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Science

A combined approach for a modern hydrogeological mapping: the case study of Tennacola stream catchment (central Apennine, Italy)

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ABSTRACT
The current European water legislation, specifically the one addressed to groundwater for human consumption (EU Water Framework Directive, WFD-2000/60/EC), provides clear indications on the objectives and actions to be taken for the proper management and protection of water resources. In Italy, as well as in other countries of the EU, the implementation of this Directive, in the face of an adjustment of the legislation at national level, is still far behind, as regards the obligations on the part of local administrations. Among the reasons there is a lack of cognitive tools, adequate and, above all, univocally accepted by the scientific point of view. The hydrogeological mapping here presented, which covers an area of around 44 km^2 and is edited at 1:10,000 scale, goes in this direction, combining different approaches and methodologies (field surveys, spring hydrograph analysis, surface flow measurements, numerical models …) to arrive at a complete and functional study of an aquifer exploited for drinking purposes.

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Hydrogeological mapping; spring protection zones; central Italy

1. Introduction

Within the countries of the European Community, there is an increasing demand for sufficient quantities of good quality water for all purposes. Since 1995, mostly after the report of the European Environment Agency in which the need for action to protect Community waters in qualitative and quantitative terms has been emphasized (European Environmental Agency [EEA], 1995), the Member States continued to work for an integrated Community policy on water.

The EU Water Framework Directive (European Union (EU), 2000) has been a milestones in this regard, establishing a framework for Community action in the field of water policy.

Among the main provisions (art. 4 and 7), the Directive indicates that the Member States, in order to reach ‘good status’ objectives for water bodies, shall put in place all the necessary actions to manage groundwater in a sustainable way, within 15 years after the entry into force of the directive itself (Voulvoulis, Arpon, & Giakoumis, 2017). Among the requirements:

- prevent or limit the input of pollutants into groundwaters;
- prevent the deterioration of the status of all bodies of groundwaters;
- protection, enhancement and restoration of all bodies of groundwaters.

At today, not all the Member States, including Italy, have followed the requests, or they have partially answered (Kanakoudis & Tsitsifli, 2010). The WFD recognizes that the achievement of good status might take more time in some water bodies. For this reason, it allows Member States to extend the deadline up to 2027 or beyond (European Union (EU), 2000; European Commission [EC] 2012).

In Italy, the Directive has been partially implemented through the Legislative Decree n.152 of 3 April 2006 (Italian Government, 2006). With the art. 64, the Decree has divided the national territory into eight Hydrographic Districts and provided for the drafting of a management plan for each District, assigning the respective competence to the river basin District authorities. Only some Districts have complied with the expected requirements within the established date (i.e. studies about the current and future availability of groundwater resources and/or delimitation of the safeguard areas of springs and well fields exploited for drinkable uses) and many of them with different approaches and methodologies (Bald, Borja, Muxika, Franco, & Valencia, 2005; Richter, Völker, Borchardt, & Mohaupt, 2013). The ‘Hydrographic District of central Italy’, where the test area chosen for the present work is located, is among these and many studies supporting these investigations are still being completed.

Hydrogeological mapping studies in this sector of central Italy, among other things, are not very frequent

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due to the lack of data and to the difficulty to carried out new surveys in relation to the legislative constraints. Celico (1978, 1983) investigated the study area via field surveys, mechanical prospections and geophysical analysis. Investigations identify and quantify the groundwater resources at a regional scale. Later, Boni, Bono, and Capelli (1986) use a quantitative approach to characterize the karst basin, via groundwater balances. Tarragoni, Martarelli, Pierdominici, Roma, and Boni (2011) edited an experimental hydrogeological map on fractured aquifer domains at 1:50,000 scale, basing on the results of Boni et al. (1986).

The present work wants to provide a methodological contribution to these studies by proposing a model of hydrogeological mapping that integrates some of the most common approaches in the study of groundwaters, to arrive at a scientifically reliable tool, easily readable by administrators and technicians. Such a document is very effective if used, as in this case, in an area subject to naturalistic and landscape restrictions, because located within a National Park (the Sibillini Mountains National Park) where tracers (natural and/or artificial) or invasive methodologies (monitoring wells, piezometers … .), considered dangerous for the environment, become impossible to use. Besides, in the study area as well as in other region of Italy and in several countries the Mediterranean basin a large part of drinkable sources are springs fed by non-Darcian aquifers (i.e. karst and carbonate) located in complex mountain hydro-structures (Bakalowicz, 2015; Fiorillo et al., 2015); in this context, the presence of lithological and tectonic barriers as well as an highly heterogeneous permeability makes it very difficult to create a reliable 3D hydrogeological model. For such reason the study was based on a solid reconstruction of the water budget through detailed field surveys, fracturing networks studies, river flow measurements and advanced analysis of spring hydrographs.

Concerning the qualitative aspects, specifically those aimed at the protection of groundwaters, a methodology for the definition of the aquifers vulnerability degree to pollution and a preliminary delimitation of the Springs Protection Areas, based on a mixed hydrogeological-temporal approach, is also applied. The method, starting from the work of Civita (2008) based on the recession curve analysis, has been already tested by other authors in several contexts of northern and central Italy (Biava, Consonni, Francani, Gattinoni, & Scesi, 2014; Menichini et al., 2015) and tries to bring reliable situations where field test data are not available.

2. Study area

2.1. Geological setting

The study area (about 44 km^2) is located in the north-east sector of the Sibillini Mountains and encompasses an entirely mountainous territory between Mt. Sassotetto (1625 m a.s.l.) to the north and Pizzo Tre Vescovi (2091 m a.s.l.) to the south. Particularly, the area involves the mountain portion of the Tennacola stream catchment between Mount Valvasseto (1526 m a.s.l.) and Mount Castel Manardo (1977 m a.s.l.) and partially falls within the *Sibillini Mountains National Park* which, with an extension of about 700 km^2, is the second largest in central Italy (Figure 1).

The present landscape is characterized by the presence of medium-high reliefs (Figure 1). The fluvial system, generated deep and narrow valleys bordered by steep slopes: in this context, rare and thin are the continental deposits, almost always associated to periglacial, gravitational or fluvial morphogenesis (Aringoli et al., 2015).

Concerning the bedrock, all the outcropping formations belong to the *Umbria-Marche Succession* (Centamore & Deiana, 1986; Cosentino, Cipollari, Marsili, & Scrocca, 2010; Pierantoni, Deiana, & Galdenzi, 2013), a sedimentary sequence consisting of limestones, marly limestones and marls interested since early Pliocene by an east-verging compressive tectonics followed by extensional tectonics and uplifting started at the end of early Pleistocene (Calamita & Deiana, 1988; Pierantoni et al., 2013). The *Succession* testifies the Jurassic transition between a platform sequence (Calcare Massiccio Fm.) to a basinal sequence (Corniola Fm., Bosso Fm. and Calcari Diasprigni Fm.), as well as condensed sequences (Buganore Fm.) lying on high tectonics reliefs. Basinal sequence continues through the Cretaceous and Tertiary with an alternation of limestone and marls (Maiolica Fm., Marne a Fucoidi Fm., Scaglia Bianca Fm., Scaglia Rosata Fm., Scaglia Cinerea Fm. and Schlier Fm.). Tortonian sandstone and clays uniformly cover the sequence (Schlier Fm. and Flysch della Laga Fm.) (see the Main Map for more details).

2.2. Hydrogeological setting

The presence of lithotypes with different degree of permeability (for both the lithological characters and the different state of fracturing), generated three main aquifer complexes, alternated with low permeability formations (aquicludes or aquitards) (Figure 2). The most important is the *Basal aquifer complex*, made by the *Calcare massicio* and the *Corniola* formations and limited at the base by an impermeable evaporitic member of Triassic age, the *Anidriti di Burano* (Centamore & Deiana, 1986), made by alternances of dolomitic limestones, dolomites and evaporites. This complex hosts the regional basal aquifer of the central Apennines and feeds, by the linear streambeds (Boni et al., 1986), the major rivers which cut the Apennine chain in E-W direction.

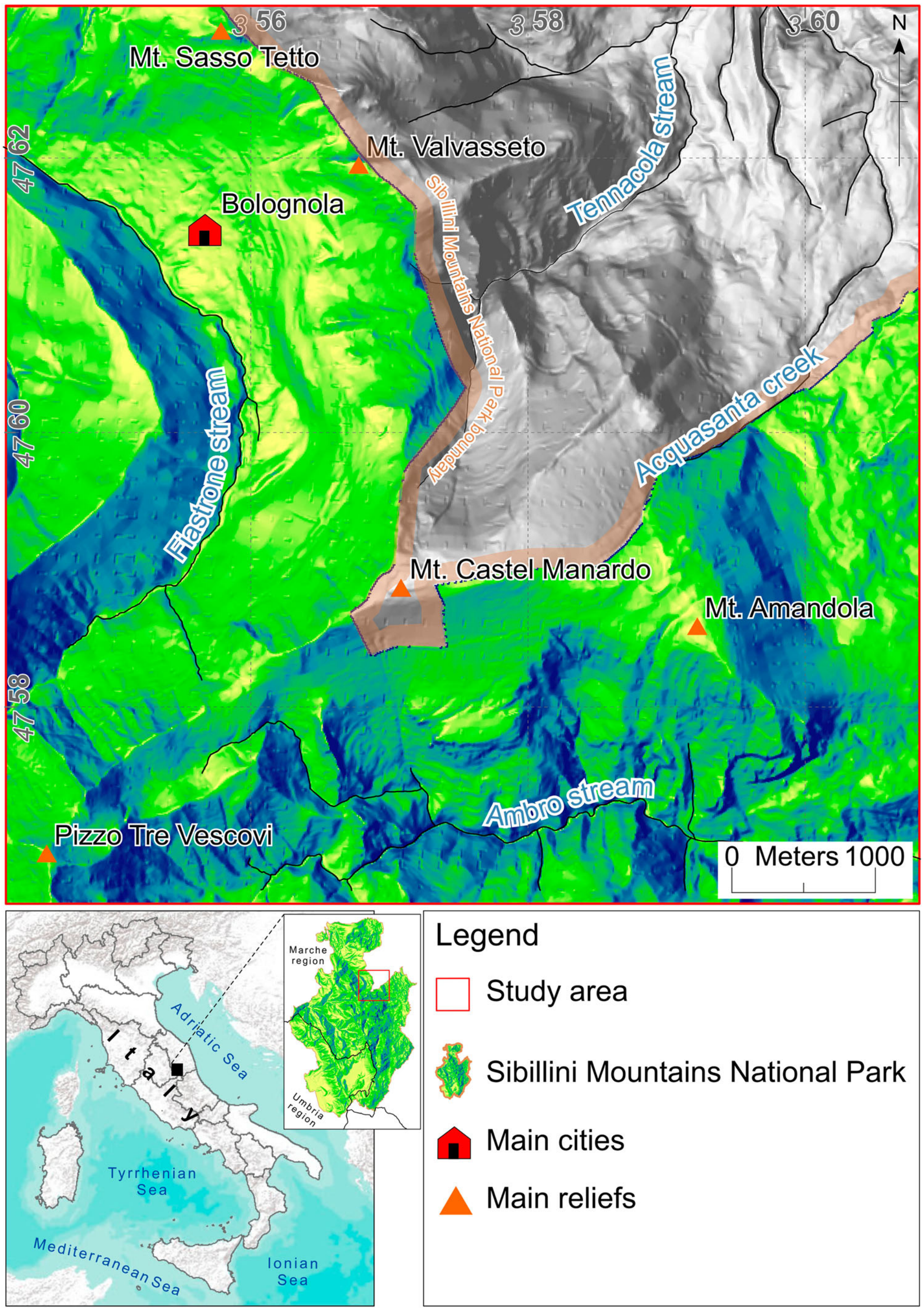


Figure 1. Geographic framework of the study area.

Proceeding upward in the succession (Figure 2), two other aquifer complexes, *Maiolica* and *Scaglia calcarea*, are found in this order: they may constitute important reservoirs, but show usually a minor and irregular discharge.

Finally, the presence of tectonic elements with different hydrogeological behavior (i.e. as flow/no-flow boundaries) and the presence, locally, of more or less intense karst processes, can lead to the formation of local aquicludes/aquitards or create, on the other hand, hydraulic connections between different aquifer complexes (Boni et al., 1986; Nanni, 1991).

The geological formations of the Umbria-Marche succession are characterized by a typical chemistry allowing to formulate hypotheses on the hydrogeological circulation within different hydrogeological complexes (Nanni, 1991). Consequently an enrichment in specific elements could be related to a flow mixing from different aquifer structures; enrichments in sulphates and magnesium ions may in fact be associated to a deeper circulation that affects the dolomitic-anhydritic basement of the Umbria-Marche succession (Banzato et al., 2016; Nanni, 1991).

The study area, which includes the mountain portion of the Tennacola river catchment from the watershed to the outlet located at an elevation of around 700 m a.s.l., is part of a larger hydrostructure elongated circa N-S (Boni, Baldoni, Banzato, Cascone, & Petitta,

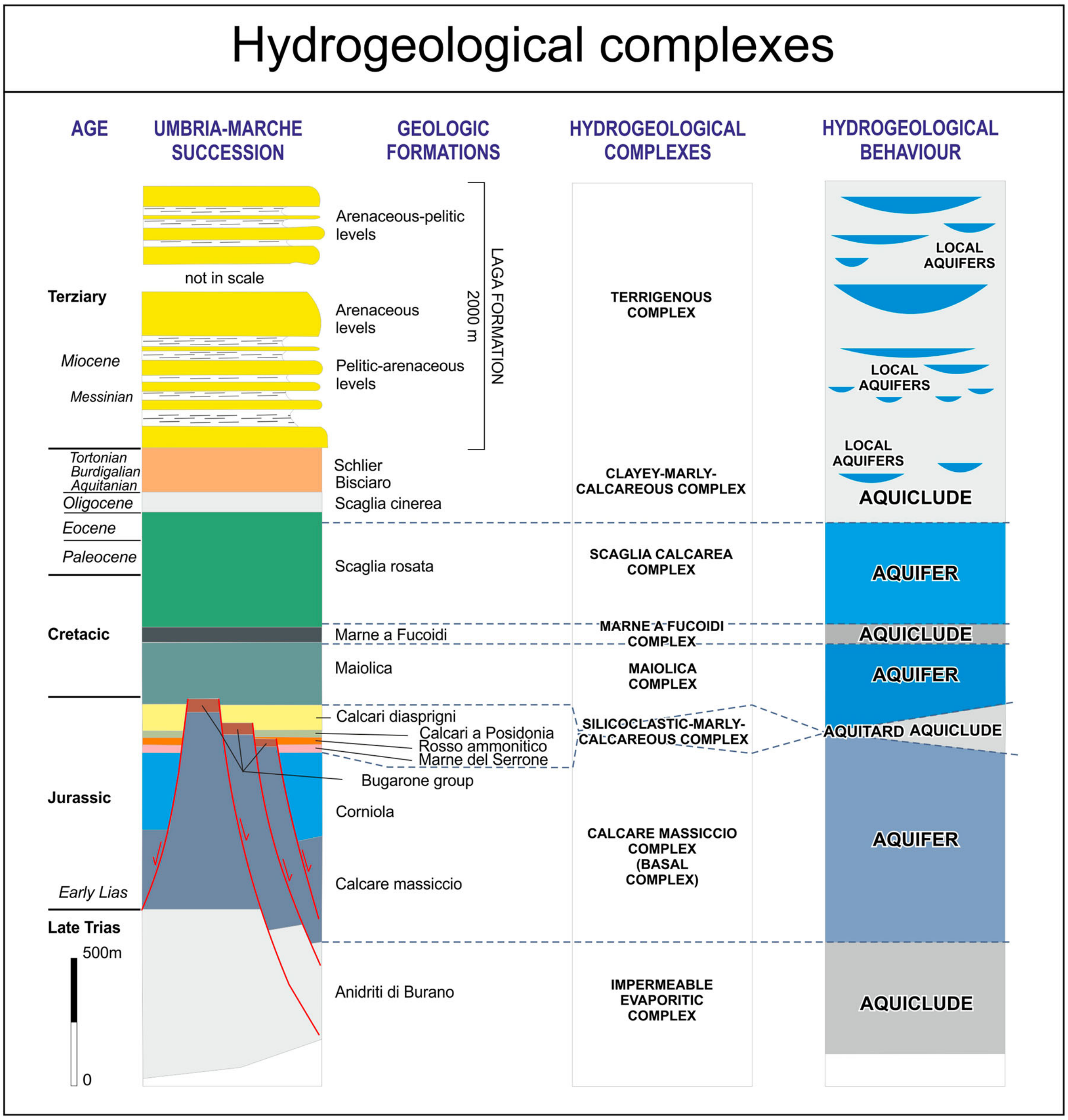


Figure 2. Hydrogeological complexes of the Umbria-Marche succession (modified from Giacopetti et al., 2016b).

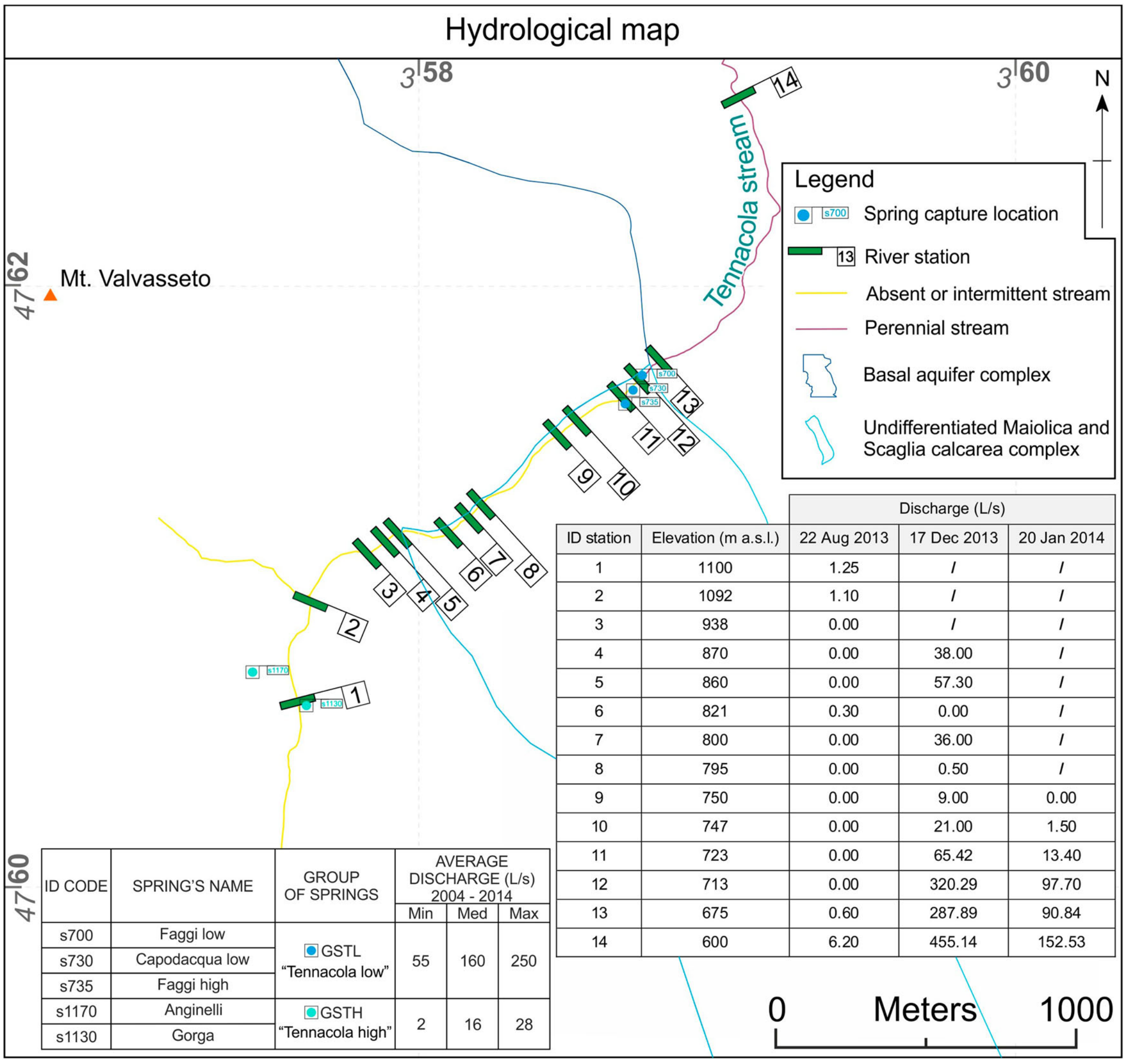
2010) and limited to the east by the thrust of the Sibillini Mountains (which realizes the contact between the calcareous complexes and those terrigenous present outside the Apennine chain) and to the west by extensive Jurassic tectonic elements, reworked in compressive tectonic regime; these latter act as more or less confining hydraulic barriers (Pierantoni et al., 2013). According to Boni et al., 2010, the hydrostructure is fully fed by the basal flow which is directed towards the northern sector; the hydraulic gradient within the hydrostructure ranges between 50‰ and 85‰ (Boni & Petitta, 2007).

The upper portion of the Tennacola stream catchment hosts several important springs exploited for drinking water supply and located at a different elevation with respect the thalweg. For their location and basing on the respective hydrogeological characteristics, they can be grouped as follows (Figure 3):

- Group of springs 'Tennacola high' (GSTH) (mean annual discharge – 16 L/s);
- Group of springs 'Tennacola low' (GSTL) (mean annual discharge – 160 L/s).

All the springs show an extremely variable discharge, ranging from few to hundred L/s. The GSTH daylights in the uppermost portion of the basin at the contact between the fractured formation of *Calcari Diasprini* and the underlying low permeability formation of *Calcari a Posidonia* (*silicoclastic-marly-calcareous complex*). More in detail, the group is composed of two different point springs, 'Anginelli' and 'Gorga', located respectively on the hydrographic left and right (Figure 3); the emerging waters are collected on two different tapped structures but measured together at a collector placed downstream.

The GSTL, on the other hand, is made by several emergencies located at a different elevation on the



ID station	Elevation (m a.s.l.)	Discharge (L/s)		
		22 Aug 2013	17 Dec 2013	20 Jan 2014
1	1100	1.25	/	/
2	1092	1.10	/	/
3	938	0.00	/	/
4	870	0.00	38.00	/
5	860	0.00	57.30	/
6	821	0.30	0.00	/
7	800	0.00	36.00	/
8	795	0.00	0.50	/
9	750	0.00	9.00	0.00
10	747	0.00	21.00	1.50
11	723	0.00	65.42	13.40
12	713	0.00	320.29	97.70
13	675	0.60	287.89	90.84
14	600	6.20	455.14	152.53

ID CODE	SPRING'S NAME	GROUP OF SPRINGS	AVERAGE DISCHARGE (L/s) 2004 - 2014		
			Min	Med	Max
s700	Faggi low	● GSTL "Tennacola low"	55	160	250
s730	Capodacqua low				
s735	Faggi high				
s1170	Anginelli	● GSTH "Tennacola high"	2	16	28
s1130	Gorga				

Figure 3. Hydrological map of the spring groups studied.

hydrographic right of the Tennacola catchment, between 700 and 735 m a.s.l. (Figure 3). It daylights at the contact between the *Scaglia* aquifer complex and the *Scaglia Cinerea* aquiclude (see the cross sections on the Main Map).

Less important in this portion of the basin is the role of continental deposits (slope and alluvial), covering limited areas and characterized by low thickness. Only in correspondence with the GSTL tapped work and in the area close to the thrust, such deposits may create small aquifers or affect the runoff (Figure 4).

3. Material and Methods

The hydrogeological map (Main Map) has been edited at a scale of 1:10,000. The basic topography was derived simplifying and adapting the national topographic map at 1:25,000 scale edited by the Italian Military Geographic Institute (Istituto Geografico Militare [IGM], 1992). The WGS84 datum is adopted, and the metric coordinates reported within the map refer to the UTM 33N Projection Zone.

The hydrogeological symbols adopted are partly based on the recommendations of the Italian Official Guidelines for Hydrogeological Surveys and Representation (Mari, Motteran, Scalise, Terribili, & Zattini, 1995), edited by the Italian Geological Survey and inspired by past experimental maps and proposals of implementation (La Vigna et al., 2016; Roma & Vitale, 2008; Tarragoni et al., 2011). In particular, different lithotypes were grouped in hydrogeological complexes by considering their relative permeability and their role according to groundwater circulation within the study area. The areal symbols for their representation adopt light to dark brown colors for medium-high permeability complexes and greenish to grayish colors for low and negligible permeability complexes (Main Map). A specific symbology, overlapping the areal symbol, was adopted where the complex showed a double behavior.

The hydrogeological survey in the study area and the data collection as a whole have been carried out in the period encompassing October 2012 and June 2014. For the location of all the hydrological and hydrogeological elements a 'Geomax' total station,

Figure 4. The image describes the hydrogeological configuration around a captation of the GSTL in two different period. On 22 August 2013 the Tennacola stream was dry; the piezometry was probably below the current thalweg, drained by the thicknesses of continental deposits covering the riverbed. On 17 December 2013 the Tennacola stream showed an increase of discharge probably due to the snow melting contribute and/or influence exerted by the Basal aquifer complex.

based on both GPS and GLONASS Satellite Navigation Systems, has been used.

Climatological analyses have been conducted elaborating rainfall, snowfall and temperature data from 16 weather stations provided by the Regional Civil Protection Agency of the Marche Region. In the Main Map the spatial distribution of the main parameters (rainfall, temperature, evapotranspiration, effective rainfall) within the study area have been described. The study area is characterized by an Apenninic-Adriatic regime with rainfall almost uniformly distributed throughout the year; Highest values are recorded late in Autumn and during spring while lowest one, in July and January. The total annual precipitation often exceeds 1500 mm with the 1000 mm isohyet encompassing the whole mountain area. A snowy contribute from November to April is also present; quantity and persistence of snow increase with the altitude (Fazzini & Giuffrida, 2005). More in particular, in the study area, effective rainfall (Main Map) ranges from about 600 m/y to about 1200 m/y; assuming a negligible runoff in the study area (Boni et al., 1986; Giacopetti, Crestaz, Materazzi, Pambianchi, & Posavec, 2016b) and a highly fracturing of the outcropping lithologies, the value of the effective infiltration can be assumed as equal to the effective rainfall.

Spring discharge data, which covers a time span of around 10 years with a weekly frequency, have been kindly provided by the Tennacola Water Consortium, which is the managing company of the water plants. The captured springs are represented in the map with a light blue circle inside a black square; not captured or not investigated springs are described using a simple light blue circle. The size of symbols is proportional to the average discharge of each spring (see the Main Map).

Geochemical data for both the groups of springs, come from unpublished data collected by Baggio Compagnucci (2008) and consist of a single sampling carried out in July 2008. In the Main Map the above mentioned data were displayed using Piper's and Schoeller's diagrams.

Concerning runoff measurement, a preliminary monitoring of fluvial discharge has been carried out along the uppermost portion of the Tennacola stream catchment, between the watershed and the outlet located at an elevation of around 600 m a.s.l., at the transition between the calcareous ridge and the terrigenous lithotypes. This monitoring was developed by three campaigns of measurement between August 2013 and January 2014, in correspondence of 14 river stations (Figure 3); however, during December 2013 and January 2014 it was not possible to collect data on the first three and on the first eight stations respectively (located in the uppermost portion of the Tennacola stream catchment) due to snow avalanche hazard and/or to bad weather conditions. Stream flow measurements have been collected by a USGS Type AA Current meter, after a detailed geometric reconstruction of the river cross sections.

Finally, the main groundwater flow (basal), hosted within the *Basal aquifer complex*, and that related to GSTH and GSTL have been reconstructed integrating new field surveys (i.e. fluvial discharge monitoring and geological-structural surveys), hydrogeological cross sections interpretation and bibliographic data (Boni et al., 2010; Boni & Petitta, 2007). The piezometric field of the *undifferentiated Scaglia calcarea and Maiolica aquifer* was derived by numerical analyses and hydrogeological cross sections (Giacopetti et al., 2016b). All the elements related to the *Basal aquifer complex* were described in the map (Main Map) with a dark blue, on the other hand a sky blue was adopted for the *undifferentiated Scaglia calcarea and Maiolica aquifer*. Four hydrogeological cross sections (Main Map) have been realized in order to describe the groundwater circulation within the study area; the saturated portion of the aquifers has been here represented using a specific symbol.

Concerning the GSTL and GSTH, a preliminary definition of the Spring Protection Zones was carried out using a mixed temporal-hydrogeological approach, developed starting from the methodology proposed by Civita (2008) for fissured/karst aquifers.

4. Results

4.1. Spring hydrograph analyses and water budget

Spring hydrograph analyses referred to the period 2004–2014 (Main Map) and performed using the Maillet equation (Maillet, 1905) and the MRC methodology (Posavec, Bačani, & Nakić, 2006; Posavec, Giacopetti, Materazzi, & Birk, 2017; Posavec, Parlov, & Nakić, 2010), have been carried out in order to evaluate the main hydrological features of the GSTH and GSTL (Giacopetti, Materazzi, Pambianchi, & Posavec, 2017). The analysis of individual recessions periods showed substantial homogeneity of the recession constants (α), which range between $4.2{\cdot}10^{-3}$ and $8.0{\cdot}10^{-3}$ (average value $6.0{\cdot}10^{-3}$) for the GSTL and between $1.0{\cdot}10^{-2}$ and $2.0{\cdot}10^{-2}$ (average value $1.3{\cdot}10^{-2}$) for the GSTH, confirming the results obtained by the application of the MRC method (see the spring hydrograph analyses in the Main Map).

Starting from the spring hydrograph analysis, a water budget for the same time span (2004–2014) was developed (Giacopetti, Aringoli, Materazzi, Pambianchi, & Posavec, 2016a) for both the groups of springs (Main Map), applying the methodology described by Korkmaz (1990).

The analysis of the water budget evidenced a weak correlation between the peaks of spring discharge and peaks of rainfall (Giacopetti et al., 2017). It demonstrates the important role of the dynamic reserves (the volume of water stored at the end of the period of recession) mostly for what it concerns the GSTL; the average renewal rate (T_{rn}) (the percentage of the resource renewed during one hydrological year as an effect of real infiltration) here shows a value of 56% while is higher (82%) for the GSTH.

Quite interesting is also the delay time expressed in days, that indicates the period of time for which the system would be able to supply a continuous flow at the minimum rate, in the absence of replenishment by infiltration (Civita, 2008). The analysis gave a mean value of 160 days for the GSTL and 92 days for the GSTH, indicating a good capacity of both systems to overcome periods of drought.

Comparative analysis between total volumes delivered by the springs and hydrogeological cross sections, made possible to define also the possible geometry and size of the recharge areas, which is about 3.8 km^2 for the GSTL and 1.08 km^2 for the GSTH. The reconstruction for the GSTL has been also verified by a numerical model developed using the software FEFLOW (Giacopetti et al., 2016b).

4.2. Aquifers geometry and groundwater pattern

Groundwater circulation in the study area can be split onto two distinct levels: a slower and deeper circulation, linked to the basal aquifer, and a more superficial one, closely connected to the upper aquifer complexes (*Maiolica* and *Scaglia calcarea*). Hydrochemical analyses (Main Map) confirm the presence of calcium bicarbonate facies for both GSTH and GSTL, with enrichment in sodium, potassium, chlorine ions and medium-low values for sulphates and magnesium. Although these characteristics are typical of groundwater circuits inside the formations of the *Maiolica* and *Scaglia calcarea*, the GSTL shows values of sulphates and magnesium slightly higher than the GSTH, highlighting a possible flow mixing from different aquifer complexes. A chemical analysis of one water sample taken from the source area of the Aso river during July 2009 (Banzato, 2014; Banzato et al., 2016) has been considered to the present work to make a comparison with the GSTL (Main Map). The source of the Aso river, emerging from the *Basal aquifer complex*, is characterized by an enrichment of sulphate and magnesium ions respectively with values 6 and 20 times higher than those collected from the GSTL. The available samples of the springs studied are both useful in order to give a preliminary characterization of their chemical composition; of course a single sample of water cannot be fully representative of the spring recharge system, but the comparison with the sample of the source of the Aso river (fully feed by the *Basal aquifer*) can be useful in order to add information about the hypothesis of a partial feeding by the *Basal aquifer* for the GSTL (Giacopetti et al., 2016b).

The results of the spring hydrograph analyses and the water budget, described in the previous paragraph, allowed to confirm the main hydrogeological features of the geological formations involved in the groundwater circulation (Giacopetti et al., 2017).

The GSTH is probably characterized by the presence of lithotypes with well-interconnected joints, resulting in a small recharge area and rapid emptying of the reservoir.

The GSTL is composed by the *Maiolica* and *Scaglia calcarea* formations characterized by a pervasive fracturing and a low permeability matrix, allowing the gradual release of water over time and, as a consequence, slower emptying of the reservoir.

For both cases, the presence of conduits, associated with typical karst systems, cannot be ruled out, even though its evaluation requires more data (Ford & Williams, 2007).

Concerning the uppermost groundwater flow, the interpretative cross-sections shown in the hydrogeological map (Main Map), evidence how the recharge to the GSTH comes from the *silico-marly calcareous complex*, here with the role of aquifer/aquitard, highly fractured and with a low presence of marly levels, and partially from the *Maiolica* complex.

On the other hand, the feeding of the GSTL can be mainly associated to a recharge area constituted by the *undifferentiated Scaglia calcarea and Maiolica aquifer*. The *Scaglia* and the underlying *Maiolica* aquifer, which are here stratigraphically reversed, form a unique hydrogeological complex and are hydraulically connected for the reduced thickness of the *Marne a Fucoidi* low permeability formation interposed in between; this formation is partially elided or absent because of the effects of the compressive tectonics and the presence of the thrust planes (Main Map).

Nevertheless, as above stated, Giacopetti et al., 2016b have hypothesized, in the north-eastern sector, the presence of limited drainance phenomena (Figure 5); more in detail, a mean annual contribution of around 11.7 Mm^3/y (corresponding to 20% of the mean annual

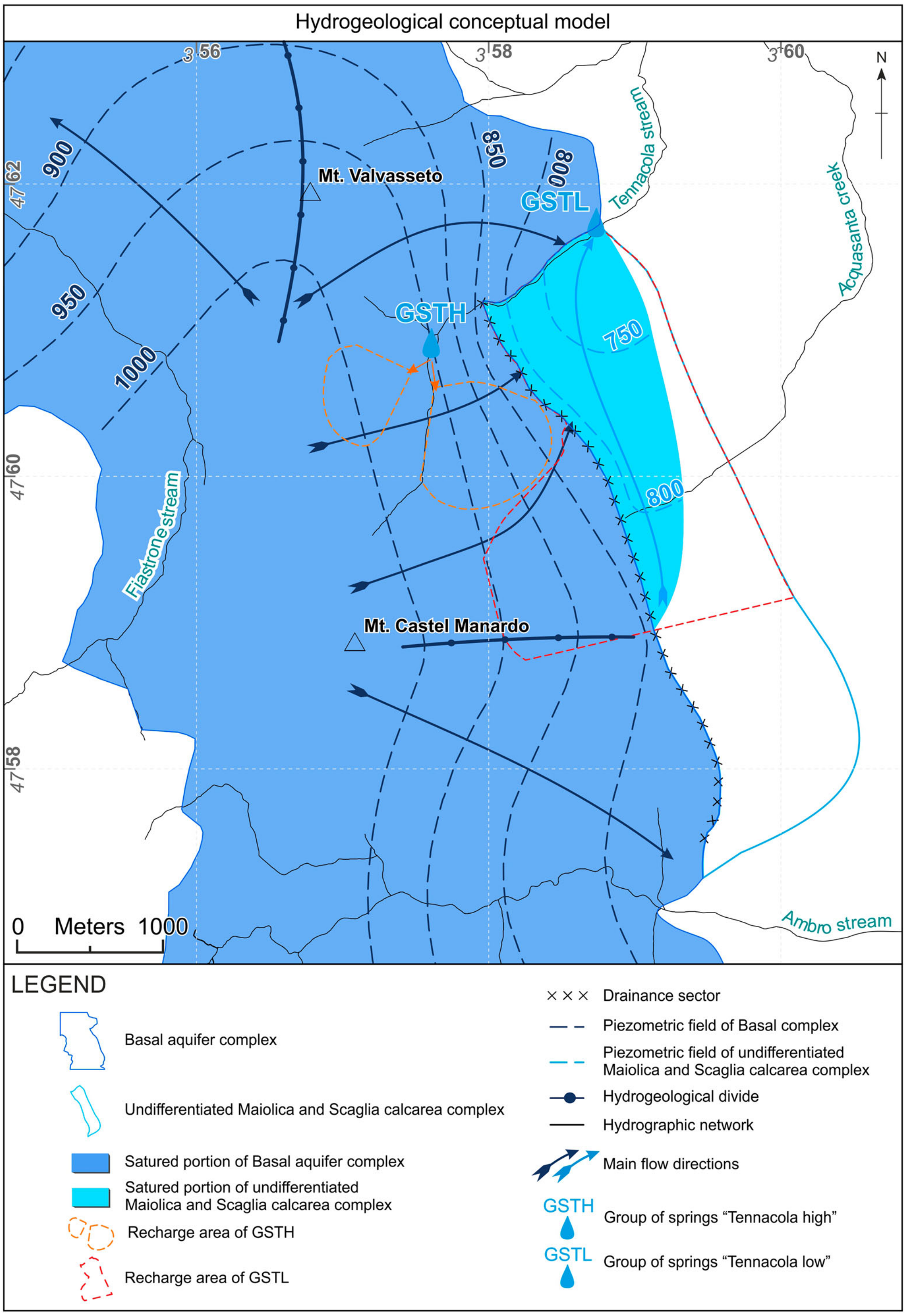


Figure 5. Hydrogeological conceptual model of the spring groups studied.

discharge) coming from the *Basal aquifer* has been hypothesized (Giacopetti et al., 2016b).

The spring hydrograph analysis (Main Map) evidenced also an increase in the slope of the recession curve probably associated with snow melting contribution and/or influence exerted by the Basal aquifer, as mentioned previously (Giacopetti et al., 2017).

The fluvial discharge surveys (Figure 3) carried out over the years 2013–2014 highlighted, in the monitored stations, a high discharge variability along the river bed; the river is almost dried in August, while shows significant increases in December and January.

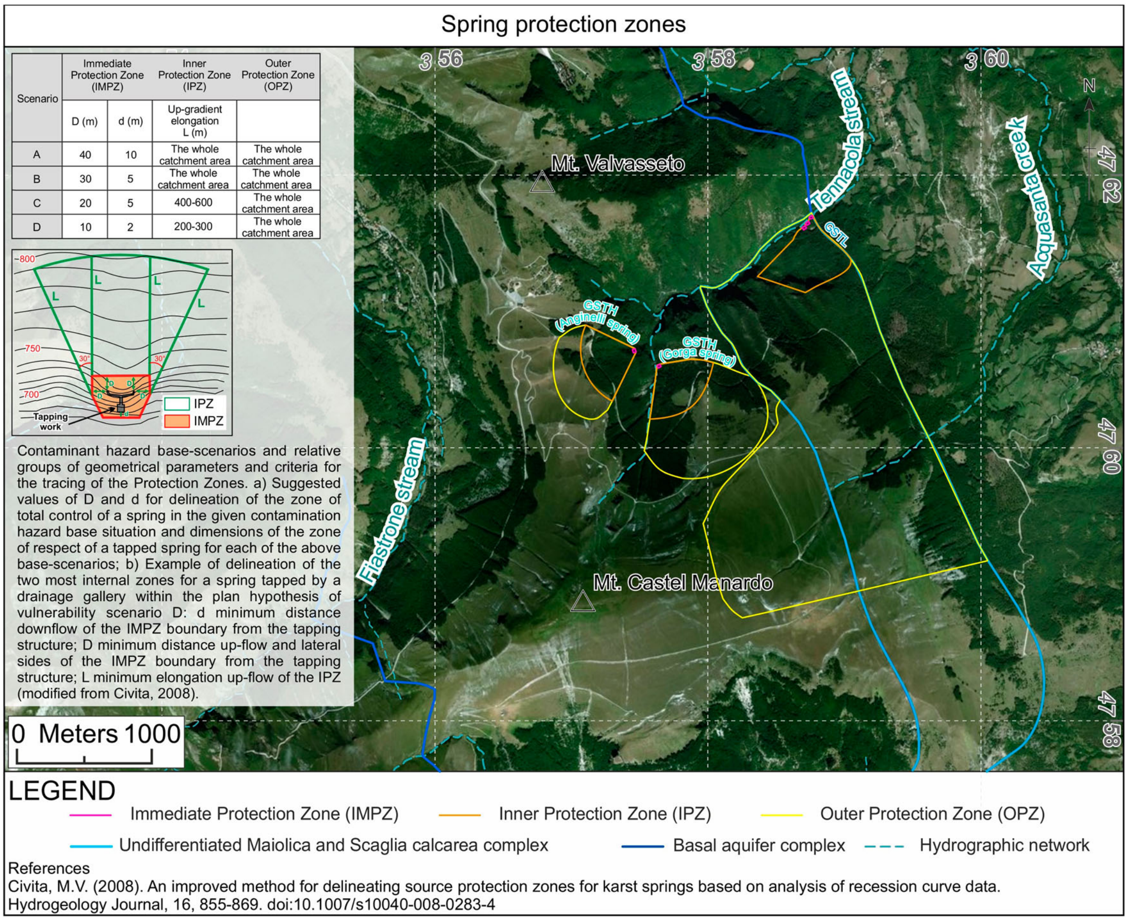
4.3. Spring protection zones definition

The method of Civita (2008), here adopted for the definition of the Springs Protection Zones for both GSTH and GSTL, takes into consideration the annual maximum discharge half-time (MDHT) of the spring (Civita, 2008); this is an easily recordable parameter which can be related to the mean time of propagation of a generic hydro-conveyed pollutant towards a spring without any attenuation. Depending on the MDHT, four contaminant hazard base-scenarios, associated with as many groups of geometrical parameters and criteria for the tracing of the relative Protection Zones, can be identified (Figure 6).

Basing on this method and the related nomographs (Civita, 2008), and after a careful choice of the best representative recession periods during the years, the class C (MDHT ranging from 20 to 50 days) for both the GSTL and the GSTH has been obtained and three Protection Zones have been delineated:

1. an Immediate Protection Zone (IMPZ), considered the one with the highest defence, with a minimum distance of 5 m down-flow of the boundary from the tapping structure and a minimum distance of 20 m up-flow and lateral sides of the boundary from the tapping structure;
2. an Inner Protection Zone (IPZ), strictly based to the time of travel of a generic contaminant, with a minimum elongation of 400 m up-flow, according to an arc of circumference of about 60°;
3. an Outer Protection Zone (OPZ), outlined with a hydrogeological criterion and which includes the entire recharge area of the aquifer (around 3.8 km^2 for the GSTL and 1.08 km^2 for the GSTH).

The definition of Protection Zones automatically will provide for the imposition of restrictions on the


Spring protection zones

Scenario	Immediate Protection Zone (IMPZ)		Inner Protection Zone (IPZ)	Outer Protection Zone (OPZ)
	D (m)	d (m)	Up-gradient elongation L (m)	
A	40	10	The whole catchment area	The whole catchment area
B	30	5	The whole catchment area	The whole catchment area
C	20	5	400-600	The whole catchment area
D	10	2	200-300	The whole catchment area

Contaminant hazard base-scenarios and relative groups of geometrical parameters and criteria for the tracing of the Protection Zones. a) Suggested values of D and d for delineation of the zone of total control of a spring in the given contamination hazard base situation and dimensions of the zone of respect of a tapped spring for each of the above base-scenarios; b) Example of delineation of the two most internal zones for a spring tapped by a drainage gallery within the plan hypothesis of vulnerability scenario D: d minimum distance downflow of the IMPZ boundary from the tapping structure; D minimum distance up-flow and lateral sides of the IMPZ boundary from the tapping structure; L minimum elongation up-flow of the IPZ (modified from Civita, 2008).

LEGEND
Immediate Protection Zone (IMPZ)
Inner Protection Zone (IPZ)
Outer Protection Zone (OPZ)
Undifferentiated Maiolica and Scaglia calcarea complex
Basal aquifer complex
Hydrographic network

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Civita, M.V. (2008). An improved method for delineating source protection zones for karst springs based on analysis of recession curve data. Hydrogeology Journal, 16, 855-869. doi:10.1007/s10040-008-0283-4

Figure 6. Spring Protection Zones for both the spring groups studied.

territory; these restrictions, in Italy, have been regulated within the art. 94 of the Legislative Decree n.152 of 3 April 2006.

5. Discussion and concluding remarks

The hydrogeological map of the upper Tennacola stream catchment (Main Map) represents a step forward towards a more modern concept of hydrogeological mapping, integrating data and information typical of the traditional mapping (i.e. field surveys and/or in situ and laboratory measurements) with the analytical potential provided by numerical models and by the use of Geographical Information Systems.

First of all, it has been designed to let itself easy to use by experts, public administrations and stakeholdersand to represent overlapping information layers: hydro-structures are mapped together with equipotential lines and relative flowpath arrows, water divides and other hydrogeological features.

The reading and identification of the hydrogeological complexes has been improved using a specific abbreviation, resulting particularly useful in situation where the hydrogeological complex shows a double behavior, e.g. the Marne a Fucoidi formation can play the role of aquitard (MFCb) or aquiclude (MFCa) between the Scaglia calcarea and Maiolica aquifer, depending on the structural and tectonic context.

The evaluation of the double behavior of the *silico-clastic-marly-calcareous complex* in the study area was a new important information in the Main Map; a red symbol was adopted to describe the degree of fracturing of the complex in the sector close to the emergence of the GSTH. Moreover the study has evidenced the presence of a drainance sector (described by a black linear element) in between the *undifferentiated Scaglia calcarea and Maiolica aquifer* and *Basal aquifer complex* (Main Map) highlighting a possible hydraulic connection.

All the hydrogeological features have been synthesized in a hydrogeological conceptual model (Main Map) in order to clarify the assumptions at the base of the present work.

The evaluation of the spring protection zones has represented a crucial point of the present study; the application of Civita method has been necessary due to the complex and heterogeneous geological features of the study area. On the other hand, the application of a traditional methodology on the study area, on the other hand, would induce a subjective and simplified interpretation, which does not take into account all the variables involved.

In conclusion, for a modern hydrogeological mapping, a combined approach is all the more fundamental, as in the present work, if used to support the definition of the vulnerability degree to pollution of an aquifer that requires qualitative and quantitative information about the numerous aspects involved (aquifer type, characteristics, direction and velocity of groundwaters, presence of potential sources of pollution …); all this in compliance with the indications provided by the current European water legislation. The hope is that such a modern approach will can provide a baseline for future monitoring in view of an increasingly correct and rational use of water resources, especially when used for drinking water purposes.

Software

All data processing and spatial analysis regarding the map were performed by ESRI ArcGIS software. Cross sections and the final editing of the map were performed using CorelDRAW Graphics Suite.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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