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Hydrogeology of the western Po plain (Piedmont, NW Italy)

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ABSTRACT
This paper describes the hydrogeological map of the western Po Plain, located in Piedmont (north-western Italy). Po plain represents a hydrogeological system of European relevance, and the Piedmont Plain is the most important groundwater reservoir of the Region. The 1:300,000 scale map was realised using previous and new data to update the knowledge of this area. The map provides information about the hydrogeological complexes and their type and degree of permeability, water table levels and depth, piezometric level fluctuation, lithostratigraphic cross-sections, thickness, and percentage of the permeable deposits between 0 and 50 m from the ground surface. All this information is essential to public administrations, stakeholders, researchers, and professionals for defining possible tools for groundwater protection and management and for planning new groundwater exploitation (i.e. municipal drinking water supplies).

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1. Introduction

The hydrogeological map of the Piedmont plain (NW Italy) is presented in this paper. The Piedmont plain is located in the westernmost part of the Po Plain, representing a hydrogeological system of European relevance (WHYMAP, 2008).

The study starts from previous researches, especially PR.I.S.M.A.S. (acronym of PRogetto Interregionale Sorveglianza e Monitoraggio delle Acque Sotterranee ‘Interregional Groundwater Monitoring Project’), PR.I.S.M.A.S. II and VALLE TANARO projects, conducted from 1996 and 2000. These projects aimed to reconstruct the hydrogeological model of the Piedmont Region and to realize a groundwater monitoring network under a quantitative and qualitative point of view. These data were used for a publication on Piedmont Region hydrogeology (Bove et al., 2005), characterized by a limited number of printed copies and distribution on a local level.

In the present work, preliminary hydrogeological information has been improved using new and updated data, especially regarding the piezometric reconstruction. Moreover, a collection of recently published papers and unpublished technical reports concerning the different aspects of Piedmont plain hydrogeology was compiled and used for updating.

The hydrogeological map of the Piedmont plain at a scale 1:300,000 shows some of these findings. More specifically, it provides information about the hydrological complexes and their type and degree of permeability, water table levels and depth of water table, water table level fluctuation, thickness, and percentage of the permeable deposits between 0 and 50 m from the ground surface and lithostratigraphic cross-sections.

The hydrogeological map was produced in English and Italian because this study is addressed not only to an international audience of researchers, but also to public administrations, stakeholders, and local professionals working on groundwater management. More specifically, this map represents a basic step for future investigations (aquifer vulnerability, recharge areas, wellhead protection areas …) or studies aimed at solving current problems of groundwater resources in Piedmont, such as groundwater contamination (Lasagna et al., 2013, 2015, 2016b, 2018; Lasagna & De Luca, 2016, 2019; Martinelli et al., 2018), overexploitation (De Luca et al., 2018; Lasagna et al., 2014, 2019a), piezometric level variations as response to climate change (Lasagna et al., 2019b, 2020).

2. Study area

Piedmont is a region in north-western Italy, extended for approximately 25,400 square kilometers. Piedmont plain covers 27% of the regional territory, and is surrounded by the alpine chain on the north and east sectors, and by the Apennines Mountains on the south. Consequently, about 43% of its territory is constituted by mountains and 30% by hills. Piedmont plain, that represents the westernmost part of the Po Plain (Figure 1), is the most important groundwater reservoir of the

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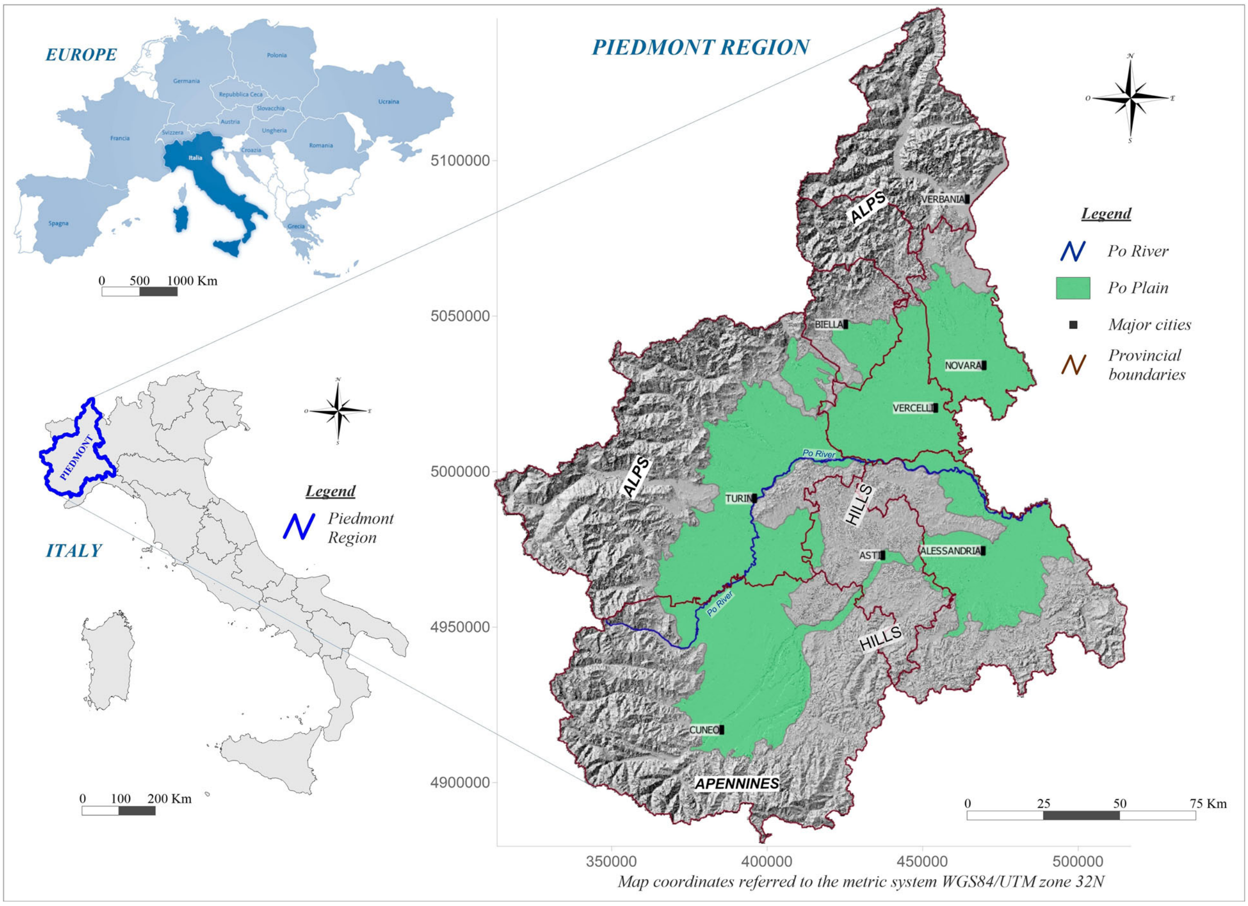

Figure 1. Location of the study area.

Region because of its size, the features of its deposits, and its possibility to recharge (Debernardi et al., 2008).

The hydrogeological conceptual model of Piedmont plain (Figure 2) consists of superimposed complexes represented, from top to bottom, by Alluvial deposits complex (lower Pleistocene-Holocene), ‘Villafranchiano’ transitional complex (late Pliocene–early Pleistocene) and Marine complex (Pliocene) (Barbero et al., 2007; Bortolami et al., 1976; Bortolami et al., 1990; Bove et al., 2005; Cavalli & Vigna, 1992; Civita et al., 2005; Comazzi et al., 1988; Debernardi et al., 2008; Forno et al., 2018; Lucchesi, 2001; Vigna et al., 2010).

The shallow unconfined aquifer is hosted in the Alluvial deposits complex, consisting of coarse gravel

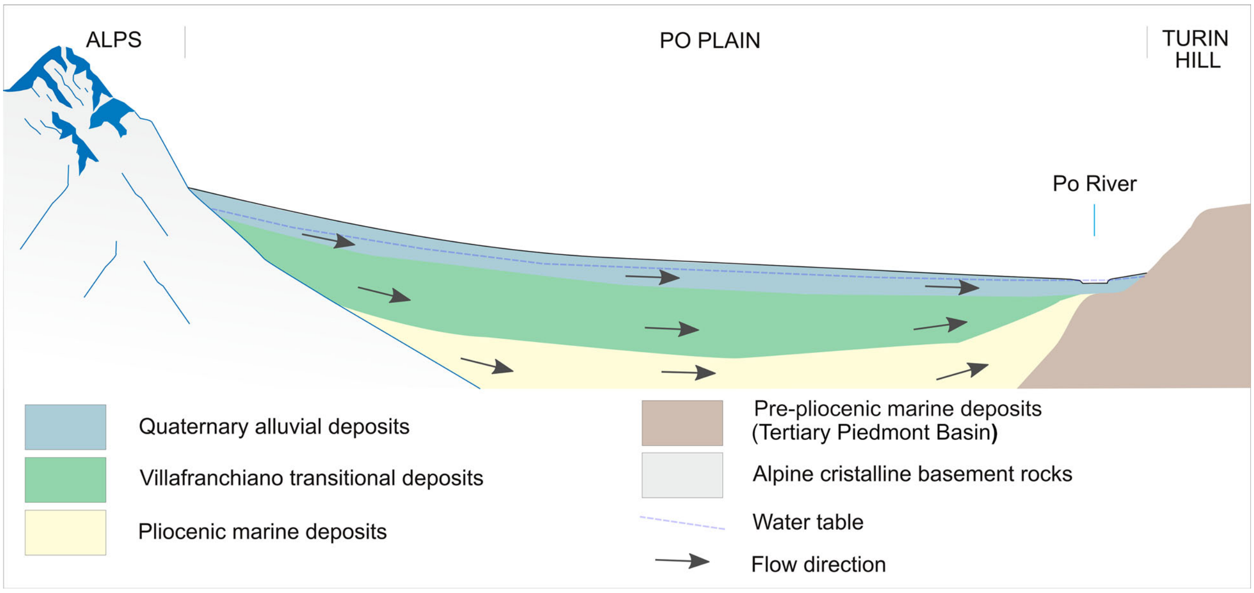

Figure 2. Sketch of the hydrogeological complexes of the alluvial Po plain. The cross-section has a W-E orientation, passing through Turin city. The black arrows represent groundwater flow direction in the different aquifers.

and sand of fluvial or fluvioglacial origin, with subordinate silty-clayey intercalations. This complex has a thickness generally ranging between 20 and 50 m and high permeability ($k = 5*10^{-3} \div 5*10^{-4}$ m/s).

Deeper aquifers are present in the underlying fluvial-lacustrine 'Villafranchiano' complex and the pliocenic marine sediments. They generally serve as key sources of drinking water in the Piedmont plain, because of their productivity and the better groundwater quality compared to the shallow aquifer (De Luca et al., 2019d).

Highly consolidated sediments, especially marls, clays, silts, clayey limestone, conglomerates, sandstone, and gypsum, generally represent the Tertiary Piedmont Basin deposits (Eocene-Miocene). These sediments have low permeability and permit only a limited groundwater circulation along fractured zones with the presence of springs with low and very low discharge (smaller than 1 L/s or few L/s).

Crystalline rocks of the Alps border the plain on the northern and western sides. They are mostly impermeable or slightly permeable by fissuration. In the mountain area, water resources are mainly located in the valley-floor aquifers, in sedimentary non-cohesive bodies (e.g. debris, landslide, and glacial deposits), or in intensely fractured rocks. Springs with low discharge (smaller than 1 L/s or few L/s) are generally connected to thin and discontinuous Quaternary deposits. Springs with higher discharge are, instead, linked to significant aquifers corresponding to large and thick landslide bodies or very fractured bedrocks affected by deep-seated gravitational slope deformations (DSGSDs) (De Luca et al., 2015, 2019c). Moreover, in alpine areas, locally karstic circuits can exist in calcareous rocks.

Glacial deposits are at last present in amphitheaters of Rivoli-Avigliana, Serra d'Ivrea and Upper Novarese. They are composed by glacigenic successions with interglacial paleosols and deposits, ranging in age from terminal Early Pleistocene to Late Pleistocene (Gianotti et al., 2015). The permeability of these deposits vary depending on the grain size, weathering, and argillization of its sediments; glacial and fluvioglacial deposits may host a shallow aquifer and some perched aquifers.

Recharge areas of the shallow aquifer are located in the entire plain, due to infiltration of rainfall and secondly by surface water in the high plain sectors. The low plain sectors are generally discharge areas, and the Po River represents the main regional discharge axis for the groundwater flow (Lasagna et al., 2016a). Along the main watercourses of Piedmont plain more than 200 quarry lakes are present (Castagna et al., 2015a, 2015b; De Luca et al., 2007) connected to quarries for extraction of sand and gravel.

The recharge areas of the deep aquifers occur in the high plain sectors, close to the Alps, where the hydrogeological complexes hosting deep aquifers outcrop or the low permeable intercalations have limited spatial continuity and thickness (De Luca et al., 2019a).

Groundwater flow is therefore conditioned by different factors: (i) the presence of the Alps that drives groundwater flow direction from the high to the low plain; (ii) GW-SW interactions, where main watercourses are generally losing rivers close to the Alps and gaining river in the low plain; (iii) grain size of shallow aquifer, that normally decreases from mountains to low plain, along Po River. When a sharp decrease in slope of the topographic surface is present in the middle plain or when shallow groundwater, flowing in the coarse-grained sediments in the high plain, meets the fine-grained sediments, groundwater rises to ground level and provides the origin of the *fontanili*, typical springs of the Po plain areas (De Luca et al., 2009, 2014; Minelli et al., 2002).

3. Materials and methods

The plain area of Alessandria, Asti, Biella, Cuneo, Novara, Turin, and Vercelli provinces were investigated, and the new insights were mapped in a hydrogeological map at a scale 1:300,000. A hydrogeological map represents a complex system of water and rocks and describes their properties and interrelations (Struckmeier & Margat, 1995). The analyses were conducted starting from a collection of available published and unpublished papers, maps, and technical reports, concerning different hydrogeological aspects.

The hydrogeological map of the western Po plain resumes different elements such as hydrogeological complexes, piezometric lines, depth of the shallow aquifer, phreatic level fluctuation, lithostratigraphic cross-sections, permeable deposits distribution between 0 and 50 m from the ground surface (described as thickness and percentage).

3.1. Hydrogeological complexes

Starting from the lithologies of the geological map at a scale 1:100,000 of the study area, the hydrogeological complexes were defined based on the prevalent type and degree of permeability. Then, hydrogeological complexes were digitalized in a vector format and implemented in a Geographical Information System (GIS), georeferenced in the UTM projection WGS84/zone 32N.

3.2. Water table level map and water table depth map

A field campaign was conducted in Piedmont plain in summer 2016 for the measure of water table depths. Phreatic groundwater levels were measured in correspondence of 588 points (wells and piezometers) homogenously distributed in the plain. These piezometric data were then integrated using monitoring wells 92 belonging to of the Piedmont Region monitoring network (www.regione.piemonte.it/monitgis/public/welcome.do) and 41 belonging to of the Città Metropolitana di Torino monitoring network (https://webgis.arpa.piemonte.it/geoportale/index.php/). The reason for the integration was dual: (i) control and validation of piezometric data previously collected; (ii) integration in areas where groundwater information was insufficient.

Water stages from the gauge stations on the watercourses were also used (www.regione.piemonte.it/monitgis/public/welcome.do). All data were at last collected in a database to produce the piezometric map of the shallow aquifer at a scale 1:300,000.

Starting from piezometric data, the isopiezometric lines were interpolated with the triangulation method using the Surfer 11 software (Golden Software, Golden, CO, USA). Then, the piezometric map was manually edited because many features of the study area, such as the presence of high terraces, large towns, *fontanili* springs, and rivers, made the triangulation interpolation inaccurate.

Control factors were also considered. A topographic control has been obtained using a Digital Elevation Model (DEM) with a resolution of 50 m, avoiding a water table above the topographic surface. The congruence of the water table with geological and geomorphologic data has been verified. Moreover, the relations between groundwater and surficial water bodies have been taken into account. Piezometric lines (equidistance 10 m) were plotted in a map with the hydrogeological complexes. The data interpretation was made at a scale 1:50,000 and then simplified and reported on a scale 1:300,000.

Main groundwater flow directions were indicated using flow lines. Successively, GIS application has allowed subtracting the groundwater levels grid from a DEM to obtain the values of depth to the groundwater table. These values were classified into 5 groups (0–5 m; 5–10 m; 10–20 m; 20–50 m; higher than 50 m) and mapped (1:600,000 scale).

3.3. Water table level fluctuation

Phreatic groundwater levels, registered in 37 Piedmont Region monitoring wells, were collected for the period 2002–2017. Moreover, rainfall data from 30 rain gauges managed by the Regional Agency for Environmental Protection Piedmont (ARPA Piemonte) and located in the Piedmont Plain were collected for the same period. Piezometric and rainfall data were validated by ARPA Piemonte and made available online to local authorities and professionals (www.regione.piemonte.it/monitgis/public/welcome.do; http://www.sistemapiemonte.it/cms/privati/agricoltura/servizi/378-ram-banca-dati-agrometeorologica-consultazione-dati-giornalieri-dati-storici-statistiche).

Then the average monthly water table level was calculated for the subsequent analyses.

The average monthly water table levels for the period 2002–2017 were plotted with the average monthly rainfall of the same period. In the hydrogeological map of the western Po plain, seven bi-plot are presented, showing some characteristic behavior of the study area.

3.4. Lithostratigraphic sections

Nine lithostratigraphic cross-sections were identified using the lithological data from 124 boreholes. Borehole data were collected from the database of the Earth Science Department (Hydrogeology Research Group) of Turin University. All boreholes are characterized by spatial coordinates (UTM projection WGS84/zone 32N). Profiles were chosen to describe all different lithostratigraphic situations of Piedmont plain. Particularly 2 profiles are located in Cuneo Plain, 2 in Turin Plain, 2 in Vercelli Plain, 1 in Novara Plain, 2 in Alessandria Plain. Longitudinal and transverse profiles are shown on the hydrogeological map of the western Po plain.

3.5. Map the permeable deposits between 0 and 50 m from the ground surface

Lithologic data related to 0–50 m depth from ground level are derived from 2000 stratigraphic logs from the database of the Earth Science Department (Hydrogeology Team) of Turin University. These logs describe the sediment for depth greater than or equal to 50 m.

Different subsoil layers have been classified in lithologic classes, and the thickness of the various deposits has been calculated. At last, the sum of the layers thickness of permeable deposits (gravel and sand) were calculated.

A map (scale 1:600,000) representing the thickness and relative percentage of permeable deposits in the Piedmont plain has been realized by using a kriging statistical interpolating method.

4. Results and discussion

Ten hydrogeological complexes were recognized and mapped in the Piedmont plain based on their geological media and permeability (degree and type). More specifically, the following hydrogeological complexes were identified (in order from youngest to oldest):

(1) Recent fluvial deposits (FS1) (Upper Pleistocene-Holocene): incoherent and heterometric sediments of fluvial (Holocene) and fluvioglacial

(Upper Pleistocene) origin, mainly gravelly-sandy and secondly silty-clayey; the general grain-size decreases from the mountains towards the axis of the plain at the Po River. These sediments are located in the bottom of the valleys and in the Piedmont Plain; they have a prevalent permeability for porosity from high to medium and contain a shallow unconfined aquifer, locally confined, in connection with surface rivers.

(2) Medium and ancient fluvial deposits (FS2) (Middle – Lower Pleistocene): incoherent and heterometric sediments, locally cemented, gravelly-sandy, and silty-clay, sometimes in alternation; the fine fraction may be prevalent. These deposits, which border the Apennine-Alps chains from Tanaro River to Maggiore Lake, are in contact with the morainic arches to which they are genetically connected. These deposits are sometimes characterized by the presence of a loessic covering and, in the most ancient terms, by a reddish-colored cover, with a thickness of few meters. A prevalent permeability of medium-grade, due to porosity, characterizes these deposits, but a lower degree of permeability is frequent, especially in the oldest and altered terms. They contain a shallow unconfined aquifer, locally confined, in continuity with the aquifer hosted in the FS1 Complex; perched aquifers can be located in correspondence with the terraced areas.

(3) Slope glacial and morainic hills deposits (GS) (Pleistocene): slope glacial deposits and deposits of the morainic amphitheaters of Rivoli-Avigliana, Serra d'Ivrea and Upper Novarese; they consist of sediments with variable grain-size from silt and clay with pebble to sand and boulder. This complex may include various types of deposits such as ablation, bottom, fluvioglacial, and lacustrine deposits. The prevalent permeability for porosity varies from medium to low, locally high. The slope glacial deposits on the mountainsides host a shallow unconfined aquifer while the moraine of the plains can constitute a multi-aquifer system.

(4) Lacustrine, swamp and fluvial sediments (Villafranchian series) (V) (Upper Pliocene-Lower Pleistocene): predominantly lacustrine, swamp and fluvial sediments outcropping near the Alpine arc (Stura di Lanzo fan, Serra d'Ivrea and Maggiore Lake), in the Alessandria plain and in the Poirino Plateau. They form a litostratigraphic complex consisting of both permeable deposits (pebble, gravel, sand) and low-permeability deposits (silt and clay). The prevalent permeability for porosity is of medium degree, even if they are characterized by high heterogeneity, depending on the depositional environment. They contain a shallow unconfined aquifer, where they are undifferentiated or in coarse facies; they constitute the main multi-aquifer system (confined and semi-confined aquifers) of the Piedmont plain, where represented by an alternating facies.

(5) Marine sands (MS) (Pliocene): very or little stratified yellow sands, with fossiliferous banks with faunas of the shallow sea, sometimes strongly cemented; sandstones, sands and pelites of a marine environment. At times, they have gravel levels (Asti, Alessandria and Biella areas) and marly or sandstone intercalations (Asti and Alessandria areas). The prevalent permeability for porosity has a medium degree. The coarser terms of this complex represent confined aquifers of good productivity, sometimes artesian (Villafranca d'Asti and Val Maggiore area). Marine sands can host shallow unconfined aquifer if the sediments are in outcropping.

(6) Marine clayey silt (MC) (Pliocene, Piacenzian): Blue clay and silt, clayey and sandy marl with abundant marine fossils and with microfaunas; upwards, intercalation of yellow sands. These are sediments with permeability generally from low to very low, which constitute aquitards or aquicludes. They can represent local confined and poorly productive aquifers in correspondence to the coarsest deposits.

(7) Sedimentary rocks of the Tertiary Piedmont Basin Auct. (MT) (Lower Pliocene – Oligocene): sedimentary rocks of the Tertiary Piedmont Basin Auct. (including the Formation of Cassano Spinola, Messinian-Pliocene Inf). Complex characterized by extreme lithological variability (conglomerate, sandy-arenaceous, marly-clayey formations, with a prevalent calcareous component, evaporitic (gypsum) and alternations of deposits with different permeability). The prevalent permeability is low and very low, even if very variable depending on the grain-size, the degree of cementation and fracturing. Aquifers productivity is generally low. In chalk, there is frequent groundwater circulation for karst. The natural quality of the water is generally acceptable, except in chalky terms.

(8) Calcareous and dolomitic rocks (CR) (Triassic – Paleogene): limestone-dolomitic rocks and strongly tettonized evaporitic-carbonatic levels (carbonates breccias) of the Alpine and Apennine substratum. They are characterized by a remarkable water circulation due to the development of superficial and deep karst phenomena. In the most calcareous deposits, the prevalent permeability (for fracturing and karst) results from high to medium; in the dolomitic rocks, the permeability and karst phenomena are smaller. This

complex often feeds springs with high flow rates (Le Vene, Dragonera and Bossea) very often above 100 L/s (average annual flow). The natural quality of the water is generally good except in the presence of evaporitic terms (carbonates breccia, anhydrite, gypsum and related cataclasite).

(9) Alpine and Apennine Flyschoid rocks (FR) (Late Cretaceous-Early Eocene): alternations of argillaceous schists with clay or sandstone limestones, or with sandstones, brown argilloschists, slate schists and subordinately limestone and conglomerates (Alpine flyschoid rocks); alternations of calcareous, calcareous-marly, arenaceous layers and blackish clayey banks and gray-blackish argillites (Apennine flyschoid rocks). In both cases, the prevalent permeability is low or very low. The extent of water circulation, generally limited and of local importance, is related to the lithology and the degree of fracturing.

(10) Metamorphic, volcanic and plutonic rocks (MVP) (Paleozoic – Neozoic): magmatic (plutonic and volcanic) and metamorphic rocks of the Alpine and Apennine substratum. They are gneisses, mica schists, quartzites, green stones (serpentinites, amphibolites and prasinites), granites, porphyries and their metamorphic derivatives. Groundwater circulation is absent or limited to surface fracture systems and significant faults. The prevalent permeability is variable from low to very low. The degree of permeability can also be medium along with the most fractured bands. Springs are characterized by modest flow rates (few L/s) and by good natural quality (mineral waters).

The water table level map in the western Po plain normally follows the topography of the land surface. Due to the morphological assessment, piezometric lines are generally parallel to the Alps reliefs. Po River represents the base level and the main gaining stream of the plain. The main watercourses are usually gaining in the middle and low plain.

Groundwater generally flows from the Alps to the low plain; high terraces, consisting of medium and ancient fluvial deposits, modify the morphology of piezometric lines. In the Novara plain and the northern Vercelli plain, the groundwater flow direction is from N to S. In the southern Vercelli plain and Biella plain groundwater flows from W-NW to E-SE. Flow direction in the northern Turin plain is NNW- SSE, while in the southern plain it is directed from W to E with some exceptions. In Cuneo plain the shallow groundwater flows from SW to NE in the central and southern portions of the plain, and from S to N in the northern sector. Alessandria plain is characterized by groundwater flow from SE to NW.

In high plain, the hydraulic gradients show the maximum values (e.g. 7–8% near Biella). Lowest values are located in the low plain (about 0.01%).

The water table depth map in the Piedmont plain shows a high variability of this parameter moving from the high to the low plains. In the low plain, the most frequent range is inferior to 5 m, especially along the Po River and near the main rivers of the plain. The highest values (more than 50 m) are distributed in Cuneo plain and in the northern part of Turin plain due to the presence of a high morphological terrace.

Average monthly water table levels in the period 2002–2017 highlight different situations. Starting from the north of Piedmont plain, monitoring well PII27, located in Novara plain, shows a quite constant water table level during the year. A little variation of the phreatic level is due to the precipitation regime. In Vercelli plain, monitoring well PII1 displays a high seasonal change, with a water table level fluctuation higher than 4 m. A maximum phreatic level is registered in August and a minimum in March. The fluctuations are not exclusively connected to rainfall but also irrigation practices (flooding of paddy fields). The maximum water table level and rainfall, indeed, are not always contemporary. P26 in Turin area does not show a notable variation of phreatic level and scarce correlation with rainfall. Monitoring well P17 in the southern Turin plain reveals a close relation between phreatic level and rainfall, with a maximum in May and a minimum in August. In Cuneo and Asti plain, two analysed monitoring wells (T2 and T30) shows a little variation of phreatic level during the year, lower than 1 m. T12 located in Alessandria plain displays a maximum phreatic level in March and a minimum in September.

Lithostratigraphic cross-sections were useful to highlight the different lithologies in the study area and their geometric relationship.

Section 1 is characterized by a high sequence of coarse deposits of the Cuneo plain. The Alpine crystalline substrate is crossed on the eastern part, under alluvial deposits.

Section 2 shows the different lithology corresponding to recent fluvial deposits (mainly gravel and sand with subordinate fine-grained intercalations) and medium and ancient fluvial deposits (silt and clay). A high thickness of fine deposits alternated with coarse-grained deposits is present on the western portion of the section.

Section 3 is located in Turin plain and highlights the presence of Pliocene and pre-Pliocene marine deposits under the fluvial deposits. Fluvial deposits consist of coarse-grained sediments with local conglomerate in the shallow subsoil and alternating fine and grained-sediments at a depth superior to 40 m.

Section 4 crosses the plain from NW to SE, close to the Turin Hill. It highlights a thick sequence of fluvial deposits, more coarse in the shallow subsoil and fine in-depth, and the presence of Pliocene marine sediment on the eastern portion.

Section 5 is located in Biella plain. It crosses the crystalline substrate in the northern part of the section, close to the Alps, and a thick sequence of fluvial deposits in the plain.

Section 6 has N-S development in Novara plain. It crosses the crystalline substrate at a high depth from ground level (about 150 m). Fluvial deposits are generally coarse, and fine levels appear at a depth higher than 100–120 m from ground level.

The cross-section in Vercelli plain (section 7) has E-W development. Alternating fine and grained-sediments are present in the plain, with a predominance of gravel and sand in the first tens of meters of depth. On the western portion of the section, silt and clay layers are predominant.

Sections 8 and 9 are positioned in Alessandria plain and show quite different situations with respect to the previous ones. Section 8 highlights the presence of a sedimentary basin filled by a succession of generally coarse deposits. Pre-Pliocene deposits are present on both ends of the sections.

Section 9 does not intercept the Pre-Pliocene deposits, located at a greater depth. Sediments are prevalently fine-grained, with a thickness higher than 120 m on the NE end of the section. In the other portions, fine deposits are located at a depth inferior to 50, and coarse sediments are present in the shallow subsoil.

The map of the permeable deposits between 0 and 50 m from the ground surface highlights better the situation described by the cross-sections and the areal distribution of sediments.

5. Conclusions

The hydrological map of Piedmont plain summarizes the knowledge about litostratigraphy and hydrogeology of this area, representing the most important groundwater reservoir of the Piedmont Region and having hydrogeological features common to alluvial basins located close to mountains worldwide.

The availability of this knowledge is essential to create the basis for groundwater planning and protection. Indeed, this information is fundamental for researchers, public administrations, stakeholders and professionals for defining possible tools for groundwater protection and management, for planning new groundwater exploitation (i.e. municipal drinking water supplies), and finally for environmental impact studies of soil and subsoil.

The next step will be the collection and analyses of groundwater chemistry data and deep groundwater circulation, to obtain a more complete overview of this essential resource.

Software

Data processing and statistical analysis were performed by Surfer 11 software. The elaboration of the individual maps was produced using QGIS 2.18. The assembly of individual maps in the final map was achieved by Surfer 11.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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