Occurrence and flow of groundwater in crystalline rocks of Sardinia and Calabria (Italy): an overview of current knowledge

Acque sotterranee in rocce cristalline di Sardegna e Calabria (Italia): una panoramica delle attuali conoscenze

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Riassunto: Le rocce cristalline costituiscono acquiferi di interesse per l'approvvigionamento idrico in molti paesi. In Italia, le caratteristiche idrogeologiche delle rocce cristalline non sono ben note e l'interesse per questi acquiferi è ad oggi piuttosto scarso. Tuttavia, una analisi preliminare della resa in acque sotterranee degli acquiferi cristallini è giustificata dalla vasta estensione areale di queste rocce nelle regioni Sardegna e Calabria e dalla scarsità di risorse idriche ad esse associata. Il presente studio ha considerato i dati disponibili riguardanti condizioni climatiche, il tipo di rocce cristalline, l'assetto strutturale, le caratteristiche di pozzi e sorgenti, il flusso di base di torrenti e fiumi e i risultati di prove di pompaggio. Le informazioni disponibili confermano che le rocce cristalline della Sardegna e della Calabria formano acquiferi a bassa permeabilità in cui la circolazione delle acque sotterranee avviene nello strato alterato e, soprattutto, negli strati maggiormente fessurati prossimi alla superficie. In zone particolarmente fratturate, la circolazione idrica sotterranea può verificarsi anche a profondità maggiori. I principali recapiti sono generalmente i corsi d'acqua delle aree vallive, numerose sorgenti con bassa portata e gli acquiferi limitrofi. La resa in acque sotterranee è fortemente influenzata dal clima, dalla copertura dell'ammasso roccioso e dalla tettonica e, nell'ambito del presente studio, è stata valutata da 1 a 2 L/s per km^2 e da 2 a 12 L/s per km^2 rispettivamente per la Sardegna e per la Calabria. Questa prima quantificazione dimostra che i quantitativi in gioco sono meritevoli di ulteriori approfondimenti, al fine di ottimizzare l'uso attuale delle risorse idriche sotterranee in queste aree particolarmente sfavorite.

Parole chiave: rocce cristalline, acquiferi a bassa permeabilità, Sardegna, Calabria.

Keywords: *crystalline rocks, Low-permeability aquifer, Sardinia, Calabria.*

Abstract: *Crystalline rocks constitute aquifers that are of interest for water supply in many countries. In Italy, the hydrogeological characteristics of crystalline rocks are not well known and the interest in these aquifers is generally scarce. Nevertheless, the large extent of these rocks in Sardinia and Calabria regions and the local scarcity of water resources justify this preliminary analysis. Crossing the information derived by the available data on climate conditions, type of crystalline rock, structural setting, characteristics of wells and springs, base flow of streams and rivers and pumping test results, a preliminary quantification of the potential yield of the crystalline aquifers of both regions was performed. The processing of data involving different aspects confirmed that the crystalline rocks of Sardinia and Calabria form low-permeability aquifers where groundwater circulation occurs in the weathered layer and, mainly, in the most fissured layers closest to the surface. In the heavily fractured zones, it was seen that the groundwater flow is more active and can also occur at a greater depth. Groundwater mainly outflows in the valleys, feeding streams, numerous low discharge springs and surrounding aquifers. Climate, rock covers and tectonic style influence the aquifer yield, which has been evaluated herein to range from 1 to 2 L/s per km^2 and from 2 to 12 L/s per km^2 in Sardinia and Calabria, respectively. This preliminary characterization shows that there are reasons to deepen the present knowledge on these aquifers in order to optimize the present use of their groundwater resources.*

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Introduction

Crystalline rocks constitute aquifers that are of interest for water supply in many countries. In Italy, the hydrogeological characteristics of crystalline rocks are not well known. The interest in these aquifers is generally scarce, because their groundwater yields (generally less than 5 L/s per km^2) are lower than those found in the more common carbonate and alluvial aquifers (up to 30 L/s per km^2), which are widely used in Italy for water supply (Civita 2008). The European Commission included the crystalline and metamorphic aquifers in "dry areas", with no groundwater at all or with small local aquifers (Commissione delle Comunità Europee 1982). Nevertheless, the large extent of these rocks in Sardinia (51 % of the regional area) and Calabria regions (39 % of the regional area) and the scarcity of water resources justify this preliminary analysis. This study proposes a review of current knowledge about the crystalline rocks hydrogeology and a preliminary groundwater resource assessment. The aim is to examine the role that these aquifers can play for water supply.

Water resources of Sardinia

In Sardinia, it is possible to recognize two main geological complexes on a large scale: the complex of the Hercynian basement, and the complex of the post-Hercynian covers and Quaternary deposits. The Hercynian basement includes metamorphic rocks (from medium to high grade) and intrusive rocks of late Paleozoic, predominantly granitoid rocks (Carmignani et al. 2001; 2008). They outcrop extensively in the eastern and in the south-western sectors of the island (approximately 13000 km^2; Figure 1).

Hercynian tectonics has produced major deformation of these rocks and the magmatic intrusive and effusive phenomena.

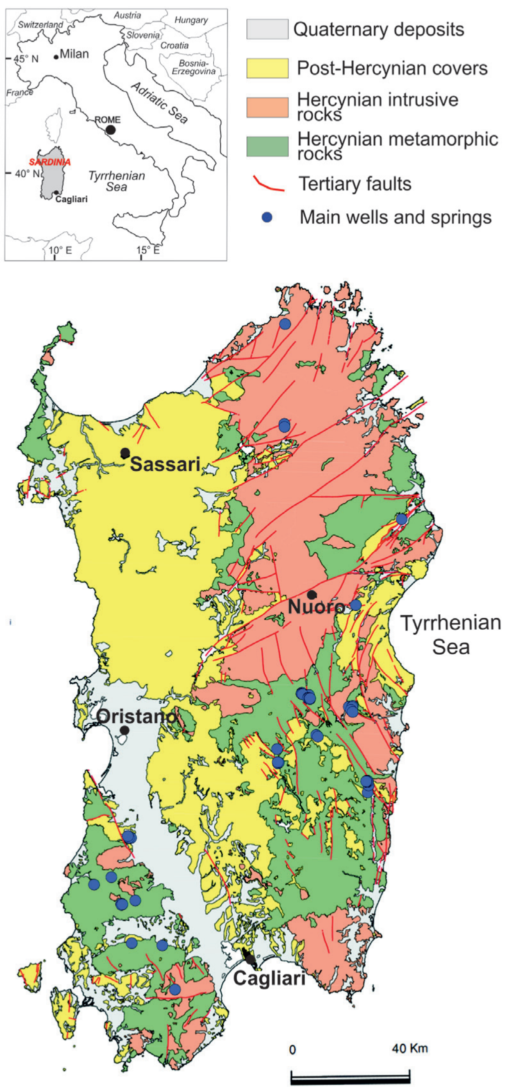

Fig. 1 - Crystalline rocks in Sardinia (modified from Carmignani et al. 2012).

Fig. 1 - Rocce cristalline in Sardegna (modificata da Carmignani et al. 2012).

These rocks were then affected by late Hercynian and post-Hercynian tectonic phases, that are mainly represented by normal and strike-slip faults (Carmignani et al. 2001; 2008).

The island's climate is typically Mediterranean with mean annual precipitation between 450 mm in the plains and up to 1000 mm on the reliefs; mean annual air temperature is between 17 °C in the plain and 13 °C on the reliefs. Studies on precipitation over the island highlight a decrease in the average values of 18 % from the 1922-1975 period to the 1985-2002 period, which corresponds to a decrease in the average flow over the island of 53 % (Viceconte 2004a).

Water resources currently derive primarily from surface water: 57 dams and 22 barrages are the main storage facilities for drinking, irrigation and industrial purposes (Regione Autonoma della Sardegna 2006a; 2006b).

The future water requirements (2024) have been evaluated approximately in 310 Mm^3/yr for potable use, 765 Mm^3/yr for irrigation and 40 Mm^3/yr for industrial use (for a total of 1115 Mm^3/yr). Taking into account the need of instream flow for aquatic life (estimated in 48 Mm^3/yr), a deficit of at least 22 % for future needs is expected. Projects to compensate this deficit include: the construction and completion of dams, pipes leakage containment, the efficiency of irrigation, reuse of treated wastewater and the construction of desalination plants (SOGESID 2002; Viceconte 2004a; Regione Autonoma della Sardegna 2006a; 2006b).

Groundwater withdrawals of about 254 Mm^3/yr are estimated from wells and springs, fed mainly from Mesozoic-Cenozoic carbonate and volcanic aquifers, and from Pliocene-Quaternary alluvial aquifers. Studies on the environmental state have highlighted the eutrophication phenomena of surface waters in some dams and the saline intrusion phenomena in coastal aquifers (Regione Autonoma della Sardegna 2006a; 2006b).

Water resources of Calabria

The Calabria Region corresponds to the main sector of the Calabrian Arc. It is made of nappes of Jurassic to Early Createaceous ophiolite-bearing sequences, and Hercynian and pre-Hercynian basement (Amodio Morelli et al. 1976; Van Dijk et al. 2000). The Paleozoic crystalline basement includes high-grade metamorphic rocks and intruded plutonic bodies; it outcrops in the central part of the region (for about 5900 km^2) constituting the main reliefs of the peninsula (Sila, Serre and Aspromonte massifs) (Fig. 2). Late Miocene-Quaternary sedimentary deposits cover the Mesozoic sedimentary complexes and the Paleozoic basement. The tectonic setting of Calabrian Arc is a consequence of the pre-Hercynian to Cenozoic events, which favored the exhumation of thick Hercynian crustal sections. The most recent tectonic processes are also well represented. They are linked to an extensional stage, such as the normal faults oriented NW-SE and NE-SW, which divides the crystalline basement and its sedimentary cover into several blocks (Caggianelli et al. 2000; Van Dijk et al. 2000; Tansi et al. 2007).

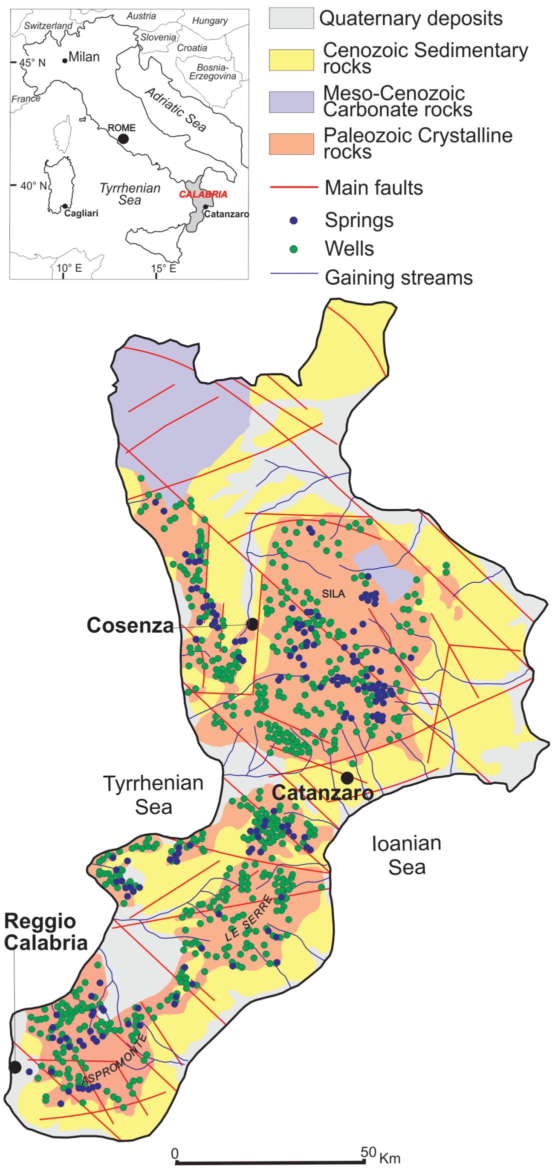

Fig. 2 - Crystalline rocks in Calabria.

Fig. 2 - Rocce cristalline in Calabria.

Typical Mediterranean climate, with maxima rainfalls in autumn and winter and minima during the summer, characterizes the region. The mean annual values for precipitation range from 600 mm in coastal areas up to 2000 mm on reliefs; the mean annual air temperature ranges from 8 °C on the reliefs to 17 °C in the coastal areas. For the period 1960-2006 it was assessed a reduction of precipitation from 2 to 15 mm/yr and of flows from 5 to 20 % (Viceconte 2004b).

Water resources of the region currently derive primarily from surface water and groundwater. There are 21 dams built mainly on the Paleozoic crystalline rocks, but only 11 are in operation. These reservoirs have multiple purposes (mainly for hydroelectric and irrigation uses). The drinking water supply is highly fragmented, taking place from numerous wells and springs. The current drinking water needs is approximately 393 Mm^3/yr, supplied by regional and municipal waterworks. No substantial changes are expected in future demand (2022) (Viceconte 2004b; Regione Calabria 2008), although some urban areas already have significant water deficit (e.g., Reggio Calabria town). Crop irrigation of the plain areas is supplied by surface water and pumping from many wells, managed by consortia or private farmers. Even if the irrigation consortia would cover the water needs (about 818 Mm^3/yr), they only manage the 36 % of the total irrigable area, because of the high number of private wells, whose amount of abstraction is unknown. Industrial water demand is not known in detail as well. However, it has a secondary weight on the total water demand; the few industrial sites are generally supplied by public waterworks or private wells (Viceconte 2004b; Regione Calabria 2008).

The main aquifers of the region include Pliocene-Quaternary coastal alluvial aquifers, Mesozoic carbonate aquifers and Paleozoic crystalline aquifers. The aquifers of the coastal plains are intensively tapped by approximately 6000 abstraction points, mainly wells. These aquifers present pollution phenomena due to marine intrusion, farming practices, animal husbandry and landfills (Regione Calabria 2008).

The projects aiming at rationalizing the use of water resources in coastal plains and towns (i.e., places with more pressure on the alluvial aquifers) include: completion of dams, optimization of the consortia irrigation networks and reduction of pipes leakage (Regione Calabria 2008).

Current knowledge about occurrence and flow of groundwater in crystalline rocks

Current knowledge on the hydrogeology of the crystalline rocks of Sardinia and Calabria is scarce. General considerations on occurrence of groundwater flow and some studies limited to specific areas are reported in the scientific and technical literature (e.g., Celico et al. 2000; Barrocu 2003; Allocca et al. 2006; Regione Autonoma della Sardegna 2006a; 2006b; Barrocu 2007; Regione Calabria 2008; Baiocchi et al. 2014; Baiocchi et al. 2015).

These aquifers are generally characterized by a low yield due to their low intrinsic primary permeability and porosity. They comprise a weathered mantle (with a thickness up to a few dozen meters) and fissured bedrock (up to 50-100 m of depth), where the groundwater movement takes place. The hydraulic conductivity and storage of the weathered mantle and underlying fissured bedrock are derived from geodynamic and geomorphic processes. The fissures have been explained by several processes, such as lithostatic decompression, tectonic activity, cooling stress, and weathering processes. These two layers make up a composite aquifer followed in depth by the fresh basement, which is permeable only if tectonic fractures are locally present.

In Sardinia, the crystalline rocks are usually considered impervious, as proved by the presence of many dams and barrages. However, several springs (few thousands) with a flow rate ranging between 0.1 and 1 L/s are fed by crystalline rocks. Several tens of wells drilled in the fissured layer of granitoid rocks (and in some cases also including their weathered mantle) show yields between 0.1 and 2 L/s, values of transmissivity between 10^{-6} and 10^{-4} m^2/s and of storativity between 0.05 and 2 % (Barrocu 2003; 2007). In Southern Sardinia, some wells drilled near a faulted zone in the fissured layer of low-grade metamorphic rocks show yields between 1 and 3 L/s, values of transmissivity between 10^{-4} and 10^{-3} m^2/s and of storativity between 0.03 and 3 % (Baiocchi et al. 2015). At present, only about thirty springs (Fig. 1) and wells fed by the crystalline rocks are tapped for water supply (with a discharge between 0.5 and 2 L/s) (Regione Autonoma della Sardegna 2006a; 2006b).

In Calabria, the crystalline rocks are tapped by many scattered wells, having usually flow rate less than 3 L/s, and feed some thousands springs, having usually a discharge less than 5 L/s (Fig. 2). In streams, a considerable water flow occurs even during dry periods, which may be related to groundwater. Significant streamflow rate has been found even at high elevations, where metamorphic rocks outcrop, and preferentially in the incised streams at the base of granitoid massifs (Celico et al. 2000; Allocca et al. 2007). Values of transmissivity between 10^{-6} and 10^{-4} m^2/s and of storativity between 0.2 and 1 % have been found for the fissured layer of granitoid and metamorphic rocks of the Serre Massif (central Calabria) (Baiocchi et al. 2014). In these areas, wells drilled in the fissured layer of the granitoid rocks at the base of the massif showed a yield up to 6 L/s.

Preliminary assessment of groundwater resources of crystalline aquifers

Given that detailed hydrogeological investigations are only locally available, a preliminary assessment of groundwater resources of crystalline rocks was conducted by examining the streamflow of some significant basins of the two regions. Basins characterized by intrusive and metamorphic rocks were considered, 2 in Sardinia and 9 in Calabria (Fig. 3). These basins are characterized by a small surface area (from 40 to 230 km^2) and negligible water withdrawals. At least 20 years recordings of monthly average flow and rainfall are available for the selected basins (SIMN 1916-2000; Regione Autonoma della Sardegna 2013).

In figure 4, monthly average streamflow and rainfall are reported for each basin as obtained from the previously mentioned database. From these graphs one can see the presence of a significant discharge in the streams in the period with low rainfall (from July to August). To preliminarily quantify the groundwater contribution to the river discharge, the hydrograph separation was performed assuming that the minimum discharge of the river totally comes from groundwater and remains constant along the year. This assumption clearly underestimate the yearly groundwater outflow. The low precipitation and high evapotranspiration rates in the dry period, together with the limited surface area of the basins under examination and, for the Calabria basins, with the high mean basin slope, allow to state that

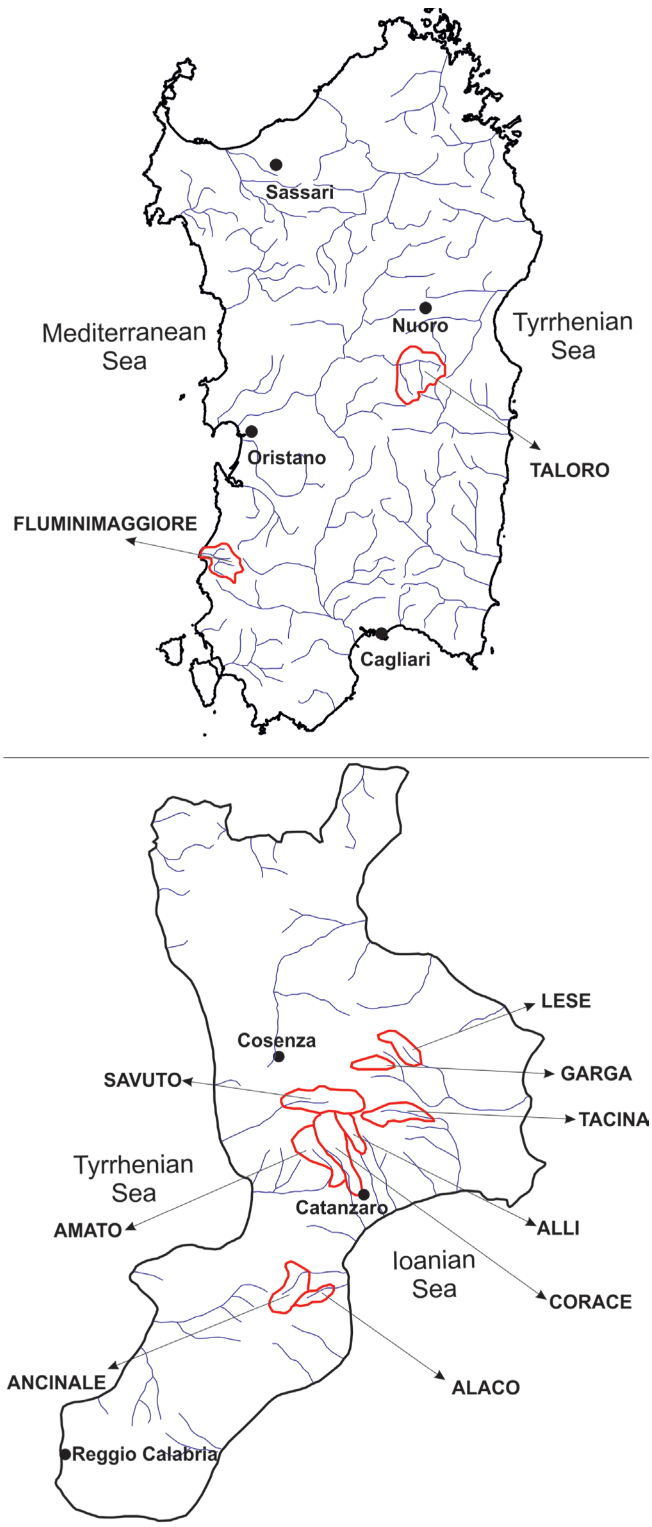

Fig. 3 - Location of the basins considered for groundwater yield estimation.

Fig. 3 - Localizzazione dei bacini considerati per la stima della resa in acque sotterranee.

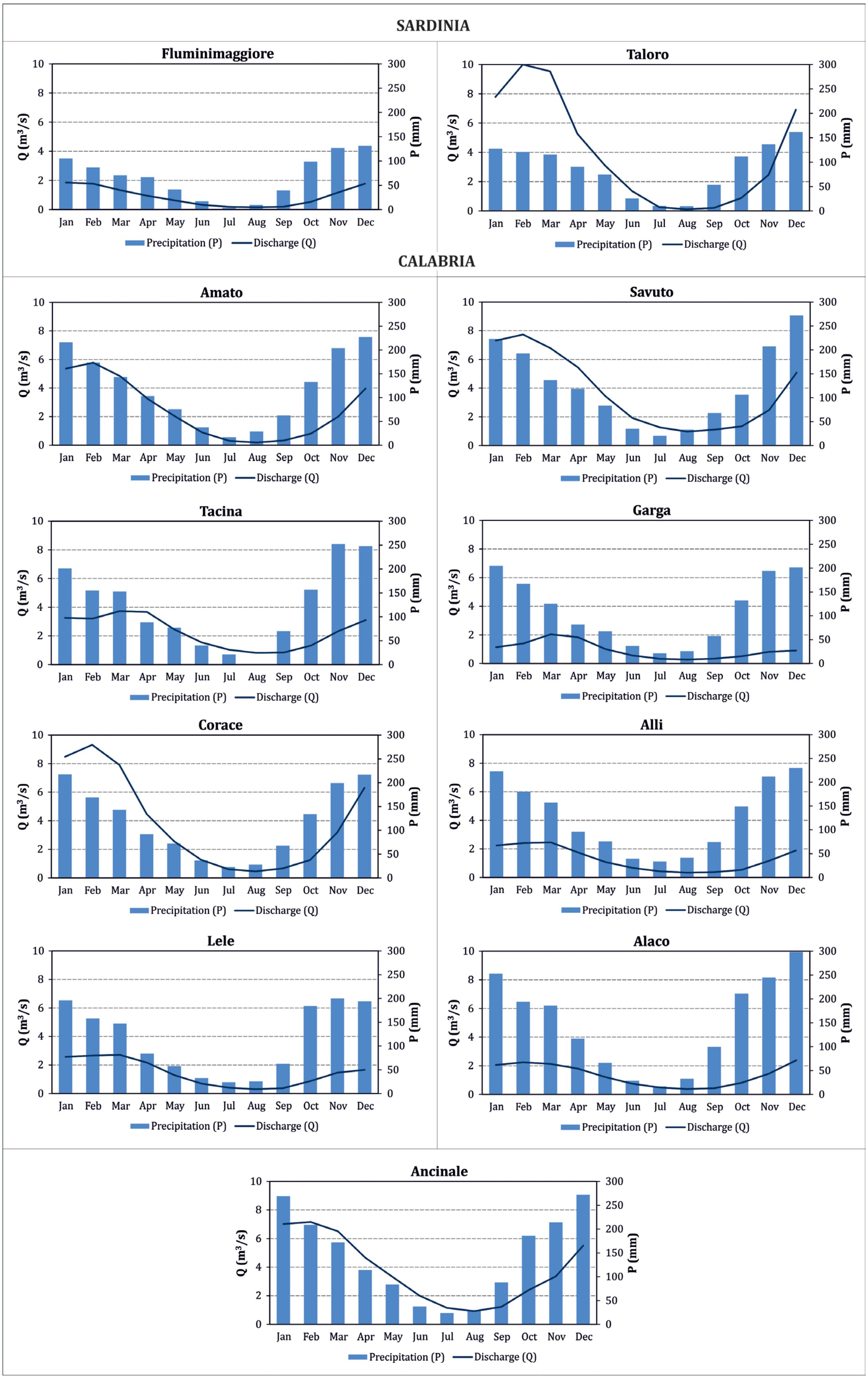

Fig. 4 - Graphs showing the monthly average flow and rainfall of the basins.

Fig. 4 - Portate e precipitazioni medie mensili relative ai bacini indagati.

the discharges recorded in the dry period are entirely due to groundwater contribution. Considering the average streamflow of the two dry months, the yield of groundwater of different basins was determined through the ratio between the average flow rate in dry period and the surface area of the basin. It was found that the yield of the basins ranges from about 1 to 12 L/s per km^2 (Table 1).

Although for Sardinia the analysis concerns a lower number of basins compared to those of Calabria, the yield is lower for the crystalline rocks (from 1 to 2 L/s per km^2) with respect to those of Calabria (from 2 to 12 L/s per km^2). The reason for this difference may lie in the different climate and topographic conditions of the crystalline rocks in the two regions. Other factors that distinguish the crystalline rocks in the two regions are an intense fracturing degree in the Calabria massifs, induced by the most recent tectonic processes, and the presence of an almost continuous weathering mantle above the fissured bedrock (Celico et al. 2000; Allocca et al. 2006). These last two factors facilitate infiltration and flow in the crystalline rocks of Calabria when compared with those of Sardinia.

Based on the lowest groundwater yield among those determined for the sample basins and the outcrop extension of crystalline rocks, approximately 350 and 450 Mm^3/yr can be estimated for the groundwater resources of Sardinia and Calabria, respectively. Even considering only 50 % of these resources, in order to safeguard the aquatic life in the streams, they represent a significant contribution to water supply in the two regions.

Conclusions

In Sardinia and Calabria, crystalline rocks form low-permeability aquifers where groundwater circulation occurs in the weathered layer and in the most fissured layers closest to the surface. In the most heavily fractured zones (i.e., near the faults), the groundwater flow is more active and can occur at a greater depth. Groundwater outflows in the valleys, feeding the streams, numerous low discharge springs and surrounding aquifers.

Climate, topographic conditions and tectonic style influence the difference in groundwater resources and flow of the crystalline aquifers of the two regions. The available data of transmissivity lead to attribute the crystalline rocks to the classes III and IV of the classification proposed by Krasny (1993), corresponding to rocks from low to intermediate transmissivity magnitude. A preliminary analysis indicated that groundwater yield ranges from about 1 to 12 L/s per km^2. A detailed estimate at the basin scale would provide higher rates, since the preliminary hydrograph separation method used herein overestimate runoff at the expenses of the basal flow.

This overall characterization showed that there are reasons to deepen the knowledge on these aquifers in order to optimize the present use of their groundwater resources. In particular, given the low groundwater yield of the crystalline aquifers when compared with other aquifers (i.e., carbonate and alluvial aquifers), they can support the sustainable development of rural areas and small towns in the two regions that often fall into basins constituted by these rocks.

Tab. 1 - Discharge of the dry months, rainfall and groundwater yield of the basins.

Tab. 1 - Portate in periodo secco, precipitazioni e resa in acque sotterranee dei diversi bacini.

Region	Stream	Basin area (km^2)	Rock	Mean discharge in dry period (m^3/s)	Mean annual rainfall (mm)	Estimated yield of groundwater (L/s per km^2)
Sardinia	Fluminimaggiore	83	Metamorphites	0.18	798.4	2.17
Sardinia	Taloro	226	Granitoids	0.19	1037.6	0.85
Calabria	Amato	115	Metamorphites	0.28	1421.7	2.43
Calabria	Savuto	141	Metamorphites and granitoids	1.12	1496.7	7.94
Calabria	Tacina	77	Granitoids and metamorphites	0.90	1491.7	11.69
Calabria	Garga	43	Granitoids	0.31	1316.9	7.21
Calabria	Corace	178	Metamorphites and granitoids	0.58	1398.9	3.26
Calabria	Alli	46	Metamorphites and granitoids	0.30	1511.8	8.26
Calabria	Lese	60	Granitoids	0.37	1365.2	6.17
Calabria	Alaco	38	Granitoids	0.44	1748.3	11.58
Calabria	Ancinale	116	Granitoids	1.10	1698.9	9.48

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