Hydrogeology of a high Alpine carbonate aquifer (Pale di San Martino, Dolomites, Northern Italy)

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Abstract

A 1:50,000 hydrogeological map of the Pale di San Martino Mountains (Northern Italy) was created. The map presents the merge of various pre-existing data with new field data collected between the years 2014 and 2016. Through the use of symbols and specific colours, the map shows various groundwater-related data such as the hydrogeological complexes, the location and size of the main springs, the extension of the recharge areas, the hydrogeological boundaries, as well as information on groundwater usage. Given the absence of hydrogeological maps in the entire mountain range of the Dolomites, the approach followed in this study could be used as a guide for future representations in this alpine region. At the local scale, the map could serve as a conceptual base for future research involving groundwater and for water management planning.

1. Introduction

Hydrogeological maps are a powerful tool to represent water-related data and one of the most clearly understandable documents regarding water resources. They can be used to assist the work of a broad spectrum of experts, such as water engineers and resource managers, town planners, decision-makers and politicians (Struckmeier & Margat, 1995). Since the 1980s, hydrogeological mapping has been one of the main activities of Italian hydrogeologists and numerous maps were elaborated for the Italian territory. Most of them are at scale lower than 1:100,000 and cover the central and southern portions of Italy (Boni, Bono, & Capelli, 1986; Boni, Bono, & Capelli, 1988; Celico, 1983; Gragnanini, Mastrorillo, Vignaroli, & Rossetti, 2015; Manca, Viaroli, & Mazza, 2017), whereas coverage at a larger scale is fairly poor, especially for the alpine mountain aquifers (Capelli & Mazza, 2009). Only the hydrogeological map (1:50,000) of Kanin massif, an important transboundary aquifer between Italy and Slovenia, appears to be currently published (Muscio, Casagrande, & Cucchi, 2011). The main reason for this gap is the scarce accessibility of high-altitude areas and thus the difficulty of performing hydrological observations and measurements on a continuous basis (Gerrard, 1990). In mountain terrains, hydrological variables are also measured with a lower accuracy than in the lowlands because high slopes and strong winds affect the efficiency of precipitation gauges (Klimes, 1990).

The hydrogeological map presented in this work aims at filling the gap of hydrogeological information for the Italian Alpine area, starting from a mountain range known as the ‘Dolomites’. The study focuses on a 250 km² portion of this chain that includes the Pale di San Martino, Pale di San Lucano and Mt. Agner group of mountains (referred to together as the ‘Pale di San Martino’). All the Dolomites, including the study area, are a UNESCO World Heritage Site, known worldwide for its outstanding landscape (Dolomiti UNESCO Foundation, 2009, available at http://www. dolomitiunesco.info/i-nove-gruppi-dolomitici/?lang=en). Two main components of attraction characterize the territory: first of all, the vertical and steep mountain peaks, which reflect the complex tectonic pattern of the area; second the hydrological heritage, expressed in the widespread presence of turbulent streams, springs and high-altitude lakes. The great amount of water resources is clearly visible when moving in the Dolomites region, but up to now the volume of these resources and their potential is unknown. Hydrogeological studies available in the literature are scarce and related to specific topics such as fluvial geomorphology or to karstic aspects (Borsato, 2001; Frondini, Zucchini, & Comodi, 2014; Testa et al., 2013; Van de Griend, Seyhan, Engelen, & Geirnaert, 1986). This work aims at proposing a cartographic approach to represent groundwater-related data in the Pale di San Martino Mountains, suggesting a methodology that could be applicable in the future also to other sectors of the Dolomites. The map contains two types of information: (i) hydrogeological information deriving from already
existing archives and reports; (ii) data deriving from field surveys performed between the years 2014 and 2016. The aims of the representation are the following:

- Quantification of the amount of renewable groundwater resources
- Identification of the recharge areas and the main reservoirs containing groundwater resources
- Identification of the spatial distribution of the main groundwater outflows
- Quantification of water usage and their impact on the available groundwater resources.

To achieve these results, a 1:50,000 scale hydrogeological map of the Pale di San Martino was elaborated with a focus on water usage. Water usage knowledge is fundamental for a sustainable management of the resources. This map could serve as a quick and easily readable document to be used in water management decision-making or it could be used as a base for future scientific researches in the field of water resources.

2. Study area

The Pale di San Martino Mountains are a 250 km² wide carbonate massif with various peaks rising above 3000 m. The terrain elevation ranges between approximately 600 m a.s.l. in the valleys and up to 3192 m at the highest peak, the Mt. Cima Vezzana (Figure 1). A high-elevated karst plateau (mean altitude 2650 m a.s.l.), known as ‘Pale di San Martino Plateau’, covers the central part of the massif. From a geological point of view, the Pale di San Martino consists in a thick Middle-Triassic sequence of dolomites that are underlain by Permian to Lower Triassic terrigenous and evaporitic deposits (Bosellini, 1996). All the sedimentary sequence of the Pale di San Martino lies on top of the metamorphic Paleozoic basement or on top of a thick Permian porphyry plateau. In the northern part of the Pale, the emplacement of Middle-Triassic submarine volcanic deposits complicates this setting. Numerous dikes cross-cut the sedimentary succession and pillow lavas and breccias are in contact with the carbonate sediments. Quaternary deposits of alluvial and glacial origin fill the valleys and accumulate on the mountain flanks. Several tectonic phases affected the area generating a complex pattern of faults and fractures. The last one occurred during the Tertiary and is the W- to S- trending Alpine compression (Castellarin et al., 1992; Doglioni, 1987). This phase provided the uplift of the area through a series of thrust and backthrust faults (Schönborn, 1999). From a geomorphological point of view, the Pale di San Martino is characterized by six main valley systems that deeply cut into the carbonate ridges: the Pradidali-Canali, Gares, Focobon, Venegia and Angheraz-San Lucano Valleys (Figure 1).

3. Methods

This study combines geological and hydrological data deriving from already existing public and private databases with new fieldwork carried out between the years 2014 and 2016. With respect to administrative borders, the Pale di San Martino belongs to the Trento Province to the west and to the Belluno Province to the east and is part of two natural reserves, the Parco di Paneveggio-Pale di San Martino Provincial Park and the Dolomiti Bellunesi National Park. Due to this transboundary setting, all the existing geological and hydrogeological data were captured using different technologies and were published with different legends and scales. These data include geological maps, spring cadasters, water supply inventories, historical archives and other water-related information. To deal with this great variety of sources, a large part of the work was dedicated to data collection and data processing. All the available information was homogenized using a Geographic Information System (GIS).

3.1. Cartographic materials

Concerning the geological data, no official geological map covering the entire mountain group of the Pale di San Martino was available. The only official geological maps of the area date back to the 1970s and are the sheets 22 and 11 of the 1:100,000 scale National Geological Service (SGN, 1970a, SGN, 1970b). However, even these two maps were represented using different scales, as such as symbols and legends. More recent open access digital maps are available online: the 1:250,000 Veneto Region Lithostratigraphic map (Veneto Region, n.d.) and the 1:200,000 Trento Province lithological map (Bosellini, Castellarin, Dal Piaz and Nardin, 1999). Nevertheless, when matched in a GIS environment and zoomed at a larger scale, these products show major incompatibilities such as gaps between adjacent polygons, distortions, displacement of the vectors and different attributes (Figure 2). In 2006, a 1:25,000 geological map was elaborated by the Autonomous Province of Trento [PAT], but this map covers only a small portion of the western side of the Pale di San Martino (Massironi, Preto and Zampieri, 2007).

The most detailed geological map with a comprehensive coverage of the Pale di San Martino is a 1:35,000 map included in a 1939 monography (Castiglioni, 1939). Given the fact that this map was the result of a detailed geological survey and was accompanied by accurate descriptions, it was preferred to more recent geological products (Figure 3). The paper map was digitalized and the geological shapefiles were merged and re-organized on the basis of updated lithological classifications (ISPRA, 2007). The WGS84 datum was
adopted, and the metric coordinates were referred to the UTM 32N projection zone.

After a quality check, the lithological shapefiles were grouped into six hydrogeological complexes.

Hydrogeological complexes consist in geological units that exhibit a similar capacity of storing and transmitting water, according to their lithological properties (Gragnanini et al., 2015; Mastrorillo et al., 2009). An estimate of the hydraulic conductivity was associated to each complex and was obtained by merging field observations, such as stratigraphical relationships, density of fractures, grain size and clay content with the results of in situ tests performed in the area (unpublished reports).

3.2. Acquisition of hydrogeological data

Given the map content, data collection focused more specifically on groundwater-related data. For this purpose, many private water suppliers and public authorities were contacted and data was provided in different forms, such as tables, databases, online Web GIS platforms and vector files. Information acquired concerned the following elements:

- Meteorological data (retrieved from PAT meteorological service: http://storico.meteotrentino.it/ and from the Veneto Region Environmental Protection Agency [ARPAV] meteorological site http://www.arpa.veneto.it/bollettini/storico/Mappa_2015_TEMP.htm)
- The location, size and use of the springs (retrieved from ARPAV (2007) and from PAT (n.d.) at URL http://www.protezionecivile.tn.it/territorio/Banche/Arpa/Arpa_accessowebgis/)
- The location of artificial withdrawals and water supply facilities (unpublished raw data from local water suppliers)
- The location of diversion dams and hydropower plants (unpublished raw data retrieved from the Province of Belluno and local water suppliers)
- Cave cadasters (from Proteo Vicenza Speleological Club, 2016).

New data was collected seasonally between the years 2014 and 2016 and included hydrogeological surveys and measurements, such as the detection of physical-chemical parameters of the spring water (pH, Electrical Conductivity, Oxidation Reduction Potential and...
Temperature) and progressive discharge measurements by current meter along the main streams. According to the spring cadastres, more than 500 springs are present only in the Pale mountain group. Considering the purpose and the scale of this study, only the springs with a discharge rate greater than

Figure 2. Incompatibility of digital geological maps across the border between the Trentino and Veneto regions when imported in a GIS environment. On the left side: Carta litologica del Trentino – Lithological map of Trentino (scale 1:200,00 from Bosellini et al., 1999) on the right side Carta Litostratigrafica del Veneto – Veneto litostratigraphic map (scale 1:250,00 from Veneto Region, n.d.).

Figure 3. Available geological maps of the Pale di San Martino mountain group: on the left the geological map of the Pale di San Martino from Castiglioni, 1939; on the right more recent geological maps covering only a limited portion of the Pale (SGN, 1970a; Massironi et al., 2007).
0.005 m$^3$/s were measured and were represented in the map. To avoid the overlap of symbols, some springs were identified as spring groups and were represented with a single symbol (for instance the Acque Nere springs). To identify each spring an increasing numerical code, based on the mean discharge, was used. With reference to discharge, measurements were carried out along the main streams that deeply cut into the massif (Venegia, Angheraz – San Lucano, Pradidali – Canali, Focobon and Gares Valleys). These streams originate from large springs that are usually located in the upper part of the valleys and progressively increase their flow rate thanks to the contribution of other point and linear springs emerging along the streambed. For this reason, discharge measurements were carried out at different sections of the streambed, moving from the top of the valleys towards the lowlands. When the discharge increase was not justified by the amount of water fed by tributaries or by anthropic releases in the stream, it was assumed that the groundwater emerged directly in the streambed representing an invisible submerged spring (i.e. linear spring; Boni et al., 1986; Mastrorillo and Petitta, 2014). In order to assess the natural discharge of springs, a good knowledge of surface water usage is required. For this purpose during the field surveys, all the artificial withdrawals were identified and the discharge values were corrected adding the amount of discharge withdrawn.

A total of 20 discharge measurements were carried out and repeated in six surveys in order to estimate the total volume of groundwater discharging from the whole hydrogeological structure.

To evaluate the recharge rate, pluviometric data were acquired from the official meteorological service, mentioned above. The gaps in the official weather data, especially at high altitude where official stations are absent or defective, were filled by a one year monitoring (year 2015) of a monthly cumulative volume of precipitation at different elevations, included in the field campaign activity.

### 3.3. Data elaboration

All discharge values were elaborated to evaluate the mean, minimum and maximum values and the results are contained in Table included to the map. For the high-yielding springs the maximum and minimum values are always available, because they were measured during the 2014–2016 field survey. Data of the remaining springs were provided by Public Water Services as average values. Any other relevant collected information about the springs is reported in the text below.

The yearly cumulative rainfall values were interpolated through the Inverse Distance to a Power method using the software Surfer (Golden Software) making a rainfall spatial distribution map.

All the available information was merged in a geo-database in order to obtain a comprehensive knowledge on the Pale groundwater system. Then, data was added to the map as GIS layers together with the hydrogeological complexes. Data were grouped in four main categories: (i) hydrostructural elements: containing all the structural elements that affect the flow, by creating boundaries or preferential pathways; (ii) recharge: representing all the elements related to recharge, such as recharge areas, points of preferential infiltration, etc.; (iii) discharge: including all the different types of groundwater outflows, such as point and linear springs; (iv) water usage: representing all the springs used for water supply and diversion dams. Each group was symbolized using specific colours: red was used to represent recharge symbols; blue was selected for discharge; black and grey shades represent hydrogeological boundaries and orange was used for symbols related to water usage. In order to better understand the hydrogeological setting, three schematic hydrogeological cross sections were created. In the sections, the structural–geological complexity was simplified to visualize the hydraulic boundaries and the geometrical relationships between the complexes. Two of the sections were oriented NNW–SSE, sub parallel to the maximum compressive crustal stress direction (Castellarin et al., 1992), in order to show a good approximation of the real thickness of the units (sections AA’ and BB’). The third section, section CC’ is oriented perpendicular to the other two in order to investigate the groundwater flow in the E–W direction.

### 4. Results and discussion

The outcomes obtained in this study are related to four main topics: (i) hydrostructural elements, (ii) recharge, (iii) discharge, (iv) water usage. The integration of the main results allowed to gather an initial interpretative model of the hydrogeological setting of the Pale massif, depicted below.

In the study area six hydrogeological complexes were identified. A concise description of their characteristics is contained in the map legend, as well as an estimate of the relative hydraulic conductivity.

The carbonate complex, (c) in the map, covers most of the area and is characterized by a dominating presence of the Sciliar Formation (Bosellini, 1996), with an overall thickness of over 1500 m (Figure 4a). Due to the high permeability, acquired mainly by fracturing and karstification, this complex hosts the regional fractured aquifer, characterized by two different groundwater flows. The upper flow develops in a karstic and fast flow network and is active during periods of high flow; the lower flow is slower and perennial and develops through the diffused fracture system (Figure 4b). The more erodible deposits that underlie the carbonate complex form the terrigenous and evaporitic complex
This complex includes shallow marine terrigenous and evaporitic type of rocks (respectively the Werfen and Bellerophon Formation), mainly silts and clays that share a low degree of relative hydraulic conductivity. Due to these characteristics, the complex assumes the role of the regional aquiclude for the groundwater circulation. This setting is complicated by the presence of the Quaternary sediments that fill the valleys and accumulate on the mountain flanks. These coarse to fine grained deposits were grouped in the alluvial, rockfall and glacial complex, (a) in the map. The complex is characterized by a high porosity of the media and acts as a regional porous aquifer in connection with the adjacent carbonate one. The other complexes play a minor role in the groundwater flow and are described in the map legend. This hydrogeological framework is clearly marked in the three (3) schematic hydrogeological cross sections, annexed into the map. The aquifer–aquiclude contact assumes the hydrogeological role of a no-flow boundary and forces the groundwater to flow out at this limit (Figure 4d). Due to this setting, the Pale di San Martino can be considered an isolated hydrostructure with well-known boundaries. Where the outcrops of the aquifer-aquiclude contact is hidden (buried) by the alluvial, rockfall and glacial complex, the groundwater transfers to the regional porous aquifer and outflows from the valley bottom.

This aquifer/aquiclude limit is the main hydrostructural element indicated on the map (no-flow boundary). All the fault traces available in the literature were also represented in the map in order to identify areas of possible groundwater divide.

Groundwater recharge areas were identified based on lithological constraints. Considering the wide scale of the map, it was assumed that the outcrop of the aquifers corresponds to the areas of recharge. A surface of 100 km² is covered by the carbonate complex, 33 km² are covered by the alluvial and rockfall aquifers (complex a1), 5 km² are covered by the glacial deposits (complex a2) for an overall recharge area of 138 km². This value should be considered as an approximation.
because in reality recharge is likely to exhibit local variations. The carbonate complex is characterized by a wide exposure of bare, fractured rocks that favour a direct recharge with strong vertical components. Caves and karst shafts represent preferential points of infiltration as well as dolines that also host small
ephemeral lakes due to their depressed shape. Recharge is ensured by precipitation in the form of rainfall and snowmelt. Glaciers and ephemeral lakes present on the topographic surface create an additional source of recharge for the groundwater system (Figure 5). The spatial distribution of precipitation (Figure 6) indicates a mean annual value between 915 mm (Biois a Cencenighe station; 770 m a.s.l.) and 2402 mm measured at the highest station (Rosetta; 2660 m a.s.l.) for the year 2015 (Table 1). This result indicates that, topography plays a major role in precipitation distribution, as expected in mountain terrains. Because of the short time of the data set (data collected only for the year 2015), it was not possible to quantify in detail the spatial distribution of rainfall values, especially at the highest altitude sectors, and thus the calculation of a mean precipitation value could not be significant. It is reasonable to suppose that the 2015 recharge through the outcrops of the carbonate complex was just under 2000 mm.

Discharge zones correspond to the main springs of the area, which are located at the no-flow boundary or at the valley floors in the streams. 42 springs with a discharge greater than 0.005 m$^3$/s were identified in the Pale di San Martino mountain group in total. The characteristics of the springs are summarized in Table 2. The identification number of each spring is the same used in the Main Map. The average values of discharge are between 1.20 m$^3$/s of the Tegnas stream linear spring and 0.01 m$^3$/s of Polver spring located in the lower Angheraz Valley. Most of the discharge flows out in the form of linear springs and is concentrated to the east and to the south of the Pale, respectively in the Angheraz-San Lucano Valley and in the Pradidali-Canali Valleys. The overall mean discharge deriving from the entire hydrostructure is 6.86 m$^3$/s for the monitoring period.

With reference to water usage, numerous diversion dams are present along the main streams and in particular in the San Lucano, Canali and Gares Valleys. Overall, the amount of water withdrawn for hydropower generation corresponds to 4.56 m$^3$/s. Among all the springs’ groups, 15 are used for drinking water supply for a total average abstraction of approximately 0.185 m$^3$/s (Figure 7). It should be considered that water usage data were provided by the local suppliers and represent the average operating discharge for the period of the concession. Furthermore, only available data were used to compute the water withdrawals, therefore the real withdrawals over the study period could diverge from these values. Other uses, such as abstraction for irrigation, are negligible for the study site (Trentino-Alto Adige irrigation state report available at URL http://dspace.inea.it/bitstream/inea/730/1/SE5-1032.pdf). In the winter months, water for artificial snow production is taken from artificial water reservoirs and rivers, contributing to water consumption. The amount of water used for snow production in the entire basin of the Cismon River, where most of the ski-plants are located, corresponds to 0.01 m$^3$/s (permitted amount according to PAT, 2006) and is negligible compared to the total volume of the resources.

### Table 1. Meteorological data used for the interpolation (year 2015).

| Station id | Gauging station name        | Elevation (m.a.s.l.) | Mean precipitation (mm) | Max. snow height above the ground (cm) | Mean temp. (°C) |
|------------|-----------------------------|---------------------|-------------------------|----------------------------------------|----------------|
| VW         | Tonadico Castelpietra -Villa Welsperg | 1038                | 1258$^a$               | 24$^b$                                  | 8$^a$          |
| PC         | Passo Cereda                 | 1322                | 1297$^a$               | /                                      | 7.4$^a$        |
| RS         | Rosetta                     | 2660                | 2402$^a$               | 340$^d$                                | 1.7$^d$        |
| SM         | S. Martino di Castrozza      | 1470                | 1453$^a$               | 57$^n$                                 | 5.8$^n$        |
| PR         | Passo Rolle                 | 2012                | 1850$^a$               | 90$^b$                                 | 4.1$^b$        |
| AG         | Agordo                      | 585                 | 932$^c$                | /                                      | 9.5$^c$        |
| BC         | Biois a Cencenighe           | 770                 | 915$^c$                | /                                      | 9.3$^c$        |
| SC         | Scallette                    | 860                 | 1452$^a$               | /                                      | /              |
| FL         | Falcade                     | 1145                | 952$^c$                | /                                      | 7.5$^c$        |
| GR         | Gares                       | 1360                | 1108$^c$               | /                                      | 6.9$^c$        |
| SA         | S. Andrea (Gosaldo)          | 1250                | 1287$^c$               | /                                      | 7.7$^c$        |

Data derived from the gauging station of Roma Tre$^b$, Meteotrentino$^b$, Arpav$^c$, Meteotriveneto$^c$.

5. Conclusion

The GIS-based 1:50,000 scale hydrogeological map presented in this study provides a simple and intuitive
### Table 2. Characteristics of the springs with a discharge greater than 0.005 m$^3$/s identified in the Pale di San Martino mountain group.

| Spring no. | Name/location | Elevation (m a.s.l.) | Mean $Q$ (m$^3$/s) | Min $Q$ (m$^3$/s) | Max $Q$ (m$^3$/s) | Mean physical and chemical parameters | Spring use | Mean withdrawals (m$^3$/s) |
|------------|---------------|----------------------|---------------------|-------------------|------------------|--------------------------------------|------------|---------------------------|
| 1          | Tegnas stream – from Casera Paluch to Ai Vanti dam | 765–741 | 1.20 | 0.17 | 2.29 | 151 | 8.2 | 106 | 7.8 | hg | 1.075 |
| 2          | Pradidali stream – from the origin to La Ritonda bridge | 1420–1190 | 0.75 | 0.45 | 1.04 | 145 | 7.9 | 52 | 5.7 | nu | >1.15 |
| 3          | Canali stream – from Acque Nere springs to Castrona dam | 1145–1030 | 0.65 | 0.13 | 1.38 | 232 | 8.0 | 101 | 6.3 | hg | 0.75 |
| 4          | Liera stream – from Gares Waterfall to the dam | 1344–1130 | 0.50 | 0.12 | 0.70 | 175 | 8.0 | 114 | 7.7 | hg | 1.5 |
| 5          | Tegnas stream – from Ai Vanti dam to Enel plant | 740–663 | 0.45 | 0.34 | 0.75 | 195 | 8.1 | 52 | 5.7 | nu | 0.015 |
| 6          | Fontane Angheraz sx | 1018 | 0.35 | 0.18 | 0.57 | 140 | 8.1 | 122 | 4.9 | nu | | |
| 7          | Travignolo stream – from Tre sorgenti springs to Malga V. | 1783–1759 | 0.30 | 0.00$^*$ | 0.41 | 243 | 8.0 | 127 | 5.5 | nu | | |
| 8          | Canali stream – from re-emergence to Acque Nere springs | 1215–1154 | 0.30 | 0.17 | 0.48 | 322 | 8.2 | 107 | 5.9 | nu | | |
| 9          | Pradidali spring group | 1456 | 0.21 | 0.06 | 0.34 | 111 | 8.1 | 101 | 4.3 | nu | | |
| 10         | Travignolo stream – from the origin to Tre sorgenti springs | 1945–1783 | 0.20 | 0.00$^*$ | 0.64 | 277 | 8.0 | 103 | 5.8 | nu | 0.079 |
| 11         | Angheraz stream – from the origin to Col di Pra | 1015–860 | 0.20 | 0.10 | 0.35 | na | na | na | na | nu | | |
| 12         | Bordina stream – from the origin to Col di Pra | 1520–833 | 0.15 | 0.00$^*$ | 0.30 | 189 | 8.2 | 144 | 10.4 | nu | | |
| 13         | Tegnas stream – from Col di Pra to Cozzolino | 860–826 | 0.15 | 0.11 | 0.30 | 155 | 8.3 | 86 | 7.7 | nu | | |
| 14         | Fontane Angheraz dx | 980 | 0.15 | 0.06 | 0.18 | 133 | 7.6 | 98 | 5.0 | nu | | |
| 15         | Acque Nere springs | 1150 | 0.14 | na | na | 313 | 7.8 | 109 | 5.7 | dws | | |
| 16         | San Lucano spring | 900 | 0.13 | 0.03 | 0.14 | 145 | 8.1 | 80 | 5.7 | nu | | |
| 17         | Comelle Valley from the origin to Gares waterfall | 1729–1480 | 0.12 | 0.00$^*$ | 0.17 | 167 | 7.6 | 106 | 5.9 | nu | | |
| 18         | Focobon stream – from the origin to the camping Eden | 1720–1678 | 0.12 | 0.01 | 0.44 | 354 | 7.5 | 142 | 5.8 | nu | | |
| 19         | Travignolo springs | 1583–1678 | 0.10 | 0.00 | 0.13 | 311 | 8.1 | 122 | 4.9 | nu | | |
| 20         | Focobon spring | 1720 | 0.10 | na | na | 188 | 7.3 | 130 | 4.6 | nu and dws | 0.03 |
| 21         | Le fontane spring | 935 | 0.08 | 0.03 | 0.12 | 156 | 8.2 | 118 | 5.2 | nu | 0.054 |
| 22         | Canali stream – from the origin to Vallon della caccia | 1580–1450 | 0.08 | 0.01 | 0.15 | 179 | 8.3 | 97 | 6.5 | nu | | |
| 23         | Mandra della grava spring | 1458 | 0.06 | 0.04 | 0.10 | 124 | 7.9 | 136 | 4.1 | nu | | |
| 24         | Travignolo springs | 1960 | 0.05 | 0.00$^*$ | 0.09 | 143 | 8.0 | 114 | 2.2 | nu | | |
| 25         | Antersass spring | 1719 | 0.04 | na | na | na | na | na | na | dws | 0.007 |
| 26         | Fontanelle spring | 1195 | 0.04 | na | na | na | na | na | na | dws | 0.03 |
| 27         | Fontanazzi (Treviso) spring | 1580 | 0.03 | na | na | 163 | 7.9 | 134 | 4.0 | dws | na |
| 28         | Fontane Fosche springs | 1122 | 0.03 | na | na | 245 | 7.7 | 151 | 6.2 | dws | 0.014 |
| 29         | Fontanazzi spring group | 1245 | 0.03 | na | na | 199 | 7.9 | 114 | 5.3 | nu | | |
| 30         | La Busna spring | 990 | 0.03 | na | na | na | na | na | na | nu | | |
| 31         | I Fontanoi spring | 755 | 0.02 | na | na | 175 | 7.9 | 95 | 6.7 | nu | | |
| 32         | Castelpieatra spring | 992 | 0.02 | na | na | na | na | na | na | dws | 0.018 |
| 33         | Vicia spring | 1290 | 0.02 | na | na | 2035 | 7.4 | 78 | 7.5 | dws | 0.003 |
| 34         | La Roa spring | 1222 | 0.02 | na | na | na | na | na | na | dws | 0.003 |
| 35         | Scalette spring | 725 | 0.01 | na | na | 220 | 7.4 | 85 | 5.4 | dws | 0.008 |
| 36         | Laresi spring | 1980 | 0.01 | na | na | 219 | 8.2 | 163 | 4.3 | dws | Included in 41 |
| 37         | Venegiotta spring | 1810 | 0.01 | na | na | 188 | 7.7 | 152 | 4.2 | nu | | |
| 38         | Colonia don bosco spring | 1208 | 0.01 | na | na | na | na | na | na | nu | | |
| 39         | Salto busa dei laibi spring | 1860 | 0.01 | na | na | 147 | 7.3 | 55 | 5.3 | dws | Included in 41 |
| 40         | Crozz del cogol spring | 1200 | 0.01 | na | na | na | na | na | na | nu | | |
| 41         | Le tre sorgenti spring group | 1785 | 0.01 | na | na | 279 | 7.9 | 107 | 6.3 | dws | 0.01 |
| 42         | Polver spring | 903 | 0.01 | na | na | 150 | 8.0 | 112 | 5.8 | dws | 0.001 |

$^*$ The spring is subject to freezing few metres below the emergence.

na, information is not available; hg, hydropower generation; dws, drinking water supply; nu, not utilized.
representation of hydrogeological information in a mountain area. By using different colours, the map represents various water-related data that were grouped in four main categories to better visualize the related information. These data include: (1) the identification of the hydrostructural elements; (2) the identification and the extension of the recharge areas; (3) the identification and quantification of the main discharge zones; (4) anthropogenic interventions on groundwater resources and the quantification of the abstractions. The map is accompanied by cross sections to show the hydrogeological setting of the area and to picture the main discharge zones.

The interpretation of all the hydrogeological information allowed to propose the following preliminary interpretative model of the hydrogeological setting of the Pale massif. The hydrogeological unit of the ‘Pale di San Martino Dolomitic group’ hosts a main fractured and karstified aquifer, which is hydraulically connected with the rockfall, alluvial and glacial porous aquifers of the valleys. The carbonate aquifer is underlain by a clayey aquiclude and the aquifer/aquiclude limit outcrop induces the outflow of perennial springs. Where this limit is covered by debris, a hydraulic connection between fractured and porous aquifers is expected and the groundwater, transferring from carbonate aquifer to the porous aquifer, outflows diffusely in the valleys.

Thanks to the information and to the data presented in the map it was possible to reach the following objectives:

i. Quantification of the amount of renewable groundwater resources.

As the groundwater system can be considered hydraulically isolated, the amount of renewable groundwater resources corresponds to the value of the discharge outflowing from the hydrostructure. Based on the values measured during the monitoring period, the groundwater resources of the Pale hydrostructure are approximately $216 \times 10^6$ m$^3$/year.

ii. Identification of the recharge areas and the main reservoirs containing groundwater resources.

The main recharge area corresponds to the outcrop of the carbonate complex and it extends for approximately 100 km$^2$ and ensures most of the recharge to the groundwater system. This recharge, for the year 2015, was estimated to be approximately 2000 mm, equivalent to $200 \times 10^6$ m$^3$/year, comparable to the order of magnitude of the total discharge volume.

Recharge is ensured by precipitation in the form of rainfall, snowmelt and glacier melt and is diffused in all area thanks to the numerous subvertical fractures widespread on the surface. Karstic features, such as karst shafts and dolines, provide preferential infiltration zones, favouring a concentrated recharge.

Due to its high hydraulic conductivity, also water falling on the alluvial, rockfall and glacial complex recharges the groundwater system, but the uncertainties on valley-floor rainfall values do not allow to evaluate a representative recharge volume.

The two reservoirs may be considered hydraulically connected as the quaternary deposits accumulate on the mountain slopes and therefore are in contact with the carbonate complex. Mean precipitation varies with altitude and ranges between 915 mm in the valleys up to 2400 mm at the highest elevations.

iii. Identification of the spatial distribution of the main groundwater outflows.

Groundwater emerges in the form of linear and localized springs and it outflows mainly towards the east and towards the south-west direction. The Angheraz Valley and the connected San Lucano Valley are characterized by the springs with the highest discharge of the Pale (overall a mean $Q$ of 2.5 m$^3$/s). The second most important spring group of the Pale (mean $Q$ of 2.0 m$^3$/s) is located in the Canali and Predali Valleys. A minor part of the discharge is directed also to the north and mainly towards the Venegia and Gares Valleys.

iv. A first estimate of water usage and the impact on the available groundwater resources.

Approximately 3% of the water emerging from the Pale hydrostructure is used for drinking water supply whereas a much larger amount, approximately 66%, is utilized for hydropower generation (Figure 7). Given this framework, it is clear that industries connected to hydropower generation tend to play a major role in the water usage. The workflow followed in the production of this map could be applicable in the future also in other sectors of the Dolomites in order to fill the gap in hydrogeological representations. When used at the scale of entire mountain groups, this type of maps can be a useful base for a preliminary understanding of the groundwater system and therefore as a starting point for a water management planning. In view of the future climate changes, hydrogeological maps could serve as operating documents for water managers and practitioners to discuss local strategies for a sustainable management of groundwater resources.

**Software**

All data processing and spatial analysis regarding the map were performed with a GIS software (Arc GIS 10). The cross sections were edited by using a vector graphics software (Adobe Illustrator CS6).
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