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Urban groundwater warming in Turin area (NW Italy)

Arianna Bucci (a), Diego Barbero (b), Manuela Lasagna (c), Maria Gabriella Forno (c) & Domenico Antonio De Luca (c)

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KEY WORDS: groundwater temperature, seasonal oscillation, anthropogenic heat sources, ground-source heat pumps.

ABSTRACT

This study investigated the thermal regime of shallow groundwater in the Turin area (NW Italy), where the large energy demand has driven a new interest for ground-source heat pumps (GSHPs). The strongest vertical variability of groundwater temperature is found within 10-20 m below ground surface. In spring, deeper temperatures are higher than shallow temperatures, while in autumn the trend is reversed. These variations are connected with the heating and cooling cycles of the ground surface due to seasonal air temperature oscillation, propagating into the aquifer.

The areal temperature distribution shows an increase from the foothill sectors close to the Alps towards the central Po Plain, driven by the progressive warming along the flow path. In the Turin city aquifer temperatures are 0.6 ÷ 1.6 °C higher than rural sectors. This groundwater warming is linked to the urban heat island effect, mainly driven by the typical artificial land use. Sparse warmer outliers (16-20 °C) are in some cases connected to documented point heat sources, such as GSHP systems, industrial districts and landfills.

STUDY AREA

The area investigated is located in Piedmont Region (NW Italy) and includes both the narrow sector of the western Po Plain between the Western Alps (W) and Turin Hill (E) and the internal plain sector of the Ivrea Morainic Amphitheatre. The regional climate is driven by the orographic component (ARPA 2007): air temperatures show a regular decrease with elevation in western direction towards the alpine chain and can be changed by local conditions, such as urban areas. The average annual temperature of Piedmont Po Plain ranges between 10°C and 12.5°C, with higher average monthly values in autumn than in spring (Table 1).

From a hydrogeological point of view, the Quaternary alluvial sediments of the Po Plain represent a continuous highly permeable porous medium that hosts many groundwater systems. Conventionally, one shallow and various deep aquifers have been described in Piedmont Region (Bortolami et al., 1988; Bove et al., 2005; De Luca et al., 2014; Lasagna and De Luca, 2017). The shallow aquifer, hosted in late Pleistocene and Holocene units, is mostly unconfined and supplied by the infiltration of rainfall and secondarily by rivers in the high plain sectors. Due to the mainly sandy–gravelly texture, many quarry activities are exploiting this complex (De Luca et al. 2007; Castagna et al. 2015a, 2015b). The maximum aquifer thickness is 50 m and the water table generally has depths between 1 and 50 metres below ground level, with minima located in the high plain sectors. In most of the wells (78%) the water table depth is found between 1 and 20 metres b.g.l. (Bucci et al., 2017). The low plain sectors, far from the Alpine chain, are generally discharge areas and the Po River represents
the main regional discharge axis for the groundwater flow (Debernardi et al., 2008; Lasagna et al., 2016a, 2016b).

**TEMPERATURE MODEL AND METHODS**

The shallow subsurface temperature is mainly controlled by the temperature at the ground surface, which strictly depends on the local climate and on the land use conditions. The temperature temporal oscillation in the unsaturated zone, solved by a 1D heat diffusion model for a semi-infinite medium characterized by homogeneous properties and negligible vertical water movements (Banks, 2008; Taylor and Stephan, 2009), consists of an oscillating temperature around the average annual ground temperature. The fluctuations undergo a decay and an increasing time lag with depth. This means that longer temperature cycles -decades, centuries- are, the more they penetrate the subsurface, whereas the short cycles -days, months- but their amplitude is increasingly damped and lagged by the heat dissipation within the geologic medium. The heat transfer processes become more complex when the ground temperature inputs reach the groundwater: the flow of the water in the porous medium, the inertial effects and eventual turbulence enlarge the apparent thermal diffusivity until it reaches several orders of magnitude greater than the molecular thermal diffusivity (Taylor & Stephan 2009). This means an increased rate of heat transport due to hydrodynamic effects that are highlighted by distortions in borehole temperature logs.

The aquifer depth interval affected by temperature oscillations, known as the “surficial zone”, is generally 10 to 20 m deep; it is followed by the so-called “geothermal zone”, in which the geothermal gradient drives a constant increase in temperature (Anderson 2005). However, previous works in NW Po Plain alluvial aquifers (e.i. Barbero et al., 2016) revealed a “homoeothermic zone” with no temperature oscillations in time. The temperature below the surficial zone is usually 1 to 2 °C higher than the average annual temperature at the ground surface (Anderson 2005).

The mean annual average temperatures and the amplitude of temperature oscillations in the vadose zone and in the aquifers strictly depend also on the local land use: variations in reflectance and porosity of soil are able to influence the transmission of solar radiation and water infiltration. Consequently, temperatures are affected by anthropogenic elements found at ground surface: buildings, roads, paved surfaces and so on. The temperature rise varies depending on the type of element: for example, Taylor and Stefan (2009) observed increments of up to 3 °C linked to isolated roads. The most evident thermal footprints occur beneath urban areas: Menberg et al. (2013) estimate a temperature difference between rural and urban areas equal to +1.9 °C to +2.4 °C in some German cities. Warmer temperatures below cities are also linked to the global warming (Taniguchi et al., 2007; Bayer et al., 2016).

Thermal logs, the typical survey method for aquifer temperature detection (Taniguchi, 1993; Pasquale et al., 2011), were carried out throughout the water column of around 50 observation wells of Turin area, all wells are screened in the shallow aquifer. Temperature acquisition interval was 1 to 5 m (depth-wise increase) and an electronic water level metre equipped with a thermometer (±0.1 °C accuracy) was used. For assessing possible city-related effects, temperatures were collected in rural and urban (Turin city) sectors. A multi-temporal approach was used to detect the seasonal fluctuations. The largest part of the wells was surveyed in 2014 in a spring-autumn survey. In 2016 further observation points were added with measurement frequency equal to 1 month. The depths of monitored wells have the following ranges: <10 m (2.4%), 10 to 20 m (42.9%) and >20 m (54.7%).

According to the afore mentioned temperature model and to air temperatures, the maximum expected groundwater temperature below the surficial zone with climatic variations is between 12 and 14.5 °C in the Turin plain.

**RESULTS AND DISCUSSION**

The most evident feature of the temperature profiles measured in the monitored wells of the area investigated is the vertical variability in the shallow portion of the aquifer, according to the afore mentioned models. The temperature delta along the water column of the well, obtained by the difference between top and bottom well temperature, indicates the warming/cooling of very shallow groundwater; as expected, the temperature variation along the well water column diminishes significantly with the depth of groundwater level (Fig. 1). This trend is season-driven: in spring deep values are higher than the shallow ones (ΔT<0), while in autumn a decrease of temperature with depth occurs (ΔT>0). Such depth and time variations are connected to the heating and cooling seasonal cycles of ground surface temperatures, propagating into the shallow portion of the aquifer. Furthermore, the seasonal amplitude reduction with increasing depths means that the vadose zone plays a major role in damping the oscillations, according to similar studies by Burns et al. (2016).

Underneath the seasonal oscillation zone, groundwater temperatures are approximately constant in most wells, according to Barbero et al. (2016): in Fig. 1, below 10 m the residual changes (less than ± 1 °C) can be connected to other processes, such as advective heat transport within the aquifer. Deviations from constant temperature in the thermal profiles can be read as either upward or downward
water movements, in recharge and discharge areas, or as lithological heterogeneities in areas with nearly horizontal flow. The groundwater temperature in Turin plain, averaged on spring and autumn values extracted from Bucci et al. (2017), is 14.1 °C, that is within the expected temperature range (see previous paragraph).

Lateral variations of aquifer temperature in autumn 2014 are displayed by plotting the bottom well temperatures, not affected by seasonal oscillations (Fig. 2), that were measured at the average depth of 25 m. There is a gradual groundwater warming from high plain sectors close to the Alps towards the Po River. This feature is consistent with the main groundwater flow direction, meaning that colder aquifer temperatures of recharge areas -due to colder air temperatures in high plain sectors- warm up during their pathway.

The second most evident feature is the high concentration of warm temperatures below the Turin city: compared to rural values, the urban aquifer is 14-16 °C and rural aquifer is 12-14 °C. More precisely, the urban warming intensity can be calculated with the difference
between the average temperatures in the city area and rural area: in the Turin case in 2014 it is +1.6 °C in spring and +0.6 °C in autumn. This feature is likely linked to the groundwater warming caused by the large urbanized area of Turin: the extensive cover of roads and buildings warms up the land surface and then this heat is transferred to the underlying aquifer.

Sporadic high temperatures (>16 °C) have local significance and may be related to point heat sources. In the case of La Loggia observation well (Fig. 2), located few kilometres south of the Turin city, groundwater reaches a temperature of around 17 °C. In this case the groundwater heating is likely linked to the presence of an industrial district that may be responsible of intense heat fluxes due to the huge volumes of warm indoor air and/or to industrial exothermic processes. Other outliers are: a well in Turin city close to an open-loop geothermal system working in heat injection mode, which displayed temperatures up to 23 °C -not in figure- and the Caselle T.se observation well (N of Turin), which showed a high maximum temperature in autumn (18.6 °C) and a marked difference with the spring value (13.4 °C). Without any further knowledge on heat sources in the surroundings and lithological variations at the site, such behaviour may be related to a significant seasonal effect on groundwater: the small groundwater table depth (< 5 m) and the limited well depth (20 m) make the groundwater at that site largely influenced by the seasonal oscillations, even at the bottom of the observation well, where the plotted measurement was taken. Furthermore, the land use of both sites is constituted by large paved parking areas that might have amplified the heat accumulation during summer, with consequent high temperatures in autumn.

Fig. 3 and 4 show the typical urban thermal logs from the 2016 survey and their evolution in time. The 4 monitoring points (green dots in Fig. 2) were grouped in 3 sites: PZC1 and PZE6 (Site 1), are in the same site, a former illegal landfill; PZ3 A is in Turin city neighbourhood with early urbanization (Site 2); PZ34 is located in an industrial waste landfill (Site 3). Site 1 and 3 have less dense urbanization. The strongest vertical variability is evident in the wells of Site 1 with shallow water table depth, whereas in Site 2 and 3 the groundwater temperatures are approximately constant in depth because the water table is below 20 m b.g.l., where the seasonal effects are supposed not to influence the groundwater temperatures. The huge differences between PZC1 and PZE6 of Site 1 are mainly due to the position with respect to the landfill (PZC1 is downstream, PZE6 is upstream) and, secondarily, to the land use: PZC1 is drilled few centimetres far from an asphalted road, while PZE6 is some meters far from an unpaved road and around 10 m far from buildings. Overall, groundwater in PZC1 is overheated by the heat transported from the polluted sector, where exothermic reactions of organic matter degradation likely occur (the site has methane burners), and by the asphalted road that, according to previous studies (i.e. Taylor & Stefan, 2009), can increment the temperatures up to 3 to 4 °C.

CONCLUSIONS

The climatic component has a major influence on the shallow aquifer temperatures in Turin area, creating vertical temperature heterogeneities up to 10 m depth. Seasonal thermal variations are more effectively damped as long as the vadose zone is thicker. Other factors play an important role at regional level, such as recharge conditions and altitude of infiltration waters: the high plain sector has colder waters, compared to the low plain sectors. Anthropogenic heat sources were also recognized: a diffuse temperature increase below the Turin city was indeed detected that ranges between 0.6 and 1.6 °C season-wise. At the same time, warmer outliers linked to local heat
sources (polluted sites, industrial districts, geothermal systems) and/or site-specific conditions were also detected. For instance, S/or Turin a contaminated site constitutes an interesting case study of pollution-driven groundwater warming. Other outliers need further surveys for better comprehension of the measured temperature values.

Concerning the geothermal applications, the groundwater temperatures of shallow aquifer can be assumed as relatively constant throughout the year if compared with the wider seasonal air oscillation recorded in a medium temperature climatic of continental Europe. The thermal features of shallow aquifer, combined with the high productivity and the legal protection of deeper aquifers, contributes to create favourable conditions for the large-scale diffusion of groundwater-coupled heat pumps (GWHPs).

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REFERENCES


Water-budget as a tool to evaluate the sustainable use of groundwater resources (Isonzo Plain, NE Italy)

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INTRODUCTION

Most of the liquid freshwater resources are stored as groundwater (99%) (Bäumle & Siemon, 2017). Their regional distribution on earth is dependent on climatic conditions as well as the geology of the subsurface. Detailed knowledge of groundwater resources enables its sustainable use. In this framework, the awareness of the regional distribution of resources, the hydraulic characteristics of the aquifers as well as the regional and temporal variations of the water quantity results are fundamental in order to evaluate the amount of the resource.

As de Vries & Simmers (2002) report, in the mid-1980s, groundwater-recharge studies exploded in number. There were few studies dealing explicitly with groundwater recharge as a component of the water balance. But even if water is a circulating, naturally recharged resource, the climate system puts an upper limit on the circulation rate of available Renewable Fresh Water Resources (RFWR).

Although actual world global withdrawals are below the upper limit, many people live in highly water-stressed areas because of the uneven distribution of RFWR in time and space (Corbatto et al., 2016). As reported by Oki & Kanae (2006), climate change is expected to accelerate water cycles. This means that there will be a change in seasonal patterns and a continuous increase in extreme events as testified also by the data collected and analysed by Calligaris et al. (2016) for the study area.

Whether the concept expressed by Oki & Kanae (2006) is right or wrong, a detailed study of the territories in which we live represents a preliminary insight leading to a broader knowledge, understood as a first step to the conscious use of the groundwater resource.

The Friuli Venezia Giulia Region (NE Italy) is a small territory (7,845 km²) where surface fresh waters, springs and groundwaters are abundant (fig.1) and the area is reported as the rainiest in Italy. The waters are an important natural wealth in terms of quantity, quality and ease of supply. This optimal condition, however, is thought to allow for irrational and poorly controlled exploitation. This inevitably produced tangible consequences on the water resources availability. In the last twenty years, a lowering in the phreatic groundwater levels of the High Plain and a lowering of pressure in the confined aquifers of the Low Plain has been noted (Cucchi et al., 1999; Martelli & Granati, 2010; Bezzi et al., 2016; Calligaris et al., 2016). These phenomena are accompanied by the gradual amplitude range reduction of the spring belt (Vella, 2013), resulting in a decrease of the amount of available water to the naturalness of the lowlands, in an impact on ecosystems and related loss of traditional habitats such as wet meadows.

Unless appropriate measures are taken at a regional level, the intense human pressure will probably cause the persistence or the increase of the previously described phenomena.

The recharge, the natural runoff and groundwater exploitation rates have also to be known in light of a sustainable groundwater management.
GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The Soča/Isonzo Plain is located in the north-eastern corner of Italy, on the eastern side of the Friuli Venezia Giulia Region bordering Slovenia (Fig. 1).

The karst spring of the Soča/Isonzo River originates under the glaciated Julian Alps in Slovenia. The river crosses the Italian border after a path of about 100 km, flowing into the Adriatic Sea. It is the second largest river of the region. Its average annual discharge, measured at the entrance in Italy (Solkan gauging station, SLO) was estimated to be 90 m$^3$/s (Bat et al., 2008; Siché & Arnaud-Fassetta, 2014), the average discharge at the river mouth is estimated to be about 170 m$^3$/s.

The plain area, subject of the present study, is the result of a significant sediment transport which occurred during the Quaternary. It is enough to consider the period after the Würmian glacial age when from the frontal side of the alpine glacier, the glacial outlets flowed, modifying the environment and building up the actual morphology (Venturini, 2003). The Soča/Isonzo River modified its flow path. During the Roman age it flowed bordering the Karst hydrostructure near the small town of Ronchi dei Legionari. During the Middle Ages, that river branch was abandoned and the river moved to its current location (Venturini, 2003).

Quaternary deposits forming the plain are characterised by a variable thickness: from 100 m in a depression sited S of Gorizia, up to 350 m in the Villesse area (Treu et al., 2017). The thickness gradually decreases towards the NE at the border with Slovenia where it is between 20 - 30 m (Zini et al., 2011).

These deposits are characterised by the presence of an extensive alluvial unconfined aquifer, which evolves southward into a multi-layered confined/semiconfined aquifer. The aquifers greatly differ from a textural viewpoint: the northern part of the plain, the so-called High Plain (fig.1, in yellow), is more gravelly, while the Low Plain (Fig. 1, in red) in the southern part, mainly consists of finer deposits sizing from gravel to sand and silty-sand. From the ground level to the pre-Quaternary bedrock, six aquifer systems are recognised and referred to using a letter of the alphabet.

Aquifer A, generally positioned between 10 m and 40 m b.s.l., is widely present in the Low Plain and is characterised...
by permeable layers from sandy to sandy-gravelly deposits. Their total thickness is around 30 m.

Aquifer B is a permeable gravelly and sandy layer, fairly constant with the top at about 70/80 m b.s.l. with an average thickness of 15 m.

Aquifer C can be identified at depths of around 110 m b.s.l. and consists of mainly sandy permeable layers with an average thickness of 15 m.

Aquifer D is made up of a set of thin layers (sandy-gravelly deposits). The top of this system stands at about 140 b.s.l., with an average thickness of about 10 m.

Aquifer E is an interval consisting of clean and coarse gravel in the northern part shifting into gravel with sand and silt to the south with a thickness of only few meters. It is not always continuous with a top identifiable at approximately 180 m b.s.l.

Aquifer F is made up of a set of different permeable complex levels of gravelly-sand deposits. The top of this system is present at 190 m b.s.l. The average thickness is about 15 m.

In the Low Plain a shallow and not continuous phreatic aquifer is also present.

Slovene waters flowing in the Soča/Isonzo mountain basin recharge the river. Prior to its course reaching the Italian border its flow is intercepted by the Solkan dam. Once in Italy, the Soča/Isonzo waters contribute to the aquifer recharge which, in turn, also partially contribute to the recharge of the Classical Karst hydrostructure with about 10 m³/s (Zini et al., 2013a).

Aquifer G is made up of a set of thin coarse gravelly deposits. The top of this aquifer is present at about 100 m b.s.l. (approximately 15 m).

Aquifer H is a set of complex levels of gravelly-sand deposits. The top of this aquifer stands at about 70/80 m b.s.l. with an average thickness of about 15 m.

The orography of the study area is extremely favourable for the computation of the water budget. Noteworthy, the recharge of the High Plain aquifers comes from the infiltration of the rainfall and snowmelt. The discharge of groundwater is highly variable due to the water supply systems for drinking purposes. These numbers are linked to the good quality waters present in these aquifers and to the withdrawals due to the water supply systems for drinking purposes.

The well withdrawal amounts were evaluated based on the number of declared wells and the number of people supplied (ISTAT, 2001), while the "licenced withdrawals", instead subjected to a required license for withdrawing. The domestic withdrawals were estimated based on the real water consumption recorded via counter meters.

The well withdrawal amounts were evaluated on an annual basis and are expressed as m³/s. The withdrawal quantity is calculated for the year 2016 (which is considered to be a mean year).

In the High Plain, considering the use of 290 l/d for a single person, there is a withdrawal of 0.01 m³/s for domestic use from the phreatic aquifer. The total licensed withdrawal amount was calculated to be 0.70 m³/s with a prevalence for the use of drinking water (42%) industrial uses (34%) and the agricultural requirements (8%) (tab. 1). In the Low Plain, downstream from the spring belt, most part of the withdrawals are related to a shallow aquifer system (A+B) with a withdrawal volume of about 2.60 m³/s (1.11 m³/s licensed and 1.49 m³/s domestic) mainly due to domestic (57%) and drinking (29%) uses over the others.

In the Aquifer C system, the domestic withdrawals are few, only 0.02 m³/s, 6% of the total amount in that aquifer system compared to that for drinking water (which reaches 0.49 m³/s, the 94%). Increasing the depth, the situation is similar, from D to F. In these deep aquifers, 81% of the waters are used for drinking, and the rest is used for other purposes. These numbers are linked to the good quality waters present in these aquifers and to the withdrawals due to the water supply systems for drinking purposes.

The considerable water withdrawals and the rapid deterioration of the groundwaters have highlighted the necessity for an assessment of its sustainable consumption and future use. In order to complete this assessment, hydrogeological balance can be considered a useful tool in the evaluation of the available resources.

The table below shows the withdrawals in m³/s calculated for the phreatic and confined aquifers of the High and Low Plain.

<table>
<thead>
<tr>
<th>Aquifer Type</th>
<th>Licensed withdrawals [m³/s]</th>
<th>Domestic withdrawals [m³/s]</th>
<th>TOTAL [m³/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Plain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phreatic aquifer</td>
<td>0.70</td>
<td>0.01</td>
<td>0.71</td>
</tr>
<tr>
<td>Confined A+B</td>
<td>1.11</td>
<td>1.49</td>
<td>3.59</td>
</tr>
<tr>
<td>Confined C</td>
<td>0.49</td>
<td>0.02</td>
<td>0.51</td>
</tr>
<tr>
<td>Low Plain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phreatic aquifer</td>
<td>0.16</td>
<td>0.00</td>
<td>0.16</td>
</tr>
<tr>
<td>Confined A+B</td>
<td>1.11</td>
<td>1.49</td>
<td>3.59</td>
</tr>
<tr>
<td>Confined C</td>
<td>0.49</td>
<td>0.02</td>
<td>0.51</td>
</tr>
<tr>
<td>Deep aquifers</td>
<td>0.72</td>
<td>0.12</td>
<td>0.84</td>
</tr>
</tbody>
</table>

The equation: \( P = ET + R + I \) on a 500 m regular grid.

The terms of the equation are respectively:

- \( P \): which represents the precipitation;
- \( ET \): which is the crop evapotranspiration;
- \( R \): being the run-off;
- \( I \): which is the effective infiltration.
To compute the budget, well withdrawals in the phreatic and confined aquifers must be subtracted.

In the budget computation, the precipitation amount (P) was summarised using the daily rainfall data; the process of snow accumulation and snow melting was taken into account.

The evapotranspiration (ET) was quantified as "crop evapotranspiration" and calculated using the two step approach as a product between reference evapotranspiration, calculated using a modified Hargreaves-Samani formula (Hargreaves, 1994; Allen et al., 1998; Carobin, 2008) and crop coefficient (Kc). The formula was chosen according to the results obtained by Carobin (2008) which modified the Hergaves-Samani formula to obtain results similar to that of the Penman-Monteith FAO-56 formula. The Hergaves-Samani was site-specific calibrated to reduce overestimation.

The run-off component (R) was calculated using the curve number methodology modified by Kannan et al. (2008) for continuous analysis.

The effective infiltration was calculated subtracting from P, R and ET seeing that the data regarding the soil characteristics were not always available and homogeneously distributed over the territory. We assumed I=0 in case of negative values.

**RESULTS**

For the Judrio and Versa rivers, the mountain basin discharge was calculated to be 7.6 m³/s taking into consideration the run-off and the effective infiltration. During the wet months, 90% of the discharge infiltrates, while during the dry season all the waters infiltrate and the riverbed is dry. For this reason, the infiltration was calculated on a monthly basis and then summed obtaining a value of 7.4 m³/s.

For the Soča/Isonzo River basin, run-off (R) and infiltration (I) not being available, we used the total river discharge. For the reconstruction of the discharges and leakages we used data coming from several hydrological and hydrogeological surveys carried out in the framework of the ITA-SLO 2007-2013 Camis Project (A.A.V.V., 2015). The main difficulties in measuring the discharge were due to the hydropicking at the Solkan dam (SLO), which seldom allows for discharge measurement in stationary conditions. The subsequent elaboration of the H/Q rating curve had to take into account the changing discharge effect (with the same hydrometric stage, the river can show different discharges) and the derivations for agricultural purposes.

These effects were overcome thanks to the huge amount of measurements made and a multi-section approach (4 discharge sections along 14 km of river flow):

- different single measurements (not contemporary through different sections) were done in different hydrologic conditions (about 40 measures per section);
- continuous discharge measurements (1 discharge measure every 30 minutes for a 4-5 hour hydropeaking cycle) during hydropeaking were carried for entire loading/unloading cycles and for different cycles. According to the river base flow, the cycle generally starts at discharges of 30-40 m³/s (base flow) up to 120-140 m³/s (peak discharge);
- during the stationary phases, contemporary discharge measurements (1 measure per section every hour; for 5-6 hours) were carried out in correspondence of cross-sections spaced 5 to 10 km apart.

The result was the evaluation of a mean daily discharge river for the 2014-2016 period. The mean annual discharge was found to be 141 m³/s for the 2014, 55 m³/s during 2015 and 101 m³/s in 2016. The differences in the resulted river discharges are in agreement with the differences in the precipitation regime recorded in the mountain basin during the study period.

The reliability of the discharge measures corresponds to the 5% of the measured discharge (referred to a single measure which is the mean of 4 values), which is due to the limit of the instrument and to the measurement and validation approach.

The river leakages were also defined thanks to:

- contemporary flow rate measurements in different but close river sections (2-3 km away one from each other);
- the drilling of 6 piezometers in 2 different backswamps of the flood plain where the water level, temperature and electrical conductivity were measured continuously.

The natural variations of these parameters, jointly with the grain size analyses and the geophysical investigations, allowed for the estimation of the quantities of the Soča/Isonzo leakages as 0.2 m³/s/km during low flow conditions up to 1.6 m³/s/km during high flow conditions (Casagrande & Avon, 2016).

The approach with discharge measurements on close sections and the computation of the average monthly discharge rate at the sections, confirmed the magnitude of the leakages which corresponds to the estimation of 15% of the annual discharge measured at Gorizia.

For the Vipacco River, as for the Soča/Isonzo, the available discharges measured at Miren, close to the ITA-SLO border, were used in order to estimate the value of the leakages which were considered to be 10% of the measured discharge.

For the Torre River, discharge values were available in the regional archives (Regione Autonoma Friuli Venezia Giulia, 2012) and an infiltration value was calculated to be 1.3 m³/s.

For the High Plain area, the effective infiltration (I) was 3.6 m³/s, to which the contribution of the irrigation return flow (0.5 m³/s) was added.

In order to compute the groundwater balance from all the input which contributes to the High Plain it is necessary to subtract the waters which contribute to the recharge of the karst hydrostructure valued at 10.0 m³/s. The number corresponds to the discharge measured at the Timavo springs area in low flow conditions (after a very dry period) when it has been demonstrated (Doctor, 2008; Zini et al., 2013b) that the drained waters are mainly due to the leakage from the Soča/Isonzo River which, in turn, recharges the western part of the Classical Karst.

In the High Plain area, it is necessary to subtract the component due to the discharge in correspondence with the spring belt, estimated at around 16.0 m³/s (Zini et al., 2011).

Only a modest amount of water remains (3.4 m³/s) to recharge the systems of aquifers of the Low Plain once all the withdrawals have been subtracted. To this volume, we
added the contribution to the recharge coming from the karst aquifer (estimated at about 1.0 m³/s), proven by the presence of springs bordering the karst hydrostructure in contact with the alluvial plain (in the Ronchi dei Legionari area). When these numbers are applied the balance is positive, with a value of 0.5 m³/s (Fig. 2).

**CONCLUSIONS**

The proof of the sustainable use of the resource derives from the congruity between recharge and withdrawals, whereas discharge measured in correspondence with the spring belt is an indirect indicator of the balance of the system. Its decrease could dramatically compromise these delicate wet ecosystems with an irreparable loss of the present environment.

At the current state of knowledge of the study site, it is possible to assert that the groundwater budget indicates that the balance is fragile. The calculated values are the expression of detailed work carried out over years in order to reduce uncertainties (Zini et al., 2011; Cuccchi et al., 2015). The discharge values measured have an accuracy of +/−5%, due to the methodological approach, the validation of the measures and the limits of the instruments used. The uncertainty of the input received from the karst is mainly due to two factors: the discharge estimation (Gemiti, 1984; Casagrande, 2015) and the current lack of knowledge regarding the submerged springs discharge which has been well estimated (Gemiti, 1984; Gemiti 1995) but never measured. These considerations adduce to a +/−5-10% of uncertainty to add to the final water balance which means that in a world where climate change is a reality with periods of very dry seasons which alternate with extremely wet periods, the priority is to continue to measure all the factors which contribute to the balance in order to guarantee the sustainable use of the water resource for present and future generations.

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Electrical Conductivity as a tool to evaluate the various recharges of a Karst aquifer

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ABSTRACT

One of the challenges in karst hydrogeology has always been the necessity to identify the various contributions to groundwater recharge in order to evaluate and protect water resources. Over the centuries, several different techniques have been used such as the chemical analysis of major ions, isotope analyses, dye-tracing and trace element analyses. Electrical Conductivity, which is easy to collect and inexpensive to carry out, can also be used to discriminate between the different contributions of recharge, if the only meaningful differences in the ion composition is due to the concentration of calcium bicarbonate. In the Classical Karst Region (NE Italy-SW Slovenia), researchers focussed on this parameter in order to distinguish between the allogenic and autogenic contributions in the chosen sampling points under various hydrogeological conditions.

KEY WORDS: karst, hydrogeology, electrical conductivity, Classical Karst Region Soča/Isonzo River, Italy.

INTRODUCTION

The human race, as all the other living being, need the freshwaters to survive. In a karst environment, like the Classical Karst Region (NE Italy-SW Slovenia), it is almost impossible to find surface waters. The surface hydrography is usually absent, the waters swallow and flow in the depth of the karstified hydrostructure remaining stored representing an important source of drinking fresh water. Only few are the water-points, mainly identified as springs where people could benefit in the past and still continue to benefit now of the fresh drinking waters (Cucchi et al., 2015).

Over the centuries, several techniques have been used to investigate the karst groundwaters trying to identify the unknown paths, the hydrodynamics and the geochemical characteristics of the waters. Dye-tracing is a worldwide used technique to pinpoint the water flow direction (Mull, 1993; Ford & Williams, 2007; Gabrovšek et al., 2010). In the Classical Karst Region, Sella (Boegan, 1938; Galli, 2012), in the 1927, used marked eels in order to identify the secret paths of the Reka/Timavo aquifer system. Nowadays modern techniques are applied and coloured dye-tracing as the uranine or the rhodamine-B are used (Smart, 1988). To assess the origin of the waters, chemical and geochemical analyses can be used efficiently. The major ions analysis allow identifying the chemical facies, while the environmental isotopes (δ18O, δD, 86Sr/87Sr,...) permit to discriminate the origin of the mixing waters in case of more and highly differentiated water sources (Cartwright et al., 2010; Calligaris et al., 2018).

Electrical Conductivity, which is easy to collect and inexpensive to carry out, can also be used to discriminate between the different contributions to recharge (Kalbus et al., 2006). This can be done only in case of meaningful differences in the ion composition which is due to the concentration of calcium bicarbonate. The EC role in the data analysis is important also because the groundwater contributions are usually different according to the analysed groundwater regime (high flow or low flow conditions) and the differences in the EC values can be easily recorded also with in continuous devices. The chemograph analysis is one of the technique allowing to analyse the groundwater flow behaviour within the hydrostructure.

Thanks to the experience gained over the last decade and thanks to the help received by some Italian speleological groups (G.S. Amici del Fante and G.S. Talpe del Carso, Adriatica di Speleologia - SAS), a monitoring campaign regarding caves, piezometers and springs took place over the last years.

The data collected and analysed allowed to better understand the hydrodynamic of the area where the connections at a small scale are quite clear, but at a large scale are still clouded despite the 200 years of carried out investigations.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The study area, is a carbonate plateau approximately 750 km2 wide and about 2000 m thick, characterized by limestone, dolomitic limestone and dolostone, aged between the Cretaceous and Paleogene. Structurally the Classical Karst Region is an asymmetrical anticline NW–SE oriented whose structure is complicated by a set of secondary folds and faults (Jurkovšek et al., 2016).
Along the coastal areas, the layers become subvertical and sometimes overturned. At the border, N and S of the anticline, outcrops the Eocene Flysch which represents the aquiclude of the karst aquifer.

It is a mature karst (Ford & Williams, 2007) witnessed by the density of karst features as caves and dolines, calculated to be up to 130 cave /km\(^2\) with an average value of 15 cave /km\(^2\) and 22.5 dolines /km\(^2\) with peaks of 130 dolines /km\(^2\) (Zini et al., 2015).

This intense karstification, jointly with the scarce presence of surface deposits, favours a fast drainage of precipitations to the aquifer. The latter is replenished also by the leakages of two rivers present in the area (Reka/Timavo and Soča/Isonzo, Calligaris et al., 2019) (Fig. 1).

At the extreme South-East of the karst plateau, the Reka River flows for approximately 50 km over a Flysch basin. Once reached the carbonates, it is completely swallowed, disappearing into the Vreme and Škocjan swallow holes with an average discharge of 8.6 m\(^3\)/s. On the western side of the study area, the Soča/Isonzo River (with its source in the Slovenian Julian Alps), has an influent character toward the alluvial plain which in turn recharges the Classical Karst hydrostructure with about 10 m\(^3\)/s (Zini et al., 2013; Calligaris et al., 2016). The third contribution is due to the effective infiltration estimated at 21 m\(^3\)/s (Civita et al., 1995). This autogetic recharge has a specific geochemical signature and in the past has been defined by Gemiti in 1994 and later by Doctor in 2008 as karst waters.

The three inputs outflow into a wide spring area which extends for about 9 km, from Monfalcone (to the W) to Aurisina spring (to the East), consisting of more than 50 spring points having a total discharge of about 35 m\(^3\)/s (Gemiti, 1984; Zini et al., 2013).

The main spring is the Timavo with an average discharge of 29.3 m\(^3\)/s. Moving west worth, Sardos spring has a mean value of 1.9 m\(^3\)/s. To these main springs have to be added other smaller ones as Moschenizze with a discharge of 0.5 m\(^3\)/s, Pietrarossa and Sablici 1.2 m\(^3\)/s (Gemiti et al., 1984). Along the cost, several small springs are present. Among them there is Aurisina which has an average estimated discharge of 0.4 m\(^3\)/s.

The present paper focussed to the western part of the Classical Karst Region, the one South of Gorizia town which has been less investigated with respect to the eastern area.

Fig. 1 - Study area overview, lithological setting and sampled points. In green the Classical Karst Region. The sampled points are: Soča/Isonzo River (Is); Castelnuovo cave (Cast); Doberdo Lake (Dob); Pietrarossa Lake (Pet); Cavernetta di Comari (Com); Abisso Samar (Sam); Abisso di Trebiciano (Tre); Sablici (Sab); Sardos (Sar); Moschenizze N (MoN); Timavo (Tim); Aurisina (Aur) and Škocjan caves (Sko). Friuli Venezia Giulia Region (FVG in the map) is the northeastern Italian region bordering Slovenia.
MATERIALS AND METHODS

Within June 2015 and November 2016, 78 field surveys were realised usually done the end of drought periods or just after important stormy events. Water samples were collected in correspondence of surface waters (Soča/Isonzo River), springs, caves, wells and piezometers.

To measure the EC, a portable instrument manufactured by WTW was used, which had an accuracy of 0.1 μS/cm and a resolution of ±0.5 °C (between 0-15 °C) and ±0.1 °C (between 15-35 °C).

Some of the collected samples were chemically analysed by the HERAtech S.r.l. laboratory which for major ions used the ion chromatography (940 Professional IC Vario by Metrohm with the IC-NET software) with a precision less than ± 10 % and detection limit of 0.1 mg/L for Cl, SO\textsubscript{4}\textsuperscript{2-}, PO\textsubscript{4}\textsuperscript{3-} and NO\textsubscript{3}-. For Na\textsuperscript{+}, K\textsuperscript{+}, Mg\textsuperscript{2+}, Ca\textsuperscript{2+} the detection limit was of 0.5 mg/L. Bicarbonates (HCO\textsubscript{3}) were analysed using the Titrimetry with a sensitivity of 1 mg/L.

In some specific points, CTD-diver datalogger devices constantly recorded (sampling rate of 30 min) water level (WL), temperature (T) and Electrical Conductivity (EC) (Fig. 1 and Fig. 3). The divers were installed in different hydrogeological contexts as in caves (Abisso Samar, Castelvecchio, Cavernetta di Comarie), lake (Doberdò) and the main springs (Sardos, Moschenizze Nord and Timavo).

The instruments measured the water level ranges with an accuracy of ±0.05 % and a resolution of 0.02% of the measured value. Temperatures were recorded in the range between -20 and 80 °C with an accuracy of ±0.1 °C and a resolution of 0.01 °C. For the EC, the measured range is 0-120 μS/cm with an accuracy of ±1 % and a resolution of 0.1 μS/cm.

RESULTS AND DISCUSSION

From the chemical viewpoint, the Soča/Isonzo waters are characterised by a lower content in calcium bicarbonate and a higher content in magnesium than the karst waters. In fact, from the analyses, emerge that Soča/Isonzo waters have an average value of 42 mg/l of Ca\textsuperscript{2+} and 9 mg/l of Mg\textsuperscript{2+}. Karst waters instead are characterised by mean values of 90 mg/l of Ca\textsuperscript{2+} e 5 mg/l of Mg\textsuperscript{2+}. For all other ions, there are not meaningful differences between the two kind of waters.

As calcium bicarbonate forms more than 90% of the dissolved salts in the karst waters and about 80% of the Soča/Isonzo waters, the EC measured at 20°C (K20) represents a simple and fast method allowing to follow the mixing process of the two waters along their paths to the springs.

Soča/Isonzo waters are characterised by an average Electrical Conductivity (EC) value of 240 μS/cm.

Karst waters are well represented by the average chemical-physical values recorded in the piezometers which are widespread into the Classical Karst Region. Moreover these waters can be sampled at Trebiciano cave and Aurisina cave, but only during extremely low flow conditions when the discharge of the Reka River at the Škocjan cave is only few l/s.

With these specifications, to karst waters we assigned an EC value of 470 μS/cm. The range of variability for the two waters do not exceed 10% of the average value.

From the hydrodynamic viewpoint (Fig. 3), witnessed by the several studies realised in the area as Boegan (1938), Galli (2012) and Cucchi et al. (2015) and all the references included, it emerged that in the whole eastern sector; from Aurisina to Timavo springs, groundwaters are influenced by the floods of the Reka River. The latter has a mean value of 310 μS/cm, which, during floods, could decrease to 200 μS/cm.

The western sector of the Classical Karst instead, is not influenced by the Reka River but only by Soča/Isonzo and karst waters (Fig. 2).
Focusing only on the western sector of the Classical Karst Region, the Soča/Isonzo contribution is highlighted thanks to the EC and T lower values. Moving east worth, from Soča/Isonzo to the springs, there is an increase in the absolute EC and in the T values indicating the always more important influence of the karst waters.

During drought, decreasing the effective infiltrations, the contribution due to the karst waters decrease with a prevailing influence of the Soča/Isonzo waters (lower EC values).

During floods, the above mentioned effect is the opposite with a higher influence of the karst waters (higher EC values).

**CONCLUSIONS**

The large amount of chemical and hydro-chemical data collected in the surface waters and groundwater in the western part of the Classical Karst Region south of Gorizia, allowed to evaluate, quantitatively, the main contributions to the recharge. From the analyses emerges that only two are the contributions:

1) the karst waters;
2) the Soča/Isonzo waters, in other words, the leakages of the Soča/Isonzo River which recharge the porous aquifer which in turn recharge the karst hydrostructure.

Given the EC value of the Soča/Isonzo waters and the EC value of the karst waters, it is possible, in different hydrodynamical regimes, to define their contributions to each water point (tab. 1).

During low flow, the contribution due to the Soča/ Isonzo waters is prevailing: in all the monitored water points, in fact it reaches more than 75% (tab. 1).

During high flow, the contribution due to the karst waters is higher and the Soča/Isonzo one decreases up to 40-45% (tab. 1).

**TABLE 1**

<table>
<thead>
<tr>
<th>ID</th>
<th>Low flow</th>
<th>Average flow</th>
<th>High flow</th>
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</thead>
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<tr>
<td>EC</td>
<td>% Isonzo</td>
<td>EC</td>
<td>% Isonzo</td>
</tr>
<tr>
<td>Dob</td>
<td>288</td>
<td>79</td>
<td>308</td>
</tr>
<tr>
<td>Pet</td>
<td>300</td>
<td>74</td>
<td>333</td>
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<tr>
<td>Sab</td>
<td>298</td>
<td>75</td>
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</tr>
<tr>
<td>Com</td>
<td>292</td>
<td>77</td>
<td>310</td>
</tr>
<tr>
<td>MoN</td>
<td>289</td>
<td>79</td>
<td>307</td>
</tr>
</tbody>
</table>
Examining extreme events, like the one occurred in the middle of October, 2015, the situation is emphasised. During that heavy rainfall, the precipitations were concentrated only on the western part of the Classical Karst Region with more than 100 mm of cumulated rain, while in the rest of the catchment, one third of rain fell. This took to a prevailing influence of the karst waters at the spring areas as it happened at Doberdò with EC values of 467 µS/cm (30% Soča/Isonzo waters), at Pietrarossa with 422 µS/cm (21% Soča/Isonzo waters) and at Sablici and Moschenizze Nord with 414 µS/cm (24% Soča/Isonzo waters). At the Comarie cave, during the same rainy event, were recorded EC values of 467 µS/cm highlighting only the presence of karst waters.

The research carried out highlighted the importance of the EC as an easy applicable and low cost tool in the analyses of the contribution to the water recharge in the Classical Karst Region. The handiness of data acquisition and the consequent possibility to quickly collect a huge amount of data in a wide area and in different hydrogeological conditions, keep the EC a performing analysis in the knowledge and in the consequent protection of a karst aquifer.

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Hydrogeological and hydrogeochemical monitoring in the Cumae archaeological site (Phlegraean Fields, southern Italy)

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ABSTRACT

The Cumae archaeological site is extended along the Tyrrhenian coast of the Campania region (southern Italy), in the western sector of the Phlegraean Fields active volcanic field. It is the first Greek colony in mainland Italy, which was founded in the 8th century B.C., and occupied continuously until the 12th century A.D. A hydrogeological and hydrogeochemical monitoring from December 2013 to February 2015 on 13 wells (6 shallow wells and 7 deep wells), joined with 222Rn measurements in groundwater have been carried out, with a monthly frequency. The study was motivated by the frequent flooding of archaeological excavations due to the rise of groundwater level, which threatens the integrity of ancient Roman ruins and prevents the continuation of archaeological researches. Therefore, reconstructing a comprehensive hydrogeological model of the archaeological site was considered an important goal to achieve for designing mitigation measures. Hydrostratigraphic and hydrogeological data allowed recognizing a multi-layered volcanic-sedimentary aquifer system, formed by shallow unconfined and deep semi-confined aquifers. The groundwater flow was assessed being strongly controlled by vertical and lateral lithological heterogeneities of volcanic-sedimentary deposits, as well as by groundwater pumping and drainage channel system.

The dominant hydrochemical facies were CI-NO3NaK, HCO3CaMg and HCO3NaK types, which were found spatially and temporally variable due to: i) localised rise of deep and highly mineralized fluids through faults and fractured zones of the western edge of Campanian Ignimbrite caldera boundaries, as indicated by outstanding levels of F- and 222Rn; ii) freshwater-saltwater interactions, induced by groundwater exploitation.

KEY WORDS: Conceptual hydrogeological model, hydrogeochemistry, groundwater flooding, buried monuments, Cumae archaeological site, southern Italy.

INTRODUCTION

The deterioration of in situ archaeological deposits (Holden et al., 2006) can be enhanced by environmental and hydrogeological changes, caused by climate or land use changes. Monitoring hydrological and hydrochemical processes and understanding hydro-environmental systems represent a crucial prerequisite for the in situ preservation of archaeological remains (Holden et al., 2006; de Beer and Matthiesen, 2008).

The ancient city of Cumae was the first Greek colony, named Kyme, which was founded in the mainland of southern Italy along the Tyrrhenian coast (Fig. 1a) in the 730 B.C., and occupied continuously until the 1207 A.D. (Boardman, 1995). Currently the Cumae site is an important archaeological park, among the most important and visited of the southern Italy, which is included in the Phlegraean Fields Regional Park. The park includes a number of artefact, cultural remains and ancient monuments, dating back to the Greek, Roman, and Byzantine epochs. Along the northwestern side of the city wall (Fig. 1c), is located the Monumental Roman Necropolis, a small sub-flat area used as burial environment in Roman period (Munzi and Brun, 2011).

In the last years, the rising of groundwater up to +1.20 m above the base of archaeological remains (Fig. 2) determined a sharp slowdown of archaeological researches and the reburial of several sepulchral chambers to prevent damage to structural and decorative elements. The rising of groundwater levels has been observed and studied in other coastal plains of the southern Italy (Allocca and Celico, 2008; Allocca et al., 2016) and archaeological sites of the Mediterranean region (Abdallah and Abd El-Tawab, 2013).

The main objectives of the study were to characterize the coastal volcanic-sedimentary aquifer system, determine the physical-chemical properties of the groundwater of Cumae site, and assess processes that control groundwater geochemistry and its spatio-temporal evolution. A special attention was given to understanding effects of groundwater exploitation, salt-water intrusion (Bucci et al., 2011) and the upwelling of highly mineralized deep fluids.

The study was carried out through a multidisciplinary approach by hydrogeological, hydrogeochemical, and isotopic surveys.
STUDY AREA DESCRIPTION

The Cumae archaeological site is extended over about 2.0 km² along the Tyrrenian coast of the Campania region (southern Italy), in the northwestern sector of the Phlegraean Fields active volcanic field (Fig. 1a). The caldera morphology of the volcanic field (Fig. 1b) was originated by the superposition of two main collapse episodes related to two large eruptions occurred during the Pleistocene: the Campanian Ignimbrite (CI) eruption, dated 39 k-years ago. The caldera morphology of the volcanic field (Fig. 1b) was originated by the superposition of two main collapse episodes related to two large eruptions occurred during the Pleistocene: the Campanian Ignimbrite (CI) eruption, dated 39 k-years ago.
B.P. (De Vivo et al., 2001), and the Neapolitan Yellow Tuff (NYT) eruption, dated 15 k-years B.P. (Deino et al., 2004).

In detail, the Cumae site is located along the western edge of CI caldera boundary (Fig. 1a), where several buried normal faults, deep fractures and crater rims (Figs. 1b and 1c) characterize this sector of the Phlegraean Fields (Bravi et al., 2003; Vitale and Isaila, 2014).

The Cumae archaeological site and its surrounding coastal plain are parts of the Phlegraean Fields Regional Park and of the wetlands of the Mount of Cuma’s Forest. During the Holocene period, this area underwent significant palaeogeographical changes due to volcanic activity, eustatic sea-level variations (Bravi et al., 2003), shoreline changes (Stefaniuk et al., 2005), formation of coastal lagoon and palustrine wetlands, bradyseismic movements of the ground and reclamation practices in historical times (since VI-V centuries B.C.).

The study area is characterized by a complex volcanic-sedimentary series formed by sands, silts, and clays of marine and lagoon environment. These deposits are adjoined and interfingered laterally with unconsolidated ash-fall pyroclastic deposits and locally with consolidated yellow tuffs. Currently the morphological features of the studied area are typical of a coastal plain, with altitude ranging from 0 to 15 m a.s.l.

The regional groundwater circulation is globally unitary (Celico et al., 1991; Celico et al., 1992; Allocca et al., 2007), westward oriented, towards the coastline (Fig. 1b). The surface hydrographic setting is characterized by a drainage system of micro-channels, whose altitude is often very close to the sea level or just below it (Fig. 1c).

DATA AND METHODS

A 2D hydrostratigraphic model of the aquifer system was carried out by:

- stratigraphic data of 5 boreholes (B1-B5) and 13 wells (P1-P13) (Fig. 1c);
- vertical logs of the hydraulic conductivity.

In the period December 2013-February 2015, spatio-temporal variations of groundwater table levels and hydrogeochemical features were analyzed by:

- monthly monitoring of groundwater levels and physical and chemical parameters (T, pH, EC, major elements and 222Rn carried out on 13 wells (P1-P13) (Fig. 1c);
- reconstruction of multi-temporal maps of groundwater table levels by the Kriging geostatistical method;
- Hierarchical Cluster Analysis (HCA) of groundwater hydrochemical data.
RESULTS

The study area is characterized by a multi-layered aquifer system (Figs. 3a and 3b), which is formed by a phreatic shallow and a semiconfined deep aquifer, separated by a tufaceous aquitard (YT). The aquitard pinches out seaward and along the coastline a single phreatic shallow aquifer was only recognized (Fig. 3a). The groundwater flow of the phreatic shallow aquifer is northward oriented and controlled by surface drainage channels, showing negligible differences between recharge and recession periods (Figs. 4c and 4d).

Among the principal results obtained by the reconstruction of groundwater contour patterns, a westward oriented groundwater flow was recognized for the semi-confined deep aquifer during the recharge period (Fig. 4a). In the recession period (Fig. 4b), a significant lowering of groundwater levels allowing the seawater intrusion (Fig. 3c) was recognized and ascribed to well pumping.

The dominant hydrochemical facies of were found of ClSO₄NaK, HCO₃CaMg and HCO₃NaK types (Fig. 5), whose spatio-temporal variations (Figs. 5a, 5b and 6), between the recharge and recession phases, appeared being affected by: i) localised rise of deep and highly mineralized fluids, along fault zone of the western edge of CI caldera boundaries (Figs. 1 and 3a). This finding is also supported by high levels in deep groundwater of F (6.4 mg L⁻¹; data not shown), and ²²²Rn (31,500 Bq m⁻³) (Fig. 6); ii) freshwater-saltwater interactions, induced by groundwater exploitation (Figs. 3c and 4b).

The HCA (Fig. 7) allows recognizing clearly three main clusters (A, B and C). Clusters A and C comprise groundwater of deep wells, whereas cluster B, with the exception of the well P7, groups shallow wells. This result is consistent with the conceptual hydrogeological model of the study area.

CONCLUSIONS

This study is a first attempt to reconstruct a conceptual hydrogeological model of the Cumae archaeological site, which is characterized by a complex alluvial-marine-pyroclastic aquifer system and controlled also by seawater intrusion, groundwater exploitation and upwelling of deep mineralized fluids.

Fig. 4 - Local groundwater flow of the deep semi-confined aquifer (a and b) and of the shallow phreatic aquifer (c and d) in February 2014 (a and c) and July 2014 (b and d).
1) Deep well; 2) Shallow well; 3) Groundwater levels measured in shallow wells P2 (February 2014: +1.76 m a.s.l.; July 2014: +1.34 m a.s.l.) and P11 (February 2014: +3.37 m a.s.l.; July 2014: +3.21 m a.s.l.); 4) Groundwater contour line (m a.s.l.); 5) Groundwater flow line; 6) CI caldera boundary; 7) Normal fault; 8) Drainage channel; 9) Waste water channel; 10) Archaeological site; 11) Box of the figures 1c and 1d; 12) Hydrogeological section track of the Figure 3; 13) Study area.
Fig. 5 - Piper diagrams of the groundwater of deep semi-confined (a and b) and shallow phreatic (c and d) aquifers in the February 2014 (a and d) and July 2014 (b and c). SW seawater.

Fig. 6. 222Rn specific activity and EC in deep (a) and shallow (b) wells measured in April 2014 (recharge phase) and July 2014 (recession phase).

Fig. 7 - Output of hierarchical cluster analysis (HCA). Letters indicate clusters or groups.

Results obtained suggest urgent reclamation strategies to mitigate the hazard related to groundwater level rising and impacts on archaeological remains. Therefore, they will help local authorities in adopting effective strategies for the preservation of the archaeological ruins.

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ABSTRACT

In the framework of Life-Ecoremed Project, aimed at the eco-compatible remediation of contaminated soils, the beryllium and tin transfer from soil towards groundwater has been evaluated in an experimental site near the small town of Teverola (Campanian plain, southern Italy). Building a 3D hydrostratigraphic model through interpretation and interpolation of borehole data supported the study; groundwater has been characterized and monitored by means of periodic (almost monthly) piezometric measures, sampling and chemical analyses. In the site, two overlapping aquifers are present and separated by an impervious paleosol. The 3D hydrostratigraphic model supported the development of the groundwater flow model of the shallow aquifer. All chemical data indicate the absence of migration of the contaminants towards the aquifers, also the shallower, in accordance with the characteristics of the aquifers and the low solubility of the contaminants present in the soil.

KEY WORDS: groundwater, contamination, tin, beryllium, Campania.

INTRODUCTION

Pollutants present in soil can move to the underlying aquifer and degrade groundwater quality, especially in the case of unconfined, shallow aquifers. Chemicals in soils are often transferred towards the water table in relation to their solubility, depending on the natural conditions of the environment (e.g. pH of the soil; Zhang et al. 2010). Soil remediation, in turn, can reduce or eliminate this transfer and thus improve groundwater quality.

Life-Ecoremed Project has been aimed at the eco-compatible remediation of contaminated soils by means of Bio - and Phyto-remediation (plantation of plant essences, es.: arundo donax also called giant cane) in experimental sites near the city of Napoli (Campania) (Ducci et al., 2017).

In the framework of this Project, we studied an experimental site, near the small town of Teverola (Fig. 1), covering about 1900 m². The site was severely degraded, as it has been used in the past as an illegal dump (AA.VV., 2017). In this site, beryllium and tin were present in the soil, sometimes with concentrations higher than 2 and 1 mg/kg respectively, more than the threshold concentration of contamination provided by Italian law for residential areas (D. Lgs. 152/06).

To evaluate a possible migration of the contaminant from the soil towards the aquifers, these ions were monitored in groundwater during more than one year. The methodological approach included: a) the definition of the stratigraphy of the area, b) the identification of different aquifers and their hydraulic characteristics, c) the configuration of the groundwater flow and d) the definition of the chemical characteristics of groundwater, with special focus on the areas upstream of the contaminated site.

MATERIALS AND METHODS

The stratigraphic succession of the site has been defined drilling 8 boreholes, 5 of them with continuous core recovery (Fig. 1). A 10 m deep monitoring well was drilled (P1 in Fig. 1) and completed with non-toxic PVC (Ø 15 cm) with a screen length of 3 m (0.5 mm slots).

The P1 well has been equipped with a multi-parametric probe (Seba Hydrometrie Dipper-PTEC) to determine groundwater level (m b.g.l.), temperature (°C), electrical conductivity (µS/cm) and Total Dissolved Solids - TDS (mg/L), with a sampling rate of 1 hour. Data acquired and stored, in the datalogger of the probe, were periodically downloaded for post-processing. In this monitoring well and in the piezometers shown in Fig. 1 we periodically sampled groundwater for analysing major ions and some minor elements; among these beryllium and tin, given the presence of these ions in the soil. Analyses were performed at the Department of Chemical Sciences (University of Naples Federico II). Anions and cations were determined by ion chromatography using a Metrohm 761; trace elements were analysed with IPC-Ms technique; electrical conductivity, pH, alkalinity and temperature were determined in situ (Tab. 1).

Slug-tests were carried out in four piezometers (S1, S1bis, S2 and S4 - Fig. 1) to determine the hydraulic conductivity (K; Tab. 2). The unsteady-state flow pumping test was performed in well P1 during 16 hours. In this time the
discharge was constant (0.95 l/s); depressions in the well P1 and in piezometer S1bis (9 m depth) were continuously monitored with a pressure transducer connected to a datalogger. The results of unsteady-state flow pumping test in the P1 were interpreted using the classical Theis-Jacob method.

Stratigraphic data have been organized in a geodatabase, imported within the software RockWorks16 and interpolated, by means of kriging method, to reconstruct a 3D stratigraphic grid model of the experimental site (Ducci et al., 2012). The kriging method was also used to interpolate the piezometric data in order to build up the piezometric surfaces of the aquifers. The groundwater surfaces were merged into the stratigraphic model to obtain a 3D hydrostratigraphic model. This model supported the definition of the geometry of a groundwater flow model, ie. the extension of the modeled area and of hydrogeological units and their location in space (Anderson & Woessner, 1992), in steady state conditions. The groundwater flow model was developed using the MODFLOW code (Harbaugh, 2005), by means of the Groundwater Vistas 5 programme package (Environmental Simulations Inc.).

The information about stratigraphy, piezometric heads and hydraulic conductivity of the test site was used to model the groundwater flow in the site. The modeled area (252 m x 276 m) is centered on the test site (Fig. 2a).

### Table 1

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The calibration of the model was performed using a multiplier to perturb each parameter: during the calibration of the model, the parameter values are increased by 2% at each iteration and the modelled piezometric heads were compared with the observed ones in target points. The procedure determines also the sensitivity of the calibration in order to changes only the sensitive parameter values. The model was calibrated considering 5 head target points: 4 piezometers and the well that intercept the shallow aquifer (P1, S1bis, S3bis, S4, S5 - Fig. 1). The number of the target points and their spatial distribution on the site area (Fig. 1) are suitable for the site extension and for the purpose of the calibration.

RESULTS

The 3D hydrostratigraphic model has been useful to study the spatial distribution of the stratigraphic units, to draw up the sections (Fig. 3) and to calculate the thickness of the single stratigraphic units. Moreover, it was a valid support in the study of the position and of the relationship between the two aquifers described below, and it has been used as a platform for the development of the groundwater flow model (Ducci et al., 2012). The subsoil consists of some meters of loose pyroclastics, with levels of peat, above a clayey paleosol (Fig. 3); these sediments overlay a tuff (Campanian Ignimbrite), locally unwelded (De Vivo et al., 2001). The silt-clayey and impervious paleosol forms the base of the shallow, phreatic aquifer made of a few meters of loose pyroclastics. At the same time, the paleosol confines groundwater (Fig. 3) contained in the tuff at the bottom. The thickness of the silt-clayey and impervious paleosol is about 2 meters in the northern sector of the site and progressively increases up to 5-6 meters towards south. Therefore, in the site, two overlapping aquifers were identified, with groundwater flowing in a quite different way (Fig. 4). The groundwater flow in the shallow aquifer is from W to E, while groundwater flow in the aquifer below the paleosol is prevalently SW-NE. Both groundwater flows are not influenced by the waters of the Regi Lagni channel that flow from NW-SE to NE of the site (Fig. 1) in a waterproof concrete channel. In the deeper, confined aquifer (piezometers S1, S2 and S3), the groundwater head is about one meter higher than in the shallow aquifer (piezometers S1bis, S3bis, S4, S5), reflecting their separation (Corniello & Ducci, 2014). This difference in groundwater heads, between the shallow and the deeper aquifer, was observed throughout the whole monitoring period in the site (2015-2016; Tab. 1).

The processing of the piezometric data, deriving from the continuous monitoring of the multi-parametric probe, highlighted that the rain has a quick response on groundwater heads. The latter show a maximum oscillation of about one meter. Moreover, TDS values decrease in the period of low rainfall and increase at the first significant rainfall (October 2015). During the winter time, TDS decreases proportionally to decrease of the rainfall (Fig. 5).

Slug - test results and the hydraulic characteristics of the shallow aquifer are synthetized in Table 2.

The boundaries of the model are approximately 100 m far from the boundaries of the site, in order to make the model results unconstrained by the boundary conditions (Harbaugh, 2005). The boundary conditions (Fig. 2a) have been defined according to the hydrogeological study of the area and the piezometric pattern; along the east and west sides of the model, the general head boundary (GHB) conditions have been assigned (Anderson & Woessner, 1992), while along the north and south sides of the model the no-flow conditions have been assigned by default, due to the flow direction of the shallow aquifer. The spatial discretization of the model is a variable mesh: 5 m spacing in areas outside the limits of the site, and 2.5 m spacing inside the limits of the site (Fig. 2a). Vertical discretization was applied only to the shallow aquifer, formed by two layers (Fig. 2b): the first layer (shallow aquifer) composed by loose pyroclastics with peat levels (Pr) and the bottom layer represented by an impervious paleosol (Pals). The hydraulic conductivity of the first layer (Pr) was assigned on the basis of the results of the field measures (slug test and pumping test) described below. The net recharge (R) of 204 mm/y, evaluated on the basis of the last 30 years rainfall and of the hydrogeological characteristics of the area, was applied to the aquifer; other external stresses were not considered.

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The boundaries of the shallow aquifer are synthetized in Table 2.

**TABLE 2**

Slug - test results (Hvorslev method); Cls: Campanian Ignimbrite unwelded; pr: loose pyroclastics material.

The boundaries of the shallow aquifer are synthetized in Table 2.
Fig. 2 - a) Model grid and boundary conditions (GHB: General head Boundary), b) Vertical discretization of the shallow aquifer: loose pyroclastics with peat levels (Pr) and impervious paleosol (Pals).

Fig. 3 - Hydrogeological sections; the location is in Fig. 1; the blue line refers to the piezometric surface of the deeper aquifer, the dotted blue line indicates the water table of the shallow aquifer. Legend: pr: loose pyroclastics material, mainly sandy; pals: silt-clayey paleosol; CIs: low-welded Campanian Ignimbrite.
T (transmissivity): 4.3 x 10^{-3} m²/s; K (hydraulic conductivity): 6.1 x 10^{-4} m/s; S (storage coefficient): 0.02.

The value of this coefficient is quite coherent with the fine granulometry of the aquifer. In the piezometer S1 (drilled in the deeper aquifer and with screen at 13.5 m b.g.l.) no level variation has been recorded during the pumping test. This confirms that the paleosol represents an effective hydraulic separation between the aquifers at the top and at the bottom of the impervious layer. For the impervious layer the hydraulic conductivity was considered equal to 1.0 x 10^{-8} m/s.

The parameter calibrated were hydraulic conductivity (horizontal and vertical ones) of each layer, the net recharge, and the conductivity parameter of the GHB condition. The results of the calibration (Tab. 3) significantly confirms the horizontal hydraulic conductivity of the first layer; while the vertical hydraulic conductivity of the shallow aquifer has been calculated as K=6.0x10^{-6} m/s. Recharge rate is slightly higher than the expected (R=6.8x10^{-9} m/s), corresponding to a recharge of 214 mm/y, but basically confirms that the equilibrium of the phreatic aquifer was not affected by the change in land-use (arundo donax plantation).

According to the hydrogeological setting and to the aim of the study, the monthly sampling was concentrated in the shallow aquifer, more susceptible to any transfers of pollutants from the soil (Tab. 1). Indeed, the boreholes P1, S1bis, S4 and S5 intercepted the water table 2-3 meters below the ground level.

Groundwater sampled in the experimental site, both in the shallow and in the deeper aquifer, are of calcium bicarbonate type (Tab. 1). Major ions in groundwater did not show significant variations throughout the monitoring time, while manganese content, strongly influenced by pH or Eh, presents a random variability.

In the shallow aquifer, fluoride content is almost always above the admissible concentration in drinking water (1.5 mg/L - D. Lgs. 31/2001); fluoride is relatively lower in the deeper aquifer. However, fluoride content is not related to an anthropogenic contamination but to the geological structure of the area, for the natural leaching of the minerals present in the volcanic rocks of the aquifers (Corniello & Ducci, 2014).

In the shallow aquifer, nitrate exceeds the limit of 50 mg/L almost everywhere, except in the piezometer S4 (Fig. 1), where nitrate was consistently below 10 mg/L. In

<table>
<thead>
<tr>
<th>ID</th>
<th>Target Type</th>
<th>Observed m a.s.l.</th>
<th>Computed m a.s.l.</th>
<th>Residual m</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Head</td>
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<td>11.86</td>
<td>-0.089</td>
</tr>
<tr>
<td>S01bis</td>
<td>Head</td>
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<td>11.85</td>
<td>-0.104</td>
</tr>
<tr>
<td>S03bis</td>
<td>Head</td>
<td>12.32</td>
<td>11.91</td>
<td>0.413</td>
</tr>
<tr>
<td>S04</td>
<td>Head</td>
<td>11.72</td>
<td>11.86</td>
<td>-0.138</td>
</tr>
<tr>
<td>S05</td>
<td>Head</td>
<td>11.9</td>
<td>11.9</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Summary Statistics

<table>
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<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of Squared Residuals</td>
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</tr>
<tr>
<td>Residual Mean</td>
<td>0.017</td>
</tr>
<tr>
<td>Absolute Residual Mean</td>
<td>0.149</td>
</tr>
<tr>
<td>Residual Standard Dev.</td>
<td>0.203</td>
</tr>
<tr>
<td>Minimum Residual</td>
<td>-0.138</td>
</tr>
<tr>
<td>Maximum Residual</td>
<td>0.413</td>
</tr>
</tbody>
</table>
the same piezometer S4 the value of sulphate is low, while manganese is higher than elsewhere (Fig. 5). This set of elements is consistent with the presence in this area of a reducing environment (Corniello & Ducci, 2014; AA.VV., 2017).

Beryllium and tin, whose mobility is also connected to the pH of the soil (Razo et al., 2004; Zhang et al., 2010), were detected in soil (see Introduction) and also in all the groundwater samples, but always with concentrations < 1 µg/L, which did not change significantly during the entire monitoring period (Fig. 5).

4. DISCUSSION AND CONCLUSIONS

To evaluate a possible migration of the contaminant from the soil towards the aquifers in an experimental site in southern Italy, we carried out a stratigraphic, hydrogeological and hydrogeochemical study and monitoring. The stratigraphical study clearly indicates the presence of two overlapped aquifers separated by an impervious paleosol.

The groundwater flow model was developed on the basis of the 3D hydro-stratigraphic reconstruction, using
borehole and piezometric data. The calibration of the flow model shows that the shallow aquifer has anisotropic behavior, horizontal permeability is about $K=6.0 \times 10^{-4}$ m/s, while vertical permeability is lower of two orders of magnitude. The net recharge of the aquifer has been calculated at 214 mm/year, almost the same of the average annual value already known in the literature. Therefore, the change in vegetation coverage (made by the phyto-remediation operation) not affected the equilibrium of the shallow aquifer.

The shallow aquifer, with a water tables 2-3 meters below the ground level, is the most prone to contamination. Chemical data indicate undoubtedly the absence of migration of the contaminants present in the soil towards the aquifers, also the shallow one.

Often groundwater below contaminated soils is uncontaminated and complied with the guideline limits, thanks to the effect of diffusion, dispersion, dilution and/or adsorption in the vadose zone, even if the latter is thin (Razo et al., 2004; Wu et al., 2015). In this context, a non-secondary role is played by the low permeability of the materials of the shallow aquifer (Tab. 2). Moreover, the results of this study are in accordance with the low solubility of the beryllium compounds (solubility that increases slightly with higher pH values, Matthess, 1982; Hrkal, 2011) and with very little mobility of the beryllium ions in solution (Hem, 1985). Furthermore, clay minerals can easily adsorb beryllium ions at low pH. All that causes an extremely low concentration of beryllium (highly toxic) in natural waters. Finally, for tin significant concentrations are reported in oil field brines (Matthess, 1982; Hrkal, 2011) and with very little mobility of the beryllium ions in solution (Hem, 1985). Consequently, the storage of tin and water in the vicinity of an abandoned e-waste recycling site: implications for dissemination of heavy metals. Sci. Total Environ., 506–507, 217–225.

In conclusions, the very low concentration of contaminants in groundwater over the monitoring period makes it difficult to assess whether, and to what extent, the phyto-remediation of the soil, has contributed to reducing the level of pollutants in the soil.

REFERENCES


The management of water resources between traditions and sustainability: the Qanats of Shahrood Province (North-Eastern Iran)

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ABSTRACT:

This short note presents the preliminary characterization of some qanats located in the Shahrood Province, as a result of a join agreement between the University of L’Aquila, the Institute of Chemical Methodologies of the National Research Council and the University of Technology of Shahrood. These underground water supply systems by gravity, whose conception dates back three thousand years, are still of great importance to exploit groundwater resource, that is strategic in peri-desert and desert areas. Qanats are endangered by the increasing use of drilled wells, which have exacerbated aquifers’ overexploitation. To overcome this issue, these ancient underground water works can effectively offer “sustainable withdrawals” (tapping only the upper part of aquifer), if strategically implemented and following rational groundwater uses, taking into account cultural heritage, tourism enhancements and other uses related to new technologies (greenhouses heated by low-enthalpy plants, qualitative and quantitative improvement of traditional, typical and new varieties of crops, such as: peaches, apricots, pistachios).

KEY WORDS: groundwater management, arid environment, conceptual model, cultural heritage.

INTRODUCTION

Many towns and villages in Iran are nowadays supplied by qanats. Qanat is a hydraulic and mining technology dating back thousands years (Todd, 1980), probably native of Middle East area and widespread in Asia and North Africa. This hydraulic system allows aquifer drainage, transferring groundwater by gravity from the spring to another area, where it can be used for agricultural, drinking and sanitary purposes. Qanats have been realized entirely by hand, starting from the outlet (water supply area) to the aquifer recharge points (“mother wells”), excavating several vertical accesses (shafts) and connecting them to each other with very low gradients (sub-horizontal) tunnels. The length of these works can range from several hundred meters to several tens of kilometers. The depth of shafts may exceed 200 m. To make drainage more effective, generally a qanat is made of two or more sub-horizontal branches, converging to a main tunnel ending at the outlet (Kazemi, 2004). Many researchers have investigated the possibilities on how these ancient hydraulic can meet modern needs and/or technologies (Salih, 2006), not neglecting their fascinating history and cultural heritage (Jomehpour M., 2009). As part of a scientific cooperation agreement between the University of L’Aquila, the Institute of Chemical Methodologies of the Italian Research Council (IMC-CNR) and the Shahrood University of Technology, some qanats of the Province of Shahrood were selected for the present study. The qanats selection was made in function of their use (e.g. drinking, irrigation, or mixed uses), thus related to socio-economic-cultural aspects, to the geographical position with respect to the Kavir desert and Alborz mountain range, and to the potential different drained water characteristics. A multidisciplinary approach was adopted in order to explore the potential of these hydraulic systems, enhance their water uses and their cultural/touristic value.

Several field activities have been undertaken: flow rates measurements at Qanat outlets, water chemical and physical-chemical parameters measurements, survey of the qanat shafts (position, depth, accessibility, conservation status) aimed at georeferencing, cataloging, and 3-D reconstruction of the qanats. Evaluation of Radon concentrations in the hand-dug shafts of the qanats and in their water. Moreover, some meteorological stations have been installed to acquire information on meteorological data highly influencing the water/groundwater availability.
MATERIALS AND METHODS

The cultural, political and scientific aims are to preserve qanats’ functionality: developing an integrated management of these resources with modern ones (drilled wells), trying to identify new uses (recreational, tourism, exploitation of geothermal potential) and rationalization strategies (e.g. use of water resources not only during irrigation period). To achieve these goals, it is important to know their engineering characteristics, water availability, geological and hydrogeological setting, lithotypes in which they have been dug, social-economic and cultural aspects, the risks and hazards they are exposed to. The information framework must be aimed at building a conceptual model able to take into account this complexity.

After a preliminary survey, three qanats were selected (Fig. 1): the qanat of Shahrood town (150,000 inhabitants), that supplies about a third of the urban water demand; the qanat of Beyarjomand, used to meet the local agricultural water needs; the qanat of Torud, which is the traditional water resource of the village (2000 inhabitants) located within the Kavir Desert.

On the estimates of water demand, fragmented and non-updated data have been collected. Urban water demand for the city of Shahrood is about 20 million cubic meters per year (over 50000 m³/day). The qanat supplies an average of 16000 m³/day (Bakhshi, 1998). For Torud and Beyarjomand sites, scarce reliable information are available, since no flow measuring devices are present at their outlets. In Beyarjomand, qanat water is used for irrigation only between March and June, most of the year water flows freely. Urban water demand in Torud and Beyarjomand is met by drilled wells.

The study sought to reconstruct the geometry of these hydraulic systems, to assess water availability and characteristics, and to identify associated structures such as old mills and checkpoints.

Surveys of qanats were carried out, locating areas and points of recharge (“mother wells”).

Qanat branches were tracked starting from outlets and, as far as possible, a large number of shafts were identified by ID name, GPS position, photos, status (accessible, buried, dangerous), depth (distance between shaft head and bottom of the underground channel). In some shafts and at the outlets, water sample were collected to measure chemical-physical parameters (e.g. Temperature, Electrical Conductivity and pH; instrument: Horiba D-54, EC and Ph –meter).

Moreover, the presence of Radon in waters and inside the maintenance wells (shafts) was detected (instrument: E-Perm electret with SST configuration for water; LLT for the shafts).

Discharge flow measurements were performed along outlets channels (instrument: OTT C2).

In order to complete the information framework of the studied areas, three meteorological stations were installed (recorded parameters: temperature, relative humidity and rainfall data; instrument: Spectrum Technologies WatchDog Datalogger Model 450). Interviews with technical and qanats maintenance personnel were conducted to better understand management processes and related issues. At the same time, investigations on historical artifacts related to the hydraulic works were performed (named points of interests. e.g. mills and checkpoints located along their tracks).

Documents regarding both water works and geological information were also acquired.

Field data and geological maps were geo-referenced to implement 3D-reconstruction of water supply systems in GIS environments and to assist the definition of preliminary hydrogeological conceptual models. The acquired information was structured in a database implemented with MS Access, creating visual masks for outlets, shafts, “mother wells” and points of interest, reporting: (i) identification name, (ii) geographic data, (iii) status, (iv) photographic and/or bibliographic documentation, (v) physical-chemical parameters, (vi) discharge measurements. In addition, Visual Basic codes have been developed, creating KML (Keyhole Markup Language) files and custom 3D objects (COLLADA files) in order to be visualized in the Google Earth environment. For the implementation of 3-D shapes (shaft muck cones, shaft ducts, sub-horizontal tunnels, manholes, buildings), Google Sketchup application was used.

RESULTS

As already stated in the previous section, the selected qanats are located in different geographical positions. Shahrood qanat lies at the foothills of Alborz Mountains, Torud qanat is at the northern edge of Kavir Desert, while Beyarjomand qanat is located at an intermediate position. They share a common characteristic: they have been dug into powerful deposits of alluvial and eluvio-colluvial materials, in valley areas at the foot of important limestone/volcanic mountain ranges. The lengths of the qanat of Shahrood, Beyarjomand and Torud are respectively: 25, 10

Fig. 1 - Location of the three study sites (Satellite photo: Google Earth; Geographic Map: Wikipedia).
and 8-10 km. While the Shahrood and Torud qanats are characterized by the presence of two drainage branches, Beyarjomand qanat has five branches of different order. In fact, these five branches can be traced back to two main ones, draining waters at different temperatures.

The measured water availability (December, 2009) for the studied qanats ranges between 40 L/s and 120 L/s (Shahrood: 120 L/s; Beyarjomand: 45 L/s; Torud: 52 L/s). Bibliographic reference (Kazemi, 2004) and collected interviews indicate a gradual decrease of flow rates over time.

The acquired values of physical-chemical parameters and Radon concentrations in the water are reported in tab. 1.

Water temperatures of qanats are quite variable but can reach values up to 20-25 °C (tab. 1). Temperature measured at the shafts (BJ171, BJ128, BJ053 and BJ117 in Tab. 1) is influenced by the sampling procedure (sampling bottle recovering may take some minutes). Water electrical conductivity varies between 450 and 5800 uS/cm. The Radon concentration in qanat water is quite low for the three different places, while this gas seems to be highly concentrated inside the shafts. In fact, the passive measuring devices (electrets in LLT configuration) suspended into these vertical ducts (one for each of the two branches of Beyarjomand qanat) were completely discharged after about 9 months of exposure (thus it was not possible a quantitative evaluation of Radon concentration).

About meteorological data collected by the stations installed near the outlets of the three qanats, daily data have been recorded for the year 2009 (acquisition step: one hour). Available information concerns only air temperature and relative humidity, but not rainfall, since there have been problems trying to retrieve data from the devices. Relative humidity values show wide daily and seasonal variations from sensors full-scale (20,7%) to measures close to 100% for all the three sites (Average annual values of relative humidity RH: Shahrood, 44,9%; Beyarjomand, 39,5%; Torud, 30,5%). RH average annual values decrease from the area near Alborz Mountains (Shahrood - 44,9%) towards Kevir desert (Torud - 30,5%). Air temperatures have day and night shift of more than 10 degrees, while seasonally, they range from minimum values close to zero in winter reaching maximum values in summer, over 40°C. Seasonal average temperature values respectively for Shahrood, Beyarjomand and Torud, during 2009, are: 8,1, 9,50 and 13,0 °C in Winter; 16,1, 19,2 and 23,3 °C in Spring: 25,9, 27,7 and 32,7 °C in Summer; 13,1, 12,5 and 16,0 °C in Autumn. These values show how seasonal temperatures tend to increase moving towards the desert.

A qualitative comparison with rainfall data retrieved from websites (https://www.worldweatheronline.com/shahrood-weather-averages/hormozgan/ir.aspx), concerning the Shahrood Province, showed a good correlation between these two parameters. Figure 2 shows an example of 3D-reconstructions of the qanat systems obtained in GIS environment and the database interface developed for surveys acquired data.

Fig. 2 - Example of database interface developed in the MS Access environment and 3D reconstruction of the structural elements of the supply system with overlapping of the geological map, represented by the false colors assigned to plain, mountains and foothills (Google Earth environment).

TABLE 1

Qanats water physical-chemical parameters (December, 2009). The electrical conductivity values are normalized at 25 °C. SH: Shahrood; BJ: Beyarjomand; T: Torud. EC: Electrical Conductivity.

<table>
<thead>
<tr>
<th>ID_Name</th>
<th>Date Time</th>
<th>T (°C) -pH-</th>
<th>pH</th>
<th>EC (uS/cm)</th>
<th>T (°C) -EC-</th>
<th>Rn (Bq/l)</th>
<th>Monitoring point description</th>
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</thead>
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<tr>
<td>SH-OUT</td>
<td>15/01/2009 11:00</td>
<td>12.9</td>
<td>8.10</td>
<td>474</td>
<td>13</td>
<td>5.79</td>
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</tr>
<tr>
<td>BJ171</td>
<td>16/01/2009 11:00</td>
<td>12.0</td>
<td>8.70</td>
<td>684</td>
<td>11.8</td>
<td>cold branch, first shaft (250 m) downgradient mother well (depth 90.6 m)</td>
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<td>BJ128</td>
<td>16/01/2009 12:12</td>
<td>18.0</td>
<td>9.22</td>
<td>779</td>
<td>16.8</td>
<td>cold branch</td>
<td></td>
</tr>
<tr>
<td>BJ053</td>
<td>16/01/2009 15:30</td>
<td>19.9</td>
<td>8.14</td>
<td>911</td>
<td>21.8</td>
<td>warm branch (Rn measurement)</td>
<td></td>
</tr>
<tr>
<td>BJ117</td>
<td>16/01/2009 11:30</td>
<td>17.4</td>
<td>8.48</td>
<td>797</td>
<td>18.4</td>
<td>cold and warm branches confluence</td>
<td></td>
</tr>
<tr>
<td>BJ-OUT</td>
<td>16/01/2009 09:46</td>
<td>18.0</td>
<td>8.70</td>
<td>807</td>
<td>18.6</td>
<td>9.49</td>
<td>Beyarjomand outlet</td>
</tr>
<tr>
<td>T-OUT</td>
<td>17/01/2009 12:57</td>
<td>24.5</td>
<td>9.00</td>
<td>5840</td>
<td>24.4</td>
<td>0.96</td>
<td>Torud outlet</td>
</tr>
</tbody>
</table>
Groundwater in peri-desert regions in Iran, as the Shahrood Province, is a strategic resource, regardless of its intended use. Droughts and related water crises have multi-year duration, for example in the periods 1988-1990 and 1999-2001 (Foltz, 2002; Kazemi, 2004; Golian et al. 2015; Madani et al., 2016). In this context, qanats have some advantages compared to drilled wells, among which tapping only the upper part of aquifers and draining groundwater by gravity. On the other hand, groundwater withdrawals/drainage take place uninterrupted throughout the year.

This aspect raises use efficiency-related issues, especially for agricultural activities, which are in most cases seasonal based. The increasingly use of drilled wells and the uncontrolled withdrawals are damaging the qanats’ functionality, bringing aquifers into over-exploitation. For a detailed comparison of advantages and the advantages of these two really contrasting technologies (i.e. qanats vs drilled wells), see Kazemi (2004). The measured qanats’ flow discharge rates are fairly significant (40-120 L/s). Construction features of their hydraulic structures (i.e. tunnel dimensions, traditional supply water distribution system at qanat outlets) make it reasonable to assume that these flow rates are stable over the seasons (otherwise they would have been destroyed by “flood” events).

This is also confirmed by field site evidences as from a previous study (Kazemi, 2004). On the opposite, many authors denote a significant negative trend over the years, due to the decrease of the, already low, rainfalls (e.g. annual average rainfall in Shahrood for the period 1950-2002: 152 mm; Kazemi & Mehdizadeh, 2003). Modarres and Sarhadi (2009), considering a set of 145 precipitation gauging stations in Iran, highlight how annual rainfall is decreasing at 67% of the stations, while the 24-hr maximum rainfall is increasing at 50% of the stations.

Considering the qualitative aspects of groundwater drained by the qanats, electrical conductivity values can be related to the location of each qanat with respect to Alborz mountains range and the Great Salty Desert (Kavir means “salty marsh”). In fact, such data increase from the mountains southwards the desert. Water temperature values, compared to air temperature data, suggest the possible use of qanat waters for low-enthalpy geothermal purposes and/or production of greenhouse crops.

The very low Radon concentration in water allow its risk-free use, while potential risks must be studied for qanat maintenance personnel (moaq-qani).

Geological information, field surveys and 3-D reconstructions allowed to propose the following common conceptual model (Fig. 3), contributing to detail the one proposed by Kazemi (2004) for the qanat of Shahrood. Inter alia, the sketch emphasizes the areas of system recharging, drainage and tunnel losses, potential pollution points and possible interference due to drilling wells. It should be noted that qanat length is often conditioned by the need to transfer water resources to areas where soil characteristics are more suitable for agricultural activities.

The survey highlighted two valuable aspects regarding possible actions to be undertaken for a rationalization in the use of qanat groundwater resources. The first one is the strategic need, for the qanats of Torud and Beyarjomand, to use the favorable flow rates available (40-50 L/s) also during non irrigation periods (autumn and winter). The second one is the thermal difference between temperatures of qanats water (18 - 24 °C) and the average air winter temperatures (8.0 - 13.0 °C), which, coupled with the unused winter water availability, represents a considerable potential for geothermal low enthalpy applications (greenhouses) or recreational use (SPAs). The Shahrood qanat supply system have to be harmonized with drilled wells withdrawals in order to mitigate the effects of droughts or water scarcity events. Winter qanat surpluses could be destined for the developing of agricultural technologies, located in town surroundings.

CONCLUSIONS

Despite the increasingly widespread recourse to drilled wells to tap groundwater, qanats still play a pivotal role in water supply resources, especially in areas located near deserts. Wells withdrawals are depressing groundwater levels, decreasing (or, at worst, preventing) the sub-horizontal gravity drainage of these traditional water works. The performed investigations identified some potential novel uses for the studied qanats. For Torud and Beyarjomand sites, considering the remarkable flow rates available in winter (40-50 L/s, when water demand is lower and traditional agricultural activities stop) and thermal differences between qanats water temperatures and winter air temperatures (respectively 11.4 °C and 9.1 °C), the main agricultural use of their resources, low enthalpy geothermal exploitation systems (also in cogeneration, with solar energy) may be implemented aimed at creating greenhouses for winter crops and/or SPAs. The Beyarjomand site has also some tourism potentials due to the old mills located along the ancient ending part of the qanat. The Shahrood qanat is a strategic resource for the urban drinking water supply, it needs to be harmonized with drilled wells withdrawals. Winter and spring surpluses could supply the irrigated areas owing to the Center of Agricultural Excellence located north-east of the town. The conducted surveys led to setup a procedure for the characterization and recording of qanats in the Shahrood area, which can be improved with the future development of the mentioned international collaboration.
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Analysis of annual mean recharge in main karst Systems of Southern Italy

Francesco Fiorillo (1), Mauro Pagnozzi (1) & Gerardo Ventafridda (2)

STUDY AREAS

The Alburni karst system covers a wide area of Southern Italy, extended hundreds of kilometer squares, with high ground elevation up to 1742 m a.s.l.; it constitutes a well-defined massif, characterized by steep slopes bounding a flat summit area.

Two main rivers bound the karst massif: on southwestern side the Calore Lucano, and on the northeastern side the Tanagro river; their valley are filled by heterogeneous alluvial deposits, slope breccias, sand and conglomeratic deposits (Fig. 2).

The Alburno massif is formed by Mesozoic calcareous series (Jurassic – Cretaceous) and belongs to Alburno-Cervati Unit (Scandone 1972; Ippolito et al.1973; Patacca and Scandone, 2007). It is characterized by a monoclinal structural assessment, gently dipping toward SW, and it is typified by several fault systems. This massif is bounded by flysch sequence constituted by argillaceous and sandstone series (Burdigalian –Serravallian); several faults have caused the uplift of the massif during the Pliocene and Pleistocene, causing the formation of a wide karst summit plateau, which is involved in deep karst processes (Santo 1988, 1988a; Santangelo & Santo 1997). In particular, the karst massif is bounded by steep slopes associated to main fault scarps; the flat summit area is a consequence of the bed-attitude of strata, which maintain a general sub-horizontal layout. The powerful springs (Pertosa, Castelcivita, Basso Tanagro) can be considered the basal springs of the karst system, and drain the saturated zone of the aquifer (tab.1); a systematic record of their discharge is missing, and only sporadic measurements can be found in the technical report and literature.

The other karst massifs considered in this study, are the Matese and Picentini mountains (Fig. 1). They are mainly formed by Mesozoic carbonate sequences and are characterized by a high-elevated reliefs, delimited by faults or flysch sequences. These karst massifs are affected by wide endorheic zones, connected to tectonic activity during Pliocene-Pleistocene, when a general uplift by normal faults occurred, with formation of graben zones. During the following continental environment (Pleistocene-Holocene), karst processes have transformed these zones in endorheic ones, allowing the complete absorption of runoff, and the formation of seasonal lakes. The wide endorheic zones constitute the most important recharge areas of karst massifs of central-southern Italy, and have also an important role in the groundwater protection.
Fig. 1. a) Italian peninsula; b) Main karst areas in southern Italy and main karst springs, with location of Alburni, Matese and Picentini massifs (black rectangle draw with dashed line).

Fig. 2 Hydrogeological sketch of Alburni massif; Legend: 1) Slope breccias. Alluvial and lacustrine deposits (Quaternary); 2) argillaceous and sandstone complex, flysch sequences (Burdigalian – Serravallian); 3) calcareous dolomite series (Jurassic – Cretaceous); 4) main karst and sandstone complex, flysch sequences (Burdigalian – Serravallian); breccias. Alluvial and lacustrine deposits (Quaternary); 2) argillaceous and flysch sequences (impervious terrains). Following this assumption, the total discharge, \( Q \), from the percolation of vadose zone; suspended springs can be also taken into account.

The main hydrological and hydrogeological features of the Matese and Picentini massifs are described by Fiorillo and Pagnozzi (2015) and Fiorillo et al. (2015), respectively.

### MATERIALS AND METHODS

Rain gauge and thermometers data allowed to find out a relevant correlation between the catchment elevation, annual mean rainfall and temperature. Then the annual scale recharge model was applied, considering some parameters as total (meteoric) afflux, actual evapotranspiration, effective (meteoric) afflux on which the model relies on; these amounts are implemented in GIS environment. Based on resolution of 20 x 20 m of digital elevation model of catchment, the spatial annual mean rainfall, and annual mean temperature has been estimated by GIS tools using the linear correlation found (rainfall vs elevation; temperature vs elevation); the equation provided by regression line was implemented using raster data, and raster calculator tools in GIS environment.

Very reliable statistical correlations were found considering regression line of annual mean rainfall \( (R^2 = 0.94) \) and annual mean temperature \( (R^2 = 0.93) \) for Picentini massif (Fiorillo et al., 2015); also for Matese massif a strong correlation about rainfall vs ground-elevation \( (R^2 = 0.94) \), and temperature vs ground-elevation \( (R^2 = 0.92) \) were founds (Fiorillo & Pagnozzi, 2015); for Alburni karst massif statistical correlation index was lower than Picentini and Matese ones \( (R^2 = 0.56) \); rainfall vs ground-elevation; \( R^2=0.63 \), temperature vs ground elevation.

Then, using the Turc (1954) formula, the long-term annual mean of the actual evapotranspiration has been estimated; this grid has been subtracted from the annual mean rainfall distribution grid, providing the long-term annual mean effective rainfall distribution grid.

In endorheic areas, \( A_E \), as the runoff cannot escape, the recharge amount, \( R \), can be considered equal to effective afflux, \( F_{eff} \):

\[
(R)_{A_E} = (F_{eff})_{A_E}
\]  

### TABLE 1

Annual mean discharge of basal springs for Alburni karst massif; discharge value for each spring and total discharge volume are listed (data from Celico et al. 1994; Santangelo & Santo 1997; Ducci 2007).

<table>
<thead>
<tr>
<th>Item</th>
<th>Spring/group</th>
<th>Elevation m.a.s.l.</th>
<th>Annual mean discharge m³/s</th>
<th>Annual mean discharge m³/x10⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Postiglione 570</td>
<td>1,00</td>
<td>0,10</td>
<td>233,30</td>
</tr>
<tr>
<td>1b</td>
<td>Sicignano degli Alburni 825</td>
<td>1,00</td>
<td>0,01</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Petina 780</td>
<td>1,00</td>
<td>0,10</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Pertosa 250</td>
<td>1,00</td>
<td>1,10</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>San Rufo 669</td>
<td>1,00</td>
<td>0,01</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Auso 277</td>
<td>1,00</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Castelcivita 70</td>
<td>1,00</td>
<td>1,50</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Controne 100</td>
<td>1,00</td>
<td>0,10</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Basso Tanagro 70</td>
<td>1,00</td>
<td>3,50</td>
<td></td>
</tr>
</tbody>
</table>
If the water abstraction occurs inside endorheic areas, the (net) recharge can be considered reduced:

\[
(R)_A = (F_{\text{eff}} - Q_P)_{A_1}
\]

where \(Q_p\) is the annual water amount abstracted from the endorheic areas. The value of \(Q_p\) has to be known a priori in case of abstraction from wells.

In the open areas the recharge amount, \((R)A_o\), can be estimated assuming that all the groundwater flow feeds the spring discharges, \(Q_s\), and no-flow boundaries occurs towards argillaceous, terrigenous and flysch sequences (impervious terrains). Following this assumption, the total discharge, \(Q_s\), from springs is:

\[
Q_s = (R)_{A_1} + (R)_{A_o}
\]

which allows to obtain the recharge in the open areas:

\[
(R)_{A_o} = Q_s - (F_{\text{eff}} - Q_P)_{A_1}
\]

and the total recharge on the catchment area, \(A_c\), is:

\[
(R)_{A_c} = (R)_{A_1} + (R)_{A_o} = Q_s - Q_p
\]

The model assumes that all the amount of the recharge reaches the basal water table, even if the vadose zone could formed by portion of saturated zones, characterized by leakage, and contributing the percolation of vadose zone; suspended springs can be also taken into account.

Recharge can be expressed in term of fraction of the effective afflux, providing the effective recharge coefficient, \(C_r\); if water pumping does not occur, \(Q_p=0\), the following equations can be deducted:

\[
(C_r)_{A_1} = 1; \quad (C_r)_{A_c} = \frac{(R)_{A_1}}{(F_{\text{eff}})_{A_1}}; \quad (C_r)_{A_c} = \frac{(R)_{A_c}}{(F_{\text{eff}})_{A_c}}
\]

In general, these coefficients express the infiltration capacity of karst slopes and depending on the slope angle distribution, vegetation, soil type, and on the degree of karstification.

The role of endorheic areas (closed areas) in contributing spring discharge is expressed by the coefficient \(C_{s}\), effective contribute to spring discharge (Fiorillo et al. 2015):

\[
(C_s)_{A_1} = \frac{(F_{\text{eff}} - Q_P)_{A_1}}{Q_s}
\]

and, as a consequence, the effective contribution to spring discharge of open areas is:

\[
(C_s)_{A_o} = 1 - (C_s)_{A_c}
\]

RESULTS

The annual recharge analysis, focused on Terminio, Cervialto and Matese massifs, point outed the similar recharge coefficient obtained for open areas of catchments (0.66 for Cervialto and Matese, 0.67 for Terminio, Tab.2); these values can be explained with a similar slope distribution of their hydrogeological catchments. The annual scale recharge model analysis allows to assess runoff amount and the endorheic areas contribution to spring discharge (Fiorillo et al., 2015; Fiorillo & Pagnozzi 2015). A crucial point concerns the runoff on the open areas of the Matese massif, which has been estimated as 34 % of the effective afflux, \(F_{\text{eff}}\); considering results obtained for the Cervialto massif; in term of the total afflux, the runoff percentage is 23%. This percentage appears lower than values (30-35 %) found by Selmo (1930) who carried out the hydrological balance of Matese lake for hydroelectrical purpose during the 1920s, and higher (7.4 %) than Civita (1973) who assigned empirically the fraction of precipitation which infiltrate into aquifer (Fiorillo & Pagnozzi 2015).

Table 1 shows the annual mean outlet from each basal spring of Alburni Karst system; the annual mean volume discharged by all springs was quantified as 233.3 m³ x 10⁶. The fundamental role of karst plateau (internal runoff area) is highlighted by effective contribute to spring discharge value (\(C_r = 0.54\)) higher than open area one (\(C_r = 0.46\) even if the plateau is characterized by area (111.5 Km²) smaller than open area one (151.3 Km²); 57.6 % of total catchment). For the open area, the analysis has provided an high effective recharge coefficient (\(C_r = 0.91\)) which means that the annual runoff amount is 13.4 m³ x 10⁶.

The annual effective afflux (\(F_{\text{eff}}\)) of catchment area is 244.1 m³ x 10⁶, the annual spring discharge is 233.3 m³ x 10⁶; their ratio provides a total (effective) recharge coefficient; \(C_r = 0.95\) (tab.2).

The difference between effective afflux (7.8 m³/s) and spring outlets (7.4 m³/s) quantified as 0.4 m³/s could be associated with runoff loss and other minor springs.

DISCUSSION

The annual scale recharge model needs the assessment of some fundamental hydrological parameters. GIS tools allows to consider a better distribution of the actual evapotranspiration and rainfall in all the catchments analyzed.

Hydrological analysis carried out defining annual recharge allows to assess in a detailed way the several parameters included in the model (Tab.2).

The most relevant parameters analyzed in long term period was \(C_{s}\) that allows to smooth the influence of a specific year and provides useful tools to find the amount of rainfall feeding spring outlet.

We found comparable values of recharge coefficient along the slopes of open areas, \((C_{s})_{A_o}\) (Fiorillo and Pagnozzi, 2015), and a different value for the Alburni massif, \((C_r = 0.91\), Tab.2). This means that the runoff coefficient, \((C_{s})_{A_o}\) (Fiorillo et, 2015), along the steep slopes of open areas of the Alburni massif would be only 0.09 \((C_{s} = 1 - C_{o})\). To explain this different hydrological response of the Alburni massif, needs to take into account other geomorphological data and karst landforms in order to better describe the recharge phenomena for Alburni massif. However, while for the Terminio, Cervialto and Matese springs are available discharge measurements for long time periods, for the basal springs of Alburni massif are available poor discharge measurements, especially for the Tanagro group springs which constitutes the major outlets.
CONCLUSIONS

To assess groundwater recharge of some karst massifs in Southern Apennines (Terminio, Cervialto, Matese and Alburni massif), a specific procedure has been used concerning the assessment of annual scale recharge model. In particular, the afflux, recharge and, consequently, the runoff are computed in GIS environment, allowing an estimation of recharge and runoff coefficients, distinguished for open and endorheic areas (or internal runoff area).

The model assumes as the endorheic area are typical features where no-flow boundary occurs towards impervious terrains. Recharge coefficient found in Cervialto and Terminio annual hydrological analysis is similar to Matese one because the massifs have similar topographical and morphological features (Fiorillo & Pagnozzi, 2015); for this reason, the models proposed was also applied for other nearby karst massifs in southern Italy as Alburni massif, on which several analyses were carried out in order to better understand the overall recharge phenomenon on catchment affected by high geomorphological complexity. To simplify the hydrological analysis, the Alburni massif was considered as a lumped system affected by two main macro areas: internal and external runoff area, associated to a summital karst plateau and open areas respectively.

The hydrological analysis underlines how the ground-elevated flat area play an important role in karst aquifer hydrological behavior, being the hydrogeological structure that mainly contributes to basal springs discharge; for this reason, because on the plateau the predominant kind of recharge is that provided by concentrate infiltration it could be mainly vulnerable to water contamination risk (Ducci 2007), overall considering that some karst landforms can be considered as preferential vehicles for a generic polluting.

For Terminio, Cervialto and Matese massifs, other parameters could be analized, as volumetric water content, piezometric level, water suction to integrate the annual recharge analysis described; nevertheless data detection belongs to a preliminary research phase, and their processing could help the enhancement of annual groundwater recharge model proposed.

ACKNOWLEDGEMENTS

Authors are grateful to “Direzione Approvvigionamento Idrico - Acquedotto Pugliese S.p.A” for helpful support given to research, providing rainfall and springs discharge data; thanks also to two anonymous reviewers for their helpful advice to improve the manuscript.

REFERENCES


TABLE 2

Summary of hydrological parameters inferred by annual groundwater recharge analysis for Alburni, Cervialto, Terminio and Matese massifs; F, afflux; F_eff, effective afflux; RO, runoff; Q_p, pumped water; C_R, effective recharge coefficient; C'_R, total recharge coefficient; C_s, effective contribute to spring discharge.

<table>
<thead>
<tr>
<th>Area</th>
<th>Mean elevation (m a.s.l.)</th>
<th>Area</th>
<th>Km²</th>
<th>F (m³X10⁶)/y</th>
<th>F_eff (m³X10⁶)/y</th>
<th>RO (m³X10⁶)</th>
<th>Q_p (m³X10⁶)</th>
<th>R (m³X10⁶)</th>
<th>C_R</th>
<th>C'_R</th>
<th>C_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALBURNI</td>
<td></td>
<td>Plateau area</td>
<td>1124.5</td>
<td>111.5</td>
<td>180.3</td>
<td>122.8</td>
<td>0.0</td>
<td>0.0</td>
<td>122.8</td>
<td>1.00</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open areas</td>
<td>828.2</td>
<td>151.3</td>
<td>207.9</td>
<td>121.3</td>
<td>13.4</td>
<td>0.0</td>
<td>108.0</td>
<td>0.91</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total catchment</td>
<td>953.9</td>
<td>262.8</td>
<td>388.2</td>
<td>244.1</td>
<td>13.4</td>
<td>0.0</td>
<td>230.7</td>
<td>0.95</td>
<td>0.59</td>
</tr>
<tr>
<td>CERVIALTO</td>
<td></td>
<td>Closed areas</td>
<td>1249.3</td>
<td>27</td>
<td>58</td>
<td>44</td>
<td>0.0</td>
<td>0.0</td>
<td>44</td>
<td>1.00</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open areas</td>
<td>1153.9</td>
<td>83</td>
<td>172.4</td>
<td>128.3</td>
<td>43.8</td>
<td>0.0</td>
<td>84.5</td>
<td>0.66</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total catchment</td>
<td>1176.4</td>
<td>110</td>
<td>230.4</td>
<td>172.3</td>
<td>43.8</td>
<td>0.0</td>
<td>128.5</td>
<td>0.75</td>
<td>0.56</td>
</tr>
<tr>
<td>TERMINIO</td>
<td></td>
<td>Closed areas</td>
<td>959.1</td>
<td>68.6</td>
<td>132.1</td>
<td>93.1</td>
<td>0.0</td>
<td>6.3</td>
<td>86.8</td>
<td>0.93</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open areas</td>
<td>934.9</td>
<td>94.3</td>
<td>180.2</td>
<td>125.0</td>
<td>41.4</td>
<td>0.0</td>
<td>83.7</td>
<td>0.67</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total catchment</td>
<td>944.5</td>
<td>162.9</td>
<td>312.3</td>
<td>218.1</td>
<td>41.4</td>
<td>6.3</td>
<td>176.8</td>
<td>0.81</td>
<td>0.57</td>
</tr>
<tr>
<td>MATESE</td>
<td></td>
<td>Closed areas</td>
<td>1229.3</td>
<td>123.8</td>
<td>221.8</td>
<td>162.5</td>
<td>0.0</td>
<td>42.2</td>
<td>0.0</td>
<td>0.78</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open areas</td>
<td>919.8</td>
<td>427.7</td>
<td>701.2</td>
<td>476.4</td>
<td>162.0</td>
<td>0.0</td>
<td>162.0</td>
<td>0.66</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total catchment</td>
<td>988.8</td>
<td>551.5</td>
<td>923.0</td>
<td>638.9</td>
<td>162.0</td>
<td>42.2</td>
<td>162.0</td>
<td>0.69</td>
<td>0.48</td>
</tr>
</tbody>
</table>


Selmo L. (1930) Note idrologiche sul lago del Matese. L'Energia Elettrica, 7, 190-199

Monitoring composition of LNAPL: essential tool for the estimation of free LNAPL specific volumes

Eleonora Frollini (a), Alessandro Lacchini (b), Valentina Marinelli (b) & Marco Petitta (b)

INTRODUCTION

LNAPLs (light nonaqueous phase liquids), characterized by a slight solubility in water, are the most common and harmful contaminants in groundwater because they are potential long-term sources of contamination and they are carcinogenic or toxic for human health (Baciocchi et al., 2010). Once LNAPL has been released in the subsoil, it migrates downwards under the influence of gravity until the capillary forces exceed the residual soil retention capacity (CL:AIRE, 2014). When this exceedance occurs, LNAPL reaches the water table and starts spreading laterally (Baldi and Pacciani, 1997; Brost and DeVauill, 2000). This happen unless LNAPL has a sufficient potential energy able to displace water and allow LNAPL to penetrate the water table (CL:AIRE, 2014). In order that occurs, it is necessary that the LNAPL reaches and exceeds the entry pressure, which is inversely proportional to the pore throat radius. Therefore, LNAPLs occupy preferably the large pores, while the small pores are occupied by water.

Once in the subsoil, LNAPL can divide itself, basing on its chemical-physical properties, in four different phases: 1) vapour phase (present mainly in the vadose zone), 2) dissolved phase (which forms plumes of contaminants that flow following the groundwater flow direction), 3) residual phase (trapped between solids particles due to capillary forces) and 4) free phase (a liquid separate phase immiscible in water). The last one represents, together with the residual phase, the 99% of LNAPL in the subsoil and it is difficulty detectible and quantifiable (Iwakun et al., 2010). Therefore, the volume estimation of free phase is essential in order to recover the supernatant and to remediate a contaminated site.

Properties of the LNAPL type in the subsoil influence the subdivision of contaminant in the several phases (vapour, dissolved, residual and free phases), therefore LNAPL type and its properties are affecting the volume of free phase in the subsoil and its estimation. For this reason, during the free phase volume estimation, it is fundamental considering the LNAPL type present in the subsoil.

Based on the above, in this paper a sensitivity analysis has been carried out considering different LNAPL types in order to quantify the influence of LNAPL type on volume estimation.

MATERIALS AND METHODS

During the time, two different conceptual models have been developed for the free LNAPL volume estimation. These two models, Pancake Model and Vertical Equilibrium Model, essentially differ for their assumptions about the product distribution in the subsoil.

According to the Pancake Model, the migration of LNAPL to the water table and its lateral spreading through the capillary fringe create a buoyant uniform and constant saturated pool (Baldi and Pacciani, 1997; CL:AIRE, 2014). In addition, according to it, the measured product thickness in the monitoring well is an apparent thickness understimating the real thickness of LNAPL present in the aquifer (Dippenaar et al., 2005). This difference is due to the absence of capillary fringe in the monitoring well, while in the aquifer the LNAPL is suspended on the capillary fringe since hydrocarbons are assumed immiscible in water. Indeed, the absence of capillary fringe...
in the monitoring wells conducts to a lower level of water table in the well compared to water level in the aquifer. This difference of levels allows the free product to flow more easily into the well, creating an exaggerated thickness of supernatant (Gruszczenski, 1987; Hughes et al., 1988; Testa and Paczkowski, 1989; Dippenaar et al., 2005). In addition, the weight of free phase depresses further the water table level in the monitoring well, facilitating the flow of free product in the well. Since such difference between measured thickness (MT) in the well and real thickness (RT) in the aquifer exists, the Pancake Model requires the correction of the measured thickness, known also as apparent thickness, in order to obtain the real thickness. The correction of measured thickness can be obtained using either empirical factors as those proposed by several authors (De Pastrovich et al., 1979; Hall et al., 1984; Testa and Paczkowski, 1989), or factors derived by field test. Among the last ones, the exaggeration factor is obtained by baildown tests, which are affected by soil type and LNAPL type present in the monitoring well. The exaggeration factor is obtained by the ratio between measured thickness and real thickness. The last one derives from the difference between the product level and the groundwater level observed in the baildown test chart inflection point, applying the Gruszczenski method (Gruszczenski, 1987). Instead, when the Hughes method is applied (Hughes et al., 1988), the real thickness is calculated as the difference between initial product level and the product level in the chart inflection point. Gruszczenski method is applied when both groundwater and LNAPL are pumped during the baildown test; conversely, the Hughes method is used when only LNAPL is pumped. Known the real thickness, the specific thickness can be obtained multiplying the real thickness for the soil effective porosity ($n_e$).

Vertical Equilibrium Model can be applied only if there is not persistence of release of contaminant (Lundegard and Mudford, 1998). According to this model, the LNAPL does not create a floating discrete layer on water table, but it can penetrate also below the water table leading to the fluids (LNAPL, water and air) coexistence in the pores. For this reason, the LNAPL saturation cannot be considered uniform, constant and equal to 100%, but it varies with depth creating different saturation profiles in function of soil type and LNAPL type (Lundegard and Mudford, 1998; ITRC, 2009). Hence, the relationship between the LNAPL thickness measured in the monitoring well and the LNAPL specific volume present in the aquifer, derives from the capillary properties of the soil and the LNAPL characteristics. Therefore, according to the Vertical Equilibrium Model, LNAPL saturation profiles are necessary to calculate the specific volume (expressed in m$^3$).

Saturation profiles can be obtained, for example, through the LDRM (LNAPL Distribution and Recovery Model) software distributed by the American Petroleum Institute (API, 2007). This software, based on input parameters, provides saturation profiles and consequently the specific volume $D_n$ (m) and the recoverable specific volume $R_n$ (m), which depend on product thickness, groundwater elevation, ground surface elevation, soil properties and LNAPL characteristics.

Hence, as said above, in both models the LNAPL type influences the volume estimation. Indeed, the exaggeration factor obtained by the Pancake model performing the baildown tests is influenced by LNAPL characteristics such as e.g. density and viscosity that control the flow of LNAPL into the well during pumping. Instead, in the Vertical Equilibrium Model, LNAPL characteristics (such as density, viscosity, surface and interfacial tensions) affect the LNAPL saturation profiles.

Although the Pancake Model assumption of a buoyant pool saturated of LNAPL is inaccurate, because it is now clear that LNAPL and water saturation vary in the subsoil in function of capillary pressure (Lenhard et al., 2017), even now, in Italy, this model is still applied by practitioners and regulators due to its elementary applicability. For this reason, in this paper, both Pancake Model and Vertical Equilibrium Model have been applied to calculate the free LNAPL volume.

A sensitivity analysis has been carried out in order to quantify the LNAPL type influence on free LNAPL volume estimation, on selected monitoring wells, using both the conceptual models above described.

Soil type, LNAPL type and available baildown test have been considered for the monitoring well selection. In order to neglect the influence on volume estimation of soil properties, such as porosity and hydraulic conductivity, monitoring wells characterized by same soil type (sands) have been selected. The effective porosity of these sands has been estimated in 0.25 (Fetter, 2001) and a hydraulic conductivity, derived by Hydrus software, of 6.43 m/d (Sim n et et al., 2013) has been considered. For each different LNAPL type (gasoline, diesel and mixtures of gasoline and diesel), a monitoring well has been selected, among those where baildown test have been carried out (Fig. 1).

Basing on above considerations, the following three monitoring wells have been selected: PZ1, PZ2 and PZ3. The features of LNAPL type present in each of selected monitoring wells and the exaggeration factors derived by baildown test are showed in table 1. In PZ1 there is gasoline (characterized by more of 70% of C$_6$-C$_9$), in PZ2 diesel occurs (characterized by more of 70% of C$_{10}$-C$_{30}$) and in PZ3 there are mixtures of gasoline and diesel (with intermediate percentages of the two hydrocarbons groups).

The sensitivity analysis has been carried out hypothesizing the presence in each analysed monitoring well of a different LNAPL type. In other words, for each monitoring well, the specific thickness/volume has been calculated applying the exaggeration factor (in the Pancake Model) or the LNAPL properties (density, viscosity, surface and interfacial tensions) (in the Vertical Equilibrium Model) of the three different LNAPL compositions. Consequently, in PZ1, where gasoline occurs, the specific thickness/volume has been estimated applying for the Pancake Model the exaggeration factor 6.30 coming from baildown test, and applying, in the Vertical Equilibrium Model, the density, viscosity, surface, and interfacial tensions of gasoline (as showed in the line 1 of the table 1). At the same time, in order to carry out the sensitivity analysis, the alternative presence both of diesel and mixtures of gasoline and diesel has been considered for the same monitoring well. In the first case, the specific volume has been estimated applying for the Pancake Model the exaggeration factor 9 (obtained by baildown test carried out in the PZ2 where there is diesel) and for the Vertical Equilibrium Model the diesel features (showed in the line 2 of the table 1). In the second case, instead, for the Pancake Model an exaggeration factor 4.50, obtained by baildown test carried out in PZ3, where there are mixtures of gasoline and diesel has been applied;
RESULTS AND DISCUSSION

The results of sensitivity analysis carried out applying the Pancake Model show a great influence of the LNAPL type on the volume estimation. Indeed, the Figure 2 shows that in the PZ3, characterized by mixtures of gasoline and diesel, the estimated specific thickness is 0.036 m. Instead, if in the same monitoring point the presence of gasoline is considered, a specific thickness of 0.026 m, calculated using the exaggeration factor 6.30, is derived from baildown test carried out in the PZ1 (characterized by the presence of gasoline); this result is about 29% lower of the estimated specific thickness for mixtures of gasoline and diesel. Instead, the estimated specific...
thickness decreases up to 50% if the possible presence of
diesel is applied; in fact, the specific thickness, estimated
using the exaggeration factor 9.0 (derived by baildown
test carried out in the monitoring point with diesel),
would be only 0.018 m. At the same time, in PZ1, where
gasoline occurs, the estimated specific thickness for this
LNAPL type results to be 0.013 m; conversely, applying
the exaggeration factor derived from mixtures of gasoline
and diesel (4.50), the estimated specific thickness becomes
0.018 m, with a possible increase of about 29%. Instead, if
it is considered a diesel occurrence, the estimated specific
thickness obtained reduces to 0.009 m, about 30% lower
than in previous case. Finally, for PZ2 where diesel occurs,
the estimated specific thickness is 0.030 m, but it reaches
respectively 0.060 m and 0.040 m for mixtures of gasoline
diesel and for gasoline; therefore the increase of
specific thickness for these LNAPL types is of about 50%
and 30% in comparison to the diesel specific thickness.

The results obtained using the Vertical Equilibrium
Model show a greater influence of the LNAPL type on the
specific volume estimation. In fact, the Figure 3 shows that
in the PZ3 the specific volume (Dn) is 0.021 m, but applying
in LDRM the gasoline features, the specific volume rises
to 0.038 with an increase of 45% in comparison to the
mixtures specific volume. At the same time, considering in
PZ3 the presence of diesel, the specific volume decreases of
about 91%, with an absolute value of 0.002 m. In PZ1, the
specific volume of gasoline, estimated through the Vertical
Equilibrium Model, is 0.010 m; but the input in LDRM of
mixtures of gasoline and diesel features leads to a reduction
of 61% of specific volume, indeed the estimated specific
volume is 0.004 m. Potential occurrence in PZ1 of diesel
produces by applying LDRM a specific volume of 0.0002
m, that highlights a decrease even of 98% in comparison to
the estimated specific volume for gasoline. Potential occurrence in PZ3 of
diesel produces by applying LDRM a specific volume of 0.0002
m, that highlights a decrease even of 98% in comparison to
the estimated specific volume for gasoline. Lastly, in the
PZ2, where there is diesel, the estimated specific volume
with LDRM is 0.008 m, against a specific volume of 0.054
m for mixtures of gasoline and diesel that is 85% higher of
specific volume estimated for diesel. An increase of 90% in
comparison to diesel estimated specific volume is observed,
applying to PZ2 the presence of gasoline, estimating a
specific volume of 0.085 m.

Vertical Equilibrium Model results clearly depend on
LNAPL type, respect with Pancake Model. At the same
time, the specific volumes (m) obtained for the same
monitoring point considering the three different LNAPL
types have a wider range (from 45% up to 98%) respect
with the correspondent specific thicknesses (m) obtained
through the Pancake Model. This high sensitivity to
LNAPL type in the Vertical Equilibrium Model can be
attributed to two factors. First of all, the Pancake Model
consider the exaggeration factors obtained by baildown
tests, while the LNAPL properties (such as density,
viscosity, surface and interfacial tensions) applied in the
Vertical Equilibrium Model come from average values
and literature data. Consequently, the differences between
the characteristics of the three LNAPL types used in the
Vertical Equilibrium Model, depending on three factors,
are expected to be higher than those observed through
baildown test. In addition, for the Pancake Model a sole

<table>
<thead>
<tr>
<th>N. line</th>
<th>Monitoring wells</th>
<th>LNAPL type</th>
<th>Exaggeration Factor</th>
<th>LNAPL density (gm/cc)</th>
<th>LNAPL viscosity (cp)</th>
<th>Air/Water surface tension (dynes/cm)</th>
<th>Air/LNAPL surface tension (dynes/cm)</th>
<th>LNAPL/Water interfacial tension (dynes/cm)</th>
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<td>1</td>
<td>PZ1</td>
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<td>6,3</td>
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<td>27,07</td>
<td>29,60</td>
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<tr>
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<td>25,86</td>
<td>14,06</td>
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</tbody>
</table>

TABLE 1

LNAPL features and exaggeration factor in the selected monitoring wells.

Fig. 2 - Specific thickness estimated using Pancake Model and considering different LNAPL types in every monitoring well.

Fig. 3 - Specific thickness estimated using Vertical Equilibrium Model and considering different LNAPL types in every monitoring well.
parameter (exaggeration factor) expresses the LNAPL type, while for the Vertical Equilibrium Model the LNAPL type is described by several parameters (density, viscosity, surface and interfacial tensions) that differently influence the saturation profiles and so the specific volume (m).

CONCLUSIONS

The specific thicknesses/volumes of free LNAPL in groundwater have been estimated through two different conceptual models: Pancake Model and Vertical Equilibrium Model. In the first model it is assumed that LNAPL floats on the water table creating a pool of free phase with uniform and constant saturation (equal to 100%). The second model, instead, assumes that LNAPL can penetrate also below the water table bringing to a coexistence of fluids (LNAPL, water and air) in the pores. This coexistence leads to a variation with depth of LNAPL saturation that never reaches the 100% value.

In both models, the LNAPL composition influences the specific thickness/volume estimation. Indeed, for the Pancake Model the exaggeration factor derived by baildown test is required to correct the apparent thickness measured in the monitoring well, to obtain the real thickness present in the aquifer, from which the specific thickness (as the product of real thickness for effective porosity) can be derived. The result of baildown test is obviously dependent by LNAPL characteristics and soil type. For the Vertical Equilibrium Model, instead, LDRM requires a lot of information about LNAPL characteristics (density, viscosity, surface and interfacial tensions) to provide the saturation profile and so the specific volume (Dn) (measure unit in m) which is function of LNAPL saturation and effective porosity.

The sensitivity analysis results, obtained applying the two models and considering the several LNAPL types (gasoline, diesel, mixtures of gasoline and diesel), show that the LNAPL composition has a great influence on the estimated specific thickness/volume, since it can vary from 29% to 98% considering different LNAPL type.

Consequently, it is possible to affirm that the monitoring of LNAPL composition is a fundamental and essential information for reducing uncertainty of estimation of LNAPL specific thicknesses/volumes (expressed in m) and therefore of the free LNAPL volume (expressed in m³). Although in absolute value the difference between the estimated specific thicknesses/volumes obtained applying the different LNAPL types is small (maximum few centimetres), when successively these specific thicknesses/volumes are applied to the area of interest, the difference of estimated LNAPL volumes (expressed in m³) can become considerable (also thousands of m³).

For this reason, with the aim to have a reliable estimation of free LNAPL present in a contaminated site, it is appropriate to monitor periodically not only the product thickness, but also the product composition.

ACKNOWLEDGEMENTS

ENI and Italian Amec Foster Wheeler are acknowledged for providing data about examined monitoring wells.

REFERENCES


A proposal for groundwater sampling guidelines: application to a case study in southern Latium

Eleonora Frollini (a), David Rossi (a), Martina Rainaldi (a), Daniele Parrone (a), Stefano Ghergo (a) & Elisabetta Preziosi (a)

ABSTRACT

The notable differences observed in the analytical results for groundwater samples collected by different operators in several sites in Italy, pointed out the need for a standardized procedure for groundwater sampling at the national level. This “best practice” document, produced by IRSA-CNR and here described, aims to uniform the sampling procedures in order to have comparable results and to manage groundwater monitoring in a more participated and efficient manner. The proposed guideline underlines the relevance of the conceptual model implementation, as well as of the planning and sampling phases.

The application of this “best practice” in a case study in southern Latium where dramatic exceedances for Fe, Al, As, Mn in groundwater were reported, demonstrated how sampling procedures could have an important influence on analytical results, mainly the water filtration for inorganic compounds. In the case study, there were no exceedances of the CSC in the filtered samples, except for Mn in SV-PM1 well.

Common and standardized sampling procedures should always be applied, in order to have comparable results and avoid legal disputes about the obtained results.

KEY WORDS: sampling procedure, in-line filtration, monitoring, conceptual model, manganese.

INTRODUCTION

Chemical monitoring of groundwater is required, in order to protect the environment, by legislation, in different sectors and at variable spatial scales, from groundwater body status assessment, to the control of the impact of anthropic activities at the site scale. The aim of the sampling procedure is to collect an undisturbed sample, which can be considered representative of the groundwater. In order to reach this goal, sampling, transport and preservation must strictly follow standardized and common procedures. This is because of the great uncertainty connected to sampling, which can be also 30-50% of the uncertainty connected to the final analytical results (APAT-IRSA.CNR, 2003).

The current lack, in Italy, of specific national guidelines for groundwater sampling, has led in the past to significant differences in the analytical results derived in samples collected by different operators in several sites, raising uncertainties on the effective chemical status of the groundwater body and thus on the assessment of the impact of anthropic activities therein.

In order to fill this gap, the Water Research Institute was asked to produce a “best practice” document for groundwater sampling, based on national and international literature (Barcelona et al., 1985; EPA/540/S-95/504, 1996; EPA, 2000; Peruzzi 2007; Cal-EPA, 2008; ISO 5667-11, 2009), and suitable in the Italian legislative framework.

In this short note, we describe the application of the proposed procedure to a case study in southern Latium, where a phreatic aquifer of local interest is threatened by an industrial area including a waste-to-energy plant. Our aim is to obtain a snapshot that is deemed representative of the chemical status of the groundwater both within and outside the site, with particular attention to redox sensitive elements like As, Fe, Mn and Al.

PROPOSED “BEST PRACTICE”

The proposed procedure, whatever the aim of monitoring activity, includes three main aspects: 1) implementation of the conceptual model, 2) sampling strategy planning phase, 3) sampling phase, which includes an appropriate treatment and preservation of samples and quality control (e.g. field and transportation blanks, blind samples, etc.) (Preziosi et al., 2017).

The preliminary conceptual model is needed to define the sampling strategy. The conceptual model is developed on the basis of the available information regarding: geographical, geological and hydrogeological setting; anthropic pressures (land use, human activity, possible sources of contamination); characteristics of geological materials that control the geochemical behaviour and transport of examined substances (lateral and vertical extension, horizontal and vertical flow direction, hydraulic conductivity and conductivity contrast between different geological materials); hydrogeochemical data coming both from scientific and grey literature.

The sampling strategy is defined, during the planning phase, on the basis of the conceptual model and the aim of the monitoring activity. It takes into account the sampling aim; the geological and hydrogeological setting; the planned number of water points (function also of the available budget); accessibility; wells/piezometers characteristics...
The sampling phase consists of a sequence of operations to be followed in order to obtain a representative sample of groundwater. The operative sequence includes: 1) selection of sampling point; 2) census and inspection of sampling point and collection of relevant information; 3) piezometric level measurement in wells/piezometers or measurement of discharge in springs; 4) purging of wells/piezometers until chemical-physical parameters stabilization; 5) measurement of chemical-physical parameters with probes in flow cell; 6) in-line filtration, collection of groundwater samples in suitable containers, adding of chemical preservatives where appropriate; 7) transport of samples in refrigerate box; 8) preservation of samples in refrigerator (4°C), where appropriate, until analysis. During sampling, blank samples, using MilliQ water (18.2 MΩ/cm), are also collected in order to check the quality of sampling procedures.

CASE STUDY: SAN VITTORE DEL LAZIO (SOUTHERN LATIUM)

The study area, is located in the southern Latina valley (Latium, Italy), and it is included between Venafro Mountains at North and Rocca d’Evandro at South, near Monte Porchio. The altitudes range between 35 and 90 m a.s.l. in the lowland, while Monte Porchio reaches 280 m a.s.l. The hydrographic pattern follows the main longitudinal and transversal tectonic elements and the final receptor is the Peccia River (in the eastern and southern area), which marks the regional boundary between Latium region and Campania region. In the area, there is elevated high anthropic pressure due to the presence of a highway, two railway lines and an industrial area including a waste-to-energy plant which was the target of this study.

In the waste-to-energy plant groundwater monitoring network, exceedances for Mn, Fe, As and Al have been reported in the past, by the Regional Environmental Agency and by the site managers. The available data show that these exceedances were found in the unfiltered samples, except for manganese (Fig. 1). The activity of IRSA-CNR aimed at solving the controversy among different operators on the correct sampling procedures.

MATERIALS AND METHODS

The starting point for assessing groundwater body status is, as mentioned above, the implementation of the conceptual model.

The lithostratigraphic units have been identified based on lithostratigraphic criteria considering facies analysis, grain size, mean thickness and geometry of geological formations and their stratigraphic positions.

The digital terrain model (DTM) of the study area has been developed using a numerical matrix of coordinates and elevations.

Fig. 1 - Iron, arsenic, manganese and aluminium concentrations observed in the past (2011-2015) in 4 monitoring points (PM1, PM2, PV1, PV2) located in the waste-to-energy plant. Squares represent the concentration of unfiltered samples (UF); circles represent the concentration of filtered samples (F).
The hydrogeological and hydrogeochemical setting has been reconstructed implementing the available data with new investigations. These investigations include census and sampling of 32 private wells outside and 4 monitoring wells inside the waste-to-energy plant. Every sampling point was associated to a record with information about the observed piezometric depth, duration and flow rate during the purging phase, using a multiparameter probe in a flow cell when anoxic and reducing conditions are expected, to avoid the oxygenation of the sample. Chemical-physical parameters have been measured, during the purging phase, using a multiparameter probe in a flow cell and occasionally single probes to check the measurements, especially for DO and Eh. These parameters, such as temperature, pH, electric conductivity, and especially redox potential (ORP) and dissolved oxygen were collected in field because they can easily vary after the sampling. In addition, it is particularly recommended to measure these parameters in flow cells when anoxic and reducing conditions are expected, to avoid the oxygenation of the sample. The chemical-physical parameters monitoring during the purging phase is necessary to identify the most appropriate time to collect a representative sample of the groundwater circulating in the aquifer. This phase ends when the chemical-physical parameters have stabilized (Tab. 1), which ensures to collect a representative sample of the groundwater. The collected samples have been analysed for anions, major cations and trace elements, plus additional anions analysis and one fraction of 100 mL for major cations and trace elements determination through ionic chromatography, ICP-OES and ICP-MS following standardized procedures (APAT-IRSA.CNR, 2003).

RESULTS AND DISCUSSION

Conceptual model of study area: geological and hydrogeological settings

The study area is characterized by a carbonate substratum (Cretaceous-Miocene limestones) dislocated by extensional faults, visible only in few small outcrops such as Monte Porchio, covered by the Pliocene-Quaternary units (Fig. 2a, 2b, 2c). The last ones consist of alluvial deposits and eluvio-colluvial deposits, overlying the rehashed pyroclastic deposits, interbedded to gravel-sandy deposits, calcareous pebbles lens and volcanic sands. The pyroclastic deposits originate from the Roccamonfina volcano, developed, during the Pleistocene, in the most southern-eastern Latina Valley.

According to the most recent hydrogeological cartography (Capelli et al., 2012), in the study area, there are five main hydrogeological units: a) recent alluvial deposits outcropping along rivers; b) lacustrine and fluvial deposits; c) stratified tuffs and phreatomagmatic deposits outcropping in the lowland of the study area; d) marl-flysch representing the regional aquiclude underlying the lacustrine Pliocene-Quaternary deposits and the pyroclastic deposits; e) carbonate platform limestones and marl-carbonate platform limestones. The latter, according to Boni and Bono (1973) and Boni et al. (1986), hosts the regional aquifer feeding the Gari and Cassino springs and the Peccia River springs. The investigated aquifer is hosted in the lacustrine and fluvial deposits and in the stratified tuffs and phreatomagmatic deposits, which have, according to stratigraphic data and information provided by the owners of sampling wells, a variable thickness until 90-100 m. This thickness seems to increase toward South.

The phreatic aquifer is deeper in the southern part of the study area and the piezometric trend is mainly N-S, but a change of direction towards the main receptor, Peccia River, was observed. Piezometric levels decrease from about 86 m a.s.l. to about 36 m a.s.l. (Fig. 2d).

### TABLE 1

<table>
<thead>
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<th>Parameter</th>
<th>Stabilization criteria</th>
<th>References</th>
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<td>Temperature</td>
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<td>Cal-EPA, 2008; U.S. OSMRE, 2012</td>
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<tr>
<td>pH</td>
<td>±0.1</td>
<td>EPA, 1996; Cal-EPA, 2008; U.S. OSMRE, 2012</td>
</tr>
<tr>
<td>Electric conductivity</td>
<td>±3%</td>
<td>EPA, 1996; Cal-EPA, 2008; U.S. OSMRE, 2012</td>
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<tr>
<td>Redox potential</td>
<td>±10 mV</td>
<td>EPA, 1996; Cal-EPA, 2008; U.S. OSMRE, 2012</td>
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<tr>
<td>Dissolved oxygen</td>
<td>±10%; ±0.3 mg/L</td>
<td>EPA, 1996; Cal-EPA, 2008; U.S. OSMRE, 2012</td>
</tr>
</tbody>
</table>

Parameter Stabilization criteria References

The sampling phase realized in every sampling point follows the sequence of operations described above. Following the inspection and collection of relevant information from the well owner, the static piezometric level in the well was measured before the purging. The collected samples were preserved at 4°C in laboratory until analysis.
Fig. 2 - a) Simplified geological map of the study area, location of sampling points and profile track AA'; b) 3D diagram of simplified structural setting of study area; c) profile AA': 1-2) Current and recent alluvial deposit; 3) Plio-Quaternary deposits; 4) Miocene limestones; 5) Cretaceous carbonate platform limestones; d) water table resulting from the application of ordinary kriging (stable model) to the 36 monitoring points measured during the monitoring campaign. Site boundary in red.
Analytical results

The chemical analytical results show a calcium-bicarbonate facies in most of the sampling points trending towards alkaline-bicarbonate facies in the southern sector of the investigated area, where a potassium enrichment has been observed. Reducing or weakly oxidizing conditions have been observed in the whole area. In the collected samples, no exceedances of the standards or threshold values set by the various environmental acts concerning groundwater (i.e. standards/threshold values set by D.lgs. 30/2009 and s.m.i., or “CSC” set by D.lgs. 152/2006 and s.m.i.) have been detected. Indeed, the maximum value measured for F is 0.6 mg/L (CSC 1.5 mg/L), the maximum concentration of SO₄ is 53.8 mg/L vs its bound of 250 mg/L and the maximum concentration of nitrates is 35.3 mg/L, lower than its standard of 50 mg/L set by the law (D.lgs. 30/2009). At the same time, also for metals and trace elements no exceedances of their CSC have been observed in most of the collected samples, the only exception being the SV-PM1 (waste-to-energy plant monitoring point) where the manganese concentration (548.9 µg/L) exceeds the CSC (50 µg/L) (Fig. 3a). This exceedance of CSC has been observed in the same monitoring well, both in filtered and unfiltered samples, also in the past, both by site managers and control agency.

The maximum concentrations of Fe, Al and As are respectively 114.3 µg/L, 119.9 µg/L and 4.9 µg/L against their CSC of 200, 200 and 10 µg/L (Fig. 3b, 3c, 3d).

CONCLUSIONS

The sampling procedures followed during the monitoring of groundwater, can produce a great uncertainty, which can strongly affect the final analytical results. Indeed, in the past, the analytical results for samples collected by different operators or following different procedures showed significant differences. In addition, in Italy, an official national guideline is not yet available; the “best practice” document for groundwater sampling, based on national and international literature, provide a standardized procedure.

The “best practice” proposed in this paper underlines two main aspects: 1) the need and the relevance of the implementation of the conceptual model of the study area, 2) the requirement of a standardized and common planning and sampling phase, which includes an appropriate treatment and preservation of samples and quality control (e.g. field and transportation blanks, blind samples, etc.).

The application of the “best practice” to a case study in southern Latium showed as the implementation of different sampling and treatment procedures can produce significant differences in the analytical results, with subsequent legal decisions, which can influence the site management.

As a conclusion, when the proposed guideline apply, most of the exceedances observed by previous monitoring activities do not occur; hence, they can be ascribed to unfiltered samples and/or incorrect extraction procedure. The latter can be due to the inadequate well efficiency that can produce turbid samples. It is important to remember the different sampling and treatment procedures can produce significant differences in the analytical results, with subsequent legal decisions, which can influence the site management.

As a conclusion, when the proposed guideline apply, most of the exceedances observed by previous monitoring activities do not occur; hence, they can be ascribed to unfiltered samples and/or incorrect extraction procedure. The latter can be due to the inadequate well efficiency that can produce turbid samples. It is important to remember
that turbid samples may be not representative of the dissolved ions concentration in groundwater and therefore should be discarded.

Based on the above, it is important to underline that all the operators involved in the same site, including site managers, control agencies as well as researchers, should share the same sampling procedures in order to have comparable results. This would avoid legal disputes about the obtained results, and the subsequent decision linked to them could be implemented in a more participated manner.

ACKNOWLEDGEMENTS

ARIA (Aacea Risorse e Impianti per l’Ambiente) S.r.l. is acknowledged for partly funding the field activity and allowing IRSA-CNR to access the waste-to-energy plant. The population of San Vittore del Lazio, Cervaro and Cassino are also acknowledged for allowing us sampling in private wells.

REFERENCES


Co-seismic and post-seismic changes in groundwater discharge:
first results from the epicentral region of the Central Italy
earthquake 2016

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Manuscript submitted 02 July 2017; accepted 13 September 2018; editorial responsibility and handling by C. Meisina and S. Da Pelo.

ABSTRACT

Short and mid-term effects of earthquakes on groundwater flow were documented in several studies. The hydrogeological response of groundwater flow systems to earthquakes is very complex and due to significant changes in permeability. Such hydrologic changes may occur even at great distances from the epicentre and their magnitude may be related to the proximity to the earthquake focus.

Central Italy has been hit by several large earthquakes since August 2016. With reference to the carbonate aquifers located in the epicentral region, the following short term effects were observed: a significant increase of the spring discharges and the disappearance of several perched springs.

The deep-seated fault movements and fluid redistribution may cause water-level fluctuations as well as changes in groundwater discharge and composition. This study describes a preliminary characterization of such processes.

KEY WORDS: Earthquake, groundwater flow, seismic change, Central Italy.

INTRODUCTION

It is well known that hydrological changes caused by earthquakes are very common in countries exposed to high seismic risk. Several studies report variations of spring discharges as well as of water table elevations even hundreds of kilometers away from seismogenic faults (Muir-Wood & King, 1993; Carro et al., 2005; Hartmann & Levy, 2005; Amoruso et al., 2011; Manga et al., 2012). On 24 August 2016 a Mw=6.0 earthquake struck a large area located among the Lazio, Marche, Abruzzi and Umbria regions (Central Italy) and caused human casualties and severe damages to buildings and infrastructures (Aringoli et al., 2016; Civico et al., 2018; Villani et al., 2018).

The epicentre of the main shock was located a few kilometers north of the village of Accumoli (Rieti) and was followed by thousands of aftershocks, which are continuing to shake the area since that time.

With regard to the seismic sequence started on 24 August 2016, more than 1000 earthquakes with magnitude greater than 3 Mw were recorded in the first six months (Fig. 1); within the seismic sequence seven earthquakes with magnitude greater than 5 Mw were recorded (Tab. 1).

The Mw 6.0 Amatrice and the Mw 6.5 earthquakes occurred at depths of between 7 and 9 km along the Mt. Gorzano Fault and the Mt. Vettore Fault Systems, which develop through the marly and clayey carbonate sedimentary succession of the Central Apennines (Arimcoli et al., 2014; Luca et al., 2017). Such fault systems are the main seismically active extensional faults of the Amatrice-Norcia area, where outcrop pre-orogenic and syn-orogenic deposits. Since Middle Pliocene the Mt. Sibillini thrust has been dismembered by NW-SE and SW/NE dipping extensional faults (Pierantoni et al., 2013).

In this study the ongoing monitoring of three groundwater springs utilized for drinking purposes and located in the Sibillini Mountains allows to point out the effects of the Mw 6.0 Amatrice earthquake on groundwater flow.

MATERIALS AND METHOD

The study area includes a wide sector of Central Apennine, which involves the Sibillini Mts. ridge and is bounded on the north by the Potenza river (Fig. 1).

The outcropping geological formations are mainly composed by calcareous, marly and siliciclastic lithotypes (from Trias to Miocene in age) that belong to the Umbria-Marche Succession (Pierantoni et al., 2013).

The main rivers cross roughly east–west the calcareous ridges and, more in general, the hydrographic network generated deep and narrow valleys, bordered by steep slopes (Materazzi et al., 2010).

From the hydrogeological point of view the presence of lithotypes with different permeability allows the formation of different overlapped hydrogeological complexes, characterized by springs with different discharges and regimes (Boni et al., 1986; Boni et al., 2010; Aquilanti et al., 2016; Giacopetti et al., 2016a; Giacopetti et al., 2016b; Giacopetti et al., 2017; Posavec et al., 2017).

In the present study, discharge data coming from three different springs located both in the epicentral and...
in relatively remote areas (Fig. 1) have been analysed and discussed:

- the Pescara d’Arquata spring, located in the south-eastern sector of the Amatrice-Norcia area;
- the Forca Canapine spring, located in the south-eastern sector of the Amatrice-Norcia area;
- the Niccolini spring, located in the northern sector of the Amatrice-Norcia area.

RESULTS

The preliminary results evidenced both “positive” and “negative” variations; in particular all the springs showed a variable trend.

Starting from July 2016 the Niccolini spring was characterized by a recession trend; in the period 22-23 August 2016 the discharge decreased of about -1 L/s following a high slope curve; starting from the 23 August 2016 until the main shock event the discharge increased of about +3.63 L/s. Following the main shock the discharge value increased of about +10 L/s (the discharge value recorded was equal to the 84% of the average discharge value of the spring) until the 27 August 2016, after that the discharge value decreased until the 25 October 2016 following a low slope curve (recession coefficient equal to 0.003) than that recorded on July before the main shock (recession coefficient equal to 0.01), probably also feeding by heavy rainfall event.

The earthquake of October was characterized by a high discharge variability in the days before the first event of the 26 October 2016; after the second event of the 30 October 2016 the spring recorded a discharge increase value equal to +16 L/s than the value recorded on 25 October 2016, just before the first event (the discharge value recorded on 30 October 2016 was equal to the average discharge value of the spring). The month of October was characterized by heavy rainfall that may also influenced the discharge trend during the seismic event (Fig. 2a).

On January the Niccolini spring was characterized by an increase of discharge in the previous days of the seismic event probably related to rainfall and snowfall contributions (Fig. 2a); on 18 January 2017 the discharge started to decrease until the 22 January 2017 of -2 L/s than the discharge value recorded on the 17 January 2017. Starting from the 23 January 2017 the discharge values rapidly increased, probably also influenced by precipitation, reaching the peak of discharge on 16 February 2017 equal to the + 55% of the average discharge value of the spring (Fig. 2a).

The Forca Canapine spring (Fig. 3b) showed a critical trend. In the period 19-23 August 2016 the discharge value quickly increased of about +2 L/s with respect the value recorded on 18 August 2016; after that it exhibited a decrease of the discharge value equal to –1 L/s than the value recorded on the previous day; on 24 August 2016 the discharge value decreased again of about -6 L/s than the value recorded on 23 August 2016. After the main shock, the discharge increased of about +14 L/s until the 26 August 2016; from the 27 August 2016 the discharge quickly decreased (Fig. 2b) following a curve characterized by a higher recession coefficient (equal to about 0.01) than the value detected on the month of July before the seismic event (equal to about 0.002).

During the month of October the discharge continued to decrease until the seismic event of the 26 October 2016 where it slightly increased before to drop rapidly to zero. At the moment, the Forca Canapine spring is dry.

The Pescara d’Arquata spring (Fig. 3c) showed a similar trend to the above springs. After the main shock the discharge value decreased of about –16 L/s (taking into account the value recorded on the 23 August 2016) until the 27 August 2016; starting from this moment the discharge value increased of +136 L/s than the value recorded on 27 August 2016.

From the 31 October 2016 and the 29 November 2016 data are missing due to instrument malfunction.

On January the discharge continued to decrease following a curve characterized by a high slope (Fig. 2c); the discharge trend did not show any influence matching to the seismic events of the 18 January 2017.

Fig. 4 shows the percentage variation in daily discharge with respect the value recorded on 24 August 2016, which corresponds to the zero value of the graph; the comparison between the springs confirmed a general increase of discharge during the 24 August 2016 Accumoli earthquake: Forca Canapine, Pescara d’Arquata and Niccolini springs showed a discharge increase of roughly 60%, 50%, 9% respectively after 2, 28, and 3 days from the earthquake, if compared with the value recorded on 24 August 2016. Niccolini Spring, despite being the spring farthest from the epicenter of the 24 August 2016 (Fig. 1), and the Forca Canapine spring were characterized by a

TABLE 1

<table>
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rapid response to the main shock; on the contrary, that of Pescara d’Arquata spring, was characterized by a gradual increase culminating only about one month after the main event.

The discharge value recorded on 30 October 2016 with respect to the value recorded on 24 August 2016 was characterized by a discharge variation of about +10% and -17% respectively for Pescara d’Arquata and Forca Canapine springs; Niccolini spring showed on 30 October 2016 a discharge increase of about +27% than the value recorded on 24 August 2016.

**DISCUSSION AND CONCLUSIONS**

The present study allowed to characterize the co-seismic and post-seismic effects on discharge values of three springs of the central Italy.

All the springs showed a general increase of discharge during the 2016 August earthquake, even though with different trend: the Niccolini spring hydrograph indicates a rapid response to the seismic events of August while the Pescara d’Arquata and Forca Canapine springs are characterized by delayed response of 4 and 1 day respectively with respect to the main event. A similar situation was
Fig. 2 - Spring hydrographs relative to the seismic sequence; a) Niccolini spring, b) Forca Canapine spring, c) Pescara d’Arquata spring. RG, Rain Gauge.
detected after the events at the end of October. Pescara d’Arquata spring was characterized by a continue decrease of the discharge value, Forca Canapine and Niccolini springs showed a similar trend up to October 30, after this date the Forca Canapine spring started a progressive reduction until the total disappearance. Finally, only the Niccolini spring showed an increase of discharge following the seismic event of January 18, certainly influenced by rainfall and snowmelt contributions.

Several studies show that the discharge increases were probably caused by ground-shaking, while the decrease could be related to a change in coseismic volumetric strain; both the effects can lead to postseismic changes in groundwater pressure.

The disappearance of Forca Canapine spring could be related to a change in the groundwater flowpaths. In fact, several authors suggested that seismic waves may enhance rock permeability (e.g. by removing particles from clogged fractures, or enlarge fractures), which in turn may lead to a redistribution of pore pressure and consequently changes of water level and discharge in areas close to the local pressure source. So this effect could lead to a deep modification of groundwater flowpaths with consequent re-distribution of water resources.

The behavior of the springs in the period September-October 2016 would seem somewhat anomalous; in fact after apparently consistent rainfalls, no particular changes were observed in the regime of the spring flow, which continued to show a fairly marked recession. This fact could however be linked to the particular drought period that characterized spring and summer 2016; more accurate hypotheses can be formulated once the data of the following seasons are available.

In conclusion, the further application of specific methodologies (e.g. spring hydrograph analysis, numerical modelling) and chemical-physical data (e.g. temperature, conductivity, pH and major ions) in the near future will allow to integrate the results obtained in the present study.

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“La Maddalena” exploratory adit - base tunnel of the Turin-Lyon high speed rail project: hydrogeological monitoring data analysis

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INTRODUCTION

“La Maddalena” is a 7 km-long exploratory tunnel located in Italy. The excavation started in January 2013 and was completed in February 2017. This tunnel is one of the four exploratory adits excavated as part of the Turin-Lyon high-speed rail project, which includes the 57.5 km-long twin-tube Mont Cenis Base Tunnel. The excavation of the “La Maddalena” exploratory tunnel, with diameter of 6.30 m and length of 7 km, began using conventional tunnelling (hydraulic hammer) for the first 198 metres through Quaternary deposits and rock cover, followed by mechanized tunnelling using a main beam TBM through the metamorphic Ambin Massif of the Briançon area. The pre-set goals of the “La Maddalena” exploratory tunnel were different, such an increasing knowledge of the massif in depth, complete a mechanized excavation test and to be an intermediate access point for construction and operation of the Mont Cenis Base Tunnel (e.g. Parisi et al., 2017). The monitoring of different mechanical, hydraulic and hydrogeological parameters characterising the rock mass is fundamental in any underground work, both at the excavation area and in a wider sector.

In this paper, the attention has been focused on the hydrogeological monitoring to understand the interaction between the water inflow and the tunnel excavation. The interaction between tunnelling and groundwater is a very relevant problem due not only to the need to safeguard water resources from impoverishment and pollution risk, but also to guarantee the safety of workers during the construction, the long-term stability of the underground works and the effectiveness of the draining towards the external environment after the tunnel construction.

In the tunnelling activities, groundwater should therefore be considered at the same time a natural valuable asset to be defended and a source of risk to be prevented during the underground construction phases (e.g. Lo Russo et al., 2015).

The results of the hydrogeological monitoring stressed the importance of realizing exploration tunnels with particular reference to the knowledge of the rock mass, especially when the cover is very thick and the tunnel length is extensive. Moreover as reported by Perello et al. (2013), the back analysis of excavated tunnels is not only relevant for gaining new information on methods that allow an evaluation of inflows, but also for the appraisal of the mechanisms governing groundwater circulation in crystalline geological contexts, their interaction with the excavation progress, and local-to-large scale consequences on shallow aquifers, springs and rivers (e.g., Maréchal 1998; Gargini et al. 2009). These data collected in the exploratory tunnels are in fact extremely useful for the construction of the main tunnels.

A monitoring program must begin before the opening of the tunnel and must continue after the end of the construction. In the tunnelling activities, we can distinguish three important phases:

• design
• construction
• operating (post-construction)

A suitable surface and groundwater monitoring program should identify wells, springs, and streams that might be affected by the construction of the tunnel, but
also water monitoring points outside the area overlying the tunnel track, which can provide a useful control of undisturbed conditions (e.g. Nebbia et al., 2006). Monitoring should also include water inflows in the tunnel.

Yield, chemical features and temperature data of the main water inflow can provide information for multiple purposes. The early knowledge of these data can be important to previously size an adequate drainage system or to predict the presence of aggressive water. Moreover, the forecast of water inflows into tunnels excavated in crystalline rocks of mountain chains is a challenging issue that has a fundamental impact on final tunnel design, to choice devices and techniques for groundwater evacuation. The analysis of temperature of water inflows can provide information on groundwater circuit affecting the rock mass and can underline a potential geothermal reuse of water inflows. According to law, water inflows should be treated as discharge water. However, if characterized by quite stable flow rate and temperature, they might be considered a potential geothermal energy source. Indeed, recent progress in underground excavation technologies has allowed the construction of deep tunnels for the complementary exploitation of road, civil and hydroelectric infrastructures, e.g., the uptake of renewable hydroelectric and geothermal energy sources, showing a positive effects of a civil work on a social and manufacturing community (e.g. Torri et al., 2014).

In this work we highlighted the results of the inflow groundwater monitoring activity performed during the excavation of the “La Maddalena” exploratory tunnel in order to evaluate the reliability of the design hypotheses (e.g. Italferr, 2009) and the correlated Geological Reference Model.

GEOL GICAL REFERENCE MODEL

The processing of the geological reference model included the elaboration of existing hydrogeological and geological bibliographic documentation, field surveys and geological drilling.

The excavation involves the “Pennidic Domain”, and more in details the tectonic contact between Piemontese Zone (mainly Calcschists and Green Stones Unit) and Brianzozene Zone (Ambin Massif Unit and related cover). Based on current geodynamic and paleogeographic models, the Calcschists and Green Stones Unit (Piemontese Zone) includes portions of oceanic crust (“Ophiolites”) with associated sedimentary cover (“Calcschists”) belonging to the Piedmont oceanic basin (e.g. Debelmas & Lemoine, 1978; Dal Piaz et al., 1972). The Ambin Massif Unit (Brianzozene Zone) outcrops in the left slope of Val di Susa. It is structurally under the oceanic units previously described. This unit includes a crystalline basement concerning two geological complexes (Clarea Complex and Ambin Complex) and the Mesozoic cover.

According to the Final Project of Maddalena exploratory tunnel (e.g. Italferr, 2009) four main hydrogeological complexes have been forecasted along the excavation: Quaternary Deposits (Hydrogeological Units Q), Calcschists of Piedmontese Zone (Hydrogeological Units 6), Carniole (Hydrogeological Unit 1), Gneiss and Micaschists of Clarea and Ambin Complex (Hydrogeological Complex 5).

The lithologies and their geomechanical characteristics encountered during the excavation did not differ much from the provisional longitudinal profile except for the absence of the Hydrogeological Complex 6 (Calcschists of Piemontese Zone) which were expected between chainage (hereafter ch.) 0+130 and 0+205.

As reported by Parisi et al. (2017) the initial 120 m of the exploration tunnel passed through Quaternary deposits represented by glacial and fluvio-glacial deposits. Then between chainage 120 and 198 m the units encountered were carbonate cataclasites and dolomitic marble, probably related to the tectonic Gad Unit, and mica schist and calcareous schist, probably related to a Mesozoic cover of the Ambin.

The excavation of this section was completed without encountering water inflows and without any particular geomechanical problem. Starting from chainage 0+198, excavation took place only in the formations of the domed structure of the Ambin Massif. More specifically, up to ch. 1+148 aplitic gneiss of the Ambin Complex (AMC), from ch. 1+148 to 1+350 the transition zone (AMD), and from ch. 1+350 to the end of the tunnel alignment grey mica schist and minute gneiss of the Clarea Complex (CL) were encountered. (Fig. 1).

During the excavation of the tunnel, no metabasite lenses were encountered, although reported in literature and in some cases found in outcrops of the Clarea Complex. The volcano-sedimentary components of the sequence were explicable only in connection to hornblende schists in the tunnel. The main schistosity is oriented on average in direction NE-SW, with local N-S deviations; the inclination of the schistosity has angles ranging from low to medium (from 10° to 50°) up to 90° to 140°. Within the Ambin Complex, the schistosity has a steeper inclination while in the Clarea Complex it tends to incline at nearly horizontal angles. An average of five to six families of discontinuities (joints and fractures) occur with a certain frequency, in some cases interconnected, typically arranged NE-SW and NW-SE and in certain cases N-S. The most pervasive families are nearly always set on the pre-existing schistosity. In general, all the faults crossed are minor faults, with a maximum thickness of a decimetre. Generally, these structures seem to develop mostly with the presence of cataclasite and only marginally of clay (Parisi et al; 2017).

MATERIALS AND METHODS

HYDROGEOLOGICAL MONITORING DATA

The monitoring data analysed cover the period since the beginning of the excavation of “La Maddalena” exploratory adit to the ch. 5+548 m (July 2016). The hydrogeological monitoring was set up, allowing the collection of multiple data concerning:

- daily measure of the total inflow rate;
- bimonthly measure of conductivity, temperature and pH of each punctual water inflow;
- sampling and chemical analysis of some of the main inflows.
RESULTS AND DISCUSSION

RATE FLOW ANALYSIS

The comparison between the expected stable total water inflow as designed in the tunnel project and the total water inflow actually measured during the excavation of “La Maddalena” exploratory tunnel is very important. In fact, the measured total water inflow was significantly lower than expected at the design stage, despite the measured data referred to a transient value of total inflow that should be higher than the stabilized flow rate.

The recorded values were in fact lower than the expected minimum inflows in steady state conditions. This difference is due to an overestimation of 57.8 to 106 l/s expected as inflows related to some Hydrogeological Units such as Quaternary Deposits (Hydrogeological Units Q), Carniole (Hydrogeological Units 1) and Calcschists (Hydrogeological Units 6). During excavation, only dry Quaternary Deposits were in fact crossed and no karst conduits were intercepted in the Hydrogeological Unit 1 - Carniole (e.g. Parisi et al. 2017). Water inflow began only at ch. 0+244 when the Hydrogeological Complex 5 - Gneiss and Micaschists of Clarea and Ambin Complex, was crossed by excavation (Fig. 2). At the Hydrogeological Complex 5 a low hydraulic conductivity value ranging between $5 \times 10^{-8}$ and $5 \times 10^{-7}$ m/s was assigned (e.g. De Matteis et al., 2016). These values, was related to the presence of faults and fractures.

The total inflow measured until ch. 5+548, is then related only to Hydrogeological Unit 5 (Gneiss and Micaschists).

However, if we consider only the expected inflow related to Hydrogeological Unit 5, the value of the measured inflow is generally between the minimum and maximum stable expected values (Fig. 3). At ch. 5+548 (27-07-2016) is in fact reported a total inflow of 55.4 l/s which is just below the minimum stable expected inflow rate.

Another crucial point related to the inflow monitoring data is the lack of a clear distinction, which was an initial assumption in the design studies, between single point inflows and distributed inflows. According to design forecasts, single point inflows would have ranged between 25 and 50 l/s at ch. 1+340 and ch. 5+000 at the interception of two main faults.

The measured data differ from the expected values, since only a few single point inflows, lower than 1 l/s, were intercepted during excavation. The expected strong single point inflows, related to specific faults, were recorded as minor distributed inflows of the rock as a whole. This aspect is fundamental in the design of the intercepted water collection system.

Possible correlations between precipitation and flow rates measured at the portal have also been considered. The comparison between the flow rate recorded at the portal (647 m) for the period 2014-2016 and rainfall patterns registered in four rainfall stations have been analyzed showing a generalized lack of direct correlation with precipitation. However, it cannot be excluded that some structural discontinuities could have a direct connection to the meteoric water.

CHEMICAL ANALYSIS

Sampling and chemical analysis of some of the main single point inflows represented another important element for hydrogeological monitoring. Despite the lithologies affected by the excavation belongs to the Hydrogeological Complex 5 - Gneiss and Micaschists - three dominant hydrochemical facies has been observed, that can be summarized as follows:

- Ca-(Mg)-HCO$_3$ dominant type between ch. 0+300 and ch. 1+160
- Na-(K)-Cl dominant type between ch. 1+168 and ch. 2+000
- Na-(K)-HCO$_3$ dominant type between ch. 3+245 a circa la ch. 4+850
The results of the chemical analyses of the recorded water inflows were then compared with the chemical analyses of the springs located in the hydrogeological units crossed by the exploring tunnel. This comparison made it clear that a few inflows sampled in the first section of the excavation (ch. 0+300 to 1+160) and a few springs show similar hydrogeochemical facies, both characterized by Ca-(Mg)-HCO₃ dominant type waters. However, according to the available monitoring carried out both before and during excavation, the hydrodynamic regime of the springs does not appear to have been disturbed by the exploratory tunnel excavation. Since hydrochemical facies are a
function of lithology, solution kinetics, and flow patterns of the aquifer (e.g. Back, 1960), the similar hydrogeochemical features of springs and water inflows could therefore be related to the similar lithology that characterizes the recharge basins.

**TEMPERATURE ANALYSIS**

During the excavation the temperature of the rock has also been recorded in addition to the water inflows monitoring. The temperature of the rock tends to become higher with depth; generally the average geothermal gradient is about 3°C/100 m but this geothermal gradient can otherwise vary locally. Subsurface rock temperatures range in mountain areas depend in fact on many influence factors: cover thickness, three-dimensional topography, lithologic structure (with anisotropic thermal conductivity), hydrogeology (permeability distribution and water circulation), as well as transient effects like uplift/erosion and past climatic changes (e.g. Rybach, 1995).

In Fig. 4, a comparison between rock temperature and water inflow temperature measured in the tunnel is presented. The overburden over the tunnel is also reported. The temperature values represent the average of temperatures measured bimonthly for each single inflow during the monitoring between May 2014 and July 2016. Fig. 4 shows how the average water temperature increases progressively with the excavation. The average temperature of inflows varies between 13.7°C at ch. 0+246 and 39.5°C at ch. 5+289 (20-22-07-2016). These values and trends are coherent with the thermal conditions designed in the project.

The rock temperature was measured by mobile stations that are moved only when a steady value of temperature is reached. Measurement points are located at an average distance of 50 meters each other along the excavation. In Fig. 3 the average temperature of rock is reported. Excluding the positive anomaly (from ch. 3+400 to ch. 4+050), the average geothermal gradient in the tunnel seems to be near 1.2 ± 1.3°C/100 m (e.g. Bufalini & Parisi, 2017).

The average rock temperature measured from the start of the excavation to about ch. 5+450, is always higher than the average water temperature along the excavation. This consideration is valid if we compare both average value of rock and water temperature in the same point along the excavation and the temporal trend of water inflow and rock temperature.

The monitoring data show that the water temperature is generally lower than the rock temperature measured over time along the excavation. The recorded water temperatures and water temperature trend, which increase with the tunnel depth, may indicate a quite slow hydrogeological circuit regarding the excavation area and a quite long residence time in the aquifer.

**CONCLUSIONS**

The comparison between the hydrogeological monitoring data collected during excavation of the “La Maddalena” exploration tunnel and the design hypotheses has highlighted a general overestimation of the forecast water inflow. This difference is mainly due to an overestimation of the forecast inflows related to Quaternary Deposits and Carniole (Hydrogeological Unit 1). Otherwise the flow rate regarding the only the Gneiss and Micaschists of Clarea and Ambin Complex (Hydrogeological Complex 5), the only complex to be
really interested by water inflow along the excavation, falls within the forecast ranges. Furthermore, a clear distinction between single point inflows and distributed inflows along the exploratory tunnel, which was an initial assumption in the design studies, has not been found. Temperature and chemical composition of punctual water inflow have given the possibility to find out some characteristics concerning the hydrogeological water supply circuits: a quite slow hydrogeological circuit seemed to interest the excavation area, even if the water temperature is generally lower than the temperature of the rock measured over time along the excavation.

“La Maddalena” exploratory adit experience confirms the importance to realize exploratory tunnels previously to the excavation of a main tunnel. Thanks to the hydrogeological monitoring, an increased level of understanding of some hydrogeological complexes, which will interest the future Mont Cenis Base Tunnel has been gained, in particular for those interesting the Ambin Massif Unit.

Finally thanks to the temperature monitoring of the main water inflow La Maddalena” exploratory adit can also represent in perspective a very interesting possibility to exploit the related geothermal potential.

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Assessment of vulnerability to pollution and seawater intrusion of groundwater in the anthropized reclamation area of Arborea (W. Sardinia)

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ABSTRACT

The phenomenon of seawater intrusion is one of the major problems in Sardinian coastal aquifers (Italy). In particular, it has been detected in the reclamation area of Arborea plain (west Sardinia) where intensive agriculture and dairy farming are the mainstays of the local economy.

In this research SINTACS and GALDIT vulnerability indexes and the numerical model for simulating groundwater flow have been applied for evaluating respectively the intrinsic vulnerability to pollution, seawater intrusion and groundwater flow for a typical Mediterranean phreatic sandy aquifer such as Arborea plain aquifer.

This research may offer a valuable contribution to the team of existing tools in the field of seawater intrusion and groundwater quality modelling.

KEY WORDS: Seawater intrusion, SINTACS, GALDIT, numerical model, Sardinia - Italy.

INTRODUCTION

Groundwater represents an important very sensitive natural resource exploited for human consumption, agricultural and industrial activities. In Mediterranean area, one of the common environmental hazard for groundwater, that may affect coastal aquifers, especially in agricultural areas, is represented by the phenomenon of seawater intrusion (Barrocou, 2008; Mas-Plat et al., 2014). The intensive use of groundwater resources for the agricultural practices and for irrigation may generate the deterioration of groundwater quality, in the areas particularly vulnerable to seawater intrusion. Such phenomenon is one of the major problems in Sardinian coastal aquifers (Italy). In particular, it has been detected in the reclamation area of Arborea plain (west Sardinia) (Barrocou et al., 2004; Barrocou et al., 2006; Cau et al., 2007) where intensive agriculture and dairy farming are the mainstays of the local economy.

In this work, two different parametric models to evaluate the vulnerability of groundwater in Arborea plain are presented and compared in order to evaluate respectively the Intrinsic Vulnerability to contamination and Specific Vulnerability to seawater intrusion. The vulnerability values of the aquifer have been compared with the simulated groundwater flow obtained by with modular three dimensional finite difference groundwater flow model (MODFLOW).

STUDY AREA

The study area (Fig.1), Arborea plain, extends over roughly 70 Km² and it is part of the coastal flood plain near the Gulf of Oristano in Western Sardinia.

The hydrogeology of the area is characterized by Sandy Hydrogeological Unit (Ghiglieri et al., 2016), which is represented by a phreatic aquifer hosted in the Holocene littoral sands deposited during the most recent marine transgression. Details on hydrogeological and geochemical features of the study area are reported in Ghiglieri et al, 2016; Pittalis et al., 2018; Biddau et al., 2019.

MATERIALS AND METHODS

In this research, SINTACS and GALDIT vulnerability indexes and the numerical model for simulating groundwater flow have been applied for evaluating respectively the intrinsic vulnerability to pollution, seawater intrusion and groundwater flow for the phreatic aquifer of the Arborea plain. These three methods have been applied under variable hydrogeological conditions and water samples collected in 35 wells by the society ARPAS (Regional Agency for Environmental Protection of Sardinia) in different research periods (from 2007 to 2015). All parameters used for this vulnerability assessment were prepared, classified, weighted and integrated in a GIS environment.

As concern the definition of the Intrinsic Aquifer Vulnerability to Contamination, different methods can be applied. In this work, as suggested in Italian guidelines for aquifer vulnerability characterization (ANPA, 2001) the SINTACS method has been applied (Civita & De Maio M., 2000). This method takes into consideration the seven parameters that describe the site characteristics, each of them has a score ranking from 1 to 10 depending on
its influence on vulnerability taking into consideration a series of multipliers weight coefficients linked to the real impact of each specific coefficient to the vulnerability.

The parameters are: groundwater table depth from surface (S), infiltration through the soil (I), self-depuration effect unsaturated zone (N), soil cover and texture (T), hydrogeological characteristics of the aquifer (A), hydraulic conductivity of the aquifer (C) and topographic slope (S) and a series of weight coefficient multipliers for every impact situation examined. The governing equation of the model defines the Intrinsic Aquifer Vulnerability to Contamination Index (V.I.) as follows:

\[
V.I. = \sum_{i} x_i \times w_i
\]

Where \( x_i \) is the rating of each one of the seven parameters and \( w_i \) the relative weight of each parameter. The intrinsic vulnerability obtained with the SINTACS method is achieved by the overlay mapping of seven maps resulting from the sum of the products of scores and weights. The Intrinsic Aquifer Vulnerability to Contamination Index gives a value of the vulnerability degree, for each finite square element, variable in a very wide range.

The GALDIT method (Chachadi et al., 2001; Chachadi et al., 2007) takes into consideration the most important factors controlling seawater intrusion were found to be: Groundwater occurrence (aquifer type; unconfined, confined and leaky confined) (G); Aquifer hydraulic conductivity (A); height of groundwater Level above the sea level (L); Distance from the shore (distance inland perpendicular from shoreline) (D); Impact of existing status of seawater intrusion in the area (I); and the Thickness of the aquifer that is being mapped (T). These factors, in combination, were found to include the basic requirements needed to assess the general seawater intrusion potential of each hydrogeological setting.

GALDIT Index is the obtained by computing the individual indicator scores and summing them as per the following expression:

\[
GALDIT = \sum_{i} w_i \times x_i
\]

Where \( w_i \) is the weight of the \( i \)th indicator and \( x_i \) is the importance rating of the \( i \)th indicator (Chachadi et al., 2001). The Aquifer Vulnerability to Seawater Intrusion Index gives a value of the vulnerability degree, for each finite square element, variable in a very wide range.

Numerical flow simulation using MODFLOW numerical code, by means of data collected in 35 wells by the ARPAS (Regional Agency for Environmental Protection of Sardinia), was modeled and calibrated for steady state conditions by simulating flow variations in 2001 and 2007 and was validated with data recorded during the 2007 field measurements (Galiano et al., 2014). Subsequently, for transient state conditions the model has been applied for nine years, from 2007 to 2015, where hydrological and hydrogeological factors have been evaluated for stress periods (every six months).

The results show a general good correspondence between calculated and measured piezometric levels values; the results obtained from the comparison between the measured and calculated values show a standard error equal to 0.465 m while the normalized average squared deviation is 8.83%, less than 10%.

RESULTS AND DISCUSSION

The Intrinsic Vulnerability map (Fig. 2) has been obtained by applying the SINTACS equation. The zones with Very High Intrinsic Vulnerability value are located in the coast N-W of the plain (where on the sandy land there is very low protection for the groundwater). In these
Fig. 2 - Intrinsic vulnerability map. Scale 1: 50,000.

Fig. 3 - Seawater intrusion Vulnerability map. Scale 1: 50,000.

Fig. 4 - Numerical flow simulation.
areas the geology is formed by alternating layers of clay and limestone. The zones with high intrinsic vulnerability value are located in the most part of the study area, where the soil is characterized by alternating layers of gravel and sand; the zones with low intrinsic vulnerability value are located in the S-W coastal shores and small claimed areas where the clay matrix forms a protection against the groundwater pollution.

The Seawater Intrusion Vulnerability map (Fig. 3) has been obtained by applying the GALDIT equation. The zones with very high vulnerability value are located along the entire coast and includes the territory between the coast and the inland to a distance of about 700 meters; the zones with moderate vulnerability value are located in the other part of the study area. There are no areas that are not affected by the Seawater Intrusion phenomenon.

The numerical flow simulation results (Fig. 4) can be considered satisfactory as they confirm the trend of the flow lines (resulting from the measurement campaigns held in 2015) in an E-W direction for the groundwater that flows into the sea and the lagoons.

CONCLUSIONS

The methods applied have demonstrated that the study area is particularly vulnerable to contamination and to seawater intrusion phenomenon. The obtained results highlights that the coastal areas characterized by a very high vulnerability to seawater intrusion are also characterized by low piezometric head values.

This research confirms that parametric methods coupled with groundwater flow modelling can be valuable tools for the definition of action plans aimed at tackling seawater intrusion phenomenon.

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Quality of water in two areas affected by past mining activities in alpine context

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ABSTRACT

Abandoned mines can pose serious pressure on local water sources. Analyses of the possible water related environmental problems connected to past mining activities was performed in two mining areas, Campello Monti and Gorno in NW Italy. To study impacts on local water sources water sampling campaigns and analyses were performed. The samples were analyzed to measure alkalinity, electrical conductivity, pH, chemical elements: Hg, Tl, Cd, Cr (total), Cr (VI), Ag, As, Pb, Se, Ni, Co, Mn, Al, Fe, Cu, Zn, B and other analytes: CN-, Fl-, Mg2+, Na+, SO4\(^{2-}\), NO3\(^{-}\), Cl-. The water samples collected in Campello Monti area showed nickel contamination. The water samples collected at Gorno showed no contamination. Both Gorno and Campello Monti are two areas that were affected by intense mining activity in past. The absence of contamination in water (groundwater and rivers) in Gorno compared to Campello Monti may be due to several concomitant factors apart from the different geological context: in Gorno the higher pH of groundwater, which facilitates the precipitation of heavy metals and the increased flow velocity in the karst limestone rocks.

KEY WORDS: hydrogeology, groundwater circulation, abandoned mines, hydrochemistry, mine waters.

INTRODUCTION

During the stages of exploration, extraction, and processing of mineral ores, large amount of solid and liquid waste are generated along with emissions of particulate matter and harmful gases into the atmosphere. Mining sites accompanied by associated facilities for the preparation and processing of ores, rock waste disposal sites and tailings are potential polluters. In the past upon the cessation of mining, mines have been left abandoned without proper mine closure and environmental impacts planning. These abandoned mines are left to the nature and the mines can become flooded (Atanacković et al., 2013). Mine waters start circulating through the mine tunnels and eroding rock waste heaps coming in contact with primary and secondary minerals. These facts leads to the general consensus that abandoned mine sites have harmful levels of metals and other contaminants in superficial water and groundwater (Iavazzo et al., 2012, Mehta et al., 2017). However, the water quality depends on factors like ore-deposit type and processing, exploitation method, geochemical and hydrogeochemical conditions (Banks et al., 1997). This dependency of quality of water sources on local conditions make it necessary to assess the quality of water sources nearby abandoned mine sites. In this study, regional investigations were conducted to determine the hydrochemical characteristics of superficial water and groundwater in two abandoned mining sites of North Italy.

SITE STUDIES: GEOGRAPHICAL, GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The present study was conducted in abandoned mine sites of Campello Monti and Gorno of North Italian Alps. Fig. 1. shows the geological setting of Campello Monti and Gorno. The geographical location, geological setting and hydrogeological setting is described in following sections.

CAMPELLO MONTI

Campello Monti is a small settlement of Valstrona Village in the northern sector of Piemonte (northwestern Italian Alps). The village lies in the Strona Valley, bordered on the Anzasca Valley to NW, on the Ossola Valley to E-NE, and to the Sesia Valley to S-SE. It is a small Walser community 1305 m above sea-level to the south of Monte Rosa, close to Monte Prevor (1726 m.a.s.l.), Monte Capezzone (2421 m.a.s.l.) and Altemberg which encircle Lake Capezzone.

The rocks in this area are rich in nickel, copper and cobalt. The area was exploited for nickel production from Fe-Ni-Cu-Co magmatic sulphide deposits occurring from the Sesia to Strona valleys, mostly in the ultramafic layers of mafic complex of Ivrea Verbanzo Zone, a tectonic unit cited as an example of exposed continental crustal section which has preserved the transition from amphibolite to granulite facies (Schmid et al., 1987, Barboza & Bergantz, 2000, Boriani & Villa, 1997, Reddler et al., 2012). The mafic formation consists of a sequence of cumulate peridotites, pyroxenites, gabbros and anorthosites, together with a large, relatively homogeneous body of gabbro-norite, grading upwards...
into gabbro-diorite and diorite. Campello Monti area consists of lherzolites, in places with titanolivin, in large and smaller masses.

Focusing on the mining activities, it has to be highlighted that the nickel extraction from the ore deposit lasted from 19th Century (1865) and continued until 1940s. The extractive activities caused a huge production of extractive waste (mainly waste rocks and operating residues), dumped in extractive waste facilities located on the left side of the valley, from the eastern margin of the Campello Monti village to about 1 km eastward, from 1200 to 1600 m a.s.l.; no roads reach these extractive waste facilities except for some pedestrian paths.

The main stream of the valley is the Strona Creek. It is fed by springs located in the surrounding reliefs. The Strona creek start from Campello Monti and ends at river Toce. Other minor creeks are located in the valley.

With respect to hydrogeological aspects, the rocks are essentially impermeable or weakly permeable due to fracturing. In this context, groundwater circulation in the area takes place in fractured rocks, in waste dumps and in mining tunnels used for extracting metal (Fig. 2).

Gorno mining basin is situated about 70 km northeast of Milan and about 25 km northeast of Bergamo. It lies at 710 m a.s.l. on the left side of Riso Valley, a lateral valley of Seriana Valley, in Orobian Alps. Gorno is composed by many settlements: Villassio, Campello, Chignolo, Contrada San Giovanni, Erdeno, Riso, Sant’Antonio.

The mining area of Gorno is located in Triassic carbonate rocks in the Eastern Italian Alps, belonging to the so-called “Lombardian Basin” formed by a strong subsidence occurred in Permian-Triassic age (Assereto et al., 1978). The Triassic series comprises alternating carbonate platform and terrigenous sediments, that overlies the volcanoclastics of the Collio- Verrucano Lombardo formations. The youngest formation is Gorno Formation (lower Carnian), which consists of marly micritic and marly sandstone, limestones with thin dark grey laminations. The upper part of the sequence consists of a gradual transition to thin grey / greenish sandstone levels in alternation with green petites. Gorno Formation is linked to the evolution of depositional systems in the central Southern Alps (also known as Bergamasc Prealps), begun during Carnian age due to the rise and subsequent dismantling of a volcanic system located south to the Orobic basin. Gorno formation outcrops in the bottom sector of the left side of Riso Valley, where the former mining activities had taken place. Below Gorno Formation the Calcare Metallifero Bergamasco is found (lower Carnian), which represents the “metallifero” member of the above mentioned Gorno area. The lithofacies is predominantly composed by micritic, bioturbated dark limestones, associated to peritidal, partially dolomitized limestones. The upper part has black chert elongated nodules and thin marly-clayey intercalations with Pb, Zn, fluorite and quartz (Omenetto & Vailati, 1977, Rodeghiero & Vailati, 1978, Jadoul et al., 2012).

The mines were exploited for a long period: from Roman Age until 1980s producing around 6 Million tons of ore in total. The minerals extracted were zinc and lead rich: mainly sphalerite (ZnS), with variable amount of galena (PbS) and calamine. The Gorno ore deposits are spread over and the prevailing distribution trend is approximately N-S. The shape is represented by tubular
“columns”, longitudinally developed from 200 meters to over 2 km with widths ranging from 50 to 400 meters and the thickness between 3 to 20 metres. In these deposits lie different galleries where mining was carried out. Thus the mining waste is spread over the area with different dumps.

The Riso creek represent the main watecourse of the Riso valley, in wich flows for 9.6 km before to reach the Serio river, the main water artery of the Val Seriana. In the Gorno area dolomites and limestones outcrop, thus groundwater flows in fractured karst media with high permeability. Numerous springs are present and used for civil purposes.

Moreover the study area is located in the recharge area of Nossana Spring, located around 3 km far from Gorno village, in the right side of the Seriana Valley (Gattinoni & Francani, 2010). This is a very important spring, used for the water supply of Bergamo city.

METHODS

To study the impacts on local water sources, water sampling campaigns and analyses were performed.

In Campello Monti three sampling campaigns were conducted in June, July and October 2016. Some samples of water were collected, and particularly groundwater (GW) from springs and water flowing from tunnels and surface water (SW) in the Strona creek and minor creeks in the valley. During the three sampling campaigns, 30 water samples were collected. The chemical analyses from samples of Campello Monti was performed on 17 water samples, considered the most significant, more specifically 11 from GW and 6 from SW. The GW was sampled in correspondence to springs and drainage water from mining tunnels. The SW was sampled in correspondence of Strona creek and minor creeks in the valley. Wherever possible, SW samples were taken in the creeks upstream and downstream from the mine dumps. Moreover 3 water samples were analyzed for cyanide, located in the Strona creek and downstream from mine waste deposits.

In Gorno two sampling campaigns were conducted in September and October 2016. Some water samples were collected, and particularly groundwater (GW) from springs and water flowing from tunnels, and surface water (SW) in the Riso creek and other creeks. During the two sampling campaigns, 21 water samples were collected. The chemical analysis from samples of Gorno was performed on 17 samples from GW and 4 from SW. The GW was analyzed in correspondence to 11 springs, 5 drainage water from mining tunnels and one sample was analyzed in correspondence to the retaining wall of tailing. The SW was analyzed in correspondence of the Riso creek and minor creeks in the valley.

The physical-chemical parameters, temperature, pH, and electrical conductivity (EC) were measured in situ for all samples.

Chemical analyses, performed to investigate the distribution and of the most common elements and metals in water, were performed in the laboratory of N.S.A. - Nuovi Servizi Ambientali S.r.l. (Robassomero, Turin, Italy). The analysed compounds comprise aluminium, antimony, silver, arsenic, beryllium, cadmium, cobalt, total chromium, chromium VI, iron, mercury, nickel, lead, copper; manganese, selenium, thallium, zinc, boron, fluorides, sulphates, nitrate (NO₃), chlorides, total phosphorus (P), calcium, magnesium, sodium, potassium, total alkalinity (sum of CO₃⁻ + HCO₃⁻), titanium, molybdenum, tin, nitrites (NO₂⁻), cyanide.

RESULTS AND DISCUSSION

CAMPello MONTI

With regard to physical parameters, GW temperature varies from 7.0 °C to 15.6 °C, with the lowest values (7-8 °C) in mine tunnels. SW temperature ranges between 8.5 °C and 14.9 °C and is highly dependent from the season; indeed the coldest temperature in creeks and rivers were measured in October and the highest in July.

Electrical conductivity in GW swings between 18 µS/cm and 127 µS/cm. The highest values (70-127 µS/cm) were measured in situ in the mine tunnels. In springs the EC varies between 18 and 69 µS/cm. EC in SW swings between 14 and 75 µS/cm, with values comparable to springs. The EC values in Strona creek show the lowest values (about 30 µS/cm) upstream to Campello Monti. The highest values (75 µS/cm) is located in correspondence to SW sampling point downstream to mine wastes.

Water samples were found to have pH in alkaline range. The pH value varied from 7.1 to 8.1 (Fig. 3a). In groundwater the highest values are located in correspondence to mine tunnels (7.7-8.1). Values ranging from 7.1 and 7.6 were measured in correspondence to the springs. In surface water pH values swings between 7.4 and 7.8, in the river flowing through the mines area. The possible reasons of these pH values could be the presence of mafic silicate mineral phases like olivine, pyroxene and anorthetic plagioclase, which leads to neutralization of mine waters. The similar phenomenon was observed at nickel sulphide mine hosted in mafic intrusions in Ballangen, Nordland, Norway (Banks et al., 1997).

In Campello Monti mining area, nickel is the only parameter that exceeds the limit (20 µg/l, according to Italian Law Decree 152/06). The concentrations range between values inferior than the detection limits (1.0 µg/l) and 512 µg/l; 9 samples (5 in GW and 4 in SW) show concentrations <20 µg/l, and 8 samples (6 in GW and 2 in SW) show levels >20 µg/l.

More specifically, the springs in the right of the Strona river have nickel concentration less than the detection limit. On the left side of the valley, Ni concentrations greater than 20 µg/l are present in the springs downstream the mine area; also GW in the mine tunnels show generally Ni concentration greater than 20 µg/l up to 304 µg/l. In surface water, Ni concentration less than 20 µg/l were detected in the creek that crosses Campello Monti and in the Strona creek. On the contrary, in the creek that crosses the mine area were detected high Ni levels, up to 512 µg/l at the bottom of the mountainside, after having crossed the entire mine area (Fig. 3b).

Considering other metals, some water samples show also concentrations greater than the detection limits, but less than maximum allowable concentration, of Al, Cu, Zn, Co, Cr (total), both in GW and in SW. Cyanide ions were not detected in all the samples.
GORNO

As regard as physical parameters, GW from mine tunnel shows temperature swinging between 8.2°C and 12.6°C. SW show a wide range of temperature, between 14.2°C and 25.3°C (registered in a secondary creek near Ponte Nossa).

EC in GW swings between 190 µS/cm and 335 µS/cm, next to a retaining wall of tailing. In SW the EC is quite constant (308-348 µS/cm).

The pH values varies from 7.39 and 8.4 in GW. In SW the values are quite constant (8.4-8.52) (Fig. 4a). The water samples collected at Gorno showed higher pH than in Campello Monti which may be due to presence of carbonate minerals like calcite and dolomite.

The surface water samples collected at Gorno showed no parameter exceeding the limits, according to Italian Law Decree 152/06. Although the mine activities for the extraction of sphalerite and calamine, water samples showed no contamination of Zn in both groundwater and surface water (Fig. 4b). The SW samples collected in the Riso Creek in the lower part of the valley shows concentration of Zn, respectively 14.8 µg/l and 7.6 µg/l.

The chemical analyses of the GW from the mine tunnels highlight that GW generally do not present metal concentrations. Only one tunnel located in the mine area have concentration in Al, Cd, Fe, and Zn.

Considering the springs, the GW collected in the right side of the valley presents only very low concentrations of Al (inferior than 2 µg/l). The GW collected in the left side in the mining area, instead, shows concentrations of Al (up to 5.7 µg/l), Cd (0.3 µg/l) and Zn (69.0 µg/l). Free cyanides were never detected.

The absence of contamination in water (groundwater and rivers) may be due to several concomitant factors: the higher pH of groundwater, which facilitates the precipitation of heavy metals and the increased flow velocity in the karst limestone rocks.

CONCLUSIONS

The superficial water and groundwater act as important drivers of metal ions from source of pollution to different receptors. It is therefore imperative to carry out hydrochemical investigations at abandoned mine sites. Investigation of the hydrochemical characteristics of 38 samples from abandoned mine sites of Gorno and Campello Monti (N Italian Alps) revealed that no significant contamination was present apart from presence of Ni in some samples of Campello Monti. The study confirms that lithologies play strong role in pH and thus in the concentration of dissolved ions. It also shows that not all
the mine waters need constant intervention and/or heavy treatment processes. Although it should also be noticed that shifting the mine wastes away from natural lithologies may or may not lead to contamination of water sources at new place.

The present research will serve as important starting point for prioritization of sites for potential remediation and intervention activities. Further evaluation of the scale of the environmental impact will require future work to analyze more samples from the sites, understanding of the mechanisms governing the dissolution rates of metals and geochemistry of mine-water evolution.

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Squaring the cycle: the integration of Groundwater processes in nutrient budgets for a basin-oriented remediation strategy

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KEY WORDS: Po plain, nutrient mass balance, surface-groundwater interaction, socio-hydrogeology, groundwater dating.

INTRODUCTION

Diffuse contamination of surface- and ground-waters resulting from the green revolution represents a major threat to the long-term sustainability of water resources worldwide. Nutrients' budgets, calculated in a wide array of river basins, have shown that a high amount of nutrients can be retained or lost within the watershed, where site-specific characteristics contribute to define their fate (Mulholland et al., 2008; Schlesinger, 2009). In the Lombardy plain (North Italy), the uneven distribution of nitrates in groundwater, not fully matched to any of the urban, industrial and agricultural sources, suggests that local features and processes (e.g. depth of water table, land use, denitrification processes etc.) play a key role in preserving or removing nitrogen from water (Fig 1; Laini et al., 2011; Sacchi et al., 2013).

Based on the outcomes of previous investigations in the Oglio river basin (Bartoli et al., 2012; Delconte et al., 2014), it was hypothesized that the high soil permeability in the higher plain promotes the leaching of nitrogen excess to the subsoil and its subtraction from the shallow environment. Nevertheless, the nitrogen residence in the aquifers is only temporary, since groundwater naturally outflows in correspondence of the transition between the higher and lower plain, in the so-called "fascia dei fontanili" (springs belt). Here, numerous semi-natural outflows ("fontanili") are present, which return the deep groundwater, partially mixed with recently infiltrated irrigation water, and the dissolved nutrients back to the surface water compartment. By contrast, in the lower plain groundwater is deprived of nitrates due to high rates of bacterial denitrification, hence when contributing to river recharge it dilutes its nitrate content.

In this framework, the INTEGRON project aims at evaluating the role of groundwater as a temporary or permanent sink or as a source term in nutrient mass balances at the catchment scale in two key sub-basins of Po River, the Adda and the Ticino (Fig. 2).

MATERIALS AND METHODS: THE INTEGRON APPROACH

An innovative and integrated approach is proposed and currently tested, considering both surface and groundwater, combining hydrogeology, biogeochemistry and socio-hydrogeology, and targeting both inorganic nitrogen (N) and phosphates (P) species (Fig. 3) as detailed below.

CALCULATION OF THE NUTRIENTS MASS BALANCE AT THE CATCHMENT SCALE

The nutrient surplus in the agricultural lands and the loads exported by rivers at the closing section are calculated, in order to quantify the nutrient amounts retained within the basin. The nutrient budgets are calculated by applying the Soil System Budget approach (Oenema et al., 2003),
converting statistical data (agricultural surfaces, livestock density, etc.) into N and P loads by agronomic coefficients (i.e. livestock N and P excretion factors, crop yields and N and P contents). The N and P surplus are determined as a difference between the total inputs (livestock manure, synthetic fertilizers, atmospheric deposition, biological fixation - the latter term only for N budget) and the total outputs (crop uptake, ammonia volatilization and denitrification in soils, the latter two terms only for N budget) across agricultural surface.

ASSESSMENT OF GROUNDWATER CONTAMINATION AND RESIDENCE TIME IN THE AQUIFERS FROM THE HIGHER PLAIN

To infer the residence time of nutrients, groundwater dating is performed. In the study area the alluvial sequence creates a multilayer aquifer system, mainly composed by gravels and sands in the higher plain, becoming progressively finer towards the lower plain. Groundwater depth also decreases from north to south, ranging from more than 70 m depth to less than 2 m. Aquifers are separated by aquicludes which are discontinuous at regional scale. The shallow unconfined aquifers, the most vulnerable, reach a cumulative thickness of more than 100 m in the higher plain and 20-30 m in the lower one. Based on the available piezometric maps and well logs, transects of aligned wells tapping the unconfined aquifer and extending from the foothills to the springs belt area are identified. Groundwater is sampled from 5 wells per transect and analyzed using CFCs and SF$_6$, allowing to establish the groundwater residence time and apparent flow velocity. The combination of the chronological
information and the nitrate concentration trends in time permits to infer the nutrient dynamics in the aquifers and to estimate the timing for groundwater recovery in different watershed management scenarios.

EVALUATION OF THE HYDROLOGICAL RESPONSES AND PROCESSES OCCURRING AT THE OUTFLOW

The amount of nutrients exchanged between surface- and ground-waters is estimated and the quantity and quality of recently infiltrated irrigation water evaluated. Finally, the processes occurring at the interface which can affect nutrient loads (e.g. nitrification, denitrification) are identified. In this task, both discrete outflows such as springs and diffuse input to the Adda and Ticino rivers are investigated. During an extensive seasonal monitoring of nutrient contents and discharge, groundwater outflows are classified according to their hydrological response type. This classification permits the selection of a few representative springs to be monitored more frequently during an irrigation season. River water sampling and discharge measurements are performed via open-channel approach (Izagirre et al., 2008) during irrigation and non-irrigation periods in a segment of each river within the river-groundwater interaction zone.

INVESTIGATION OF THE ENVIRONMENTAL FACTORS CONTROLLING THE N AND P DYNAMICS IN GROUNDWATER

The investigation of the factors promoting the retention or removal of nutrients (e.g. denitrification, P adsorption) is performed. The seasonal evolution of nitrate and P concentrations in groundwater, coupled to nitrate isotope determinations is studied in rice paddies from the Ticino basin and in the lower plain of the Adda basin. Results permit to identify the conditions and the pathways for denitrification in groundwater, in order to exploit its full potential while reducing the negative impacts on the global environment. In addition, the environmental conditions and processes affecting P mobilization, transfer to groundwater and recycle to surface waters, with implications on their trophic status, are investigated as a function of redox potential and soil texture.

IDENTIFICATION OF THE STAKEHOLDERS INVOLVED, THEIR RELATIONS AND POSSIBLE EXISTING CONFLICTS

To identify key actors for the implementation of new management practices a socio-hydrogeological analysis is carried out (Re, 2015; Tringali et al., 2017). This is performed using the Net-Map toolbox (Schiffer & Waale
2008), an interview-based tool method, facilitating the identification of all the actors involved in a given issue (including marginal ones) while also highlighting their power relations, their influence and their main goals. Different groups of key informants are involved in drawing a so-called Influence Network Map (INM), depicting the social network affected directly or indirectly by groundwater contamination. Each of these INMs permits to visualize the social network perceived by the key informants, the stakeholders involved and their perceived influence, while also highlighting the relationships among them (money, conflicts, authorization and control, advice and technical information flows). Degree of centrality and network density are computed to identify relevant actors in the studied issue and to evaluate the differences in perception among the groups of key informants (Hauck et al., 2015).

PRELIMINARY RESULTS

N AND P MASS BALANCES AT THE CATCHMENT SCALE

Agriculture land covers a similar area in the Ticino and Adda basins (19% and 23%), but the two watersheds differ in terms of livestock density (0.7 and 2.3 livestock units per ha of agricultural land) and main crops (rice for Ticino and maize and fodder crops for Adda). The two watersheds are similar in terms of population density (257 and 264 inhabitants per km²). N and P availability in agro-ecosystems is in excess compared to crop demand, resulting in a different average areal surplus between the two basins: 71 kg N ha⁻¹ yr⁻¹ and 24 kg P ha⁻¹ yr⁻¹ for Adda and 40 kg N ha⁻¹ yr⁻¹ and 6 kg P ha⁻¹ yr⁻¹ for Ticino. The main sources of nutrients are manure spreading due to high livestock density for Adda and synthetic fertilizers for Ticino.

ESTIMATION OF NITRATES TRENDS

Comparing the mean NO₃⁻ values detected in the monitoring network during the period 2006-2008 with those detected during the period 2014-2016 (data of the Regional Agency for the Environmental Protection) differing trends emerge between the shallow and the deeper aquifers. An overall stability of nitrates contamination in the shallow aquifers emerges. In fact, the percentage of wells in which a decrease higher than -1.00 mg/L was recorded (42.6%; mean: -17.4 mg/L) is similar to the percentage of wells in which an increase greater than +1.00 mg/L (44.3%; mean: +11.6 mg/L) was observed. By contrast in the deeper aquifers 26.8% of wells show decreasing concentrations (mean: -18.7 mg/L) and 51.2% increasing ones (+7.0 mg/L). Finally, monitoring data confirm a general reduction of groundwater contamination at the transition between the lower (mean 2006-2008: 20.7 mg/L; mean 2014-2016: 19.8 mg/L) and the higher plain (mean 2006-2008: 30.4 mg/L; mean 2014-2016: 29.1 mg/L).

GROUNDWATER OUTFLOWS: SPRINGS AND INPUT TO ADDA AND TICINO RIVERS

During the non-irrigation period, water NO₃⁻ concentration in both rivers is constant (< 5.5 mg/L) along the reaches in correspondence of the transition between the higher and lower plain, where rivers cross the springs belt area. During the irrigation period, water NO₃⁻ concentration in both rivers increases along the same reaches from 1.8 to 4.4 mg/L for Adda River and from 1.3 to 4 mg/L for Ticino River. Groundwater-fed springs (fontanili) located in the Adda basin show higher median NO₃⁻ concentrations (25.6 mg/L) compared to the Ticino basin (14.3 mg/L). Median values of NO₃⁻ concentration, measured in the Ticino and Adda river water, result lower than those measured in spring waters (Ticino river, 5.4 mg/L; Adda river, 4.6 mg/L), indicating a difference between river and groundwater chemistry.

DENITRIFICATION AND P MOBILITY IN GROUNDWATER FROM RICE PADDIES

Monitoring conducted during one irrigation season in very shallow groundwater (1-2 m below ground) below rice paddies detected elevated P (up to more than 2.2 mg/L) and NO₃⁻ (up to more than 250 mg/L) contents, but also limited denitrification. The direct relationship between the two nutrients and measured Eh suggests their input from the surface related to the use of fertilizers. The investigation is presently addressing deeper portions of the aquifer in order to assess the presence and extent of denitrification, and its relationship with the total P contents.

MARGINALITY OF INFLUENT ACTORS AND DIFFERENCES IN PERCEPTION

Three groups of key informants were involved: authorities (A), researchers (R) and farmers (F), and three preliminary INMs obtained (Fig. 4). Differences in perceptions between groups were mainly associated to (i) the number of actors identified to compose the network (A: 44; R: 36; F: 20), (ii) their influence level and (iii) the density and kind of links. The lack of correspondence between the actors with a higher influence level and the ones with a higher degree centrality value, recurring in all INMs, points out the commonly perceived marginality of influential actors. Deep differences in number (A: 302; R: 295; F: 55) and kind of the perceived links between actors emerged: in each INM different kinds of links prevail (authorization and control, and money flows in the farmers’ network; technical information and advice in the authorities’ network; conflict flow in the researchers’ network); the efforts carried out by the authorities in communicating technical information and good practices is poorly perceived by the farmers.

CONCLUSIONS

The protection and management of water resources requires to identify and to quantify which features and processes could affect the nutrients removal and retention within the watersheds. The proposed integrated approach suggests a multiple role played by groundwater in defining the fate of nutrients in the studied basins, depending on extremely variable and site-specific processes. A nutrient excess compared to the crop uptake requirements is available every year in the agricultural lands. The connection between surface and groundwater, strengthened by the hundreds of springs placed
Fig. 4 - Influence Network Maps (INMs) of the three groups of key informants. In the right column advice and technical information links perceived by each group are represented. In the left one the relationship of authorization and control, money and the existing conflicts are reported. Abbreviations: Agr. (Agricultural), Ass. (Association), Adm. (Administration), Econ. (Economy), Env. (Environmental), Ind. (Industries), Int (international), LS (large-scale), Reg. (Regional), Sub-reg. (Sub-regional), T.U. (Trade Unions). Research institutes: CNR, CREA, CRPA, ISPRA, ERSAF.
in the transition between higher and lower plain, defines an increase in NO$_3^-$ concentration in rivers, promoted by the contribution of the irrigation water. Temporal and spatial trends of groundwater contamination confirm that remarkable differences in nutrient values are present between the higher and the lower plain. In conclusion, the integrated evaluation of all contributing factors and processes provides a suitable strategy to deal with the complex task of “squaring the cycle” and to move towards a more effective management of water resources, especially in areas where regulations seem not to be effective. Using a socio-hydrogeological approach permits to point out the inherent limits of the social context to the implementation of good practices in groundwater management, as well as the marginality of the influent actors or the deep differences in perception between the involved groups, and to highlight feasible strategies to overcome these criticalities.

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The role of the hydrogeological and anthropogenic factors on the environmental equilibrium of the Ugento Wetland (Southern Italy)

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ABSTRACT

The Ugento Wetland, recognized as a Site of Community Importance (SCI, European Directive 92/43/CEE) from 2005, is a “Regional natural littoral Park” from 2007. It includes some coastal reclamation works. It is a Groundwater Dependent Ecosystem (GDE); its environmental peculiarities are due to a complex hydrogeological pattern and to a peculiar dynamic equilibrium with sea, also due to the role of the wide coastal aquifer of Salento. The main objectives of the present research is the definition of the hydrogeological conceptualization to be integrated with the knowledge of the physical environment, to be used as a basis for the design of effective management of water resources to safeguard the ecological and environmental equilibria, considering the relevant impact of anthropogenic activities. The overlapping of geological and hydrogeological factors and anthropogenic modifications is discussed using selected indicators, with reference to two macro-indicators, water and soil. The critical issues related to the human activities potentially dangerous for the wetland environment, was considered with the definition of guidelines for their mitigation, based on the discussion of the indicators.

KEY WORDS: artificial wetland, hydrogeology, groundwater depending ecosystem, monitoring network.

INTRODUCTION

The Ugento Wetland, which corresponds to the coastal area between Torre San Giovanni and Lido Marini, located along the Ionian coast, in south-eastern part of Salento (Fig. 1), was recognized as a Site of Community Importance (SCI, European Directive 92/43/CEE) from 2005. It is a “Regional natural littoral Park” from 2007. It is a Groundwater Dependent Ecosystem (GDE); its environmental peculiarities are due to a complex hydrogeological pattern and to a peculiar dynamic equilibrium with sea, also due to the role of the wide coastal aquifer of Salento (Cotecchia & Polemio, 1999; Polemio, 2016). It includes some coastal reclamation works realised in more phases, starting from thirties. These works, at the end, which have created the most important lacustrine system of the Salento Peninsula, that includes seven artificial basins of different extensions, connected to the sea and to each other by channels with reclamation purposes.

Currently, the wetland system is in a state of huge environmental degradation due to low functional importance of reclamation works, anthropogenic pressure and local physical-environmental situations.

Anthropogenic pollution has been detected both for groundwater and for surface water bodies, probably due to illegal dumps and the use of fertilizers and nitrogen compound for agricultural purposes (Basset et al., 2003). This pollution caused events of exponential growth of floating macro-algae mass in surface water basin, up to the eutrophication, with effects which include is the sharp reduction, almost to zero, of the surface water velocity, up to, in some cases, to a widespread fish mortality. Besides the water pollution effects, during the dry season, due to groundwater overexploitation, the sharp piezometric level lowering occurs, affecting the balance of surface water bodies and the impact of salinity, due to the sea direct effect together with seawater intrusion (Fidelibus et al., 2004; Polemio et al., 2002).

To understand the interactions between physical and anthropogenic factors that regulate the evolutionary dynamics of the wetland, a careful geological and hydrogeological survey and study have been realized and merged with the characterization of the land use modifications since the fifties. The attention is focused on the analysis of the complex hydrogeological characteristics, which is due to the overlapped effects of shallow and deep aquifers and of their outflow along the coastal area. The focal role of the shallow groundwater, which is considered predominant and extremely importance for the wetland hydrological balance and so for the ecological equilibria, was characterised with a specific monitoring groundwater network of quantitative and qualitative parameters (De Giorgio, 2010).

GEOLOGICAL SETTING

The wetland area is located in the southernmost area of the Apulian foreland. It is possible to distinguish two major morpho-structural sectors, one inland and one coastal, with peculiar geological and morphological characteristics (Fig. 1). Thick sequences of Cretaceous limestone and dolomitic-limestone outcrop in the inner sector; on these discontinuous layers lie calcarenite rocks of medium Pleistocene, coarse stratified, hold and porous, relate to the “Calcarenite di Gravina” Formation.
The coastal zone is characterized by the outcrop of quaternary sedimentary sequences, represented by calcarenites and sands belonging to the Terraced Marine Deposit, sandy beach deposits and fine sands and silts deposit of lacustrine origin. On the basis of stratigraphic information of some wells drilled in the area, it was possible to ascertain that these deposits rest on a thick, non-emerging succession of clayey silt, fossiliferous, belonging to the Subappennine clay Formation (Calò and Tinelli, 2004), which stand in stratigraphic continuity with the underlying Calcarenite of Gravina Formation. At the base of this unit, is present the Galatone Formation (Oligocene). The presence of this formation has been indirectly inferred from the analysis of the lithological descriptions of deep-well stratigraphs made at Torre Mozza (Margiotta et al., 2004). It consists of an irregular alternation of black gray clays, marls and laminar limestones, to which thin layers of lignite are intertwined. It has a total thickness between 20 and 30 m and is related to internal-beach-lagoon sedimentation environments. The limestone substrate, in this area, is lowered by a fault of about 100 meters (Margiotta et al., 2004).

**HYDROGEOLOGICAL SETTING**

The groundwater flow that occurs in this sector of Salento aquifer is characterized by two different main types (Fig. 2) (Romanazzi et al., 2015; Zuffianò et al., 2016). The former type is the wide and deep coastal carbonate aquifer which includes the whole Salento Peninsula, interested by seawater intrusion from the Ionian Sea to the Adriatic Sea. It consists exclusively of the Mesozoic calcareous and dolomitic rocks. In the study area, the groundwater flow happens with very low piezometric gradient, with the piezometric head ranging from 1 to 0 m a.s.l. The recharge mainly happens inland, due to rainfall infiltration, far from the coast, where the effect of seawater intrusion is relevant.

The latter type involves the coastal area corresponding to the study area. The peculiar stratigraphical succession together with hydrogeological rock characteristics and boundary conditions, permit to hypothesize the activity of two aquifers overlapped to the deep carbonate aquifer. From the top, the shallow aquifer consists of the Terraced Marine Deposits; in this case, the groundwater flow happens on the almost impervious bottom due to the underlying Subappennine Clay. The outflow of this groundwater feeds the surface water system, mainly constituted by reclamation works, basins and the collecting channels. Due its geometrical peculiarities, it seems hit by salinisation due to deep seawater intrusion and secondly through surface drainage system.

The aquifer recharge is due to rainfall infiltration and to a high rate of leakage from the deep limestone aquifer. Numerous shallow digging wells use this groundwater.

The top of the second (or intermediate) aquifer is due to the Subappennine Clay; it corresponds to the rocks of Calcarenite of Gravina Formation. The amount of data and knowledge on this aquifer is almost low; the most hypotheses are summarised. This aquifer bounded at the bottom by lower permeability rocks of Galatone Formation. As it doesn’t outcrop, it is only fed by the deep limestone aquifer, with relevant effects of seawater intrusion (Fig. 2a).

The deep carbonate aquifer, of regional extension, underlies these two coastal groundwater systems. All together show hydrogeological relationship with the sea and different effects in terms of seawater intrusion.
GEOCHEMICAL CHARACTERISTICS

The location of water sampling points is shown in Fig. 1; ion chromatography results are shown in Fig. 2b. Groundwater of the deep carbonate aquifer highly affected by seawater intrusion are represented by samples P3 and P7; these samples are characterized by a predominance of alkaline ions (Na⁺-K⁺), and show high content of chloride ion. These waters could be classified as Na-Cl rich. The sample PWF is indicative of the fresh groundwater of the limestone aquifer.

Groundwater samples of shallow aquifer (S1 and S2) show the chemical characteristics of fresh water lowly mixed with seawater intrusion.

MAIN RESULTS

To describe the environmental situation of wetland, two macro-indicators were selected: water and soil. The main critical issues identified for the first one are the following: anthropogenic pressure on the water resource due to the increase of water demand during summer period; decrease of quantity (considering the annual water balance) and quality of shallow groundwater; increase of seawater intrusion; pollution of groundwater and surface water.

The main critical issues identified for the second macro-indicator are the following: land use changes; increase in waterproofing surfaces; increase of soil erodibility; presence of polluted areas.

For the Water macro-indicator, the strong anthropic pressure on shallow aquifer has been analysed by means of chemical analyses of water samples (Fig. 2b), applying a traditional hydrogeological approach to the water balance (Cotecchia et al., 1990), and by piezometric monitoring (surveys were realised by 2008 to 2009) (Fig. 3).

In terms of natural recharge, a relevant decreasing trend was determined, especially from the end of eight. This Figure is confirmed to a wider scale by previous results (Polemio and Casarano, 2004).

Focusing on the shallow aquifer, the piezometric head shows high spatial-temporal variations but is generally low respect to the sea level (Fig. 3). The piezometric slope ranges from 0.1% in the northern zone to 0.3% in the southern one.

The piezometric map, i.e. in the case Fig. 3b, shows the draining action of all the reclamation basins, towards which all the main flow path lines seem oriented. In this period, winter, the shallow groundwater outflow increases for the effect of the recharge and for the reduction of well exploitation.

The piezometric map of March 2009 (Fig. 3c) shows many similarities with the previous of December. In the map of June 2009 (Fig. 3d), the morphology of the piezometric surface is somewhat different from the previous ones, and there is a noticeable decrease in the level of the piezometric surface, as an effect the approached dry season, which triggers the huge increase of well exploitation. Therefore, the quantitative and qualitative status of the shallow groundwater is influenced mainly by human activity and in a subordinate way by the meteoric contributions. Excessive withdrawals also contribute to the progressive intrusion of saline waters of sea origin.

For the soil macro-indicator, the analysis of the use of the soil was accomplished by stereoscopic observation of aerial photos of 1950, 1972, and 1990 and through interpretation of satellite images of 2004, covering a total surface area is equal to 3017 ha. For the representation of the identified classes, Corine Land Cover Legend was used, with a detail of the III level. Artificial surface, mainly urbanised areas, constitutes the first macro category (level I) in the Corine land cover legend and includes 4 categories of lower hierarchical order (level II), which in turn consists
of 11 land use classes, included in the third legend level. The increase of artificial surface was high equal to 138 ha from 1950 to 2004 (0.59% in the 1950 and 5.16% in the 2004). The highest increase was recorded from 1972 to 1990.

The used agricultural surface corresponds the second major category of the Corine Land Cover legend, which consists of 4 hierarchical lower order levels (Level II), which in turn are formed by 11 classes of land use of Level III. The increase from 1950 to 2004, equal to 117 ha, mainly due the reclamation works (Fig. 4b) was high but with a very low incidence (68.37% in the 1950 and 72.21% in the 2004). The olive groves present the highest incidence.

The woody surface and other natural land surface correspond the third major category of the Corine Land Cover Legend and is made up of three categories of the second hierarchical order, each of which consists of four classes of third levels. Of the twelve classes officially present in the legend, six are identified in the survey area, two of which are representative of the wooded areas, one of the most predominantly shrubby and/or herbaceous vegetation environments and three of the open areas without vegetation. The loss from 1950 to 2004 was high, roughly equal to 200 ha (27.59% in the 1950 and 21.01% in the 2004). The peak decrease was recorded between 1990 and 2004 (fig 4c).

The wetland surface corresponds to the fourth major category of Corine land cover legend and consists of two-second level orders, which in turn include four classes of level III. Of these, only one was observed in the study area, that of the brackish marshes, belonging to the category of sea wetlands, and only present in the land use map of 1950, where it occupied the Rottacapoza area for a total area of about 73 ha and with a percentage incidence of 2.45% over the entire study area. The analysis of aerial photographs of 1972 and 1990 and the satellite images of 2004, whose land use maps do not highlight the presence of this class, confirm the relevant effect of the recent phase of reclamation works (realised after fifties), with the consequent disadvantageous disappear of the natural wetland (Fig. 4 d).

**FINAL REMARKS**

The Ugento coastal wetland is an Apulian protected area hit by relevant anthropogenic impacts mainly started with the remediation works started in the thirties. The anthropogenic load due to tourist settlements, mainly realized close to the coast, highly increased in the last decades.

The reclamation works, realised by the deepening, by excavation, of the topographically depressed areas

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**Fig. 3 - Piezometric maps of the shallow aquifer:** (a) August 2008; (b) December 2008; (c) March, 2009; (d) June 2009.
and channels, have improved the water salinisation of surface water system, due to the intruded seawater, reducing the extraordinary combined effect of the original hydrogeological and environmental characteristics of the site, typical a retrograde marsh originating from the continuous outflow of fresh spring water, apart from the role of the discontinuous role of runoff from the surrounding reliefs.

The surveys carried out highlighted the particular hydrogeological complexity of the study area. A number of factors, grouped in two macro-indicators, water and soil, were selected and discussed.

For the water macro-indicator, the following elements of interaction were found: high pressure in terms of quantitative status of groundwater, mainly due to the trend to recharge reduction and water demand increase, with depletion of water resources availability, groundwater and surface water pollution. The remarkable water stress during the summer period is effectively attenuated during the late autumn, winter and spring months.

The pollution seems mainly due to the anthropogenic activities realised inland, with particular reference to the considerable amount of fertilizers used in agriculture. This Figure contributes to explain the significant growth of the macro-algal mass, which caused events during which nullification of surface water velocity was observed, promoting eutrophication.

The elements of interaction with the soil-macro indicator are the following: changes in the use of soil, surface waterproofing, increased soil erodibility, and, secondly, contaminated site presence.

Changes in land use were assessed from the analysis of maps made for the years 1950, 1972, 1990 and 2004. From these data, it emerged that the category that shows the greatest expansion rate on percentage is the artificial surface, while very is the contraction of wooded surface and other natural surfaces.

The works is in progress to complete the conceptualisation with new surveys, which include isotope determinations on each water body, and with the design of a monitoring system of surface water flow exchanges, which includes automatic main water chemical and physical measurements. These tools will be at the core of the definition of management criteria to protect the

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**Fig. 4** - Land use maps: (a) Artificial land surface; (b) used agricultural surface; (c) wooded surface and other natural land surface; (d) wetland (dark yellow) and water surface due to reclamation works (blue).
hydrological and ecological equilibria which are typical of this wetland system.

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A hydrogeological study to support the optimized management of the main sea level aquifer of the island of Malta

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ABSTRACT

The Maltese Islands are located in the central Mediterranean area, on the Malta-Sicily Platform. The archipelago consists of three main islands, Malta, Gozo and Comino, and several other small uninhabited islets. Malta, the largest of the three islands, has an extent of 246 km². The aim of this paper is to describe the collaboration between CNR-IRPI and EWA (Energy and Water Agency of Malta) and the efforts to upgrade the hydrogeological knowledge of the Malta Island, pursuing the sustainable utilisation of groundwater resources. This will support the water management activities for optimizing the use of Malta’s groundwater resources. Firstly, a review of the hydrogeological environment of the aquifer systems has been undertaken, identifying so some important data gaps that should be filled up. The eventual groundwater body management tool to be developed under this collaborative initiative will enable the formulation and testing of updated groundwater exploitation strategies. These plans ensure the protection of the groundwater bodies from regional and localized effects of climate change, including the variability of recharge, sea level and seawater salinity.

KEY WORDS: management groundwater resources, coastal aquifer, seawater intrusion, safe yield, Malta.

INTRODUCTION

The Maltese Islands are located in the central Mediterranean at about 90 kilometres south of Sicily and about 320 kilometres from the North African coast. The Maltese archipelago consists of five islands: Malta, Gozo, Comino, Cominotto and Filfa, mainly constituted by a layered succession of carbonate formations. The largest island is Malta (246 km²), then Gozo (67 km²) and finally Comino (2.7 km²) as shown in Fig. 1. The islands present a typical central Mediterranean semi-arid climate with hot dry summers and mild wet winters. The mean-annual rainfall stands at around 550 mm but with high inter- and intra-annual variability. The island sizes and the hydrogeological peculiarities preclude the formation of significant surface water bodies and therefore the main natural water resources of the islands are the groundwater aquifer systems, in particular the sea-level aquifers present in the two larger islands. These aquifers are sustained in a carbonate formation (the Lower Coralline Limestone) and take the typical shape of a Ghyben-Herzberg freshwater lens.

These types of aquifers summarise managing complexities of groundwater resources due to the intrinsic high hydrogeological parametrisation difficulties, high vulnerability, and the combined effect of seawater intrusion and overexploitation (Polemio, 2016).

Focusing on the anthropogenic role, the high population density of the islands is also reflected in a high level of urban development, where around 25% of the total land area of the islands has been built up. This has altered the physical characteristics of the landscape by significantly increasing the quantity of impermeable surfaces, thereby reducing infiltration processes to groundwater, and increasing the generation of rainwater runoff following rain events.

The islands thus present a mixed land-use scenario where domestic, agricultural and commercial activities are operating side by side and depending on the same type of water resources. Of particular reference is the islands’ highly developed tourism and recreational sector, which places added strain on the water supplies during the dry summer months. Groundwater use for municipal supply is supplemented by the use of seawater desalination by reverse osmosis. The agricultural sector is mainly dependent on groundwater resources, although water re-use is currently being introduced on a wide scale to supplement (and eventually replace) groundwater use. The use of alternative water resources will thus, in the coming years progressively reduce the pressures on groundwater resources.

GEOLOGICAL SETTING

A schematic geological map of the Malta Island is shown in Fig. 1. All exposed rocks are mainly represented by limestone with subsidiary marls and clays, accumulated in a marine environment during the Oligocene and Miocene periods of geological time (Pedley et al., 1978; Alexander, 1988).

No Pliocene deposits are found in the island; therefore, the definitive emergence above sea level of the whole
The Maltese Tertiary rocks are arranged in a simple sedimentary succession deposited within a variety of shallow marine environments, the depositional area subsided probably before to be subjected to a gradual shallowing (Felix, 1973; Pedley et al., 1978). Therefore, the sedimentary sequence starts with the Lower Coralline Limestone, deposited in a shallow gulf-type area followed by a sea with shoals. The Globigerina Limestone and Blue Clay show a deepening in an open marine environment, to a maximum depth 150 m to 200 m, as suggested by the foraminiferal fauna (Magri, 2006). The foraminiferal associations belonging to the upper two formations (Greensand and Upper Coralline Limestone Formation) indicate so a gradual shallowing to an area with shoals but still in an open marine environment (Magri, 2006). The lowermost unit, the Lower Coralline Limestone Formation consists of massive biogenic limestone beds, characterized, both laterally and vertically, by a lithological heterogeneity. The age of the Lower Coralline Limestone Formation is Upper Oligocene: Rupelian or Chattian according to Bianucci et al. (2011), and Felix (1973).

**HYDROGEOLOGICAL SETTING**

Based on the geological setting, the geomorphological and structural features and the hydrogeological characteristics, two types of unconfined aquifers, namely the Mean sea-level aquifer (MSLA) and the Perched aquifer (PA), are present within the studied area (Fig. 1 and Fig. 2). Both aquifers are sustained in carbonate formations mainly constituted by limestones. The Mean sea-level aquifer is a coastal aquifer occurring as a freshwater lens found in the Lower Coralline Limestone Formation and somewhere in the Upper Coralline Limestone Formation, when the bottom of the latter is depressed below the sea-level. The mean sea-level aquifer stretches across an area of 216 km² mostly south of the Victoria fault (Great fault, in Fig. 1). To the North of the fault, it is depressed locally below sea level and overlain by the Blue Clay (Fig. 1). The Lower Coralline Limestone exhibits an irregular permeability, due to the widespread presence of algal reefs within the geological formation (Bakalowicz and Mangion, 2003). In specific locations, higher permeability could be recorded by the existence of local coral reefs (Bakalowicz and Mangion, 2003). Moreover, the Lower Coralline Limestone heterogeneity is further accentuated by the presence of scattered patch reefs in lateral contact with lagoonal and forereef facies (Bakalowicz and Mangion, 2003). The mean sea-level aquifer is in contact with seawater and reaches a piezometric height of around 3 m above sea level (Bakalowicz and Mangion, 2003). Due to the structural setting and the hydrogeological characteristics of the studied area, saline intrusion is a common phenomenon, taking place within the mean sea-level aquifer. The Perched aquifers (Fig. 2) are small aquifers located within the Upper Coralline Limestone Formation, overlying impermeable successions. They are located in the North-Western region of Malta and in Gozo and are generally delineated by faulted block (Fig. 1); especially in the grabens, structural synclines seated over the impermeable clays give rise to important aquifers with the occurrence of springs.

BRGM (1991) reports a detailed widespread analysis of on-site tested hydraulic transmissivity together with model calibration difficulties for the same parameter. On these bases, the existence of a layer of higher transmissivity within the Lower Coralline Limestone is hypothesized. The following research activities aims to confirm the existence of this layer.
According to previous studies (Bakalowicz and Mangion, 2003), both types of aquifers are mainly fed by rainfall infiltrating through cracks, fissures and rock porosity crossing all the geological formations (Fig. 2): the infiltration zone of the Mean sea-level aquifers results to be 50-100 m thick while it is thinner in the Perched aquifers (20-50 m as maximum).

PRELIMINARY RECHARGE ASSESSMENT

A preliminary study of climate variables useful for the recharge assessment was realised in the context of the WATERMAP project (Corbelli et al., 2008; Voudouris et al., 2010) using a two-step process, focusing on the Malta Island. First, the 10-year average rainfall contour for Malta was obtained by contouring the mean average rainfall for the last ten years as recorded in WSC (Water Services Corporation) meteorological stations. A contour map of rainfall depth was realised in a GIS environment (Fig. 3); the effective rainfall (effectively contributing to the national water resources) is significantly less than rainfall due of the effect of the actual evapotranspiration. The second step entailed the definition of the different recharge zones, which were identified on the basis of varying infiltration coefficients. The identified recharge zones are:

(i) areas where the impermeable Blue Clay formation occurs (very low infiltration coefficient);
(ii) areas where the Globigerina Limestone formation outcrops (high infiltration coefficient);
(iii) areas where the Lower Coralline Limestone formation outcrops (very high infiltration coefficient);
(iv) quarries (maximum infiltration coefficient);
(v) urban areas (very low infiltration coefficient);
(vi) water courses and valleys (very high infiltration coefficient).

The anthropogenic leakage or artificial recharge refers to recharge derived from anthropogenic activities within the catchment area of the aquifer. In this preliminary assessment, this component was assumed to consist primarily of the leakages from the potable water distribution system. The amount for recharge from leakages was calculated by using the leakage figures for every water-supply cluster provided by the Water Services Corporation. The recharge depth was then estimated by assuming that the recharge volume is uniformly distributed over the area of the whole cluster (Fig. 4).

GHEOCHEMICAL CHARACTERISTIC

The quality of groundwater in Malta is highly variable with contamination of groundwater by nitrates and chlorides being the main quality issues of concern (Stuart et al., 2008).

Thus, nitrate contamination in groundwater is largely attributed to anthropogenic activities, e.g.: agricultural practices through the application of nitrogenous fertilizers on arable land; and contamination from human or animal wastes and refuse dump runoff (Heaton et al., 2012). Nitrate concentration in the perched aquifers varies seasonally and by location, with maximum concentrations corresponding to the rainy season (October–March) as a result of the leaching of nitrates in the unsaturated zone. This because of the karstic nature of the Upper Coralline Limestone. (Sapiano et al., 2006). Groundwater in Malta has generally high levels of chloride concentrations as a result of overexploitation of groundwater and seawater intrusion. The situation is further influenced by the large perimeter in comparison to the area of the islands and the karstic nature of the aquifer. Generally, chloride levels in the perched aquifer are significantly lower than the mean sea-level aquifer, and these lower values result from the topographical characteristics of this aquifer, which is largely protected from seawater intrusion due to the altitude of the bounding formation being higher than sea level (Sapiano et al., 2006).

PROJECT WORK PLAN

The work plan consists in formulating a detailed framework of hydrogeological knowledge as basis for
the development of the numerical groundwater model to estimate the sustainable yield of the mean sea level aquifer system and to support groundwater management resources, as realised for other wide limestone coastal aquifers of the Mediterranean Sea (Polemio et al., 2011; Romanazzi et al. 2015; Zuffianò et al. 2016).

The Energy and Water Agency is currently undertaking the implementation of Malta’s 2nd River Basin Management Plan under the process of the EU’s Water Framework Directive. This plan sets out a programme of measures addressing the qualitative and quantitative status of groundwater, with the aim of ensuring the achievement of good status for the resource. The achievement of good quantitative status is assessed by means of the water balance calculation, which compares inputs and outputs from the groundwater system (Cotecchia et al., 1990). The system inputs define the sustainable yield of the particular groundwater system, where for the achievement of good status, system outputs must not exceed this sustainable level. In the case of a coastal aquifer, increased abstraction can lead to seawater intrusion, worsening the groundwater quality at the local level. Hence, the theoretical definition of regional safe yield is almost controversial, and local controls should be given due considerations.

The first step of the work plan is focused on the realisation of a complete database, implementing all the geological, hydrogeological, geochemistry, climatic data, together with the land use, underground groundwater exploitation works which are available for the Maltese island, as described later on. All these data will be employed in the next steps. Raw data (generally available on paper format) and digital data will be merged together with geolocation attributes. All information will be computerised in a number of relational geodatabase using the WGS84 UTM reference system. The Geological Database will include geological map, isobaths maps of the top/bottom geological formations, tectonic map and quarry distribution map. The Hydrogeological Database will include mainly well data, concerning litho-stratigraphical information, permeability tests and spring discharge rate. The Drainage Gallery Database will include geometrical data to support modelling of gallery effect on groundwater. The Time Series Database will include time series concerning climate, focusing on rainfall and temperature, piezometric data and groundwater discharge data. The Chemical Database will include all data concerning physical, chemical, and isotopic characteristics of groundwater.

Apart from the public groundwater abstraction system, the assessment of private groundwater abstraction, mainly due to productive activities, will be assessed using both direct (metering) and indirect (demand) spatial information. The available information will be collected in the productive abstraction (discharge) Database.

The existence of anthropogenic recharge contribution, as due to leakage from water distribution systems, will be characterised by all the data collected by Leakage Database.

The different components of the information system will be integrated in the whole geodatabase, as they will be available, up to the final implementation of all existing and useful data.

At the end of proper data mining activity, new data from field activities will be added to the geodatabase. The field activities and data analyses will support the geological and hydrogeological conceptualisation, as starting point of the numerical modelling. For this scope, it will be basically oriented to define geometrical patterns of the hydrogeological complexes and to improve the determination of the hydrogeological parameters. The next steps will be essential for model validation, improving the quality and the accuracy of modelling results.

The field activities will include the drilling of new boreholes and field surveys, including also geochemical and isotope characterisation of groundwater by field and laboratory activities. The new borehole drillings and all the other geo-hydro-geochemical activities will be performed...
in order to improve the knowledge of the physical and chemical parameters of both the geological formations and the fluids encountered. In particular, a series of surveys and in situ investigations during the drilling stage (permeability tests, multi-parameter borehole logs, push and pull tracer tests, installation of multilevel sampling ports to accurately delineate the mixing zone between fresh and saline waters) will be performed.

At the same time, the existing groundwater monitoring network will be enlarged and enriched, also using new boreholes, using all useful international experiences, including peculiar monitoring experience of coastal aquifers (Cotecchia & Polemio, 1999).

On the basis of the conceptual model drawn from field and laboratory activities, density-dependent flow and transport numerical simulations will be implemented and calibrated according to up-to-date groundwater modelling guidelines (Sinclair Knight Merz and National Centre for Groundwater Research and Training, 2012). Scenarios will be simulated considering climate change in terms of natural recharge modifications together with sea level and seawater salinity changes.

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Multivariate statistical analysis supporting the hydrochemical characterization of groundwater and surface water: a case study in northern Italy

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ABSTRACT

Multivariate statistical analysis is a useful method for supporting the interpretation of experimental data, particularly in the case of large datasets. In the present study, cluster analysis and factor analysis are used to support the hydrochemical characterization of groundwater and surface water in an area located in the Oglio River basin (N Italy).

During a field survey performed in Fall 2015, 58 groundwater, 20 river (Oglio River and its main tributaries), 1 Lake Iseo and 7 spring samples were collected for chemical analysis.

Results of multivariate statistical analysis led to the identification of the following 5 main clusters which characterize the hydrological system: (1) higher plain groundwater and springs, characterized by oxidized hydrofacies with higher NO₃, (2) lower plain groundwater, characterized by a reduced hydrofacies with higher As, Fe and Mn, (3) Oglio River (4) Oglio River tributaries and (5) outliers. This characterization will bear the improvement of the hydrogeological conceptual model of the area, also oriented to groundwater/surface water interactions, that, in turn, will support the numerical flow modeling of the system.

KEY WORDS: Cluster Analysis; Factor Analysis; Nitrate; Arsenic; Oglio River.
20-30 km downstream, then it becomes gaining up to the confluence into Mella River. In the unconfined aquifer of the higher plain, the groundwater table has a depth of ~50 m b.g.s. in the northern part, progressively decreasing to a few meters b.g.s. moving south towards the spring belt and the lower plain; groundwater in the higher plain mainly flows from N to S with a slight shift towards the Oglio River where it is gaining (Fig. 1b; Éupolis Lombardia, 2015). In the lower plain, the groundwater table depth approaches ground level; in the shallow aquifer, the groundwater flow direction is influenced by the gaining behaviour of Oglio River and its tributaries (Fig. 1b) whereas in the intermediate and deep aquifers groundwater mainly flows from NW to SE, that is the regional groundwater flow direction (Éupolis Lombardia, 2015). The Lake Iseo tends to fully circulate only irregularly, during harsh and windy winters (i.e. only two deep water mixing during 2005 and 2006 in the last 35 years; Leoni et al., 2014; Valerio et al., 2015) therefore, only the shallower lake water can be considered as water input to the Oglio River.

HYDROCHEMICAL DATA

During a field survey performed from October 26th to November 16th 2015, 58 groundwater, 20 river (Oglio River and its main tributaries), 1 Lake Iseo and 7 spring samples were collected for chemical and isotopic analysis. In the higher plain, the screens of the wells tapping the mono-layer unconfined aquifer are entirely positioned between 20 and 90 m b.g.s. In the lower plain, the sampled wells selectively tap the different overlaying aquifers that form the multi-layer system covering the whole 20-190 m b.g.s. depth interval. In all the 86 water samples, physico-chemical parameters (water temperature, pH, electrical conductivity (EC) and dissolved oxygen (DO)), major ions (alkalinity, Ca, Mg, Na, K, Cl, SO₄, NO₃ and NH₄) trace elements (As, Fe and Mn) and water isotopes (δ¹⁸O and δ²H) were measured.

Before sampling, water wells were purged until physico-chemical parameters were constant, generally after 2−3 well volumes were removed. Samples were filtered through 0.2 µm filters in the field, those for As, Fe and Mn analysis were acidified with nitric acid; after collection, samples were stored in a portable fridge at 4°C. Water temperature, EC, pH, and DO were measured in the field using the WTW Multi 3430 meter in a flow cell. Alkalinity was analysed by HCl titration within 24 hours from the sampling. Major ions were analysed by ion chromatography. Ammonium was analysed by spectrophotometry with Nessler’s reagent within 24 hours from the sampling. Iron and manganese were analysed by Inductively Coupled Plasma - Optical Emission Spectroscopy (ICP-OES) whereas arsenic was analysed by Graphite Furnace Atomic Absorption Spectrometry (GFAAS). Water isotopes were analysed by wavelength-scanned cavity ring-down spectroscopy (WS-CRDS).

MULTIVARIATE STATISTICAL ANALYSIS

The cluster analysis (CA) was performed on total 18 variables and 86 samples; data were auto-scaled (i.e. mean value = 0 and variance = 1). The Ward hierarchical method (Ward, 1963), based on the squared Euclidean distance as a measure of similarity between samples, was used. This method is used to group commonly measured water quality parameters; the resulting clusters indicate different types of water with particular features (Gibrilla et al., 2011).

The factor analysis (FA) was conducted using 18 variables and 82 samples, since 4 samples (LR59, LR61, OV77 and S123) were excluded from this analysis. These exclusions were due to (a) disproportionately high As values for samples LR59, LR61, OV77 and (b) a particular chemical composition of sample S123 allowing it to be considered as an outlier. Results of a preliminary FA including also these 4 outliers (not shown) evidenced mainly the difference between these 4 samples and all the other samples, hiding most of the information contained in the data. The eigenvalues for each factor were calculated with the auto-scaling method. The Kaiser criterion (Kaiser, 1958) was used to determine the significant factors. This method concerns the selection of those factors for which the eigenvalues are higher or equal to 1.

The software IBM SPSS® was used for performing both CA and FA.

Results of multivariate statistical analysis were combined with the geomorphological and hydrogeological knowledge of the study area in order to give a hydrological explanation of each data cluster.

RESULTS AND DISCUSSION

Results of CA are showed by the dendrogram in Fig. 2. Locations of sampling points for each cluster are reported in Fig. 1b. The CA grouped the sampling points into 16 clusters within the first grouping level, however, in order to give a hydrological and hydrogeological explanation of each data cluster, data were firstly associated to 5 main groups, then up to 3 sub-groups were identified for each main group. The following 5 main groups of data were identified (Fig. 2): (G1) higher plain groundwater and springs, (G2) lower plain groundwater; (G3) Oglio River and Lake Iseo, (G4) Oglio River tributaries and (G5) outliers. Mean values of measured chemical parameters for each group and sub-group are showed in Tab. 1.

The G1 (i.e. higher plain groundwater and springs) is characterized by an oxidized hydrofacies with higher EC (average of 661 µS/cm) and NO₃ (average of 41.6 mg/L). The higher values of these parameters, that indicate a worse water quality, could be related to anthropogenic activities (mostly agriculture) and to the hydrogeological features of the higher plain aquifer, that is more permeable, and thus, more vulnerable to the existing anthropogenic pressures. The fact that higher plain groundwater and springs fall in the same group agrees with the fact that the spring belt can be considered as a surface discharge of groundwater coming from the higher plain. Within the G1, three sub-groups can be identified: (G1a) groundwater with the highest NO₃ concentrations (average of 76.4 mg/L that exceeds the regulatory limit of 50 mg/L) and a more enriched isotopic signature (average -7.8‰ of δ¹⁸O and -50.6‰ of δ²H) that approaches that of local precipitation (-7.7‰ and -50.1‰ of δ¹⁸O and δ²H, respectively, at Sarnico station; Longinelli and Selmo, 2003); these samples are located in the northern part of the higher plain; (G1b) springs and groundwaters located around the spring belt and characterized by intermediate NO₃ concentrations...
Fig. 1 - a) Location of study area. b) Location and type of sampling points; colors represents the different groups and sub-groups resulting from cluster analysis (see the text for details); groundwater flow directions were deduced from the potentiometric map made by Eupolis Lombardia (2015), groundwater flow directions within the lower plain are referred to the shallow aquifer. c) Lithological cross-section outlining the aquifer systems of higher and lower plains.
The G2 (i.e. lower plain groundwater) is characterized by a reduced hydrofacies with higher As, Fe, Mn and NH₄ that frequently exceed regulatory limits (10, 200, 50 and 500 µg/L, respectively). This hydrochemical feature is related to the hydrogeological properties of the lower plain aquifer system, that has a multi-layer structure, allowing the presence of different overlaying confined aquifers with longer residence time and so older groundwater ages, and contains relevant amounts of buried organic matter as peat sediments. This natural source of organic matter fuels the ecological succession of terminal electron accepting processes allowing the establishment of reducing conditions and high concentrations of their products, as Mn and Fe. The release of As is likely related to the reductive dissolution of Fe-oxides whereas the high concentration of NH₄ is directly produced by the organic matter degradation (Rotiroti et al., 2014). Also within the G2, three sub-groups can be identified: (G2a) samples with more reduced states, (G2b) samples with earlier reduced states and (G2c) samples with the highest As concentrations. The G2a contains groundwaters from mostly deep (>100 m b.g.s.) and intermediate (40-100 m b.g.s.) wells, where reducing processes can evolve to more advanced stages (Rotiroti et al., 2015b). Indeed, the G2a has high average concentrations of As (14.5 µg/L), Mn (90 µg/L), Fe (211 µg/L) and NH₄ (694 µg/L) that all exceed the respective regulatory limits. Groundwater samples forming the G2b are located close to the transition between higher and lower plain and/or close to the Oglio River. Therefore, the presence of earlier reduced stages, evidenced by lower As and NH₄ and higher Mn, Fe and SO₄ with respect to the G2a (see Tab. 1), could be related to shorter groundwater circulation and/or some interactions with surface waters. Since the Oglio River is gaining in this zone, the latter mean recharge from leaking irrigation channels and/or recharge of Oglio River water induced by extensive well pumping, that could locally reverse the natural interrelation between Oglio River and groundwater (i.e., gaining river). The G2c is composed of three groundwater samples with the highest As concentrations (average of 195.2 µg/L). These samples are all located in the south-eastern margin of the study area.

The G3 (i.e. Lake Iseo and Oglio River) is characterized by lower EC (average 364 µS/cm) and a more depleted isotopic signature (average δ⁸O and δ²H of -9.49 and -65.25‰, respectively). The former indicates a general better water quality with respect to groundwater. The latter is due to the fact that Lake Iseo, that feeds the studied stretch of Oglio River, collects waters of Alpine origin that have a more depleted signature (Longinelli and Selmo, 2003). The G3 can be subdivided into 3 sub-groups: (G3a) Lake Iseo and the upstream Oglio River stretch with losing behavior, (G3b) the downstream Oglio River stretch with gaining behavior and (G3c) groundwater and spring directly fed by Oglio River water. The G3a has lower EC (average of 271 µS/cm) and NO₃ (average of 3.6 mg/L), confirming the better water quality of Oglio River in its losing stretch. The G3b experiences a decrease of water quality as evidenced by the higher EC (average of 407 µS/cm) and NO₃ (average of 14.6 mg/L). This could be the effect of the gaining of groundwater from the higher
plain, which has a worse quality, as discussed above. It should be noted that a groundwater sample from the lower plain (LL78) falls within G3b. This could be related to a recharge to the well mainly by surface water, however, a more detailed analysis through new samplings is required to better understand what drives the hydrochemistry of this sample. The G3c consists of two groundwater (HL03 and LR53) and one spring (S121) samples. The well HL03 is located 100 m from the Oglio River in its losing stretch, so a relevant recharge by river water on this well seems reasonable. The well LR53 and the spring S121 are located close to a big irrigation channel fed by Oglio River water (Fig. 1b). Since most of the irrigation channels leaks water to the aquifer (Facchi et al., 2004), the recharge by river water via irrigation channels on these two monitoring points seems plausible.

The G4 is composed of four of the five tributaries of the Oglio River sampled within the study area. The average values of EC (730 µS/cm) and NO₃ (32.6 mg/L) in G4 are higher with respect to those of G3 (364 µS/cm and 10.7 mg/L, respectively) indicating that tributary rivers have a general worse water quality with respect to Oglio River itself. The only one tributary sample that is out from G4 (R104) is from a channel named Scolmatore di Genivolta, that is fed by irrigation water sourced by Oglio and Adda rivers. The fact that this channel is fed by Oglio River, together with the absence of anthropogenic pressures on it, leads the sample R104 to be grouped into G3b rather than G4.

The G5 collects four groundwater and spring samples (HL14, LL33, LL47 and S123) that can be considered as outliers. The samples HL14 and LL33 have respectively a higher Cl concentration (43.9 mg/L) and EC value (879 µS/cm) that could be related to local anthropogenic influences. The sample LL47 has high As, Fe and Mn concentrations (higher than regulatory limits) and, at the same time, higher EC, Cl and SO₄ (with respect to the other lower plain groundwater samples). This could be due to a mixing in the well of groundwater coming from different overlying aquifers with different hydrochemical features. The spring S123 has a more reduced hydrofacies (DO of 0.04 mg/L and Mn of 194 µg/L) with respect to the other spring samples and the highest measured values of K (10.8 mg/L). This could be due to a particular recharge system of this spring that could likely involve reduced groundwater from lower plain aquifers together with possible anthropogenic influences.

Results of FA generally confirm the sample grouping derived from the CA. More specifically, results of FA showed that only the first four factors have an eigenvalue higher than 1, and thus, can be considered as significant factors. These explain the 79.7% of the variance of the original dataset (cumulative explained variance). The F1 and F2 explain the 37.9% and 23.2% of the variance, respectively, whereas the F3 and F4 explain lower percentages of variance, that are 11.3% and 7.4%, respectively.

### Table 1

Number of sampling points and average values of measured parameters for each group and sub-group resulting from the cluster analysis.

<table>
<thead>
<tr>
<th></th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
<th>G5</th>
</tr>
</thead>
<tbody>
<tr>
<td>n. samples</td>
<td>TOT 28</td>
<td>G1a 3</td>
<td>G1b 8</td>
<td>G1c 17</td>
<td>TOT 28</td>
</tr>
<tr>
<td>pH</td>
<td>7.4</td>
<td>7.2</td>
<td>7.3</td>
<td>7.5</td>
<td>7.8</td>
</tr>
<tr>
<td>Temp (°C)</td>
<td>15.3</td>
<td>14.6</td>
<td>15.2</td>
<td>15.4</td>
<td>14.7</td>
</tr>
<tr>
<td>EC (µS/cm)</td>
<td>661</td>
<td>841</td>
<td>741</td>
<td>592</td>
<td>488</td>
</tr>
<tr>
<td>DO (mg/L)</td>
<td>5.46</td>
<td>5.46</td>
<td>5.43</td>
<td>5.47</td>
<td>0.34</td>
</tr>
<tr>
<td>Alkalinity (meq/L)</td>
<td>5.0</td>
<td>6.2</td>
<td>5.7</td>
<td>4.5</td>
<td>4.9</td>
</tr>
<tr>
<td>Cl (mg/L)</td>
<td>12.7</td>
<td>28.9</td>
<td>13.0</td>
<td>9.8</td>
<td>2.7</td>
</tr>
<tr>
<td>NO₃ (mg/L)</td>
<td>41.6</td>
<td>76.4</td>
<td>49.9</td>
<td>31.5</td>
<td>1.2</td>
</tr>
<tr>
<td>SO₄ (mg/L)</td>
<td>41.6</td>
<td>34.9</td>
<td>44.4</td>
<td>41.5</td>
<td>13.1</td>
</tr>
<tr>
<td>NH₄ (mg/L)</td>
<td>0.005</td>
<td>0.005</td>
<td>0.001</td>
<td>0.006</td>
<td>0.856</td>
</tr>
<tr>
<td>Ca (mg/L)</td>
<td>108.0</td>
<td>141.5</td>
<td>121.2</td>
<td>95.9</td>
<td>74.6</td>
</tr>
<tr>
<td>Mg (mg/L)</td>
<td>14.5</td>
<td>18.3</td>
<td>16.3</td>
<td>13.0</td>
<td>12.2</td>
</tr>
<tr>
<td>Na (mg/L)</td>
<td>6.0</td>
<td>7.5</td>
<td>7.3</td>
<td>5.1</td>
<td>9.7</td>
</tr>
<tr>
<td>K (mg/L)</td>
<td>1.4</td>
<td>1.3</td>
<td>2.0</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>As (µg/L)</td>
<td>0.6</td>
<td>0.5</td>
<td>0.7</td>
<td>0.6</td>
<td>29.8</td>
</tr>
<tr>
<td>Fe (µg/L)</td>
<td>4</td>
<td>&lt;0.1</td>
<td>2</td>
<td>6</td>
<td>482</td>
</tr>
<tr>
<td>Mn (µg/L)</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>109</td>
</tr>
<tr>
<td>δ²H (% VSMOW2)</td>
<td>-58.95</td>
<td>-50.68</td>
<td>-59.81</td>
<td>-60.00</td>
<td>-59.89</td>
</tr>
</tbody>
</table>
The Fig. 3 shows the loading and the score plots of F1 vs F2. Concerning the loadings of F1, the most important original variables result EC, alkalinity, Mg, Ca, water isotopes, Cl and pH, the latter is negatively correlated to the other parameters. In general, this factor seems to represent major ions and water isotopes. Concerning the loadings of F2, its most important original variables are associated into two groups that are negatively correlated each other: a) the first group is formed by NH₄, As, Fe and Mn, b) the second group involves DO, NO₃ and SO₄. Therefore, the F2 likely represents the redox conditions of water samples.

In the score plot of Fig. 3b, the sampling points are classified for each group resulted from the CA. In general, each group and sub-group identified in the CA is also well identifiable in the score plot of F1 vs F2 confirming the strength of the hydrochemical characterization performed.

Along the F1, a gradual evolution from surface waters (G3) with higher pH and lower EC and major ions to higher plain groundwater (G1) with higher EC and NO₃ is pointed out. Moreover, along the F2, the evolution from the oxidized hydrofacies of surface waters (G3) and higher plain groundwater (G1) to the reduced hydrofacies of lower plain groundwater (G2) is also well represented.

CONCLUSIONS

This work presented a joined hydrochemical characterization of either surface water and groundwater based on multivariate statistical analysis, such as cluster analysis and factor analysis.

Results pointed out that Lake Iseo and Oglio River, higher plain groundwater and springs, lower plain groundwater and Oglio River tributaries form 4 discrete groups with particular distinctive features. Each group can be subdivided into up to 3 sub-groups on the basis of different hydrodynamic, hydrogeological and hydrochemical features.

In general, results confirm how multivariate statistical analysis can support the interpretation of large hydrochemical datasets. The main advantage of using this technique for interpreting hydrochemical data with respect to “traditional” methods, such as Piper diagram and bivariate plots, is that multivariate statistics are independent and quantitative methods that are able to extract information from all available data by elaborating jointly and simultaneously all measured variables and samples. In the present work, results of multivariate statistical analysis led to improve the hydrological and hydrogeological conceptual model of the area and elucidate the effects on water chemistry of groundwater/surface water interactions. The improvement of the conceptual model will support the future implementation of a numerical flow modeling of the studied system.

ACKNOWLEDGEMENTS

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Groundwater recharge estimation in karst aquifers of southern Apennines (Italy) by integration of remotely sensed data

Giovanni Ruggieri (a), Vincenzo Allocca (b), Flavio Borfecchia (c) & Pantaleone De Vita (b)

INTRODUCTION

In many Italian regions, karst aquifers are main sources of drinking water and play a crucial role for socio-economic development of the territory. Hence, estimating groundwater recharge of these aquifers is a fundamental task for a proper management of water resources, also considering impacts of climate changes.

In karst areas of the southern Apennines, the assessment of hydrological parameters needed for the estimation of groundwater recharge is a challenging issue, specifically for the spatial discontinuity of the rain and air temperature monitoring networks and variability of land use. In such a framework, the integration of terrestrial and remotely sensed data is a promising approach to limit these uncertainties.

This research deals with the estimation of groundwater recharge for karst aquifers of southern Apennines by the application of remotely sensed data gathered by the MODIS satellite in the period 2000-2014 for assessing actual evapotranspiration (MODIS Eta). To assess uncertainties in the estimation of Eta affecting conventional methods based on empirical formulas, MODIS Eta values were compared with those calculated by Turc, Coutagne and Thornthwaite methods. In addition, annual rainfall time series of 266 rain gauge and 150 air temperature stations, recorded by regional meteorological networks in the period 2000-2014, were considered to reconstruct regional distributed models of Eta and groundwater recharge.

Considering the MODIS Eta, a mean annual groundwater recharge of about 448 mm\text{-}\text{year}^{-1} was estimated for karst aquifers of southern Apennines. Instead, by the Turc, Coutagne and Thornthwaite formulas, Eta mean annual values of 494, 533 and 437 mm\text{-}\text{year}^{-1} were estimated respectively.

The obtained results open a new perspective in the assessment of actual evapotranspiration and groundwater recharge of karst aquifer at the regional and mean annual scales allowing a reduction of uncertainties and achieving a spatial resolution greater than that of the existing meteorological networks.

KEY WORDS: groundwater recharge, karst aquifer, evapotranspiration, remote sensing, Southern Italy.
related to the morphological evolution of original fault line scarps (Allocca et al., 2014; Allocca et al., 2015; Manna et al., 2013a).

Moreover, depending on their proximity to the volcanic centres (Fig. 1), some of these aquifers were covered by variable thicknesses of ash-fall pyroclastic deposits (De Vita and Nappi, 2013; De Vita et al., 2013; Napolitano et al., 2016; Fusco et al., 2017) deposited during the Quaternary, whose presence influences the epikarst (Celico et al., 2010).

The karst aquifers are featured by a basal groundwater flow, which feeds huge basal springs (spring discharges up to 5.0 m$^3$s$^{-1}$) located in the lowest point of the hydrogeological contact with the low-permeability terrigenous and alluvial units. The groundwater flow is also controlled by structural features (fault systems and thrusts) existing into the carbonate rock mass.

A less relevant perched groundwater circulation also exists (Allocca et al., 2008; 2015) feeding small springs at high altitude, whose formation is controlled by stratigraphic, structural and karst factors. Moreover, decadal climate variability strongly controls the recharge processes in karst aquifers of southern Italy. Specifically, a strong relationship between annual recharge of karst aquifers and the North Atlantic Oscillation was found (De Vita et al., 2012; Manna et al., 2013b).

**DATA AND METHODS**

This study was carried out in a large sector of the southern Apennines, covering approximately 19,339 km$^2$ (Fig. 1). On the basis of preceding hydrogeological studies carried out for singular karst aquifers (Celico, 1983; Allocca et al., 2007; 2014), 40 principal karst aquifers covering approximately 8,560 km$^2$ were identified and characterized (Fig. 1).

In a GIS environment, the following datasets of the karst aquifers were implemented and analysed, along with the time series of annual ETa:

- hydrogeological map of southern Italy, 1:250,000 scale (Allocca et al., 2007);
- Digital Elevation Model (DEM) with cells of 20×20 m;
- Corine Land Cover Project (2006 version);
- Land System Map of the Campania Region, 1:250,000 scale;
- time series of annual precipitation and air temperature, from 2000 to 2014, recorded by meteorological networks (266 rain gauge station and 150 air temperature station);
- annual NDVI and ETa estimated by the MODIS Global Evapotranspiration Project (ETa MODIS) for the period 2000-2014, by an advanced algorithm (Mu et al., 2011) based on the Penman-Monteith equation (Monteith, 1965).

By means of regression kriging method (Hudson & Wackernagel, 1994), mean annual rainfall and air temperature regional distributed models were reconstructed and implemented (Fig. 2), thereby accounting for variations due to orographic control (Houze, 2012) and altitude (Brusndon et al., 2001) of mountain ranges.

To assess uncertainties in the estimation of mean annual ETa, values of MODIS ETa were compared with those calculated by the Coutagne (1954), Turc (1954), and Thornthwaite (1948) empirical formulas.

Finally, by assessing ETa for each karst aquifer, the mean annual groundwater recharge was estimated by using the Annual Groundwater Recharge Coefficient of the karst aquifers of southern Apennines (Allocca et al., 2014).

**RESULTS**

The spatial analysis of mean annual MODIS ETa revealed a strong spatial variability at different temporal scales for karst aquifers (Fig. 3). In addition, significant relationships between MODIS ETa, and mean altitude, air temperature, rainfall, land use and vegetation coverage of karst aquifers were found (data not showed).

At the regional scale, the mean annual MODIS ETa is about 670 mm·year$^{-1}$ and about 599, 539 and 695 mm·year$^{-1}$, for estimation by Turc, Coutagne and Thornthwaite formulas respectively. By the reciprocal comparison, the best match was found between MODIS ETa and Thornthwaite ETa, with a mean difference lower than 6%. Instead a mean difference up to 7% and 10% among MODIS ETa, Turc ETa and Coutagne ETa was observed.

At the regional scale, the mean annual groundwater recharge (Fig. 4) was estimated in about 448 mm·year$^{-1}$, considering MODIS ETa, and 494, 533 and 437 mm·year$^{-1}$ for estimations derived respectively by the Turc, Coutagne and Thornthwaite formulas.

Accordingly, groundwater recharge values estimated by the MODIS ETa are similar to those coming from the use of Thornthwaite ETa (Fig. 5), with a mean difference of...
6.7% Instead, a mean difference varying between 11.2% and 13.6%, was found among results obtained by MODIS Eta, Turc ETa and Coutagne ETa values (Fig. 5).

Finally, for the 40 karst aquifers of the study area, the total volumes of mean annual groundwater recharge were found ranging from $3,634\times10^6$ m$^3$ year$^{-1}$ to $4,155\times10^6$ m$^3$ year$^{-1}$.

CONCLUSIONS

The results of this research open a new perspective in the assessment of mean annual actual evapotranspiration and mean annual groundwater recharge of the karst aquifers. At regional scale, the integration of terrestrial and remotely sensed data is a consistent approach for modelling the evapotranspiration and groundwater recharge of the karst aquifers in the southern Apennines, which allows overcoming the lack of high-altitude meteorological dataset and increasing the spatial resolution (1 km) in comparison with that of the current meteorological networks.

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Fig. 4 - Distributed models of the mean annual groundwater recharge for karst aquifers estimated by Coutagne ETa (a), Turc ETa (b), Thornthwaite ETa (c) and MODIS ETa (d).

Fig. 5 - Comparison of the mean annual groundwater recharge (mm·year⁻¹) estimated by Coutagne ETa (green histogram), Turc ETa (blu histogram), Thornthwaite ETa (hallow histogram) and MODIS ETa (red histogram).
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Sustainable karst groundwater management in a semiarid region: the case of Su Gologone spring (Sardinia, Italy)

Francesco Sanna (1), Laura Sanna (2), Jo De Waele (3) & Bartolomeo Vigna (4),

ABSTRACT

The Su Gologone karst spring has been recently investigated to assess how the karst aquifer would react in possible different meteorological conditions. The aim of the project is to develop a flexible and appropriate approach for its karst groundwater exploitation both taking into account the special features of the Supramonte karst landscape and without affecting the quality and quantity of the resource. For this purpose, the spring water level was continuously measured while flow rates measurements were performed monthly. From 1-year monitored, a high discharge variance and an impulsive behaviour to recharge input was detected indicating the presence of a transmissive drainage network with high hydraulic conductivity. The storage capacity associated to the low-conductive fracture system is still unknown. On the basis of these results, a new setup of the pumping facility together with a flexible management of water withdrawal is proposed, allowing the adaptation of the quantity of exploited groundwater depending on the hydro-meteorological conditions.

KEY WORDS: groundwater management, karst hydrogeology, sustainable exploitation, karst spring, Supramonte.

INTRODUCTION

The availability of water resources to be used for human consumption is affected by strong seasonal variations of rivers and springs discharge in response to the climate regime. The main reason of changes in water availability is the scarcity of the cumulative rainfall over a long period (Fiorillo & Guadagno, 2010). From recent projections of climate change simulations emerges a global and regional pronounced decrease in precipitation especially in the warm season (Giorgi & Lionello, 2008). On the basis of changes in mean surface air temperature and mean precipitation, the Mediterranean region is identified as one of the most vulnerable areas for water management responsive to global change (Giorgi, 2006). In this area, an inter-annual variability and a prominent warming is projected in summer due to an increased anticyclonic circulation associated with a shift of the Atlantic storm track (Giorgi & Lionello, 2008). Especially in the Western Mediterranean climate change represents a challenge for the public authorities responsible for ensuring the supply of drinking water to the communities and the habitat preservation in semi-arid regions. Future climate scenarios indicate a decrease of the water resources at least in qualitative terms (Di Matteo et al., 2017). In the last IPCC report (2013), the region is projected to experience the greatest droughts in the last decades of the twenty-first century and has been incorporated in the list of major “climate change hot spots” concerning the threats posed to the good-quality water security.

Also Sardinia (Italy) is included as one of the zones with the highest sensitivity to water deficiency.

In this island, the karst water supply is of strategic importance in particular during dry periods and considering its growing demand of good-quality water. It is therefore of primary importance to ensure the long-term adequate quantity of drinking water.

One of the main karst aquifers in Sardinia is the Supramonte massif in the catchment area of Su Gologone (Central-East Sardinia), an important source of drinking water for the local population, declared protected zone by the European Commission (Site of Community Importance, SCI code ITB022212).

This note focuses on the assessment of the water resources of this karst spring and reports the preliminary results obtained in the framework of a study endorsed by the Regional Department for Public Works of Sardinia, which promoted this initiative with the precise goal of carrying out a detailed monitoring of the spring. This project aims at precisely measuring the Su Gologone flow rates relative to the meteoric recharge of the Supramonte aquifer. The main objective is identifying possible water withdrawals directly from the aquifer operating in an area outside the perimeter of the SCI without compromising the integrity of this karst water resource. The main point is avoiding the progressive depletion of the water resource and preserving the aesthetic value of the site without prejudging the regional legislative decree set up for landscape and environmental protection of the site (DADA, 1998).

STUDY AREA

Su Gologone karst spring receives most of the Supramonte groundwater and drains it through two outlets of different size, just 50 m apart from each other. Both these two emergences are located a few meters away
from the right bank of the Cedrino river and immediately upstream of the Preda ‘e Othoni dam, in the northern part of the karst massif. This artificial lake (0.95 km²) was built in 1984 for the storage of the Cedrino’s surface water with the aim to use it for irrigation purpose and at the same time to laminate its high discharges (twice per year, on average) in order to protect the downstream urban areas from flooding risk. After an expensive purification treatment, part of the eutrophic water from the Preda ‘e Othoni artificial lake is also supplied to the downstream municipalities (about 20,000 inhabitants). During the 1990s, in the western part of the Supramonte plateau another dam was built (Olai dam, 1.32 km²) on the Taloro river with the same purpose. Prior to the construction of the dams, the smallest outlet of Su Gologone was equipped with a provisional water pumping system that currently withdraws an annual average of about 100 L/s supplying the municipalities of Oliena and Dorgali (about 16,000 inhabitants). In addition to this water abstraction, the springs provide a further very variable flow rate, but never less than 85 L/s. This discharge is the minimum baseflow without considering the water that is pumped and is reached after the prolonged summer and autumn droughts, during which the later stage of maximum baseflow recession of the karst aquifer occurs.

HYDROGEOLOGICAL SETTING

The Supramonte aquifer is comprised of a thick Middle Jurassic - Upper Cretaceous carbonate sequence, composed of folded and faulted dolostones and limestones (Fig. 1), confined at the bottom by a Palaeozoic impervious basement dipping NE, and at the North and East bordered by major tectonic contacts (Pasci, 1997). This geometry forces the groundwater, infiltrating in the South of the massif, to flow northward (Fig. 1B). Here, due to the verticalization and overturning of the contact between the Palaeozoic rocks and the Mesozoic carbonate cover, groundwater is forced to emerge along this permeability threshold at the Su Gologone springs (Sanna et al., 2002), feeding the Cedrino river, a perennial stream that flows for 80 km along the western and northern border of the Supramonte plateau, from Fumai Mount in the Gennargentu Massif (1,316 m asl) to the Tyrrhenian Sea.

As mentioned above, Su Gologone receives most of the Supramonte karst groundwater and drains it through two outlets. The main spring (the so-called Su Gologone) is an elongated pond of about 20,000 inhabitants. In addition to this water abstraction, the springs provide a further very variable flow rate, but never less than 85 L/s. This discharge is the minimum baseflow without considering the water that is pumped and is reached after the prolonged summer and autumn droughts, during which the later stage of maximum baseflow recession of the karst aquifer occurs.
at 103 m asl, surrounded at present by a crude masonry structure built in the past without a specific design idea, and containing the pumps for an authorized withdrawal that cannot exceed 130 L/s. The exploited water is actually limited to a maximum of 115 L/s due to the precarious setting and the poor efficiency of the existing pumping structure, subject to periodic flooding by the Cedrino River. Downstream along this river, the perennial spring of San Pantaleo (95 m asl) currently submerged by the waters of the Preda ‘e Othoni dam (De Waele, 2008), and the ephemeral outlet of Su Tippari (101 m asl) are also found (Fig. 1B). At a higher altitude respect to Su Tippari, the Guano Cave with its 2 km long passages characterized by predominant phreatic morphologies, constitutes an overflow karst resurgence of Su Gologone, that activates only temporarily during very significant rain events. Another important overflow during intense meteoric precipitation is represented by Mussintommasu Cave (also known as Peppino Ladu Cave), a vertical shaft that opens at 120 m asl along a small valley 300 m upstream from Su Gologone. This cave reaches the saturated zone and has been dived to 60 m from the cave water table (Penez, pers. commun.). Other caves in the Lanaitto valley at around 130 m asl (Su Bentu-Sa Oche-Sas Ballas karst system) are subject to periodic flooding, functioning as temporary overflows of the aquifer during storm events (see Figure 1A for location) (Sanna & De Waele, 2017).

METHODS

At the beginning of the hydrological year 2013-14, during minimum discharge, Su Gologone spring has been equipped with a multi-parametric probe (STS DL-N70) for continuous monitoring placed a few meters beneath the piezometric level, recording every 30 minutes the values of pressure (and therefore water level), electrical conductivity and water temperature. For the purposes of this work, the data were filtered on a daily scale.

The recharge was calculated from rainfall data of the local meteorological station (Oliena) supplied by the Department of Meteorology and Climatology of the Environmental Protection Agency of Sardinia (ARPAS).

During the 1-year monitoring, flow rate measurements were performed monthly at the spring by hydraulic spinner (SIAP ME 4001) and later (2015 and 2016) with a precise electromagnetic water flow meter (OTT MF pro). The water levels were related to a survey point, of which absolute sea level elevation was known with centimeter accuracy, located near the measuring section. This has allowed the reconstruction of a reliable flow rate pattern through which it is possible to trace the extent of the spring discharge on the basis of the absolute water level (m asl) for a range between the minimum flow (reached in fall during maximum water drop and corresponding to 60 L/s) and a medium discharge of 3,000 L/s.

RESULTS

The analysis of historical and present-day discharge of the main spring has yielded a rating curve (Fig. 2) based on the range between the minimum discharge values and 3,000 L/s.

Built on the flow rate scale and the daily detection of the absolute elevation of the water level, the flow duration curve of Su Gologone was reconstructed for the whole hydrological year 2013-2014 (Fig. 3), with average discharges of about 120 L/s during low flow conditions and up to 5,000 L/s during ordinary floods. The duration curve shows the number of days for this hydrological year in which the daily spring discharge was equal to certain flow rate values expressed in m³/s. During the first monitoring year, the maximum and minimum flow rates recorded at the spring were about 30 m³/s and 0.085 m³/s, respectively. The observation period was also rather interesting because in November 2013 the Cedrino basin was affected by a flash flood related to an exceptional rainfall that caused casualties and severe economic damage to infrastructures and land in many areas of Sardinia (Cossu et al., 2014). Moreover, the flow duration curve shows that the number of days for which the flow rate was equal to or greater than 3,000 L/s and 1,200 L/s was 45 and 135, respectively. The small chart at the top on the right (Fig. 3B) zooms in the flow rates between 1,000 L/s and 85 L/s and indicates that the spring has kept its discharge equal to or greater than 200 L/s for 231 days, whereas the low flow rate of 85 L/s recorded in the middle of autumn 2014 represents the minimum discharge of the spring for this hydrological year.

It is worth to point out that the above-mentioned flow rates are those detected at Su Gologone main spring and are therefore calculated without taking into account the 100 L/s of water pumped for drinking water purpose, plus the perennial discharge of Sa Vena, with a variable regime never inferior to 15 L/s (reached only after long droughts).

The analyses of the relationship between the daily rainfall recorded in the main meteorological stations around
the catchment area of Supramonte and the Su Gologone spring to the recharge inputs (Fig. 4). The precipitation vs spring discharge diagram confirms this behaviour already observed in the past (Sanna, 1995; Murgia, 2010) and closely related to the entity and the spatial distribution of the infiltration phenomena. Especially in the case of storms spread across the karst area, a very short-time response of this spring to the aquifer recharge occurs, showing a sudden increase in piezometric elevation, and thus of the flow rate (from discharge of 100 L/s before the rain to 8,000 L/s within 12 to 24 hours after the meteoric event).

Moreover, the spring functioning has a typical piston flow response to precipitation, as indicated by the increase in electric conductivity during discharge peaks (Fig. 4). The pattern marked by a quick substitution of the groundwater from newly, less-mineralised infiltrating water during the flash flood of November 2013 is an exception to the normal behaviour. However for this extreme event, the influence of the water of Cedrino river overflooding the spring is not excluded. Furthermore, the relationship between the spatial distribution of rain contribution and the variations in the spring flow is evident if the data from dry and wet periods are analysed separately.

**DISCUSSION**

The extreme variability of the flow rates of Su Gologone spring results in equally variable water resource availability during an average hydrological year. Currently, the Sa Vena outflow is subject to an average annual water pumping of 100 L/s, which could be increased to 130 L/s independently of the hydro-meteorological regime. However, due to the inefficiency of the pumping facility, the withdrawal never exceeds the rate of 115 - 120 L/s.

The data show that in a safeguarding approach aimed at ensuring the persistence of the water resource and the preservation of the aesthetic value of the surrounding
landscape, the effect of an increase in groundwater withdrawal up to 150 L/s (50 L/s more respect to the present pumping) would be negligible on the instantaneous spring flow if carried out for no more than 180 days per year. The flow duration curve for the year 2013-2014 shows that in this period spring discharge (at the net of pumped and exceeded water flow from Sa Vena outlet) remains at or above 600 L/s thanks to a constant baseflow recharge from the karst network in the upstream part of the aquifer. This is confirmed by direct speleological observations and dye tracer tests carried out inside the Supramonte caves (Sanna & Cabras, 2015) where perennial groundwater streams guarantee a constant minimum contribution even during very dry summers. During drought periods, however, it is not to be ruled out that supplementary withdrawals to those already in place are able to change the instantaneous discharge of Su Gologone, incompatible with the environmental constraints existing on the site. This would be the case in which the active zone of the Supramonte karstic aquifer, evaluated by Murgia (2010) in a water volume between 26 and 30 million m$^3$, was actually much smaller. However, the impossibility of monitoring the flow rates of the other springs along the Cedrino river (San Pantaleo and Su Tippari) during the dry season does not allow a reliable estimation of the size of the active zone of the karst aquifer using traditional procedures based on the analysis of the recession characteristics (Civita, 2005).

The high discharge variance and the impulsive behaviour of the spring indicate that the Supramonte karstic aquifer has a very transmissive drainage network characterized by high hydraulic conductivity. However, the perennial water flow even at the end of the dry season testifies the presence of a low-conductive fracture system whose storage capacity is still unknown.

Considering the higher quality of the spring groundwater compared with water stored in dams, and then the considerably lower treatment costs when drinking water is directly taken from the aquifer, the current ambition of the Sardinian authorities is guided by the need to identify a capable alternative to the existing poorly-efficient supply system. Their efforts are aimed to rely on the groundwater exploitation of the karst aquifer, guaranteeing as far as possible a decisively higher quality of water supply to the local population and a reduction of the potability charges on the entire community.

Apparent an optimal solution would seem to take Su Gologone groundwater with a new pumping facility located in the zone immediately downstream of the springs. This setup would theoretically collect the whole Su Gologone groundwater resource, including the water usually dispersed during the drought period (discharge between 200 L/s and 85 L/s) and overcoming the precarious conditions of the existing pumping facility. In fact, the present water abstraction is carried out within a rock fracture where, due to the narrow space available, a single pump is forced to work in a very unproductive way, with great energy waste and considerable maintenance costs.

However, the possibility of building a new pumping infrastructure downstream the spring is technically impossible for several reasons. First, this choice requires the separation of Cedrino river water from groundwater emerging from Su Gologone spring by constructing a cofferdam and other hydraulic engineering works within the river bed. This involves the deviation of the natural thalweg in the area just in front of the spring, with the consequence of facing insuperable difficulties in ensuring the safety, stability and durability of the pumping system. This kind of interventions is not permitted by the European and Italian regulatory framework. Moreover, due to the high exposure of this area to flooding, the cost for maintaining the efficiency of these infrastructures would be huge.

In addition to the complications mentioned above, it is worst to note that an environmental constraints and landscape protection are operative in this site. In fact, the area surrounding Su Gologone spring, where the Cedrino thalweg would be forced to divert for the construction of a new pumping system, as well as the space in front and immediately downstream and upstream of these karst outlets lie within a Site of Community Importance (UE Habitat Directive) and Sardinian protection zone (the Natural Monument of Su Gologone) (DADA, 1998). This regional decree, while allowing the use of water for drinking purposes, prevents the possibility of altering the aesthetic and landscape value of the zone around the spring, with the requirement not only to safeguard the flora and fauna, but above all to maintain the persistence of the water outlets.

In this framework, in order to develop a sustainable water management, a trial period is required to perform appropriate tests that explore the effects on the spring hydrodynamic regime that variations in the amount of water resources directly exploited from the aquifer produce. A flexible management of pumping that contemplates the possibility to vary the quantity of exploited groundwater from year to year in relation to the actual weather conditions should be applied. This means more water can be pumped during the wettest years and vice-versa. These experiments should be carried out from a sampling point placed at a sufficient distance from the outlets to ensure negligible alteration of its natural recession curve. This means the water withdrawal has to guarantee that the maximum width of its zone of influence has a piezometric level approximately equal to the static level of the spring. Furthermore, this approach requires the continuous monitoring of spring discharges associated with the detection of its main groundwater physical-chemical parameters. This setup is able to use in dry periods alternative water sources thanks to the available artificial reservoirs of Preda ’e Othoni and Olai dams. A hypothetical experimental site could be Mussintommasu cave which hosts conduits connected to the karst aquifer large enough to accommodate the water pumping system much more efficiently than the current one at the Sa Vena outlet, also because in sheltered position from the Cedrino floods. The advantage of this arrangement would be to allow the dismantling of the existing pumping facility and the reduction of its visual impact, with the possibility of a complete restoration of the environmental state of the Natural Monument of Su Gologone.

CONCLUSIONS

On the basis of the results of 1-year continuously discharge monitoring, the functioning of Su Gologone spring has been described for the hydrological year 2013-2014. It has been shown that this spring drains a very transmissive karst network. Its discharge varies from...
100 L/s during low flow condition up to 5,000 L/s during ordinary flood, reaching 30 m³/s during extreme events. The analysis of its flow duration curve indicates a reasonable amount of water availability (200 L/s for at least 231 days), even though the aquifer storage capacity associated to the low-conductive fracture system is still unknown.

The rating curve based on the range between the minimum values and 3000 L/s has allowed the calculation of the amount of water directly exploitable from a sampling point placed at a sufficient distance from the Su Gologone spring without perceptibly altering its hydrodynamic regime and following its natural recession curve.

Finally, a new setup of the pumping facility in the Mussintommasu cave has been proposed, arranging the withdrawal infrastructure in sheltered position from the Cedrino floods and reducing the visual and noise impact of the existing one for the complete landscape restoration of the Natural Monument of Su Gologone.

Considering climate regime and the relationship among rainfall, spring discharge and physical parameters, the development of a sustainable management of this karst groundwater should consider a withdrawal that adapts the quantity of exploited groundwater depending on the hydro-meteorological conditions. This approach requires the permanent monitoring of the spring in order to forecast groundwater decrease some months before the depletion of the water resource.

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REFERENCES


Temperature logs to evaluate groundwater - surface water interaction (Sabato River at Avellino, Campania)

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ABSTRACT
The overall aim of this study is to investigate groundwater and surface water mixing by temperature versus depth logs application in Campania (Southern Italy). The study area is located in Pianodardine (Avellino), on the left side of the Sabato River. Down-hole temperature logs in 9 monitoring wells, referred to two monitoring campaigns carried on in April and October 2016, have been compared. Results coming from these surveys suggest that stream discharge interacts with the groundwater local flow, due to the specific geological setting, which is responsible of temperature anomalies. These waters interaction is related to the seasonal groundwater level variations and it may define, eventually, two mixing processes for groundwater and surface water. The case study shows how temperature logs may give a cheap tool for acquiring fast, reliable data for supporting hydrogeological studies at small sites, with high heterogeneity conditions.

KEY WORDS: temperature log, groundwater, surface water, mixing.

INTRODUCTION
Exchanges between streams and shallow groundwater systems play a key role in controlling water temperatures. As a matter of fact, in recent years, temperature has been more and more used as natural tracer in hydrogeological field investigations, in order to characterize groundwater flow systems and interaction between Surface water bodies and groundwater (Reiter, 2001; Anderson, 2005; Vandenbohede & Lebbe, 2010). In this sense, down-hole temperature measurements are useful tools for groundwater investigations in order to provide information about groundwater flow paths and residence times within small sites with complex hydrogeological settings. In deeper wells, for example, temperature anomalies, resulting from groundwater circulation in surrounding formation or within the well itself, can be significant (Michalski, 1989; Ferguson et al, 2003; Xu et al., 2011; Colombani et al, 2016; Irvine et al., 2017). The use of heat as a tracer relies on the measurement of temperature gradients, and temperature is an extremely sounding property to monitor. Moreover, temperature data are immediately available as opposed to most chemical tracers, many of which require laboratory analysis (Constantz & Stonestrom, 2003).

STUDY AREA AND GEOLOGICAL FRAMEWORK
The study area is located at Pianodardine (Avellino) on the left hydrographic side of the Sabato River, near a waste processing plant, which is subject to potential contamination and extending over an area of approximately 61,000 square meters. Field surveys were carried out at 17 wells, in 2015, during a first investigation campaign, in order to obtain a description of the geological and hydrogeological setting of the study area. The main lithological units outcropping in the study area are (Fig. 1):

- Backfill Soils, which cover a large part of the area unsaturated zone with variable thicknesses;
- Alluvial Deposits, emerging in the river bank areas, but also outcropping downstream the study area;
- Pyroclastic Deposits, distributed over almost all the area, which are a lower permeability level with respect to the rest of geological successions;
- Clay Layer, belonging to the Altavilla Unit. This unit defines the no flow boundary for the overlying aquifer, and base of the Sabato River riverbed.

A detailed hydrostratigraphic section from S4 to S7 wells was represented in order to describe the profiles of the geological layers and their role in the groundwater circulation processes, especially for groundwater-surface water mixing (Fig. 2).

The top of clay bottom soils, with relatively higher altitudes, has been a barrier to the Sabato River outflow, causing a shift and the development of the large meander present in southern part of the study area (Fig. 1). The underground profile of the clay layer plays a key role in the quantitative distribution of groundwater flows. In particular, on one side, this layer is a very low permeability level that sustains groundwater feeding the Sabato River, on the other side, downstream, it constitutes the very low permeability level for the river hyporheic flow.

MATERIALS AND METHODS
Down-hole temperature logs were carried out in 9 monitoring wells of reference, homogeneously distributed...
in the study area. These logs, referred to two monitoring campaigns (April and October 2016), were compared to evaluate seasonal mixing and changes. Groundwater and surface water temperatures were recorded using a SEBA KLL-Q multi-parameter probe (Seba Hydrometrie). The temperature sensor used has a large measurement range (from -5°C to 50°C) with a 0.01 °C resolution and a ± 0.1°C accuracy. Down-hole temperature measurements were made at 1 m step, from the bottom to the top of the water table, after waiting for the sensor reaching an equilibrium with groundwater. The results from these surveys have been coupled with the lithological descriptions obtained from the well logs of the study area.

RESULTS AND DISCUSSION

Results coming from the comparison of down-hole temperature logs suggest that stream discharge interacts with groundwater local flow in some areas due to the specific geological setting and is responsible of the measured temperature anomalies.

Temperature logs results show that in those wells positioned downstream, near the river flow, surface water interacts with groundwater, highlighting a substantial seasonal difference in water table temperature ($T_w$) between October and April 2016 (Fig 3). On the contrary, upstream and in the most part of the inner area, there is no interaction.
In these areas, all the wells show limited temperature different values of the water table. In particular, wells with a lower temperature difference between October and April 2016 (DT), are those characterized by a greater thickness of the clay layer, which tends to block, as a barrier, surface waters coming from the Sabato River and its possible mixing with groundwater.

Fig. 3 shows the T versus depth profiles obtained for S2 and S8 wells and the related hydrogeological conditions. The columns represent, for each well, three different layers: the unsaturated zone (orange), the highly permeable saturated zone (blue), and the aquitard (grey) made of less permeable clay soils. On average, all temperatures have increased from April 2016 to October 2016. The minimum value of 12 °C was recorded during the April campaign in the S2, while the highest (about 19 °C) in the S15 during the October campaign. The thermometric surveys highlight sensitive changes in temperature values, reflecting the local hydrogeological setting, due to groundwater-surface water mixing.

The water table levels also reflect, in these cases, seasonal variations related to the Sabato River level range. As temperature can be considered an environmental tracer in complex hydrogeological systems, in this study a 1D vertical temperature adaptive model has been set up. This model is based on a function depending on depth, able to represent both ordinary linear increasing/decreasing of the temperature and moderate or high thermal change, occurring at localized depths, where the surface water-groundwater interface is present. This proposed model is defined by a regression function of values measured in this study (Fig. 4) that can be assumed as common to the vertical thermic profile, when two or more different water flows are combined in the aquifer.

So, the regressive model, acting to reproduce the shape of 1D thermic groundwater profile, can be represented by
the following expression, set up, starting from previous studies (Reiter, 2001), to best fit temperature trends with depth in this specific case:

$$T(z) = T_0 + \alpha \exp\left(\frac{-c z}{\beta z^2}\right)$$

Where: $T_0$ is the water table temperature (°C), $\alpha$ is the non-linear gradient coefficient, $c$ is the depth of the inflection point corresponding to the thermic change (m), $\beta$ controls the rate of changing and the terminal part of the $T(z)$ curve, and $z$ is the progressive depth (m). Positive value of $\alpha$ detects the change along depth from upper cold water flow to relatively warmer bed water flow; conversely, when it is negative. Considering these properties, the single parameter $\alpha$ assumes a key role in the detection of the vertical water temperature trend. Therefore, detecting $\alpha$ in many points and performing the spatially distribution by GIS analytic tools, it is possible to generate maps in which is possible to identify the flow directions and mixing zone when both involved the same aquifer. In Fig. 5, next to the river flow, red areas (S1, S5, S6, S7, S8 and S13) are characterized by no interaction between surface water and groundwater, with negative values of $\alpha$. In the yellow areas of the map, there is a greater interaction, outlined by positive values of $\alpha$ parameter (S2, S3, S11 and S15).

CONCLUSIONS

Down-hole temperature logging was carried out, during two different field surveys (April and October 2016), in 9 monitoring wells of a waste processing plant area near Avellino (Italy). The goal of the study was to identify in which areas of the plant a possible mixing between groundwater and surface water of the Sabato River might be present. As temperature can be considered an environmental tracer in complex hydrogeological systems, in this study a 1D vertical temperature adaptive model has been set up.

Results show that there are different areas characterized by a remarkable mixing. Large part of this area is located downstream respect to the Sabato River, in the S2, S3, S11 and S15 wells. Upstream, in S1, S5, S7, S8 there is less interaction between groundwater and surface water due to the greater thickness of the clay layer that stops and deflects the hyporheic flow of the Sabato River. This study shows that down-hole temperature logging may be a useful tool to evaluate groundwater-surface water interaction at site scale using temperature as a water tracer.

REFERENCES


The hydrochemical database TANGCHIM, a tool to manage groundwater quality data: the case study of a leachate plume from a dumping area

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ABSTRACT

Hydrochemical data from groundwater monitoring produce large dataset that require to be properly handled in order to provide well-structured data. This work presents a preliminary conceptual model of a groundwater pollution from a dumping area using the hydrochemical database TANGCHIM as a supporting tool. TANGCHIM is an on-line database able to store, compute, display and share hydrochemical data from groundwater. TANGCHIM is linked to the hydrogeological wells database TANGRAM, forming an integrated platform able to manage all data referred to wells water.

Results of both statistical and spatial analysis of hydrochemical data referred to a dumping area showed that groundwater is affected by a leachate plume contamination that likely comes from a closed-old landfill built before environmental regulation. This landfill is located upstream to a currently used-new landfill preventing a proper monitoring of the groundwater contamination in the area.

KEY WORDS: groundwater management; GIS; landfills; groundwater pollution; Alpine aquifer.

INTRODUCTION

Hydrochemical data (e.g. concentration of pollutant, isotopes) have a key role in hydrogeological studies. Previous works showed that the reconstruction of the aquifer structure (Dagan & Lessoff, 2007; Bonomi, 2009), the comprehension of groundwater flow dynamics (i.e. groundwater/surface water interaction) (Angelone et al., 2009; Folch et al., 2011; Menciò et al., 2014; Colombani et al., 2016) as well as groundwater contamination by both human (Bonomi et al., 2015) and natural activities (Guffanti et al., 2010; Rotiroti et al., 2014; 2017; Ducci et al., 2016; Dalla Libera et al., 2017) cannot be dealt without a joint analysis of the hydrochemical and hydrogeological data.

The European Water Framework Directive (WFD) (European Community, 2000; European Union, 2006) required to reach a good status for both quality and quantity of the water resource. In particular, as regards to the groundwater, it is necessary to: (1) ensure the gradual reduction of existing contamination; (2) prevent further deterioration of the groundwater and (3) ensure sufficient supply of the resource. To achieve the WFD aims, it is important to begin with the definition of the conceptual model of the aquifer. This allows to design and plan proper monitoring networks and field surveys frequency, with the aim of obtaining new and more representative data to assess groundwater status and plan remedial actions. Historical data are always required in order to design a proper conceptual model of an aquifer. However, these data are often difficult to obtain and share because they are managed by different public or private operators that store data in different formats and on different information supports. Furthermore, new data are progressively added to the existing ones by new wells drilling (e.g. pumping test in the existing or new drilled well, stratigraphic logs) and groundwater field surveys (e.g. groundwater depth, hydrochemical data), inducing a process that, if not properly managed, it could lead to redundancy as far to leak of data.

Nowadays, database able to store hydrogeological and hydrochemical data already exist, but they manage data referred to a specific project or specific area. Moreover, they are designed as a “tank” of data without provide any support to data analysis and without promoting data sharing.

The above considerations highlight the importance to design platforms able to store, manage, compute, link, display and share both hydrogeological and hydrochemical data which could be from different geographical contexts or projects.

The first release of TANGCHIM was in 1999 (Cavallin et al., 1999). In this work the new version of TANGCHIM database is presented. This is now an available online hydrochemical database (http://www.tangchim.samit.unimib.it/) joined to the existing hydrogeological database TANGRAM (http://www.tangram.samit.unimib.it/) (Bonomi et al., 2001; 2014; 2015). The TANGCHIM idea arises from the necessity to provide an on-line platform able to: (1) easily manage hydrochemical time series keeping the connection with the hydrogeological data; (2) manage data derived from different geographical contexts, authorities, projects or private companies; (3) provide an easy access to the data without losing data confidentiality; (4) provide database access by using whatever devices that

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TANGCHIM DATABASE

TANGCHIM and TANGRAM allows a better understanding and concentration time-series graph. The coupled use of simple statistical reports (i.e. descriptive statistics), boxplot and concentration time-series graph. The use of TANGCHIM and TANGRAM allows a better understanding of the results of groundwater monitoring.

Furthermore, the ability of TANGCHIM to manage wide dataset and provide well-structured data makes it useful to support the application of different tools (Rotiroti et al., 2015; Ducci et al., 2016; Dalla Libera et al., 2017) designed for the derivation of the Natural Background Levels (NBLs).

In this paper, the potentiality of the TANGCHIM database are showed through the analysis of the hydrochemical and hydrogeological data coming from the monitoring of groundwater pollution related to a dumping area located in an Alpine fluvial valley (NW Italy). In this area an old landfill located close and upstream to a legal and currently used landfill prevents a proper monitoring of groundwater.

MATERIALS AND METHODS

TANGCHIM DATABASE

The development of the TANGCHIM database followed four main steps: design, achievement, pre-processing of the hydrochemical dataset and implementation of the database.

The TANGCHIM database was developed by using HTML, ASP.net, SQL and JavaScript programming languages. It followed a classical RDBMS (Relational Database Management System) (Codd, 1969; 1970) approach. In particular, entity relationship (Chen, 1976), enhanced entity relationship (Teorey et al., 1986), data normalization (Codd, 1971) and queries (Zloof, 1977) were set up. TANGCHIM is composed of tables (relations) each of which connected with one or more tables by means of relational operators which allow to manipulate data in tabular form.

Fig. 1 shows a schematic way the main tables and the relations existing within TANGCHIM. The hydrochemical and hydrogeological data connection is made by joining TANGRAM and TANGCHIM databases. In particular, the well code both used in TANGCHIM and TANGRAM, allows this relationship. The structure of TANGCHIM database (Fig. 1) mainly consists of: (1) a chemical compound table (CC); (2) a synonymous table (SN); (3) hydrochemical dataset tables (HD); (4) a metadata section. The chemical compound table was composed of the name of chemical compounds, an internal identification code number (i.e. compound_ID) assigned for each compound, a chemical classification for each compound (based on three sublevel) previously compiled from existing chemical online databases (GESTIS, 2016; Kim et al., 2016), the CAS-NUMBER of the compounds and other attributes to define if compounds have or not law regulation limit for groundwater. Now TANGCHIM stores more 433 compounds subdivided in 5 groups: Inorganic (85 chemical compounds), Organic (328 chemical compounds), Chemical-Physical (4 parameters), Microbiological (4 parameters) and Others (14 compounds). The name of the compound coupled with the identification code number (i.e. compound_ID) uniquely identifies a chemical compound within TANGCHIM. The synonymous table was designed in order to provide well-structured data and to avoid synonymous troubles about chemical compounds name. In particular, the same compound_ID was assigned to each synonymous of a specific chemical compound listed into the hydrochemical dataset tables stored into the database. TANGCHIM was designed to handle data from different sources (e.g. local authorities, research projects or private projects) by assigning to each of them a different hydrochemical dataset table (HD). These tables must contain at least: well name, well code (from TANGRAM), chemical compound names, concentration of the chemical compounds, unit of measurement and any other useful information. TANGCHIM also stores information related to the source and the provider of data (metadata table).

In order to guarantee normalization, consistence and integrity of the database, the updating or the adding of new data regarding the chemical compound table (CC) and synonymous table (SN) must be carried out by the database Manager. A specific section of the TANGCHIM on-line interface allows the authorized users to upload new data for existing hydrochemical dataset by using a spreadsheet file format (e.g. *.xls, *csv).

Data export and data analysis are allowed by a query section based on: (1) single chemical compound, (2) homogeneous groups of chemical compounds or (3) all chemical compounds. This query can be applied to: (1) all existing wells, (2) wells in a specific area, or (3) a single well. Each query can be referred to different periods of time: a single year or a specified time period.

TANGCHIM can display concentration time series, box-plot and compute simple statistical report (i.e. minimum value, first quartile, median, third quartile, maximum value and all data used to the graph) for each well and for a selected chemical compound (Fig. 1c). In order to do that, a numerical format of the data is always required. However, concentrations could be below the method or instrumental detection limit (“<DL”), in that instance, a simple internal script converts the “<DL” in “DL” considering this value for both graphs and statistical reports.

CASE STUDY

Study area

The study area is located in an Alpine fluvial valley (NW Italy) where lacustrine, alluvial and fan deposits (Quaternary in age) filled an Alpine valley eroded by previous glacial activity. In this valley, a gravelly mono-layer unconfined aquifer with a local subdivision into an unconfined shallow aquifer and a semiconfined aquifer occurs due to a discontinuous silty layer. Groundwater mainly flows from West to East with some local perturbations due to wells withdrawal and surface water drainage.
Fig. 1 - (a) Simplified structure of TANGCHIM hydrochemical database and the connection with TANGRAM hydrogeological database. (b) Water table elevation (m a.s.l.) measured in P-A and P-B (see Fig. 2b for locations) piezometers displayed by TANGRAM. (c) Concentration time series graphs, box-plot and simple statistical report for P-A and P-B piezometers referred to COD and NH₄-N displayed in TANGCHIM.
The study area consists of a dumping area composed of two main landfills: a legal landfill (more recent and currently used) and an old illegal landfill (currently closed) plus other smallest waste deposits of which the locations are unknown. The old landfill and the waste deposits located in the area are related to the historical usage of the area (before environmental regulations) as an uncontrolled disposal area of waste.

Downstream to the new landfill the main regional river flows from SW to NE. The legal landfill was used as point of collection of municipal solid waste and sludge of wastewater treatment plants, whereas both the illegal landfill and the other smallest deposits were filled with inert, plastic and urban wastes of different and unknown composition. Only the legal landfill has an impermeable surface (a clay layer) 1 m thick. An important aspect to consider is that the old landfill is located close and upstream to the legal landfill (Fig. 2), preventing a proper groundwater monitoring downstream the currently used landfill.

Hydrogeological and hydrochemical data

The dumping area is monitored by more than 39 piezometers (about 15 m deep) located around the two main landfills (Fig. 2). The available data were: 14 well logs, hydraulic head data from 2012 to 2015 and hydrochemical data from 2006 to 2014.

The hydraulic head data were analysed in order to identify the groundwater flow direction and seasonal water table oscillations (Fig. 1b). A piezometric map referred to March 2014 was built by using Ordinary Kriging interpolation (Fig. 2).

The available hydrochemical data (a total of 6695) were: Dissolved Oxygen (O₂) from 2012 to 2013; Chemical oxygen demand (COD) and Ammonium nitrogen (NH₄-N) from 2006 to 2014; Electrical conductivity (EC) from 2012 and 2014; Iron (Fe), Manganese (Mn) and Arsenic (As) from not filtered samples were from 2006 to 2010 while those from filtered samples were from 2011 to 2014 (tab. 1). The latter samples were filtered in the field through cellulose acetate membrane with a pore size of 0.45 µm.

All available data were pre-processed and stored in TANGCHIM database. The IBM SPSS® software was used to perform the statistical analysis. In particular, the correlation matrix was calculated on the available data (without considers filtered As because data were available for only 14 piezometers) in order to evaluate if some relations exist within the hydrochemical data.

The statistical analysis was combined with the median maps (performed by GIS software) of the hydrochemical data and the hydrogeological data (e.g. piezometric map) in order to understand the role of each landfill and the unknown waste deposits on the groundwater contamination located beneath the dumping area.

RESULTS AND DISCUSSION

The available 14 well logs (stored in TANGRAM database) up to 15 m deep showed that gravelly-sandy as well as gravelly-silty deposits are common in the subsoil beneath the dumping area. The piezometric data showed that the water table depth ranges from 0.8 to 9.9 m with seasonal fluctuations up to about 2 m. Groundwater table oscillations were similar during the years due to the drainage effect of the river that flows close and downstream of the dumping area (Fig. 2).

Fig. 1c shows an example of the graphical output achievable by TANGCHIM on-line interface. The graphs are referred to hydrochemical data from two piezometers of the monitoring network of the dumping area (i.e. P-A and P-B). In particular, concentration time series and boxplot for COD and NH₄-N (i.e. Azoto Ammonia acelare in the Fig. 1c) were displayed. The P-A piezometer is located downstream of the old landfill, whereas P-B is downstream of the new one and along the same groundwater flow direction of the P-A (Fig. 2b). The hydraulic head data for P-A and P-B showed that the water table is low during winter season and high during summer (Fig. 1b). Both piezometers recorded the highest concentrations of both compounds during the low flow period that occurs in winter season. (Fig. 2b-c).

Tab. 1 shows the statistical summary of the available data. All hydrochemical compounds have a wide range of variation highlighting that groundwater contamination is characterized by a wide range of concentration at local scale within the studied site.

The correlation matrix (tab. 2) shows high-positive correlation between EC, COD, NH₄-N and As. In particular, the correlation index is 0.793 for COD and NH₄-N and 0.985 between EC and COD. Furthermore, the correlation index between As and Fe is positive and quite high (i.e. 0.674). A positive correlation index (~ 0.8) between filtered and not filtered Fe and Mn was also remarked. As regards to O₂, the correlation index is always low (absolute value) and negative (i.e. less than -0.483).

Median maps of COD, EC, COD, NH₄-N, O₂ were reported in Fig. 2a. Furthermore, Fig. 2a shows redox-sensitive species (i.e. Fe, Mn, As) as overlapped layers in two maps for filtered and no filtered samples. Concerning the EC, 30 piezometers had median values lower than 1500 µS/cm, whereas 7 piezometers were up to 7000 µS/cm. The highest values were located between the old and new landfill as well as downstream of the latter. Two piezometers in the south-west side of the landfill showed high values of EC (i.e. >1500 µS/cm).

Although the COD is generally used to quantify the amount of organic matter in water, its content is also affected by other reduced species like Fe, Mn or H₂S that can significantly contribute to it. For this reason, COD is usually used as tracer for leachate plume in groundwater (Fatta et al., 1999; Mor et al., 2006; Clarke et al., 2015). In this area COD showed the same concentration pattern of the EC with median values ranged between 3 to 322 mg/L. Five piezometers had COD median values more than 50 mg/L, between these, two are located between the old and the new landfill, one is along the same groundwater flow direction of the previous ones but downstream of the new landfill and two are on the south-west edge of the new landfill.

The median values of the NH₄-N ranges between 0.01 to 153 mg/L. In particular, 22 piezometers were below 1 mg/L, 5 piezometers were between 1 and 10 mg/L, while the remaining ones reached 153 mg/L. The redox sensitive species (i.e. Fe, Mn) were always present in all piezometers, both no filtered and filtered, whereas the filtered As was
Fig. 2 - (a) Median maps of available data: COD (mg/L), EC (µS/cm), NH₄-N (mg/L), O₂ (mg/L), redox-sensitive species (Fe, Mn, As). The last three compounds are both filtered and no filtered. (b) Location of P-A and P-B piezometers and piezometers groups.
measured on 14 piezometers. As regards to the Fe, median values ranged from 20 to 9400 µg/L for the no filtered samples and from 10 to 11500 µg/L for the filtered samples. In particular, 24 piezometers had median values lower than the Italian regulatory limits (200 µg/L) for both no filtered and filtered samples.

The median values of Mn were more frequently higher than the regulatory limit (50 µg/L) with respect to the Fe medians. As for no filtered Mn samples, 17 values of median were lower than 50 µg/L (regulatory limit), 10 piezometers were lower than 500 µg/L and 9 piezometers were between 500 to 2100 µg/L. Concerning the filtered Mn samples, 16 median value were lower than 50 µg/L, 12 were between 50 and 500 µg/L and 9 were between 500 to 3030 µg/L.

The regulatory limits' exceeding values for Fe and Mn were detected: 1) between the old and the new landfill, 2) from piezometers located on the east side of the new landfill and 3) upstream of the new landfill (south-west side).

### TABLE 1

<table>
<thead>
<tr>
<th>Sampling points</th>
<th>Hydrochemical and hydrogeological available data from the dumping area.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Piezometers</strong></td>
<td><strong>Well-logs</strong></td>
</tr>
<tr>
<td>39</td>
<td>15</td>
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</table>

**Hydrogeological data**

<table>
<thead>
<tr>
<th>Data availability</th>
<th>n. of data</th>
<th>n. of piezometers</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Dev. Std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic head (m a.s.l.)</td>
<td>2012-2014</td>
<td>731</td>
<td>36</td>
<td>534.34</td>
<td>530.79</td>
<td>536.23</td>
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</table>

**Hydrochemical data**

<table>
<thead>
<tr>
<th>Data availability</th>
<th>n. of data</th>
<th>n. of piezometers</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Dev. Std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC (µS/cm)</td>
<td>2012;2014</td>
<td>224</td>
<td>37</td>
<td>1439</td>
<td>159</td>
<td>20700</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>2006-2014</td>
<td>1470</td>
<td>37</td>
<td>60.81</td>
<td>0.5</td>
<td>3810</td>
</tr>
<tr>
<td>NH4-N (mg/L)</td>
<td>2006-2014</td>
<td>1470</td>
<td>36</td>
<td>38.26</td>
<td>0.003</td>
<td>12246</td>
</tr>
<tr>
<td>O2 (mg/L)</td>
<td>2012-2013</td>
<td>322</td>
<td>36</td>
<td>2.71</td>
<td>0.05</td>
<td>7.34</td>
</tr>
<tr>
<td>Fe (µg/L)</td>
<td>2006-2010</td>
<td>633</td>
<td>36</td>
<td>1291.18</td>
<td>5.91</td>
<td>24000</td>
</tr>
<tr>
<td>Mn (µg/L)</td>
<td>2006-2010</td>
<td>633</td>
<td>36</td>
<td>395.95</td>
<td>0.25</td>
<td>4170</td>
</tr>
<tr>
<td>As (µg/L)</td>
<td>2006-2010</td>
<td>323</td>
<td>36</td>
<td>5.19</td>
<td>0.21</td>
<td>100</td>
</tr>
<tr>
<td>Fe Filtered (µg/L)</td>
<td>2011-2014</td>
<td>200</td>
<td>39</td>
<td>1216.29</td>
<td>0.05</td>
<td>24500</td>
</tr>
<tr>
<td>Mn Filtered (µg/L)</td>
<td>2011-2014</td>
<td>200</td>
<td>39</td>
<td>245.05</td>
<td>0.19</td>
<td>3980</td>
</tr>
<tr>
<td>As Filtered (µg/L)</td>
<td>2011-2014</td>
<td>150</td>
<td>14</td>
<td>3.95</td>
<td>0.18</td>
<td>64.02</td>
</tr>
</tbody>
</table>

**TABLE 2**

Pearson correlation matrix for available data from groundwater around dumping area. F is referred to filtered sample.

**Correlation is significant at the 0.01 level, *Correlation is significant at the 0.005 level.**

<table>
<thead>
<tr>
<th></th>
<th>O2</th>
<th>EC</th>
<th>COD</th>
<th>NH4-N</th>
<th>As</th>
<th>Fe</th>
<th>Fe F</th>
<th>Mn</th>
<th>Mn F</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>-0.335*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td>-0.248</td>
<td>0.985**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH4-N</td>
<td>-0.370*</td>
<td>0.806**</td>
<td>0.793**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As</td>
<td>-0.464**</td>
<td>0.663**</td>
<td>0.666**</td>
<td>0.597**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>-0.428*</td>
<td>0.502**</td>
<td>0.490**</td>
<td>0.527**</td>
<td>0.674**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe F</td>
<td>-0.401*</td>
<td>0.351*</td>
<td>0.335*</td>
<td>0.394*</td>
<td>0.494**</td>
<td>0.807**</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>-0.483**</td>
<td>0.105</td>
<td>0.035</td>
<td>0.104</td>
<td>0.312</td>
<td>0.323</td>
<td>0.224</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Mn F</td>
<td>-0.428*</td>
<td>0.053</td>
<td>-0.010</td>
<td>0.068</td>
<td>0.112</td>
<td>0.163</td>
<td>0.190</td>
<td>0.765**</td>
<td>1</td>
</tr>
</tbody>
</table>
The high correlation between EC, COD and NH$_4$-N suggests that the groundwater pollution is induced by organic matter infiltration likely coming from the landfill. The organic matter induces the decrease of the dissolved oxygen (which is always negatively correlated with other parameters) explaining the high concentrations of Fe, Mn and As that affect groundwater beneath the dumping area (Fatta et al., 1999; Christensen et al., 2000; 2001; Mor et al., 2006).

The positive correlation between As, COD, NH$_4$-N and EC provides further supports to the hypothesis that the high concentrations of the redox-sensitive species are induced by the infiltration of organic matter from the waste deposits that have been placed in the dumping area. On this basis, the available hydrochemical compounds could be clustered into two main groups: the leachate plume indicators (composed by EC, COD and NH$_4$-N) and the redox-sensitive species indicators (composed by Fe, Mn, As, filtered Fe, filtered Mn).

The spatial distribution of the median maps suggests that the highest concentrations of the previous two groups of compounds (i.e. a leachate plume indicators and a redox-sensitive species indicators) are mainly located between the old landfill and the new landfill. However, high concentrations are also found in five piezometers located close and downstream of the new landfill (Fig. 2b - diamond symbol). This group of piezometers is likely affected by leaks of leachate that comes from to the old landfill built without a bottom impermeable surface before environmental regulation. The median maps also show that three piezometers located upstream to the new landfill (West side) are polluted mostly by COD, Fe, Mn (filtered and not filtered). This contamination could be related to previous uses of the dumping area as an uncontrolled disposal of waste.

On this basis and taking into account both groundwater flow direction and median maps of the available hydrochemical data, the piezometers around the dumping area were grouped in: (1) Unpolluted - located upstream and downstream of the new landfill; (2) Polluted - located downstream of the old landfill and downstream of the new one, along the same flow direction and (3) Polluted with unknown source - located upstream of the new landfill; this pollution could be related to waste deposits with unknown location or leaks from the new landfill and/or their related sub-services (Fig. 2).

CONCLUSION

This work presents a preliminary characterization of a groundwater pollution from a dumping area using the new online hydrochemical database TANGCHIM as supporting tool.

TANGCHIM addresses the need to provide an integrated platform able to manage, analyze and share all available data (i.e. hydrogeological and hydrochemical) referred to wells and groundwater by the connection with the TANGRAM hydrogeological database.

Results of the groundwater quality monitoring in the study area (NW Italy) showed reducing conditions with low dissolved O$_2$ and high EC, COD, NH$_4$-N, Fe, Mn and As that are typically found in leachate groundwater plume. The analysis of both hydrochemical and hydrodynamic data suggested that the plume is mainly sourced from the old landfill and, likely, from other unknown waste deposits located into the dumping area.

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Ducci D., De Melo M.T.C., Preziosi E., Sellino M., Parrone D. & Ribeiro L. (2016) - Combining natural background levels of pollutants and other variables to improve groundwater quality data interpretation and management.


**Groundwater temperature as a natural tracer to characterize hydraulic behaviour and geometry of carbonate aquifers: Mt. Nerone karst system, central Italy**

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**ABSTRACT**

Temperature variations in groundwater discharge from the Giordano karst system (northern Apennines) have been observed continuously for six months (from January 2016 to July 2016), to determine the flow patterns and geometrical properties of aquifer. The karst system discharge about 32.2 L/s on average during over the hydrological year and it's characterized by two outlets: a basal-continuous spring (BCS) with a mean discharge of 8.9 L/s and an upper-intermittent spring (UIS) with a mean discharge of 23.3 L/s, located about 60 m above the previous one.

Results show significant difference in the two spring outlets between the time lags as well as non-simultaneous and not analogue responses of temperature (T) to the same recharge events: temperature of UIS range from 9.7 to 10.7°C whereas temperature of BCS remain rather stable, ranging from 9.8 to 9.9°C. This data suggests a stratification of the water along the aquifer probably associated by different residence times and linked to the structural organization of karst aquifer (conduit and fracture networks): deeper and oldest water in the BCS and youngest water in the UIS.

**KEY WORDS:** Groundwater temperature, spring, karst aquifer, Apennines

**INTRODUCTION**

Groundwater physical and geochemical parameters are widely used as natural tracers in hydrogeological investigations. Seasonal and daily water temperature variations of karst springs permit to characterize different flow types and the structural organization of drainage patterns (Roy & Benderitter, 1986; Birk et al., 2004).

Several processes may affect water temperature during seepage, such as heat exchange, mainly by conduction, with the reservoir host rock mass, advection exchange into or out of the groundwater mass and heating and cooling in the underground karst conduits where convective exchange with air becomes important (Martin & Dean, 1999; Convington et al., 2011).

The discharge of a karst spring generally responds to recharge events much quicker than the physico-chemical properties of the discharged water, such as temperature (Brookfield et al., 2016). The increase in hydraulic pressure due to recharge is almost instantaneously transmitted through phreatic (water-filled) conduits to the spring, while the fluid properties change only after the actual recharge water reaches the spring (Birk et al., 2004). In this way, the lag between the hydraulic and physico-chemical response times corresponds to the physical path of the infiltrating water through the conduit system, which consequently can be estimated once spring discharge is known (Sauter, 1992; Ryan & Meiman, 1996).

**GEOLOGICAL AND HYDROGEOLOGICAL SETTING**

The study area is located in the northern sector of the Umbria-Marche Apennines in the SW flank of Mt. Nerone (1525 a.s.l.) as an asymmetric NE verging anticline with the axis striking NW-SE that is part of a fold-and-thrust belt. The investigated karst system developed in a carbonate massif of Ceno-Mesozoic Formations including the Calcare Massiccio Fm. (Hettangian-Carixian), Bugarone Fm. (Upper Toarcian-Lower Tithonian) and the heavily fractured and faulted Maiolica Fm. (Upper Tithonian-Lower Aptian). This carbonate reservoir is confined by Triassic evaporites at the base and Fucoidi Marls at the top. The total thickness of the karst reservoir is approximately 1000 m, about 800 m of which pertain to the Calcare Massiccio Fm., the regional basal aquifer of the Umbria Marche Apennines with an average discharge of about 30 L/s/km² (Boni et al., 1986). The karst block seems to be limited by a structural depression of the Pieia Valley in which drainage is controlled by the fractures and bedding discontinuities.

The Giordano karst system drains a basin of about 3.8 km² (Tamburini, 2016), from which a discharge of about 40 L/s is collected and diverted by “Marche Multiservizi” company to supply local villages and town. The karst system is characterized by two main spring outlets: a basal-continuous spring (BCS) located at 535 m a.s.l. and an upper-intermittent spring (UIS) located about 65 m higher (Fig. 1). Several linear springs are located along the stream, as linear springs are partially intercepted by shallow wells.
MATERIALS AND METHODS

Time-series analysis is a robust method of investigation in karst hydrogeological systems and cross-correlation functions (CCF) are widely used to analyse the linear relationship between input (rainfall or snowmelt - P) and output (discharge or temperature variations). This relationship can be expressed with the following equation (Padilla & Pulido-Bosch, 1995):

\[
C_{xy}(k) = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})(y_{i+k} - \bar{y})
\]

\[
r_{xy}(k) = \frac{C_{xy}(k)}{\sigma_x \sigma_y}
\]

where \( k \) is the time lag; \( n \) is the length of time series; \( x \) and \( y \) are input and output time series, respectively; \( \sigma_x \) and \( \sigma_y \) are the standard deviations of the time series and \( r_{xy}(k) \) is the cross-correlogram (Box et al., 1994). The delay, which is the time lag between lag 0 and the lag of the maximum value of the cross-correlation coefficient \( r_{xy}(k) \), gives an estimation of the pressure pulse transfer times thorough the aquifer (Panagopoulos & Lambrakis, 2006).

The objectives of this study are (1) to investigate temporal relationships between karst spring discharge and water temperature, (2) to compare the different residence times of two spring outlets belonging to the same karst system, and (3) to define the structural organisation of the karst aquifer.

DATA COLLECTION

Discharge and groundwater temperature were monitored simultaneously at the basal-continuous spring (BCS) and the upper-intermittent spring (UIS). Discharge data were provided by an automatic collecting system that continuously records the daily values of the hydrographic level in a discharge gauge. Groundwater temperature was measured automatically using waterproof commercial temperature loggers manufactured by Onset Computer Corporation and installed in both outlets. The loggers have temperature and response time accuracies of 0.1°C and 0.01% respectively. Between January and July 2016, the temperature loggers measured temperature every 15 minutes, in order to also record the rapid response to rainfall events. Daily mean values of precipitation were monitored by a gauge station located near the study area.

RESULTS AND DISCUSSION

Water temperature and discharge recorded at the upper-intermittent spring (UIS) and the basal-continuous spring (BCS) in the first half of 2016 are related to the rainfall events and have both different discharge rates and groundwater temperature trends (Fig. 2). UIS shows a higher discharge than BCS, with a mean value of 23.3 L/s, and rapid response to precipitation episodes (Fig. 2b). Similarly, UIS groundwater temperature also varies frequently from a minimum of 9.7°C to a maximum of 10.7°C; moreover, it decreases rapidly during rainfall episodes of varying magnitudes (Fig. 2a).
BCS, on the other hand, discharges a mean volume of 8.3 L/s and shows a slow response in the discharge rate, displaying a maximum difference that varies between 5.62 to 10.49 L/s (Fig. 2d). Even from a physico-chemical point of view, this spring outlet shows opposite behaviour to the UIS; in fact, groundwater temperature remains rather stable and is not affected by rainfall events, showing only one step between March 7th and 12th, when water temperature decreased by 0.1°C, passing from 9.9 to 9.8°C (Fig. 2c).

These results give some clues both of the residence (or transit) time of recharge water in the aquifer and of the structural organisation of the karst system. In the UIS, the rapid response of water temperature to recharge events indicates a short transit time of youngest, infiltrated water, which is quickly drained by conduit systems with high hydraulic conductivity. BCS, on the other hand, shows a long groundwater residence time, indicating the presence of deeper and older water in the basal portion of the aquifer and low hydraulic conductivity.

A cross-correlation analysis of precipitation and discharge with groundwater temperature for UIS and BCS (Fig. 3) confirm the contrasting hydrodynamic behaviour of the karst system being studied. Groundwater temperatures of the UIS have maximum $r_k$ coefficients of 0.2 (grey line in Fig. 3a), indicating that the input signal from precipitation is significantly reduced during its passage through the system. On the other hand, the function also shows a rapid response, expressed by the sharp peak, with a time lag of 472 hours (about 19 days). CCF of discharge and groundwater temperatures (Q-T°) of the UIS are well correlated (r_1=0.45), showing a rapid decrease and a time lag of 269 hours (11 days) (blue line in Fig. 3a). This indicates the presence of a quickflow component that regulates the discharge in UIS and is likely connected to the drainage of the conduit network during high-water table condition (HWT).

The cross-correlation function between precipitation and groundwater temperature (P-T°) in the basal-continuous spring (BCS) shows a maximum $r_k$ coefficient...
of 0.05, indicating non-correlation between rainfall and water temperature in this portion of the aquifer (green line in Fig. 3b). Indeed, the discharge-groundwater temperature (Q-T°) correlation functions decrease very slowly following a maximum peak of 0.78 and a time lag of 496 hours (about 21 days) (blue line in Fig. 3b). This slow response of water temperature to a variation in discharge rate indicates the presence of a baseflow component, likely linked to the drainage of fracture networks during lower water table conditions (LWT).

Analysis of the temperature variations of groundwater drained by the UIS and BSC enables us to make a qualitative analysis of the development of the karstic drainage pattern and the structural organisation of the aquifer. Groundwater from two karst outlets shows the same mean temperature of 9.9°C but does not present the same behaviour during rainfall events. This suggests a distinctive degree of karstification in the carbonate massif, enabling a partial mixing of the groundwater stored in the aquifer with the infiltrated, "new" and "colder" rainwater.

Indeed, the UIS displays higher variation in groundwater temperatures with several peaks of different magnitude and a rapid response after recharge events (19 days). These data are interpreted as the consequence of high groundwater velocity (short residence time), probably linked to water coming from the infiltration zone (IZ) that is then quickly drained through the conduit zone (CZ) to the upper-intermittent spring (Fig. 4).

On the contrary, groundwater exiting the BCS shows a stable temperature trend and a non-correlation with recharge events, which means a long residence time in the basal portion of the aquifer. These results indicate that a quickflow component is absent and the drainage is ruled by "diffuse flow" behaviour (baseflow condition), probably due to high fracturation and poor karstification (fractured zone, FZ).

The degree of karstification influences the flow-path length, water velocity and heat exchange (Anderson, 2005). After recharge events, the karst system reaches a HWT condition and the flow path is relatively short. Hence, heat exchange is low and groundwater temperature is lower (9.7°C).

During dry periods, the water table decrease and the karst system reaches a LWT condition, resulting in a longer flow path. In such conditions, a favourable heat exchange produces higher groundwater temperature (10.1°C). These effects are caused by thermal interaction between the fractures water and the adjacent rock. As heat transfer from the fractures wall into the fracture water is fast, water infiltrating the aquifer rapidly adjusts to the rock temperature. Hence, the first recharge water arriving at the spring has adjusted to temperature values close to the preevent aquifer temperature, while ongoing infiltration causes continuing cooling of conduit walls and consequently decreasing water temperatures (Birk, 2002).

![Fig. 4 - Simplified aquifer model during high and low water table condition. Main fractured and conduit zone are also indicated.](image-url)
The results confirm as the temperature signals potentially carry significant information about the mode of recharge (Liedl et al., 1998; Birk et al., 2006; Luhmann et al., 2011) and on the structural properties of rock traversed (conduits-dominated or fracture-dominated).

**CONCLUSIONS**

The fact that the outlets of the same carbonate massif display different responses to the same input highlights differences in the degree of karstification of their aquifer systems and consequently in their hydrogeological behaviour (Líñán Baena et al., 2009). The groundwater temperature trend in the two spring outlets seems to indicate different water storage geometries linked to the structural organisation of the karst system: basal aquifer characterized by high fracturation (FZ) and a conduit zone characterized by a well-developed karst network.

Finally, interpretation of groundwater temperature records of a karstic system provides supplemental information about groundwater circulation, drainage components and structural organisation of an aquifer, producing results coherent with other techniques used in hydrogeological investigations.

**ACKNOWLEDGMENTS**

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Flow parameters in porous alluvial aquifers evaluated by multiple tracers

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ABSTRACT

Dye tracer tests are a good technique useful to determine the hydrogeological parameters of aquifers, especially in alluvial plains, where the heterogeneity of the lithology is a key factor leading the groundwater circulation. In the last decade, new tracers have been developed and introduced in the hydrological and geological context, including DNA tracers, that are used in the same way as the traditional tracers. In this study, some experiments were performed in a porous aquifer with the aim of comparing the behavior of different tracers for the evaluation of aquifer's parameters, and of testing the suitability of a DNA tracer in this geological context. Single well and multiwell tests were performed during the winter and spring 2017, involving one piezometer and 4 wells. The tracer test results highlighted faster zones of flow in the alluvial plain, being located at different depths, whose levels are characterized by gravel and sand layers. A maximum groundwater velocity of around 170 cm/day was revealed by the single well tests, whereas the main direction of flow was along the watercourse axis, as resulted by the multi well tracer test.

The overall results obtained confirmed that fluorescent tracers are a very valuable and reliable tool for the determination of groundwater velocity, groundwater flow direction and dispersion parameters, even in cases of multi-layered aquifers, whereas DNA tracers are very helpful in the determination of faster circuits and vertical flow even in multi-layered aquifers.

KEY WORDS: Artificial tracers, DNA, groundwater velocity, alluvial aquifer, piezometer.

INTRODUCTION

The main aim of this study was to evaluate the suitability of various tracers in heterogeneous alluvial aquifers where wells and piezometers were used to perform several tests with the goal of determining the principal hydrogeological parameters by operating with different tracers. The present research was also started with the objective of enhance the knowledge of alluvial aquifers potential and water resource utilisation for specific scopes, given the growing interest for these aquifers, in view of the groundwater exploitation for drinking purpose, agriculture and energy (Comodi et al., 2011).

In addition, a DNA tracer (previously tested in fractured aquifers) was used and the results collected with such a tracer were compared with those obtained using the other tracers, to check its suitability in such an environment too.

The use of artificial tracers in hydrology and hydrogeology has been developed since the last century, when field tracer tests experiments over the world were performed as a helpful tool for supporting quantitative hydrology studies. Their use is restricted to a short time test duration and involves the following area of application: determination of mean groundwater velocity and dispersivity, transport of pollutants, flowpaths and directions of groundwater, identification of aquifers connection and aquifer parameters characterization (Sutton et al., 2000; Leibundgut & Seibert, 2011).

Within their application, tracers can give good results and answer to different questions and issues but, at the same time, they are subjected to some problematic aspects that should be carefully taken into account in order to avoid errors in the parameter calculation. Among the others, adsorption and physical and chemical retardation phenomena have to be adequately considered. Sorption on the organic matter, soil and rock, in fact, is still a current issue to be properly faced, in order to select a correct tracer suitable for the specific environment to be investigated. An ideal tracer, indeed, should not to be absorbed by the solid phase or at a minimum extent; Fluorescein, for example, shows sorption properties very limited with respect to forest soils and is considered to be an optimal tracer (Gerke et al., 2013), while all fluorescent tracers generally exhibit good behavior with respect to calcareous and arenaceous rocks (Sabatini, 2000) and suffer the presence of clay minerals (Kasnavia et al., 1999; Magal et al., 2008). In particular, acide dye tracers (like Fluorescein and Rhodamine WT) show best performances given the exhibition of less sorption than other fluorescent dyes and higher mobility in water (Flury & Wai, 2003; Mon et al., 2006).

Potential limitations of such kind of test are connected to very low flow velocities (i.e. long time of tracer recovery, especially for DNA that has a maximum utilization time of one month), layers of clay and silt (which can limit the tracer mobility due to sorption phenomena) inserted among the aquifers and the eventual occurrence of chemical reactions with groundwater solutes (Leite et al., 2003).
In both past and recent years, various tracers have been used in tests involving alluvial aquifers (Drost et al., 1968; Tazzioli, 1973; Uggeri & Vigna, 1997; Panini et al., 1999). Mainly electrolytic tracers (such as NaCl, NH₄Cl, KCl and so on) and fluorescent tracers (Fluorescein, Rhodamine WT, Eosin) have recently been utilised, while in the past radioactive tracers were thought to be more reliable and very helpful to obtain information about the vertical flow and groundwater Darcy velocity and direction (Evans, 1983; Cook & Herczeg, 2000; Elliot, 2014).

The parameters achievable with tracer tests are the Darcy velocity (at different depths), the actual groundwater velocity, the effective porosity, the vertical flow in wells, the hydraulic conductivity and transmissivity of aquifer as well. Tests usually performed in wells and piezometers consist of the so-called “single well dilution test” (that is performed by diluting a known mass of tracer along the water column of a single well and by the tracer concentration recovering over time and depth), “multiple wells” (that consist in the injection of tracers in a well and in tracer recovery in several wells placed downflow), “injection well and pumping well” (that is a particular type of the former test, Rainwater et al., 1987; Mandel, 1991; Margrita & Gaillard, 1991; Divine & McDonnell, 2005). Each test can be implemented in both static and dynamic conditions (obtained with pumping) and the injection can affect the entire water column in the well or specific selected single zones (Muldoon & Bradbury, 1998; Sutton et al., 2000).

In this study Fluorescein, NH₄Cl and DNA tracers have been used in a single piezometer of the alluvial plain of the Betelico river (Marche region).

SITE DESCRIPTION

The study site is in the Aspio watershed, in the central part of Marche region (central Italy), very close to the water course of the Betelico river (tributary of the Aspio river, Fig. 1).

The area is characterised by hills with gradual slopes and the alluvial plain, well extended in the final part of the watershed, very narrow in the initial part; the Betelico river sources from the western slopes of the Mt. Conero (572 m high) and flows into the Aspio river after about 7 km. The river drains the limestone massif of the Mt. Conero in its initial stretch, then passes through the Neogenic units of the Umbria-Marche sequence, and the Plio-Pleistocene terms in the final part.

As stated by previous studies (Tazzioli et al., 2015; Mussi et al., 2017) the geology in the area is given by the outcrops of the Meso-Cenozoic series (from the Maiolica Fm. in the eastern side of the Mt. Conero to the Scaglia Cinerea Fm.), the pre-orogenic Miocene (Bisciaro, Schlier and Gessoso Solfifera Fms.), the Pliocene sequence (mainly constituted by blue clays with arenaceous, arenaceous-pelitic and pelitic facies) and the Pleistocene Holocene covers (Quaternary continental deposits, Fig. 1). The geostuctural setting is marked by the presence of folds and faults having Apennine and anti-Apennine directions. The hydrogeological features of the area are characterised by the occurrence of two kind of aquifers, namely the limestone aquifer in the Northeast (with permeability due to both fissures and porosity) and the alluvial aquifer in the central part (porous heterogeneous aquifer, mainly characterised by alternation of gravel, sands and silty sands). The aquiclude formations are represented by the
outcropping marly terms of the Umbria-Marche succession (Scaglia Cinerea, Bisciaro and Schlier Fms.) and Pliocene and Pleistocene clays outcropping in the slopes or present in lens and thin strata in the alluvial plain.

In the middle-high part of the alluvial plain a borehole (10 cm diameter) was drilled in 2016 (equipped with piezometric pipe and a datalogger recording level and temperature). The monitoring well (30 m depth) was drilled to be specifically employed for tracer pilot tests. In the nearby, some wells for urban water supply are present, with depth varying from 12 to 17 m below ground surface (b.g.s.), located both upflow (about 170 m) and downflow (150 and 250 m) respect to the monitoring well.

The stratigraphy is reported and described in Fig. 2. The bedrock is represented by the Schlier Fm. and is found at about 28 m b.g.s.; an alternation of silty sands, sandy silts, gravels with silty sands, gravels and sands and silty sand occurs from 10 m to about 17 m; below them clayey terms are dominating.

**METHODS**

**TRACERS**

The choice of tracers was led by the mineralogical and lithological properties of the aquifers and aquicludes and by the chemical properties of groundwater present in the experimental site. Ammonium chloride, despite its well-known sorption and degradable behavior with respect to certain porous media was selected as electrolytic tracer on the basis of the groundwater chemistry, containing tens of mg/l of Na+, K+ and Ca++, thus suggesting the choice of different substances. Fluorescein was selected as fluorescent dye owing to its well-known and tested properties as a hydrogeological tracer. DNA is a new hydrogeological tracer never used before in alluvial aquifers, but successfully applied in carbonatic rocks and hydrological studies (Ptak et al., 2004; Foppen et al., 2013; Aquilanti et al., 2016, Tazioli & Palpacelli, 2016). Its behavior in water is very specific and greatly differs from the other traditional tracers, since it does not form a solution with water, but rather undergoes a dispersive colloidal transport characterized by its peculiar snake-shape able to easily pass through the voids within the aquifer. The overall outcome is a marked hydrodispersive behavior that results in advantaging the DNA molecule with respect to other substances characterized by high solubility in water: the observed peak preceding is a consequence of this property (Ptak et al., 2004).

Ammonium chloride (NH₄Cl) was then used as electrolytic tracer diluted with ethanol at 1:5 ratio in order to compensate for density effect; different amount of tracer was used during the field campaign, in the test involving the entire length of the borehole 150 g of tracer was injected in the piezometer, while only 50 g were used during the tests involving single sections of the well. Injection was made by means of a stainless-steel syringe 2” diameter and 50 cm length, which allows for instantaneous injection of the tracer at the desired depth. Tracer detection was made by means of electrical conductivity and level datalogger CTD diver by Schlumberger Water Services.

Sodium fluorescein (C₂₀H₁₀O₅Na₂) is a fluorescent tracer used in liquid or powder form, showing high solubility and low detection limits, with emission wavelength of 515–525 nm and an excitation wavelength peak of 490-495 nm (Aquilanti et al., 2016). Injection of liquid Fluorescein was made by means of a smaller stainless steel syringe (1” diameter and about 35 cm length), which can be filled with up to 12 ml of tracer and grant instantaneous injection of the tracer.

Tracer detection was made directly in situ with a PME (Precision Measurement Engineering Inc.) Cyclops-7 Logger, mounting a Turner Design sensor fluorometer, with minimum detection limit of 10⁻⁶ ppb. Background values were always below the instrument detection limit.

**Fig. 2 - Stratigraphy of the borehole located in Fig. 1.**
The DNA tracer, consisting of a single stranded DNA molecule of 72 nucleotides that had previously been used in groundwater tracing tests (Aquilanti et al., 2013 and Aquilanti et al., 2016), was purchased by MWG-Biotech in a HPLC-purified, lyophilized form at a final yield of 254.4 nmol, equivalent to $10^{17}$ DNA molecules. Injection was performed by means of the same equipment as per Fluorescein; samples were collected at selected time interval by means of manual stainless steel sampler specifically designed. Detection of the biotracer were made by quantitative Polymerase Chain Reaction (qPCR), as previously described (Aquilanti et al., 2013).

TRACER TESTS

Tracer tests were performed by injecting tracers at different time and depths in the piezometer (screen length between 8 and 27 m b.g.s.); single well test along the entire column of water and in selected sections were made with different tracers to evaluate the groundwater Darcian velocity (or specific discharge) at different depths, without using Teflon rings, packers or other insulating systems; this could lead to intra-well mixing processes, adding some bias to the obtained flow results. Dilution tests for vertical flow evaluation were also made in two different levels of the piezometer. The tracer amount injected in the piezometer varied from about 50 to 150 g of salt, solution of 100 ppb of Fluorescein and $10^{16}$ molecules of DNA.

Darcian velocity of groundwater ($v_f$, m/day) was determined (at different levels) applying the formula by Drost & Klotz (1983):

$$v_f = \frac{\pi \cdot r^2 \cdot \alpha \cdot t}{2 \cdot \ln \frac{c_0}{c}}$$

where $r$ (m) is the internal radius of the monitoring well, $c_0$ the tracer concentration (ppm) at time 0, $c$ the concentration at time $t$ (days) and $\alpha$ is a coefficient considering the distortion of the flow-net by the presence of the well (generally included between 1.5 and 4); $t$, $c_0$ and $c$ were obtained from the tracer tests.

RESULTS AND DISCUSSION

SINGLE WELL DILUTION TEST (NH$_4$Cl)

1st and 2nd tests were made with NH$_4$Cl (dilution both along the entire water column and at 9-14 m, 14-18 m, 18-28 m depth). The results (Fig. 3) show three different zones of flow: from 9 to about 13 m b.g.s. there is an area with relatively medium specific discharge (20-30 cm/day), from 13 to 13.8 m b.g.s. high specific discharge (corresponding to gravel and sand layer), below 14 m a low flow velocity area (under 2-3 cm/day).

Fig. 3 - Results of the NH$_4$Cl tracer test. In the center: tracer concentration trend with depth at different time from the injection. On the sides: calculated groundwater velocity at selected levels.
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SINGLE WELL DILUTION TEST (FLUORESCIN AND DNA)

3rd test was made with Fluorescein and DNA in three selected areas of the piezometer (10-12.5 m b.g.s., 11.8-14.2 m b.g.s., 13.8-16 m b.g.s.). The evaluated velocity confirms the data obtained with the previous test, with a faster layer around 13.8 m b.g.s. (Fig. 4).

DNA was injected at 13.8 m depth, and the obtained results in terms of specific discharge were very close to those achieved with the other tracers (Fig. 5).

In particular, on the more permeable layer (13.6-13.9 m b.g.s.) the calculated groundwater velocity was about 125 cm/day (evaluated during the NH₄Cl test), 138 cm/day (Fluorescein test) and 168 cm/day (DNA test). This fact implies that all tracers allowed a good estimation of the specific discharge of groundwater and that DNA seems to run faster than others, probably sneaking in the preferential pathways of flow due to its specific molecule shape. Such a behaviour was previously observed also by Ptak et al. (2004) and Aquilanti et al. (2013) and is due to the DNA shape and to its specific property of being not soluble in water, so that its molecules can run in groundwater selecting pathways characterised by greater pores.

Fig. 6 reports the trend of groundwater velocity with depth, compared to the stratigraphy of the borehole.

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![Fig. 4 - Results of the Fluorescein tracer test. On the left: tracer concentration trend with depth, at different time from the injection. On the right: calculated groundwater velocity at selected levels.](image)

![Fig. 5 - DNA tracer test results. Concentration dilution trend (up) in the selected point (13.8 m b.g.s.) and calculated groundwater velocity (down).](image)
VERTICAL FLOW EVALUATION

The 4th test was made by injecting Fluorescein in two points to evaluate the occurrence of vertical flow in the piezometer. Injection at 9 m b.g.s. allowed for descendant flow determination (discharge of about 0.06 l/s), a further injection at 16 m depth highlighted an ascendant flow of 0.5 l/s at 15.4 m b.g.s.

CONCLUSIONS

The obtained results confirm that the traditional tracers, namely salt and fluorescent tracers, are a reliable and very valuable tool for the determination of groundwater velocity, groundwater flow direction and dispersion parameters, even in cases of multi-layer aquifers. The results obtained with the DNA tracer are very encouraging, fostering for a development on the use of these biotracers in groundwater; in fact, the DNA tracer tested was helpful in the determination of faster circuits and vertical flow even in multi-layered aquifers, and the results overall collected with this tracer were consistent with those obtained by the other tracers.

The comparison between the fluorescent and the electrolytic tracer were very promising. Future applications of DNA tracer in different kinds of aquifer are scheduled, especially aiming at evaluating transfer time of pollutants through the more permeable levels, from the source of contamination to the target points.

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Pollutants transfer from Soil to water: geochemical investigation in different watersheds

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ABSTRACT

Policies for sustainable management of watersheds and groundwater quality still exist, but decline of water quality is being observed, especially due to the human impact on the environment.

In this study, a comparison between two areas in the Marche region, very different from a geological, pedological and hydrological points of view, has been performed with the objective to identify and study the transfer mechanism of pollutants from the pollution source, through the soil matrix to the surface and ground waters.

The first area is characterized by a high human impact, in terms of agriculture activities, industries and urban settlements; the geology is quite different, with the outcrops of the Umbria-Marche limestone ridge at the center of certain zones of the watershed. The geology is quite different, with alluvial plains, sands and clays of the Plio-Pleistocene and sandstone of the Pliocene. The second area is more natural, but small crops (as alfalfa and cilantro) are cultivated in different zones of the watershed. The geology is quite different, with the outcrops of the Umbria-Marche limestone ridge at the center of the basin.

Periodic sampling of soils, surface water and groundwater were performed in the investigated period, and chemical and isotopic (2H and 18O in water samples) contents were determined in each sample. All the samples were collected in the spring/summer period, when the crops were in active form.

The results indicated some differences in the two study sites, related to the difference in land use, geology and hydrological behavior. Chemical contents of Nickel were high in both the investigated sites (up to 31 mg/l), also in the more natural one, depending on the mineralization of water by rocks and soils. The isotopes, compared to the isotopic content in precipitation, confirmed the supposed mechanism of pollutants transfer and helped in the aquifers and rivers recharge identification. Further investigations are in progress in the areas to better detect and validate the proposed mechanism.

KEY WORDS: Pollutants, water isotopes, groundwater, surface water, soil.

INTRODUCTION

Despite guidelines and policies for sustainable management in basins, there is a growing deterioration of water quality in Italy mainly due to the strong anthropogenic impact associated with the activities of urban and industrial settlements, agriculture and livestock. In Italy over 130000 tons of phytosanitary products are used every year in the agriculture, thus increasing the pollution risk both in soils and in the waters (ISPRA, 2016). In the Marche Region, a rather differential situation exists: the quality of rivers in the inner areas (mountainous and hilly) is generally good; in the subcollinary areas, which fall into the central part of the region, the state of the environment is generally “sufficient”. Degradation is then progressively significant and, at the outfalls, quality swings through the years, depending on the meteoclimatic conditions, between a “poor” environmental state and a “bad” state; more rarely in the river mouth area this state reaches sufficient values.

The principal cause of the progressive increase in pollution from the sources to the mouths is generally identified in the increased man-made impact, which reduces the self-purifying capacity of the watercourse especially in periods of low water (Regione Marche, 2010).

For these reasons, it is basic to investigate the fate of pollutants in the different environmental matrices (soil, rain water, surface water and groundwater), and to analyze the way that they pass through the matrices, i.e. their principal transfer mechanisms. To increase the knowledge of such mechanisms it is essential to examine each part of the hydrological cycle in a more extended way, taking into account also the human impact (i.e. the influence of human-related activities such as agriculture, industry, urban settlements and so on) and using tools capable of evaluating the relationships among every single step of the cycle.

Chemistry (applied to the analysis of pollution in watersheds and to the connection among contamination sources, pollutants and chemical concentrations in different matrices) and isotopes (useful to evaluate the recharge area of aquifers and to study connections among different water bodies, Cervi et al., 2015; Cervi et al., 2016), for example, can be a good integrated tool to investigate this subject. Geochemistry and isotope hydrology, indeed, give a good contribution to the study of pollutants movement in groundwater and soil and in the identification of the contamination sources (Tazioli et al., 2012).

A problem of great concern is related to the connection between human impact and agricultural pollution in a watershed. Essentially, high or low human impact affects in the same way the environment or a clear difference of chemical concentration and distribution can be recognized...
in different areas? In the present work, some specific chemicals indicator of pollution have been selected, with the aim of underlining how the anthropic presence affects the quality of the environment indifferent conditions. The main aim of this paper is therefore to discuss this aspect, taking into account all the mechanisms involved in the transfer dynamics of agricultural pollutants from the soil matrix to groundwater and river water, stressing the importance of the recharge process and lithology. This was made by a comparison between two areas in the Marche region (central Italy) performed with the objective to study the different ways of transferring pollutants from the contamination source to the soil and water matrices, and to identify changes in the distribution of the contamination in the watershed. The selected sites are very different from a geological, pedological and hydrological points of view and distinctive land use (Tazioli et al., 2015; De Bernardi, 2017).

METHODS

AREA DESCRIPTION

The study focused on two areas of Marche Region characterized by very different hydrological, geological and hydrogeological features, and very unlike human impact and land use.

The first area (Scaricalasino sub-basin of the Aspio watershed, Fig. 1) is located near Ancona, center of Marche region, and shows high human impact, especially due to agriculture activities, industries and urban settlements; the watershed is therefore characterized by high natural and anthropogenic hazards. The Scaricalasino sub-basin is about 30 km² wide and its main watercourse is a tributary of the Aspio River.

The geology of the area (Fig. 1) is mainly represented by alluvial plains, sands and clays of the Plio-Pleistocene and sandstone of the Pliocene. In the eastern part of the watershed the Meso-Cenozoic sequence outcrops (in the Mt. Conero area), covered towards west by the Mio-Plio-Pleistocene sequence (marly clays, alternating marly clays and sandstone layers, clays and marly clays, sands with gravel lenses and alternating sandstone and clays layers) and thick Quaternary continental deposits made by silty clay and clayey sand, eluvial-colluvial deposits and debris slope (Tazioli et al., 2015; Mussi et al., 2017). In the Scaricalasino subbasin (where the sampling campaigns took place) the eluvial-colluvial covers, being up to 25 m thick, are mainly made of sands, silty-sands and clayey silts. Silty and clayey terms widely outcrop in this watershed.

The second area (Tarugo watershed) is more natural, with small crops (as alfalfa and cilantro) cultivated in certain zones of the watershed (Fig. 2). The human impact is very limited especially in the investigated (central) part of the watershed, with only sparse buildings and almost no factories and plants. The Tarugo river is a tributary of the Metauro river, located in the northern part of the Marche region; the sub-basin is about 82 km² wide. Maximum elevation of over 900 m a.s.l. is reached in the area by the Mt Paganuccio.

The geology is quite different respect the first site, with the outcrops of the Umbria-Marche limestone ridge (Aquilanti et al., 2016) at the center of the basin (Scaglia rossa, Scaglia cinerea Fms.) and a very poorly extended alluvial plain. The Miocene sequence outcrops (Bisciario Fm., Schlier Fm.) in the border of the investigated site, in which also debris slopes are present.

Fig. 1 - On the left: location of the first area of study; on the right: geological map of the Scaricalasino sub-basin.
Soils, river water and groundwater samples were collected in the investigated period (March-July 2016), and chemical (F, Cl, Br, NO₃⁻, HPO₄²⁻, SO₄²⁻, Ca²⁺, Na⁺, pesticide, organic and biomass carbon, FDA, Ni) and isotopic (²H and ¹⁸O in water samples) contents were determined in each sample. Soil sampling involved the river banks and the plots adjacent to the river sections examined, and were performed by means of a hand auger; the samples put into a sealed bag and stored at 4 °C until the analyses. Water sampling were performed by means of manual sampler and glass bottles.

All the samples (Tab.1) were collected in the spring/summer period, when the cultivations were in progress or the soil was in preparation, so it was possible to pick up during the pesticide treatments to the pre-emergent crops. Samples of soil and surface water were collected during the same sampling campaigns in the same points. In total, four sampling campaigns have been done in the investigated sites in the studied period, during the recession part of the surface water hydrograph. In addition, samples of rain water were monthly collected in the two areas in order to achieve the isotopic gradient of precipitations.

In the Scaricalasino river (first area) the sampling was carried out in four points: S1 was selected because it is located immediately after the confluence between the Offagna and S. Valentino creeks, S2 is just within the more industrialized area, S3 it is located in the closing section of the entire basin; in addition, periodic sampling of groundwater in the alluvial plain was performed in order to compare its chemical and isotopic values with surface water (near the S2 point).

Three samples of surface water (T1, T2 and T3) were taken in the Tarugo river, respectively located at the beginning, upstream and at the end of the geological formation of the limestone gorge of Mt Paganuccio.

The first withdrawals were made in May 2016 in both the studied areas. In the first area, it was chosen to carry out a second sampling campaign in June/July. This decision was made since the area of the Scaricalasino basin and even more the sampling points were characterized by the presence of numerous plots cultivated according to conventional farming methods, subject to frequent treatments, so it was found suitable repeating the samplings in periods of further distributions of treatments.

In addition, specific sampling campaign in the waters of the Tarugo river (time interval 15 days, from May to September) were carried out during the recession period to better understand the mechanism of river recharge by groundwater.

ANALYTICAL METHODS

Isotopic contents were determined by means of mass spectrometry at the Stable Isotopes Laboratory of National Research Council of Pisa (FINNIGAN MAT252 for oxygen-18 and Europa Scientific GEO 20-20 for deuterium). Analytical precision on samples is higher than 0.10‰ for δ¹⁸O‰ values and 1.5‰ for δ²H. Isotope results are reported as permil (Rozanski et al., 1993), respect to the international standard V-SMOW (Vienna-Standard Mean Oceanic Water).

The isotopic contents of surface water and river water (on samples collected during the campaigns) and on rain water (on samples monthly collected in the rain...
gauge stations indicated in Fig. 1 and Fig. 2) have been determined.

Samples for chemical analyses were pre-treated by liquid/liquid extraction with 30 ml of dichloromethane, then dried with a Rotavapor and solubilized using 1 ml of methanol. Pesticides investigated in the extracted samples, were evaluated using a Perkin Elmer series 200 HPLC system. Output data is reported on a computer equipped with a specific software that returns the results as a chromatogram. Pesticides (separated by multiresidual analysis) were quantified by comparing the areas of the respective chromatographic peaks and those of the relevant reference solutions, based on appropriate calibration lines.

Determination of the anionic content (F, Cl, Br, NO3-, HPO42- and SO42-) of the aqueous samples was carried out by ion chromatography. The calcium and sodium content was determined by direct suction of the sample in the flame (air-acetylene) of an atomic absorption spectrophotometer.

For the determination of Organic Carbon in soils samples, the Walkley & Black method (1934) has been applied: the organic-C is oxidized by addition of chromium in an acidic environment, then the amount of C-organic is obtained by the difference between the initial chromium content and that determined for the current sample.

The biomass carbon was determined by calculating the difference between the amount of organic carbon soluble in potassium sulphate and that of the same non-fumigated sample (since the fumigation involves the death of microorganisms, Vance et al., 1987).

The global hydrolysis capacity of the microorganisms was evaluated using the Fluorescein Diacetate (FDA): the hydrolytic enzymes present in the soil sample shake the FDA into sodium acetate and fluorescein, which gives the solution a yellow coloration, the intensity of this coloration (from which its activity is obtained) is read by a Spectrophotometer (Schnurer e Rosswall, 1982).

Ni in water and soil was analyzed using an atomic absorption spectrophotometer equipped with graphite furnaces.

RESULTS AND DISCUSSION

Chemical and isotopic analysis were made on the samples of soil, river water and groundwater collected in the investigated areas during the recession hydrologic period, when the river discharge was lowering and groundwater level decreasing. In general, geology affects the chemical content of soils and waters, but it is possible to identify a direct contribution connected to the agricultural activities, by observing some specific indicators of pollution. The following paragraphs illustrate the chemical and isotopic results, analyse how and how much lithology affects the chemical concentrations and what is the influence of human impact and land use, suggesting a mechanism to explain the movement of pollutants in the studied environment.

CHEMISTRY

Soil chemistry was examined to understand which kind of pollutants are transferred into the soil matrix, depending on cultivations, type of treatments and prevailing land use. Chemistry of surface water and groundwater in the areas is in fact suggestive of the pollutant transfer mechanism and is also strongly related to the hydrologic features. The results show that the two case studies have different dynamics depending on diversified land uses, geology and hydrological behaviors.

The highest values of Ca, Na, anions (Tab. 1) were found in waters of the Scaricalasino river (Aspio watershed, first area). This was rather expected due to the geology and the land use. The Scaricalasino river, in fact, flows on Plio-Pleistocene deposits that naturally contain salt water, while the Tarugo river crosses the carbonated aquifers of the Umbro-Marchigiana ridge; moreover, the land use in the first area is characterized by more anthropic activities near the riverbed, largest number of settlements and greater agricultural activity than in the Tarugo basin.

The concentrations of the four investigated pesticides in waters (Tab. 1) never exceeded the limits of law, with higher levels in the Tarugo waters than in the Scaricalasino, despite the former is the area with fewer plots for agriculture close to the river. In addition, the Tarugo hydrographic network is more capillary than the Scaricalasino one and therefore drains more extended surface. This specific hydrologic feature could explain higher concentrations of pollutants focused on an area characterized by lower agricultural impact.

Regarding Biomass Carbon, Organic Carbon and FDA analyses conducted on soils (Tab. 2), the highest values of these parameters, which are indicators of soil health status, were found in the Tarugo samples, specifically Carbon Biomass are generally low (probably due to conventional cultivation method), except for the two alfa alfa fields sampled in the Tarugo basin where the fertility value stands around an average level. Organic carbon in all samples is in line with the average values found in soils at the national level, indicating a poor supply of organic matter. This result confirms the great naturality of the second area respect to the first one, while indicates that the Scaricalasino watershed was strongly overexploited by anthropic activities and its soil reflects such a past situation.

Nickel analyses, conducted on soil and water samples (Tab. 1 and Tab. 2), have yielded quite unexpected results since higher values in the Tarugo basin (apparently less compromised by the anthropic activity) than in the Scaricalasino have been found. The reasons for these outcomes can be multiple: possible punctual contamination by fraudulent action; presence of naturally rich substrates of such metal; influence of the different flowpath of groundwater recharging the rivers. In particular, the higher levels of Ni in the Tarugo river may be due to the non-local recharge of the river (whose water comes from very distant areas, as suggested also by the isotopic results) and to the great capacity for mobilization of Ni from soils to waters considering that this element is stable in solution and is characterized by considerable mobility in pedosphere (Di Giuseppe, 2010).

Chloride, nitrate and sulphates concentrations grow from T1 to T3 (second area), while phosphates are higher in the T1 point, located upflow; nitrites and phosphates (and, less, sulphates) are mainly connected to the use of different fertilizers in the cultivated fields, whereas a general increase of chemical concentration is expected downflow due to the contribution of the limestone aquifer to the recharge.
The purpose of isotopic analyses was mainly to achieve the recharge elevation of aquifers and rivers and also to study the dynamics of recharge and properties of the hydrological cycle. In fact, the comparison between the isotopic contents in precipitation and groundwater and river water isotopic values, confirmed the supposed mechanism of pollutants transfer and helped in the aquifers and rivers recharge identification. A mean value of about -6.9‰ VSMOW in the first area and -7.8‰ VSMOW in the second area was determined for the oxygen-18 in surface waters (Tab. 1).

Fig. 3 shows the range of the isotopic values recorded in the pluviometers of the first (Poggio and Portonovo rain gauges) and in the second (Mt. Paganuccio rain gauge)

| TABLE 1 |
| Results of the chemical analyses on groundwater and surfacewater. Values are expressed as ppm. |

<table>
<thead>
<tr>
<th>SCARICALASINO RIVER</th>
<th>TARUGO RIVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of sample</td>
<td>River Water</td>
</tr>
<tr>
<td></td>
<td>S1</td>
</tr>
<tr>
<td>13/05/16</td>
<td>-7.04</td>
</tr>
<tr>
<td>11/06/16</td>
<td>-45.6</td>
</tr>
<tr>
<td>Ni</td>
<td>2.44</td>
</tr>
<tr>
<td>Ca</td>
<td>115.6</td>
</tr>
<tr>
<td>Na</td>
<td>40</td>
</tr>
<tr>
<td>F-</td>
<td>0.22</td>
</tr>
<tr>
<td>Cl-</td>
<td>62.42</td>
</tr>
<tr>
<td>Br-</td>
<td>0</td>
</tr>
<tr>
<td>NO3-</td>
<td>15.38</td>
</tr>
<tr>
<td>PO43-</td>
<td>0.31</td>
</tr>
<tr>
<td>SO4=</td>
<td>56.92</td>
</tr>
<tr>
<td>Metalaxil</td>
<td>1.26</td>
</tr>
<tr>
<td>Terbutylazine</td>
<td>0.09</td>
</tr>
<tr>
<td>Linuron</td>
<td>0.01</td>
</tr>
<tr>
<td>Metolachlor</td>
<td>-0.07</td>
</tr>
</tbody>
</table>

TABLE 2

Results of chemistry on soil in the investigated basins.

<table>
<thead>
<tr>
<th>ID</th>
<th>Notes</th>
<th>Date</th>
<th>(ppm)</th>
<th>mg/Kg</th>
<th>µg/(g*h)</th>
<th>g/Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Notes</td>
<td>Date</td>
<td>Ni</td>
<td>C-Biom</td>
<td>FDA</td>
<td>C-Org</td>
</tr>
<tr>
<td>1</td>
<td>Field 1 Scaricalasino (S1)</td>
<td>13/05/2016</td>
<td>11.53</td>
<td>142.48</td>
<td>0.47</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Riverbank 1 Scaricalasino (S1)</td>
<td>3.08</td>
<td>100.58</td>
<td>0.28</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Riverbank 2 Scaricalasino (S2)</td>
<td>1.91</td>
<td>100.58</td>
<td>0.21</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Riverbank 3 Scaricalasino (S3)</td>
<td>8.02</td>
<td>67.05</td>
<td>0.12</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Field 2 Scaricalasino (S2)</td>
<td>6.22</td>
<td>176.01</td>
<td>0.44</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Field 1 Scaricalasino (S1)</td>
<td>2.58</td>
<td>209.54</td>
<td>0.38</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Field 2 Scaricalasino (S2)</td>
<td>17.33</td>
<td>205.35</td>
<td>0.46</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Field 3 Tarugo (T1)</td>
<td>26.81</td>
<td>284.97</td>
<td>0.58</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Field 4 Tarugo (T2)</td>
<td>27.35</td>
<td>284.97</td>
<td>0.54</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Riverbank 4 Tarugo (T2)</td>
<td>13.67</td>
<td>75.43</td>
<td>0.02</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Field 5 Tarugo (T3)</td>
<td>30.65</td>
<td>192.77</td>
<td>0.48</td>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>
areas, compared with the isotopic contents of samples collected in different points in the Scaricalasino and in the Tarugo rivers (Tab. 3). The surface water of the first area show values that fall within the range of local rainfall variability. This consideration confirms that the catchment area of the Scaricalasino is characterized by local recharge (using the isotopic gradient proposed by Mussi et al., 2017, indeed, an average recharge elevation of 80-100 m can be obtained), and that the alluvial aquifer directly recharges the river over the year. In the Tarugo, by contrast, the water recharging river infiltrated at a much higher altitude than those of the stations in the riverbed, with the area of recharge likely located in the Mt Paganuccio limestone massif, leading to a non-local recharge.

**ISOTOPIC TREND DURING THE RECESSION PERIOD IN THE TARUGO RIVER**

In a limestone ridge (as the Tarugo area) the isotopes trend after the recharge period is significant to highlight the potential occurrence of different zones of recharge and/or to identify the signal of the end of the recharge.

In Fig. 4 the oxygen-18 trend of the T1 and T3 points is reported; the first point is located at the beginning of the limestone ridge (after the terrigeneous rocks), the second one at the end of the limestone gorge. Lowest values were observed in the first part of the graph (where the effect of the winter recharge is still relevant) until the end of July, in which more positive values have been recorded because of some spring/summer recharge signals occurring in the Mt. Paganuccio area. The hydrographs of the two stations show the discharge trend, mainly visible in the T1 point (in which the contribution of the terrigeneous rocks plays a basic role), compared to precipitations in the Mt. Paganuccio rain gauge station. Slight differences recorded in the oxygen-18 values between T1 and T3 stations are mainly related to some changes in aquifers recharging the Tarugo river in this tract: the T3 station is in fact more affected by the recharge of the limestone ridge of Mt. Paganuccio than the station T1, owing to more depleted values recorded in this point, corresponding to a recharge elevation higher.

Even the effect of precipitations on the river stage is clear, with well response especially in the recharge period and at the end of the recharge, after that rainfall events can make a rise in the river stage of only few centimeters.

**DILUTION EFFECT, POLLUTANT TRANSFER MECHANISM AND DISCUSSION**

A marked dilution effect has been observed in the Scaricalasino samples: in the same points, but at different sampling times, the chemical concentrations changed.

### TABLE 3

<table>
<thead>
<tr>
<th></th>
<th>Mt Conero</th>
<th>Portonovo</th>
<th>Mt Paganuccio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d18O</td>
<td>d2H</td>
<td>d18O</td>
</tr>
<tr>
<td>jan-15</td>
<td>-8.1</td>
<td>-49.6</td>
<td>-5.3</td>
</tr>
<tr>
<td>feb-15</td>
<td>-9.0</td>
<td>-55.6</td>
<td>-7.5</td>
</tr>
<tr>
<td>mar-15</td>
<td>-7.9</td>
<td>-49.1</td>
<td>-6.8</td>
</tr>
<tr>
<td>apr-15</td>
<td>-6.9</td>
<td>-41.7</td>
<td>-6.2</td>
</tr>
<tr>
<td>may-15</td>
<td>-6.5</td>
<td>-32.5</td>
<td>-5.2</td>
</tr>
<tr>
<td>jun-15</td>
<td>-5.4</td>
<td>-32.0</td>
<td>-4.7</td>
</tr>
<tr>
<td>jul-15</td>
<td>-4.3</td>
<td>-25.9</td>
<td>1.9</td>
</tr>
<tr>
<td>aug-15</td>
<td>-4.6</td>
<td>-26.7</td>
<td>2.5</td>
</tr>
<tr>
<td>sep-15</td>
<td>-9.3</td>
<td>-55.6</td>
<td>-7.0</td>
</tr>
<tr>
<td>oct-15</td>
<td>-6.5</td>
<td>-36.9</td>
<td>-6.1</td>
</tr>
<tr>
<td>nov-15</td>
<td>-13.0</td>
<td>-85.5</td>
<td>-12.2</td>
</tr>
<tr>
<td>dec-15</td>
<td>-7.2</td>
<td>-46.3</td>
<td>-6.5</td>
</tr>
<tr>
<td>jan-16</td>
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<td>-37.2</td>
<td>25.3</td>
</tr>
<tr>
<td>feb-16</td>
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<td>-31.9</td>
<td>-22.8</td>
</tr>
<tr>
<td>mar-16</td>
<td>-8.9</td>
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</tr>
<tr>
<td>apr-16</td>
<td>-9.1</td>
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<td>-53.3</td>
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<tr>
<td>may-16</td>
<td>-6.5</td>
<td>-37.3</td>
<td>-31.7</td>
</tr>
<tr>
<td>jun-16</td>
<td>-5.4</td>
<td>-35.1</td>
<td>-41.8</td>
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<tr>
<td>jul-16</td>
<td>-5.4</td>
<td>-25.6</td>
<td>-21.8</td>
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<tr>
<td>aug-16</td>
<td>-4.9</td>
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<td>-20.0</td>
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<td>sep-16</td>
<td>-7.7</td>
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<td>-47.2</td>
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<td>oct-16</td>
<td>-6.7</td>
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<td>-32.3</td>
</tr>
<tr>
<td>nov-16</td>
<td>-8.7</td>
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<tr>
<td>dec-16</td>
<td>-8.8</td>
<td>-48.8</td>
<td>-15.1</td>
</tr>
</tbody>
</table>

---

Fig. 3 - Results of the isotopic analysis: rainfall (rectangles) isotopic content are expressed as a range of values, surface water (triangles and circles) isotopic content are relative to the sampling campaigns. GMWL: Global Meteoric Water Line.
substantially. Both the dilution effect and the pathways of waters reaching the river are shown by the comparison among rainfall amount, hydrometric stage and chemistry (Fig. 5) as well as the results of isotopic analyses.

Due to the different recharge regimes of the studied basins (local for the Scaricalasino and non-local for the Tarugo), the dilution effect by rainfall is more apparent in the first than in the second area.

In the Scaricalasino basin the contamination source transfers the pollutant to the soil and water fairly quickly because the cultivated lands are very close to the river and the alluvial aquifer is usually heavily influenced by precipitation: from hydrological and isotopes data results that the river drains the alluvial aquifer all over the year. Consequently, levels of contamination are similar for river water and groundwater.

In the second area the transfer mechanism is quite different; most of the river water, indeed, comes from more distant zones (the limestone ridge is in fact the main source of river recharge) and only few parts are in direct connection with the surrounding areas. For this reason, direct leaching of soil is therefore more limited.

These results and the application of isotopes as recharge mechanism recognizers, lead to the formation of two different conceptual models for the Scaricalasino and Tarugo areas. In the latter, minor human impact and the occurrence of few agricultural fields cause environmental consequences similar to the former area, characterized by major human impact and intensive and widespread agricultural activities. The anthropic effects were measured using Nickel, sulphates, chlorides, nitrates and phosphates as indicators of pollution, especially related to agricultural activities. In this context, recharge plays a key role, particularly in two processes: (i) the transfer of pollutants from the source to the soil and water matrices and (ii) the different position of the recharge areas in the two sites. In fact, recharge areas very far from the Tarugo river are likely responsible for high content of some pollutant indicators (like Nickel), lowering the environmental state of a more undisturbed natural area and making the level of contamination very similar to those of the Scaricalasino area.

CONCLUSIONS

The isotopes results showed some differences in the recharge mechanism in the two investigated sites: in the first one (characterised by high human impact and prevailing clayey and sandy Plio-Pleistocene sediments) the river is recharged by the alluvial aquifer with local precipitation fell in the neighbour areas. In the second site (which is more natural, with few human settlements and activities) the limestone aquifer (recharged in faraway areas, at more elevated altitude) mainly recharges the river.

Dilution of chemical compounds (found in the soil of the two studied sites) is closely related to the hydrological cycle and the hydrogeological settings of the areas. In particular, the isotopes and geochemistry highlight some features of the studied watersheds, useful for the increasing knowledge of water pathways and pollutant transfer mechanisms. In general, the two sites show similar pollution in soil and waters despite very different human impact and agricultural activities.

Further investigations are in progress to better detect and validate the proposed mechanism.
REFERENCES

Aquilanti L., Clementi F., Nanni T., Palpacelli S., Tazioli A. & Vivalda P.M. (2016) - DNA and fluorescein tracer tests to study the recharge, groundwater flowpath and hydraulic contact of aquifers in the Umbria-Marche limestone ridge (central Apennines, Italy). Env. Earth Sci., 75, 626.


Variations of springs discharge due to seismic events are rather common. On 2016 October 30th a Mw 6.5 earthquake occurred 5 km NNE of Norcia Town (Central Italy), at a depth of around 9 km b.g.l. The Torbidone spring, dry since 1979, was re-activated after the Norcia earthquake, and its discharge rose up to 1.6 m$^3$/s in the following weeks. The Torbidone, with other minor springs, feeds the baseflow of the Sordo River (Nera River basin), the discharge of which increased up to 2 m$^3$/s after the earthquake. The seismic events did not affect only the Torbidone spring but also the entire groundwater circulation of the Nera River hydrogeological basin.

We analyzed the Torbidone spring area and its geological framework using hydrogeological, structural and geochemical methods, to evaluate the causes of the perturbations and the possible system evolution.

The main factors thought to be responsible for the perturbations are the changes of permeability and the variations of hydraulic head. The mechanisms of these hydrogeological changes are currently being studied in order to define a conceptual model consistent with the observed response of Torbidone spring to the seismic event.

KEY WORDS: Earthquake, Groundwater flow, Spring, Groundwater geochemical, Central Italy.

ABSTRACT

INTRODUCTION

Earthquakes are known to be responsible for different kind of modifications in hydrological systems, such as transient and permanent changes of springs and streams discharge and alteration of water chemistry. These effects are frequently related to co-seismic temporary increase of water pressure and/or to dynamic strain modifications inducing temporary changes in permeability (Manga & Wang, 2015).

Permanent or long-lasting changes of spring discharge are more frequent in the near field, where modifications of the stress state induced by fault movement can cause permeability variations and changes in groundwater circulation. In particular, long lasting spring excess flow is known to accompany major normal faults earthquakes.

In karst and fractured aquifers, seismicity causes mid- and long-term effects on groundwater circulation, due to the formation of microcracks (Casini et al., 2006), unblocking of pre-existing fractures, fracture cleaning and/or fracture dilatancy and closing (Wang and Manga, 2010; Falcone et al., 2012).

The seismicity of the Norcia Plain is one of the highest in the Central Apennines. This area was affected in the past by strong earthquakes such as those in 1703 (Mw ~6.8) and in 1979 (Mw 5.9) (Borre et al., 2003).

The October 30th (Mw 6.5) main shock caused the reactivation of the Torbidone spring, 5.5 km south of the epicenter, and significantly affected the groundwater circulation of the area.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The Norcia Plain, 10 km long and 3 km wide, represents an intermountain basin formed during the extensional tectonic phase which reached this part of the Apennines in the lower Pleistocene (Galadini & Galli, 2003). The basin is infilled with Pleistocene-Holocene alluvial fan deposits (including cemented limestone breccias) and lacustrine sediments (sandy clays with gravels at the bottom), reaching a thickness of several hundred meters (Boncio & Lavecchia, 2000; Messina et al., 2002).

The Norcia Plain is surrounded by carbonate reliefs typical of the Umbria-Marche Apennines, made up of a thick carbonate shelf unit (lower Lias), overlain by stratified pelagic sediments (middle Lias - Oligocene), all belonging to the Umbria Marche sedimentary sequence.
This sequence overlies a Triassic evaporitic sequence which does not crop in the area. The overall thickness of the whole succession is 2500-3000 m (Di Naccio et al., 2005). The structural setting of the carbonate reliefs is the result of two distinct deformational events. The first compressive tectonic stage (late Miocene - early Pliocene) caused the eastward tectonic overlap of the carbonate units and the construction of an E-vergent arcuate shaped thrust-and-fold belt (Leoni et al., 2007; Calamita et al., 2012). A subsequent extensional tectonic stage active since the lower Pleistocene produced a series of NW-SE trending normal fault segments which are still active and released the strongest historical and recent earthquakes (Blumetti & Dramis, 1992; Boncio et al., 1998; Galli et al., 2005; Bindi et al., 2011). The tectonic evolution of the Norcia basin has been controlled by two main NW-SE fault systems located along the mountain slopes bordering the plain: SW-dipping normal fault system (Nottoria-Preci) and NE-dipping system interpreted as antithetic to the SW-dipping system (Borre et al., 2003).

The hydrogeological setting of Norcia Plain (Fig. 1) is strongly connected with the stratigraphic and structural features of the Umbria-Marche domain. In the surrounding reliefs, regional aquifers are hosted into the most massive, thick and calcareous formations of the Umbria-Marche sequence. These formations are classified in hydrogeological complexes with different hydrodynamic attitude (Di Matteo et al., 2013). The Calcare Massiccio-Corniola complex and the Maiolica complex constitute the basal regional aquifer, with at the base the Triassic evaporites (aquitudine). The Calcareous siliceous marly complex, present in the reduced sequence into the most massive, thick and calcareous formations of the Umbria-Marche sequence. These formations are classified in hydrogeological complexes with different hydrodynamic attitude (Di Matteo et al., 2013). The Calcare Massiccio-Corniola complex and the Maiolica complex constitute the basal regional aquifer, with at the base the Triassic evaporites (aquitudine). The Calcareous siliceous marly complex, present in the reduced sequence between Calcare Massiccio and Maiolica complexes, acts as an aquitard. Some upper aquifers are located inside the Scaglia calcarea complex (Scaglia bianca and Scaglia rossa fms, Turonian-middle Eocene). The Marne a Fucoidi complex represents the aquiclude dividing the two main aquifers described above (Mastrorillo et al., 2009; Boni et al., 2010; Mastrorillo & Petitta, 2014).

The porous aquifer, hosted in the Alluvial-lacustrine complex of the Norcia Plain, is mainly fed by lateral inflows from the adjoining carbonate complexes and only 30% of its groundwater amount is recharged by the rainfall on the plain (Mastrorillo et al., 2009; Boni et al., 2010). The alluvial aquifer is drained by the Sordo River, which, prior the October 30th, emerged in correspondence of the San Martino spring (S2 in Fig. 1) at an altitude of around 600 m a.s.l., with a mean discharge of about 0.06 m³/s. From 600 m to 540 m a.s.l. significant streambed discharge was measured at the Torbidone spring section (Lippi Boncambi, 1963). After the October 30th seismic event the Torbidone spring was re-activated and, after 7 months, it showed a discharge of about 1.6 m³/s and represents the highest head of Sordo River. The October 30th event caused also a discharge increase of about 0.200 m³/s for the San Martino spring (S2 in Fig. 1).

**MATERIALS AND METHODS**

In this paper, the first results of hydrogeological, hydrochemical and geo-structural collected data are presented. The monitoring of the study area is still ongoing and additional measurement points will be provided to implement this research project.

The Hydrographic Service of Umbria Region (Servizio Risorse Idriche e Rischio Idraulico) monitored stream discharge by flowmeter at the Torbidone spring section located at 615 m a.s.l. Discharge values were measured starting from November 11th 2017, and the monitoring is ongoing weekly. The direct measure of the S2 spring discharge was not possible because of the widespread outflow. Therefore, the S2 discharge was evaluated as the difference between the discharge measured in the Sordo River at an elevation of 590 m a.s.l. (S13) and the Torbidone discharge values. Sporadic manual discharge measurements were also taken within the Sordo River at 540 m a.s.l. (S14), from December 2016 to February 2017. The daily rainfall data from October 25th, 2016 to June 25th, 2017, referred to the Norcia weather station was acquired from the Umbria Region pluviometric network.

In the study area (Fig. 1), the water chemical composition of seven springs, collected from August 2016 to February 2017, were directly analyzed, whereas the chemical compositions of S8 and S10 are from Chiudini et al. (2013). In S2, two water samples were collected at different spill elevation (600 m and 610 m). For each sampled spring, temperature, pH, Eh, electrical conductivity and total alkalinity were determined directly in the field. Alkalinity was determined by acid titration with HCl 0.01N. Water samples for chemical analyses were filtered with 0.45 µm filters and collected in three 100 mL polyethylene bottles. One aliquot was immediately acidified with HCl 1:1. Dissolved anion (Cl, F, SO₄, NO₃), were determined by ion-chromatography, Ca and Mg were determined by AA flame spectroscopy on the acidified sample, while Na and K were determined by AE flame spectroscopy, at the laboratory of Dipartimento di Fisica e Geologia of Università degli Studi di Perugia. All the laboratory analytical methods and the field alkalinity determinations have an accuracy of better than 2%.

In order to investigate the possibility of a hydraulic connection between the Torbidone spring and the fractured aquifers hosted by the carbonate ridges along the eastern edge of Norcia plain, a geological cross section with SW-NE direction, was drawn (trace in Fig. 1). The section was built up by integrating information obtained from published geological maps (Foglio 132, Servizio Geologico d’Italia, 1941; Regione Umbria, 2012; Pierantoni et al., 2013), and data from original field surveys. Later, the section was synthesized in the hydrogeological complexes as represented in the map of Fig. 1.
RESULTS

The preliminary results of this study, started after the October 30th event, include a hydrograph of Torbidone spring discharge (Fig. 2), the Langelier-Ludwig diagram of the chemical composition of the seven sampled springs (Fig. 3) and the hydrogeological section crossing the Torbidone spring (Fig. 4).

During the first 35 days of measurements, after the Torbidone spring was reactivated, a linear increase of spring discharge was observed with a growth of about 0.025 m³/day. Lately, the discharge raised of about 0.017 m³/day, reaching values of about of 1.5 m³/s during January-May 2017. Both the amount and the abrupt increase of discharge, in the first months after the main shock, are not related to natural recharge effects, given the very low precipitation recorded in Norcia in this period (Fig. 2).

The overall baseflow discharge reached by the Sordo River at 540 m a.s.l. (S14), after the seismic event, is up to 4 m³/s while before the earthquake it was about 1.6 m³/s (Petitta, 2011).

From the physico-chemical point of view the sampled springs are characterised by temperatures ranging from 6.7 to 11.7 °C, pH from 7.30 to 7.95, electrical conductivity from 230 to 572 µS/cm. The diagram of Fig. 3 shows that all groundwater samples are characterised by Ca-HCO₃ composition with increasing content of SO₄ and Mg. The Mg increase is associated with the increase of salinity (diagram b in Fig. 3). In particular, the two springs which showed an abrupt and substantial discharge increases, Torbidone (S1) and San Martino (S2), are especially rich in SO₄ and in Mg.

The hydrogeological section (Fig. 4) shows both the compressional features (reverse faults and thrusts folds)
and the more recent extensional structures which dissect the previous ones.

The main compressional structure consists of an east-verging thrust sheet which doubles the whole calcareous sequence from the Corniola-Calcare Massiccio complex to the Scaglia calcarea complex. To the west of the Norcia Plain, the hanging-wall of this thrust sheet crops out and the thrust is buried at a depth of around 800 meters. The sequence is downthrown by the NE-dipping faults with an offset of about 1000 meters. In the central part of the section, in correspondence of the Torbidone spring area, the lower Cretaceous Maiolica complex and the underlying Calcareous siliceous marly complex crop out. This part of the outcropping sequence is also part of the hanging-wall block of the thrust sheet. In the eastern flank of the Norcia Plain, the thrust sheet crops out at the foot-wall of the main SW-dipping normal faults. The offset accommodated by the SW-dipping normal faults bordering the eastern flank of the Norcia Plain is in the order of 1500 meters. The eastern part of the section crosses the footwall of the thrust sheet.

In the study area, there exist two main sets of SW-dipping normal faults, the Nottoria-Preci faults system (N.P.F.S.) and the Vettore-Bove fault system (V.B.F.S.). These faults produced a general down throw towards SW in the order of more than 2 km and, at present, they are responsible for most of the seismicity of the area (Boncio & Lavecchia, 2000). In particular, along the Vettore-Bove fault system, a co-seismic displacement of about 1.5 m (Chiareluce et al., 2017) was documented during the seismic sequence began on August 24th, 2016.

Fig. 2 - Manual measurements of Torbidone spring discharge (m$^3$/s) (red dots), vs daily rainfall(mm) of Norcia weather station.

Fig. 3 - a) Langelier-Ludwig diagram; b) Mg vs SO$_4$ diagram, electrical conductivity (EC) reported in µS/cm.
SPRINGS DISCHARGE VARIATIONS INDUCED BY STRONG EARTHQUAKES: THE MW 6.5 NORCIA EVENT (ITALY, OCTOBER 30TH 2016)

DISCUSSION AND CONCLUSION

After the October 30th, 2016 seismic event, the hydrogeological setting of Norcia Plain has radically changed.

The aquifer of the Norcia Plain is drained by the Sordo River the origin of which, prior the October 30th, was in San Martino spring (S2), at an altitude of around 600 m with a mean discharge about of 0.06 m³/s. According to Petitta (2011), the Sordo River came out in the plain with a baseflow discharge about 1.6 m³/s.

After the October 30th 2016 seismic event, at least 2.4 m³/s of groundwater has been added to the original baseflow amount of Sordo River, as measured at 540 m a.s.l. discharge section (S14). A large part of this additional groundwater contribution is getting out from the Torbidone (1.6 m³/s) and San Martino springs (0.2 m³/s). These springs also show a different chemical composition compared to the other springs nearby. In particular, SO₄ and Mg enrichment has been observed.

The October 30th seismic event seems to have caused, the following hydrostructural changes:

- the total groundwater contribution to the Sordo River discharge, from Norcia Plain aquifer, increased of about 2.4 m³/s;
- in the eastern sector of the Norcia Plain the hydraulic head increased of about 15 m, with respect to the water table recorded in 2010-2011 (Petitta, 2011);
- the hydraulic conductivity increase, because of the intensification of brittle deformation in the dilated area, caused more rapid flow and hence increased discharge.

The mechanisms of the hydrogeological responses to earthquake shock are currently being studied; at the present state it is possible just to make a few hypotheses.

The reconstructed structural setting allowed us to suppose a hydraulic connection between Torbidone spring and the eastern carbonate basal aquifers: groundwater flowpath comes from the deepest part of basal aquifers. This statement is supported by the water chemical characteristics of Torbidone and San Martino springs. The higher sulphate-magnesium concentrations probably originate from the dolomitic-evaporitic bedrock that sustains the regional basal groundwater flow.

These first results allow to hypothesise that the additional discharge coming out because of the seismic event is fed by groundwater reserves stored in the eastern aquifers. If the proposed hydrogeological model will be confirmed, the study about possible changes of the groundwater availability should be a further step of the research project.

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Two-dimensional numerical modelling of the Riardo Plain aquifer (Campania, Italy) to constrain the recharge from the deep reservoir – Preliminary results

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ABSTRACT

A local preliminary 2D model was built in the Riardo Plain in order to preliminary evaluate the regional hydrogeological conceptual model. The used finite element code was FeFlow 6.2 and calibration of data was performed via inverse modelling through PEST (PEST code).

A volcanic and a carbonate aquifer can be distinguished at regional scale. The multilayered volcanic aquifer presents a radial flow towards gaining streams and it is recharged by direct infiltration.

Regional information about the carbonate aquifer are not available. The basement upraise and the fault systems allow the local mixing between the carbonate and volcanic aquifers. Recharge of the carbonate aquifer is likely to up-flow from the deep reservoir, but no direct information is available about rates and spatial distribution. Therefore, the aim of the 2D numerical model was to test the reliability of the hypothesis of possible bottom recharge through the carbonate basement, proposed in previous groundwater budget research.

After a first steady state calibration of the model, transient calibration was performed to fit the groundwater levels of the carbonate and the volcanic aquifer monitored in 2003. The zenithal recharge was applied daily as calculated from the thermo pluviometric data elaborated by Thornthwaite’s method, and the vertical discretization of the aquifers was set according to the stratigraphic information.

A constant bottom recharge was set as upflow through the carbonate basement.

The calibration, performed over conductivity and specific storage, gave good results. The obtained budget parameters show the higher amount of the zenithal recharge (around 60%) over the carbonate recharge (around 40%), preliminary confirming the supposed recharge model.

KEY WORDS: Riardo Plain, 2D numerical modeling, Groundwater Recharge, Groundwater budget, FeFlow.

INTRODUCTION

The numerical modeling of regional aquifers is a fundamental tool for the groundwater resources management, especially in strategic aquifers affected by scarcity or non-homogeneous distribution of the dataset (Cambi et al., 2010). A numerical model must be supported by a reliable hydrogeological conceptual model (Singh, 2014), in order to define the geometry and the properties of the aquifer and the boundary conditions which influence the simulated system. In addition, the numerical modelling is a powerful tool to test conceptual models in which one parameter could not be directly measured like the contribution of deeper aquifers in vertical mixing areas (Baiocchi et al., 2013).

The implementation of a regional 3D numerical model of the Riardo Plain aquifer suffers some uncertainties due to the non-homogeneous distribution of the information. Two aquifers can be identified in the study area: a multilayer volcanic aquifer and a deep carbonate aquifer. Information about the geometry and the recharge of the deep aquifer are still debated due to the scarcity of observation points, located only in correspondence of the mineral water area near Riardo Town.

Viaroli et al. (2018) suggested a preliminary quantification of the groundwater up-flow through the carbonate aquifer based on the comparison of the groundwater budget calculation and the long term aquifer monitoring.

Numerical modelling is a powerful tool to test hypothesis, but often the high number of unknown parameters limits this aptitude. A possible approach can be the use of a series of model with increasing complexity.

Two-dimensional numerical models can represent the first step in this process, representing a valid support to subsequent regional 3D modelling. In fact, local numerical investigations can be performed isolating just a few salient hydrogeological properties, to explain dynamics, which could not be understood otherwise, due to the high number of unknowns at regional scale. The local preliminary 2D model was built on a 1.5 km section in correspondence of a high concentration of groundwater levels monitoring data, in order to verify the presence of a deep groundwater inflow and to define the quantitative relationship with the direct infiltration.

The aim of this study is a preliminary application of a 2D model in order to verify the reliability of the possible inflow through the carbonate basement, in accordance with the complex recharge processes suggested in Viaroli et al. (2018).
**GEOLOGICAL AND HYDROGEOLOGICAL FRAMEWORK**

The study area corresponds to the Riardo Plain, located in the north Campania Region, Italy. Two main geological domains can be recognized:

- Sedimentary basement characterized mainly by the Lias – Cretaceous shelf limestone succession, highly deformed since the Miocene, during the orogenetic phase, and later by the Plio-Pleistocene tectonic activity, which created a horst and graben framework. (Giordano et al., 1995).
- Volcanic deposits (lava, pyroclastic fall deposits and ignimbrites) erupted from the Roccamonfina Volcano during its activity, from 550 to 150 ka (Rouchon et al., 2008).

The local geological setting (Fig. 1) of the modelled area was elaborated using borehole stratigraphic data provided by Ferrarelle S.p.A. In the eastern section of the model, the limestone basement was detected at an elevation of around 30 m. a.s.l., directly covered by volcanic deposits. Moving westward the basement is progressively deepened by the extensive tectonic activity. In fact, it was detected at an elevation of around -110 m a.s.l. in the western portion of the model, covered by around 20 meters of undistinguished clay deposits and by 240 meters of volcanic deposits.

The complete volcanic and volcanoclastic sequence in the Riardo Plain was subdivided in four main units (Viaroli et al., 2016b):

- Basal volcanoclastic unit: alternation of reworked volcanic deposits with a granular range spanning between ash and pumices. The unit is characterized by an overall good primary porosity. The presence of layers with different porosity reduces the vertical permeability of the unit.
- Brown Leucitic Tuff ignimbrite (BLT) unit: lithic tuff in ash matrix, characterized by low primary porosity (Luhr & Giannetti, 1987). The unit sometimes show a vertical fracture pattern. The unit shows variable thickness and features according to the ignimbrite deposition.
- Upper pyroclastic unit: alternation of reworked volcanic deposits and pumice – rich ignimbrite unit. The unit shows an overall good primary porosity and lower vertical permeability.
- Campanian Ignimbrite unit: ashy matrix ignimbrite characterized by low primary porosity erupted from the Campi Flegrei volcanic district, after the end of the activity of the Roccamonfina Volcano.

According to this geological framework, a multilayer volcanic and a carbonate aquifer can be distinguished at the regional scale.

The multilayered volcanic aquifer presents a radial flow from the Roccamonfina Volcano towards gaining streams and it is recharged by direct infiltration (Viaroli et al., 2016a, 2016b).

The volcanic aquifer is exploited for different uses, especially for agricultural and drinking purposes, which corresponds almost to the entire groundwater requirements (Viaroli et al., 2018).

Regional information about the carbonate aquifer are not available, since the monitoring points are mainly placed in the Ferrarelle S.p.A. mineral bottling plant, near Riardo Town, where the basement upraise and the fault systems allow the local mixing between the carbonate and volcanic aquifers (Cuoco et al., 2010). As a result, the potentiometric levels of the two aquifers nearby the mixing area are very similar in absolute values and trends.
The groundwater budget was calculated according to the information collected in the 1992-2014 period on the recharge area of the Riardo Plain hydrogeological system. It shows a significant water deficit (around 485 L/s) but almost stable groundwater levels and springs discharge (Viaroli et al., 2018). This information suggests the presence of an external inflow through the carbonate aquifer, probably from the carbonate ridges surrounding the Roccamonfina Volcano. Direct information of the external recharge rate is not available but it was assumed that it is similar to the calculated water deficit and with almost stable quantities according to the presumably big dimensions and good self-regulation capabilities of the deeper aquifer.

Detailed hydrogeological surveys (Capelli et al., 1999) identified also a perched aquifer hosted in the actual alluvial and detrital deposits of the plain and sustained by the Campania Ignimbrite unit. This aquifer is less productive than the others and it is exploited only for domestic uses. This aquifer was not taken into account in this model due to the minor productivity and to the absence of a long time monitoring dataset.

**HYDRAULIC PROPERTIES**

The maximum hydraulic conductivity and the specific storage were estimated by the interpretation of borehole stratigraphic data, by step drawdown tests and aquifer pumping tests. Pumping rate and drawdown data of seven tests, performed in different conditions on PzV observation point and on other three similar monitoring wells tapping the volcanic aquifer (“Pt zone”), were elaborated using MLU 2.25 software (Hemker & Post, 2013; Hemker & Randall, 2013). MLU is based on an analytical solution involving Stehfest's numerical inversion of the Laplace transform and the Levenberg-Marquardt algorithm for parameter optimization (Sahoo & Jha, 2017; Abdelaziz & Merk, 2012). MLU assumes a homogenous, isotropic, and uniform aquifer.

The elaborations gave similar results in hydraulic conductivity and storage, therefore, a mean value of each parameter was associated to the “Pt zone”. Pumping tests on wells tapping the “Pi zone” are not available, anyway, the same initial conductivity and storage values were associated also to this zone, taking into account the similarities in the stratigraphy with the “Pt zone”.

The hydraulic parameters of the “Carb zone” were calculated from five tests conducted on the PzC observation point.

**RECHARGE**

The recharge of the volcanic aquifer was calculated elaborating local daily thermo-pluviometric data in the 2000/04 period. The monthly evapotranspiration, the monthly water surplus ($W_{s,m}$) and the water deficit were calculated using the Thornthwaite’s method (Thornthwaite & Mather, 1955) for each weather station. The recharge period was usually identified from November to April. Anyway, it could change every year according to the rainfall amount. Considering the existing correlation of the weather variables with the ground elevation, cokriging was applied to spatialize the data, using GIS.

A coefficient of daily available water surplus (CoDAWS) was calculated for each month splitting the monthly water surplus calculated using Thornthwaite’s method and the monthly rainfall ($P_{m}$)

$$CoDAWS = \frac{W_{s,m}}{P_{m}}$$

The CoDAWS were then multiplied by the daily rainfall data ($P_{d}$), in order to estimate the daily $W_{s}$ ($W_{s,d}$).

$$W_{s,d} = CoDAWS \times P_{d}$$

Usually, the recharge applied in long time models is calculated monthly and applied as mean values to
every day. Daily calculation of evapotranspiration were elaborated only on local models with a small thickness, focusing on the unsaturated zone and on the shallow aquifers (Mastrocicco et al., 2011; Colombani et al., 2016).

The daily effective infiltration \( I_d \) was calculated multiplying the \( W_s \) by the mean value (0.55) of the coefficients of potential infiltration grid elaborated over the basin.

\[
I_d = W_s \times 0.55
\]

The value of each cell derives from the coefficients of potential infiltration assigned to each hydrogeological complex according to previous local studies (Autorità di Bacino dei Fiumi Liri – Garigliano e Volturro, 2008; VIGOR Project, 2012), and the slope of the ground surface, as described in Viaroli et al. (2018).

A mean recharge value was applied to the nodes of the first row of the model as Neumann boundary condition (Fluid flux BC) during the steady state simulation. In the same way, during the following transient state model, the daily effective infiltration time series was applied.

The recharge of the carbonate aquifer is likely to under-flow from the deep reservoir, according to the hydrogeological conceptual model (Viaroli et al., 2018), but no direct information is available about rates and spatial distribution. The bottom recharge was included in the model as a constant value through the Neumann boundary condition applied to the nodes of the lower row of the mesh, falling within the “Car zone”.

Withdrawals

Anomalous oscillations in the groundwater level can be noted in the two observation points PzC e PzV if compared to the monthly water surplus/water deficit calculated using the Thornthwaite’s method (Fig. 2). A progressive water level increase could be observed during every recharge period. After the end of the recharge, the groundwater level quickly decreases according to the natural discharge of the hydrogeological system, with an annual minimum level measured in July or in August. An anomalous increase of the groundwater level was detected from August to November, even if there is not usually the aquifer recharge. No information about withdrawals for agricultural use is present in specific databases, but they could be preliminary evaluated according the local climatic conditions elaborated with the Thornthwaite’s method and the land use information (Viaroli et al., 2018). The presence of water deficit every year in July and August implies the absence of available water in the soil, with the evapotranspiration still exceeding the rainfall amount. Thus, the plantations are supposed to be irrigated in order to avoid the plant drying. The groundwater required for the plants growth was preliminary and conservative evaluated equal to the water deficit. In the 2D model, the effect of the withdrawals was recreated using the single well boundary condition (Well BC). The estimated monthly withdrawal was divided and applied on the 1056 nodes of the “Pt zone”, exploited by most of the agricultural wells. Agricultural withdrawals applied only during July and August (when a water deficit is calculated) seems not be reliable according to direct field observations. Therefore, such mentioned agricultural requirement was spread over the four summer months.

**CALIBRATION**

The numerical model was calibrated firstly under steady – state conditions via inverse modelling through FePEST (graphical user interface of the PEST code, Doherty, 2010). Zonal calibration was performed over hydraulic conductivity, using mean head values for the PzC and PzV observation points. For each zone, the interval ± one order of magnitude of the values calculated from the pumping tests was assigned. Wider range of possible calibrated results was associated to the other zones. A successive transient – state calibration was performed over hydraulic conductivity and specific storage, according sixty hydraulic head values measured in the PzC and PzV observation points during the 2003.

**DISCUSSIONS AND CONCLUSIONS**

A preliminary 2D model of a 1.5 km section of the Riaro Plain was realized in order to validate the hypothesis of a multiple recharge of the aquifer, both from the direct infiltration and both from a deeper inflow through the carbonate basement described in Viaroli et al. (2018). The direct infiltration was calculated daily using the daily precipitation data and the CoDAWS calculated for the simulation period.

The CoDAWS is a smart tool to maintain a daily resolution of large models, according also with the frequency of the observation data and precipitation time series.

The model was zonal calibrated over conductivity and storage under steady and transient conditions, according to the hydraulic head data measured in 2003 of two observation wells, one tapping the volcanic aquifer and the other tapping the carbonate aquifer. The results of the parameters calibrated in transient mode are shown in Tab. 1A.

In the next step, the zenithal recharge, the withdrawals and the hydraulic head observations of the 2000-2004 period (1461 days) were set in the model. The simulated values on the longer period agree with the measured data.
with a $R^2 = 0.89$ and with a RMSE value of 0.3 m (Fig. 3).

The mathematical model allowed to evaluate the groundwater budget inflows and outflows, related to the applied boundary conditions (Tab. 1B).

The amount of storage release, higher than the storage capture term, describes the response of the aquifers according to their storage characteristics during the simulated drought period. The total budget calculation is in balance but with hydraulic head levels progressively decreasing, as per the storage unbalance.

The volume of total inflow during the simulated period, through the Neumann boundary conditions was computed by the model, but its absolute value has no physical meaning, due to the lack of the third dimension in the 2D model. Focus in this case is on the relative percentage between the zenithal infiltration and the groundwater upraise from the carbonate aquifer. The higher amount of the recharge derives from the rainfall infiltration, around 60% of the total recharge, whereas the calculated carbonate recharge was around the 40% of the total recharge. The preliminary numerical results confirmed the need to apply a deep inflow through the carbonate basement, not recharged by local rainfall, as hypnotized in previous groundwater budget calculations (Viaroli et al., 2018), in order to calibrate the model with reliable parameters. In addition, the proportion between the direct infiltration and the deeper inflow suggested in groundwater budget calculation was confirmed.

Future numerical simulations on longer time series (up to thirty years) could allow to estimate the time variability or the almost stability of the deeper inflow. Future simulations allow the comparison of the results between models in which the direct infiltration is applied daily and calculated using the CoDAWS and models with a mean monthly value of zenithal recharge calculated using the Thornthwaite's method. The information of the deeper inflow will be included in sequent 3D model at the catchment scale of the aquifer system.

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Groundwater level forecasting using linear time series modeling: the case study of the thermal aquifer system of Monsummano Terme (central Italy).

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ABSTRACT

Groundwater level forecasting can support a more efficient and sustainable groundwater management. In the present study, linear models are implemented on hydrogeological and meteorological time series related to the thermal aquifer system of Monsummano Terme (Pistoia province, Tuscany region in central Italy), in order to develop a tool for short-term groundwater level forecasting.

Groundwater level data were analyzed along with daily precipitation and used for training Autoregressive (AR) models and Autoregressive models with Exogenous Input (ARx). The best performing AR model consisted in a linear combination of the past 9 groundwater level measurements whereas the ARx model concerned, in addition, the precipitation values of the past 10 days. As a result, these models show an optimal performance in terms of Normalized Root Mean Square, and their residuals (i.e. modeled – measured values) can be associated to a white noise containing no relevant information. This study shows how linear models can be useful and easy-applicable tools for groundwater level forecasting in systems characterized by a linear relationship between recharge and groundwater level increase.

KEY WORDS: Time Series Analysis, AR, ARx, Exploratory Analysis, Residual Diagnostics.

INTRODUCTION

Groundwater level modeling is a useful tool to support groundwater resource management (Prinos et al., 2002). Beyond sustaining an efficient and sustainable water exploitation, groundwater level modeling and forecasting can provide a better understanding of the dynamics governing groundwater levels oscillations (Moosavi et al., 2013). Conceptual or physically based models are widely considered the main type of model used to represent hydrological variables and their relationships in terms of physical processes occurring in a particular system (Adamowski and Chan, 2011). At the same time, the increasing availability of detailed hydraulic heads temporal data, and the lack of geological and lithological data led to an increasing attention toward data-driven time series analysis methods.

Several modeling approaches were presented in literature. More than a few studies performed innovative non-linear black-box models such as Artificial Neural Network (Coppola et al., 2003; Daliakopoulos et al., 2005; Nayak et al., 2006; Mohanty et al., 2010; Shiri & Kiş, 2011; Izady et al., 2013); however, some authors (e.g. Beriro et al., 2013) argued that the application of a linear model can be more appropriate in simple systems characterized by linear relationships between the hydrological variables.

This work focuses on groundwater level forecasting in an aquifer system where a linear relationship between recharge by rainfall and hydraulic head response can be assumed. This aquifer system consists in a fractured aquifer which can be considered as a closed system. That might be the case where a linear model can successfully capture the dynamics of the system. The purpose of this study is to test the effectiveness of linear models, such as Auto Regressive model (AR) and Autoregressive model with exogenous input (ARx), in forecasting groundwater levels when a linear relation between groundwater response and recharge can be assumed. In conjunction with this main goal two other key aspects were taken into consideration and highlighted, which are (a) the usefulness of the exploratory analysis as a basis for the model choice and implementation and (b) the importance of combining quantitative and qualitative error analysis.

STUDY AREA

This study involves the thermal aquifer system of Monsummano Terme in central Italy (Pistoia province, Tuscany Region). This system is located at the transition between the northern Apennines and the Arno Plain and consists of a fractured carbonate aquifer.

A previous study (Grassi et al., 2011) pointed out that the Monsummano Terme aquifer has a short extension (~1-2 km of length and width and 600-700 m of thickness) and can be considered as a closed system which is independent and physically separated from the nearby Montecatini Terme aquifer system and has no interrelations with surface water bodies. The system is recharged upstream by local precipitation in an hilly area where carbonates outcrop (Monsummano Alto, at 150-300 m a.s.l approximately)
and discharges downstream through natural springs and well abstractions (Monsummano Terme, at ~50 m a.s.l.). More specifically, the conceptual model for water circulation in the Monsummano Terme system (Grassi et al., 2011) considers that, after infiltrating in the recharge area, water mainly moves downward toward the aquifer basinement (at 600-700 m of depth) due to the predominant vertical fracturing. Successively, the water flow assumes a predominant orizontal component toward the discharge area; during this circulation, the water increases its temperature due to the interactions with deep thermal fluids. Finally, in proximity of the discharge area, the water mainly moves upward due to a) its lower density caused by the temperature increase and b) the presence of low-permeability deposits at the transition between carbonates and alluvial deposits.

Grassi et al. (2011) identified a linear and quick response of the groundwater levels in the discharge area to the precipitation in the recharge area.

The features described above allow to consider the Monsummano Terme system as a proper case study in order to test the groundwater level forecasting capability of linear models.

MATERIALS AND METHODS

This work was carried in two phases consisting in a) an exploratory analysis and b) the implementation and evaluation of linear models. In each phase different statistical techniques were applied with a specific objective. In the exploratory analysis Auto Correlation, Partial Autocorrelation, Cross Correlation and Impulse Response were applied, aiming at understanding the information contained within the available data. In the second phase AR and ARX (Box & Jenkins, 1979) models were implemented and evaluated as tools to perform short term forecasting of the groundwater level.

AVAILABLE DATA

The present study is based on two available time series: 1) a sequence of daily groundwater levels (Fig. 1, b, black line) measured at the monitoring well of Grotta Giusti (Fig. 1, a), located in the discharge area of the Monsummano Terme system and 2) a sequence of daily precipitation (Fig. 1, b, blue line) registered at the Montecatini Terme station, that is ~5 km far from Monsummano and can be considered representative of the precipitation in the recharge area of the Monsummano Terme system. Both time series cover a period of almost 10 years, from 26/12/2005 to 07/05/2015.

The monitoring well at Grotta Giusti is 158 m deep and filtered from about 70 m of depth. The average groundwater level on the considered period is 57.86 m a.s.l., with a standard deviation of 1.18 m. Since 2008 (Fig. 1), monitoring showed a significant monthly variability that was not found in the first period from 2005 to 2008. A seasonal pattern is evident, with the minimum in summer months and maximum (with daily peaks) between November and December.

Precipitation (Fig. 1b) shows a seasonality as well, but it is stationary on the considered period as there is no trend; the wettest months are in the period between November and January, while in the period between June and August the frequency of rainy days decreases. The rainiest year in the considered series is 2014 with a cumulative precipitation amount of 1662 mm, while the driest is 2011 with 848 mm.

Within the groundwater levels sequence, a certain number of missing data were pinpointed. The development of auto regressive models requires continuous sequences of data, without any missing data. Similarly, for the validation of these models, it is appropriate to apply them to sequences of continuous data in order to evaluate their quality and their forecasting power. Since the absence of some data is a common condition in almost all the environmental data sets, techniques have been developed, such as interpolation, able to reconstruct the gaps.

The Fig. 1 (b) shows the missing data within the available groundwater level sequence and how they are grouped within circumscribed time windows, whereas suitable subsequences of continuous data are recognizable. Therefore, the three longest continuous subsequences were identified to process the data (Fig. 1, b). In this way, it was possible to avoid dealing with reconstructed data, basing the analysis only on actually measured data. The three sequences were used at different stages of the analysis and development of the regression models. In particular, the most populated sequence was used as training set while the two remaining sequences, shorter than the first one, were successively used as test sets in order to evaluate the performance of the model trained on the training set:

- Training set: 1246 groundwater level measurements from 19/06/2008 to 16/11/2011 with an average value and standard deviation of 57.62 m a.s.l. and 1.22 m, respectively; the average daily precipitation is 3.45 mm.
- Test set A: 354 groundwater level measurements from 12/09/2006 to 30/08/2007 with an average value and standard deviation of 57.40 m a.s.l. and 0.89 m, respectively; the average daily precipitation is 2.84 mm.
- Test set B: a total number of 613 groundwater level measurements from 12/10/2012 to 16/06/2014 with an average value and standard deviation of 58.71 m a.s.l. and 1.08 m, respectively; the average daily precipitation is 4.55 mm.

TIME-SERIES EXPLORATORY ANALYSIS

The first phase of the present work consisted in exploratory analysis, aimed at identifying the information contained within the available data, in order to steer the models implementation. Since the studied data consist in time-domain sequences, the exploratory analysis was conducted by means of techniques belonging to the family of the time-series analysis. More specifically, Auto Correlation and Partial Autocorrelation were applied as univariate statistics, whereas Cross Correlation and Impulse Response were used as bivariate statistics.

Time series are characterized by autocorrelated data: given the groundwater level of the k-1 day, it can be stated that the groundwater level of the next day k falls within a set of values close to the one of the day k-1, so a totally random value cannot be assumed. On the other hand, it is also plausible to assume that the groundwater level of the
day \( k \) depends only on a finite number of previous values. The Auto Correlation is a measurement of this relationship between different values of the same variable (in this case groundwater level) at different time: it represents the correlation between the groundwater level detected at a given time \( k \) and the groundwater level data collected at previous time steps. Autocorrelation values close to zero indicate that there is no correlation while values close to 1 or -1 (or higher than a significance level) indicate strong positive or negative correlations.

The formal definition of Auto Correlation (Eqn. 1) considers the linear dependence of a feature with itself at different time lags. A process can be defined stationary if the Auto Correlation between any two measurements only depends on the number of time lags between them.

\[
C(k) = \frac{1}{n} \sum_{t=1}^{n-k} (x_t - \bar{x}) \cdot (x_{t+k} - \bar{x}), k \geq 0
\]

(1)

\[
\gamma(k) = \frac{C(k)}{C(0)}
\]

(2)

Fig. 1 - a) Location of Grotta Giusti monitoring well. b) Schematic representation of the aquifer and water flow paths according with the conceptual model presented by Grassi et al. 2011. c) Groundwater level and precipitation time series.
Where $C(k)$ is the correlogram, $n$ is the time-series length, $k$ is the time-lag, $x$ is the value of the variable at time $t$, and $\bar{x}$ is the average of the $x$ variable; is the autocorrelation function.

The Partial Autocorrelation, denoted $\phi_{xy}$, is the Auto Correlation between $y_i$ and $y_{i+k}$ after removing any linear dependence on $y_t, y_{t+1}, ..., y_{t+k-1}$ in order to avoid correlation resulting from a mutual linear dependence on the time lags between $t$ and $t+h$ (Box et al., 2015). Partial Autocorrelation values close to zero indicate no correlation, while values higher than the significance level indicate that a correlation exists. Auto Correlation and Partial Autocorrelation functions are sequences of, respectively, $\rho_h$ or $\phi_h$ for each $h=1, 2, ..., n$ and they can be useful tools for choosing the model and the model orders (Mishra & Desai, 2005). An AR model can be a suitable solution for systems whose Auto Correlation Function tails off gradually whereas its Partial Auto Correlation Function cuts off after $n$ lags. More specifically, if the values of the Partial Autocorrelation function are zero at lag $n+1$ and greater the process can be represented with an AR(n) model based on $n$ previous values.

The Cross Correlation is a measure of the linear correlation between two variables at different time-lags. An estimate of the samples Cross Correlation is:

$$C_{xy}(k) = \frac{1}{n} \sum_{t=1}^{n-k} (x_t - \bar{x}) \cdot (y_{t+k} - \bar{y}), k \geq 0 \quad (3)$$

$$y_{xy}(k) = \frac{C_{xy}(k)}{\sigma_x \sigma_y} \quad (4)$$

Where $C_{xy}(k)$ is the cross - correlogram, $n$ is the time-series length, $k$ is the time-lag, $x$ is the value of the output variable $x$ (groundwater level in this case) at time $t$, and $\bar{x}$ is the value of the input variable (precipitation) at time $t$, and $\bar{y}$ and $\bar{y}$ are the averages of the $x$ and $y$ variables and $\sigma_x$ and $\sigma_y$ the standard deviations. $y_{xy}(k)$ is the Cross Correlation function.

The information obtained from a Cross Correlation graph is smoothed by the effect of the Auto Correlation that is still present within the data time series, in order to avoid this effect, the Impulse Response function has been examined. This function focuses on the relationship between the two variables avoiding the influence of the Auto Correlation, by filtering the input and the output data with an autoregressive polynomial function before calculating the Cross Correlogram in Eqn. 3 (see Signal Processing Toolbox™ User’s Guide, R2016a). Both the Cross Correlation and the Impulse Response functions provide information about the relationship between groundwater level and precipitation at a certain time lag: values close to zero indicate that there is no relationship while values outside the significance boundaries indicate a significant effect of the precipitation on the groundwater level.

LINEAR MODELS

A system is definable linear if the output generated by the linear combination of two or more inputs is equal to the linear combination of the outputs generated by the single inputs. It is also definable time - invariant when the output generated by a delayed input is equal to the output generated by the delayed original signal (the system response is not directly dependent from the instant $t$).

Discrete-time and univariate models were applied in the second phase of the present work to process and reconstruct the time series of groundwater level and precipitation of the Monsummano Terme system. These are AR and ARx linear models, both implemented using MATLAB®. The AR and ARx (Eqn. 5 and 6) are both part of the linear models family, and therefore are usually adopted to model linear systems.

Given $k$ the current instant, the purely AR model of the hydraulic heads sequence $y[.]$ (Eqn. 5) states that each $y[k]$ value is a linear combination of the $n$ past values (where $n$ is the order of the model), with coefficients, assumed to be constant. In the development of an ARX (Eqn. 6) the exogenous input (rainfall) has been also considered. The ARX model defines each $y[k]$ value as a linear combination of $n$ previous values of $y$ and $p$ values of the input variable, where $n$ and $p$ values are called orders of the model and reported with the notation $[n \ p]$.

$$y_t = \sum_{j=1}^{n} \theta_j y_{t-j} + \epsilon_t \quad (5)$$

$$y_t = \sum_{j=1}^{n} \theta_j y_{t-j} + \sum_{j=1}^{p} \phi_j u_{t-j} + \epsilon_t \quad (6)$$

Where $y$ and $u$, are, respectively groundwater level and precipitation value at time $t$; $\theta$ and $\phi$ are the coefficients of the models and $\epsilon$ is a white noise element with 0 mean and variance $\sigma^2$. The parameters $n$ and $p$ are the model orders. For the determination of the coefficients ($\theta$ and $\phi$) a non-iterative algorithm has been used, aiming at minimizing least squares errors.

The definition of the orders of the models, respectively, $n$ and $[n \ p]$ is based on “a priori” considerations on the data and on the conceptual model and “a posteriori” considerations based on comparing the effectiveness of AR and ARX models with different orders.

The AR and ARX models where trained on the training set and their effectiveness was determined by applying them on the test sets. The quality of the elaborated AR and ARX models was evaluated in terms of Normalized Root-Mean-Square Error (NRMSE) (Eqn. 7):

$$NRMSE = 100 \left(1 - \frac{\sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{y})^2}}{\sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \text{mean}(y))^2}}\right) \quad (7)$$

A second criterion has been taken into consideration as a tool to compare different models which is the normalized Akaike Information Criterion (nAIC); nAIC unifies in one value the information about the effectiveness of the model and its complexity, penalizing either bad accuracy and excessive complexity, as expressed by Eqn. 8:

$$nAIC = \log \left( \text{det} \left( \frac{1}{n} E^T E \right) \right) + \frac{2 \times np}{n} \quad (8)$$
Where $E$ is the $N$-by-1 matrix of prediction errors, $n_p$ is the number of free parameters of the model and $n$ is the number of data in the dataset. The best model has the lowest $nAIC$ value.

Besides the effective performance of the models expressed as NRMSE and AIC, the choice of the model order was based on a detailed analysis of the model errors, aimed at ensuring that no relevant information was contained in the residual of the model (Ginocchi et al., 2016). Specifically, all the techniques used in the exploratory analysis of the data sequences (Auto Correlation Function, Partial Autocorrelation Function, Cross Correlation and Impulse Response) were applied on the residual of the models. Residuals were calculated for each sample as the difference between the measured and modelled values. A model can be considered effective when the error is associable to a white noise (i.e. its residuals have no significant Auto Correlation or Cross Correlation with its input).

RESULTS AND DISCUSSION

EXPLORATORY ANALYSIS

Exploratory analysis was performed in the first phase of the present work, in order to determine how much the groundwater level at a certain time $t$ is affected by previous values of groundwater level (Auto Correlation and Partial Autocorrelation) and past precipitation events (Cross Correlation and Impulse Response).

Fig. 2 (a,b) shows the Auto Correlation and Partial Autocorrelation Functions of the groundwater level data and the Cross Correlation and Impulse Response between groundwater level and precipitation. For each graph the estimate of the function for 15 time lags (days) is represented, and the significance level with a 95% confidence is shown as a horizontal line. Fig. 2 (a) shows that a strong Auto Correlation (outside the significance boundaries) exists within all the first 15 lags, slowly decreasing from $t_0$ to $t_{-15}$, while the Partial Autocorrelation reaches significant values until the 9th lag.

As regards the input-output relationship between precipitation and groundwater level, the Cross Correlation and Impulse Response (Fig. 2 c and d) resulted with similar trends. The Cross Correlation is smoothened by the implicit effect of the data auto-correlation which means that the groundwater level at a certain time is affected by the precipitation but also by previous days groundwater levels. The Impulse Response function, that is a cross correlation calculated after filtering out the effect the autocorrelation of the data, shows a more evident cut off after the 10th lag when it decreases below the significance limit.

The resulted trends of, respectively, Auto Correlation and Partial Autocorrelation, Cross Correlation and Impulse Response support the original hypothesis of the system linearity and suggest that a AR and ARx models can be appropriately applied to the available data. Particularly, the results of Partial Autocorrelation suggest that the groundwater level measured at a certain time is affected by 9 past values of groundwater level while the Impulse Response indicates that it is also affected by 10 past precipitation values, leading to hypothesize that an AR(9) model and an ARx([9 10]) model could appropriately represent the system.

![Fig. 2 - a) Auto Correlation function b) Partial Autocorrelation Function c) Cross Correlation Function d) Impulse Response Function.](image-url)
IMPLEMENTATION OF LINEAR MODELS

In this phase AR models with different orders (up to 15) were elaborated on the training set and compared by applying them on both training and test sets, in order to determine whether the information obtained by the exploratory analysis could actually lead to the best performing model.

Tab. 1 shows the fitting power, in terms of NRMSE, of the AR models with increasing orders elaborated on the training set. Fitting values are reported for both the training and the test sets.

Results show that the fitting on the training set increases progressively from 92.36% to 94.45%, from a model of order 1 to a model of order 15. The forecasting fitting power on the test sets instead grows uninterrupted in the case of the test set A (implying that the reversal point concerns even higher orders) whereas the test set B shows a maximum for the model of order 5.

In general, it is expected that the value of the fitting on the reconstruction of the training set gradually increases with increasing order of the models, whereas the fitting on the prediction of different values (test set) increases in a first phase but it drops once an optimum has been reached. On this basis, our results suggest that the AR(5) model would offer the best predictive power. However, the residuals analysis of AR(5) shows values of Auto Correlation higher than the significance level (horizontal line) for lags 6, 7 and 14 (Fig. 3, a), so that these residuals cannot be considered as a white noise and that means that the model is not representing correctly the Auto Correlation of the data, so that it cannot be considered as the best performing model.

<table>
<thead>
<tr>
<th>Model order</th>
<th>Fitting on Training Set</th>
<th>Fitting on Test Set A</th>
<th>Fitting on Test Set B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>92.36</td>
<td>92.16</td>
<td>87.27</td>
</tr>
<tr>
<td>2</td>
<td>94.18</td>
<td>94</td>
<td>89.02</td>
</tr>
<tr>
<td>3</td>
<td>94.35</td>
<td>94.06</td>
<td>89.22</td>
</tr>
<tr>
<td>4</td>
<td>94.37</td>
<td>94.08</td>
<td>89.25</td>
</tr>
<tr>
<td>5</td>
<td>94.37</td>
<td>94.08</td>
<td><strong>89.25</strong></td>
</tr>
<tr>
<td>6</td>
<td>94.37</td>
<td>94.08</td>
<td>89.24</td>
</tr>
<tr>
<td>7</td>
<td>94.38</td>
<td>94.08</td>
<td>89.23</td>
</tr>
<tr>
<td>8</td>
<td>94.39</td>
<td>94.1</td>
<td>89.2</td>
</tr>
<tr>
<td>9</td>
<td>94.43</td>
<td>94.17</td>
<td>89.17</td>
</tr>
<tr>
<td>10</td>
<td>94.44</td>
<td>94.21</td>
<td>89.16</td>
</tr>
<tr>
<td>11</td>
<td>94.44</td>
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<td>94.44</td>
<td>94.24</td>
<td>89.13</td>
</tr>
<tr>
<td><strong>15</strong></td>
<td><strong>94.45</strong></td>
<td><strong>94.25</strong></td>
<td>89.13</td>
</tr>
</tbody>
</table>
In the case study the AR(9) model shows the best predictive power among AR models with different orders, whereas within the ARx models the ARx([9 10]) outperforms the others. Both AR(9) and ARx([9 10]) showed high performances on both one or three days ahead predictions where in both cases the one day ahead prediction resulted more accurate than the three days ahead one. The performance of the models on the test set B that has values outside the range of the training set slightly decreases compared to the accuracy on the training set but the accuracy is still high.

Furthermore, this study highlights the importance of exploratory analysis that can constitute a solid and meaningful basis for choosing model type and model orders. In particular, the exploratory analysis leads to the following remarks:

- data characterized by a smoothly decreasing Auto Correlation Function, whose Partial Autocorrelation Function cuts off after a certain value can be represented by AR;
- Partial Autocorrelation Function offers an effective indication of the AR model order;
- Cross Correlation Function and Impulse Response can support the implementation of an ARx model by graphically highlighting the range in which can follow the relevant number of past precipitation level.

Finally, this study underlines the importance of a detailed residual analysis: error functions such as NRMSE or AIC do not provide alone an exhaustive indication of the model performance since they only consider residuals quantitatively. On the other hand, Auto Correlation Function of the residuals and the Cross Correlation between residuals and the input of the model (in this case precipitation) can actually help understanding whether the error still contains relevant information, a condition that should be avoided.

REFERENCES


Research articles
Il Ponte Sfondato sul torrente Farfa (Sabina, Lazio)

Marco Pantaloni (1) & Fabiana Console (2)

ABSTRACT

Ponte Sfondato is a hamlet of Montopoli di Sabina, Rieti; this name derives from a natural arch on the Farfa river, originating from a particular type of erosive phenomenon.

This paramount landform and its formation represent an intriguing history. The Ponte Sfondato was a unique example of geomorphosite formed by the erosion of a long rocky relief originating from the over-excavation of a recessed meander. The lithology of the relief, characterized by the presence of weakly cemented gravel with arenaceous levels, has facilitated the erosive activity of the Farfa river. It has been able to “break through” the rocky promontory causing the formation of the arch, creating a water path below. The natural arc has a high degree of instability; overtime, in fact, this particular morphotype tends to thin out and collapse.

The arch was used for traffic road until 1960 when it was replaced by a modern bridge and it collapsed in 1961.

Ponte Sfondato is a place of geological-historical memory, representing an important site of geological-landscape interest. Because of its evolution, this site is no longer visible and it remains in the collective imagination through writings, maps, publications, paintings, and also through mentions in novels, pictures and movies.

In questo lavoro, attraverso una approfondita ricerca di materiale cartografico, bibliografico e iconografico, vengono documentate molte delle fasi evolutive del Ponte Sfondato, dalle sue prime rappresentazioni su carte storiche fino alle immagini fotografiche del ‘900, prima del suo crollo definitivo avvenuto nel 1961.

Per secoli, infatti, il Ponte Sfondato ha rappresentato il valico naturale del torrente Farfa nella sua media valle, sul quale passava uno dei tanti tracciati, o derivazioni, della Salaria.

L’arco naturale venne utilizzato fino alla fine degli anni ‘50 del secolo scorso quando fu sostituito da un moderno ponte in cemento armato; immediatamente dopo l’abbandono il Ponte Sfondato collassò per cause non ancora chiarite.

Questo lavoro ha l’obiettivo di ricostruire l’evoluzione dell’arco naturale nel tempo, le modalità di rappresentazione nel corso dei secoli e la ricostruzione delle cause della sua origine e gli eventi che ne hanno causato il crollo. La distruzione dell’arco, di origine naturale o antropica, ha segnato il destino del Ponte Sfondato; questo morfotipo, per le sue caratteristiche peculiari, rientrerrebbe a pieno titolo tra i geositi a valenza globale (Wimbledon, 1996) e sarebbe oggi soggetto ad azioni di tutela e conservazione.

Il Ponte Sfondato rappresenta un tipico esempio di luogo della memoria geologico-storica (Console et al., 2018), ossia di un sito che ha rappresentato, in passato, un importante luogo di interesse geologico-paesaggistico ma che oggi, a causa della sua evoluzione, non è più visibile. In virtù delle sue caratteristiche il Ponte Sfondato resta quindi nella memoria storica e nell’immaginario collettivo attraverso scritti, cartografia, pubblicazioni scientifiche, dipinti, e, in questo caso, anche attraverso citazioni in romanzi d’appendice, fotografie e pellicole cinematografiche.

INQUADRAMENTO GEOLOGICO-GEOMORFOLOGICO

Il toponimo Ponte Sfondato compare su tutte le carte stradali come frazione del comune di Montopoli di Sabina, in provincia di Rieti, dal quale dista circa 6 km.

Poco noti sono i motivi di questa curiosa denominazione derivante da un arco naturale che, nominato negli scritti...
fin dal Medioevo, è sopravvissuto fino al 1961 quando, quasi improvvisamente, è crollato.


Sulla carta topografica dell’IGMI (foglio 144 Palombara Sabina), il toponimo è indicato come “Ponte Sfondato”; esso ha costituito, per secoli, il passaggio naturale che ha permesso di attraversare il torrente Farfa.

Il Farfa è uno degli affluenti di sinistra nella media valle del Fiume Tevere, e rappresenta uno dei più importanti della provincia di Rieti. Nasce in località Ponte Buida alla confluenza del Fosso delle Mole e dal contributo delle sorgenti “Le Capore” nel territorio di Frasso Sabino (RI), che tuttavia sono quasi completamente captate dall’acquedotto del Peschiera - Capore che alimenta la città di Roma.

Oltrepassato il Ponte Sfondato, il Farfa prosegue nei comuni di Torrita Tiberina e Nazzano in provincia di Roma; la confluenza con il Tevere ha luogo all’interno della Riserva Naturale Regionale Nazzano, Tevere - Farfa nella media valle del suo corso.

La media valle del Tevere si è impostata su un bacino distensivo orientato NNW-SSE sviluppato a partire dal Pliocene medio a Ovest della catena centro-appenninica (Faccenna & Fuciniello, 1993).

La successione dei sedimenti affioranti nella media valle del Tevere permette di identificare due distinte fasi tettoniche; la prima, sviluppata dal Pliocene medio al Pleistocene inferiore, coincide con la formazione del graben del Tevere ed è caratterizzata da una rapida subsidenza che ha comportato la deposizione di estesi corpi ghiaioso-sabbiosi di ambiente fluviale e delitzio.

La seconda fase deposizionale ebbe inizio nel Pleistocene superiore ed è correlata all’orogenesi appenninica. Durante questo periodo, si assiste all’emersione della media Val Tiberina e allo sviluppo del vulcanismo laziale. Contemporaneamente, si crea un reticolo fluviale fortemente condizionato dal sollevamento, che comporta la deposizione di sedimenti di aggradazione e degradazione. Questa fase comprende i termini vulcanici e vulcano-sedimentari del Complesso Cimino e i depositi fluviali terrazzati della piana del Tevere. Le unità fluviali sono ricoperte dai depositi vulcanici dei distretti Vulcino, Vicano e Sabatino del Pleistocene medio-superiore. Il ciclo è chiuso da depositi travertinosi antichi e recenti e dai depositi fluviali attuali (Mancini et al., 2003-2004; Petronio et al., 2011).

Nell’area del Ponte Sfondato affiorano ghiaie di natura calcarea, silicea e arenacea a luoghi cementate, con stratificazione incrociata concava e piana (Chiocchini et al., 1975). La matrice dei corpi litoidi è costituita da sabbia grossolana quarzosa con minerali femici; Mancini et al. (2003-2004), indicano questi depositi come “Unità di Graffignano”, datandoli al Pleistocene medio. Nel foglio geologico 144 Palombara Sabina (Servizio Geologico d’Italia, 1970; Chiocchini et al., 1975) l’unità è indicata con la sigla q1 e attribuita a “terreni palustri”; in essi vengono descritti anche livelli lignitiferi e presenza di rari ostracodi e molluschi dulcicolli (Fig. 1).

Questa unità è stata descritta e caratterizzata presso le cave “dei Pretti” e “Ponzano”, dove è rappresentata da sabbie cementate con noduli e tubuli e al “Ponte Sfondato”, che rappresenta il tipico ambiente deposizionale fluviale caratterizzato da ghiaie in matrice di sabbie calcaree debolmente cementate (Fig. 2) (Giustini et al., 2018).

Una prima descrizione della stratigrafia dell’area viene fatta da Vinken (1963) che riporta una sezione eseguita proprio al Ponte Sfondato. L’autore segnala la presenza di una parte basale di argille rosse marine del Pliocene superiore, di spessore affiorante superiore a 2 metri, sovrastate da ghiaie grigie di origine fluviale con livelli sabbiosi e argillosi di 29 m di spessore. La successione prosegue poi con circa 40 m di argille e sabbie, bianco-giallastre, con scarsa ghiaia e resti fossili di ostracodi e da ghiaie di origine fluviale. Il ciclo sedimentario si chiude con depositi travertinosi e depositi vulcanoclastici del Pleistocene superiore.

Da un punto di vista geomorfologico, il Ponte Sfondato costituisce un tipico arco naturale, cioè una struttura che, a causa dell’erosione di livelli litologicamente più erodibili, assume l’aspetto di un arco, creando una via di passaggio sottostante. Il processo erosivo può essere causato da elementi climatici (termo- o crioclastismo) o, più verosimilmente, dallo scorrimento dell’acqua.

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**Fig. 1 - Stralcio del foglio geologico 144 Palombara Sabina della Carta Geologica d’Italia alla scala 1:100.000 (Servizio Geologico d’Italia, 1970).**

Legenda: qa = Alluvioni attuali e recenti (Olocene); q1 = Depositi palustri e lacustri recenti; qat = Alluvioni fluviali prevalentemente ghiaiose e sabbiose, del II ordine dei terrazzi (Olocene); tps = Tufi pedogenizzati, stratificati, provenienti dagli apparati Sabatino e Vicano (Pleistocene); b7 = Alternanze di tufo di colore ocreato, tufo litoidi gialli, lapilli, cineriti e pomici (Pleistocene); qts = Depositi travertinosi con resti vegetali intercalati a vari livelli nelle formazioni vulcaniche; q1 = Depositi fluvio-lacustri o palustri: conglomerati in genere poco cementati, ghiaie, sabbie e argille, con resti vegetali. Presentano spesso stratificazione incrociata (Pleistocene); q1 = Sabbage gialli, livelli conglomeratrici più o meno cementati e sabbie argillosse, argille grigie più o meno sabbiose, prevalenti verso la base (Pliocene-Pleistocene).
genere, si tratta di morfotipi instabili; col tempo, infatti, l’arco naturale tende ad assottigliarsi e a crollare.

Rovereto (1923) ne testimonia la presenza soprattutto nelle valli cieche, attribuendone l’origine al deflusso sotterraneo di falde acquifere e il successivo crollo della caverna nella quale avveniva il deflusso.

L’origine del Ponte Sfondato, che in geomorfologia viene chiamato arco o ponte naturale, è ancora incerta. Inizialmente il Farfa, il cui drenaggio era diretto verso Nord, aveva sovraescavato i depositi fluvio-lacustri erodendo un meandro che, volgendo con uno stretto cambio di direzione verso Sud, aveva isolato un dorso roccioso orientato N-S, chiuso in un meandro a forma di omega molto stretto (Fig. 3).

Iniziò quindi una lenta e continua erosione del dorso roccioso posto all’interno del meandro che causò la formazione di cavità naturali su entrambi i lati del rilievo, facilitata dalla presenza di partizioni sabbiose nell’unità fluvio-lacustre. Con il procedere dell’erosione, le cavità poste sui due lati del dorso roccioso si incontrarono e si fusero, originando una perforazione all’interno della quale il fiume riuscì a trovare un passaggio naturale. Si originò così un arco naturale e il meandro incassato venne, da questo momento in poi, abbandonato (Fig. 3).

Generalmente la volta degli archi naturali è costituita da rocce a maggior competenza ma, nel caso specifico, si tratta diversamente di depositi ghiaiosi e sabbiosi debolmente cementati; questa caratteristica litologica lascia supporre una precarietà nelle condizioni di stabilità dell’arco naturale che, nel nostro caso, probabilmente è stata all’origine del crollo improvviso della volta, avvenuto nel 1961.

Holmes (1947, 1965) descrive un caso analogo per il Rainbow Bridge, percorso dal Bridge Creek, nello Utah (Rainbow Bridge National Monument, 2018) (Fig. 4) e riporta come, a causa del sollevamento che ha interessato la regione dello Utah (USA), si sono sviluppati numerosi casi simili al Rainbow Bridge: il Ponte Sfondato rappresenta, a nostro avviso, un caso assolutamente analogo.

**IL PONTE SFONDATO NEI DOCUMENTI STORICI E NELLA CARTOGRAFIA**

In merito al periodo di origine dell’arco, e al conseguente abbandono dell’ansa incassata del Farfa, esistono opinioni contrastanti.

Inizialmente, il corso del torrente formava una strettaansa fluviale, delimitando un promontorio roccioso sulla sommità del quale sorgeva il Castrum di Tribuco, del quale si ha conoscenza ancora nel Medioevo.

In età medievale, almeno fino all’XI sec., il promontorio era utilizzato come passaggio verso il “Castro di Tribicum”: “Prope montem unde homines, vadant in castellum Tribucum” (Di Catino, 1903); studi recenti indicano una intensa attività produttiva nell’area del Ponte Sfondato, testimoniata dalla presenza di alcuni mulini, di cui almeno quattro attivi fino al 1124 (Santini, 2006).
Maria Pia Muzzioli (1980), riferendosi al manoscritto di Mariano Vittori "De Reatinis antiquitatibus" conservato presso la Biblioteca di Rieti, ricorda che "Un'ansa del Farfa, visibile perfettamente nella foto aerea e ancora esistente nel medioevo quando isolava il castello di Tribuco, era già invece abbandonata dal fiume almeno nel Cinquecento avendo questo rettificato il suo corso aprendosi un varco nella roccia (Ponte Sfondato, ora crollato)" (Muzzioli, 1980). Il manoscritto di Vittori, vescovo reatino morto nel 1572, descrivendo il tracciato dell'antica Via Salaria, riporta le seguenti parole: "Reliquum viae [l'antica via Salaria] erat per amnem Farfarum prope montem, quem perforatum vocant [Monte perforato]". Ciò testimonia la presenza, almeno a far data dal 1572, dell'arco naturale.

L'indicazione dell'arco compare anche nella cartografia antica; nella carta di Mauro Giubilio e Giovanni Maggi disegnata nell'ultimo decennio del XVI secolo ma stampata nel 1617 compare, per la prima volta, l'indicazione "Môte Sfondato" sul torrente Farfa (Fig. 5).

In realtà Roberto Donati, storico della regione Sabina, afferma che "Il forte impeto delle acque del Farfa, coll'andare del tempo, si aprirono un varco sotto lo scoglio di Pietra Maggiore, formando così (circa il secolo XV) un ponte naturale, denominato poi Ponte Sfondato" (Donati, 1989), facendo riferimento al Chronicum Farfense (14, 179, c. 1076-1132), dove si parla del "castello Tribuco a Petra Maiori" (Di Catino, 1903).

A testimonianza di ciò, va ricordato che nel 1463 Papa Pio II Piccolomini, tornando dal Concilio di Mantova, si recò dapprima a Poggio Mirteto e poi percorse l'antica via Salaria per rientrare a Roma; nei suoi "Commentari" annota: "[…] attraversato il Farfa sopra un ponte (Ponte Sfondato o di Tribuco) e valicato il monte assai vicino e piuttosto elevato arrivò a delle paludi tra le quali scorre un fiumicino: alcuni ritengono che sia il Corese, il quale avrebbe dato il nome al Poggio di Corese […]" (Libro X, cap. XXXI dei Commentari).

Per comprendere la toponomastica della regione Sabina, è fondamentale analizzare la prima (sopracciata) carta a stampa del territorio realizzata dal medico Mauro Giubilio, ritrovata da Roberto Almagià presso la Biblioteca Vaticana negli anni '20 del Novecento (Almagià, 1923; Giubilio & Maggi, 1617). La carta è orientata con l'est in alto e descrive la parte di territorio di Umbria, Lazio e Abruzzo compresa tra il fiume Tevere, delimitata dal fiume Nera a nord e dal Teverone a sud. Stampata da Giuseppe De Rossi nel 1617, riporta in basso a sinistra la firma dell'incisore Giovanni Maggi.

Notizie del manoscritto di Giubilio si hanno già nel 1596 (Baccio, 1596). Il rilievo degli Appennini, con la direzione delle catene riprodotte in modo sufficientemente
preciso, è rappresentato in maniera prospettica anche se le forme sono esageratamente aspre (Riccardi, 1923) Nella rappresentazione del corso del torrente Farfa (Farfaro fluente) appare il toponimo Moûte Sfondato e il disegno rappresenta appunto un Moûte Sfondato dal corso del torrente, così come narra anche Lukas Holste (1592-1662) nel 1645 nella sua descrizione di un tratto della Salaria, dove Ponte Sfondato (monte perforato) rappresenta un passaggio sul torrente Farfa: Inde Farfarum transit propri montem perforatum [...]" (Persichetti, 1916).

Nella carta di Giubilio è indicata la strada che, transitando sul Ponte Sfondato, conduceva a Rieti partendo da "Porta Salara" (Porta Salaria) a Roma così come sembra confermare anche Guglielmo Stefani, descrivendo il percorso della strada che "Da porta Salara [...] mena in Sabina [...] corrispondente all'Antica Salaria risale[ndo] la sinistra riva del Tevere e dopo Corese si continua fino a Reate" (Stefani, 1856). Persichetti (1916) individua in questa strada non un'Antica Salaria quanto invece una semplice diramazione della stessa, "un diverticolo romano o medievale che da Roma arrivava in Umbria" (Bocci, 2011).

Il passaggio sintattico tra la dizione Monte e quella di Ponte Sfondato compare nei testi e nella cartografia del XVII secolo; Ameti (1696) (Fig. 6a) indica nella sua carta sul "Patrimonio di San Pietro" il toponimo Ponte Sfondato, così come fecero successivamente sia Cigni (1723) (Fig. 6b) che Sani (1769) (Fig. 6c) nelle varie edizioni delle loro carte del territorio della Sabina.

Pierluigi Galletti, nell'ubicare Tribuco il "castello in Sabina dove non vi sono più vestigia", lo indica nei pressi di Ponte Sfondato "così detto poiché è stato formato dallo stesso impeto delle acque che ha sfondato con la sua forza il macigno per farsi libero il corso" (Galletti, 1776).

Il Castello di Tribuco (indicato come Tribicum Castellum nelle cronache farfensis del 1026), era stato edificato probabilmente per difendere la tomba di S. Getulio martire (S. Gethulii Curtis) e compare tra le proprietà dell'Abbazia di Farfa. Il castello è passato alla storia per lo scontro tra Papa Pasquale II e gli Imperatori - Enrico IV prima ed Enrico V poi – durante il quale il Papa e sei Cardinali vi furono rinchiusi. Nel 1138 il Castello di Tribuco fu demolito dalle fondamenta e oggi non restano che effimere tracce dell'antico castello (Muzzioli, 1980), nonostante la struttura sia ancora riportata nella carta dell'Ameti (1696).

Qualche anno più tardi, nel 1782, il reverendo somasco Pier Maria Cermelli pubblica il suo libro contenente osservazioni sulla mineralogia e la paleontologia di alcune province dello Stato Romano. Nella Tavola II "Parte di Sabina", Cermelli (1782) non solo indica il Ponte Sfondato, ma attribuisce la perforazione dell'arco all'acqua del torrente Farfa ("Ponte Sfondato dall'acque", Fig. 7). Sul Ponte Sfondato, Cermelli fa passare la strada che dal Ponte di Corese conduce a Poggio Mirteto e a Salisano - Monte d'Oro. Per Cermelli, quest'ultima località risulta particolarmente interessante per la presenza di pirite, al punto da essere riprodotta in vista prospettica nel cartiglio a margine della stessa carta. Indicazione ancora più originale è la traccia dell'antico corso del torrente che appare per la prima volta su una carta, rappresentando, tramite tratteggio, il decorso del meandro abbandonato. Questa indicazione può essere considerata il primo simbolo geomorfologico, almeno nel territorio del Lazio.
L'archeologo romano Giuseppe Antonio Guattani (1748-1830), nel suo importante lavoro sui “Monumenti Sabini”, in tre volumi, delinea in maniera dettagliata l'arco naturale (Guattani, 1826-27).

Nel I volume lo descrive attribuendo all'impeto delle acque la formazione dell'arco: “Si passa sopra un ponte detto Sfondato per un foro che l'impeto della corrente si è aperto a traverso del monte tufaceo, lasciando il suo primiero letto”. L'Autore afferma che il Farfa “Passava anticamente circa 150 passi più innanzi, sotto ponte artificiale rimasto in secco”.

È sempre Guattani che ci suggerisce come, una volta originatosi, il ponte naturale diede al Monte Sfondato il nome di Ponte Sfondato così come disegnato nella Tavola III del suo primo volume dedicato ai monumenti sabini. Questa tavola, come le altre dei tre volumi, è stata disegnata da Lodovico Prosseda (1780-1860), “ingenuo pittore ed incisore sabino” di Moricone (Guattani, 1826-27) che rappresenta però la prima iconografia del Ponte Sfondato (Fig. 8a). Allegata ai volumi doveva uscire coeva anche la Carta “corografica” di Prosseda che nonostante il titolo limitativo alla sola Sabina in realtà comprende anche Lazio ed Etruria in cui ovviamente compare il toponimo di Ponte Sfondato (Fig. 8b).

Nella seconda metà dell’800, nella regione Sabina come nel resto d’Italia, prese avvio una intensa attività finalizzata alla raccolta delle informazioni scientifiche, spesso supportate dalle varie Associazioni che nascono in quel periodo.

Il 5 settembre 1876, il dottor Nicola Orsini, socio della Sezione del Club Alpino Italiano di Perugia, condusse un’escurzione da Casa Prota (oggi Casaprota) fino alle sorgenti del Farfa, che “i contadini del luogo chiamano le Capore di Farfa” (Orsini, 1876). Durante l’esplorazione prese misurazioni termometriche sulle acque e descrisse, in modo minuzioso, i caratteri geologici e idrologici del territorio percorso dal torrente Farfa; tuttavia, non accenna minimamente al Ponte Sfondato. Nemmeno nello schizzo cartografico allegato al suo resoconto (Orsini, 1876) riporta l’indicazione del Ponte e l’unico passaggio sul torrente viene indicato nel Ponte di Granica.

Paolo Mantovani, sia nella carta che nel volume “Descrizione geologica della Campagna Romana”
(Mantovani, 1875), tracciando il percorso del torrente Farfa, rappresenta il tratto terminale del corso d'acqua denominandolo Fosso Granica, dal nome di un affluente minore (Fig. 9); l’Autore, inoltre, non indica la presenza del Ponte Sfondato. Questa carta, poco conosciuta, ha dato origine a molte critiche, tra le quali la più accesa è stata quella con Ruggero Panebianco (Panebianco, 1878; Pantaloni, 2014).

Il geologo Giuseppe Augusto Tuccimei (1851-1915), che da diversi anni si stava occupando della caratterizzazione geologica del territorio sabino, pubblica uno studio sulla struttura e sui terreni della catena di Fara Sabina (Tuccimei, 1883). Nel contesto generale della descrizione della geologia del territorio farense, l’Autore dedica una nota al Ponte Sfondato, indicando che “è un magnifico passaggio che la corrente del Farfa si è scavato in un potente banco di ghiaie e sabbie quaternarie, formate dallo stesso Torrente, il cui antico letto vedesi lì presso, sulla riva sinistra. Credesi naturale, ma la questione non è risolta” (Tuccimei, 1883), esprimendo quindi dei dubbi sull’origine naturale o artificiale dell’arco.

Sul finire del XIX secolo, il matematico tedesco Filippo Keller (1830-1903), docente di Fisica all’Università di Roma, compie una serie di rilievi magnetici nell’area della Campagna romana, individuando la presenza di “punti distinti” nelle colate basaltiche, in corrispondenza di forti deviazioni dalla posizione magnetica normale. Pubblicò i suoi risultati in diversi scritti dal titolo “Sull’intensità orizzontale del magnetismo terrestre nei pressi di Roma”, nella serie “Frammenti concernenti la geofisica dei pressi di Roma”. In uno di questi scritti, riporta le misurazioni effettuate nell’area di Corese; in una nota a margine, descrive i caratteri geomorfologici e geometrici dell’arco naturale. Keller evidenzia la presenza di una “semiellisse molto allungata innalzata sul suo asse minore” dell’alveo abbandonato del torrente Farfa. Continua poi descrivendo
come l’attuale alveo “si trova ora spostato passando per via sotterranea la anzidetta collina, percorrendo cioè l’indicato asse invece del perimetro dell’ellisse” (Keller, 1896).

Un’importante indicazione, utilissima nella sua unicità, riguarda le dimensioni della galleria del Ponte Sfondato; Keller indica una larghezza del ponte in 42 m, una larghezza della luce di 28 m, una altezza di 9 m e uno spessore della volta di 8,8 m.

Dal punto di vista litologico, Keller descrive l’arco costituito da “una breccia calcarea cementata abbastanza compatta”, mentre nella parte sommitale asserisce che “manca la breccia”. Nella descrizione dei caratteri ambientali, indica la piena accessibilità della galleria, con una parte non occupata dalle acque del torrente; descrive poi la volta, con una forma piuttosto regolare, mentre definisce irregolari i piedritti a causa del distacco di blocchi rocciosi che, cadendo, ingombrano il letto del torrente (Fig. 10). Questa affermazione induce a ritenere altamente possibile il degrado naturale della struttura, che potrebbe aver portato poi al suo crollo.

Keller affronta poi la genesi dell’arco, indicando come la tradizione lo voglia di origine naturale, e ricorda i numerosi fenomeni di erosione e di escavazione del conglomerato presenti nei dintorni. Lo scienziato ritiene plausibile questa ipotesi, anche se afferma di non riuscire a dimostrarla. Ricorda infatti la diffusa presenza, nella Campagna Romana, di numerosissimi cunicoli e gallerie scavate manualmente “nel tufo vulcanico litoide o terroso”, perché facilitava l’escavazione e non necessitava di lavori di muratura per i piedritti né per la volta. Non ritiene possibile questa origine per il Ponte Sfondato perché tale pratica è compatibile solo per cunicoli di piccola sezione.

Keller compara il Ponte Sfondato a un altro arco naturale presente nel territorio laziale: il Ponte Sodo vicino all’abitato di Isola Farnese, che scavalca il Fosso di Formello (oggi conosciuto come Cremera, o Valchetta). Non esita però ad attribuire all’arco del Ponte Sfondo una indiscutibile origine antropica, sia per la sua lunghezza (68,3 m), per la sua altezza (4,9 - 4,6 m) e per la sua larghezza (4,6 - 3,6 m).

Questa circostanza induce Keller a definire, con buona certezza, che il Ponte Sfondato sia invece di origine naturale. Esclude l’ipotesi antropica per il fatto che mentre nella gran parte dei casi si tratta di rocce di natura vulcanica, per il Ponte Sfondato abbiamo a che fare con breccie calcaree erose dall’azione della notevole velocità delle acque del Farfa che, con il loro fluire, ne possono senza dubbio aver ampliato la sezione “per effetto di corrosione, tanto in profondità che in larghezza”.

Un’altra escursione, questa volta della Sezione di Roma del CAI, viene compiuta il 28 aprile 1906; in questo caso l’escursione viene effettuata proprio a Ponte Sfondato, definita una “miraibile opera della Farfa che con l’erosione di un argine naturale di puddinga si è formato un sottopassaggio attraverso l’argine stesso alla gloriosa abbazia di Farfa”.

Gli anni ‘20 del 1900 sono caratterizzati da una grande espansione dell’industria energetica idroelettrica; in tutto il Paese vengono progettati e costruiti impianti idroelettrici destinati sia alla produzione di energia che alla regimazione delle piene. Il bacino del Farfa viene, anch’esso, studiato per verificare la possibilità di costruzione di un eventuale impianto idroelettrico. Un articolo di Martino Lupi, descrive un prossimo futuro dell’area della media valle del torrente, prefigurando un infelice destino al Ponte Sfondato: “e poi andiamo verso Ponte Sfondato a vedere questo ponte scavato nella roccia dall’acqua e dalla natura, posta nel fondo alla valle sulla quale Fara guarda e troneggia. Anche quaggiù la mano dell’uomo sbarrerà le vie della natura: una potente diga arresterà il corso del Torrente e un bacino di varie migliaia di metri cubi d’acqua inghiottirà questa bellezza caratteristica della valle nativa e starà a rispecchiare eternamente un lembo di questo limpido cielo Sabino” (Lupi, 1923).

Inoltre, il 14 marzo 1923, durante una conferenza dell’Associazione Elettrotecnica Italiana e dell’Associazione nazionale degli Ingegneri e degli Architetti Italiani, furono presentati due nuovi progetti di impianti idroelettrici sul Farfa e sul Fiora.

Nella relazione l’ing. Aldo Netti, dopo aver descritto l’assetto geologico-strutturale dei Monti Tancia e i caratteri...
idrogeologici della zona, conclude affermando che "si può dedurre che nel Farfa si presentano condizioni per lo sviluppo di un notevole impianto idroelettrico, ma che le condizioni geologiche e morfologiche del terreno, continuamente variabili, dovevano non rendere facile ed economico lo sviluppo del canale derivatore e delle altre opere idrauliche necessarie all'impianto. Basta percorrere la strada che dall'antica Abbazia di Farfa conduce a Toffia, per osservare in molti punti, e specie all'incrocio con la derivazione che conduce al paese di Fara, quali contorcimenti presentano gli strati di calcari, per dedurre che il terreno è stato tormentato, ha subito continui movimenti e sconvolgimenti" (Netti, 1923). Affermazioni che lasciano dedurre la presenza di molte difficoltà nell'attuazione dell'opera che, in seguito, verrà abbandonata.

Durante la preparazione del lavoro di campagna della Scuola di Topografia dell'Istituto Geografico Militare del 1940, il Tenente Duilio Cosma compie alcuni studi sui caratteri delle abitazioni rurali costruite in Sabina dopo il 1922. Descrivendo i caratteri geologico-morfologici del territorio (Cosma, 1941), l'Autore affronta il tema del carsismo e dell'erosione fluviale. Di conseguenza, descrive la situazione del Ponte Sfondato: "Uno tra i fenomeni più caratteristici è il cosiddetto Ponte Sfondato sopra il quale passa la Via Littoria, ponte naturale dovuto alla corrosione continua delle acque del Torrente Farfa, che hanno lentamente intaccato lo strato calcareo aprendosi un varco nella pendice della collina e, abbandonando l'antico letto, hanno abbreviato il loro corso. Geologicamente il terreno è costituito in prevalenza da sabbie e conglomerati pliocenici di calcari compatti cristallini, o di calcari debolmente argillosi e di argille. Nella valle del Farfa s'incontrano, alternati con gli scisti, banchi di calcare ecocenico e verso la valle del Tevere rocce argillo-sabbiose plioceniche".

Grazie alla sua esperienza in campo topografico, Duilio include nel suo lavoro uno stralcio dettagliato della topografia del meandro abbandonato e dell'arco naturale del Ponte Sfondato, alla scala 1:25.000, evidenziando la sua attenzione per questo fenomeno naturale (Fig. 3a, b). Un elemento discordante sull'origine dell'arco naturale viene introdotto da Piero Barocelli. L'archeologo, che si recò nell'area di Poggio Mirteto – Ponte Sfondato in compagnia del geologo Maxia, afferma che "[…] il ponte naturale detto "Ponte Sfondato" costituiva un punto di passaggio obbligatorio nei tempi preistorici, quando la strada da percorrere veniva indicata dai corsi d'acqua. Lo stesso ponte divenne un punto strategico fortificato all'epoca romana, come lo attestano alcuni ruderi esistenti al lato del Ponte e abbondante ceramica di età imperiale" (Barocelli, 1945). La lettura del testo fa emergere l'ipotesi della presenza del ponte già in epoca preistorica, anticipando quindi la formazione dell'arco a quel periodo.

Qualche anno dopo, il geologo Carmelo Maxia (1948) pubblicò un lavoro nel quale analizzò le cause dell'appellativo con il quale veniva denominato il collegamento tra le due sponde del torrente Farfa sulla via Cantalupese, come era chiamata in quel periodo quella diramazione della via Salaria.

Il lavoro di Maxia fu dedicato principalmente alla descrizione geologica di questo "singolare fenomeno d'erosione nella Sabina occidentale", come recitava il titolo del lavoro, accompagnato da una lunga introduzione storica.

Secondo l'Autore, il collegamento fra le due sponde del torrente Farfa “non avviene a mezzo di un'opera d'arte, bensì ha luogo mediante un ponte che, per molti caratteri, è da ritenersi naturale" (Maxia, 1948), anche se l'arco non era stato inserito nell'elenco dei ponti naturali redatta da Achille Forti nel 1923.

Fig. 10 - Immagine del "Ponte naturale sul Farfa" di fine '800 (Collezione privata); il periodo di ripresa coincide con quello degli studi compiuti da Filippo Keller (1896).
La descrizione geologica che ne fa Maxia è particolarmente dettagliata: "l’arcata è aperta in una formazione di puddinghe costituite di ciottoli provenienti dalla demolizione di rocce mesozoiche, fortemente cementati da una sostanza sabbioso-calcarea. [...] Verso sud il conglomerato è ricoperto da una placca di strati di sabbia gialla calcarea passante, localmente, ad una roccia che ricorda il “macco”, contenente fossili, specialmente briozoi, ditrupe, piccole conchiglie di molluschi, ecc., forse appartenenti al Calabriano" (Maxia, 1948). Continua la sua descrizione correlando questi depositi con quelli rinvenuti nello scavo per la stazione di Poggio Mirteto.

Comincia quindi una analisi geomorfologica dell’area e dello stesso ponte; evidenzia, in particolare, la disposizione del ponte a forma di penisola rivolta verso “un’ampia convessità, terminazione di un meandro estinto, con la pianta a profilo di fiasco, sviluppato per una lunghezza di 825 m. [...] Il Farfa scorre, oggi, dentro un altro meandro, a raggio di curvatura assai più piccolo di quello fossile, nel quale è inscritto, corrispondendo, alla strozzatura del primo, la massima ampiezza dell’estremità dell’altro. Nel punto in cui nel meandro attuale il ramo orientale si raccorda con il tratto di massima curvatura, si apre l’arcata del Ponte Sfondato” (Maxia, 1948).

Continua poi con una descrizione meticolosa e precisa delle dimensioni e delle geometrie del ponte, definendo una luce dell’arcata di 30 m, una quota della strada rispetto all’alveo di 15,75 m a est e di 18 m a ovest, uno spessore della chiave dell’arco di 5-6 m. Questo ultimo valore è particolarmente significativo perché indica una diminuzione di spessore di 2-3 m rispetto agli 8 metri misurati da Keller (1896).

Prosegue il lavoro con le ipotesi sulla genesi dell’arco: invoca un sollevamento a scala regionale, testimoniato “dalle scarpate brusche di fianchi vulvilli conglomeratici, dove essi siano conservati senza gli addossamenti detritici posteriori. [...] All’atto della raggiunta maturità morfologica [il Farfa] occupava già i limiti del meandro antico, il quale, durante l’accmata fase epirogenetica si è incastrato nei conglomerati” (Maxia, 1948). Ipotizza quindi la concomitanza di tre avvenimenti: il lento sovralluvionamento dell’alveo del meandro antico, l’azione di dissolvimento ed erosione da parte delle allora copiose acque del Torrente e l’azione autorettificatrice del corso d’acqua.

Continua il suo lavoro escludendo l’ipotesi di una origine antropica del ponte se non, forse, nell’allargamento della luce, anche se di tale operazione si sarebbe dovuta ritrovare memoria in qualche documento storico. Maxia cita poi un evento, non confermato da fonti storiche e bibliografiche, di un possibile atto di sabotaggio compiuto dalle truppe tedesche durante la ritirata del 1944; fonti locali, non citate dall’Autore, affermavano che furono minati i prospetti del ponte con conseguente crollo di parte della volta. Nello stesso anno, una violenta piena causò l’obstruzione della luce che costrinse il Farfa a riprendere l’alveo abbandonato per alcuni giorni, aggravando forse le condizioni di tenuta dell’arco.

Il confronto tra due immagini prese prima e dopo l’eventuale sabotaggio (Fig. 10 e Fig. 11), mostra una effettiva riduzione dello spessore, e un aumento cospicuo del materiale detritico proveniente da crolli presente nell’alveo del Farfa.

In una nota redatta in corpo minore, Maxia accenna a una probabile, futura distruzione del ponte per cause naturali: “Aumentando sempre più la luce, essa potrà determinare, in avvenire lontano, il crollo della volta, segnando il passaggio dallo stadio di penisola a quello di isola come se la Natura, quasi pentita, tenda a distruggere l’utile opera sua stessa” (Maxia, 1948).

Il primo testo che riporta la demolizione, per cause antropiche, dell’arco naturale - “una delle più interessanti curiosità del Lazio” - è la Guida del Touring Club Italiano nell’edizione del 1964, nella quale si asserisce che il Ponte Sfondato è stato “semidistrutto” per fare posto al “nuovo ponte moderno”; più critica l’edizione del 1981 nella quale si afferma che il ponte naturale fu ottusamente demolito nel 1961 (Touring Club Italiano, 1981) per far spazio a un ponte moderno. L’avverbio “ottusamente” lascia spazio a un’ipotesi preoccupante nella sua stupidità, e cioè che il crollo possa essere avvenuto per cause antropiche, le
cui motivazioni sono assolutamente incomprensibili. Questa ipotesi, non confermata ma riportata sotto forma di indiscrezione, continua a tormentare coloro i quali vedevano nel Ponte Sfondato uno dei simboli iconici del territorio sabino.

La guida del Touring Club Italiano (1981) continua però esaltando i caratteri naturalistici di ciò che resta del sito: “Il luogo è ancora pittoresco per i piccoli specchi d'acqua e le cascate formate dal Torrente; a valle del ponte si vede la grande ansa formata dal letto abbandonato del corso d'acqua”.

Anche Roberto Donati, uno storico locale, suggerisce l'idea di un crollo dell'arco non per cause naturali: “Oggi il Ponte Sfondato non esiste più perché una notte è crollottato “da solo …”, ma purtroppo c'è stato anche l'intervento dell'uomo, e questi ne è la causa maggiore” (Donati, 1989).

In particolare, nell'ultima affermazione Donati fa riferimento all'azione di guerra compiuta dai soldati tedeschi durante la ritirata nel 1944 che minarono il Ponte Sfondato alla base, causando crolli di blocchi di materiale dall'arco e dai piedritti, ma non la demolizione completa. Altri testimoni (com. pers.) riferiscono di bombardamenti compiuti sul ponte, che per fortuna non riuscirono a distruggere, ma solo ad intaccare, l'opera naturale. Per tale motivo sono state effettuate ricerche presso l'Istituto Centrale per il Catalogo e la Documentazione (ICCD) del Ministero per i Beni e le Attività Culturali (MIBAC), che conserva nell'Aerofototeca Nazionale una vasta collezione delle foto aeree effettuate dai ricognitori delle forze aeree alleate tra il 1943 e il 1945. L'analisi delle immagini acquisite dalle forze aeree britanniche (volo RAF) nei giorni 26 agosto 1943 (Fig. 12) e 16 aprile 1944 non mostra però segni evidenti lasciati da eventuali azioni belliche compiute nell'area del Ponte Sfondato.

Il 1944 fu un anno particolarmente complesso per l'arco naturale: si verificarono infatti grosse piene del torrente Farfa che, trascinando tronchi e addirittura interi fienili, blocchi dai massi crollati ancora presenti nel letto del torrente, ostruirono la volta del Ponte obbligando le acque a ripercorrere, per una settimana, l'ansa ormai abbandonata (Donati, 1989).

Come detto, il crollo si verificò una notte del 1961, e corre ancora memoria di un boato udito durante la notte. Maxia fu l'ultimo a scrivere un lavoro scientifico che parlava del Ponte Sfondato, e la sua memoria rimane una traccia irripetibile per la caratterizzazione di questo interessante, e unico, sito geologico.

**II. il ponte sfondato nella storia, nella letteratura, nella pittura, nella fotografia, nel cinema**

Il Ponte Sfondato entra a pieno titolo anche nelle vicende storiche del nostro Paese; lo storico George Macaulay Trevelyan, riporta che Giuseppe Garibaldi dopo la sconfitta di Montenaro del 3 novembre 1867, si trasferisce da Monterotondo a Terni seguendo dapprima la strada che costeggiava il Tevere e, in seguito, compie una pausa di riposo di 7 ore “in a cool, wooded valley, beside a great stone bridge […] where Anita sat under a rock, smiling and talking cheerfully with Garibaldi, Ugo Bassi, Ciceriucchio and the staff” (Trevelyan , 1909). L'autore riporta anche la tesi di Hoffstetter che è, invece, incerto sulla ubicazione del sito, ipotizzandola presso qualche ponte artificiale a Passo Corese; tuttavia, la definizione di un luogo “selvaggio, stretto e boscoso nei pressi di un ponte di pietra” fa presumere, anche a Raffaello Belluzzi (come riportato nel taccuino manoscritto studiato da Macaulay), se non la sosta, perlomeno il passaggio delle truppe di Garibaldi presso il Ponte Sfondato.

Qualche anno più tardi, il 7 settembre 1870, presso il Ponte Sfondato si accampò anche la XII Divisione dell'Esercito Italiano, qualche giorno prima della battaglia del 20 settembre per la presa di Roma a Porta Pia.

Per il suo carattere rappresentativo, il Ponte Sfondato fu oggetto dell'ambientazione di differenti forme d'arte.

Una prima ambientazione si trova nel racconto “Voyage en Sabine”, pubblicato in due puntate su “Il Cicerone delle Due Sicilie” a firma di P.C. nei mesi di Agosto e Settembre del 1842.

Nel racconto si narra "Mais l'oeil est attiré sartout par l'eau limpide d'un petite rivière qui déririt régulièrement son cours au milieu de la prairie, et qui capricieuse par hasard, comme la femme qui a le bon esprit de ne pas l'ete toujours, retourne brusquement sur elle-même, et trouve son issue sous un rocher ouvert par sa perséverance, et sur lequel existe le chemin. Ce pont naturel, ce détour de l'eau qui a abandonné son ancien lit à l'herbe des champs, le vallon qui se prolonge, réservé entre deux collines, sont d'un aspect ravissant. Ponte Sfondato, tel est le nom qui était dû et qui a été donné à cette construction naturelle, digne de lever elle-même des leçons à l'art”.

Ma l'occhio è attratto dall'acqua limpida di un piccolo fiume che scorre tranquillo in mezzo al prato, e che, come la donna che ha il buon senso per non esserne sempre attratta, ritorna improvvisamente a se stessa, e trova la sua via d'uscita sotto una roccia scavata dalla sua
perseveranza, e nella quale esiste il suo cammino. Questo ponte naturale, quest'acqua che ha abbandonato il suo vecchio letto all'era dei campi, la valle che si estende racchiussa tra due colline, hanno un aspetto affascinante. Ponte Sfondato, questo è il nome che è stato dato a questa costruzione naturale, degna di dare lezioni all'arte stessa.

Il Ponte Sfondato fu anche descritto in un romanzo d'appendice francese. L'autore, Adolphe Granier de Cassagnac, a partire dall'8 settembre 1876 pubblica a puntate, nella rubrica "Feuilleton du Figaro", il suo romanzo dal titolo "Le Secret du Chevalier de Médrane". Successivamente, nel 1889, è stato pubblicato in due parti, riproduce fotografie delle opere d'arte romane in cui il primo volume contiene quadri, affreschi, disegni e mosaici, mentre il secondo riproduce sculture, architetture, vedute e paesaggi (Löfgren, 2006). La foto, indicata con il n. 17441 (Anderson, 1907), attualmente conservata nel Fondo Anderson dell'Archivio Alinari a Firenze riporta la descrizione di "Un ponte scavato nella roccia, collocato sul fiume Farfa, nella località Farra in Sabina, in provincia di Rieti", fu utilizzata per riprodurre una delle tantissime cartoline illustrate "come cornice di paesaggi", che allora venivano considerate come un mezzo pittorico attraente e poco costoso, necessario per visualizzare il mondo e che dopo l'Esposizione Universale di Parigi del 1889 ebbero una diffusione vastissima.

Negli anni '50 del Novecento venne diffusa una splendidissima riproduzione colorata a mano nella quale è evidenziata la presenza di molti blocchi crollati dalla volta e dai pietritti che ingombrano il letto del torrente Farfa (Fig. 13b).

Prendendo spunto dalle parole di Guattani, che per sottolineare la bellezza del luogo come fonte di ispirazione si ricorda che il Ponte Sfondato fosse sempre visitato da qualche "paesista a togliere qualche levata o calar di sole" (Guattani, 1826-27), gli Autori hanno rintracciato dipinti che rappresentassero tale luogo. La ricerca ha portato all'esclusione di un quadro del 1832 del pittore André Giroux dal titolo "Vue prise aux grottes de la Cervara, catacombes de Rome, sur l'ancienne route de Tivoli", esposto al museo Augustine di Tolosa che, indicato come rappresentativo dell'arco naturale, per anni ha rappresentato nell'immaginario collettivo degli abitanti il Ponte Sfondato. È stato tuttavia individuato il Ponte Sfondato nell'acquerello di Onorato Carlandi (1848-1939) intitolato "Campagna romana" (1930 ca.), confermando l'ipotesi del curatore del catalogo (Virno, 2004) (Fig. 14).

Anche il geologo Giotto Dainelli nella sua guida automobilista degli itinerari dell'Umbria [" […] raggiungere la via che scende già da Poggio Mistretto, [calando] decisamente, aiutati da qualche ansa, verso il letto del Farfa. E lo raggiungiamo, e lo passiamo sopra uno strano ponte naturale" (Fig. 15) (Dainelli & Gnoli, 1924). La fotografia inclusa nella guida, che ha la stessa inquadratura di una delle immagini pubblicata da Maxia (1948), mostra ben visibile il tracciato stradale. La presenza di una strada carrabile sul Ponte Sfondato nell'intero corso storico rappresenta un ulteriore elemento di unicità di questo arco naturale.

Il Ponte Sfondato è entrato anche nella storia del cinema italiano; in una delle scene più significative del film "Il ritorno di Don Camillo" (1953), si può ammirare una vista eccezionale dell'arco naturale, forse la migliore immagine fotografica che è possibile reperire precedentemente il crollo (Fig. 16a).

Dalla scena si evidenzia la presenza di numerosi blocchi caduti sul letto del Farfa, la gran parte arrotondata ma numerosi ancora con spigoli vivi. Da notare anche il diebro mangane nella parte sommitale dell'arco, che riduce l'ampiezza dello stesso a pochi metri. Una valutazione approssimativa degli spessori, desumibile dalla fotografia, induce a ritenere lo spessore della volta nell'ordine di 4-5 m e una luce alla base di circa 8 m. È quindi del tutto plausibile un crollo dovuto a cause naturali, visto il modesto spessore della volta. Da notare che oggi l'intera zona è completamente coperta da una fitta vegetazione, che rende impossibile un riscontro fotografico con la scena del film.

Il Ponte Sfondato appare, fugacemente, anche in una inquadratura del film "Totò e Carolina", di Mario Monicelli (Fig. 16b). Il film venne girato tra il 1952 e il 1953 e uscì nel circuito cinematografico nel 1955.

Una delle scene finali si svolge proprio sul Ponte Sfondato; Totò, che interpreta l'agente di Polizia Antonio Caccavallo, insegue Carolina, interpretata da Anna Maria Ferrero, che detiene in custodia. L'inseguimento avviene sul fianco sud-occidentale dell'arco e l'inquadratura mostra la volta ancora in buone condizioni, simile alle precedenti inquadrature del film di Peppone e Don Camillo, girato negli stessi anni. Da notare che l'allora strada Ternana percorreva l'arco senza alcuna struttura di protezione.

Anche una scena del film "Zorro" (1975) di Duccio Tessari, viene ambientata lungo il Farfa nell'area dell'ansa abbandonata del Ponte Sfondato; a causa del crollo della volta, già avvenuto, l'alveo del torrente Farfa si manifesta ingombro di blocchi di dimensioni plurimetriche.

LA SITUAZIONE ATTUALE

Oggi, l’area del Ponte Sfondato è caratterizzata da un'articolata situazione ambientale; il corso del torrente Farfa è ingombro di blocchi, di dimensioni plurimetriche, che rallentano il flusso dell’acqua e creano una serie di vasche e piccoli salti idraulici. I pietritti della volta presentano delle pareti sub-verticali con porzioni aggettanti fratturate, a rischio crollo anche a causa della vegetazione che scalza i blocchi rocciosi.

La fitta vegetazione rende difficile l’accesso e impossibile la visione panoramica del sito, rendendo le immagini storiche l’unica fonte iconografica utile per la visione d’insieme dell’arco naturale.

Il Ponte Sfondato avrebbe potuto rappresentare, a pieno titolo, un geosito di interesse nazionale (Wimbledon,
ossia un sito per il quale il geologo riconosce l'importanza nel ricostruire l'evoluzione geologica del territorio in cui si trova e che abbia interesse scientifico, talvolta anche paesaggistico, tale che sia individuabile un interesse per la sua conservazione.

Purtroppo, però, l'evoluzione dell'arco naturale ha fatto sì che questo morfotipo non venisse conservato, facendo decadere l'interesse scientifico.

Grazie alla discreta mole di materiale iconografico recuperato, è stato effettuato un tentativo di ricostruzione tridimensionale digitale finalizzato alla valutazione dell'evoluzione morfologica dell'arco naturale, a una stima dei volumi rocciosi e alle loro variazioni temporali (Cipriani et al., 2016; Petti et al., 2018). Nonostante i vari tentativi effettuati, però, a causa della bassa qualità e della mancanza di diversi punti di ripresa delle immagini non ci è stato possibile ottenere risultati significativi, tali da poter essere presi in considerazione.

Il presente contributo, tuttavia, vuole mettere in evidenza l'interesse storico e culturale che è in relazione con i caratteri geologici dei luoghi in cui si svolgono le vicende umane, e dello stretto legame fra questi.
CONCLUSIONI

L’arco naturale di Ponte Sfondato rappresenta un esempio, forse unico in Italia, di questo particolare morfotipo generato dall’attività erosiva di un corso d’acqua; la gran parte degli archi naturali presenti in natura, infatti, si originano per l’evoluzione di cavità e condotte carsiche, soprattutto in ambiente costiero.

La presenza di una ricca e differenziata documentazione disponibile ha permesso di ricostruire l’evoluzione dell’arco naturale nel tempo; grazie a un recupero delle rappresentazioni del Ponte Sfondato nel corso degli anni è stato possibile ricostruire le cause della sua origine e gli eventi che ne hanno causato il crollo.

La ricostruzione dell’evoluzione geologico-geomorfologica del Ponte Sfondato di Montopoli di Sabina è un importante caso di studio per la definizione di un luogo della memoria geologico-storica, (Console et al., 2018), ossia di un sito che ha rappresentato, in passato, un importante luogo di interesse geologico-paesaggistico ma
Fig. 16 - a) Una scena del film "Il ritorno di Don Camillo", di Julien Duvivier, del 1953. Sullo sfondo una bellissima immagine del Ponte Sfondato, pochi anni prima del suo crollo; da notare il letto del torrente ingombro di blocchi crollati dalla volta e dai piedritti. 
b) Immagine tratta dal film "Totò e Carolina", di Mario Monicelli, del 1955. L'agente di Polizia Antonio Caccavallo (Totò) insegue Carolina (Anna Maria Ferrero) lungo il fianco sud-occidentale dell'arco, prima di concludere la corsa con un tuffo nel torrente Farfa.

che oggi, a causa della sua evoluzione, non è più visibile e che quindi resta esclusivamente nella memoria storica e nell'immaginario collettivo.

Abbiamo per questo utilizzato il termine sito della memoria geologica, a rappresentare lo stretto connubio tra il luogo che rappresenta valori e tradizioni, cultura e storia del percorso umano e il luogo come risultato di fenomeni geologici che rappresentano la storia dell’evoluzione della Terra.

Significativa, e degna di essere citata in questa conclusione, è la frase scritta dal maestro e storico locale Roberto Donati: “Una notte il Ponte Sfondato crollò, recando danno a se stesso e alla bellezza del luogo” (Donati, 1989).
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Zorro (1975), regia di Duccio Tessari, soggetto e sceneggiatura di Giorgio Arlorio.
Palaeomagnetism and the debate on the size of the Earth

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ABSTRACT

During the first half of XX Century, the Expanding Earth was a promising geodynamic hypothesis, because it could explain the evidence of ancient continental connections without requiring the lateral movement of continents. If the planet was inflating, the surface would expand, breaking up continents and increasing their reciprocal separation without drift. Moreover, while Earth contraction had been justified by density changes due to heat dissipation, early expansionists suggested that the heat generated by internal radioactive sources was driving Earth expansion.

Looking for evidence in support of the expansion idea, early expansionists understood that palaeomagnetism could help quantifying the palaeo-Earth radius, and its change through time. However, palaeomagnetic data showed that no significant increase on the size of the Earth had occurred in the geological past. At the same time, continental palaeomagnetism showed that continents had continuously changed position in the geological past, supporting the mobilist model. Faced with the disappointing results from palaeomagnetic studies, the remaining supporters of Earth expansion continued to report only the palaeomagnetic data that might appear to support their hypothesis, but carefully neglected to acknowledge the disproving evidence.

KEY WORDS: Geodynamics, palaeomagnetism, pseudoscience, Expanding Earth

INTRODUCTION

Between the end of the XIX and the mid of the XX centuries, several alternative geodynamic models were proposed to replace the dominant Earth contraction model. These included also the idea that the planet Earth had gradually expanded its volume through time (Lindemann, 1927; Furon, 1935, 1941; Carey, 1958; Heezen, 1959; Wilson, 1960). The Expanding Earth hypothesis was based on the same evidence that prompted Wegener to suggest continental drift, especially the intriguing geometrical fit between the opposite coasts of the Atlantic Ocean. The idea that planet Earth had radially expanded through its history had the advantage, over continental drift, of explaining within a fixist framework the strong evidences of ancient continental connections (Fig. 1); therefore, many Earth scientists considered Earth expansion a sound and promising scientific hypothesis (Carey, 1958; Heezen, 1959; Wilson, 1960). Even the discovery of the sea-floor magnetic anomalies initially appeared to support the idea of planetary expansion: expansionists claimed that planetary inflation was connected with the opening and widening of the oceans after the break-out of Pangea, and the sea-floor magnetic striping was a clear evidence of the ongoing oceanic expansion (Wilson, 1960; McKenzie, 1969). However, after a brief experimentation with the idea of an expanding planet, the bias against mobilism was finally overcome and, within a decade, Plate Tectonics became the dominant geodynamic theory.

The vast majority of the Earth scientists accepted Plate Tectonics more than fifty years ago; nevertheless, despite the overwhelming contrary evidence, Expanding Earth continues to find supporters, although expansionist ideas are mainly confined to the underworld of the Internet, alternative journals, general press and sensationalist TV programs. Still, expansionist papers are sometimes published in peer-reviewed journals. The Expanding Earth, therefore, represents an interesting example that disproved scientific ideas could survive falsification and, mainly due to the efforts of isolated enthusiasts, occasionally resurfaces from oblivion to appear in mainstream scientific publications.

RADICAL VS MODERATE EXPANSIONISTS

Within the catchall label of Expanding Earth, grouping all the hypotheses claiming that the planet has significantly expanded through time, many variants exist, differing for details like the rate of planetary expansion, the size of the original Earth, the timing of the initiation of expansion, and the mechanism driving expansion. The lack of definition is one of the loopholes that allowed Earth expansion proponents to keep faith in their ideas regardless of any contrary evidence. Every supporter of planetary expansion could claim that a peculiar variant of the model is valid even if others were disproved (Weijermars, 1986; Edwards, 2016). However, a main division among the expansion hypotheses exists between radical and moderate expansionists, mainly based on the rate of planetary inflation.

Radical expansionists believe that the radius of the Permian Earth was 50-70% of its actual size and the whole surface of the Earth initially consisted only of continental crust. Oceans formed after the break-up of Pangea, while the planet underwent an exponential expansion. What did happen before Pangea remains open to speculations. According to some radical expansionists, the Permian
radius was the minimum radius of the Earth since its formation, and there was no change in planetary size before the Permian (Carey, 1975, 1988; Owen, 1976; Shields, 1979, 1997; Vogel, 1994; Scallera, 1998, 2001, 2003, 2006; Cwojdziński, 2003). Others believe that the palaeo-Earth was even smaller in the Archean, down to 45% (Glikson, 1980) or even 27% of the actual diameter (Maxlow, 2002). Modern (post-Plate Tectonics) radical expansionists also vigorously reject the reality of subduction and collisional margins.

The moderate expansionists support instead a slow and steady inflation from a slightly larger dwarf Earth (Egedy, 1956, 1957; Egyed, 1960, 1961; Carey, 1958; Holmes, 1965; Van Hilten, 1968; Steine, 1977; Weijermars, 1986; Edwards, 2016). This allows the proponents of the theory to circumvent many of the objections to expansion (Weijermars, 1986; Edwards, 2016). In the moderate expansionist model, for example, the Pacific Ocean existed before the brake-up of Pangea, avoiding the problem of finding proof of an ancient direct contact between the opposite coasts of the Americas and East Asia-Australia. The formation of mountains in a slow expansion model also does not differ from the explanation provided by Plate Tectonics, if a limited subduction is accepted (Weijermars, 1986; Edwards, 2016). Radical expansionists, instead, need to speculate mechanisms of vertical tectonics, like the rise of cold mantle diapirs (Carey, 1975). On the other side, the slow expansion approach loses any chance of fixing an initial planetary size. Radical expansionists claim that the original Earth had no ocean crust at all; therefore, fitting all continents on a smaller planet they are able to derive a hypothetical planetary size for the initial dwarf Earth. Slow expansionists assume that at least part of the Pacific Ocean existed before the Jurassic, but they cannot assess the initial size of the ocean and the planet.

The only justification moderate expansionists have to hold on their idea is the unsupported claim that, by decreasing the Earth’s size, they can achieve a perfect fit of the opposing continental margins when restoring Pangea, while Plate Tectonics on a constant-radius planet cannot do it. By simply geometrically restoring the continents to the Permian Pangea, keeping the Pacific Ocean, and opportunistically reducing the size of the Earth to avoid overlaps and gaps between the merged continents, moderate expansionists conclude that the radius of the supposed dwarf Earth at the break-up of Pangea ranged between 80% and 90% of the actual Earth’s radius. However, also moderate expansionists claim to achieve the best possible geometrical fit of the restored continents, even if the curvature of their palaeo-Earth is remarkably higher.

**PALAEOMAGNETISM AND THE SIZE OF THE EARTH**

Egedy (1960) was the first author suggesting a palaeomagnetic approach to the problem of determining the size of the ancient Earth. By means of palaeogeographic data, Egedy (1956, 1957, 1959, 1960) had already reached the conclusion that the radius of the Earth had inflated of 0.5 mm/yr (1%) since the Permian, but he was looking for a more robust estimate and palaeomagnetism could be the proper tool to confirm the geological evidence. Applying the palaeomagnetic method, Egedy (1961) found that the radius of the Permian Earth was 98% of the modern diameter. Following the suggestion of Egedy (1960), Cox & Doell (1961) used a method similar to the one applied by Egedy (1961), estimating a Permian radius equivalent to 99% of the modern radius. Although Cox & Doell (1961) and Egedy (1961) reached very similar results, Egedy claimed that his findings were a proof of Earth inflation, while Cox & Doell (1961) concluded that no appreciable change in Earth radius had occurred since the Permian. Cox & Doell (1961) could also confidently state that their results disproved the fast expansion rates suggested by radical expansionists. Incidentally, the results of Cox & Doell (1961) and Egedy (1961) also disprove the moderate expansion model assuming that the Permian Earth had a radius between 80% and 90% of the actual Earth. However, Cox & Doell (1961) admitted that, while they thought that any rate of planetary expansion was very unlikely, they could not prove or disprove the slow expansion rate estimated by Egedy (1961), because this was below the resolution of the palaeomagnetic method. Ward (1963) applied Egedy’s (1960, 1961) method for determining the radius of the Devonian, Permian and Triassic palaeo-Earth, finding that in each epoch the Earth’s radius was respectively 112%, 94% and 99% of the actual one. Ward (1963) concluded that these estimates were not an indication of any change in radius, even if these could not disprove the slow expansion rates suggested by Egedy (1961).
Therefore, already at the very beginning of its application to the problem of the variation of the Earth's size, the palaeomagnetic method proved to be accurate, with the expansionist Egyed (1961) and the non-expansionist Cox & Doell (1961) and Ward (1963) achieving very similar results. The authors differed only in the conclusions: the expansionist Egyed (1961) ignored the resolution limits of the method to claim a confirmation of planetary expansion. Cox & Doell (1961) and Ward (1963), although skeptical about the possibility of planetary inflation, suspended their judgment regarding expansion rates falling below the resolution of the palaeomagnetic tool.

Attempts to prove the consistency of the smaller palaeo-Earth hypothesis by means of palaeomagnetic data continued for a while: Van Hilten (1963, 1964, 1965, 1968), a supporter of expansionism, applied corrections an adjustments to the palaeomagnetic method to derive more favorable estimates supporting the fast expansion. Embleton & Schmidt (1979), and Schmidt & Embleton (1981) concluded that the data showed that no expansion had occurred since the Permian, although they admitted that, as a possible alternative model, also a smaller Earth could fit the Precambrian palaeomagnetic data.

While disproving the radical expanding model, because and allows more flexibility in continental movements compared to radical expansion

**PALAEOMAGNETISM AND THE POSITION OF CONTINENTS**

These showed that continents had moved around the planet through its history, following erratic trajectories and rearranging themselves in the most unexpected patterns (Graham et al., 1964; Burke et al., 1976; Irving, 1977, 2005; Irving and Irving, 1982; Torsvik et al., 1990; Torsvik et al., 2012; Dalziel et al., 1994). Palaeomagnetism proved to be a strong argument supporting continental drift and against fixist theories (Irving, 2005). Palaeolatitude paths derived from palaeomagnetic data immediately falsify the radical expansion hypothesis, because the reconstruction of ancient continental movements is not compatible with a model rejecting subduction (Fig. 2A). Assuming that planet Earth had a smaller size in the past, and that the dispersal of continents is due to Earth expansion, it might appear that the palaeolatitude changes could be explained with distortion of ancient continents to the increasing radius of the planet (Fig. 1). Points initially located on one planet's hemisphere might even move to the opposite hemisphere if the expansion is opportune asymmetrical, as suggested by some expansionists because of the preferential concentration of continental masses on the northern hemisphere and the Atlantic side (Carey, 1975, 1988; Vogel, 1994; Scalera, 1998, 2001, 2003, 2006). However, if this was the case, as the planet inflates the distance between adjacent points could only increase ever, very hypothetically, remain constant, but it will never decrease. This is because the older crust must stretch to adjust to a larger surface and, in a pure-inflation model as supported by radical expansionists, convergence cannot happen. Moreover, the amount of latitudinal change would be limited, contrary to the geological evidence. As an example, we could consider the case of asymmetrical expansion, which is the most favorable for the expansionist hypothesis, assuming that one of the newly formed continents was initially a crustal slice extending from the North Pole to the South Pole and that expansion would happen by the preferential generation of new crust (and sub-crustal mass) on the southern hemisphere (Fig. 1). If the radius of the dwarf planet were 50% of modern Earth's radius, the distance along a meridian between a point located at 50°S and the North Pole would be about 7782 km. As the planet asymmetrically inflates, the crustal slice adjusts to the new surface while its northern end remains anchored to the North Pole. This adjustment, of course, would actually require some stretching and rifting of the older crust to fit the smaller curvature radius of the larger planet, but let's assume that this stretching could be ignored. The planetary expansion will then make the slice of old crust that originally extended from the North Pole to the South Pole to apparently move towards the northern hemisphere, and the point at 50°S will also move North to a new latitude. Although the latitude changes, the distance between the considered point and the North Pole will remain the same, if it was possible to ignore the crustal stretch to fit the new surface curvature. Therefore, once the planet has doubled its radius, the new latitude of the point that was originally located at a latitude of 50°S, will have moved to 20°N. Any point starting with latitude relative to the same reference site. However, even according to the most extreme estimates of the radical expansionists, at 130 Ma the radius of the dwarf Earth was already at least 5268 km (83% of the actual planetary radius). This means that, considering a pure expansion model, after the Earth expanded to its actual size, the final position of India should have been located in latitude, any point in a more southerly position will show higher change in latitude. The larger latitudinal change would occur for a point located on the South Pole of the dwarf Earth, which will move to the Equator if the planet doubles its size. Any latitudinal change beyond these limits (like a continent moving from 30°S to 40°N) would be incompatible with an expanding Earth.

India represents the closest actualistic example of the latitude change described above. According to van Hinsbergen et al. (2012) in the lower Cretaceous (130 Ma) the palaeolatitude of India was about 50°S, and the continent later continued drifting northward, colliding with Eurasia and reaching a new latitude of about 30°N relative to the same reference site. However, even according to the most extreme estimates of the radical expansionists, at 130 Ma the radius of the dwarf Earth was already at least 5268 km (83% of the actual planetary radius). This means that, considering a pure expansion model, after the Earth expanded to its actual size, the final position of India should have been located in latitude, any point in a more southerly position will show higher change in latitude. The larger latitudinal change would occur for a point located on the South Pole of the dwarf Earth, which will move to the Equator if the planet doubles its size. Any latitudinal change beyond these limits (like a continent moving from 30°S to 40°N) would be incompatible with an expanding Earth.

**THE DENIAL STAGE**

Confronted with the contrary evidence of the palaeomagnetic studies, expansionist resorted to denialism. Carey (1975, 1981) and Chudinov (2001) questioned the validity of the methods used in papers disproving Earth expansion, or claimed that the resolution of the palaeomagnetic data was too low to detect even fast expansion rates. However, the vast majority of expansionists simply neglected to acknowledge the outcomes of the palaeomagnetic research. Cwojciński (2016) and Edwards (2016) presented extended historical reviews of expansionist models, including Egyed's works based on palaeogeography, but not Egyed's
papers dealing with expansion rates extrapolated from palaeomagnetism. Scalera (1998, 2001, 2003, 2006) did not mention the findings from palaeomagnetic investigations applied to the size of the ancient Earth, but considered palaeomagnetism by analyzing the supposed evidence form Polar Wander Paths in support of the inflating Earth. It is worth stressing that the Polar Wander Path is a very controversial subject from an expansionist point of view. If the Earth was actually expanding, the PWP derived for different continents should follow trajectories that steadily diverge with increasing time. Instead, the relative distance between two different PWP changes back and forth, as continents diverged or converged, often reverting orientation or changing direction of movement (Fig. 2). Therefore, the relative continental palaeopositions determined by the PWP do not agree with the Expanding Earth’s fixist approach, and indeed Cwojdzinski (2016) claimed that PWP reconstructions are arbitrary. Scalera (2001, 2003, 2006) avoided the issue by showing the trajectory of only one PWP, which could be consistent with both Earth Expansion and Plate Tectonics, and not the PWP of two different continents, which could only be consistent with Plate Tectonics.

CONCLUSIONS

Lack of constrains due to the limited data available, both in the specific field of research and the sciences in general, allows scientists to experiment with different models that could span over a wide range of often radically different options. During the first half of the XX Century, various theories were competing to replace the theory of the Contracting Earth in providing an explanation for the evolution of the surface of the Earth and the geodynamic forces that shaped it. The model of the Expanding Earth could explain within the pre-existing fixist framework the many geological evidences indicating ancient physical connections between continents separated by wide ocean basins in the modern world; therefore, many Earth scientists were initially supportive of the inflationist model.

As collected evidence increases, existing hypotheses need to integrate the newly acquired information, drastically narrowing the range of scientific speculation. The data coming from palaeomagnetic studies very likely provided the most stringent constrain for any competing geodynamic theory. The fixist Earth expansion hypothesis could hold the ground against mobilist ideas in fitting in the geological evidence of ancient continental connections, until palaeomagnetic data showed that mobilism provided a better description of the evolution of continental arrangements. However, Continental Drift could not fit in all the palaeomagnetic evidence (i.e. the sea-floor magnetic striping), and it was abandoned for Plate Tectonics. The demise of the Expanding Earth, and of other geodynamic hypotheses (Continental Drift, Contracting Earth, pulsating Earth), was not the result of an official opinion poll among Earth scientists, nor the consequence of the suppression of innovative thinking by a monolithic academic establishment: geologists just “walked away” from a failed model to follow one that worked better.

However, thanks to the efforts of a few supporters, the failed hypothesis of the Expansion Earth survived beyond its falsification, unnoticed by the larger community of
geologists, and occasionally passed the screening of peer review, finding its way to publication in the academic press. In order to keep their hypothesis alive, modern expansionists resorted to denialism, accurately picking only the data validating their ideas while rejecting or neglecting any contrary evidence. The way expansionists dealt with palaeomagnetic measurements represents a case history of the expedients expansionists adopted to defend their belief. When properly processed following standard practices, these methods bring consistent results, regardless if the users support Earth expansion or reject it. However, expansionists neglected the accuracy limitations of these tools to present their results as indications of expansion, if these fit their initial estimates of the expansion rate (Egyed, 1961). If palaeomagnetic results did instead contradict their peculiar model of expanding Earth, then expansionists applied ad-hoc corrections to the standard procedures to achieve more favorable results (Van Hiltun, 1963, 1964, 1965, 1968; Chudinov, 2001). If even this approach fails to provide positive outcomes, expansionists altogether ignored that specific field of research or questioned its validity (Carey, 1975, 1981; Scalera, 2001, 2006, 2007, 2012; McCarthy, 2003, 2005a, 2005b, 2006, 2007; McCarthy et al., 2007; Cwojdziński, 2016; Edwards, 2016).

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**“L'uomo universale del primo Rinascimento”: la geologia nel De re aedificatoria di Leon Battista Alberti**

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ABSTRACT

The geological elements found in the De re aedificatoria by Leon Battista Alberti are discussed for the first time in detail. In Alberti we find the enlightened conception of how architectural works must be conceived to adapt to natural processes and their evolution, and not vice versa. The great architect uses, in a first place, a purely pragmatic approach to geological knowledge. Noteworthy elements are the detailed study of historical earthquakes to get an idea of ‘seismic hazard’ characterizing a specific area, a deep understanding of the evolution of river systems, the use of wells to investigate the composition of the terrains in the underground to build solid foundation. These pragmatic elements are also accompanied by more theoretical interpretations, including very interesting reasoning about diagenesis, and on sedimentological aspects such as gradation, events of flooding and fluvial deposition, and river systems progradation due to the secular sediment supply. In his scientific interpretations, and in the new proposed vision of art, Alberti manages to reconcile in a harmonious way the innovations made by Brunelleschi, Masaccio and Donatello, fully embodying the spirit of the Florentine Renaissance, where art presupposes a profound understanding of nature and not its simple imitation in artist works.

PAROLE CHIAVE: Storia della Geologia, Rinascimento, Brunelleschi, Aristotele, Storia dell’Architettura.

INTRODUZIONE

C’è stato un tempo in cui, lontani dalle rigide gabbie attuali della specializzazione estrema, grandi uomini di cultura erano in grado di spaziare attraverso le più disparate branche dello scibile umano, con un atteggiamento di competenza spesso in grado di stupire il lettore moderno. Opere immortali come la Divina Commedia di Dante Alighieri: un compendio olistico della conoscenza umana all’inizio del quattordicesimo secolo, nella quale il Sommo Poeta spazia dalla politica, all’etica, teologia, filosofia, letteratura, arte, geografia, astronomia e scienze naturali *sensu lato* (si veda Antonelli, 1865; Gizzi, 1974; Boyde, 1984; Pecoraro, 1987; Cerbo, 2001; Inglese, 2002; Ossola, 2012; Romano, 2016).

Tra queste opere ad ampio respiro figura senza dubbio il *De re aedificatoria* di Leon Battista Alberti (Fig. 1), personaggio della cultura poliedrica e caleidoscopica, in grado di discutere di arte, matematica, processi e fenomeni naturali, tentando spesso una lettura anche pioneristica delle osservazioni fatte sul campo. Leon Battista Alberti (1404-1472) (Fig. 2), letterato e architetto, nato da famiglia nobile fiorentina costretta poi all’esilio politico, rappresenta in pieno la figura dell’umanista *ante litteram*, al punto di essere definito “L'uomo universale del primo Rinascimento” (Catanorchi, 2012). Il suo umanesimo si sostanzia, in primo luogo, nella riscoperta e studio degli autori e architetti antichi, nell’amore e curiosità per la natura, nella comprensione dell’armonia in essa racchiusa presa a modello per la progettazione degli edifici; e poi l’interesse per la matematica e le arti in generale, come forma massima nel processo creativo e nella ricerca assintotica del bello. Influenza maggiore per Alberti in campo architettonico derivò sicuramente dallo studio diretto delle rovine dell’antica Roma, dove il grande architetto poté studiare e misurare i canoni e le disposizioni tra le parti, attraverso il metodo che aveva appreso da Brunelleschi. Ne derivò una delle sue opere più fortunate, il noto trattato in latino *Descriptio urbis Romae*. Altri trattati sempre in campo artistico, volti alla ricerca di regole e canoni a supporto di artisti e architetti, sono il *De Pictura* (dedicato al suo amico Brunelleschi), in cui si trova una tra le prime definizioni chiare della prospevtiva, e il *De Statua*, dove sono descritte le giuste proporzioni caratterizzanti il corpo umano da imitare per le opere d'arte. Gli studi condotti da Alberti in campo artistico e architettonico divennero un nuovo modello da seguire, influenzando in maniera consistente il successivo sviluppo della architettura del Rinascimento. Anche la produzione letteraria del grande umanista risulta molto vasta, includendo, oltre le tematiche propriamente artistiche e tecniche, anche commedie morali e a tema sociale, come il *Philodoxeos* (1424), *Della tranquillità dell’animo* (1442), *De Iciarchia* (1468) e il *Della famiglia* (1433-1441).

suoi nuovi canoni architettonici con la cappella del San Sepolcro, la loggia Rucellai (fortemente influenzata dallo studio dei monumenti dell’antica Roma), la Rotonda dell’Annunziata e il noto capolavoro rappresentato dalla facciata della chiesa di Santa Maria Novella (Fig. 3). In ambito architettonico il testo di riferimento di Leon Battista Alberti è senza dubbio il De re aedificatoria, scritto intorno al 1450 e pubblicato la prima volta a Firenze in latino nel 1485 (Fig. 4). L’opera di Alberti, che può essere considerata a tutti gli effetti il primo trattato moderno di architettura, viene costruita dall’autore sul modello del trattato di Vitruvio De Architectura. L’opera conobbe diffusione in Europa nei primi anni del sedicesimo secolo, con edizioni stampate a Strasburgo e Parigi. In territorio italiano il lavoro di Alberti conobbe una maggiore fortuna grazie alle edizioni volgarizzate pubblicate da Pietro Lauro a Venezia nel 1546 e, successivamente, da Cosimo Bartoli a Firenze nel 1550 (si veda Ticozzi in Alberti, 1833).

L’edizione trattata e discussa nel presente contributo rientra nella collezione di opere dal titolo “Raccolta dei classici italiani di architettura civile da Leon Battista Alberti fino al secolo XIX” (Fig. 5), concepita, come si legge nell’introduzione, per il recupero di opere italiane centrali per il primo sviluppo dell’architettura intesa in senso moderno. Il volume dedicato all’opera di Leon Battista Alberti apre la collana ed è pubblicato a S. Pietro all’Orto con i Tipi di Vincenzo Ferraio nel 1833. Il testo originale, suddiviso in dieci libri, è introdotto e commentato dal curatore Stefano Ticozzi che fornisce un’estesa biografia di Alberti e notizie circa la fortuna dell’opera in Italia e all’estero. Ticozzi comprende in pieno la portata dell’opera dell’architetto italiano per la riscoperta dei primi avanzamenti dell’architettura rinascimentale e, in apertura del testo, lamenta giustamente la scarsa considerazione in cui è tenuta l’opera dell’Alberti. Il grande architetto, continua Ticozzi, è stato spesso dimenticato e la sua opera confusa con lavori di autori stranieri che avevano preso in prestito elementi chiave dagli scritti originali dell’italiano, con una sorta di oblio nei panorama italiano anche a causa della estrema rarità dei testi originali dell’Alberti. Secondo...
il commentatore, l’insieme di queste circostanze sfornate “deviando gli studiosi dell’arte dalla lettura de’ nostri classici, loro pongono innanzi i libri di stranieri autori, e li accostumano ad attingere a secondarie e talvolta impure fonti, che sebbene derivate dai nostri architetti de’ migliori tempi dell’arte, di mano in mano che s’allontanarono, tralagnarono dalla originaria loro limpidezza” (Ticozzi in Alberti, 1833, p. V). L’aspetto più grave, secondo Ticozzi, risiede nel fatto che questa ‘dimenticanza’ di opere italiane fondamentali sia da riferire in primo luogo proprio a nostri connazionali: ”ma è vergognosa cosa che gli stessi Italiani non conoscano le classiche opere de’ nostri scrittori cui attinsero quegli stranieri, i di cui libri credonsi adesso necessarii a coloro che presso di noi professano l’architettura” (Ticozzi in Alberti, 1833, p. V). Per riaffermare il primato di illustri italiani come veri “primi rinnovatori della greca e romana architettura” Ticozzi sottolinea come il primo architetto francese Filiberto de Lorme, dopo esser venuto in Italia per apprenderne l’arte, fu di ritorno nel suo paese quando “il Primaticcio, il Rosso ed altri illustri italiani avevano di già eseguite in quel regno opere di architettura, scultura e pittura maravigliose”; nonostante questa priorità italiana nella scoperta e rielaborazione dell’architettura classica, continua Ticozzi, “si ebbe il coraggio di associare le scoperte di questo valent’uomo a quelle dell’Alberti e del Brunelleschi che da sessantanni e più eran scesi nella tomba quando il de Lorme pose piede sul suolo italiano” (Ticozzi in Alberti, 1833, p. VI).

D’altro canto, questa sorta di snobismo italiano per le opere patrie sembra caratterizzare tradizionalmente diverse discipline dello scibile umano, tra cui anche le scienze geologiche sensu lato come già lamentato nel diciannovesimo secolo da Gian Battista Brocchi, nella sua “Conchiologia fossile subapennina” (si veda Romano et al., 2016a). Scopo del presente contributo è analizzare per la prima volta in modo organico gli elementi geologici e naturalistici sensu lato trattati da Leon Battista Alberti nella sua monumentale De re aedificatoria. Le discussioni e intuizioni geologiche di Alberti devono essere contestualizzate e apprezzate nel periodo in cui l’architetto italiano ha redatto la sua opera, precorrendo, su alcuni elementi e interpretazioni, anche il genio di molti connazionali maggiormente noti per il contributo alle scienze geologiche.

CONOSCENZA DEL PAESAGGIO E DEI PROCESSI IN CORSO: LA SCELTA DEL LUOGO ADATTO PER LE COSTRUZIONI

Il tema centrale trattato da Alberti in apertura del primo libro è la selezione e scelta accurata del luogo o sito adatto per la progettazione e costruzione di una città o qualsivoglia opera architettonica. L’autore, utilizzando e citando opere di autori classici tra cui Teofrasto, Aristotele, Calone, Varrone, Plinio e Virgilio, passa in rassegna gli elementi e i processi del paesaggio naturale che meglio si confanno alla costruzione di opere, così come le condizioni che devono essere evitate in modo assoluto per garantire una vita salubre e l’incolumità degli abitanti.

Il primo elemento essenziale sottolineato da Alberti consiste nel sincerarsi circa la salubrità dell’aria nella zona selezionata; elemento centrale messo al primo posto anche dagli architetti dell’antichità che “sopra
tutto guardavano con ogni diligenza di non avere l’aria grave, o molestia” (ibid., p. 3). Troviamo ad esempio brevi riferimenti a questo punto centrale anche nel Tesoretto di Brunetto Latini, dove il maestro di Dante discute le aree migliori per l’edificazione di insediamenti umani (Latini, 1839). Secondo Alberti bisogna dunque prediligere quelle zone dove l’aria risulti “lucidissima… sanissima, la quale è purgatissima e purissima, e che con la vista si può facilmente penetrare” (ibid., p. 4). Allo stesso modo è necessario evitare assolutamente tutte quelle zone che, per diversi motivi, sono caratterizzate da continue nebbie e “puzzolenti vapori”, che impediscono la vista e danno la continua sensazione di un fastidioso peso sugli occhi. Queste differenze nella qualità dell’aria da luogo a luogo possono essere riferite, secondo Alberti, a diverse cause e processi, di cui alcuni, per sua stessa ammissione, ancora possono essere riferite, secondo Alberti, a diverse cause e processi, di cui alcuni, per sua stessa ammissione, ancora del tutto ignoti. Tuttavia, in linea generale, sembra seguire il pensiero aristotelico, rappresenterebbe la causa principale dei venti e della formazione di nebbie e vapori che spesso interessano una medesima regione per diversi giorni. Una volta riportata la possibile spiegazione ‘scientifica’ dei fenomeni osservati, Alberti conclude quindi il discorso affermando come “Debbesti adunque eleggere di tutte le regioni quella, dalla quale la forza delle nebbie e la grossezza di ogni più spesso o rosso vapore stia lontana” (ibid., p. 5).

Secondo elemento di primaria importanza per l’Alberti è la tipologia e qualità delle acque caratterizzanti la regione da selezionare. In particolare andrebbe assolutamente evitata la vicinanza a ogni zona paludosa perché, come riportato già da Ovidio, le acque “si guastano, se non si muovono” (ibid., p. 6). Per evitare quindi l’effetto di vapori pestilenziali su cittadini o abitanti degli edifici da realizzare, Alberti consiglia fortemente di scartare, nella progettazione, tutte le aree in prossimità di lame d’acqua stagnante, dal momento che l’acqua “non agitata da alcun moto si macisce. E questa corruzione di si fatta vicinanza, sarà tanto più inferna, quanto ella sarà più esposta a’ venti men sani” (ibid., p. 6).

Considerando che l’acqua risulta un bene essenziale per la crescita di piante, semi, frutti “e dell’abbondanza delle quali cose gli uomini si rin frescano e nutriscono” (ibid., p. 9), per Alberti bisogna esaminare con estrema cura “che vene di acque abbia quella regione” dove si ha intenzione di costruire un centro abitato. Secondo l’autore sarà da considerarsi come ottima quell’acqua “che non avrà sapore alcuno” e nessun tipo di colore; deve essere quindi chiaramente e lucida “e che posta sopra un candido telo non lo macchia, e cotta non fa posatura” (ibid., p. 9).

L’area prescelta deve essere quindi ricca di fonti, le quali devono essere “assaggiate” per certificarne la bontà, e se possibile testate con il fuoco per identificare eventuali residui organici dannosi all’interno: “acciocché non vi sia mischiato punto di mucido, di viscoso e di crudo, onde gli abitatori se ne ammalino” (ibid., p. 9). Stessa esperienza per testare empiricamente la bontà delle acque è riportata e descritte brevemente da Brunetto Latini nel capitolo “Come le acque corrono per le caverne di sotto terra”, incluso nel Secondo Libro del Tesoretto (Latini, 1839). Alberti riporta poi a riguardo una serie di casi particolari descritti da Vitruvio e da Ippocrate, circa i vari effetti nocivi sul corpo umano di acque malsane, tra cui “pesti... idropisia, asima e dolori di fianchi” (ibid., p. 9).

Dal punto di vista topografico Alberti esclude l’edificazione di una città “in alcuno aspro ed inaccessibile giogo delle Alpi” (ibid., p. 7) come era stato ordinato in passato da Caligola, così come deserti solitari e lontani da corsi d’acqua o agevoli vie di comunicazione. La regione prescelta deve presentare, secondo l’architetto italiano, numerose e differenti vie e modalità di trasporto di beni di prima necessità e merci; inoltre “tal regione non sarà umida per abbondanza di troppe acque, né arida o aspra per troppo secco, ma atta ed insieme temperata” (ibid., p. 7). È abbastanza evidente come nel configurare la regione esemplare per una città ideale, Leon Battista Alberti abbia come modello mentale i luoghi ameni dello stivale, mitigati dall’influsso del mare Mediterraneo.

Altro contesto da evitare per l’edificazione, secondo Alberti, è la zona stretta tra due valli, dove gli ediﬁci restano necessariamente nascosti ed è preclusa ogni possibile visuale di paesaggio ampio: “e la veduta loro interrotta non ha nè piaceare, nè grazia alcuna” (ibid., p. 8). Inoltre la posizione nel fondovalle risulta ad alta pericolosità dal momento che gli ediﬁci, con il passare del tempo, “saran nuasti dalla rovina delle pioggie, e ripieni spesso dalle acque,
che intorno li piovono" (ibid., p. 8), rendendo l’ambiente estremamente umido e malsano per la salute degli abitanti. Il fondo valle inoltre spesso comporta un incanalamento dei venti, che soffieranno sui centri abitati con "più crudel furia che non sia conveniente" (ibid., p. 8).

Alberti fa poi un uso mirabile di evidenze e genuine osservazioni naturalistiche sul campo, come indicazioni per la scelta del luogo adatto per le costruzioni. Ad esempio, il trovare alberi rotti o piegati fortemente nella medesima direzione, "dimostrano di avere ceduto a noiose e moleste furie di venti" (ibid., p. 11) rendendo il luogo poco ideale. Altra evidenza di stampo prettamente geologico è fornita, secondo Alberti, dalle rocce presenti nel sito prescelto ("vivi sassi" nelle parole originali), distinti dall’autore in rocce in posto ("nel proprio luogo nati") o trasportate ("o da altri condottivi"). In particolare, l’evidenza di una eccessiva alterazione superficiale delle rocce ("nelle sommità delle scorce loro") indica, secondo Alberti, una continua alternanza tra condizioni di caldo e freddo estremo in zone montagnose: "dimostrano lo stemperamento del luogo, per l’aria, che ora è di fuoco e ora è di ghiaccio. E perciò quella regione dove questi furiosi assalti di tempi e tempeste si aggirano, più di alcuni’altra, si debbe schifare" (ibid., p. 11).

Elemento di estrema modernità nella pianificazione territoriale esposta da Alberti, è la considerazione attenta dei terremoti storici che hanno interessato una determinata area nel corso dei secoli. Riportando numerosi casi tratti da cronache e storie di autori classici, Alberti costruisce mentalmente una sorta di carta della pericolosità sismica ante-litteram: "dimostrano lo stemperamento del luogo, per l’aria, che ora è di fuoco e ora è di ghiaccio. E perciò quella regione dove questi furiosi assalti di tempi e tempeste si aggirano, più di alcuni’altra, si debbe schifare" (ibid., p. 11).

Altre aree sembrano essere risparmiate da questi processi naturali altamente energetici e distruttivi (risultando dunque ideali per le costruzioni). Citando Tucidide, riporta come ad esempio Deli non sia stata interessata da forti terremoti in tempi storici, "ma sempre si è stata salda sopra il medesimo sasso" (ibid., p. 12), mentre diversamente le isole vicine hanno subito gravi danni per cause sismiche ("assi volte rovinate dai tremuoti", nelle parole dell’autore). Uguale, riporta Alberti, la zona di campagna che separa Roma da Capua "è tormentata da continuí tremuoti e quasi rovinata del tutto" (ibid., p. 12). Altro esempio sono i terremoti che caratterizzano l’isola di Procida, "perciò che l’isola è vessata da tremuoti e da bocche che gettano in modo, che gli Eritrei e i Calcidesi, che già in quella abitarono, furono forzati a fuggirsi" (ibid., p. 12). Come riporta Alberti, le eruzioni e tremori del suolo devono aver rappresentato la causa principale del mito di Tifone cantato dai poeti dell’antichità; il gigante, muovendosi e dibattendosi sotto l’isola, era considerato la causa delle forti scosse del suolo. Per le stesse connotazioni geologiche dell’area i nuovi colonizzatori dell’isola mandati da Jerone siracusano per edificarvi una nuova città, "per la paura del continuo pericolo, e di tal miseria se ne fuggirono" (ibid., p. 13). Alberti conclude il paragrafo affermando chiaramente come tutte queste notizie storiche devono essere raccolte e i luoghi e fenomeni registrati tra loro comparati, in modo da poter scegliere il sito più adatto e meno pericoloso per edificare un’intera città o singoli edifici.

Il grande architetto comprende a pieno l’importanza di conoscere la sismicità storica di una zona per la pianificazione territoriale, tuttavia non fornisce o discute possibili cause per i terremoti, a parte la citazione mitologica
del gigante Tifone. Sin dall'antichità, e in particolare nella lettura di Aristotele, i terremoti erano stati interpretati come indotti da forti movimenti di aria nelle cavità della crosta terrestre. Ritroviamo la stessa interpretazione, ad esempio, nel Canto III dell’Inferno di Dante Alighieri (si veda Romano, 2016), dove il sommo Poeta scrive: “La terra lagrimosa diede vento/ che balenò una luce vermiglia/ la qual mi vince ciascun sentimento/ e caddi come l’uomo che /l sonno piglia.” Nei versi riportati, Dante descrive un vero terremoto, aggiungendo all’elemento della sossaporpora percepita un aspetto particolare che potremmo definire ‘pseudo-scientifico’: ovvero il vento percepito contestualmente al fenomeno sismico. Secondo le conoscenze del tempo, infatti, i terremoti venivano riferiti alla spinta energetica di vapori e venti sotterranei, una teoria già trovata in Ristoro D’Arezzo nella sua Composizione del Mondo pubblicata nel 1282; un fenomeno a cui Dante fa di nuovo menzione nel Purgatorio (XXI, 55-56). La teoria che vedeva i venti e vapori sotterranei come la causa di terremoti e della nascita di catene montuose è trovata per esteso anche nel medico arabo Avicenna Ibn Sing (980-1037), il quale essenzialmente rielaborò, con una visione personale, le teorie presentate da Aristotele. Inoltre, ehi di questa teoria o sistema di teorie possono essere rintracciati anche in Alberto Magno e in Ovidio (Alexander, 1986). In Aristotele questi fenomeni erano spiegati attraverso la teoria delle “esalazioni secche” (Boye, 1984). Secondo questa teoria, il calore sarebbe in grado di mutare sia la terra in gas secco che l’acqua in gas umido. Le esalazioni secche possono essere generate nel sottosuolo e le esalazioni umide possano raggiungere in infiltrazioni il sottosuolo a partire dalla superficie. Il passaggio impetuoso di queste esalazioni tra le strettte “vene” della terra, nell’ipotesi di Aristotele, sarebbe la causa principale per i terremoti. Sulla base della facilità o difficoltà trovata dalle esalazioni per passare nelle vene più o meno contorte, l’intensità del terremoto derivante risulterebbe maggiore o minore, e il processo può avere luogo anche con movimento consistente di acqua e rocce.

Dall’analisi del testo, sembra che Alberti avesse sviluppato una concezione abbastanza chiara anche dei fenomeni di esondazione fluviale ed evoluzione naturale di piana alluvionale. Secondo l’autore, infatti, nel caso in cui il sito selezionato sia rappresentato da una pianura bisogna necessariamente rialzare gli edifici da terra, considerando che le piane alluvionali causano inondazioni, deposizioni di sedimenti, e alla lunga un sollevamento progressivo del piano campagna per decantazioni secolari del materiale in sospensione nelle piene: “Perché lo allagar de’ fuuni, e le pioggie sogliono ne’ luoghi piani arrecar fango; onde accade che esso terreno si va a poco a poco innalzando, oltre che se, per negligenza de’l uomini, non sono portati via i calcinacci e le ribaldarla che tutto il giorno si lasciano, i piani facilmente si innalzano” (ibid., p. 17). Come esempi riporta l’altezza attuale del piano campagna nella città di Roma che copre per molti metri le antiche rovine, e un antico tempietto “nel ducato di Spoleto... sotterrato pure in gran parte, per lo alzarvisi e’ ha fatto il terreno distendendosi quella pianura insino sotto i monti” (ibid., p. 17). Alberti ci tiene a sottolineare che questo fenomeno dell’interramento e sollevamento del piano campagna non risulta esclusivo di pianure molto prossime a catene montuose che rappresentano l’area sorgente dei sedimenti. A tale proposito cita l’esempio del tempio presso le mura della città di Ravenna, molto vicino alla linea di costa Adriatica, che, come per il tempio osservato a Spoleto, risulta “sotterrato più che la quarta parte nel terreno per l’ingiuria de’ tempi” (ibid., p. 18).

Prima dell’opera di Alberti, riferimenti all’interramento dei letti dei fiumi, e necessità di innalzare gli argini nel corso del tempo, sono trovati nell’Inferno di Dante Alighieri (Romano, 2016), come riportato estesamente da Charles Lyell nei noti Principles of Geology. Lyell (1850) chiama in causa l’Inferno di Dante discutendo le pratiche di regimazione fluviale, messe in atto in Italia nei fiumi Po e Adige. Il geologo inglese riporta come per prevenire pericolose esondazioni, venne adottato un sistema di argini, con i corsi d’acqua maggiori e i loro tributari “attualmente confinati tra argini artificiali consistentemente rialzati”. Tuttavia, continua Lyell (1850), mentre con questo sistema una parte di materiale in sospensione raggiungeva il mare, una parte consistente dei sedimenti che naturalmente sarebbero stati deposti per esondazione nelle piane alluvionali, si accumulano nei fondi dei canali, andandone quindi a diminuire progressivamente la sezione. Per prevenire l’esondazione dei corsi d’acqua in primavera, con risultati del tutto catastrofici, risultava dunque di primaria importanza correre ai ripari rialzando ulteriormente, anno dopo anno, gli argini artificiali dei canali. La pratica della regimazione fluviale, secondo il grande geologo, fu adottata in Italia fin dal tredicesimo secolo, e come prova a riguardo, cita letteralmente il passo dell’Inferno Dantesco. Il sommo poeta parla, nello specifico, delle dighe costruite dai Fiamminghi e dai Padovani lungo il fiume Brenta. Opere ingergeristiche realizzate esattamente per arginare il sovraccarico primaverile di acqua nel fiume a seguito dello scioglimento delle nevi. Scrive il Sommo Poeta: “Ora cen porta l’un de’ duri margini / e l’innuno del ruscel di sopra aduggia; / si che dal foco salva l’acqua e li argini. / Quale i Fimminghi tra Guizzante e Bruggia, / temendo il fiotto che ’ner lor s’avena, / fanno lo schermo perché l’mar si fuggia; / e quale i Padoan lungo la Brenta, / per difender lor ville e lor castelli, / anzi che Chiarentana il caldo senta” (Inferno, XV, 1-9).

Aspetto fondamentale per la costruzione di ogni edificio, secondo Alberti, è la progettazione delle fondamenta che rappresentano, a tutti gli effetti, il basamento di tutta l’opera (si veda paragrafo successivo); ne segue dunque che la scelta del terreno, o suolo, più adatto a garantire la stabilità degli edifici, rappresenta un punto centrale per la pianificazione di ogni costruzione. Anche in questo caso è chiaro come l’approccio ‘geotecnico’ del grande architetto italiano sia assolutamente all’avanguardia, con un dettagliato elenco di casi particolari, costruzioni storiche e risposte degli edifici nel tempo a vari tipi di terreni. Per costruzioni su una spiaggia, ad esempio, non si può superare un certo carico limite, accertandosi “che le parti di sopra con lo aggravare non spinghino” (ibid., p. 18). Se il sito prescelto risulta la sommità di un altura bisognerà procedere “spianando la punta del monte”, e alzando al contempo i margini con opere architettoniche, o spianando sia il pendio che la cima per ottenere un versante più dolce e meno acclive. A questo proposito Alberti tesse le lodi dell’architetto che progettò la città di Alatri presso Roma “posta in sul sassoso monte” (ibid., p. 18).

Nella pianificazione territoriale Alberti dimostra di conoscere a pieno la potenza modellatrice dei corsi d’acqua e la possibile evoluzione del territorio causata dalla continua erosione e spostamento di sedimento. A
tal proposito riporta il caso della città di Perugia, dove il corso d'acqua che passa tra il monte Lucino e il colle dove sorge la città “per cavare continuamente rodoendo le radici del monte, si tira dietro tutta la pendente macchina che gli sta sopra: donde gran parte della città si disfa, e rovinati addosso” (ibid., p. 19). Nello stesso contesto suggerisce di evitare come sito di costruzione i luoghi caratterizzati da sassi minuti e tondi (quindi di origine fluviale) e le zone dove nascono fontane o troppo prossime a corsi d'acqua, “perciocché la natura de’ fiumi è di portar via continuamente d’imporvi per quanto dura il moto loro: e di qui avviene che perciocché la natura de’ fiumi è di portar via continuamente sassi minuti e tondi (quindi di origine fluviale) e le zone evitare come sito di costruzione i luoghi caratterizzati da sassi minuti e tondi (quindi di origine fluviale) e le zone.

Noi nondimeno veggiamo che alle prime fonti in Aristotele e Strabone. Riporta a tale concavo dell’ansa, in corrispondenza del punto di massima incidenza del filone di corrente; fenomeno importantissimo per Leonardo perché porta a un avvicinamento della parte maggiormente incidente del fiume alla città. Nonostante questa comprensione profonda e raffinata dei processi in atto e passati, tuttavia gli scritti di Leonardo restarono totalmente sconosciuti per almeno tre secoli.

Seguendo le parole di De Lorenzo (1920) quindi Leonardo può essere considerato a tutti gli effetti precursore delle Scienze Geologiche sensu lato ma non il fondatore.

Alberti sembra avere intuito anche il processo centrale della prorogazione a opera dei sedimenti portati dai fiumi al mare nel corso del tempo, con avanzamento progressivo della linea di costa: “Noi nondimeno vegghiamo che alle foci de’ fiumi per tutto i liti crescossi assai, e massime se quei fiumi sono di quelli che corrono per campagne sciolte, ne’ quali mettino molli altri fiumi. Per ciocché e’ ragunano e gettano in su le foci al lito del mare di qua e di là assai rena, ed assai sassi come quasi uno argine, e fanno il lito più addentro verso il mare” (ibid., p. 373).

Ancora in relazione alla scelta del sito migliore per la costruzione di una possibile città, Alberti mostra di avere una concezione di un Pianeta in continuo mutamento, con limite tra acque e terreemerse che può mutare diverse volte nel corso dei secoli. Una concezione per nulla scontata a inizio sedicesimo secolo, che trova tuttavia delle prime fonti in Aristotele e Strabone. Riporta a tale riguardo il caso della città di Baia in Italia sommersa dal mare, o il faro di Alessandria che, un tempo circondato dal mare, si trova attualmente sulla terraferma, ben distante dalla città; casi simili sono riportati, scrive l’Alberti, da Strabone per le città di Tiro e Clazomenae. Nei Principi di Lyell (1850) troviamo che già Erodoto (484-425 BCE) aveva ipotizzato che un tempo lontano il mare coprisse l’intero Egitto inferiore fino alle terre alte di Menfi, basandosi sullo studio e ritrovamento di conchiglie fossili nell’entroterra.

Aristotele nei “Meteoroelogica” afferma a riguardo: “La distribuzione delle terre e del mare in regioni particolari non è rimasta stabile per tutto il tempo, ma si fece mare in quelle parti dove era un tempo terra emersa, e di nuovo divenere terra dove un tempo fu mare...” (tradotto da Lyell, 1850). Anche il celebre filosofo Eratostene è tra i primi a ipotizzare correttamente una diversa distribuzione di terre e mari nel passato. Seguendo fondamentalmente le ipotesi
e tradizioni di Santo Lidio e Stratone il Fisico, Eratostene sostiene come tutti quei luoghi, dove ora si trovano le spoglie fossili, devono essere stati in passato coperti dalle acque del mare. Ipotesi simile è trovata in Strabone che utilizza forti terremoti come ipotesi per spiegare il sollevamento del mare fino a invadere territori attualmente emersi. Cambiamenti nei confini tra terre emerse e mari per il passato, ma anche per il futuro del Pianeta, sono trovati nei manoscritti di Leonardo (si veda De Lorenzo, 1920) e, nel sedicesimo secolo, nell’Historia Naturale di Ferrante Imperato pubblicata per la prima volta nel 1599. In particolare, il grande naturalista napoletano dedica all’argomento il paragrafo dal titolo “Della mutation delli paesi di terra in acqua, e di acqua i terra” dove afferma a riguardo: “Ma non sono sempre l’istessi paesi acquosi, né sempre aridi: anzi si scambiano, secondo li nuovi nascimenti de fiumi, e lor disseccamenti: perciò li termini, e di terra ferma, e di mare si mutano; e non sono sempre questo luogo terra, e questo mare: ma sopra vi era mare, ove era terra, e fassi terre, ove era mare. Il che diciamo avvenire nel corso de secoli con ordine e circolo” (Imperato, 1672, p.). Tra sedicesimo e diciottesimo secolo saranno molti gli autori italiani a sostenere una diversa estensione dei mari nel passato come spiegazione ai resti fossili, specialmente come elemento per contrastare le ipotesi Diluvialiste imperanti d’oltre Manica. Tra questi figurano sicuramente Girolamo Fracastoro, Luigi Ferdinando Marsili, Giovanni Giacomo Spada, Antonio Vallisneri, Antonio Matani, Giuseppe Baldassarri, l’Abate Passeri, l’Abate Fortis e Ambrogio Soldani, solo per nominare i principali (per una trattazione più esaustiva si veda Romano, 2018b).

Tornando all’opera di Alberti, secondo il grande architetto bisogna anche evitare di costruire le città in zone caratterizzate da pendii troppo ripidi, dal momento che l’erosione retrograda dei versanti finirà inevitabilmente per far crollare anche gli edifici stessi come mostrato, ad esempio, da diversi castelli nell’area di Volterra; sicché “Rovinano certo i luoghi così fatti in processo di tempo e si tirano dietro ciò che tu vi pon sopra” (ibid., p. 112).

Altri elementi geologici e di evoluzione del paesaggio, specialmente in riguardo alla modellazione fluviale, si trovano nella parte di testo dove vengono indicati i luoghi adatti per la costruzione di ponti (Fig. 6). Alberti mostra ancora una volta di avere una profonda conoscenza dei sistemi fluviali e del loro possibile mutamento nel tempo. In particolare, per il grande architetto deve essere scelto quel ‘guado’ che “non si vadia variando, nè movendo, ma stia uguale sempre, e da durare.” (ibid., p. 124). Allo stesso modo, continua Alberti, si devono evitare “gli avvolgenti, le voragini, e cose simili, che nei cattivi fiumi si trovano…” (ibid., p. 124) e, sopra ogni cosa, le anse strette dei corsi d’acqua (“i gomiti de le ripe”). Queste parti del fiume, infatti, sono soggette a maggiore erosione a opera dell’acqua e risultano inoltre aree di accumulo di tronchi e vegetali portati durante le piene dalle zone più interne.

Diversamente, continua Alberti, i piloni dei fiumi devono essere posizionati “dove le acque (per dir così) corrono più lente e più infingarde” (ibid., p. 125), e tali luoghi, secondo l’autore, possono essere individuati grazie allo studio dei corsi d’acqua durante i periodi di piena. Per l’Alberti è sufficiente gettare nel fiume degli oggetti galleggianti “dove le acque (per dir così) corrono più lente e più infingarde” (ibid., p. 125) e osservare dove tale materiale si raccoglie, come indicazione “che quivi sia il maggiore impeto de le acque. Nel situare adunque le pile fuggirem questo luogo, e pigliarem quel’altro, dove le cose gittate si condurranno più rare e più tardi” (ibid., p. 125).

Studi ed esperienze di questo tipo erano state condotte, sempre nel sedicesimo secolo, dal genio di Leonardo da Vinci (si veda Baratta, 1903). Per la progettazione e costruzione di ponti Leonardo infatti idealizza veri e propri esperimenti empirici, per testare le zone del fiume con maggiore velocità e capacità erosiva, e quindi ideare i ponti e le opere idrauliche per resistere a questa energia differenziale del mezzo. Leonardo ne parla, ad esempio, nel trattato “Delle varie velocità de’ corsi dalla superficie dell’acqua al fondo” (si veda Baratta, 1903). Nel testo il grande toscano spiega il funzionamento di un semplice strumento costituito da una bacchetta con un galleggiante di sughero e un peso sul fondo, immersa nel corso d’acqua da analizzare. Se la bacchetta risulta inclinata in avanti vuol dire che il corso del fiume corre più in superficie.
che sul fondo, mentre avremo la situazione opposta se la bacchetta sarà piegata nel verso opposto alla corrente.

Per raggiungere lo stesso scopo Leonardo progetta e realizza un’altra esperienza che consiste nel gettare un’ampia visuale del paesaggio, lontano da aree paludose per edificare, conclude Alberti, deve quindi risultare centrali sottoposti, con il tempo, a sollecitazioni maggiori. Considerando la maggiore resistenza richiesta ai piloni nella progettazione e costruzione di ponti, specialmente secondo Leonardo, devono essere tenuti in considerazione dell’acqua nei fiumi e massima in superficie e nel mezzo del filone e minima sul fondo e verso le pareti. Questi elementi, secondo Leonardo, devono essere tenuti in considerazione nella progettazione e costruzione di ponti, specialmente considerando la maggiore resistenza richiesta ai piloni centrali sottoposti, con il tempo, a sollecitazioni maggiori.

Per concludere il presente paragrafo, la zona adatta per edificare, conclude Alberti, deve quindi risultare abbastanza sollevata e in aree aperte che permettano un’ampia visuale del paesaggio, lontano da aree paludose e acque stagnanti, e che “da qualche fiato di lietissima aria sia continuamente agitata” (ibid., p. 8).

SCelta dei terreni adatti alle fondamenta

Elemento centrale per la pianificazione e la costruzione di qualsivoglia opera architettonica sono le fondamenta, oltre che il luogo e il terreno adatto dove progettare e metterle in opera. Anche se indicazioni in merito sono trovate in diverse parti dell’opera, Alberti discute nel dettaglio il tema delle fondazioni nel Libro III del De re aedificatoria. In questa parte del testo troviamo i riferimenti alla stratificazione dei depositi nel sottosuolo, con gli strati sedimentari ancora definiti con il termine antico di “filioti”. Seguendo l’insegnamento trasmesso da architetti del mondo antico, Alberti riferisce come gli scavi per le fondamenta devono spingersi in profondità nel sottosuolo fino a trovare “terreno sodo, imperocché la terra ha sotto filioni doppi e di più sorti: alcuni sono sabbiosi, alcuni renosi ed alcuni sassosi e simili” (ibid., p. 69). Al di sotto di questi livelli, e con caratteristiche particolari che variano da luogo a luogo ("con ordine vario ed incerto"), “si trovano uno pancone serrato e spesso, gagliardissimo a reggere gli edifici” (ibid., p. 69). È chiaro che Alberti si riferisce alla roccia in profondità non alterata, trovata al di sotto del suolo e regolite, o sottostante ai depositi di piana alluvionale. Tuttavia, una volta trovata la roccia in posto, non è detto che il litotipo risulti ottimale per il sostegno delle fondamenta dal momento che, in alcuni luoghi, risulta “durissimo e quasi inespugnabile dal ferro” (ibid., p. 69), in altri è costituito da tufo o da “creta”, o “di certa sorte di arzilla mescolata con ghiaia” (ibid., p. 69). Una volta riconosciuta e descritta questa ampia variabilità dei depositi trovati subito sotto il suolo sciolto, Alberti fornisce alcune semplici indicazioni per scegliere il substrato migliore per la messa in opera delle fondamenta. In particolare bisognerà scegliere il substrato “che difficilmente sia offeso dal ferro, e che messavi dell’acqua non si risolva” (ibid., p. 69). Dovrà essere preferito inoltre quel terreno dove lasciandovi cadere un peso da una certa altezza “non vi terrerà sotto il luogo, o non vi si dimenerà l’acqua messavi in un catino” (ibid., p. 69).

Alberti riporta il caso di una torre presso il castello dei Veneziani a Mestre che, pochi anni dopo la sua costruzione, iniziò a sprofondare velocemente per il cedimento del terreno non adatto a porvi le fondamenta. A tale riguardo l’architetto sconsiglia vivamente di costruire nuove opere sui ruderì di vecchi edifici, dal momento che non si conoscono né la tipologia delle fondamenta originarie né se queste siano state effettivamente poggiate sulla roccia in posto o, diversamente, su terreni poco stabili (e inadatti a reggere il peso continuato di un grande edificio). A questo riguardo stupisce la modernità dell’approccio proposto dall’Alberti, che prevede una vera e propria prospezione geognostica del sottosuolo tramite pozzi per intercettare i terreni in profondità, e comprendere la composizione e ‘reologia’ (per usare un termine attuale) dei depositi intercettati: “bene adunque sieno avvertiti, che la prima cosa cavino i pozzi, e questo si per l’altra cose, si ancora perché e’ si vegga manifesto, qual sia ogni filone del terreno atto a reggere gli edifici, o a rovinare, aggiuntouchi che e trovata l’acqua, e quello che di essi si caverà, gioverà molto alle comoditá di fare molte cose” (ibid., p. 70). Lo scavo dei pozzi quindi assume in Alberti una doppia valenza fondamentale: prima di tutto ovviamente l’approvvigionamento di acqua indispensabile per i centri abitati e, in secondo luogo, lo studio della stratigrafia del sottosuolo a fini architettonici e ingegneristici. In questo modo, continua l’Alberti, una volta realizzati gli scavi per ottenere un pozzo, una fognana o una cisterna, e quindi una volta analizzati i depositi “che sotto terra si nascondono, si debbe eleggere quello che sia comodissimo più che gli altri, al quale tu debba fidare l’opera tua” (ibid., p. 70).

STUDIO DELLA LITOLOGIA COME MATERIALE DA COSTRUZIONE

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il punto centrale riguardante la sfera architettonica è di natura maggiormente pragmatica, e rivolto alle proprietà delle varie litologie come materiale da costruzione.

Tra le indicazioni pratiche ereditate da Catone, Alberti consiglia di non utilizzare immediatamente le rocce una volta cavate, ma solo dopo averle lasciate ‘maturare’ ‘allo scoperto’ per almeno due anni: “acciocché le pietre non avvezz, si assuefaccino a poco a poco ai venti, ai diacci, alle pioggie ed alle altre ingiurie de’ tempi: perciocché se le pietre subito cavate della cava, pregne del nativo sugo ed umore, si pongono ai venti crudi ed a subbi diacci, si fendono e si risolvono” (ibid., p. 50). Inoltre, continua Alberti, mantenere le rocce che si vogliono utilizzare all’aperto, soggette alla continua azione degli agenti atmosferici, permette di testare empiricamente nello specifico la reazione di ogni singola roccia, “e quanto ella sia forte contro alle cose che la molestano; a questo modo qualsi che facendo esperienze di quanto elleno sieno per durare” (ibid., p. 50). Ovviamente questo processo si rende essenziale e indispensabile per i litotipi selezionati per la costruzione di teti o rivestimenti esterni in generale, che risultano maggiormente esposti a un’ampia varietà di condizioni atmosferiche. L’esperienza in tale senso mostra come alcune rocce “all’aria diventano dure, ed alcune bagnate dalle brinate contraggono certa ruggine e si disfanno” (ibid., p. 50), e devono quindi essere evitare come materiale da costruzione. Per Alberti una serie di prove in questo senso possono essere dedotta empiricamente osservando semplicemente le varie porzioni e materiali che compongono le parti di antichi edifici: “che tu potrai più tosto imparare meglio il valore e la virtù di ciascuna pietra dalle antich edifici, che driti scritti e dai ricordi de’ filosofi” (ibid., p. 51). Anche in questo caso è degno di nota l’approccio prettamente empirico sugettato dall’Alberti, da preferire sempre, quando possibile, all’autorità di autori classici.

Altro elemento importante da considerare nella selezione del materiale litico da costruzione è la presenza o meno di vene all’interno delle rocce, la loro dimensione e composizione rispetto alla litologia principale. Spesso le vene costituiscono un motivo di debolezza per il litotipo in questione. Le vene, infatti, possono essere considerate come alcune strisce di materiale litico differente rispetto alla litologia principale e, quindi, essere considerate come una serie di disegni dettagliati che caratterizzano la struttura del materiale. L’Alberti fissa in particolare una serie di test empirici che possono essere effettuati per selezionare il materiale ideale per la costruzione. Per esempio, uno dei test può essere effettuato su un pezzo di pietra che è stato esposto all’aperto, soggetto alla continua azione degli agenti atmosferici, permette di testare empiricamente nello specifico la reazione di ogni singola roccia, “e quanto ella sia forte contro alle cose che la molestano; a questo modo qualsi che facendo esperienze di quanto elleno sieno per durare” (ibid., p. 50). Ovviamente questo processo si rende essenziale e indispensabile per i litotipi selezionati per la costruzione di teti o rivestimenti esterni in generale, che risultano maggiormente esposti a un’ampia varietà di condizioni atmosferiche. L’esperienza in tale senso mostra come alcune rocce “all’aria diventano dure, ed alcune bagnate dalle brinate contraggono certa ruggine e si disfanno” (ibid., p. 50), e devono quindi essere evitare come materiale da costruzione. Per Alberti una serie di prove in questo senso possono essere dedotta empiricamente osservando semplicemente le varie porzioni e materiali che compongono le parti di antichi edifici: “che tu potrai più tosto imparare meglio il valore e la virtù di ciascuna pietra dalle antich edifici, che driti scritti e dai ricordi de’ filosofi” (ibid., p. 51). Anche in questo caso è degno di nota l’approccio prettamente empirico sugettato dall’Alberti, da preferire sempre, quando possibile, all’autorità di autori classici.

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incrostati di pietra” (ibid., p. 53).

Ancora in relazione a processi di diagene si, disfacimento meteorico di rocce, Alberti riporta come nel territorio di Firenze, e in particolar modo in un paese attraversato dal fiume delle Chiane, “i duri sassi, che in
quantità vi sieno sopra sparsi, ogni sette anni si risolvono
in zolle” (ibid., p. 54). Diversamente, citando l’autorità di
Plinio, presso Souga e Gassandrea sono state osservate zolle di terra convertirsi in “sassi”. Presso Pozzuoli si
genera una tipologia di “polvere” che, una volta mescolata con acqua di mare, “indurisce e diventa pietra” (ibid., p. 54).

Ulteriori riferimenti alla diagene sono riportati nel Capo VII del Libro III. L’autore afferma come le “pietre” sono
“create” dalla natura a partire da una massa fluida, “la quale essendo a poco a poco cresciuta ed indurita, riserva essa massa le prime Figure delle sue parti” (ibid., p. 78). Il problema della diagene e quindi della formazione delle rocce, specialmente contenenti fossili, è trattato da diversi autori italiani tra sedicesimi e diciassette secolo tra cui Ristoro D’Arezzo nella sua Composizione del Mondo, Ferrante Imperato e Agostino Scilla, anche se una delle prime trattazioni più complete e risolutive a riguardo è quella fornita da Niccolò Stenone nella sua opera miliare per le Scienze della Terra “De solido intra solidum naturaliter contento dissertationis promodus”, pubblicata a Firenze nel 1669. Nel testo Stenone fornisce tutti gli elementi necessari per la corretta interpretazione di modelli esterni e interni dei fossili, definiti rispettivamente come conchae aereae e lapidae. Nella logica stringente di Stenone se due solidi risultano inclusi l’uno nell’altro deve essere esclusa, sul piano prettamente logico, una loro contemporaneità nella formazione. In secondo luogo, uno dei due solidi in questione doveva risultare necessariamente già consolidato in origine, mentre il secondo doveva presentarsi allo stadio fluido per poterlo inglobare (si veda Pantalone, 2017).

Alberti dimostra inoltre di aver compreso il processo di decantazione differenziale in una massa fluida e conseguente gradazione dei sedimenti, quando afferma come “in esse pietre le parti di sotto sono di corpicelli più gravi e maggiori, che quelle di sopra, e v’intracoronno vene secondo che la materia, posta sopra l’altra materia, si strinse insieme” (ibid., p. 78). Tali osservazioni e deduzioni non hanno un valore solamente scientifico per il grande architetto, ma anche un significato pragmatico essenziale. Alberti riporta infatti come questi passaggi tra ‘granulometrie’ differenti rappresentino per osservazione diretta delle linee di forte debolezza per le rocce, che portano il materiale a fendersi e alterarsi in maniera preferenziale. Bisogna quindi tenere bene a mente questa ‘anisotropia’ nel materiale da costruzione prima di scegliere il suo utilizzo nell’ambito architettonico. Al riguardo Alberti conclude affermando come “nel collocare le pietre si avvertisca di porre contro le offensioni delle cose contrarie, quelle facce delle pietre che sono saldissime, e che non sono atte ad essere così presto consumate, in quelle parti massime dello edificio, che debbono essere le più gagliarde” (ibid., p. 79). Nel caso sia inevitabile utilizzare litologie con cambi di granulometrie o vene all’interno, non si dovrà mai orientare le vene in verticale “acciocché per i cattivi temporali le pietre non si scorrereccio” (ibid., p. 79), ma porre in orizzontale “acciocché aggravata per il peso delle di sopra, non apra mai in luogo alcuno” (ibid., p. 79). Una piena comprensione della gradazione dei sedimenti è trovata negli scritti di Leonardo Baratta, 1903; De Lorenzo, 1920), e l’argomento è ripreso e discusso anche dallettore siciliano Agostino Scilla nella sua Vana speculazione disingannata dal senso del 1670 (Accordi, 1978; Romano, 2014). Tuttavia, gli scritti di Alberti rappresentano il primo caso dove la gradazione osservabile nelle rocce è discussa in relazione alla bontà del litotipo come materiale da costruzione.

Tornando agli aspetti maggiormente applicativi della conoscenza delle varie litologie e terreni per le costruzioni, Alberti discute le varie tipologie di sabbie o “rene” disponibili per opere architettoniche. L’autore dà le “rene” in tre categorie principali “di cava, di fiume, e di mare” (ibid., p. 61). L’esperienza porta l’Alberti a preferire di gran lunga quella di cava, tuttavia differenziable in numerose altre categorie tra cui la “nera, bianca, rossa, incarbonchiata, e ghiaiosa” (ibid., p. 61). Alberti mostra di comprendere inoltre a pieno l’origine fossile di ogni forma di sabbia, come risultato di erosione e alterazione di rocce preesistenti: “ma s’alcuno mi dimanderà che cosa e rena, io forse gli risponderò, che ella è quella che sia fatta (rotte le maggiori pietre) di minutissime pietruzze” (ibid., p. 61). A Roma, riporta l’Alberti, utilizzarono la rena rossa per la costruzione degli edifici pubblici (probabilmente si riferisce alla pozzolana ampiamente cavata sin da tempi storia della Campagna Romana). La rena di pegger qualità per le costruzioni risulta quella bianca, mentre, continua l’Alberti, quella ghiaiosa è molto utile “nel riempire i fondamenti”. Dopo la rena di cava, la seconda migliore per le costruzioni è quella di fiume “che si cava, levatane di sopra la prima scora” (ibid., p. 61), e tra quelle di fiume si deve preferire la rena raccolta in acque correnti di zone montuose, “dove le acque hanno maggior perdito “ (ibid., p. 61). Ultima in ordine di utilità nelle opere architettoniche è la rena di mare che “si rasciuga difficilmente, e dissolubile sta umidiccia, e scorre per la sua salsedine, e perciò mal volentieri, né mai fedelmente sostiene i pesi” (ibid., p. 61). La rena dei fiumi è maggiormente umida rispetto a quella di cava e per tale ragione risulta meglio lavorabile e “migliore per gli intonaci”.

Per quanto riguarda la realizzazione della calce, e seguendo le indicazioni degli architetti del passato, Alberti consiglia la “pietra molto dura e molto serrata, e massime bianca” (ibid., p. 57), che può essere utilizzata alla bisogna anche per la costruzione delle volte, garantendo un sicuro supporto strutturale alle opere.

Riferimenti a organismi fossili


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di natura paleoecologica (si veda Romano, 2017, 2018a, 2018b, 2018c). Solo in rare eccezioni, di punta come Giuseppe Monti che contribuirono a L’interpretazione diluvianista ebbe tuttavia un largo seguito venivano ritrovati, caratterizzò in particolar modo la di animali non più veduti, di grandezza smisurata " (ibid., p. 60). Ma non si può dare un giudizio certamente su queste Figure nelle rocce che richiamano l'Abruzzo, continua l'Alberti, si possono osservare, nei territi freschi delle rocce, innumerevoli " (ibid., p. 60). Nell'area di Velino "che divide gli Abrušesi da' Marsi, altissimo più di tutti gli altri, è in tutta la sua cima calvo per una pietra bianca e viva" (ibid., p. 60). Versante della musica di Enrico, "dei 4 elementi" (ibid., p. 60). Alberti continua parlando del monte in mezzo d'un bianchissimo " (ibid., p. 346). Essendo la regione dove era costruita Babilonia estremamente arida, vennero messe in atto imponenti opere per deviare e poterli condurre i fiumi Tigri ed Eufrate. Riporta poi come se diramare il fonte nella città che era alto venti piedi, di gran lunga tutti costoro e di grandezza di muraglie, e di superò in opera senza alcun dubbio nell'antica Roma, che " (ibid., p. 346). Degne di nota sono inoltre "una fossa lunga settanta stadi, tirata per un monte alto cento cinquanta cubiti" (ibid., p. 346) presso Samir e il condotto fatto costruire da Megaro "che era alto venti piedi, mediante il quale si convenne il fonte nella città" (ibid., p. 346). Alessandro, diversamente, per rifocillare l'esercito "lungo il mare ed il lito Persico" (ibid., p. 346) fece scavare dei pozzi. Tuttavia, secondo l’Alberti, le opere più monumentali e sontuose per condurre l’acqua in città sono state messe in opera senza alcun dubbio nell’antica Roma, che “superò di gran lunga tutti costoro e di grandezza di muraglie, e di artificio del condurle, e de la gran copia de le acque condotte dentro” (ibid., p. 346).

Alberti tratta nello specifico il problema della nascita delle sorgenti nel Capo III del libro decimo dal titolo: “Che quattro sono le cose da considerare circa alla cosa dell’acqua, e dove ella si generi, o dove, ella nasca, e dove ella corra” (ibid., p. 348). Il problema circa la nascita delle acque sorgive aveva incuriosito pensatori sin dall’antichità con diverse teorie propagate in materia. Un’interpretazione classica, abbracciata inizialmente anche da Leonardo (Baratta, 1903) e sostenuta da personaggi del calibro di Cartesio, era quella dei 'lambicchi' (o alamicchi). Secondo tale teoria, le acque dolci terrestri avrebbero origine dalle acque marine, tramite un processo di desalinizzazione e filtrazione delle stesse in risalita attraverso le rocce. Nel panorama italiano questa ipotesi venne in parte supportata da autori del calibro di Bernardo Ramazzini nella sua opera De fontium Mutinensium e da Luigi Ferdinando Marsili. I due grandi scienziati, infatti, erano scettici riguardo la provenienza meteorica delle acque sorgive, per una semplice considerazione di bilancio idrico: le acque provenienti da ghiacciai, nevi e piogge non risultavano, secondo le

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Considerando l’importanza centrale della disponibilità di acqua potabile per un centro abitato, è abbastanza normale che Alberti torni più volte sul tema, dedicandogli anche un intero capo nel Libro X dell’opera, dove l’autore discute anche la possibile origine delle sorgenti. Alberti riporta in primo luogo le grandi opere del passato collegate alla regimazione idrica per poter condurre le acque all’interno delle città o in regioni che ne erano sprovviste, e le tecniche e gli strumenti per calcolare il giusto pendio delle opere idrauliche (Fig. 7). Riporta quindi come i Massageti aprirono in diversi punti gli argini del fiume Arago e in questo modo “fecero la regione aquidosa” (ibid., p. 346). Essendo la regione dove era costruita Babilonia estremamente arida, vennero messe in atto imponenti opere per deviare e poterli condurre i fiumi Tigri ed Eufrate. Riporta poi come se Semiramis fece costruire nella città di Ectabana un acquedotto realizzato forando “un alto monte per stadii 25, con una fossa larga quindici piedi” (ibid., p. 346). Allo stesso modo seguendo gli scritti di Erodoto, “il Re Arabo” condusse il fiume Coro in luoghi molto aridi d’Arabia, “avendo fatto il condotto di pelle di tori” (ibid., p. 346). Degne di nota sono inoltre “una fossa lunga settanta stadi, tirata per un monte alto cento cinquanta cubiti” (ibid., p. 346) presso Sanir e il condotto fatto costruire da Megaro “che era alto venti piedi, mediante il quale si convenne il fonte nella città” (ibid., p. 346). Alessandro, diversamente, per rifocillare l’esercito “lungo il mare ed il lito Persico” (ibid., p. 346) fece scavare dei pozzi. Tuttavia, secondo l’Alberti, le opere più monumentali e sontuose per condurre l’acqua in città sono state messe in opera senza alcun dubbio nell’antica Roma, che “superò di gran lunga tutti costoro e di grandezza di muraglie, e di artificio del condurle, e de la gran copia de le acque condotte dentro” (ibid., p. 346).

**ELEMENTI IDROGEOLOGICI E IL PROBLEMA DELLA NASCITA DELLE FONTANE**

Considerando l’importanza centrale della disponibilità di acqua potabile per un centro abitato, è abbastanza normale che Alberti torni più volte sul tema, dedicandogli anche un intero capo nel Libro X dell’opera, dove l’autore discute anche la possibile origine delle sorgenti. Alberti riporta in primo luogo le grandi opere del passato collegate alla regimazione idrica per poter condurre le acque all’interno delle città o in regioni che ne erano sprovviste, e le tecniche e gli strumenti per calcolare il giusto pendio delle opere idrauliche (Fig. 7). Riporta quindi come i Massageti aprirono in diversi punti gli argini del fiume Arago e in questo modo “fecero la regione aquidosa” (ibid., p. 346). Essendo la regione dove era costruita Babilonia estremamente arida, vennero messe in atto imponenti opere per deviare e poterli condurre i fiumi Tigri ed Eufrate. Riporta poi come se Semiramis fece costruire nella città di Ectabana un acquedotto realizzato forando “un alto monte per stadii 25, con una fossa larga quindici piedi” (ibid., p. 346). Allo stesso modo seguendo gli scritti di Erodoto, “il Re Arabo” condusse il fiume Coro in luoghi molto aridi d’Arabia, “avendo fatto il condotto di pelle di tori” (ibid., p. 346). Degne di nota sono inoltre “una fossa lunga settanta stadi, tirata per un monte alto cento cinquanta cubiti” (ibid., p. 346) presso Sanir e il condotto fatto costruire da Megaro “che era alto venti piedi, mediante il quale si convenne il fonte nella città” (ibid., p. 346). Alessandro, diversamente, per rifocillare l’esercito “lungo il mare ed il lito Persico” (ibid., p. 346) fece scavare dei pozzi. Tuttavia, secondo l’Alberti, le opere più monumentali e sontuose per condurre l’acqua in città sono state messe in opera senza alcun dubbio nell’antica Roma, che “superò di gran lunga tutti costoro e di grandezza di muraglie, e di artificio del condurle, e de la gran copia de le acque condotte dentro” (ibid., p. 346).

Alberti tratta nello specifico il problema della nascita delle sorgenti nel Capo III del libro decimo dal titolo: “Che quattro sono le cose da considerare circa alla cosa dell’acqua, e dove ella si generi, o dove, ella nasca, e dove ella corra” (ibid., p. 348). Il problema circa la nascita delle acque sorgive aveva incuriosito pensatori sin dall’antichità con diverse teorie proposte in materia. Un’interpretazione classica, abbracciata inizialmente anche da Leonardo (Baratta, 1903) e sostenuta da personaggi del calibro di Cartesio, era quella dei ‘lambicchi’ (o alamicchi). Secondo tale teoria, le acque dolci terrestri avrebbero origine dalle acque marine, tramite un processo di desalinizzazione e filtrazione delle stesse in risalita attraverso le rocce. Nel panorama italiano questa ipotesi venne in parte supportata da autori del calibro di Bernardo Ramazzini nella sua opera De fontium Mutinensium e da Luigi Ferdinando Marsili. I due grandi scienziati, infatti, erano scettici riguardo la provenienza meteorica delle acque sorgive, per una semplice considerazione di bilancio idrico: le acque provenienti da ghiacciai, nevi e piogge non risultavano, secondo le
loro osservazioni, sufficienti a spiegare le abbondanti acque trovate nelle falde e che rifornivano sorgenti e corsi d’acqua. Una delle prime esperienze empiriche contro l’ipotesi degli alambicchi venne condotta da Vallisneri il quale, utilizzando diversi tipi di rocce e granulometrie, dimostrò come fosse impossibile desalinizzare per semplice filtrazione l’acqua marina. La serie di esperimenti, e le lunghe osservazione dirette in campagna in condizioni geologiche paradigmatiche, convinsero il grande naturalista patavino che le acque di origine meteorica erano del tutto sufficienti a spiegare il fenomeno delle acque dolci sorgive (per una trattazione più esaustiva si veda Luzzini, 2013).

L’ipotesi corretta venne inoltre difesa a spada tratta da Anton Lazzaro Moro nella sua opera del 1740 “De’ Crostacei e degli altri marini corpi che si trovano su’ monti”, per criticare l’opera diluvianista dell’inglese Woodward, che escludeva categoricamente un origine meteorica per le acque sorgive (si veda Romano, 2018c).

Alberti sembra sposare con largo anticipo proprio l’ipotesi corretta secondo la quale le sorgenti hanno origine grazie all’infiltrazione delle piogge nelle regioni montuose. Per Alberti “i monti, sono come una spugna piena di pori, per i quali l’aria conceputa, diventa più serrata per il freddo, e si unisce insieme: e penso che questo accascel si per gli altri indizi, si per questo, che e’veggono che i gran fiumi nascono ne’ gran monti” (ibid., p. 349). Riporta però come secondo altri autori i fiumi non nascono sui monti ma nel bel mezzo della pianura anche se non è da biasimare “colui che dirà che la terra succia gli umori de le piogge, i quali mediante la loro gravezza e la loro sottigliezza penetrano e si distillano, e cascano nell’luoghi concavi” (ibid., p. 349).

In questa affermazione troviamo già un’interpretazione completamente corretta del processo di ricarica degli acqueriferi con accumulo nei “luoghi concavi”. Infatti, continua l’Alberti, le regioni dove le piogne sono molto rare risultano anche prive di sorgenti, mentre “I monti che stanno assai tempo coperti da la neve danno di sè gran copia di acqua” (ibid., p. 350). Riporta poi diverse notizie ricavate da autori antichi circa la comparsa o scomparsa improvvisa di sorgenti a seguito di terremoti o “spontaneamente”, “talché alcune si sieno perse nella state, ed alcune nell’invernata, ed alcune altre fonti dapi che si sono secce, essergli tornata un’altra volta grandissima abbondanza d’acqua” (ibid., p. 349).

Parlando della condizione caratterizzante Fiesole e Urbino, sembra che Alberti abbia chiari concetti come zona di ricarica e terreni di aquiclude in grado di trattenere e far scorrere le acque: “A Fiesole ed a Urbino, ancorché siano città di montagne, sono le acque assai comode a chi cava i pozzi. E questo, perché quei monti sono pietrosi e le pietre vi sono congiunte con la creta. E vi sono ancora certe zolle che con la pelle de la loro tunica tengono acqua purissima” (ibid., p. 350).

Nel testo che segue Alberti riesce realmente a stupire il geologo moderno, descrivendo la struttura interna delle catene montuose, organizzate in strati come ‘mazzi di carte’ (chiamati “scorie”), regolari ma piegati secondo diverse angolazioni. Strati e discontinuità che l’acqua derivante dalle piogne può seguire e infiltrarsi all’interno del monte; acqua che andrà poi a raccogliersi per gravità nelle zone dove le pieghe formeranno dei “seni”. Per la modernità dell’interpretazione vale realmente la pena riportare per intero il testo del grande architetto al riguardo: “Considerarono gli investigatori si ogni sorte di terreno si ancora che i monti sono fatti di scorse, quasi come di carte, alcune più serrate, alcune più rade ed alcune più sottili, e considerarono che i monti erano fatti di queste scorse poste l’una sopra l’altra... Ma da lato di dentro di...
verso il centro del monte dette scorze si chinano allo ingiù con tutta la superficie di sopra, che ugualmente pende, ma non con tirare ed indurire di sé stessa continuata fino a dentro. Perciocché ad ogni cento piedi quasi si fermano con certi gradi da lo scendere a traverso, rottasi la scorsa: e dipoi con simile interrompimento di ordini, corrono con pari sorte di gradi da l’un lato e l’altro del monte fino a centri del monte. Vedute adunque queste cose, gli uomini di sottil ingegno hanno facilmente potuto conoscere, che le acque sono o generate, o veramente che le piogge si raccolgono infra queste scorze e congiunture de’ fìlari, per il che le parti intime del monte diventano umide. Di qui presero argomento da poter avere le riposte acque, forato il monte di quel luogo massime nel quale corrono a congiungersi l’uno con l’altro i filoni e gli ordini de le linee che vanno à basso, il qual luogo è molto pronto dove i muscoli de’ monti congiungendosi l’uno a l’altro faranno qualche seno”. Alberti continua riportando come i diversi tipi di litologie sono adatti o meno a far penetrare le acque in profondità o a fermarle per la loro spiccata impermeabilità. Tra queste, ad esempio, “il sabbion muschio, e la rena… ne porgono con certezza le acque molto sane ed eterno. Il contrario interviene nella creta, che per esser troppo spessa non ti dà acque” (ibid., p. 351).

**DISCUSSIONE E CONSIDERAZIONI CONCLUSIVE**

Nel presente contributo sono stati trattati per la prima volta in modo organico gli elementi geologici discussi da Leon Battista Alberti nella sua opera monumentale in dieci libri *De re aedificatoria*. Elemento realmente degno di nota nell’opera dell’Alberti, specialmente se si considera il periodo nel quale venne scritta, è la concezione illuminata di come le opere umane debbano tener conto e adattarsi ai processi naturali e non viceversa. Nel testo traspie chiara una comprensione, molto profonda per quel periodo, di come il lento e inesigabile argomento dei processi naturali possa portare a cambiamenti anche profondi del paesaggio. Cambiamenti che le opere umane, per quanto ben congegnate, solide e costruite a regola d’arte, non possono in alcun modo arginare o contrastare. Su questo punto centrale, purtroppo lungamente trascurato nei secoli successivi e anche attualmente in diversi casi di speculazione edilizia, Alberti è oltremodo chiaro ed esplicito: “Primieramente che tu non ti metta a cosa, che sia sopra la possessia de gli uomini, e che tu non ti accinga a far cosa, che el si abbia a combattere del tutto contro alla natura delle cose” (ibid., p. 36). E anche nei casi in cui l’opera architettonica cercherà di contrastare la forza della natura con tutto l’ingegno umano, e tramite l’utilizzo delle migliori tecniche e materiali, “ella pure è tale che ella saprà superare, e gittar via ciò che se gli contrappone, e l’impedisce” (ibid., p. 36). Elemento essenziale a tale riguardo è una prima percezione nell’Alberti del concetto di ‘tempo profondo’, e di come anche processi naturali non necessariamente molto energetici possono portare a cambiamenti rilevanti se hanno a disposizione lunghi periodi temporali per agire: “e sappiamo quanto possa l’ardore del sole, quanto i diacchi, quanto le brinate e quanto i venti. Da questi tormenti veggiamo i durissimi sassi consumarsi, aprirsi ed inficrarsi; e col tempo spicciarsi da le alte ripe, e cadere sassi oltre modo grandissimi; talmente che rovinano con gran parte del monte” (ibid., p. 341).

Una serie di concetti centrali che raggiungeranno il pieno compimento e maturità nelle scienze geologiche con l’opera miliare di Lyell, sotto il cappello dell’uniformitarismo sostanziale (si veda Gould, 1965; Romano, 2015b). A tale riguardo, scrive Alberti, l’operato instancabile della natura “ogni repugnantissimo ostacolo, per dire così, di tutte le cose, che se gli oppongono con la di giorno in giorno continua perseveranza, col tempo, e con la abbondanza, rovina e getta per terra il tutto” (ibid., p. 36). Quante opere dell’antichità non sono state create nel tempo, domanda giustamente l’Alberti, “se non perché ellen contedevano contro alla natura delle cose?” (ibid., p. 36). Le stesse opere immortali e fatte a regola d’arte come il porto di Claudio presso Ostia e quello di Adriano presso Terracina “è già gran tempo, che per aver serrate le bocche dalla rena, e ripieni i seni, sono interamente mancanti, per lo assiduo combattimento del mare, che senza ripasso percorrendoli più l’uno giorno che l’altro, gli vince” (ibid., p. 36).

In pieno spirito umanista e rinascimentale la natura nell’Alberti, come nei “buoni maestri antichi” menzionati dall’autore, viene presa come esempio e canone di bellezza suprema e armonia tra le varie parti. Canone da tenere a mente e imitare nella progettazione e costruzione di un edificio, che per l’Alberti “è quasi come uno animale, sì che nel finirlo e determinarlo bisogna imitare la natura” (ibid., p. 316). Bisogna dunque comprendere, continua l’autore, per quali ragioni i corpi prodotti dalla natura “alcuni sono bellissimi, ed alcuni men belli, ed alcuni brutti e deformi” (ibid., p. 316). La bellezza, per l’Alberti, è rappresentata dalla leggiadria con cui si concordano armoniosamente le varie parti formando il tutto; e in questo l’architettura dovrebbe seguire l’esempio eccezionale fornito dalla natura. In fondo opere dell’Alberti come il De Pictura, dove si respira tutta l’innovazione apportata da personaggi come Masaccio, Brunelleschi, e Donatello, rappresentano in pieno lo spirito del Rinascimento fiorentino, dove l’arte presuppone la comprensione profonda della natura e non la sua semplice imitazione nelle opere.

Nonostante questo studio attento della natura, in Alberti persistono ovviamente interpretazioni erronee di alcuni fenomeni, elemento del tutto comprensibile se si considera lo stato altamente nebuloso in cui vertevano ancora gran parte delle scienze naturali. Un esempio è il supporto del grande architetto alla teoria della generazione spontanea di vermi dalla carne in putrefazione, come Malpighi e Antonio Vallisneri (acerrimi oppositori della generazione spontanea) e Francesco Redi, Marcello Stelluti, accademico dei Lincei, e con accese diatribe “è già gran tempo, che per aver serrate le bocche dalla rena, e ripieni i seni, sono interamente mancanti, per lo assiduo combattimento del mare, che senza ripasso percorrendoli più l’uno giorno che l’altro, gli vince” (ibid., p. 36).

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Gli elementi geologici trattati dall’Alberti nella sua opera possono essere suddivisi essenzialmente in due grandi categorie: i) elementi di stampo pragmatico, ingegneristico e geotecnico, dove la conoscenza del territorio, processi e derivanti prodotti, risultano elementi importanti in fase di progettazione di opere architettoniche; ii) elementi puramente teorico-interpretativi, dove il grande architetto non si limita agli...
aspetti puramente tecnici delle conoscenze geologiche ma discute anche la possibile origine e interpretazione di processi, spesso ancora in atto e osservabili sul terreno. Alla prima categoria possono essere riferite intuizioni veramente all'avanguardia per il suo tempo, come lo studio dettagliato dei terremoti storici in una regione per avere un'idea della 'pericolosità sismica' dell'area; la profonda comprensione dell'evoluzione e migrazione dei sistemi fluviali anche in tempi storici, e dell'influenza dei grandi eventi di piena in centri abitati attraversati da corsi d'acqua; utilizzo di pozzi scavati in profondità per indagare nel dettaglio la composizione dei terreni nel sottosuolo, come studio “geognostico” volto a comprendere la bontà della stratigrafia intercettata per la messa in opera di solide fondamenta; l'uso di un vero e proprio sperimentalismo per indagare le zone dei fiumi soggette a vortici e a maggiore erosione, da evitare nella costruzione di argini e ponti, così come l'esposizione di diverse rocce all'azione degli agenti atmosferici per diversi anni, in modo da comprendere la loro possibile risposta una volta utilizzati nei rivestimenti esterni degli edifici.

D'altra parte l'uso dell'osservazione e dell'esperimento nel processo conoscitivo viene messo al centro dallo stesso Alberti: “Non sia fuori di proposito, che il padre de le arti fu il caso ed il conoscimento: lo alunno di esse fu l'uso e l'esperimento e che crebbono mediante la cognizione ed il discorso” (ibid., p. 184).

Nella seconda categoria di elementi maggiormente teorici, troviamo ragionamenti molto interessanti sulla diagenesi e possibile formazione di vari tipi di rocce in generale. Sicuramente degno di nota è il discorso sulla formazione del travertino idrotermale osservabile direttamente in campagna, e la formazione di bacini lacustri a causa del progressivo sbarramento prodotto dalla precipitazione di questo litotipo. In questo ambito Alberti ha sicuramente un illustre predecessore italiano, Dante Alighieri, che riporta mirabilmente la formazione del travertino presso il Bullicame di Viterbo nel Canto XIV dell'Inferno (si veda Romano, 2016). Questo passo della Commedia venne considerato dal nolo geologo Robert L. Folk come uno dei primi esempi scritti in assoluto sulla diagenesi dei carbonatii (Folk, 1993).

Alberti inoltre discute aspetti di sedimentologia molto raffinati per il suo tempo, mostrando una comprensione avanzata dei processi di deposizione fluviale, rottura di argine e depositi da piena alluvionale, gradazione dei sedimenti a partire da masse sospese in acqua, prorogazione dei sistemi fluviali verso mare, grazie all’apporto secolare di sedimenti. L’autore riporta inoltre una descrizione ammirevole della struttura esterna e interna della Terra, suddivisa in strati regolari ma contorti e piegati fino a diventare verticali o rovesciati. Strati che con la loro conformazione e continuità possono convogliare in profondità l'acqua penetrata nei massicci tramite la pioggia e le nevi, e raccolta in zone concave o “seni”, dando poi luogo a sorgenti una volta incontrato un terreno impermeabile. Una concezione che riesce a stupire appieno il geologo moderno, e che sarà risolta solo due secoli dopo grazie agli studi e alle “battaglie accademiche” di altri grandi naturalisti italiani tra cui Ramazzini e in particolar modo Vallisneri (si veda Luzzini, 2013).

In conclusione, Alberti stupisce anche per la concezione veramente moderna rispetto ai tempi di un pianeta dinamico in continua evoluzione. Una concezione mobilista della Terra che sarà pienamente afferrata solo nella seconda metà del ventesimo secolo, portando a un vero e proprio cambio di paradigma (Hurley, 1974; Bosellini, 1978; Romano & Cifelli, 2015a, 2015b; Romano et al., 2016b). La visione mobilista con evoluzione del paesaggio è stata in parte sicuramente presa in prestito dal maestro Aristotele, come indicato da questa citazione letterale riportata dall’Alberti: "Aristotele dice che il moto de le cose è continuo, e che in processo di tempo avverrà che che il mare si scambierà di luogo con i monti, di qui disse colui: “Ciò ch’è sotterra in processo di tempo, Si scoprirà palese, e verrà fuori. E le cose scoperte andran sotterra” (citazione originale di Aristotele non in corsivo; ibid., p. 377).

In conclusione, il presente contributo ha messo in evidenza come l’Alberti abbia saputo attingere e
recuperare gli stili classici nell’arte (Fig. 8), così come le teorie geologiche, da autori classici dell’antichità, presentando tuttavia sempre una lettura critica e rielaborazione personale e originale delle differenti teorie. In questo recupero critico delle fonti, nello studio diretto della natura posta a modello dei canoni di perfezione ed estrema armonia delle parti, nella sua cultura e interesse onnivoro per l’umana conoscenza, Leon Battista Alberti rappresenta a pieno titolo “l’uomo universale del primo Rinascimento”.

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