Preliminary conceptual model of an Alpine carbonate aquifer (Pale di San Martino, Dolomites, Italy)

Modello concettuale preliminare di un aquifero carbonatico alpino (Pale di San Martino, Dolomiti, Italia)

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Riassunto: Un monitoraggio idrogeologico e idrochimico è stato condotto nel Gruppo montuoso delle Pale di San Martino (Provincia di Trento e Belluno, Italia) per costruire un modello concettuale preliminare della circolazione idrica sotterranea. Il modello deriva da una combinazione di nuovi dati di campagna con dati preesistenti forniti da vari enti pubblici. I nuovi dati includono un rilevamento geologico ed idrogeologico, tra cui misure in situ dei parametri chimico-fisici delle acque, campionamenti per analisi chimiche e misure di portata in alveo. Le litologie affioranti nell'area sono state raggruppate in sette complessi idrogeologici, ognuno con un proprio ruolo nella circolazione idrica sotterranea. Il corpo dolomitico che forma le montagne principali, costituisce il complesso acquifero principale che è collocato al di sopra di un acquicludo terrigeno ed evaporitico. A causa di questa relazione geometrica, il sito di studio può essere considerato un'idrostruttura isolata con limiti ben definiti a flusso nullo. Le sorgenti principali emergono in prossimità del contatto tra acquifero e acquicludo e in particolare dove questo risulta ribassato e dove la tettonica favorisce un drenaggio preferenziale. La maggior parte delle sorgenti ha una composizione bicarbonato-calcica, una bassa temperatura e bassi valori di conducibilità elettrica, a testimoniare una circolazione rapida in rocce carbonatiche con una ricarica da quote elevate. Misure stagionali di portata in alveo hanno permesso di identificare le sorgenti lineari e di fornire un primo dato di portata cumulativa uscente dall'intero massiccio. Il modello costruito mette in luce una grande variabilità spaziale e temporale delle risorse. Un primo confronto fra la geometria dell'acquifero e la marcata variabilità stagionale delle portate erogate porta ad ipotizzare l'assenza di reserve idriche significative a scala regionale.
L'idrostruttura, quindi, presenta una elevata capacità di erogazione della risorsa (portata media misurata 6 m^3/s), non associata ad un'altrettanta elevata capacità di auto-regolamentazione.
Questo aspetto deve essere tenuto presente nei programmi di pianificazione e sfruttamento a lungo termine della risorsa idrica sotterranea locale che è sfruttatata per scopi idropotabili e idroelettrici.

Parole chiave: carsismo, idrogeologia alpina, modello concettuale, Dolomiti, Pale di San Martino.

Keywords: *karst, alpine hydrogeology, conceptual model, Dolomites, Pale di San Martino.*

Abstract: *A hydrogeological and hydrochemical monitoring was conducted in the Pale di San Martino mountain ridge (Trento and Belluno Provinces, Italy) to build a preliminary conceptual model of the groundwater system. The model derives from a combination of new fieldwork and preexisting data provided by various public authorities. New data include geological and hydrogeological surveys, such as in situ measurements of the physical and chemical parameters, geochemical sampling and streamflow measurements. The lithologies outcropping in the area were grouped into seven hydrogeological complexes, each playing a different role in groundwater circulation. The dolomitic body of the ridges forms the main aquifer complex and is located above a terrigenous and evaporitic aquiclude. Due to this geometrical relationship, the site can be considered an isolated hydrostructure with well-defined no-flow boundaries. The main springs outcome near the aquifer-aquiclude boundary and in particular where the elevation of the contact is low and the tectonic pattern favors the drainage. Most of them have a calciumbicarbonate water composition, low temperature and low electrical conductivity, supporting the hypothesis of a fast flowing circulation in carbonate rocks and a high-altitude recharge. Seasonal streamflow measurements allowed the identification of linear springs and provided the first cumulative discharge data at the scale of the entire mountain group. The resulting model highlights a great spatial and temporal variability of the groundwater resources. Considering the geometry of the aquifer and the great seasonal variability of the discharge, it is possible to infer the absence of significant groundwater reserves at a regional scale. Thus, the hydrostructure shows a great capacity to supply water resources (mean discharge of 6* m^3/s*), but a low selfregulation capacity. It is necessary to consider this aspect when planning a long-term exploitation of the water resources that are used in the area for drinking purposes and hydropower generation.*

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Introduction

Carbonate aquifers, such as limestones and dolomites, are one of the main source of drinking water worldwide as it is estimated that 25% of the global population is supplied by karst water (Ford and Williams, 2007). Due to the extensive outcrops of carbonate aquifers, the Alps are considered the water tower of Europe and their water resources support the life and economy of more than 60 million inhabitants (Italian Ministry for Environmental Land and Sea, 2011). Carbonate aquifers are present in different tectonic units of the Alps, including the South Alpine, Austro-Alpine and Helvetic zone. The area investigated in this paper belongs to the South Alpine region and in particular to the Dolomites, a mountain range located in the northeastern part of Italy. In detail, the test site comprises three connected mountain groups, the Pale di San Martino, Pale di San Lucano and Mt. Agner (together referred as The Pale), with various peaks rising above 3000 m (Fig. 1).

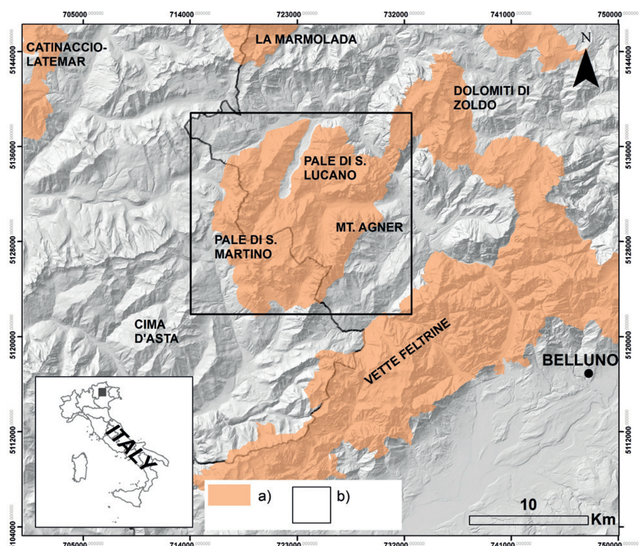

Fig. 1 - Geographical setting of the study area in the context of the Dolomites (UTM 32 WGS84 projection); a) areas that belong to the Dolomites Unesco World Heritage Site (source: http://www.dolomitiunesco.info/i-nove-gruppi-dolomitici/?lang=en), b) study area.

Fig. 1 - Inquadramento geografico dell'area di studio all'interno del contesto delle Dolomiti (proiezione UTM 32 WGS84); a) aree che appartengono al patrimonio dell'umanità di Dolomiti Unesco (fonte: http://www.dolomitiunesco.info/i-nove-gruppi-dolomitici), b) area di studio.

The core of the massif and the peaks are formed by a massive Middle Triassic carbonate platform almost entirely composed of dolomites (Blendinger et al., 2015). Even if, on a global scale, dolomite is a common mineral, pure dolomite aquifers are rare (Frondini et al., 2014) and not as widely studied as limestone systems. This study offers the possibility to investigate a dolomitic aquifer with great outcrops, from the recharge area to the discharge. It also highlights the great challenges of Alpine hydrogeology, such as the effects of the snow and glacial melting in the hydrological balance (Junghans et al., 2011; Koboltschnig and Schoner, 2011) and the complex interaction between the surface flow and the groundwater (Lauber et al., 2014). Previous hydrogeological studies in the Dolomites are scarce and are completely absent in the Pale, for several reasons. First of all, the abundance of water resources that typically characterized the Alpine regions in the past, has limited the perception of the necessity of these type of studies. Secondly, the absence of wells, together with the lack of higher altitude hydrological and meteorological data, complicates the methodological approach. Nevertheless, climatic changes, including significantly lower rainfall and higher temperatures (Beniston, 2012), are increasing the water stress and the need to study areas that have typically been rich in water. This study aims at characterizing the hydrogeological setting of the area from a qualitative and quantitative point of view, starting from the geological setting and moving through the monitoring of the main springs, in order to obtain a total estimate of the groundwater renewable resources and to investigate their spatial distribution. The study should be intended as the starting point for further and more specific researches, including the effects of climate change on aquifer recharge and base flow.

Description of the field site

The Pale are a 200 km^2 wide massif included in the Dolomites, a well-known Italian mountain range that, due to its great geological and geomorphological value, was decleared a UNESCO World Heritage site in June 2009 (see Fig.1 for the location of the study area). The terrain elevation ranges between approximately 600 m above sea level (asl) in the valleys up to 3192 m at the highest peak, the Mt. Cima Vezzana. A wide high-elevated karst plateau (mean altitude 2600 m asl), known as "Pale di San Martino Plateau", covers the central part of the massif and hosts two small glaciers, The Fradusta and The Travignolo glaciers, respectively located to the south and to the northwest of the plateau. According to recent studies, between the year 1910 and 2009, the Fradusta glacier experienced a massive retreat and a reduction of -89.4 % of its total area (Crepaz et al., 2013).

From a climatic point of view, winter snow usually begins to accumulate in December, lasting through March or April in the valleys and up to June or July on the highest peaks and on the plateau. The melting continues for several months, in some cases untill autumn. Meteorological data recorded at San Martino di Castrozza station (approximately 1500 m asl) indicate a mean temperature of 5.8°C and 1860 mm of precipitation for the monitoring period (source: www.meteotrentino.it.).

From a geological point of view, the Pale mountain group are located in a peculiar point, at the junction between three geological domanis: the Triassic reef buildups represented by the Pale, the Jurassic and Cretaceous pelagic limestones of the Vette Feltrine Mountains and the Pre-Permian metamorphic domain represented by the Cima D'Asta mountain group (Fig.1).

In detail, the geology of the Pale consisits of a thick Middle-Triassic sequence of dolomitic rocks that are underlain by

Permian to lower Triassic terrigenous and evaporitic deposits. All the sedimentary sequence of the Pale lies on top of the metamorphic Paleozoic basement or, where absent, on top of a thick volcanic porphyric accumulation. An important phase of submarine volcanic activity occurred during and after the deposition of the carbonates and resulted in the emplacement of volcanic lavas and dikes that cross cut the entire sedimentary succession. Several tectonic phases interested 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 (Doglioni, 1987; Castellarin et al., 1992). This phase provided the uplift of the area through a series of thrusts and backthrust faults (Schönborn, 1999). Previous tectonic phases are reported, such as a Middle Triassic sinistral transpression (Doglioni, 1984) and volcano tectonics related to the emplacement of the Triassic magmatism (Castellarin et al., 1988).

The hydrogeological literature of the Dolomites is poor and limited to the Brenta group (Borsato, 2001) and to the Sassolungo and Sella groups (Van de Griend et al., 1986; Frondini et al., 2014). With reference to the Pale group most of the studies deal with geological and sedimentological aspects (Zampieri, 1987; Giordano and D'Alberto, 2013; Blendinger et al., 2015). In relation to water resources, only fluvial geomorhological studies have been carried out in the Pale di San Lucano area (Testa et al., 2013), but there are no previous studies on groundwater at a regional scale.

Materials and Methods

Data collection

The Pale are a border mountain region comprised of parts of Trentino and of Veneto regions, therefore all the historical data were captured and published using different scales and different criteria. To deal with this transboundary issue, a large part of the data processing was dedicated to data homogenization using a Geographic information system (ArcGIS). A re-organization of the geological information based on their lithology and on their general mechanical properties, led to the identification of the hydrogeological complexes (Mastrorillo et al., 2009). The hydrodynamic attitude of the complexes was verified in the field according to specific field observations, such as density of fractures, grain size and clay content evaluations. Based on this process, a degree of hydraulic conductivity was assigned to each complex (from low to high) and their hydrodynamic attitude was inferred.

The second part of the work consisted in the acquisition of hydrological data from various private water suppliers and public authorities, including: a) past surveys of springs location, b) discharge data, c) pluviometric data and d) all available information related to groundwater and surface water usage.

Field and laboratory activities

The new fieldwork was conducted between October 2014 and February 2016 and it consisted in various activities repeated in different surveys, including: i) springs identification survey; ii) in situ measurements of several physical-chemical parameters of the spring water [pH, electrical conductivity (EC), oxidation reduction potential (ORP), Temperature]; iii) spring water sampling; iv) main streambeds discharge measurements.

According to the existing springs census performed by the Trento Province and by the Veneto Environmental Protection Agency (ARPAV), more than 500 springs are present only in the Pale mountain group. Considering the purpose and the scale of this study, only n.11 springs were chosen for the geochemical sampling. The main 41 springs of the area (discharge >0.005 m^3/s) were analyzed in situ for physical and chemical characteristics (see Fig. 2. for the location of the monitored springs and Tab. 1. for their characteristics). Water temperature (Temp ± 0.1, in °C), pH (pH ± 0.01), Electrical conductivity (EC, in µS/cm ± 0.5%, normalized at 25°C) and oxidationreduction potential (ORP, ± 2 mV) were measured on site using a portable pH-conductivitymeter (WTW Multi 3320; WTW GmbH, Weilheim, Germany) and an ORP meter (Hanna HI 98120; Hanna Instruments, Woonsocket, RI, USA). During the measurement, spring water samples were collected into polyethylene bottles and were kept refrigerated below 4°C until the analyses for the major ions determination. Groundwater samples were analyzed for major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, HCO_3^-). Calcium, magnesium and hydrogen carbonate concentration were determined by titration with EDTA 0.01 N and HCl 0.02 N. Sodium and potassium were measured via flame emission spectroscopy, sulphate ion through a colorimeteric method using turbidimetric techniques and chloride with an ion- selective electrode (APHA, 2005).

Discharge measurements were carried out using a magnetic current meter. All the measures were recorded far from storm events to avoid the runoff component and to obtain a base flow measurement. This task was particularly complicated during the snow melting months because in this period of the year it is difficult to discriminate the base flow component from the melting component.

A total of 20 streamflow measurements were carried out and repeated in six surveys in order to estimate the total volume of groundwater discharging from the Pale during the monitoring period and to identify linear springs. In mountain catchments, the measurement of spring discharge can be complex due to a series of overlapping factors including accessibility issues during winter months, difficulty in choosing an area of laminar flow and also the presence of diffuse seepage. Thus, instead of measuring the discharge at the spring's outlet point it was chosen to measure it in the nearest stream or river in which the spring flow converges.

Progressive gauging stations were positioned along the main streams that deeply cut into the massif, moving downflow along the streambed (Travignolo, Angheraz - San Lucano, Pradidali - Canali, Focobon and Liera Valleys). This setting was selected in order to identify the discharge increase or decrease in specific stretches of the river. When the discharge increase was not justified by the amount of water fed by point springs it was assumed that the groundwater emerged di-

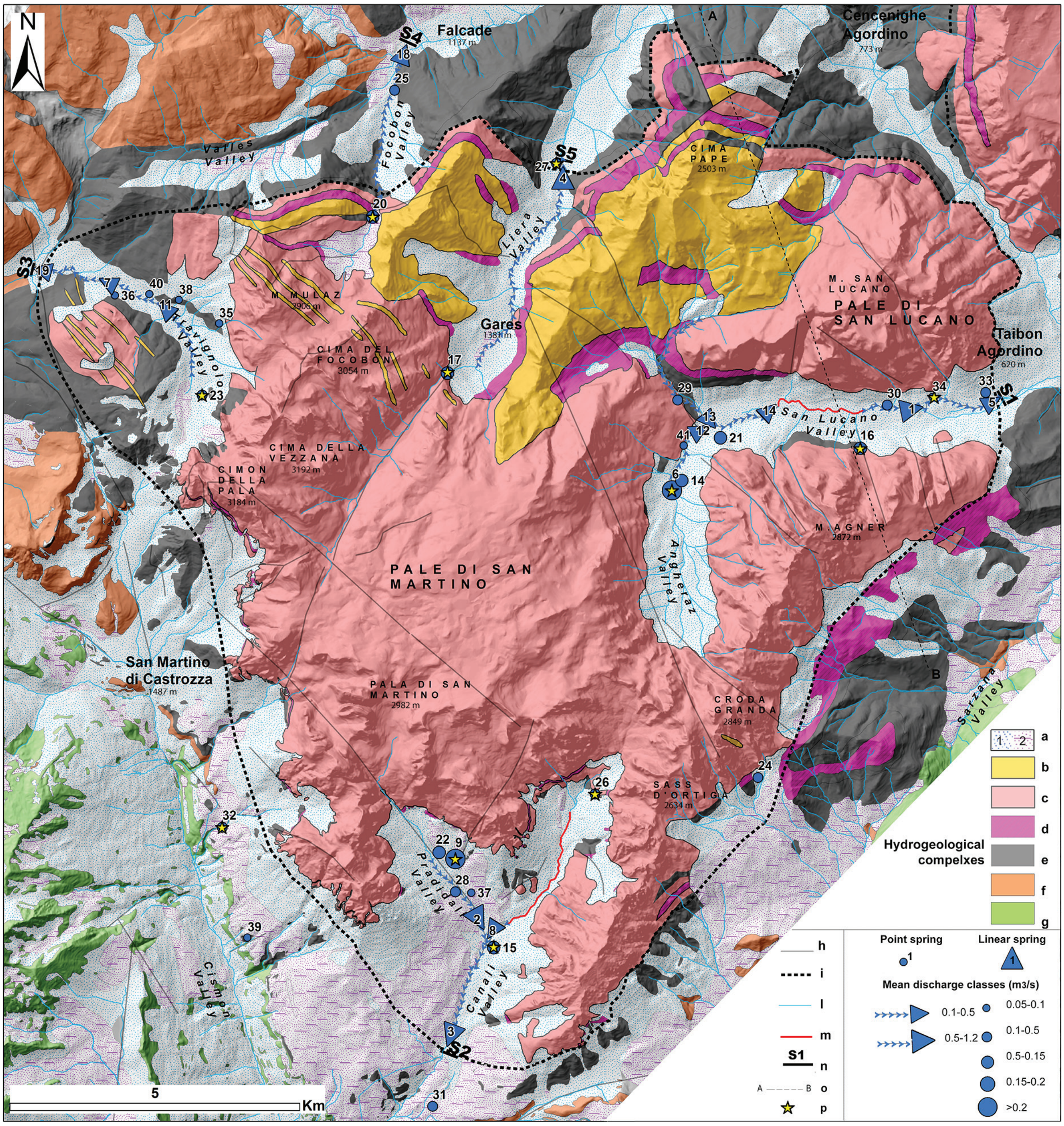

Fig. 2 - Hydrogeological map of the study area: a) alluvial, rockfall (1) and glacial complex (2); b) volcanic and post volcanic complex; c) carbonate complex; d) basinal sedimentary complex; e) terrigenous and evaporitic complex; f) porphyry complex; g) metamorphic complex; h) faults derived from literature; i) boundary of the hydrostructure; l) surface hydrology; m) streambed portion with discharge decrease; n) gauging stations at the closure of the valleys; o) approximative trace of the cross section; p) springs sampled for geochemical analyses. The digital terrain model used as a basis for the map was elaborated by Tarquini et al. (2007, 2012).

Fig. 2 - Carta idrogeologica dell'area di studio: a) complesso alluvionale, detritico (1) e glaciale (2); b) complesso vulcanico e post vulcanico; c) complesso carbonatico; d) complesso bacinale; e) complesso terrigeno ed evaporitico; f) complesso porfirico; g) complesso metamorfico; h) faglie desunte da letteratura; i) limite dell'idrostruttura; l) idrologia superficiale; m) tratti di decremento delle portate in alveo; n) sezioni di misura delle portate alla chiusura delle valli principali; o) traccia approssimativa della sezione; p) sorgenti campionate per analisi chimiche. Il modello digitale del terreno utilizzato come base della carta è stato elaborato da Tarquini et al. (2007, 2012).

rectly in the streambed representing an invisible submerged spring (i.e., linear spring) (Boni et al., 1986; Boni and Petitta, 1994; Mastrorillo and Petitta, 2014).
Furthermore, one gauging station was selected downstream at the embouchure of the each main valley as a representative station for the total groundwater discharge emerging from each hydrological basin (see Fig. 2. for the location of the five stations and Tab. 2 for the mean discharge, see pag. 34). All the discharge data presented in this paper have been corrected adding the artificial water withdrawals in order to obtain the natural value of the discharge.

Tab. 1 - Characteristics of the main springs of the area (mean discharge >0.005 m^3/s). asl, above sea level; EC, electrical conductivity; ORP, oxidation reduction potential.

Tab. 1 - Caratteristiche delle sorgenti principali dell'area (portata media > di 0,005 m^3/s). asl, sopra il livello del mare; EC, conduttività elettrica; ORP, potenziale riduzione ossidativa.

Spring Id	Name/Location	Region	Mean Q	Elevation	Mean Physical and chemical parameters				Spring utilization
			(m^3/s)	(m a.s.l.)	EC (µs/cm)	pH	ORP (mV)	T (C°)	
1	Tegnas stream - from Casera Paluch to Ai Vanti dam	Veneto	1.200	765-741	151	8.2	105.5	7.8	hydropower generation
2	Pradidali stream - from the origin to La Ritonda bridge	Trentino	0.750	1420-1190	145	7.9	52.4	5.7	
3	Canali stream - From Acque Nere springs to Castrona dam	Trentino	0.650	1145-1030	232	8.0	101.2	6.3	hydropower generation
4	Liera stream - from Gares Waterfall to the dam	Veneto	0.500	1344-1130	175	8,0	113,5	7,7	hydropower generation
5	Tegnas stream -from Ai Vanti dam to Enel Hydroelectric plant	Veneto	0.450	740-663	195	8.1	128.0	7.8	hydropower generation
6	Fontane Angheraz springs	Veneto	0.350	1018	140	8.1	122.4	4.9	
7	Travignolo stream- from Tre sorgenti springs to Malga Venegia	Trentino	0.300	1783-1759	243	8.0	126.7	5.5	
8	Canali stream - from the re-emergence of the stream to Acque nere springs	Trentino	0.300	1215-1154	322	8.2	107.3	5.9	
9	Pradidali springs	Trentino	0.210	1456	111	8.1	101.0	4.3	drinking water supply
10	Travignolo stream - from the origin to Tre sorgenti springs	Trentino	0.200	1945-1783	277	8.0	103.3	5.8	
11	Angheraz stream - from the origin to Col di Pra	Veneto	0.200	1015-860	na	na	na	na	
12	Bordina stream - from the origin to Col di Pra	Veneto	0.150	1520-833	189	8.2	144.0	10.4	
13	Tegnas stream - from Col di Pra to Cozzolino	Veneto	0.150	860-826	155	8.3	86.3	7.7	
14	Fontane Angheraz dx	Veneto	0.150	980	133	7.6	98.0	5.0	
15	Acque nere springs	Trentino	0.140	1150	313	7.8	108.7	5.7	drinking water supply
16	San Lucano spring	Veneto	0.130	900	145	8.1	80.0	5.7	
17	Gares waterfall	Veneto	0.120	1480	167	7.6	106.4	5.9	
18	Focobon stream - from the orgin to the camping Eden	Veneto	0.120	1720-1160	354	7.5	141.7	5.8	hydropower generation
19	Travignolo stream - from Malga Venegia to the parking lot	Trentino	0.100	1783-1678	311	8.1	122.0	4.9	
20	Focobon spring	Veneto	0.100	1720	188	7.3	129.8	4.6	hydropower generation
21	Le fontane spring	Veneto	0.080	935	156	8.2	118.0	5.2	hydropower generation
22	Mandra della grava spring	Trentino	0.060	1458	124	7.9	136.2	4.1	
23	Travignolo springs	Trentino	0.050	1960	143	8.0	113.7	2.2	
24	Antersass spring	Veneto	0.040	1719	na	na	na	na	drinking water supply
25	Fontanelle spring	Veneto	0.040	1195	na	na	na	na	drinking water supply
26	Fontanazzi (Treviso) spring	Trentino	0.030	1580	163	7.9	134.3	4.0	drinking water supply
27	Fontane Fosche springs	Veneto	0.030	1122	245	7.7	150.8	6.2	drinking water supply
28	Fontanazzi spring group	Trentino	0.025	1245	199	7.9	114.2	5.3	drinking water supply
29	La Busna spring	Veneto	0.025	990	na	na	na	na	
30	I Fontanoi spring	Veneto	0.020	755	175	7.9	94.5	6.7	
31	Castelpietra spring	Trentino	0.020	992	na	na	na	na	drinking water supply
32	Vecia spring	Trentino	0.015	1290	2035	7.4	-111.8	7.9	cosmetical purpouse
33	La Roa spring	Veneto	0.015	1222	na	na	na	na	drinking water supply
34	Scalette spring	Veneto	0.010	725	220	7.4	85.0	5.4	drinking water supply
35	Laresei spring	Trentino	0.010	1980	219	8.2	163.0	4.3	drinking water supply
36	Venegiotta spring	Trentino	0.007	1810	188	7.7	152.0	4.2	
37	Colonia don Bosco spring	Trentino	0.006	1268	na	na	na	na	
38	Salto Busa dei Laibi spring	Trentino	0.006	1860	147	7.3	55.0	5.3	
39	Crozz del Cogol spring	Trentino	0.006	1200	na	na	na	na	
40	Le tre sorgenti spring group	Trentino	0.006	1785	279	7.9	107.0	6.4	drinking water supply
41	Polver spring	Veneto	0.005	903	150	8.0	111.6	5.8	drinking water supply

Results

Hydrostratigraphy

Based on the stratigraphic setting of the area, seven hydrogeological complexes were identified (Fig. 3).

First, *alluvial, rockfall and glacial complex* (Q) (Holocene): it is characterized by an alternating pattern of coarse and fine grained sediments, such as heterometric carbonatic gravel, sandy and clay deposits that fill the valleys and accumulate on the mountain slopes. The complex is characterized by a high hydraulic conductivity due to the high porosity of the media.

Second, *volcanic and post-volcanic complex* (V) (Middle-Upper Triassic): the complex is represented by volcanic rocks and by the subsequent alteration products, including pillow lava and breccias, a small sill body intruded in the Livinallongo formation, a ialoclastite sequence and a series of NNW-SSE volcanic dikes. The complex is characterized by a medium-to-low hydraulic conductivity depending on the heterogeneity of the volcanic layers and on their porosity.

Third, *basinal sedimentary complex* (LI) (Middle Triassic): the complex includes the Livinallongo formation, which is a sequence of regularly bedded siliceous, shaly, micritic limestones. Due to the frequent occurrence of pelites and of siliceous beds, a low hydraulic conductivity was attributed to this complex.

Fourth, *carbonate complex* (CO, DS, DC) (Middle Triassic): the carbonate complex includes all the carbonate reef buildups of the area, including the main outcropping formation of the area, the Sciliar Formation and also the Contrin Formation and the Cassian Dolomite. This complex is the most extensive and thick of the area and is characterized by a high degree of relative hydraulic conductivity due to the presence of fractures and karst conduits. Well-developed cave systems are present especially in the northern part of the Pale, but are usually limited to vertical shafts.

Fifth, *terrigenous and evaporitic complex* (AVG, B, W) (Middle Permian-Middle triassic): this complex includes the thick succession of shallow marine and terrigenous deposits of the Werfen Formation, the shallow marine evaporites of the Bellerophon formation, the red beds of the Val Gardena Sandstones. The complex is entirely composed of a sequence of different type of rocks, mainly silts and sands, clays, marls and gypsum that share a low degree of relative hydraulic conductivity.

Sixth, *porphyry complex* (P) (Lower Permian): this complex includes a thick volcanic accumulation, outcropping mainly in the northwestern part of the Pale and is composed of compact lava flows with rhyolitic, andestic and dacitic composition. Due to the presence of fractures, a medium degree of hydraulic conductivity can be attributed to this complex.

Seventh, *metamorphic complex* (M, G) (Paleozoic): this complex consists of the Paleozoic metamorphic basement of the Dolomites, mainly phyllites and schists. The hydraulic conductivity of the complex is low.

Spring characterization

Based on six current meter discharge surveys performed in the main valleys and on pre-existing discharge data, 41 main springs were identified in the Pale area. Fig. 2 shows the location of the main springs and Tab. 1 summarizes their characteristics. The springs with the highest discharge (>0.5 m^3/s) are linear springs located in the lower part of the San Lucano Valley (spring 1 in Fig. 2) and in the Canali Valley (springs 2 and 3 in Fig. 2). In the same valleys, also the localized springs show the highest yields. Fontane Angheraz spring (6) is the largest point spring of the Pale (mean Q=0.35 m^3/s), followed

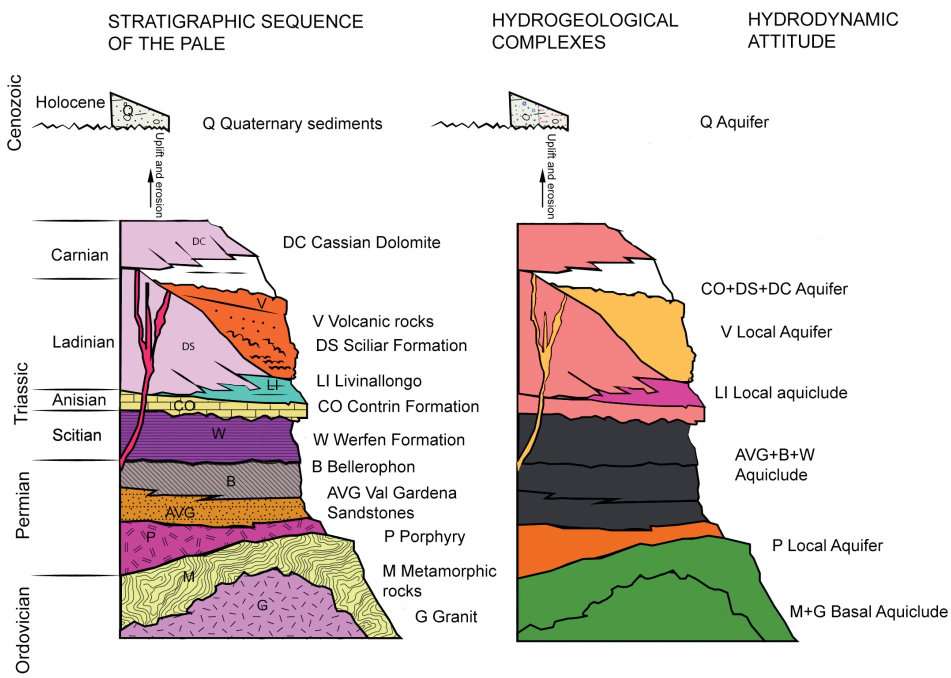

Fig. 3 - Stratigraphic succession of the study area reinterpreted in terms of hydrogeological complexes and hydrodinamic attitude (modified after Bosellini, 1996).

Fig. 3 - Colonna stratigrafica dell'area di studio e sua reinterpretazione in termini di complessi idrogeologici e di attitudine idrodinamica (modificata da Bosellini, 1996).

by Pradidali spring (9) with a mean Q of 0.21 m^3/s. The main streams originate in correspondence of these springs, which are usually located in the upper part of the valleys.

A decrease of the discharge was observed in the upper Canali Valley and in the central part of the San Lucano Valley. In the first case, the stream completely disappears under the valley-fill deposits losing approximately 0.03 m^3/s and reappears 2 km downstream. In the second case the stream does not totally sink into the sediments but exhibits a systematic discharge decrease of approximately 0.1 m^3/s.

Tab.1. also summarizes the mean physico-chemical parameters of the springs that were measured on the field. Most of the springs show low values of EC (< 250 µS/cm), thus low mineralization. The highest mean value of EC, 2035 µS/cm, is found in the Vecia spring (32), whereas the lowest corresponds to the Pradidali spring (9) (111 µS/cm). With respect to the mean oxidation-reduction potential, the springs exhibit positive values with the exception of the Vecia spring, where a negative value was measured during each survey. Mean groundwater temperature is generally low and comprised between 4 and 7°C. The lowest mean temperature is 2.2°C and it corresponds to the Travignolo springs (23).

With respect to pH, all the springs fall in the typical range of water circulating in limestone and dolomite terrains, usually comprised between 6.5 and 8.9 (Ford and Williams, 2007).

N.11 springs were also analyzed for major ion composition. A Piper diagram (Fig. 4), built on the October 2015 samples, shows that most of the springs belong to a Ca- Mg - HCO 3 type of water (Appelo and Postma, 1993).

Sulphate-calcium water type is recorded in one small spring, the Vecia spring (32), which shows also a higher electrical conductivity and a lower redox suggesting the occurrence of sulphate reduction. The Acque Nere spring (15) is still classified as a calcium-bicarbonate water type but exhibits enrichment in sulphates.

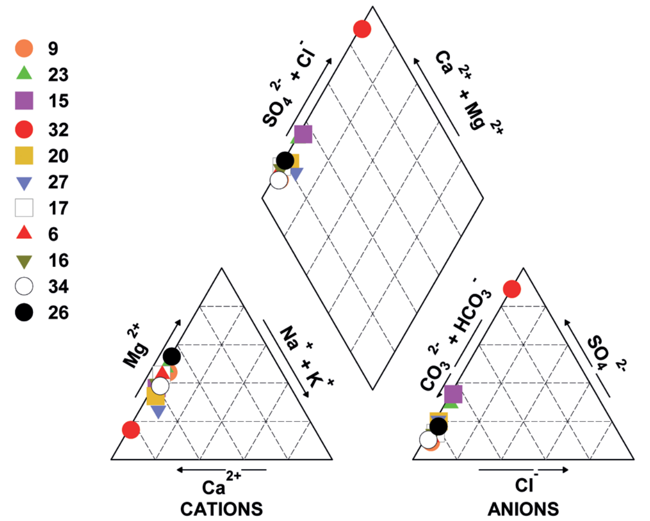

Fig. 4 - Piper diagram built using October 2015 samples. See Fig.2. for the location of the sampled springs.

Fig. 4 - Digramma di Piper costruito sulla base della campagna di Ottobre 2015. Per l'ubicazione delle sorgenti campionate si rimanda alla Fig.2.

Base flow measurements

Five gauging stations were selected at the embouchure of the main valleys to represent the total discharge flowing out from the Pale massif (see Fig. 2 for the location of the stations).

Fig. 5. represents the base flow measured in each of these stations in different seasons between the year 2014 and 2016. During the monitoring period, the highest flow rates were measured in the southeastern part of the Pale and in particular in the Angheraz - San Lucano station (S1) and in the Pradidali-Canali station (S2). The Focobon valley (station S4), instead, shows the lowest discharge rates.

An estimate of the cumulative discharge of the Pale mountain group was obtained by the sum of the discharge measured in each station and it ranges between 7.7 m^3/s in October 2014 and 2.5 m^3/s in January 2016, with a mean value of 6.0 m3/s.

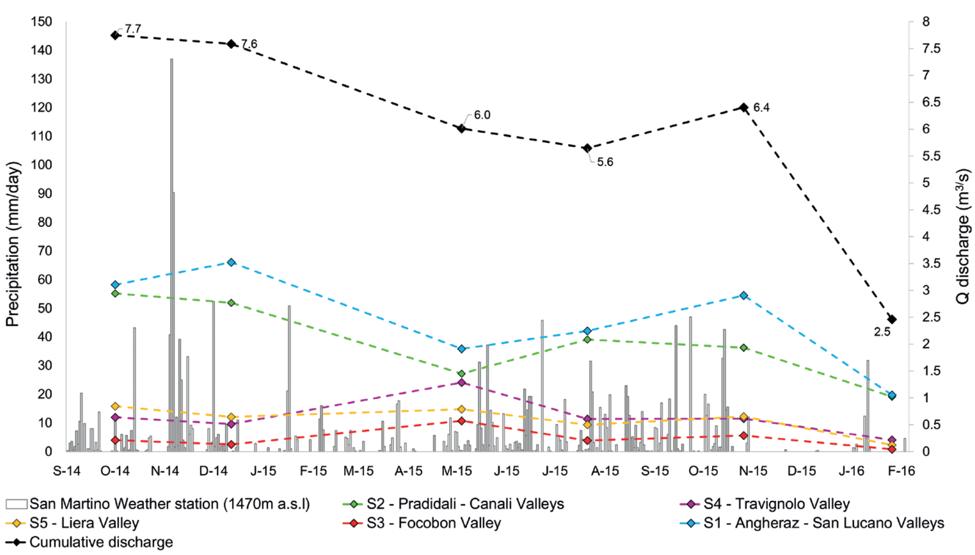

Fig. 5 - Discharge seasonal trend in the gauging stations located at the closure of the five main valleys and comparison with the precipitation measured at the San Martino di Castrozza weather station (source: www.meteotrentino.it). See Fig. 2 for the location of the stations.

Fig. 5 - Andamento stagionale delle portate misurate nelle stazioni ubicate alla chiusura delle cinque valli principali e confronto con le precipitazioni misurate alla stazione di San Martino di Castrozza (fonte: www.meteotrentino.it). Per l'ubicazione delle stazioni si rimanda alla Fig. 2.

With respects to the October 2014 and May 2015 surveys, a snow-melting component can not be excluded in all the stations, therefore the base flow could be overestimated. On the other hand, a relevant discharge decrease was observed in January 2016, as a consequence of an exceptional period without precipitation that occurred between the end of October 2015 and the beginning of January 2016. Due to the long draught period and to the absence of melting, it is assumed that the discharge measured during the last survey approximates the minimum base flow.

Tab. 2 shows a comparison between the mean discharge measured in the five stations that are located at the closure of each river basin and the mean discharge of the springs that belong to the same basin. The values are similar indicating that these gauging stations are well representative for the base flow component. Some discrepancies between the discharge values are found in the San Lucano Valley and in the Canali Valley and can be attributed to the uncertainties related to the water usage data. Indeed, these valleys are characterized by intense water exploitation, both for drinking and for hydropower supply. Further and more detailed studies are needed to obtain a better estimate of the withdrawals.

Tab. 2 - Comparison between the mean discharge measured in the five stations that are located at the closure of each river basin and the mean discharge of the springs that belong to the same basin.

Tab. 2 - Confronto tra la portata media in alveo misurata nelle sezioni terminali di chiusura delle valli e la somma delle portate medie delle sorgenti che si trovano nello stesso bacino idrografico.

station code	station name	Mean Q gauging station (m^3/s)	Sum of springs mean Q upgradient to the station (m^3/s)
S1	Angheraz-San Lucano Valley	2.51	2.93
S2	Pradidali - Canali Valley	2	2.27
S5	Liera Valley	0.62	0.62
S3	Focobon Valley	0.26	0.26
S4	Travignolo Valley	0.65	0.67

Discussion

By comparing the new field data with the pre-exisisting geological and hydrogeological information, it was possible to build a preliminary conceptual model of the Pale mountain group.

In the Pale area, the groundwater circulates in the carbonate complex and in the alluvial, rockfall and glacial complex with a hydraulic interconnection between the two complexes.

The principal aquifer is hosted by the carbonate complex, which constitutes the main body of the mountains and a vast karst plateau. The recharge to the aquifer is ensured by rainfall, snowmelt and glacier melt that infiltrates at high altitudes through a complex network of fractures and karst conduits. The main aquifer is underlain, in all its extension, by the terrigenous and evaporitic complex. Thanks to the clay-rich layers of the Werfen Formation and to evaporitic horizons of the Bellerophon Fm, this complex assumes the hydrogeological role of the regional aquiclude. The contrast in permeability between the aquifer and the underlying aquiclude forces the groundwater to circulate only in the carbonate complex, according to the geometry and the orientation of the contact surface between the two complexes.

Groundwater emerges where this contact intercepts the surface topography, as is testified by the location of the main springs of the area. A NNW-SSE cross section across the San Lucano Valley (Fig. 6) schematically represents this hydrogeological setting.

On the field, the aquifer-aquiclude contact is frequently covered by debris and talus deposits that accumulate on the slopes of the mountains. Consequently, the groundwater deriving from the carbonate complex, is transmitted in the alluvial, rockfall and glacial complex and emerges in a series of diffused springs rather than in a single yielding outlet.

From a regional point of view, the contact between the aquiclude and the aquifer complexes assumes the hydrogeological role of a no-flow limit, so the Pale can be considered as a well-defined hydrostructure. Due to the Alpine compression, this boundary reaches an elevation of approximately 2200 m asl in the northwestern sector of the Pale and of approximately 1000 m asl in the Angheraz Valley, where it outcrops at its lowest elevation.

For this reason, 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) and they can be considered as the base level of the groundwater system. The second most important spring group of the Pale (mean Q of 2.0 m^3/s) is located in the Canali and Pradidali Valleys, where the boundary outcrops at a slightly higher elevation (approximately 1500 m asl).

These results indicate that the Pale are characterized by two main groundwater flow directions, the first one draining towards east, in the Angheraz - San Lucano Valleys and the second one towards the south, in the Canali Valley.

A minor drainage system directs the flow towards the northern part of the Pale and in particular to the springs of the Travignolo, the Focobon and the Liera Valleys.

The recharge area of the springs can be identified mainly in the Pale di San Martino Plateau, due to the widespread presence of subhorizontal bare karst rocks, which favors a rapid infiltration of the precipitation. A minor but not negligible contribute to the recharge derives from the alluvial, rockfall and glacial deposits that cover the slopes on the mountains and fill up the valleys.

Therefore, the recharge area of the Pale corresponds to the outcrop of the carbonates and of the Quaternary deposits and is characterized by an area of approximately 130 km^2, with a mean elvation of 1950 m asl.

Based on the assumption that the hydrostructure is hydraulically isolated, it is possible to compare the mean cumulative discharge (6.0 m^3/s) with the extension of the recharge area (130 km^2) and a mean effective infiltration of 1455 mm can be

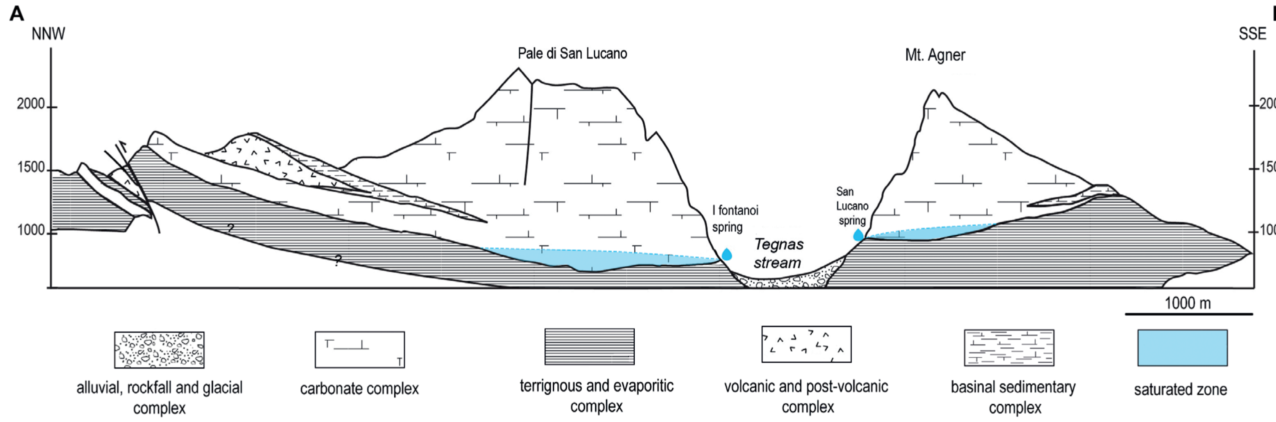

Fig. 6 - NNW-SSE schematic hydrogeological cross-section of the San Lucano Valley (modified after Castiglioni, 1939).

Fig. 6 - NNW-SSE schematic hydrogeological cross-section of the San Lucano Valley (modified after Castiglioni, 1939).

calculated for the monitoring period (Boni et al., 1986). The mean precipitation in the same period (1860 mm), measured in the San Martino di Castrozza station (approximately 1500 m asl) (www.meteotrentino.com), is compatible with the values of effective infiltration (1455 mm). Considering the extensive presence of fractures and karst features and the absence of soil in most of the recharge area, it can be assumed that 80% of the precipitation effectively infiltrated in the system. It is important to note that these computations do not take into account either the melting component, which could alterate the discharge measurement, or the variation of the precipitation with altitude. The precipitations of the San Martino di Castrozza station, in fact, are lower than the mean elevation of the plateau (approximately 2600 m asl). In conclusion, an underestimation of the precipitation and overestimation of the discharge is possible.

In all the valleys of the Pale, permanent springs with modest discharge emerge on the slopes of the mountains, at a higher elevation than the base flow level. This fact supports the hypothesis of a duality of the circulation, with a higher flow fed mostly by localized fractures and conduits, and a lower, more diffused flow.

The physico-chemical parameters and the geochemical analyses performed on the springs indicate a groundwater circulation occurring mostly in the carbonate complex. Low electrical conductivity and low temperature provide evidence of a rapid filtration from high-elevated areas and a scarce groundwater-rock interaction, typical of Alpine carbonate systems. All the samples have a calcium-bicarbonate water type with the exception of the Vecia spring (32). This spring is characterized by a sulphate-calcium composition and shows a higher mineralization. The enrichment in sulphates that was recorded with a lower degree also in the Acque Nere springs (15), together with reducing conditions of the groudwater, suggests a derivation of these sulphate water types from a progressive dissolution of gypsum and probably by the evaporitic layers of the Bellerophon Formation.

Nevertheless, this specific geochemical process is negligible in the regional context of this paper.

Conclusions

A preliminary hydrogeological and hydrogeochemical conceptual model of the Pale mountain group was elaborated based on the processing of pre-existing data and on new field data acquired between October 2014 and February 2016. The model consists in a well-defined hydrostructure formed by a thick carbonate aquifer underlied by a terrigenous and evaporitic aquiclude. Flow is controlled by the geometry and by the orientation of the contact surface between the aquifer and the aquiclude and by faults and fractures that favor the drainage in specific directions. Overall, the main direction of the flow is to the east and to the south showing that drainage occurs in the direction of the main springs of the area. The groundwater flow can be divided in a high-elevated fast flowing component, attributable to the fractures and conduits, and a lower and more diffused circulation. Cross-formational flow occurs between the carbonate aquifer and the alluvial, rockfall and glacial deposits that fill the valleys and accumulate at the base of the mountains. During the monitoring period, the discharge rate produced by entire groundwater system was an average of 6.0 m^3/s, distributed as follows: 41% in the Angheraz-San Lucano Valleys, 34% in the Pradidali-Canali Valleys. The remaining 26% of the total discharge emerges in other spring groups in the northern part of the Pale and in detail, the 11% in the Travignolo Valley, the 10% in the Liera Valley and the 4% in the Focobon Valley. The elevated groundwater potential of the system, shows a great seasonal variation, spanning from the lowest mean discharge measured in January 2016 and the highest value in October 2014. This great variability indicates a low self-regulation capacity of the groundwater system that, in turn, depends on its geometry and in particular on the subhorizontal trend of the impermeable aquiclude. At a regional scale, this setting prevents a significant storage of groundwater reserves below the base level of the groundwater system (approximately 1000 m asl).

Quantifying the relationship between recharge and discharge is a basic prerequisite for the efficient management of springs and for the protection of groundwater resources. To obtain quantitative information on this topic, further analyses of the hydrographs are needed and will be carried out in the future.

REFERENCES

APHA (2005). Standard methods for the examination of water and wastewater. 21th ed. American Public Health Association, Washington, DC, USA.

Appelo C.A.J., Postma D. (1993). Geochemistry, groundwater and pollution. A.A. Balkema, Rotterdam, The Netherlands.

Beniston M. (2012). Is snow in the Alps receding or disappearing? Wiley Interdisciplinary Reviews: Climate Change 3(4):349-358. doi: 10.1002/wcc.179

Blendinger W., Lohmeier S., Bertini A., Meißner E., Sattler C.D. (2015). A new model for the formation of dolomite in the triassic dolomites, Northern Italy. Journal of Petroleum Geology 38(1):5-36. doi: 10.1111/jpg.12596

Boni C., Bono P., Capelli G. (1986). Schema idrogeologico dell'Italia Centrale *"Hydrogeological scheme of central Italy"*. Mem. Soc. Geol. It. 35: 991-1012, 2 tavv.

Boni C., Petitta M. (1994). Sorgenti lineari e valutazione dell'infiltrazione efficace in alcuni bacini dell'Italia centrale *"Linear springs and evaluation of the effective infiltration in some basins in central Italy"*. Quaderni di Geologia Applicata 1:99-113.

Borsato A. (2001). Characterisation of a high-altitude alpine karst aquifer by means of temperature, conductivity and discharge monitoring (Centonia spring, Brenta Dolomites, N-Italy). Proceeding of the 7th Conference on Limestone Hydrology and Fissured Media 20th – 22nd September 2001 – Besançon (France): 51–54.

Bosellini A. (1996). Geologia delle dolomiti *"Geology of the Dolomites"*. Athesia, Bolzano, Italy.

Castellarin A., Lucchini F., Rossi P.L., Selli L., Simboli G. (1988). The Middle Triassic magmatictectonic arc development in the Southern Alps. Tectonophysics 146:79-89. doi:10.1016/0040-1951(88)90083-2

Castellarin A., Cantelli L., Fesce A.M., Mercier J.L., Picotti V., Pini G.A., Prosser G., Selli L. (1992). Alpine compressional tectonics in the Southern Alps. Relationships with the N-Apennines. Ann. Tectonicae 6:62-94.

Castiglioni B. (1939). Il gruppo delle Pale di San Martino e le valli limitrofe *"The Pale di San Martino group and surrounding valleys"*. Ufficio idrografico del Magistrato alle acque del Ministero dei lavori pubblici 145. Poligrafico dello Stato, Roma, Italy.

Crepaz A., Cagnati A., De Luca G. (2013). Evoluzione dei ghiacciai delle Dolomiti negli ultimi cento anni. *"Evolution of the glaciers of the Dolomites in the last one hundred years"*. Neve e Valanghe 80:20-25.

Doglioni C. (1984). Triassic diapiric structures in the central Dolomites (northern Italy). Eclogae geol. Helv. 77 (2): 261-285.

Doglioni C. (1987). Tectonics of the Dolomites (Southern Alps, Northern Italy). Journal of Structural Geology 9 (2):181-193.

Ford D.C., Williams P.W. (2007). Karst hydrogeology and geomorphology. Wiley, Chichester.

Frondini F., Zucchini A., Comodi P. (2014). Water-rock interactions and trace elements distribution in dolomite aquifers: The Sassolungo and Sella systems (Northern Italy). Geochemical Journal 48(3): 231-246. doi: 10.2343/geochemj.2.0301

Giordano D., D'Alberto L. (2013). Nuovi dati per la paleogeografia Anisica e Ladinica della Valle di San Lucano e aree limitrofe (Dolomiti Agordine, Taibon Agordino) *"New data for the Anisian and Ladinian paleogeography of the San Lucano Valley and surroundings (Agordo Dolomites, Taibon Agordino)"*. Frammenti – Conoscere e tutelare la natura Bellunese 5:65- 80.

Italian Ministry for Environmental, Land and Sea (2011). Proceedings of the III International Conference "Water in the Alps" – Alpine Water conference 2010. Bieffe s.r.l., Rome.

Junghans N., Cullmann J., Huss M. (2011). Evaluating the effect of snow and ice melt in an Alpine headwater catchment and further downstream in the River Rhine. Hydrological Sciences Journal, 56(6): 981-993. doi: 10.1080/02626667.2011.595372

Koboltschnig G.R., Schöner W. (2011). The relevance of glacier melt in the water cycle of the Alps: an example from Austria. The relevance of glacier melt in the water cycle of the Alps: the example of Austria. Hydrol. Earth Syst. Sci. 15: 2039-2048. doi:10.5194/hess-15-2039-2011

Lauber U., Kotyla P., Morche D., Goldscheider N. (2014). Hydrogeo logy of an Alpine rockfall aquifer system and its role in flood attenuation and maintaining baseflow. Hydrology and Earth System Sciences 18(11): 4437-4452. doi:10.5194/hess-18-4437-2014

Mastrorillo L., Baldoni T., Banzato F., Boscherini A., Cascone D., Checcucci R., Petitta M., Boni C. (2009). Quantitative hydrogeological analysis of the carbonate domain of the Umbria Region (Central Italy). Italian Journal of Engineering Geology and Environment 1:137-155.

Mastrorillo L., Petitta M. (2014). Hydrogeological conceptual model of the upper Chienti River Basin aquifers (Umbria-Marche Apennines). Italian Journal of Geosciences 133 (3): 396-408. doi: 10.3301/IJG.2014.12.

Schönborn G. (1999). Balancing cross sections with kinematic constraints: The Dolomites (northern Italy). Tectonics 18 (3):527-545. doi: 10.1029/1998TC900018

Tarquini S., Isola I., Favalli M., Mazzarini F., Bisson M., Pareschi M.T., Boschi E. (2007). TINITALY/01: a new Triangular Irregular Network of Italy. Annals of Geophysics 50: 407-425.

Tarquini S., Vinci S., Favalli M., Doumaz F., Fornaciai A., Nannipieri L. (2012). Release of a 10-mresolution DEM for the Italian territory: Comparison with global-coverage DEMs and anaglyph-mode exploration via the web. Computers & Geosciences 38: 168-170. doi:10.1016/j.cageo.2011.04.018

Testa B., Aldighieri B., Bertini A., Blendinger W., Caielli G., De Franco R., Giordano D., Kustatscher E. (2013). Geomorphodiversity of the San Lucano Valley (Belluno Dolomites, Italy): a Well-Preserved Heritage. Geoheritage 5 (3): 151-172. doi: 10.1007/s12371-013-0079-3

Van de Griend A., Seyhan E., Engelen G., Geirnaert W. (1986). Hydrological characteristics of an alpine glacial valley in the north Italian dolomites. J. Hydrol. 88: 275–299. doi 10.1016/0022-1694(86)90095-8

Zampieri D. (1987). Le piattaforme carbonatiche triassiche delle Pale di San Martino (Dolomiti) *"The Triassic carbonate platforms of the Pale di San Martino (Dolomites)".* Memorie di scienze geologiche 39: 73-83.

Official website of the Dolomiti Unesco foundation. Available from: http://www.dolomitiunesco.info/inove-gruppi-dolomitici/?lang=en. Last access: 04/07/2016.

Official weather website of the autonomous Province of Trento. Available from: www.meteotrentino.it. Last access: 04/07/2016.

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