A hydrological and geochemical survey of the groundwater resource of Favignana Island

Small islands suffer water shortage, and tourist pressure makes it even worse: Favignana island is the site that best represents such conditions, due to the contrast between the intense anthropization and the harsh nature of the terrains. The ENEA study hypothesized a solution in identifying the best areas where groundwater is abundant and presents the best conditions to take water samples for anthropic use. With hydrological measurements and chemical analyses, an area theoretically interesting has been identified in the eastern sector, where groundwater is better in quality and just a few meters deep below the ground. Westwards, instead, it is at a lower depth and saltier, due to its more intense contamination with seawater. Yet the amount of available groundwater is everywhere so poor that more intense water sampling is not recommended: people have always been living in good balance with nature, and they know how to manage the island's groundwater resource, fed by rare precipitations, as a supplement to the drinking water supply coming from Trapani

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M. Grillini, M. De Cassan, M. Proposito

Introduction

The small islands scattered over the Italian seas have always had to cope with a shortage of water resources, because of the harsh nature of insular grounds and the scanty areal extent of the islands themselves [1]: moreover, their aquifers are usually very thin, and the water in the wells is scarce and often brackish; in fact, often low quality is added to the natural scarcity of water resources, due to the seepage of salty water from the surrounding sea [2].
Islanders have therefore learned, over the centuries, to manage their water resources in extremely thrifty ways, developing peculiar techniques to collect and preserve the rainwater, such as conveying it from the basin-shaped roofs of their houses downward into underground cisterns [3]. Actually, agriculture has been affected too, compelling farmers to breed drought-resistant and brackish-water-tolerating cultivars [4, 5].
Nowadays, the growing tourist pressure [6, 7] is worsening the problem, particularly during the summer: if, on the one hand, it is an income source for islanders, on the other it demands larger amounts of freshwater, indispensable for restaurants and hotels [8-12].
With high summer temperatures, and scarce seasonal rains, the islands of the Egadi archipelago, off the western end of Sicily, in sight of the town of Trapani, are among the most sensitive ones to this serious inconvenience: that is why they represent the ideal subject of a study aimed at dealing with the problem [13-16].
Actually, the present ENEA study fits in the activities targeted at a more sustainable touristic offer [17,18]: in detail, the starting purpose was to detect possible areas where groundwater is of the best quality, and where it

Contact person: Marcello Grillini
marcello.grillini@enea.it

would be suitable to rationally concentrate pumping from the wells, to supplement the freshwater supply currently coming from an aqueduct from Trapani [19-22].

Geology and hydrogeology of Favignana

With a length of 9 km (west to east) and a maximum width of 4.3 km (north to south), the island of Favignana extends over an area of 19.4 km^2, along a 33 km long coastline [23, 24]. It hosts a ridge of dolomite and limestone oriented North to South -on top it stands Mt. Santa Caterina (312 m a.s.l.)- and two plain areas west and east of it, respectively (Figures 1 and 2). The ridge is bounded on both sides by a system of faults which have lowered the carbonate sequences, causing them to be covered by more recent deposits, mainly calcarenite [25-33].
Therefore, three hydrogeological basins should be considered in Favignana (Figure 3), corresponding to the two plains and the central ridge. The structural discontinuity surfaces, bordering on both sides the ridge itself, act as groundwater divide: only after heavy rain periods some limited groundwater is allowed to flow from the ridge toward the coastal plains.
In the western sector extensive outcrops of limestone can be found, side-by-side with less widespread calcarenite, as the evidence of a less deep lowering of those rocks in this area [34-39]. As a consequence, as it will be discussed later on, the groundwater in this sector is somewhat different from the water in the eastern sector: it is on average deeper and saltier.
In the eastern sector, instead, calcarenite covers the whole area, with a thickness varying from two to thirty meters. This rock has been extensively exploited over the centuries as building material (called "Tufo" all over Southern Italy) [40-44], to the extent that

FIGURE 1 Mt. Santa Caterina and the western plain

FIGURE 2 The town of Favignana and the eastern plain

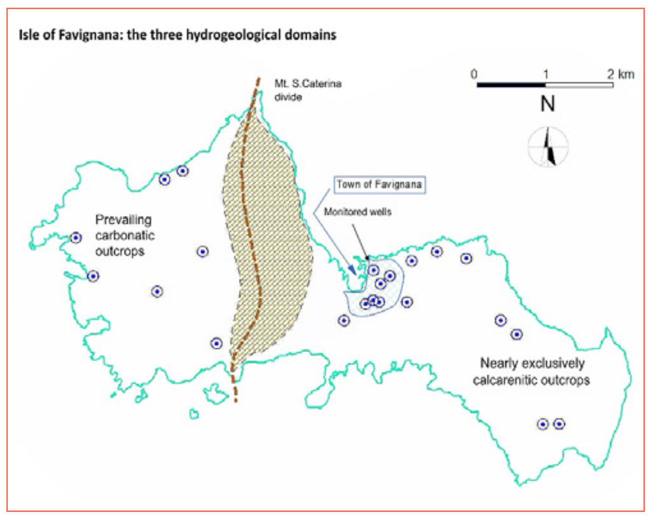

FIGURE 3 Schematic hydrogeology of Favignana

FIGURE 4 A typical quarry of "tufo"

several quarries and caves pierce everywhere the terrain, giving the landscape its characteristic rough appearance (Figure 4).
These calcarenite outcrops are not uniform, showing cross and parallel bedding. They are also commonly alternated with lenses and thin beds of sands and conglomerates. From this it ensues that the groundwater in this sector is actually not hosted in a single, large aquifer, but in a group of small aquifers, some in hydraulic continuity some isolated.
The scarcity of rainfall, the calcareous nature of the relief, and the limited extension of the island itself do not allow watercourses to form: only during some violent storm, accompanied by heavy downpours, small brooks form in some valley of the ridge, that dry up in a few hours.

The survey

In the field

In order to characterize and monitor the groundwater of Favignana, two surveys were carried out in 2012, measuring the water table from selected wells with a phreatimeter, main physical and chemical parameters (pH, temperature, electrical conductivity, dissolved oxygen, redox potential) with a multi-parametric probe, and collecting water samples for further determination of major cations, anions, and trace elements at the environmental biogeochemical laboratory of the ENEA Casaccia Research Centre.
The monitoring was not targeted at the effective potability of groundwater in a strict (and legal) sense: a rather different approach should have been necessary, planning biological analyses too, and a different and more complex handling of the samples, from their sampling to storing and analyzing. The chemical results of this survey, instead, were intended primarily to characterize the groundwater in terms of their salt content: the first step was to differentiate the waters of the various island zones, and locate the best tapping spots (if possible and suitable).
With a preliminary investigation on the island, together with Favignana municipal officials, 22 wells were selected for their practical accessibility, among the 520 registered on the whole island: 7 in the western sector, 4 in the eastern sector, and 11 in the urban area, in the center of Favignana. While almost each of them was open, and directly accessible with the measuring instruments, in some cases it was only possible to get from a tap the samples for the analyses.
Through a topographic survey performed with a DGPS equipment (Figure 5), reference ground elevations have been fixed for each site, in order to measure the elevation above sea level of the groundwater table all over the island, and its variation from one season of the year to another.
The two seasonal campaigns were performed

FIGURE 5 Measuring the DGPS position and elevation

respectively at the end of the colder and wetter season (end of April), and at the end of summer (end of September), to collect the data representative of the richer and the poorer conditions of groundwater.
The measurements and analyses described below have been followed as a routine procedure for all the 17 wells directly accessible; in the other 4, due to the reduced diameter of the wells, it was not possible to insert the probe; in one case, due to the sealed well, the sample was collected from a hose. For all those wells not directly accessible for the probe, the measurement

FIGURE 6 Monitoring procedures on a site

of chemical and physical parameters was carried out on the surface through portable meters equipped with sensors and electrodes (Figure 6).

Operating procedures

- Measuring the water table depth (static level) by inserting a phreatimeter in the well down to the water.
- Purging the well and cleaning the water: a preliminary, brief discharge of the water from the well is necessary, in order to remove the upper stagnant water layer and clean up the remaining to be analyzed.
- Measuring the physico-chemical water parameters by inserting the probe into the well. The data are taken in three steps, during a second purging. On the wells of Favignana a low-flow pumping was used, for no longer than 10 minutes, due to the scarcity of the water in the wells. As the values of pH and electrical conductivity became stable, water samples were finally collected.
- Collecting the samples of water: for the analyses of hydrogencarbonate, a water sample was taken in a 250 mL polyethylene bottle, previously rinsed with the same water. Water samples for analysis of cations and anions: each water sample was filtered with a 0.45 μm mixed esters of cellulose filter and divided into two parts. The first part was acidified to pH < 2 with HNO_3 (BDH-Aristar grade) and saved for the

- determination of major cations and trace elements, while the second was kept for anion determination. Once collected, the samples were immediately stored at 4 °C waiting for the laboratory analyses.
- For each well, the whole operation of sampling has taken about one hour and half.

For each well, the data registered by the multiparametric probe were compared to those obtained from the samples collected in parallel and analysed with the portable field analyses equipment (Figure 7): the results (for temperature, electrical conductivity and pH) were satisfactory, the average deviation between probe and field instruments never exceeding 10%, with very good R^2 values for the correlation lines. Only for the Eh data no correlation has resulted but, according to the field experience, this was to be expected in the presence of brackish waters.

Results

The water table

The comparison between the GPS elevations of the ground in the sites and the depth of the water level in the wells has allowed to outline an overall view of the groundwater table levels all over the island. The analysis of the results shows up two points:

1. All the groundwater levels lie in the 0-50 cm a.s.l. range, with a mean value of 28 cm. The western sector of the island has a ground elevation (averaged on the sites of the wells) of 15.35 m, and a water table level of 0.26 m a.s.l. In the eastern sector, with an average ground altitude of 9.21 m, the water table level is 0.29 m a.s.l. Here a further distinction can be made, most of the wells being concentrated in the centre of Favignana, with a mean ground elevation of 6.13 m and a water level of 0.31 m a.s.l.: other wells, in the rural east, lie at a ground elevation of 21.53 m showing a water level of 0.21 m a.s.l.
2. Between the wet and the dry season the groundwater levels show, on average, a difference of 2-3 cm, that is less than 10%. In detail, in the western sector the difference is 3.8%, and in the eastern sector is equal to 8.8%.

FIGURE 7 Checking the data from the probe

Chemical analyses

The concentration data of the water samples collected from the wells monitored in Favignana have been projected onto a Chebotarev quadrangular diagram (Figure 8), which allows to represent the chemical composition of water with a single point.

From the diagram a wide differentiation among the waters coming from the sampled wells can be inferred: in particular the sample from the well FA16 (Figure 8) can be considered end-member of the waters flowing through the calcarenitic terrains so widely diffused all over the island of Favignana, mainly in the eastern sector: in fact, it shows a relatively abundant content of calcium, magnesium and hydrogencarbonate ions; therefore it falls in the quadrant of the waters classified as bicarbonate-alkaline-earth waters.

The opposite end-member of the group is represented by the brackish waters (wells FA26 and FA15, Figure 8), with a high concentration of sodium (≈ 1500 mg/L) and chloride (> 2400 mg/L) ions, and with an electrical conductivity in the order of 9000 μS/cm. These waters are classified as sulfate-chloride-alkaline waters.

The rest of the waters show characteristics that are intermediate between bicarbonate-alkaline-earth and the sulfate-chloride-alkaline waters, with a prevalence of the bicarbonate-alkaline-earth kind.

In the Schoeller diagram (Figure 9), the slope of each segment joining the points of two different ions represents the characteristic ratio between those two ions: parallel segments denote waters with the same ionic composition, while segments with different gradient denote different

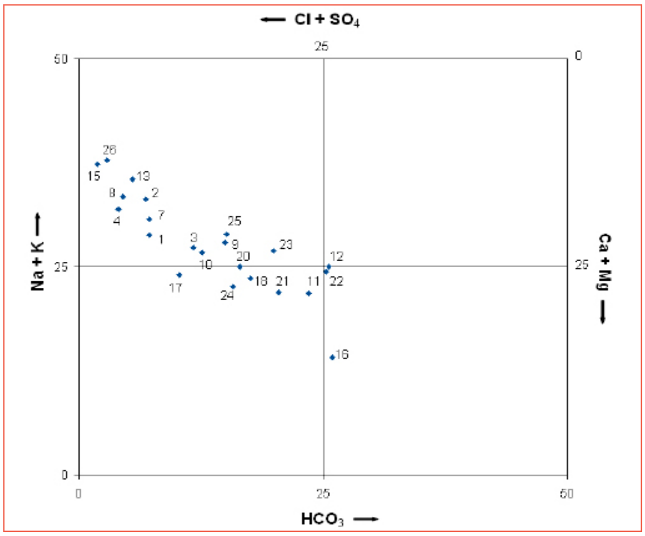

FIGURE 8 The Chebotarev diagram: water classification and evolution of the groundwater chemical composition

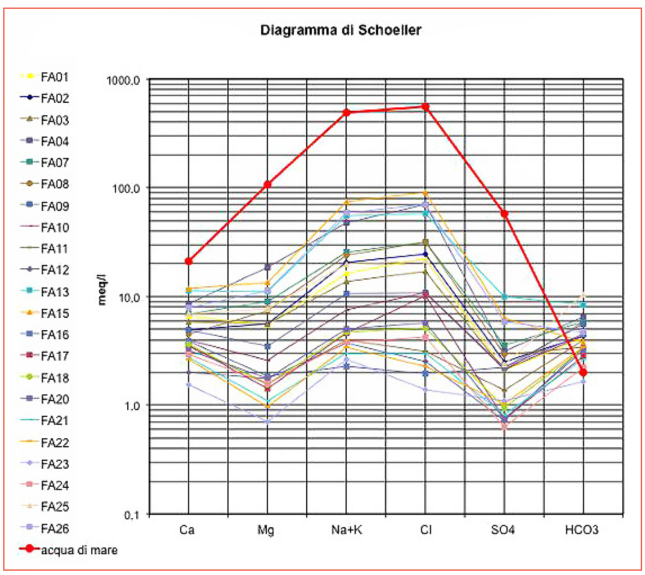

FIGURE 9 The Schoeller diagram: comparison between the ionic concentrations from the groundwater samples collected in Favignana

hydrochemical characters. A detailed analysis of the Schoeller diagram created for these water samples confirms a similar composition for most of the examined waters.

Particularly, most of the segments forming the distinctive lines of the water samples taken from wells FA04, FA13, FA15, and FA26 show a quasi-parallel trend, not only reciprocally, but also compared with the standard seawater line used as a comparison (sea water with a salinity of 35‰) [45]. These samples, showing electrical conductivity values exceeding 7000 μS/cm, represent the end-members of a geochemical facies evolved into chloride-alkaline through the mixing of originally fresh water with other saltier water due to a probable marine intrusion.

Discussion

Both in the western and in the eastern sectors, the water table is always few tens of centimeters above sea level, in wells where the mouth is as high as 32 meters as well as in wells where it is just a couple of meters above sea level (Figure 10). This result is evidence of the poor groundwater resource all over the island, independently from the nature or characteristics of the terrain, where the well has been drilled or excavated.

Between the wet and dry season the water table shows no significant differences, since they are limited to a few centimeters. Oh the other hand, the Favignana's people is accustomed since the first prehistoric colonization to cope with drought and poor water resource: they have

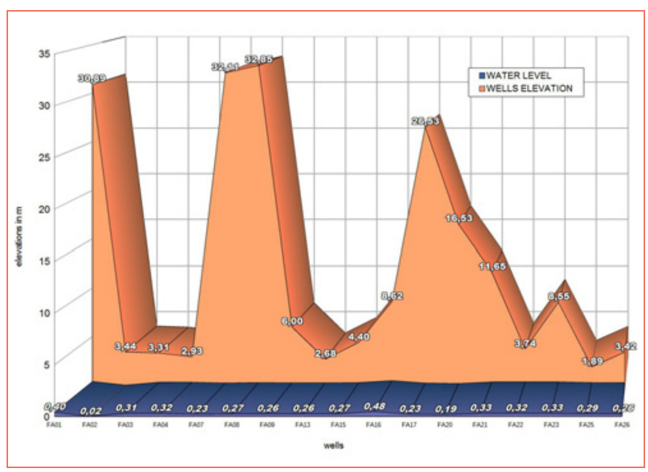

FIGURE 10 Water levels *vs.* ground elevations

FIGURE 11 Ruins of an ancient roof-and-tank set

soon learned to spare it, to manage it without wasting it, to secure at least a minimal reserve of water all over the year. Hence, in order to achieve this goal a house building technique has been developed over the centuries, that allows to collect rain water on the roof of the houses, from where it is pipe-conveyed down into cisterns often carved out right below the houses themselves (Figure 11).
According to the geographical distribution of the electrical conductivity values all over the island, two trends are distinguishable. The electrical conductivity data in the wells of the western sector range (annual average) from 2435 to 4830 µS/cm, with a maximum of

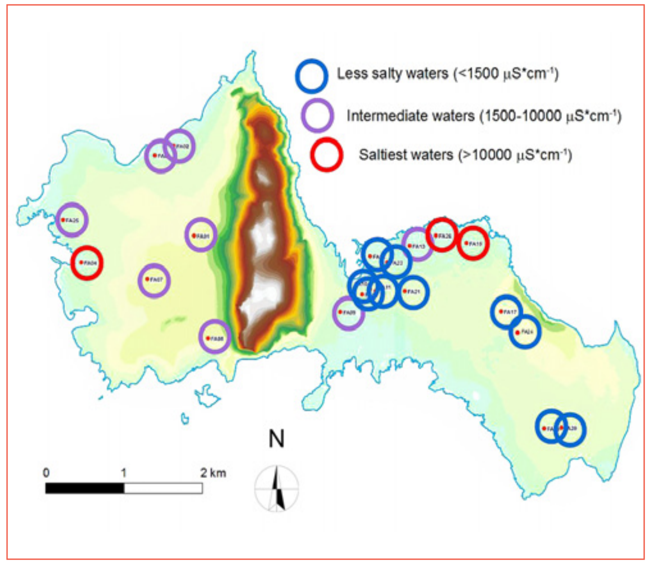

FIGURE 12 The distribution of conductivity in the two sectors of Favignana

9125 µS/cm in the well FA04. In the wells of the eastern sector, values as low as 676 µS/cm and as high as 11110 µS/cm (Figure 12) have been measured instead.
Although the mean electrical conductivity values of the two sectors are not so much different (4359 µS/cm vs 3563 µS/cm, both high values, anyway, for a groundwater), in the western area a more homogenous distribution can be observed, while eastwards the values are very different, even at a distance of a few hundred meters (Figure 12). This is coherent with the literature, where it is reported that in Favignana two wells can often be found in the very same lot, providing a different kind of water, one fresh and the other salty.
This difference mainly depends on the different geology of the two sectors, as already anticipated above (Figure 3): in the eastern one, the calcarenite outcrops are not uniform but commonly alternating with lenses and thin beds of sands and conglomerates. Therefore the groundwater in eastern Favignana should be considered as a set of little aquifers -contiguous and/or overlapping, isolated or linked together- each with different water qualities. In the western sector, instead, outcrops of carbonatic rocks are more abundant with respect to more scattered calcarenite banks.

Another cause of the difference between western and eastern sector is that the former is almost uninhabited, with few rural buildings dispersed over the country areas and no urban centers; conversely, the latter sector is the real vital center of the Island, from the town of Favignana in the center of the island to the tourist facilities on the more eastern coast.

As for the wet and the dry seasons, there are some differences indeed, nevertheless they are the most various and apparently accidental variations: somewhere they are positive, somewhere negative. No correlation has been found with the seasonal variation of the water table either.

Comparing the average electrical conductivity values with the ground elevations above sea level at the sites of the wells (Figure 13), instead, it is easy to see that higher electrical conductivity values are more common in shallower wells (even with conspicuous exceptions): it could be easy to conclude that this occurs since these wells are nearer to the seashore than the deeper ones. In fact electrical conductivity is function of the salt content, and this latter is, in turn, function of the mixing with the sea water surrounding the island. The cited exceptions, however, demonstrate that the underground conditions of Favignana are not so easy to describe: well FA22, for instance, in the middle of the town, one hundred meters from the quays, hosts water with the lowest electrical conductivity (i.e. the lowest content in salts): 676 μS/cm as annual average. In the western sector, wells FA02 and FA03, excavated in a calcareous outcrop, although situated some 100-200 meters from the rocky northern seashore, give water that is quite salty indeed (3200 μS/cm and 2435 μS/cm, respectively), but not so salty as the other wells situated slightly above sea level (where electrical conductivity rises as high as 6000, 7000, even almost 12000 μS/cm).

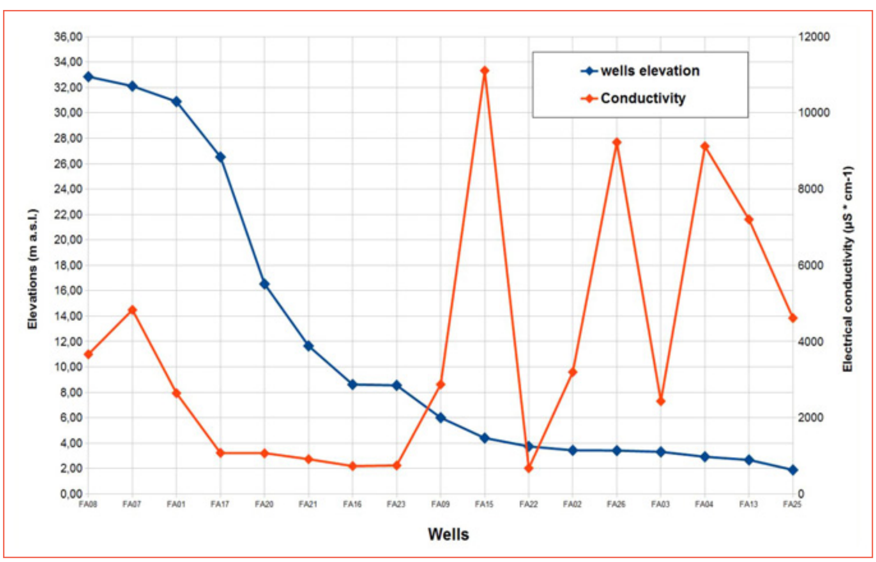

FIGURE 13 Conductivity *vs.* ground elevation

Conclusions

On the sole Favignana Island (with its area of less than 20 km^2) 520 wells are officially registered at present: even if many of them are out of service, and others belong to houses inhabited only for limited holiday periods during the year, it is still a huge number of points from which the groundwater can be tapped.

In addition to this anthropogenic potential consumption of groundwater, another way water is wasted due to the cited characteristic quarries and caves located everywhere in the eastern sector of Favignana: most if not all of them reach the water table, so their floor, and even their walls, act as evaporation surfaces contributing to the loss of the available groundwater.

All this could pose a serious threat to the survival of the natural groundwater resource, if people do not manage it with responsibility: according to the results of this survey, it can be said that there is no real danger, because water tapped from the island wells is not used extensively but only for limited domestic uses, such as irrigation of small orchards and hygienic purposes. The islanders know very well how much water they can yield from the ground, and where it is brackish and where fresher: they know very well that they cannot draw more water, nowhere, otherwise groundwater will be polluted irremediably by the ingression of sea water, which would advance to replace the overexploited fresh water. Therefore, groundwater should not be considered as a resource that could be exploited more intensively, neither all over the island nor in some chosen wells: the demand for fresh, drinking water could only be satisfied by the water supply coming from Sicily through the existing pipeline.

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Marcello Grillini, Maurizio De Cassan, Marco Proposito
ENEA, Sustainable Territorial and Production Systems Department

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