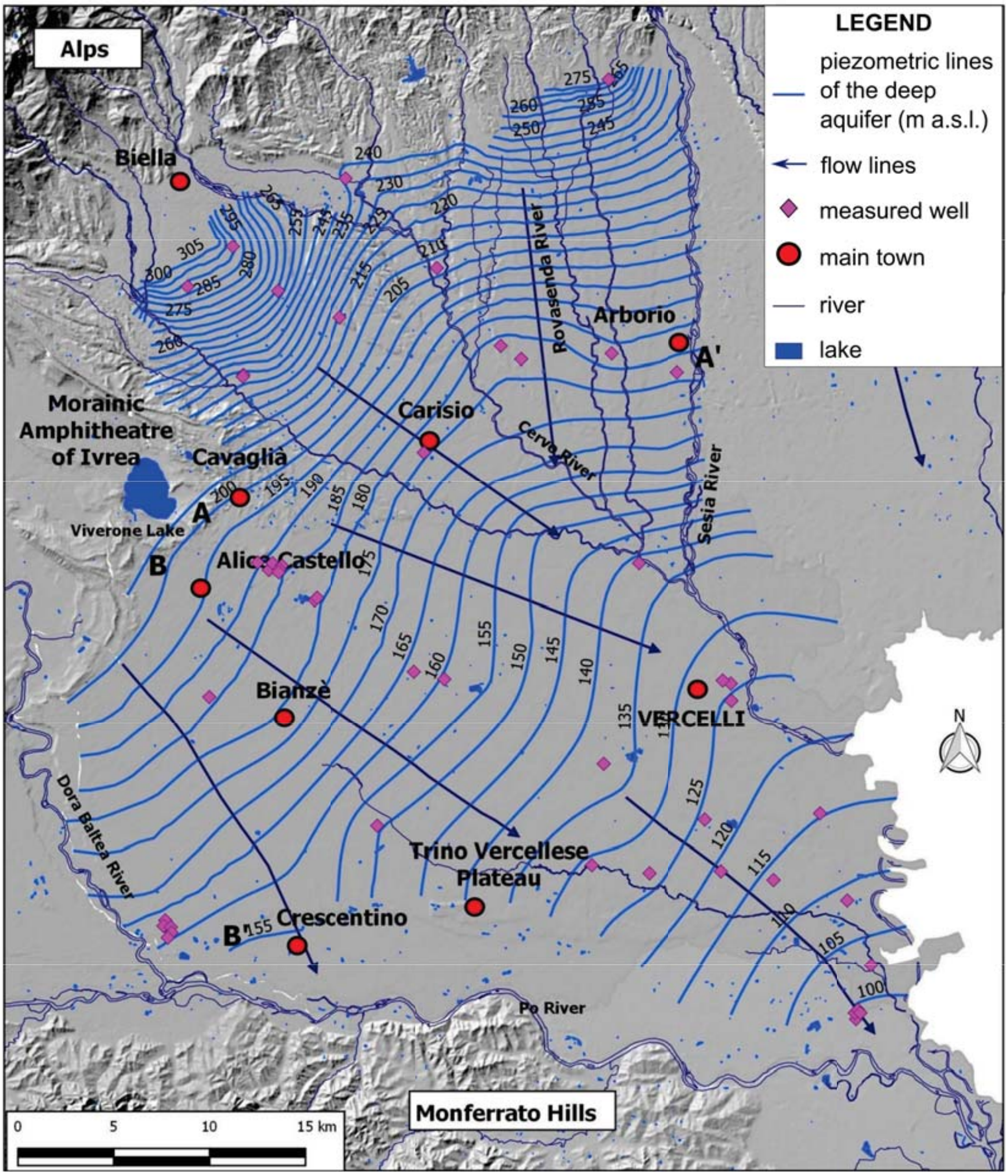

Fig. 8. Piezometric map (m a.s.l.) of the deep aquifer in the Vercelli-Biella Plain (August 2007).

4.1.2 Hydrogeological conceptual model

The hydrogeological conceptual model of the study area (Fig. 9) was developed using the geological map, the lithostratigraphical cross-sections and the piezometric maps of shallow and deep aquifers. The groundwater basin is bordered by crystalline rocks to the north, with very limited fissuration, and by impermeable Oligo-Miocene sediments of Monferrato Hill to the south. Consequently, the substratum does not generally contribute to shallow and deep aquifers. The shallow aquifer consists of alluvial deposits, characterised by gravelly sandy texture with subordinate silty–clayey intercalations. The grain size is variable and normally decreases from the mountains to the low plain along the Po River. The hydraulic conductivity is on average equal to $3*10^{-4}$ m/s (Lasagna et al., 2018).

The passage from shallow aquifer to deep aquifers can be generally recognised due to the presence of discontinuous and impervious silty and clayey layers, especially in the middle plain, where the content of fine-grained sediments increases respect to the foothills.

The groundwater flow in the shallow aquifer is directed from the mountain front to the Po River, which serves as the main drainage line (Lasagna et al. 2016a), but it is considerably influenced by the local topography and by the drainage roles of the other rivers (local flow systems). The recharge area of the shallow aquifer corresponds to all topographic surfaces because it is recharged directly through rainfall, and discharge areas correspond to the area close to gaining rivers. The shallow aquifer is separated from the deep aquifer by thick and low permeability layers that can divide local flow systems from intermediate and regional ones.

In the deep aquifer, the groundwater flow starts in the N and NW close to the alpine front, where recharge areas of the deep aquifer can be identified, and it travels SE toward the Po River. Indeed, close to the mountain front, the lower thickness and frequency of low permeability sediments levels in the Multi-layered Villafranchian complex creates conditions for deep aquifer recharging. Owing to their features, deep aquifers are generally more protected from groundwater pollution than shallow aquifers (Lasagna et al. 2015, 2016a, 2016b).

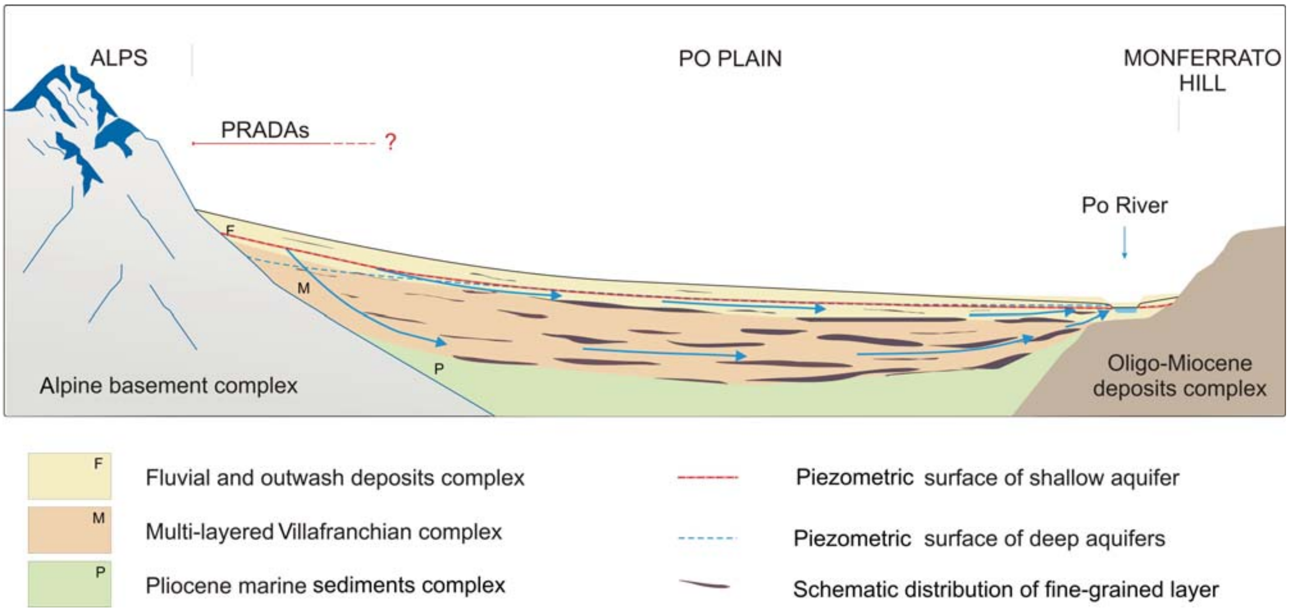

Fig. 9. Hydrogeological conceptual model of the study area.

4.2 Piezometric level difference between shallow and deep aquifer (Application of Step 1)

The piezometric level difference between shallow and deep aquifer in the Vercelli-Biella Plain was determined through the point-by-point grid subtraction of available piezometric levels of shallow and deep aquifers in the area using ArcGis software. Moreover, the calculated Δh values for the Vercelli-Biella Plain were divided into 10 classes (5 m spacing) and recorded as contours on a map (Fig. 10). Thus it was possible to evaluate the geographical distribution of piezometric level differences in the study area.

In general, areas with negative Δh cover a surface of about 520 km^2. Areas with positive Δh represent about 960 km^2. Positive Δh values are concentrated in a northeast-southwest oriented belt positioned close to the Alps and to the hills of Morainic Amphitheatre of Ivrea. In particular, more positive Δh values (+10÷+30 m) are found near morainic reliefs or in correspondence with the highest terrace in the Biella Plain. Generally, these values decrease rapidly from the reliefs to the plain, passing from Δh values of +30 m to +5 in about 10 km. On the contrary, in the central part of the plain, Δh values vary from +5 m to -5 m over a distance of more than 30 km. This trend suggests that a considerable difference between piezometric levels of shallow and deep aquifers is concentrated in a narrow area close to reliefs, whereas in the plain, a very small difference between piezometric levels is found.

Most negative values are located close to rivers. More specifically Δh values are strongly negative in a very narrow zone centred within the Sesia and Cervo Rivers. This belt of negative Δh values, wide between 1 to 10 km, extends into a plain stretching in the NW-SE direction, from Biella reliefs to the confluence of the Po River. The size of this area increases in correspondence with the confluence of the Cervo and Sesia Rivers. Another area with strongly negative Δh values is found in the SW of the study area close to the town of Crescentino and the Po River.

A large part of the study area is represented by Δh values close to zero.

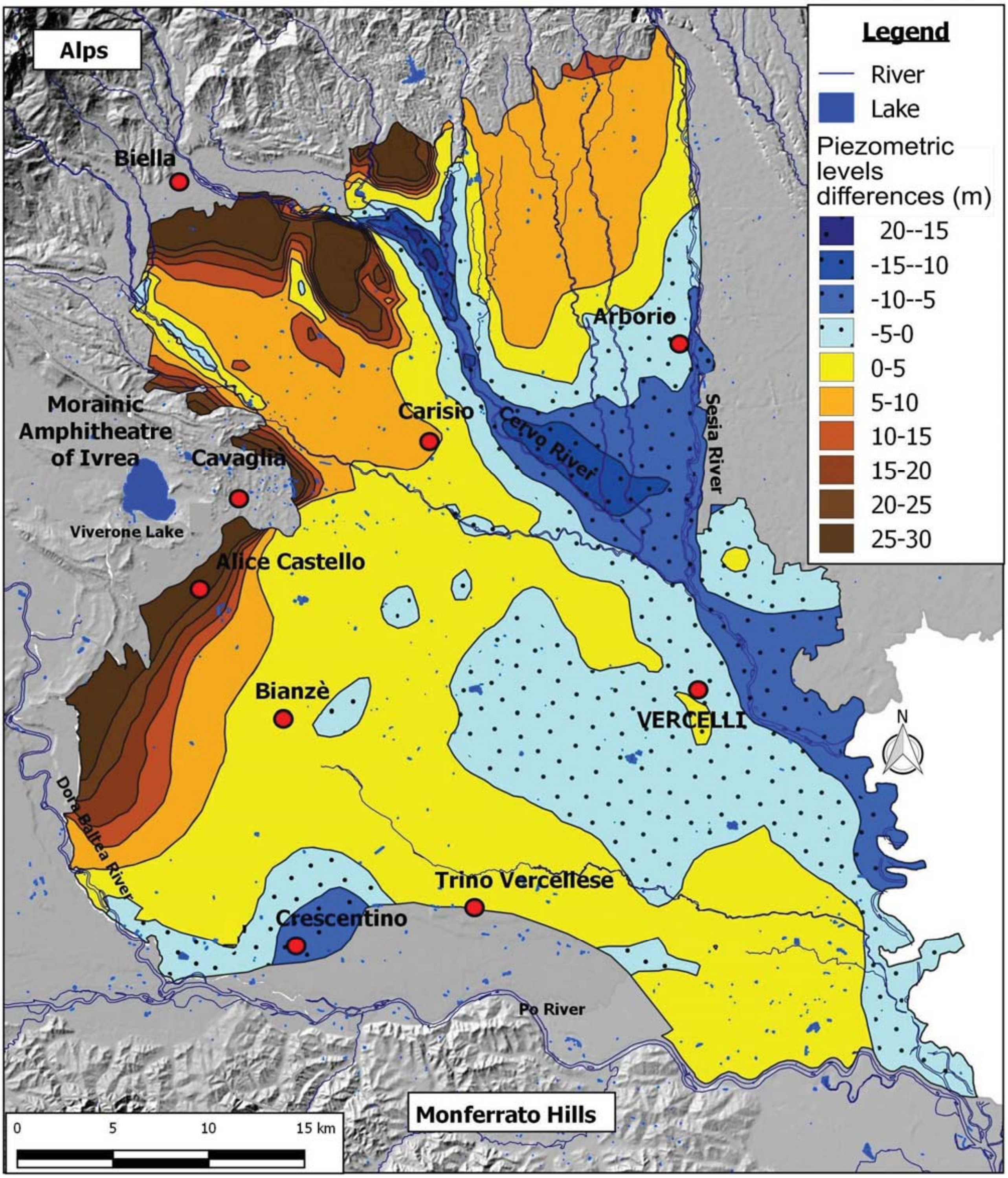

Fig. 10. The distribution of Δh values in the Vercelli-Biella Plain.

4.3 Delimitation of potential recharge, discharge and throughflow areas (Application of Step 2)

The potential recharge (PRADAs), discharge and throughflow areas of the deep aquifer (Fig. 11) were defined according to the procedure of step 2 in Fig. 2. The M value was chosen also considering the lithostratigraphic setting. In the study area, silty-clayey levels are present in the plain in the Multi-layered Villafranchian complex. Moreover, the number and thickness of fine-grained layers generally increase moving from high to low plain (Fig. 6). Thus, an M value of 5 m was chosen, because for Δh lower than 5 m the water exchange between aquifers was considered negligible and enable to produce the deterioration of the groundwater quality.

Finally, PRADAs correspond to all areas characterized by Δh values exceeding +5 m, potential discharge areas correspond to all areas characterized by Δh values lower than -5 m and throughflow areas to all areas characterized by Δh values in the range -5 m ÷ +5 m.

PRADAs form a belt close to the mountain front and close to the hills of the Ivrea Morainic Amphitheatre in the northern and western regions of the study area.

PRADAs width ranges between about 2 km close to Cavaglià and a maximum width of about 20 km in the area NW of Carisio. Areas close to the Cervo River in the proximity of the Alps, characterized by strongly negative Δh values, were included in the PRADAs for precautionary purposes. The PRADAs belt is only interrupted close to the town of Cavaglià, where morainic hills extend into the plain. A feeding to the deep aquifers from the permeable deposits upstream the morainic arc is also possible. However, the study area does not include this sector and further studies are necessary to deepen the situation in this zone.

The discharge areas of the deep aquifers are mainly located close to the Cervo and Sesia Rivers, in the eastern part of Vercelli-Biella Plain. More in details the discharge areas have a width ranging between 1 km and 10 km. The size increases near the confluence between Cervo and Sesia rivers, and indeed the discharge areas cover completely the plain between the rivers. Other discharge areas are located in a small sector located in the SW Vercelli-Biella Plain, near Crescentino. In this area the Po River acts as gaining river and cause an upward vertical flow of groundwater from the deep aquifer. Moreover this sector is characterized by impermeable Oligo-Miocene sediments located to low depth that favours the ascending flow of groundwater.

The insufficient number of piezometric measures referred to the deep aquifer close to the Po River does not permit to delimitate the discharge areas of the deep aquifers in this zone.

The central part of the Vercelli-Biella Plain shows Δh values of between -5 m and +5 m; this area, where groundwater flow is supposed to move horizontally, can be deemed as throughflow area of the deep aquifer. It occupies the greater part of the study area and fluctuates in size from less than 5 km to more than 35 km.

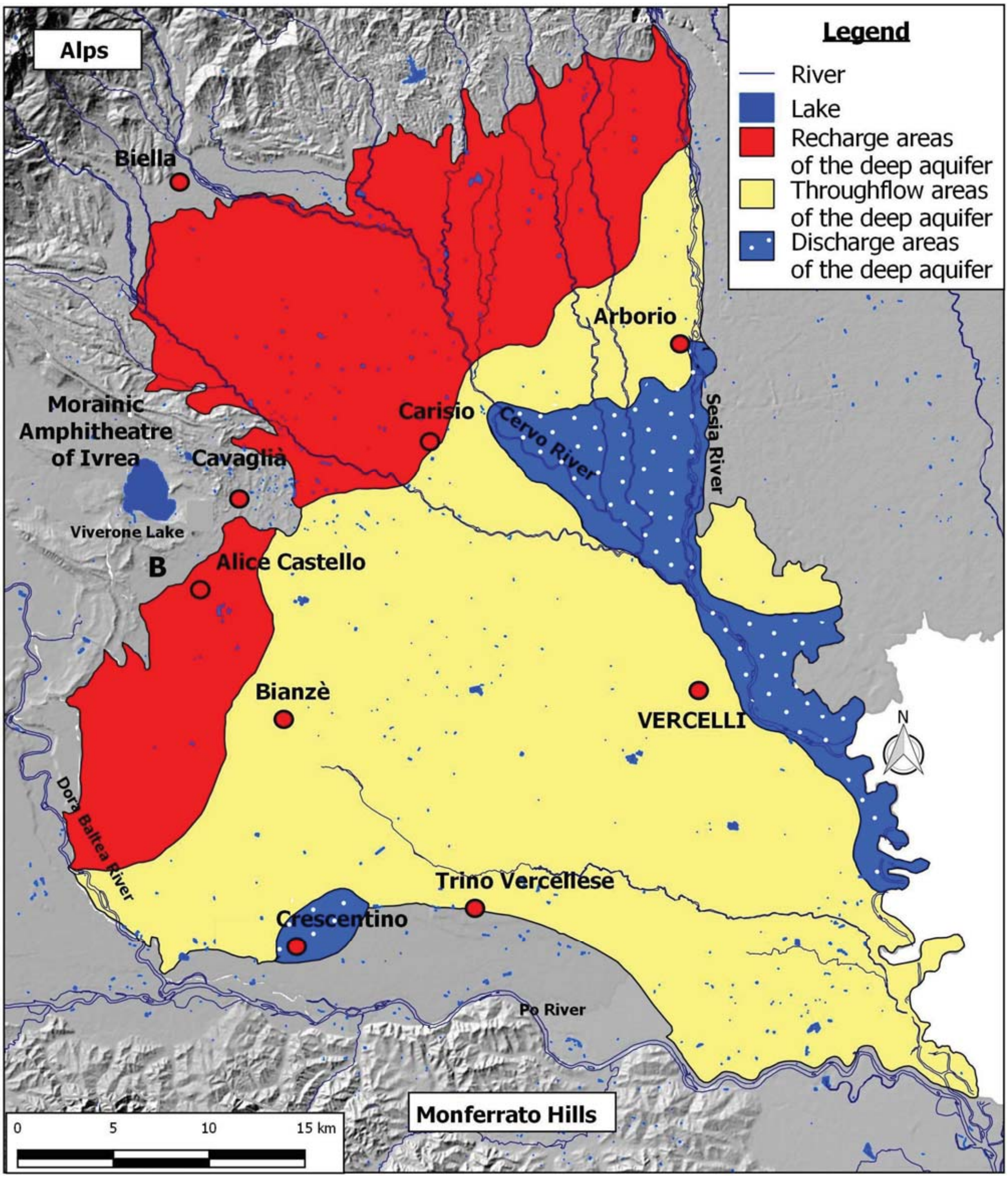

Fig. 11. Potential recharge, discharge and throughflow areas of the deep aquifer in the Vercelli-Biella Plain.

5 DISCUSSION

The proposed methods applied in the Vercelli-Biella Plain permitted to define the potential recharge, throughflow and discharge areas of the deep aquifer on a regional scale. This information is certainly important to protect the quality of the deep aquifers that normally, in the Po Plain, shows very high quality standards.

As the presence of thick and continuous levels of low permeability sediments could influence the vertical downward and upward flow of groundwater, even in areas with very positive or negative Δh values, the distribution of fine-grained sediments in subsoil was analysed starting from the performed lithostratigraphical cross-sections. In areas close to the mountain front or morainic hills, where the proposed method reveals downward flows of groundwater, silty-clayey sediments content is limited and low permeability levels are thin and characterized by reduced lateral continuity. Consequently, the distribution of fine sediments in the subsoil cannot prevent deep aquifer recharging in the mapped PRADAs. Thus, these zones present favourable conditions for deep aquifer recharging.

The piezometric level difference decreases towards the SE, from reliefs to the plain, and the content of silty-clayey sediments increases in the same direction. The passage from the shallow aquifer to the deep aquifer can be recognised due to the presence of discontinuous and impervious silty and clayey layers. This part of plain, in which the prevailing component of groundwater flow is horizontal, occupies the largest part of the Vercelli-Biella Plain (more than the 50%). These zones are defined as throughflow areas, and connect recharge to discharge areas.

The impermeable layers recognized in the throughflow areas were also found in the low plain, as far as the Po River. However, due to their discontinuity, they cannot prevent the upward flux from the deep to the shallow aquifer in the low plain, near the Po River. This sector corresponds to the discharge areas of deep and shallow aquifers.

For the validation of the proposed methods, previous studies about the recharge areas of deep aquifers in the Vercelli-Biella plain were searched in literature. However, no data about recharge areas for this area are available. Two studies conducted in adjacent areas were found, analysing the relationships between piezometric levels measured in different aquifers (Pilla et al. 2006) and using numerical model (Caviglia et al. 2009).

Pilla et al. (2006) studied the hydrodynamics of a multilayer aquifer system in an adjacent sector of the Po plain (Lomellina region). The Authors proposed a schematic description of the relationships between piezometric levels measured in the different aquifers of Lomellina plain. Particularly, in the low Lomellina Plain, as far as the Po River, piezometric level in deep aquifers is higher than the phreatic one. According to Authors, this inhibits the possibility of recent water penetrating far below the surface. Thus, the oldest waters of deep aquifers act as a piston through the lithological and granulometric discontinuities of aquicludes and aquitards, with an upward pressure transfer of deep groundwater. On the contrary, in the high Lomellina Plain piezometric level in shallow aquifer is higher than the deep ones, with a downward transfer of shallow groundwater. Because the hydrogeological setting of the Lomellina region displays features that are common to Vercelli-Biella Plain, the results obtained by Pilla et al. can be transferred to our study area, supporting the proposed hydrogeological conceptual model.

In a further study, Caviglia et al. (2009) used a numerical model to evaluate the potential contamination hazard for deep aquifers through multiaquifer wells in the northern Turin plain. The study area is located in Piedmont Region, in the southwest respect to Vercelli-Biella plain. The lithostratigraphical situation is very similar to Vercelli-Biella plain and the hydrogeological setting is comparable. As a result, two different groundwater flow patterns were distinguished, one in the shallow aquifer, generally connected to main rivers, and one in the deep aquifers. The recharge areas of deep aquifers were identified in the plain next to the Alpine chain. In the recharge areas, a flow gradient from the upper aquifer to the lower aquifer was present. In the low plain, especially close to the Turin Hill and Po River, this flux was upward and the piezometric level of deep aquifer was higher than in deep aquifers. This study confirms the hydrogeological conceptual model of Vercelli-Biella Plain and the geographical location of recharge and discharge areas.

6 CONCLUSIONS

The proposed simplified approach permits to identify locations and sizes of potential recharge, throughflow and discharge areas of the deep aquifer on a regional scale. Particularly, the piezometric level difference (Δh values) between shallow and deep aquifers is used to understand the potential direction of groundwater flows. More specifically, where main components of water flow are directed downward (Δh positive), the shallow aquifer potentially recharges the deep aquifer. Where they are directed upward (Δh negative), the deep aquifer potentially recharges the shallow one. At last, in areas characterized by null Δh values, no vertical water flow occurs.

The identification of the deep aquifers recharge areas provides the local administration with a management tool to protect groundwater, through the implementation of legislative measures and restrictions for the control over the pollution sources.

The proposed method identifies where deep aquifer recharging can occur, but not the recharge rate. Thus, delimited recharge, discharge and throughflow areas of the deep aquifer are defined as “potential” areas. . In this sense, the method represents a qualitative and preliminary approach to the identification of regional recharge areas of deep aquifers. Particularly, it permits to narrow down the large plain areas extension, highlighting where potentially recharge areas are located. Then the location and shape of the recharge areas can be defined effectively, expanding datasets and furthering analyses (hydrogeological reconstruction, hydraulic connectivity, hydro-chemical and isotopic methods…) in the identified areas.

The hydrogeological setting investigated by the method can be considered to be representative of many other anthropized and groundwater demanding plain around the world that require to be protected. Thus, the proposed method represents a useful approach for such settings for potential recharge area identification, especially in low income countries, where the availability of resources for studies and analyses are few.

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