

Reconstruction of the vertical thermal disturbance induced by a groundwater heat pump system (GWHPs): Potential of using a temperature-measuring chain as a monitoring tool

*Original*

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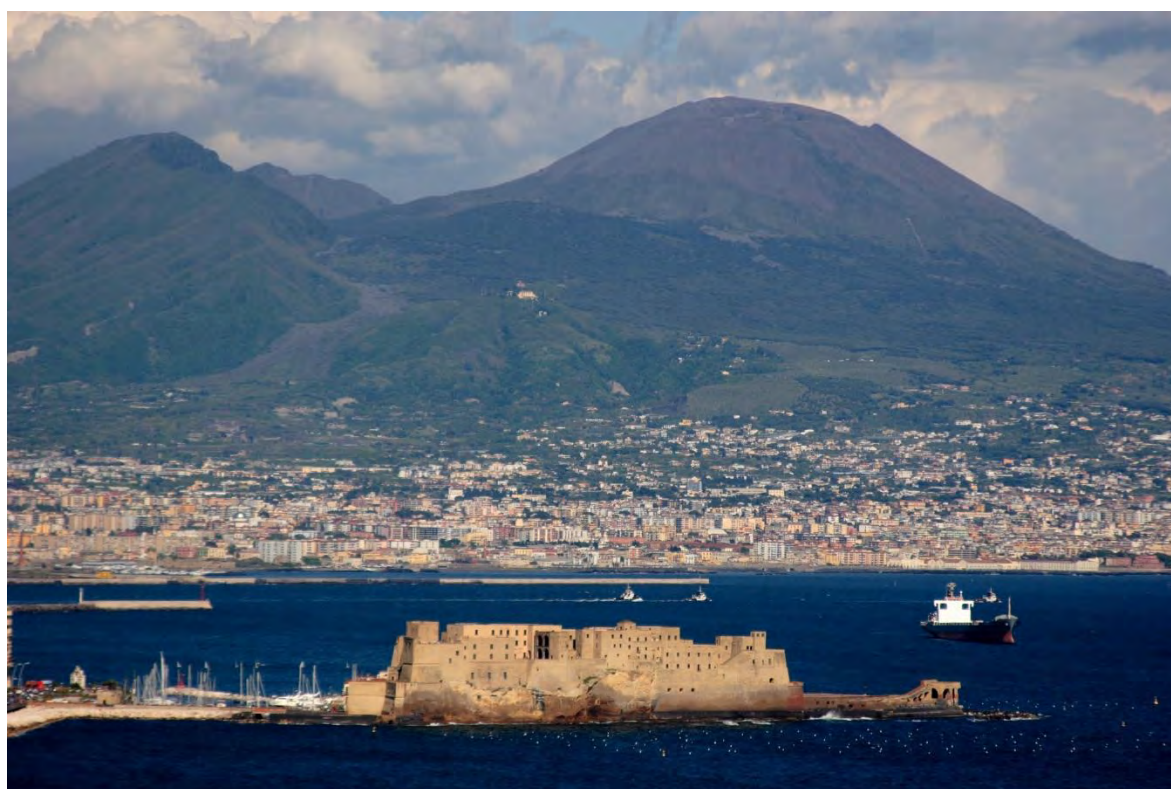
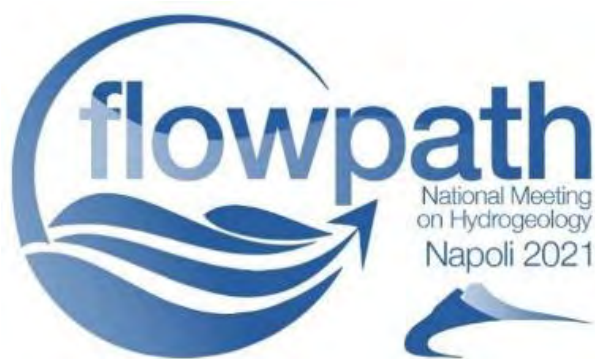
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**5<sup>th</sup> Edition of FLOWPATH**  
**the National Meeting on Hydrogeology**  
**Napoli, 1-3 December 2021**  
**Conference Proceedings Book**

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## Preface

The Italian Chapter of the International Association of Hydrogeologists (IAH) is pleased to present you the abstracts submitted to the 5<sup>th</sup> Edition of FLOWPATH, the National Meeting on Hydrogeology. The congress take place on 1-3 December 2021 in the Monumental Complex of Saints Marcellino and Festo (Historical Centre of Naples).

Following the tradition of the previous editions of FLOWPATH, the conference is an opportunity for hydrogeologists and professionals to exchange ideas and discuss different issues on groundwater resources.

The preparation of the 5<sup>th</sup> Edition of FLOWPATH hardly involved the Organizing Committee, with the full-time effort of the Chairs and the Local Organizing Committee, testified by numerous meetings (more than monthly, since 2020) and activities.

The objectives of the conference are:

- to promote dialogue and exchange of scientific knowledge among young hydrogeologists;
- to deepen the theoretical and practical aspects of our understanding of groundwater in a changing climate;
- to update all the stakeholders, researchers and professionals on recent challenges in the hydrogeological sciences;
- to encourage researchers, professionals and administrators to contribute to the improvement of a sustainable water resources management.

The congress has been structured into four sessions, i.e.:

Session 1 - Climate change and groundwater

Session 2 - Groundwater Resource and Sustainability

Session 3 - Geothermal, Urban and Contaminant Hydrogeology

Session 4 - Groundwater flow and hydrogeochemical features in volcanic, karst and coastal plain aquifers

Each session starts with a Keynote lecture, held by international experts. The members of the Scientific Committee and the Chairs of the four sessions actively contributed to this successful Congress.

This Conference Proceedings book, including one keynote lecture for each session and 116 total abstracts, represents the final step of this Congress. All these abstracts underwent a rigorous peer-review process by the Scientific Committee members and were assigned to oral (44) or poster (72) presentation. The Authors come from Universities, Public Bodies, Private Companies of Italy and some other countries.

In summary, this congress, with more than 160 participants, testified the interest in groundwater resources and their protection with a view to future challenges in the hydrogeological sciences.

We would thank especially the sponsors and the Organizations offering their patronage, with particular mention to the prestigious UNESCO-IHP, but our thanks are addressed to all people that directly or indirectly contributed to this successful edition of FLOWPATH.

On behalf the organizing committee

Daniela Ducci

Chair of the IAH Italian Chapter

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## Session 1

### Climate change and groundwater

#### **Keynote Lecture:**

*Assessment of climate change impacts on groundwater: Crossing the boundaries of hydrogeology*

Steffen Birk (University of Graz)

#### **Convenors**

Walter Dragoni (*ex* Università degli Studi di Perugia)

Adolfo Mottola (ARPA Campania)

Giovanna De Filippis (AECOM)

## KEYNOTE LECTURE

### **Assessment of climate change impacts on groundwater: Crossing the boundaries of hydrogeology**

Steffen Birk (*University of Graz*)

*As a source of water supply for households, agriculture, and industry, groundwater plays an important role in the adaptation to climate change. Yet, the development of adaptation strategies needs to consider that climate change affects groundwater resources in several ways. On the one hand, climate change alters the water cycle and thus groundwater recharge; on the other hand, human activities aimed at climate change mitigation or adaptation potentially involve impacts on groundwater. One approach to assess climate change impacts is to consider multiple global and regional climate models driven by scenarios of future greenhouse gas emissions and to propagate the model ensemble through impact models, e.g. assessing the resulting effects on the water cycle or groundwater. The uncertainty of the results, however, increases with each step of the model chain such that the outcome might be of limited use in practice. It has thus been suggested to complement this scenario-based, top-down approach by a vulnerability-based, bottom-up approach focusing on the identification and analysis of factors that are relevant for coping with climate change in a given system. Here, I further suggest that model-based approaches should be supported by experimental investigations and historic data analyses. Using lysimeters within controlled experiments provides insights into climate change effects on soil water; this may help reduce uncertainties in recharge estimates needed for groundwater models. Analysis of historic groundwater data provides information about factors controlling groundwater levels; this is needed for vulnerability-based assessments of climate change impacts on groundwater. Thus, hydrogeologists need to cross the boundaries to other disciplines and, at the same time, be inventive in the use of hydrogeological data and methods.*

## Climate and Landscape Effects on Agricultural Soil Losses in Semi-arid Watershed

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**Key words:** Soil erosion, Climate changes, SWAT model.

The assessment of soil erosion rates represents a fundamental tool for land management and planning, since it allows to correctly modify land-use practices finalizing them to a sustainable management in the long-term period (Adhikari and Hartemink, 2016). Therefore, it is necessary to consider all the available climate predictions and their uncertainties. In this study, the SWAT model, which has proved to correctly assess hydrological responses to land use and climate changes (Busico et al., 2020) was utilized to simulate and predict the soil erosion trend within a semi-arid watershed in South Portugal. The model was successfully calibrated and validated using real data of streamflow and river sediment transport. Afterwards, a predicting analysis for the period 2018-2040 was conducted using three climate models and two different emission perspectives (RCP 4.5 and 8.5). Results were extracted and analyzed including those from the four farm sites identified by the Life project “Desert-Adapt”. Despite the high variability due to the climate variation a significative increasing or decreasing trend was not identified on any survey sites. A detailed analysis was conducted for all the sites considering the morphologic, soil and land cover characteristics to identify the more sensitive factor. The result highlighted how soil erosion will be greatly and mainly influenced first from soil, then from morphology, and land cover characteristics despite climate. The study confirmed how the Leptosols category is the soil group most subjected to sediment loss due to its intrinsic characteristics, and how the agroforestry and farmed system will negatively influence soil erosion rate if no anti-erosion action will be adopted (Verheijen et al., 2009). This study highlighted the necessity to identify all aspects responsible for land degradation especially inside those Mediterranean watersheds characterized by highly variable climate condition and very shallow soils to fulfill a sustainable resource utilization.

Adhikari, K., Hartemink, A.E. (2016). Linking soils to ecosystem services – a global review. *Geoderma*. 262, 101-111. doi: 10.1016/j.geoderma.2015.08.009.

Busico, G., Colombani, N., Fronzi, D., Pellegrini, M., Tazioli, A., Mastrocicco, M. (2020). Evaluating SWAT model performance, considering different soils data input, to quantify actual and future runoff susceptibility in a highly urbanized basin. *Journal of Environmental Management*. 266. doi: 10.1016/j.jenvman.2020.110625.

Verheijen, F.G.A., Jones, R.J.A., Rickson, R.J., Smith, C.J. (2009). Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews*. doi: 10.1016/j.earscirev.2009.02.003.



## Meteorological variability and groundwater quality: examples in different hydrogeological settings

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**Key words:** groundwater; monitoring; contamination; climate variability; quality.

Rainfall and temperature variability causes changes in groundwater recharge that can also influence groundwater quality by different processes (Bloomfield et al. 2016). The aim of this study is the analysis of the hydrogeochemical variations in time due to meteorological variability in two different study areas in Italy: an alluvial aquifer in the Piedmont Po plain and an alluvial-pyroclastic aquifer in the Campanian plain.

The examined plains show groundwater with natural quality not satisfying the European drinking water standards, or anthropogenic contamination. The peculiar natural quality is due, in the Campanian plain, to the closeness of volcanic areas, and to the presence of reducing conditions. In Piedmont Plain a test site is characterised by a point-source contamination by heavy metals, due to the presence of past industrial activities. In all the examined areas there is a diffuse nitrate contamination (Ducci et. al. 2019; Lasagna and De Luca, 2019). The fluctuations of the ions As, F, Fe, Mn, Cr VI, NO<sub>3</sub> and Cl were analysed and compared, using statistical methods, with the variations over the time in precipitations, temperature, and piezometric levels, sometimes significant.

Results highlight the importance of the groundwater and meteorological monitoring and the key role of the recharge variation in the hydrogeochemical processes. The linking degree between rainfall/ temperature variability and hydrogeochemistry is variable, in function of the typology of chemical species, their origin and of the aquifer characteristics. The fluctuation of climate variables determinates sudden changes in the geochemistry of shallow unconfined aquifers (e.g. in the Piedmont plain), while semiconfined or confined aquifers (e.g. in the Volturno-Regi Lagni plain) react with a higher delay to these variations. Moreover, natural quality is more affected by climatic variations than anthropogenic contamination, which is the result of multiple environmental and anthropic factors.

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## **Co-occurrence of climatic and post-seismic events depleting groundwater resources of fractured carbonate aquifers of Sibillini Mts. (Central Italy)**

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**Key words:** spring discharge, drought, earthquakes, fractured aquifer, Central Italy.

In 2016, after a seismic sequence which struck the fractured carbonate aquifer of the Sibillini Mts., a prolonged drought period occurred in the same area.

The main effect of the earthquakes on the Sibillini Mt. hydrostructure was a sustained increased groundwater outflow. Multiple changes in water-table and in discharge of the springs occurred lasting more than two years. In the same period, a shortage in rainfall and snow-cover hits the aquifer, causing a decrease in groundwater recharge. The superposition of these events triggered one of the most serious groundwater crisis of the last years, affecting the Sibillini Mts, that is the main source of drinking water supply of the Adriatic coast.

With this work, the spatial and temporal distribution of the drought periods in the Sibillini aquifers has been investigated, to understand how much the last drought period has influenced the current water crisis, independently by the earthquake effects.

The Standard Precipitation Index (SPI) of 20 rainfall stations was calculated since the 1950s, focusing on the analysis of the more intense drought periods identified. Using GIS, the intensities of drought events were spatialized, and their temporal distribution was analyzed with statistical criteria. The results were compared with the springs discharge data provided by the local water suppliers. The discharge dataset is not homogeneous, and it covers a period from 20 to 70 years. The first results suggest that the surplus outflow induced by the earthquake would have exhausted the groundwater resources and partially depleted the groundwater reserves. This resulting condition appears to be comparable with an intense aquifer overexploitation, in which the produced imbalance was additionally enhanced by the simultaneous scarce recharge, caused by the drought period. Nevertheless, the effects on the spring discharges due to these combined causes are consistent with the hydrodynamic and geometrical parameters of the related feeding aquifer.

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# Groundwater-surface water interactions revealed by meteorological trends and groundwater fluctuations on streams discharge

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**Key words:** Aquifer-streams interaction; piezometric level; stream discharge; continuous monitoring; hydro-meteorological trends.

The importance of considering groundwater (GW) and surface water (SW) as a single resource of two interconnected components has rapidly increased during the last decades [1]. In order to investigate GW-SW interaction in aquifers exploited by several wells, an integrated continuous monitoring of the hydrological conditions have been performed. The sub-catchment (14 km<sup>2</sup>) is located in the Aspio basin (Central Italy), it is drained by a small stream and it is characterized by the presence of two aquifers: an unconfined alluvial aquifer and a confined limestone aquifer [2]. The aim of this study is to evaluate the drivers of stream drying up occurred during 2019, by applying a time series analysis on daily rainfall and potential evapotranspiration, piezometric and stream continuous monitoring and monthly pumping rates of wells. The rainfall and temperature trends were analysed over a period of 60 years, while cross correlation and autocorrelation analyses were performed on daily piezometric and stream levels over the last five years. The groundwater table elevation was compared with the baseflow index, highlighting the interconnection between both GW-SW during the years. To explore correlations with meteorological trends SW-GW levels and pumping rates, a correlation matrix and ANOVA tests were performed. The precipitation decrease and the concomitant potential evapotranspiration increase lead to gradual recharge decrease. These analyses support the hypothesis of stream drying up mainly due to decreased recharge. Even though there was an increase of groundwater withdrawals in the last two years, this might not have played a major role since pumping rates increase did not trigger excessive groundwater drawdown. This case study stresses the importance of studying GW-SW interactions in a continuously changing meteo-climatic context characterized by a decreasing precipitation trend, coupling both the advantages of a robust statistical method like time series analysis and the field continuous monitoring.

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## **New hydrogeological assessments on the groundwater dependent ecosystem of the Pilato Lake (Sibillini Mts, Central Italy)**

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**Key words:** Hydrogeology, Groundwater dependent ecosystem (GDE), Pilato Lake, Sibillini Mts, Central Italy.

Due to the endemic presence of the crustaceous *Chirocephalus marchesonii*, the Pilato Lake (Sibillini Mts, Central Italy) was in the past mainly studied from the biological viewpoint, but hydrogeological information on this groundwater dependent ecosystem is scarce.

Hydrogeological activities were conducted in 2018-2020 for verifying the effects on that ecosystem induced by the Central Italy 2016-2017 seismic sequence. Geomorphological evidences of ruptures were not observed in the study area, but only boulders detached from the surrounding slopes.

Furthermore, for investigating the lake drying in the recent 2017, 2019 and 2020 summers, the seasonal lowering of lake levels during 2010, 2012 and 2014-2020 was reconstructed. It resulted that in the pre-seismic years the lake emptying was slower (mean value 0.044 m/g) than in the post-seismic time (mean 0.066 m/g). It is then likely that seismic quaking induced increase of permeability, and consequently of infiltration velocity through the lake sustaining surficial (detrital and glacial) and/or bedrock deposits towards the subsurface. More frequent summer dryings of the lake is then predictable.

The hydrogeological conceptual model of the lake area showed that the refilling process of the lake is driven by snow and rain precipitations (P). The air temperatures during 2018-2019 and their effects on evaporation from lake (E, mean 640-710 mm) and on real evapotranspiration (ET, mean 450-480 mm/a) were estimated. Finally, infiltration through sustaining sediments ( $I=P-R-ET-E$ ; mean 525-510 mm/a; R, runoff is negligible) was calculated.

The bathymetric isolines of the lake area already obtained by drone flights, elevation contour lines of topographic maps and GPS surveys of elevation of lake borders with time. These data recently allowed the estimation with time ( $\Delta t$ ) of lake wet surface (A) and lake volume variations ( $\Delta V$ ), and then bulk permeability ( $K=\Delta V/A \cdot \Delta t$ ) of sustaining sediments was as well valuated ( $10^{-6}$ - $10^{-7}$  m/s).

## **Last century rainfall variations in northern Tuscany (Italy) and possible effects on karstic strategic groundwater**

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**Key words:** climate change, precipitation variability, Apuan Alps, north-western Tuscany.

Climate change is one of the main factors affecting groundwater resources, making an assessment necessary for the future exploitation. Recent past climate changes evaluation requires an extensive and distributed meteorological database. Some of the principal groundwater systems in Tuscany (particularly the karst aquifer systems of the Apuan Alps) are present in its northern part. Also, Tuscany has a densely distributed rain gauges network (some datasets longer than 100 years).

Bartolini et al. (2014) and D'Oria et al. (2017) already identified precipitation reduction and temperature increase in the whole of Tuscany and its northern portion for the last century.

In this work, we investigate the time evolution of rainfall in northern Tuscany in the last century both for quantity and dynamics. The number of rain gauges chosen for this analysis was heavily increased and deeply controlled for datasets continuity and homogeneity.

We studied the precipitation data in terms of mean annual precipitation differences between the periods 1990/2019 – 1921/1950 and 1990/2019 – 1951/1980; detection of trends in the yearly and seasonal precipitation via the Mann-Kendall test; rainfall events variations; spatial distribution of the precipitation trend; changing in single precipitation events extension through the last seventy years. The precipitation reduction, identified in the previous studies, is confirmed and seasonally featured. We highlight variations in the rainfall events for different rain-depth intervals. We estimate the last century annual precipitation decrease to be around 10% of the Mean Annual Precipitation in the past thirty years. However, this variation seems not evenly distributed in the analysed area.

The observed evolution in local hydrological regime represents a serious threat to the strategic karst groundwater of the area, which is sensitive to hydro-climate conditions (Doveri et al., 2019). The precipitation decrease and the change in distribution are already modifying the flow rate and regime in some major karst springs.

Bartolini G., Messeri A., Grifoni D., Mannini D., Orlandini S., 2014. Recent trends in seasonal and annual precipitation indices in Tuscany (Italy). *Theoretical and Applied Climatology*, 118:147–157. <https://doi.org/10.1007/s00704-013-1053-3>.

D'Oria M., Ferraresi M., Tanda M.G., 2017. Historical trends and high-resolution future climate projections in Northern Tuscany (Italy). *Journal of Hydrology*, vol. 555 pp. 708–723. <https://doi.org/10.1016/j.jhydrol.2017.10.054>.

Doveri M., Piccini L., Menichini M., 2019. Hydrodynamic and geochemical features of metamorphic carbonate aquifers and implications for water management: the Apuan Alps (NW Tuscany-Italy) case study. In: *Karst Water Environment: Advances in Research, Management and Policy* (T. Younos, M. Schreiber, K. K. Ficco, Editors). Springer Publishers, pp 209–249 (First Online: 27 May 2018). [https://doi.org/10.1007/978-3-319-77368-1\\_8](https://doi.org/10.1007/978-3-319-77368-1_8).

## Climate-driven groundwater evolution in different types of aquifer systems and climate contexts

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**Key words:** groundwater resources, climate changes, hydrodynamics, hydrometeorological data.

Groundwater represent the safest and most reliable source of drinking water, besides being widely exploited both for agricultural and industrial purposes. Despite their strategic importance, they are very often neither protected nor adequately studied to detect any potential threats, such as those related to anthropogenic or climate changes impacts. Although groundwater are less influenced by climate changes, it is still necessary to understand their response to climatic trends in order to improve the management of groundwater resources.

The aim of this work is to describe the evolution of groundwater tied to climate conditions, by analysing and correlating meteo-climate and hydrodynamic-physical-chemical data in three different types of aquifer systems and geographical contexts:

- The mountain aquifer hosted in the volcanic edifice of Mt. Amiata (SE Tuscany) extending over an area of about 80 km<sup>2</sup>, in the range of altitude 450-1750 m a.s.l., where precipitation (1200 mm/yr on average) is mainly rainfall and secondarily snowfall (Doveri et alii, 2017).
- The aquifer of Pianosa Island (Tuscan Archipelago), which extends for just 10 km<sup>2</sup> in a semi-arid climate due to low annual precipitation (about 500 mm), relatively high atmospheric temperature (about 18 °C on average) and windy conditions (Doveri et alii, 2012).
- The foothill aquifer system developed in the middle-high plain of the Brenta River (NW Veneto), where groundwater is closely connected to the river and consequently to the hydrologic regime of the alpine climate affecting the uppermost sector of the catchment (Sottani & Vielmo, 2014).

The availability of sufficiently large time series data allowed us to adopt an integrated hydrodynamics, physical-chemical and statistical-geostatistical approach, to underline correlation between meteorological parameters and groundwater evolution.

The results showed a general decline of groundwater yield congruently to trends of climate indicators, as well as the possibility to extend our research towards the development of predictive data-driven models concerning groundwater quantity and quality in awaited climate conditions.

Doveri, M., Menichini, M., Provenzale, A., & Scozzari, A. (2017). Groundwater response to climate changes: examples of observed and modeled trends on Tuscany aquifers (central Italy). *Atti del Convegno "XVII Giornata Mondiale dell'Acqua-"Strategie di adattamento alla domanda e alla disponibilità di risorse idriche"*, Accademia dei Lincei, Roma.

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## **Assessing long-term scenarios of groundwater recharge in karst aquifers by climate models (GCMs and RCMs)**

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**Key words:** climate change, groundwater recharge, karst aquifer.

Karst aquifers host important groundwater resources for human and agricultural use in many areas of the world and include natural landscapes and ecosystems with great geo- and biodiversities (Goldscheider, 2012). The studies of the climate-change impact on the groundwater recharger processes of these aquifers is a task of high importance due to the high relationship between the socio-economic dependence of the human activity with the groundwater availability. The aim of this review it is to verify the state of the art of the application of climate models, such as General Circulation Models (GCMs) and the more detailed Regional Circulation Models (RCMs), and analyze how these models have been used to assess groundwater recharge in different hydrogeological conditions and climate and hydrological scenarios, in the framework of Mediterranean karst aquifers. GCMs and RCMs are applied around the world with different spatial and temporal scale resolution, succeeding to reconstruct climate scenarios up to the end of the current century. The review was performed paying attention to methodologies applied for the estimation of groundwater recharge in different temporal scenarios reconstructed by the application of the GCMs/RCMs in areas with carbonate lithologies. Ensemble of different GCMs/RCMs represent the best approach for a reduction of the uncertainty of the results obtained by this modeling and the temporal analysis are carried out in various time scales for a better evaluation. Precipitations and temperature are the fundamental variables and their time series, simulated by RCMs, are easily and largely applicable for the quantification of the groundwater recharge by numerical models. However, these time series can increase the spatial resolution of the local scale climate with correct downscaling techniques/bias correction methods (Teutschbein and Seibert 2012, Gudmundsson et al., 2012) and can be used also for the quantification of the groundwater recharge through empirical models or water budget approach.

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Gudmundsson, L., Bremnes, J. B., Haugen, J. E., & Engen-Skaugen, T. (2012). Downscaling RCM precipitation to the station scale using statistical transformations—a comparison of methods. *Hydrology and Earth System Sciences*, 16(9), 3383-3390.

Teutschbein, C., & Seibert, J. (2012). Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of hydrology*, 456, 12-29.



## **Trends in long-term time series of karst springs discharge and relation to climate factors and changes**

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**Key words:** Karst, Time series, Distribution fit, Standardization, Climate change.

Karst aquifers of the Campania Region are generally drained by large basal springs, that satisfy the needs of water of numerous villages of the Southern Italy. In most cases, the discharge time series of these springs are available and provide precious data to understand the water resource availability variations under climate change. This study aims to investigate the effects of the main climate variables, rainfall and temperature, on the groundwater conditions. The main relationships between climate and discharge have been evaluated by applying different statistical analyses to long-term series of hydro-meteorological variables. In particular, the performances of different three-parameter probability distribution models for the frequency analysis of the hydrological series have been analyzed; an accurate statistical criterion has been used to select the most suitable probability model to calculate robust hydrological standardized series, in order to examine duration and intensity of hydrologically dry and wet periods; hydrological droughts have been focused, considering their role on the economies and environment. Long-term variations of hydro-meteorological variable have also been investigated by using non-parametric trend detection tests; these tests include Mann-Kendall and Sen's slope tests, that assess the sign and the statistical significance of trends in time series. Our analysis reveals the strong relationship between climate variations and groundwater system; in particular, results of the analysis shows that the intensity and the frequency of hydrological droughts have been increased over the last three decades; a statistically significant decrease of the annual mean spring discharge was observed, together with a strong statistically significant trend of the annual mean air temperature. The latter had been a strong impact on the karst aquifers and induced an increase of duration and intensity of hydrological droughts in the last decades. On the other hand, no statistically significant long-term trend seems to characterize the annual mean precipitation series.

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# **Spatio-temporal analyses and correlations between groundwater and air temperature in the Piedmont Po plain (NW Italy): preliminary results**

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**Key words:** groundwater temperature, trend, climate change, Po plain.

It's now recognized that a global climate change is taking place, leading to an increase in temperatures and a variation in precipitation regime, also affecting groundwater (GW) (Taylor et al., 2013).

In this study we want to evaluate how climate change affects GW temperature (GWT) in the Piedmont Po plain (NW Italy).

The Piedmont Po plain covers the 27% of the whole region and it's the most important GW reservoir of the Piedmont region (De Luca et al., 2020). It consists, from top to bottom, by Alluvial deposit complex (lower Pleistocene-Holocene), that hosts a shallow unconfined aquifer, the "Villafranchiano" transitional complex (late Pliocene-early Pleistocene), that hosts a multilayered aquifer, and a Marine complex (Pliocene) hosting a confined aquifer (De Luca et al., 2020).

For this research, 41 wells in the shallow aquifer and 20 weather stations were selected throughout the Piedmont Po plain area, and GWT and air temperature (AT) parameters were analysed for the period 2010-2019.

The GWT data were firstly studied with basic statistical analysis (mean, maxima, minima), then with the Mann-Kendall and Theil-Sen methods to evaluate the trend of the monthly mean GWT. GWT show a general increase in all the plain, with a mean of 0.85 °C/10years.

Same analyses were carried out for monthly means AT data and it was observed that the mean increase is 1.69 °C/10years.

To compare GWT and AT, the Voronoi polygons method was used on QGIS, centring the polygons on the weather stations.

It was possible to highlight that in most cases there is a greater increase in the AT than in the GWT. The same behaviour was observed for the monthly minima and maxima GWT and AT.

These results testify a greater resilience of GWT to climate variability. Future insights will be a detailed analysis of the factors influencing the more or less evident increase in GWT in relation to air temperatures.

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# Impact of North Atlantic Oscillation On Water Resources In South-Western Poland

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Key words: climate change, groundwater resources, SW Poland.

Research indicates that the influence of the NAO on the discharge of rivers in Poland is at its greatest in winter and early spring, i.e. during the formation of some of the country's largest water resources (Wrzesiński 2008). The studies of authors focuses on south-western Poland in 17 catchments with varying environmental features and surface areas. Used data from the years 1966 to 2015 included river flows, temperatures and precipitation. The information was subjected to mathematical and statistical transformations. Data point towards a decline in precipitation, air temperature on the other hand shows an upward trend on study area. Most of the drainage basins show a correlation between total and groundwater runoff and meteorological conditions. In light of the fact that local meteorological conditions are created by large-scale phenomena, attempted to draw a connection between runoff and the NAO indexes. In all of the drainage basins, comparisons between annual runoff (both total and subsurface) and the winter NAO index showed high correlations. The highest correlation coefficients are obtained when comparing annual NAO indices with the annual total runoff for the period between January and December in large drainage basins, and for the period between February and January and between March and February in small drainage basins. In the case of groundwater runoff, the annual NAO index correlates most strongly with the degree of the flow assessed following the algorithm based on the delayed figures, i.e. from February to January of the following year and from March to February of the following year. The situation is different when comparing the winter NAO index with the total and groundwater runoff figures from each 6-month period. The highest, statistically significant figures are calculated by comparing the winter NAO index with total and groundwater runoff for the period between March and August and April and September. This suggests a significant impact of the winter NAO index on the formation of runoff during the warmer months.

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# The first national groundwater climate-change impact indicator in Italy

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Key words: data series, monitoring network, Rome.

Precipitation is decreasing in Southern Europe. Strong pressure on water resources is expected, with a consequent reduction in water quality and quantity, especially in summer, in southern regions and small islands. The Italian National Strategy for Adaptation to Climate Change – SNACC (MATTM, 2014) identifies water resources among the most critical situations. These do not present serious problems in terms of water availability on an annual basis, but rather in terms of uneven availability over time and space and management efficiency. The Italian National Climate Change Adaptation Plan – PNACC (MATTM, 2018) identifies among the specific actions to address the reduction of water availability, the improvement of the effectiveness of monitoring, planning and efficiency of the use of the resource. For the first time an indicator aiming to detect any impact signal specifically related to groundwater resources has been identified in Italy. The indicator is based on groundwater level data series analysis of official regional monitoring stations.

The purpose of the indicator is to provide information on the evolution of groundwater levels on a national scale in relation to the different climatic zones. The groundwater level measured in conditions not influenced by other anthropogenic factors is recognized as a descriptor of the quantitative status of the aquifers (Barthel, 2011). Thus the trend of groundwater levels is able to provide a snapshot of the quantitative status of groundwater resources.

Currently, although at preliminary state, an effort has been made to select a group of representative stations for each homogeneous climate macro-region of the PNACC, and the selected stations from those available do not yet have a completely homogeneous coverage on the national territory. Keeping against this limit, the first calculations performed show how groundwater resources do not show particular crisis signals, generally showing stable or positive trends in recent years, compared to the average of the selected period, which ranges from 10 to 20 years depending on the historical data series available.

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## **Regional and local control of the North Atlantic Oscillation on the hydrological response of karst aquifers in southern Italy**

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**Key words:** climatic variability, North Atlantic Oscillation, groundwater recharge.

The importance of groundwater resources deriving from karst aquifers is known worldwide having beneficial effects on economic and social development, from the regional to local scales. For the Campania region, karst aquifers are the main source of water supply for drinking, irrigation, and industrial uses. Among these aquifers, that of the Avella Mts, managed by G.O.R.I Inc., a joint-stock company that manage the integrated water service of the Sarno-Vesuvian District of the Campania region, constitutes a strategic resource. It supplies about 80% of the total resources conducted into the aqueduct systems extending over 927 km<sup>2</sup> and providing 1.500.000 inhabitants.

Given the relevance of this karst aquifer and of its annual groundwater yield, a study of the effects of long-term climatic variability on groundwater recharge was carried out with the aim to assess possible drought scenarios. The analysis was carried out at two spatial scales, the regional and local scales. Knowing that the long-term variability of the principal climatic parameters in the Mediterranean area are also linked to the occurrence of the North Atlantic Oscillation (NAO), an atmospheric phenomenon occurring on the north hemisphere, time series of precipitation and air temperature were collected and analyzed over about a century, from 1921 to 2019. At this scope recordings of 18 rain gauges and 9 air temperature stations, chosen among the most continuous at the regional scale, and of 23 rain gauges and 11 thermometric stations, on a local scale, were analyzed. For the same period, time series of the winter NAO index and discharges of five different karst aquifers were collected. The analysis of the NAO Index and of hydrological parameters controlling groundwater recharge, precipitation, air temperature, actual evapotranspiration and effective precipitation, was carried out by the calculation of normalized annual indexes and by the application of smoothing numerical techniques for the analyses of long-term trend. The analysis of time series of normalized indexes highlighted the existence, both at the regional and local scales, of complex periodicities, from 2 to more than 30-40 years, with differences in average values of up to approximately  $\pm 30\%$  for precipitation and karst spring discharges, which were found strongly correlated with the winter NAO index.

The results of this study combine the continental scale atmospheric cycles and groundwater recharge of karst aquifers from the regional to aquifer scales depicting the use of the winter NAO index as a proxy to predict the multitemporal variability of groundwater flow in Mediterranean karst areas. Therefore, these findings could be used to assess possible drought scenarios.

## **Analyzing the groundwater management practices in the surficial aquifer of Abu Dhabi**

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**Key words:** Abu Dhabi; agriculture activities; desalinated water; solute transport model.

The groundwater resource in Abu Dhabi has been depleted by heavy pumping in the past. Water derived from the desalinated plants and Treated Sewage Plants (TSE) are significantly reducing the rate of groundwater pumping. Many reports suggest that the pumping is reduced but not less than the rate of groundwater renewability. Ranges of decline and increase in the groundwater head are noticed in some locations. It is also reported that the replacement of groundwater especially in the field of agriculture sectors demands a proper understanding of aquifer behavior. This study is conducted to understand the impacts in the aquifer system caused by the introduction of desalinated water for agriculture activities and for aquifer recharge. A regional density dependent flow model is employed in this study. The simulation is carried out from the year 2000 to 2050 using a reported rate of groundwater pumping and 0.1 g/l, 0.5 g/l, 1 g/l, 1.5 g/l and 2 g/l of desalinated water salinity. An improvement in the groundwater quality is noticed in the aquifer due to the addition of less saline water into the aquifer. In the eastern part of the aquifer, an increase in the groundwater head is noticed in few wells due to the existing reduction in the groundwater pumping. The results confirm that this region demands further management practices in quantifying the amount of alternative water sources in irrigation such as desalinated water in order to face agricultural water scarcity.

# **Changes in the discharge regime of a major spring in the Northern Apennines over a century (1920-2020): a comparison between ancient and recent monitoring surveys in relation to climate change**

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**Key words:** climate change, spring, discharge, Epiligurian unit, arenite.

It is scientifically established that global warming induced by greenhouse gases, affecting the surface energy budget, can significantly alter the Earth's water cycle, with consequent modification of precipitation typology and regime. However, the net effects of these changes on the process of groundwater discharge are still uncertain at local scale. The lack of historical series of monitoring data, dating back to at least 60-100 years ago, is among the main drawbacks, with the rare exception of major karst springs exploited for public water supply [1]. In hard rock aquifers, like those dominant in the Northern Apennines, the dynamic of spring outflow during the first half of the XX century is an absolute black-box. For this reason, it appeared noteworthy to analyze detailed monthly-based monitoring data, over the 1915-1920 time span, of the whole discharge of the Nadia spring [2], one of the most productive spring in the Emilia-Romagna region, in low flow season, among those used for drinking water. Such data were reported in a century-old study functional to the drilling of a draining tunnel for water uptake. We present a comparison between the monthly regime of the spring discharge 100 years ago and a continuous monitoring performed by the authors during the 2020/2021 hydrological year, integrated with the total water uptaken in years 2018-2020. Nadia spring discharges from an arenitic fractured aquifer deposited in a neritic setting above mainly clayey units acting as a permeability threshold. The abundance of calcite in the grains and cement of the arenite enhances corrosion and enlargement of fractures. In 2018-2021 the spring discharge range has been 80-50 L/s whereas in 1915-1920 it was 140-63 L/s. The two (ancient and recent) sets of data were compared with a focus on the evolution of precipitation and thermal regime.

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## **The Variation of the Natural Flow Regime and Trend Discharge of the Bagnara Limestone Spring (Apennines, Italy)**

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**Key words:** groundwater spring, flow regime, trend discharge, climate change.

The study of the spring flows of the Bagnara spring was undertaken in order to statistically investigate any decreases in the spring flow over the last forty years of flow records. It is found that the spring flow regime has statistically changed over the last forty years due to climate change. It is calculated that, on a multiannual scale, the tendency to decrease the spring flow is statistically significant for the minimum flows, while the multiannual decrease trend of the maximum and average flows does not appear statistically significant. The methodology used is based on the criterion of linear regression and trend analysis. It is concluded that starting from the next two decades the impact of climate change on minimum flows will be significant for the water supply for human use and for the life of biotic communities as it could lead, in a statistical sense, to the absence of spring flow during the dry season.

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## **Interdisciplinary investigations of managed aquifer recharge potential on the small island of Vis (Croatia)**

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**Key words:** Vis island, groundwater, karst hydrogeology, climate change, managed aquifer recharge.

Managed aquifer recharge (MAR) refers to a suite of methods by which excess surface water is diverted underground where it is stored for subsequent recovery. Although MAR has a long history of implementation in aquifers with intergranular porosity, its application in the karst environment presents major challenges due to the high heterogeneity of karst aquifers (Dillon et al., 2019). This research was focused on conducting a MAR feasibility study on the island of Vis, a small karstic island in the Croatian part of the Adriatic Sea, where favorable geological and hydrogeological conditions enabled the formation of high-quality karst aquifers, making the island autonomous in terms of water supply. The island's main aquifer is protected from seawater intrusions by several hydrogeological barriers, however, climate change and high seasonal pressures related to tourism pose a threat to the future availability of freshwater. To investigate whether a MAR operation is feasible and suitable for the karst aquifer on Vis, detailed field and laboratory investigations were carried out. Field investigations included in-situ measurements of physicochemical parameters on water samples from springs and boreholes, groundwater monitoring (conductivity, temperature, and water levels), geophysical methods (ERT, magnetotellurics, and seismic refraction), and structural measurements. Laboratory analyses included measurements of stable water isotopes, principal cations and anions, tritium activity, and analyses of stable isotopes from dissolved sulphates. The results corroborated the available conceptual model of the water resources detailing the geometry of the carbonate aquifer and of the fracture systems driving the water circulation. A 3D numerical model (FEFLOW) of the island will be developed to simulate various scenarios of climate change, with and without MAR. The integration of the obtained results with historical data and previous research will be used for implementing efficient and sustainable management of the karst aquifer through MAR or alternative solutions on Vis island.

Dillon, P., Stuyfzand, P., Grischek, T. et al. Sixty years of global progress in managed aquifer recharge. *Hydrogeol. J.* 27, 1–30 (2019).  
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## Session 2

### Groundwater Resource and Sustainability

#### **Keynote Lecture:**

*Groundwater Resources on the United Nations Agenda: Cross-border groundwater cooperation*

Alice Aureli (UNESCO IHP)

#### **Conveners**

Tullia Bonomi (Università degli Studi di Milano – Bicocca)

Antonio Menghini (Aarhus Geofisica S.r.l.)

Maria Filippini (Alma Mater Studiorum - Università di Bologna)

## KEYNOTE LECTURE

### Groundwater Resources on the United Nations Agenda: Cross-border groundwater cooperation

Alice Aureli (UNESCO IHP)

*Transboundary waters account for 60 per cent of the world's freshwater flow, while 153 countries have territory within at least one of the 286 transboundary river and lake basins and 592 transboundary aquifer systems.*

*Despite the fact such a large proportion of the fresh water on the planet is contained in transboundary aquifers, it was not until 20 years ago that the UNESCO ISARM initiative, a major study of "invisible groundwater", was launched.*

*Over the last 20 years, the UNESCO ISARM Initiative has significantly contributed to progress made in the assessment, cooperation and regulation of joint management of shared groundwater. Since its start in the year 2000, ISARM has launched a number of global and regional initiatives. These are designed to delineate and analyse transboundary aquifer systems and to encourage riparian states to work cooperatively towards mutually beneficial and sustainable aquifer development.*

*The Sustainable Development Goals are a universal call to action to end poverty, protect the planet and improve the lives and prospects for all. UNESCO IHP contributes to the achievement of SDG 6 to 'Ensure access to water and sanitation for all. UNESCO IHP is responsible, together with the UNECE, for the monitoring of Indicator 6.5.2 which tracks the percentage of transboundary basin area within a country that has an operational arrangement for water cooperation.*

*While substantial progress has been made in the study of transboundary aquifers, one of the results of the second phase of the monitoring of indicator 6.5.2 is to clearly address the problem of data gaps in relation to transboundary aquifers as a trigger for sustained cooperation.*

*148 countries share at least one aquifer with a neighbouring country. However, the lack of data on aquifers remains a major obstacle to achieving water security for many countries. The report, prepared by UNESCO and UNECE on indicator 6.5.2, clearly points to the need to strengthen efforts to accelerate investments and capacity development on groundwater resources studies by 2030.*

# **Machine learning in hydrogeology: a method to deal with the missing data problem in time series**

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**Key words:** time series, open-source, machine learning (ML), Euganean Geothermal Field (EuGF).

Often in hydrogeology long time series show periods of interrupted monitoring, producing missing data, while in some cases, it could be needful the availability of the complete time series. A machine learning (ML) approach can be a useful way to estimate missing data in a time series. In this work, a long time series representing the potentiometric level on the Euganean Geothermal field (EuGF) of Abano Terme (NE, Italy) is considered. Since 1977, a monitoring network is present in EuGF and the well BA2 has the longest time series of potentiometric levels in EuGF. As usual, such a time series presents missing values (96 missing data on a total of 526) and the purpose is to estimate potentiometric levels also that times. In this area, the potentiometric levels are artificial and strictly linked to thermal water exploitation, so the input data are the thermal water exploitations and the output data are the estimated potentiometric levels in BA2.

ML is a general definition concerning algorithms that give computers the ability to learn from data without being explicitly programmed, in fact, a machine-learning algorithm learns how to make decisions from the data alone. There are different ML approaches such as neural networks, deep learning, random forest, and others. Here the Gradient Boosting Machine (GBM), implemented in the h2o package in R environment, is taken into account to estimate missing data on the monthly potentiometric level of BA2 well. GBMs build an ensemble of shallow and weak successive trees with each tree learning and improving on the previous. When combined, these many weak successive trees produce a powerful “committee” that is often hard to beat with other ML algorithms.

## Specific vulnerability to anthropogenic pollution: a novel hybrid method

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**Key words:** Aquifer Pollution, Vulnerability assessment, Statistical analysis.

Managed aquifer recharge (MAR) refers to a suite of methods by which excess surface water is diverted underground where it is stored for subsequent recovery. Although MAR has a long history of implementation in aquifers with intergranular porosity, its application in the karst environment presents major challenges due to the high heterogeneity of karst aquifers (Dillon et al., 2019). This research was focused on conducting a MAR feasibility study on the island of Vis, a small karstic island in the Croatian part of the Adriatic Sea, where favorable geological and hydrogeological conditions enabled the formation of high-quality karst aquifers, making the island autonomous in terms of water supply. The island's main aquifer is protected from seawater intrusions by several hydrogeological barriers, however, climate change and high seasonal pressures related to tourism pose a threat to the future availability of freshwater. To investigate whether a MAR operation is feasible and suitable for the karst aquifer on Vis, detailed field and laboratory investigations were carried out. Field investigations included in-situ measurements of physicochemical parameters on water samples from springs and boreholes, groundwater monitoring (conductivity, temperature, and water levels), geophysical methods (ERT, magnetotellurics, and seismic refraction), and structural measurements. Laboratory analyses included measurements of stable water isotopes, principal cations and anions, tritium activity, and analyses of stable isotopes from dissolved sulphates. The results corroborated the available conceptual model of the water resources detailing the geometry of the carbonate aquifer and of the fracture systems driving the water circulation. A 3D numerical model (FEFLOW) of the island will be developed to simulate various scenarios of climate change, with and without MAR. The integration of the obtained results with historical data and previous research will be used for implementing efficient and sustainable management of the karst aquifer through MAR or alternative solutions on Vis island.

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## Hydrogeological study of the Venafrò Mts. (central-southern Italy) carbonate aquifer: numerical analysis and management scenarios

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**Key words:** central Apennines; hydrogeological conceptual model; karst; MODFLOW.

Carbonate fractured aquifers represent strategic water resources of Italy, supplying major cities and villages. These aquifers coincide with the Apennines mountain ridges and are characterized by water springs with a steady flow rate. The lack of alternative water sources, drought occurrence and increasing human water abstraction make compelling the detail characterization of these groundwater systems. In this study, the Venafrò Mts. (central-southern Italy) carbonate aquifer (370 km<sup>2</sup>), has been investigated. Selected area is relevant for water supply of Naples and its hinterland, and it is exploited by the WCW (Western Campania Water-works). Via a collection of geological and hydrogeological data (Saroli et al., 2019; Lancia et al., 2020 and references therein), a groundwater conceptual model for the aquifer is built. The definition of the lithological units and tectonic lineaments together with piezometric data, spring flow rates, and WCW abstraction rates are the basis for the setup of a numerical model via USGS-MODFLOW. The UZF (Unsaturated Zone Flow) package with an NWT-UPW (Newton Solver-Upstream Weighting) configuration allows better numerical convergence in mountain areas (Lancia et al. 2019). Steady-state simulation validates the conceptual model and the literature budgets. A further transient model, calibrated by rain gauge station data, between 2010 and 2018 years, simulates the spring flow rates during the dry and wet periods. Simulation analysis suggests Venafrò Mts. aquifer is affected by stress enhanced during drought conditions. Water springs located at higher elevations show larger flow rate variations, suffering the rainfall decreases and water abstractions. Management scenarios comprehending a drastic water abstraction cut-off are also considered. Studied aquifer shows a slow response, with recovery time estimated at the decennial scale, testifying its limited resilience to natural and human pressures. Detailed studies at long-term scale are suggested to assess the sustainability of water abstraction throughout the carbonate aquifers of the Italian peninsula.

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The full paper is published on: [Lancia, M., Petitta M., Zheng, C., Saroli, M. 2020. Hydrogeological insights and modelling for sustainable use of a stressed carbonate aquifer in the Mediterranean area: From passive withdrawals to active management, J Hydrol-Reg Stud, 32, 100749.](#)



## **Batch experiments on nutrient leaching in sandy soils amended with compost, zeolites, biochar, and graphene**

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**Key words:** nutrients leaching, batch experiment, sandy soil, soil conditioner.

Sandy coastal soils are renowned for their low water holding capacity associated with a low fertility. In view of the predicted climate change for the next decades, these peculiarities of sandy soils are expected to have negative impacts on water resources availability and consequently on the agricultural sector in many regions of the world. Moreover, the large infiltration capacity of sandy soils can trigger a fast and consistent nutrient leaching. The overlapping of these processes could generate serious water stresses and nutrients deficit in the topsoil and could worsen the vulnerability of coastal aquifers to nutrient pollution. These issues lead to a significant increase in the costs of crops managing related to irrigation and fertilization. The application of soil improvers, organic and inorganic, can adjust the soil characteristics. In this study, traditional soil improvers (compost, biochar, and zeolites) and graphene were tested in a leaching batch experiment on two different sandy soils to assess their capacity to ameliorate soil properties. The experiments were performed using the saturation soil extraction method. In the batches two different types of sand were employed: a calcareous sand and a siliceous sand, with variable grain size from medium to coarse sand, representative of the most common sandy soils along the Italian coast. Solid-liquid volumetric ratio in the batches was 1:5. For each soil improver, two configurations were tested: a minimum quantity of soil conditioner and a maximum quantity (with 3 replicates each). EC, pH and Eh were monitored in continuum for 15 days in each batch and water samples were taken for the analysis of DOC, ions, and metals. Results show an increase in pH and EC due to biochar addition, an increase of Eh and NO<sub>3</sub><sup>-</sup> due to compost addition, and the capacity of all improvers to increase the available water content.

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## Groundwater nitrate contamination mitigation through a Forested infiltration Area (FIA) system in the Arborea Nitrate Vulnerable Zone (Sardinia, Italy)

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**Key words:** Groundwater nitrate contamination, Forested Infiltration Area, Non-conventional water reuse.

After almost three decades of the Nitrates Directive (Directive 91/676/CEE) implementation, there is no significant reduction in groundwater nitrate concentration which still frequently exceed the threshold value of 50 mg L<sup>-1</sup> (Carrey et al., 2020). The sandy phreatic aquifer (SHU) and the alluvial aquifer (AHU) in the NVZ of Arborea (central-western Sardinia, Italy) are both characterized by nitrate concentrations exceeding 250 mg L<sup>-1</sup> (Ghiglieri et al., 2016). This research aims to test the Managed Aquifer Recharge (MAR) technique based on Forested Infiltration Areas (FIA) (Mezzalira et al., 2014) as a best practice to mitigate the groundwater nitrate contamination for the SHU aquifer. This activity is being carried out within the MENAWARA “Non-Conventional Water Re-use in Agriculture in Mediterranean countries” project (2019-2022) (<http://www.enicbmed.eu/projects/menawara>), funded by the EU under the 2014-2020 ENI CBC “Mediterranean Sea Basin Programme” and coordinated by the Desertification Research Centre of the Sassari University. The FIA system will be implemented in an area of around 0.4 ha and it will consist of six parallel recharge trenches placed between rows of white poplar trees (*Populus alba*). It will be supplied with non-conventional water (drainage water), pumped from an existing dewatering pumping station, and treated before the recharge through an innovative Passive Treatment System: a mixture of inert and organic materials, based on previous experiences in Tunisia and Algeria, to attenuate organic and inorganic contamination and to prevent clogging processes at the infiltrating surface. In order to define the quality baseline of drainage water and groundwater, an *ante operam* monthly monitoring started in October 2020, which showed NO<sub>3</sub> concentration from 2.5 mg L<sup>-1</sup> to 175 mg L<sup>-1</sup>. An estimation of the infiltration rate in the sandy soils based on preliminary surveys showed a potential recharge rate of around 0.7 hm<sup>3</sup> year<sup>-1</sup> per 0.4 ha of FIA system.

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Ghiglieri, G., Carletti, A., Da Pelo, S., Cocco, F., Funedda, A., Loi, A., Manta, F., Pittalis, D. 2016. Three-dimensional hydrogeological reconstruction based on geological depositional model: A case study from the coastal plain of Arborea (Sardinia, Italy). *Engineering Geology* 207, 103-114

Mezzalira, G., Niceforo, U., Gusmaroli, G. 2014. Aree forestali di infiltrazione (AFI): principi, esperienze, prospettive [Forested infiltration areas (FIA): principles, experiences, perspectives]. *Acque Sotterranee - Italian Journal of Groundwater*.

## Assessing spatial variability of groundwater evaporation rates at controlled laboratory conditions

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**Key words:** Continuous monitoring; numerical model; evaporation; bare soil; groundwater salinity.

A large tank filled with medium-coarse sand was employed to measure evaporation rates from shallow groundwater at controlled laboratory conditions. Twelve piezometers were installed in a semi regular grid and equipped with water level, temperature, and EC probes. In each piezometer, six micro sampling ports were installed every 10 cm to capture vertical salinity gradients. Moreover, TDR probes placed at 5, 20 and 40 cm depth measured water content, temperature, and EC in the unsaturated zone. Before the experiment, the tank was characterized via grain size analyses, slug tests, and a pumping test. The monitoring started in February 2020 and lasted for four months until the groundwater drawdown became residual. The groundwater evaporation rate was measured with the classical White's method (White, 1932). SEAWAT 4.0 was employed to model groundwater heads, temperature, and salinity variations. The calibrated model parameters were: maximum evaporation rate (1.5-4.4 mm/d), extinction depth (0.9 m) and mineral dissolution rate ( $5e^{-6}$  mg/d). As the water level decreased the groundwater salinity and temperature increased. Despite the drawdown was uniformly distributed, the increase of groundwater salinity was rather uneven, while the temperature increase mimicked the atmospheric temperature increase. Despite the homogeneous drawdown, the White's method produced values affected by large spatial variability. This combined with the initial groundwater salinity controlled the evapoconcentration process in groundwater. The sensitivity analysis showed that small changes in the effective porosity could lead to very different concentrations' distribution during the evapoconcentration process, thus the influence of this parameter should be carefully characterized in future studies. This study shows that evaporation from medium-coarse sand can be relevant in temperate environments if the water table is near to the ground surface (0.5-1.0 m), with a measured extinction depth (0.9 m) higher than the ones found in previous studies for sandy sediments (Shah et al., 2007).

Shah, N., Nachabe, M., Ross, M. 2007. Extinction depth and evapotranspiration from ground water under selected land covers. *Groundwater* 45(3), 329–338. <https://doi.org/10.1111/j.1745-6584.2007.00302.x>

White, W.N., 1932. Method of estimating groundwater supplies based on discharge by plants and evaporation from soil – Results of investigation in Escalante valley. Tech. Rep., Utah –US Geological Survey. Water Supply Paper 659-A.

## **Applying the Principal Component Analysis for a deeper understanding of the groundwater recharge: case study of the Bacchiglione Basin (Veneto, Italy)**

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**Key words:** groundwater, Principal Component Analysis, recharge factors, Bacchiglione.

In hydrogeology, it is often difficult to fully understand the hydraulic factors affecting the recharge of groundwater systems. Particularly, at a regional scale the groundwater system can have different hydraulic drivers depending on the considered area: for example, it can be precipitation, river dispersion, snow melting, irrigation, or a combination thereof. Chemicals or temperature can help such understanding. However, information is usually sparse at the regional scale, whereas extended groundwater piezometric head monitoring is more common. This study aims at exploiting these longitudinal observations to validate (and possibly bring more insights into) the geological structural model of the aquifer systems. Clustering the control points basing on the piezometric head average annual variations can help the system conceptualization in two ways: (i) clusters can geographically identify areas with a similar hydrogeological behavior; and (ii) the typical cluster annual variation with its ups and downs can bring insights on the recharge in the area. Nevertheless, visual clustering can be a long and subjective procedure, thus this study suggests the use of the Principal Component Analysis to cluster the control points with similar average annual variation of their recorded timeseries. This study supports the proposed analysis by applying it to the monitoring data of the Bacchiglione basin. After hydrograph normalization, necessary to highlight local seasonality and avoid clouding the analysis with the mean or the oscillation range, the Principal Component Analysis well identifies the clusters depending on the number, moment and lengths of groundwater level peaks and minima. Thus, through this work the typical cluster annual variation can be compared and associated with one or a combination of recharging factors. Additionally, most of the clusters well gather the control points in space, underpinning the groundwater hydrograph dependence on the local water balance.

# **Assessing the long-term sustainability of the groundwater resource in the Bacchiglione basin (Veneto, Italy) with the Mann-Kendall test: from controversial results to suggestions for a higher reliability**

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**Key words:** quantitative sustainability, Mann-Kendall test, Sen's slope estimator, groundwater level, Bacchiglione.

The social, economic and ecological importance of the aquifer system within the Bacchiglione basin (Veneto, IT) is noteworthy and considerable disagreement exists among previous studies over its sustainable use. This study investigates the long-term quantitative sustainability of the groundwater system. As a robust and widely used techniques' combination, we apply the seasonal Mann-Kendall test and the Sen's slope estimator to the recorded groundwater level timeseries. The analysis is carried out on a large and heterogeneous dataset gathering hourly groundwater level timeseries at 79 control points, acquired in the period 2005-2019. The test identifies significant decreasing trends for most of the available records, unlike previous studies on the quantitative status of the resource which covered the here investigated domain in a slightly different time period: 2000-2014. The present study questions the reason for such diverging results by focusing on the method's accuracy. After carrying out a Fourier analysis on the longest available timeseries, this work suggests applying the Mann-Kendall test to timeseries longer than 20 years (because otherwise the analysis would be affected by interannual periodicities of the water cycle). A further analysis of two 60-years long monthly timeseries between 1960-2020 supports the actual sustainable use of the groundwater resource, the past deployment of the groundwater resources notwithstanding. Results thus prove more reliable and meaningful inferences on the long-term sustainability of the groundwater system are possible.

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## **The COPA+K method: an index-based approach for the karst groundwater vulnerability assessment. The Valseriana springs case (Northern Italy)**

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**Key words:** Vulnerability maps; Karst groundwater systems; Nossana and Ponte del Costone springs; EPIK and COP methods; COPA+K method.

Karst aquifers are highly productive from a water supply perspective as well as highly susceptible to pollution. This is primarily due to significant lateral extension, shallow soils, and highly effective recharge points such as sinkholes, sinking streams, and polje. Therefore, attention must be given to the proper water management in these environments and the preservation of the natural state of the water system. Intrinsic vulnerability maps are currently one of the most valuable tools for assessing sensitivity to pollution of an area. Index-based methods allow for its evaluation even in cases where large amounts of data are not available and without requiring intensive computational effort. The main goal of this study was to evaluate and enhance index-based approaches for the assessment of the intrinsic vulnerability, so to consider the peculiar characteristics of the Pre-Alps region and highlight differences within catchments. The study focused on the Nossana and Ponte del Costone Springs in the middle Valseriana (Italy, BG). After applying the classical methods for karst environments (COP and EPIK), the integrative COPA+K method was developed using GIS software. The COPA+K approach exploits the potentialities of the COP method with the addition of two further factors: the influence of the main discontinuities on the water system according to their distance from the spring (A factor), and the development of the karst network (K factor). In comparison to EPIK and COP, COPA+K results showed a differentiation between the two studied catchments more coherent to their known hydrogeological behavior (dominant drainage system Nossana, dispersive system Ponte del Costone). The percentage difference between the most vulnerable areas of Nossana and Ponte del Costone increased from 5.2% to 17.5%. COPA+K also allowed a greater detail in the identification of the most vulnerable areas compared to COP (from 35.6% to 23.6% considering the whole area).

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## Digitalization of groundwater management using an agile and parsimonious approach based on open-source resources

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**Key words:** Groundwater management, Groundwater monitoring, Groundwater modelling, Computer science, Free and Open Source Software.

Scientists have been experiencing an exponential growth of collected data, to face with groundwater protection and sustainability. To manage large volumes of data, the increased use of digitalization and ICTs is being promoted by national governments and international organizations. This requires integrating the expert knowledge of groundwater scientists with computing and programming skills, to digitize the groundwater management workflow consisting of the following steps: (1) data collection, (2) data exploitation and analysis, (3) definition of hydrogeological conceptual models, (4) mathematical modelling, (5) reporting. The present work demonstrates that simple and inexpensive tools may be applied to create an agile and parsimonious methodology that connects such steps. The proposed approach focuses on a suite which can be applied to:

- harmonize and manage data;
- facilitate the interaction between the available data and numerical models;
- automate and customize the reporting step;
- support groundwater management and governance, as any inconsistency in the time/space trends of the collected data may be timely highlighted.

The suite consists of a structured database for field data storage and a Python script to manage and process the available data. The proposed approach was demonstrated by applying it to a simple, real-world case study, located east of Milan, where the infiltration mechanism through the unsaturated zone is investigated. The proposed methodology is based on the use of commonly available devices for data collection, commonly available standards for data management and Free and Open Source Software, thus it can be easily reproduced and adapted for groundwater management issues at any site. The content of this abstract uses materials of a short course held on June 10<sup>th</sup>–11<sup>th</sup>, 2019, within the framework of the “Flowpath – National Meeting on Hydrogeology” Italian congress. The short course was organized by the Italian Chapter of the Early Career Hydrogeologists’ Network (ECHN-Italy). CAP Holding S.p.A., the water authority managing the data used to test the suite, is kindly acknowledged.

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# Reactive Silica Traces Manure Spreading in Alluvial Aquifers Affected by Nitrate Contamination: A Case Study in a High Plain of Northern Italy

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**Key words:** groundwater; nitrogen; silica; flood irrigation; agricultural practices.

In the northern sector of the Po River Plain (Italy), widespread intensive agriculture and animal farming are supported by large amounts of water from Alpine lakes and their emissaries. Flood irrigation and excess fertilization with manure affect both the hydrology and the chemical quality of surface and groundwater, resulting in diffuse nitrogen pollution. However, studies analyzing the mechanisms linking agricultural practices with vertical and horizontal nitrogen paths are scarce in this area. We investigated groundwater quality and quantity in an unconfined, coarse-grained alluvial aquifer adjacent to the Mincio River (a tributary of the Po River), where steep summer gradients of nitrate ( $\text{NO}_3^-$ ) concentrations are reported. The effects of manure on solutes' vertical transport during precipitation events in fertilized and in control soils were simulated under laboratory conditions. The results show high  $\text{SiO}_2$  and  $\text{NO}_3^-$  leaching in fertilized soils. Similarly, field data are characterized by high  $\text{SiO}_2$  and  $\text{NO}_3^-$  concentrations, with a comparable spatial distribution but a different temporal evolution, suggesting their common origin but different processes affecting their concentrations in the study area. Our results show that  $\text{SiO}_2$  can be used as a conservative tracer of manure spreading, as it does not undergo biogeochemical processes that significantly alter its concentrations. On the contrary, nitrate displays large short-term variations related to aquifer recharge (i.e., flood irrigation and precipitation). In fact, aquifer recharge may promote immediate solubilization and stimulate nitrification, resulting in high  $\text{NO}_3^-$  concentrations up to 95.9 mg/L, exceeding the Water Framework Directive (WFD) thresholds. When recharge ends, anoxic conditions likely establish in the saturated zone, favoring denitrification and resulting in a steep decrease in  $\text{NO}_3^-$  concentrations.

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## Groundwater resource evaluation in Plio-Pleistocene arenaceous aquifers (Central Italy)

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**Key words:** arenaceous aquifers, water balance, recharge, urbanization.

The hilly landscape of the Periadric area in Central Italy is characterized by foredeep basin deposits (Plio-Pleistocene age), which are mainly marly-clayey and show a thickness above 500 meters. In fact, these lithotypes are generally considered aquicludes (*Desiderio et al., 2011*), if compared with the regional limestone aquifers of Apennines. However, a coarsening upward trend characterizes the upper portion of this stratigraphic sequence, with arenaceous deposits and even conglomerates on the top. From a geomorphological viewpoint, the areas with coarser outcrops show a flat shape and sub-vertical slopes, as boundaries. At the base of these scarps, springs can be found at the interface between coarse and fine deposits, whereas these arenaceous bodies are actual aquifers.

In fact, a regular landscape, high position over the sea, and natural springs are the main reasons for settlement in these plain areas since pre-history. Until the middle of the last century, contact springs were the only water resource for every purpose. Groundwater was exploited by historical complex systems of wells and drainage tunnels, nowadays abandoned (*Martella, 1981*).

Until now, hydrodynamics and hydrochemical features of this kind of aquifer have not been investigated deeply, because they have always been considered a worthy water resource. However, they could play a crucial role in an integrated water management, especially to cope with climate changes and drought periods.

Considering these, the main purpose of this study is to investigate from a hydrogeological point of view, and to assess the groundwater quantity and quality. Five examples throughout the Abruzzo region have been considered. For each, wells and springs have been monitored seasonally (i.e. hydraulic heads or discharge, and physico-chemical parameters), pumping tests have been carried out, and water balance has been calculated.

First results indicate that groundwater quantity and quality proved to be suitable for multi-purpose utilization.

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## **Groundwater chemical evolution in flysch supported by geophysical and hydrochemistry investigation**

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**Key words:** Fractured aquifer; Flysch; Hydrochemistry; Isotopes; Geoelectrical survey.

The research aims to describe the water chemical evolution along the underground flow path that connects the surface with the deep circulation in fractured flysch. The methods used in the research are potentiometric groundwater level measurements, groundwater electrical conductivity and temperature measurements in wells and springs, geoelectrical survey, water chemical (Ca, Mg, Na, K, B, Sr, HCO<sub>3</sub>, SO<sub>4</sub>, Cl) and isotopic ( $\delta$ D,  $\delta$ 18O, T, 87Sr/86Sr) analyses. The potentiometric water level measurements, the groundwater electrical conductivity and the geoelectrical survey highlight a continuous recharge flow from a surface torrent and the subsurface flysch. Along this multiple flow paths, the water chemical analyses show a chemical evolution from Ca-Carbonate to Na-Carbonate type, preserving the  $\delta$ D and  $\delta$ 18O water composition, that is corresponding to the local meteoric precipitation. During the chemical evolution, a variation is recorded in the T content and the 87Sr/86Sr value. In detail, the T decrease from the Ca-Carbonate to Na-Carbonate type and at the same time the 87Sr/86Sr value increases.

## Using multi-sensor capacitance probe for soil water management: results from sandy soils in Central Italy

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**Key words:** infiltration, sandy soils, electromagnetic methods, water resources sustainability.

The achieving of sustainable water management requires reliable soil moisture data, which are essential for understanding processes in the unsaturated zone (e.g., infiltration, migration of pollutants, etc.). The monitoring of soil water content contributes to reaching the United Nation (UN) Sustainable Development Goals (SDGs) [1]. In this framework, there is increasing interest in instruments' performance for estimating water content by electromagnetic methods. A recent study carried out in Central Italy [2] showed that the calibration and validation of an MCP (Multi-sensor Capacitance Probe, PR2/6 of the Delta-T Device) are essential to obtain reliable data. Inaccurate estimates of soil moisture data impact the evaluation of threshold value above which the runoff significantly increases. The present work shows the results of infiltration experiments carried out at laboratory scale (soil column) and in an experimental field characterized by sandy soils widely outcropping in Central Italy. Reliable soil moisture data coupled with the modeling of unsaturated parameters [e.g., 3], can accurately describe the dynamics of water in soils, contributing to water resources sustainability.

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## **Is sustainable remediation possible? A real case of groundwater remediation with no water consumption**

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Key words: groundwater, sustainability, circular economy, water reuse.

This work presents an example of design and application of the principles of the circular economy to the remediation of a contaminated site.

Located in the Piedmont plain, the site is a decommissioned industrial area with a total surface of approximately 20 ha; groundwater is impacted by total chromium, hexavalent chromium and chlorinated solvents.

For more than 10 years, a P&T system has been pumping water and discharging thousands cubic meters of water into the sewer to ensure contamination containment: despite this huge effort, the remediation goals have not been achieved yet.

Therefore, it was necessary to evaluate different solutions to optimize the time to achieve the remediation goals. The new project, based on the principles of sustainability and recovery/safeguarding of the groundwater resource, foresees an hydraulic control system obtained through downstream water pumping and upstream water re-injection, creating a groundwater recirculation cell, which isolates the source of contamination in the aquifer from the surrounding groundwater and promotes the remediation objectives: containment of the plume and removal of contamination, ensuring zero water consumption.

The Public Authorities approved the new project by accepting the remediation goals, calculated by means of site-specific Risk Assessment, and after the field tests that validated the groundwater flow model, in 2021 the system is going to be completed.

Moreover, as a further step, a pilot test based on the technology In Situ Chemical Reduction is going to be implemented: in case of positive results, this additional technology could be deployed on site to replace the hydraulic barrier with a reactive barrier, further reducing the impacts of groundwater remediation at this site.

We believe that the combination of good design and great attention to the preservation and reuse of resources can guarantee a better present for ourselves and a great future for the new generations.

## **Assessment of combined effects of 2016 seismic sequence and recharge variability on the groundwater storage and potentiality of the Pescara del Tronto aquifer (Sibillini Mts., central Italy)**

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**Key words:** groundwater resources management, seismic sequence, water budget analysis.

The long-term effects of the 2016 seismic sequence, that strongly affected the groundwater flow of the Basal aquifer in the Mts. Sibillini area, have been investigated for the aquifer feeding the tapped spring of Pescara del Tronto, host in the calcareous Scaglia and Maiolica complexes (southern sector of the Sibillini Mts).

The water budget analysis, implemented starting from the discharge data and the evaluation of seasonal and annual variability of the aquifer recharge, revealed that the progressive shortening of the discharge of the tapped spring is a result of overlapping causes, attributable both to the seismic sequence and to the recharge variability.

The baseflow recession analysis confirmed a transient enhancement in hydraulic conductivity after the seismic sequence, although the latest data support the assumption of a gradual recovery of the depletion coefficient  $\alpha$  to the pre-seismic values. The main seismic events, by pore pressure propagation, triggered a short-term general increase of the discharge of the studied spring resulted in a water surplus of about 2 million m<sup>3</sup>, zeroing the dynamic reserves and requiring a contribution from the static deep reserves too.

In conjunction, the study highlighted since 2017 a reduction of snow cover permanence, triggering a decrease the meteoric recharge of the aquifer, which hinders the recovery of the spring discharge to pre-seismic values. Further, as a result of the earthquakes, part of the groundwater previously drained by the tunnel drainage, is now flowing out at lower altitudes.

Through the analysis of the recession coefficient  $\alpha$  and of the recharge variability, future scenarios have been carried out, previewing the discharge return to the pre-seismic conditions in a limited number of years. Consequently, in the immediate future it would be recommended to use additional sources (e.g. the new ones located at lower elevation), to ensure the requested drinking water amount.

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## Hydrogeochemical characterization and quality evaluation of the water resources in the micro-basin of the Chibunga River (Ecuador)

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**Key words:** stable isotopes, water resources, recharge, hydrogeochemistry, Ecuador.

A hydrochemical and isotopic characterization of water resources was performed in the micro-basin of the Chibunga River (Ecuador). This area has suffered for years of social conflicts for the access to water, due to an inadequate water resources management system. Moreover, there is a deficiency of information about water quality and groundwater recharge.

The study area is about 14 km long from the Chimborazo volcano to the Chibunga River, it is the border between the cantons Riobamba and Colta. It is a relatively flat agricultural and livestock area of great importance in the local economy.

The multilayer aquifer system consists in volcanoclastic deposits, alternating pyroclastic and lava layers. An unconfined shallow aquifer is located in the most superficial part, feeding the plain springs. More in depth, confined and semiconfined aquifers are hosted in the more permeable layers, and are used for drinking water purposes. The plain is bordered by volcanic formations, mainly of andesitic rocks, characterised by a fractured low permeability. According to the literature, the aquifer system is mainly recharged by melting glaciers from the Chimborazo volcano. However, glaciers has been affected by a generalize retreat in the last decades that influences the waters availability.

A sampling campaign was conducted to provide hydrogeochemical characterization of the surface water and groundwater resources. The quali-quantitative state was determined through the analysis of some elements (As, B, Sb) and metals (Fe, Mn, Cr, Cd, Cu, Ni, Co, Zn), trying to explain their anthropogenic or natural origin. The isotopic analyses ( $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ) in the different water compartments have allowed, in combination with other data based on geology, hydrology, groundwater hydrochemistry, to trace the source of water and its flow pathway.

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## **Hydrogeochemical characterization as a tool to perform risk assessment on wells, springs, and surface water intake in the scope of the Water Safety Plan**

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**Key words:** Water Safety Plan, Risk Assessment, Groundwater quality.

The most recent European (Directive (EU) 2020/2184) and Italian laws on drinking water include the Water Safety Plan (WSP) approach as a requirement. The WSP approach is based on a detailed risk assessment and management of all the steps in the drinking water supply chain from collection to distribution (Lucentini et al., 2014). Although collection is the first and therefore a crucial step of the supply chain, there is no standardized procedure to assess all the possible natural and anthropogenic risks relating to water quality before any treatment. In this work, an integrated approach is proposed, to support a water quality risk assessment over different geological contexts and concerning different type of water collection (wells, springs and surface water intakes). This approach combines hydrogeological, hydrochemical and hydrodynamical characterization to reach a detailed understanding of the conceptual system, and the definition of the natural and anthropogenic risks, using the ordinary monitoring data provided by Acque Bresciane Srl in the scope of a scientific collaboration.

The study area is in northern Italy, covering 78 municipalities in the Brescia province. Water quality data of ca. 300 collection sites were analysed through multivariate statistical analysis, to identify the main hydrogeochemical phenomena occurring in different water bodies. A total of 36 hydrogeological cross-sections were elaborated, covering the morainic amphitheatres of the Lakes Iseo and Garda and the high and low plain between Oglio and Chiese Rivers. Furthermore, piezometric data were analysed, to understand flow directions, trends, and depth. The detailed understanding of the systems reached through all these different analyses led to the identification of the possible hydrogeochemical hazardous events, and to the parametrization of the different exploited water bodies' characteristics influencing the hydrogeochemical vulnerability of each water extraction system in relation to each hazardous event.

Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption [Online]. [Accessed 08 February 2021]. Available from: <http://eur-lex.europa.eu/>

Lucentini, L., Achene, L., Fuscoletti, V., Nigro Di Gregorio, F., Pettine, P., 2014. Linee guida per la valutazione e gestione del rischio nella filiera delle acque destinate al consumo umano secondo il modello dei Water Safety Plan, (Rapporti ISTISAN 14/21).

## Friuli Venezia Giulia Region: protection and management of the Karst Aquifers

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**Key words:** groundwater, karst, vulnerability, Slovene Approach.

The 40% of the whole Friuli Venezia Giulia Region (FVG) consists of carbonate aquifer and most of these are highly karstified. Waters availability and their protection is still a priority in order to sustain the always increasing water demand due to the growing population. To accomplish this aim, the Department of Mathematics and Geoscience of the University of Trieste and the Geological Service of the Friuli Venezia Giulia Region have developed a multi-year project to identify the regional and cross-border karst aquifers and to quantify their vulnerability. The first step of the project was to identify and outline the karst areas and related aquifers. This was done preparing an operative protocol based on three different criteria: the presence of karstifiable lithologies, the individuation of epigean and hypogean karst features, and the karst springs location. The lithological heterogeneity typical of the rocks present in the FVG, allowed to identify 124 different karst aquifers: 70 in limestones/dolostones, 45 in evaporates, 7 flysch (alternations of sandstones, marls and carbonatic megabeds) and 2 in conglomerates. Thanks to the data available in literature, hydrogeological maps have been realised for each aquifer. In light of protect and preserve the karst groundwaters, a new phase of the project started with the aim to evaluate the vulnerability of 15 meaningful karst aquifers. Among the several available protocols, we decided to apply a modified version of the Slovene approach, which in turn is a modified version of the Spanish COP method, in order to adequate it to the geological context of the FVG. To approach the resource vulnerability, we started with the area of Timau, a cross-border karst aquifer shared between Italy and Austria. This area having its recharge in Austria and the outflows in Italy represent the most important water supply of the high FVG mount region.

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## **Analysing long time-series of groundwater levels in a paddy field area (Piedmont region, NW Italy): preliminary results**

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**Key words:** water table, groundwater hydrodynamic behaviour, trend, paddy fields.

The analysis of the time-series of groundwater level is extremely important to observe the behaviours of groundwater over time and to identify any critical situations (Lasagna *et al.*, 2020).

The studied area is an agricultural district characterised by paddy fields, located in the eastern part of Piedmont, on the border with Lombardy. In this area long time-series of groundwater level, starting from the 1960s, have been collected in 20 wells.

Water table data have a good continuity (in the majority of the cases >90%).

Firstly, the groundwater hydrodynamic behaviour, based on water table levels, was investigated to highlight the response of groundwater to the irrigation. A basic statistical analysis was performed (mean, median, standard deviation, maxima, minima), and then trends of water table levels were evaluated in order to better observe the long-term behaviour of groundwater.

Trends were performed on average and maxima annual data, and also on the minima annual data, which are, most likely, the data less influenced by the watering of the paddy fields.

These analyses allowed to observe a groundwater hydrodynamic behaviour characterised by a repeating annual pattern (minimum in February/March and maximum in August/September) clearly linked to the phases of irrigation.

Moreover, trend analysis highlighted the presence of both wells with a decreasing water table (with maximum lowering of 4.3 m in 60 years) and wells with an increasing water table (with maximum rises of 2.8 m in 35 years). Furthermore, in most cases, it can be observed that all three trends analysed agree on being positive or negative.

Future insights will be the comparison of these long time-series with the meteorological data, and the investigation of other factors (e.g. anthropic withdrawal, variations of cultivation practices and irrigation, geology of the subsoil) to better understand the causes of the water table fluctuations and trends.

Lasagna, M., Mancini, S. & De Luca, D. A. Groundwater hydrodynamic behaviours based on water table levels to identify natural and anthropic controlling factors in the Piedmont Plain (Italy). *Sci. Total Environ.* 716, 137051 (2020)

## **The path of water in relation to human communities: history of a middle-age aqueduct in Apulia (southern Italy)**

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**Key words:** aqueduct, history, artificial cavities, Apulia.

Availability of freshwater has always played a crucial role in the foundation and establishment of human communities. In regions characterized by arid or semi-arid climates, or in karst areas where surface water is typically lacking or very scarce, this has often been a problem, forcing man to look for water through detailed knowledge of the local hydrogeology. From these issues, the realization of hydraulic works, frequently entirely or in part built underground, started in different epochs.

In the research here presented, starting from the outcomes of a project dedicated to ancient underground pipelines in Italy, we describe the hydrogeological setting and the historical framework of the “S. Angelo – Fontana della Stella” water supply system, one of the most remarkable evidence in the territory of Gravina in Puglia (Apulia). As documented by historical sources, the construction of the hydraulic work started in 1743. With an overall length of 3,500 meters, the aqueduct is one of the best preserved underground man-made structures for collection and transport of water resources in southern Italy. It starts from an intake located some kilometers north-west from the town, draining waters coming out at the contact between Plio-Pleistocene calcarenites and the overlying clays. A system of underground galleries, connected to the surface by a number of inspection wells, allowed the waters to flow to the town. The subterranean system ends up at the right valley side of the Gravina Torrent; to pass the deep canyon, and let the water reach the final destination where, a bridge-channel was built across the torrent. As described from the speleological explorations, and the historical researches as well, the “S. Angelo – Fontana della Stella” water supply system is a very important heritage for the entire region, since it represents one of the most significant ancient subterranean water systems in Apulia, also testifying the hydrogeological knowledge reached at the time of its realization.

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Parise, M., Bixio, R., Burri, E., Caloi, V., Del Prete, S., Galeazzi, C., Germani, C., Guglia, P., Meneghini, M., & Sammarco, M. 2009. The map of ancient underground aqueducts: a nation-wide project by the Italian Speleological Society. *Proceedings 15<sup>th</sup> International Congress of Speleology*, Kerrville (Texas, USA), 19-26 July 2009, 3, 2027-2032.

Parise, M., Galeazzi, C., Bixio, R. & Dixon, M. 2013. Classification of artificial cavities: a first contribution by the UIS Commission. In: Filippi M., Bosak P. (Eds.), *Proc. 16th Int. Congr. Speleology*, Brno, 21-28 July 2013, 2, 230-235.

## Hydrogeological impact of a railway tunnel. An application of time series analysis.

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Key words: hydrogeological, tunnel, time series decomposition.

In Tuscany are in progress the expansion of the A1 Highway Milan – Naples – Barberino di Mugello – Florence North stretch. As part of the environmental monitoring of this project, various investigations were carried out on the possible hydrogeological impact caused to a spring, with a reduction in flow rate, by the tunnel “*Santa Lucia*” construction with an earth pressure balance shielded tunnel boring machine (TBM – EPB). A first indication that the excavation involved the groundwater drainage, was provided by the rapid, albeit transitory, decrease in level, before the passage to the progressive of the source, in a control piezometer, located approximately in line with the tunnel and equipped with datalogger.

To confirm this impact and its unsteady condition, in addition to the usual hydrogeological assessments, a statistical analysis was carried out, conducted with the R software, applied to the time series [1] of spring flow rate data and rainfall data, recorded on a reference rainage. The analysis focused on the numerical “decomposition” of the three components: *trend*, *seasonal* and *random*. The multi-year periodicities, highlighted by the *trend* component, were analyzed and valued through the “autocorrelation” technique. Finally, the “cross-correlation” analysis was conducted on the two variables rain and flow, linked by a cause-effect relationship.

Results of the analysis showed that the reduction in spring flow rate occurred in a dry hydrogeological year. However, a transient response, in terms of anomalous reduction of the flow rate, is indicated by the same statistical analysis of the components which show, at the passage of the excavation to the progressive of the spring, the maximum subtraction of the outflow by the *random* component.

An external event that could correspond to a perturbation to the system such as that of a drainage induced by the excavation.

[1] Wuertz D., Setz T., Chalabi Y. (2017) – timeSeries: Rmetrics - Financial Time Series Objects -<https://cran.r-project.org/web/packages/timeSeries/index.html>

## 3D model of Alpine Aquifers of Lombardy (Italy)

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**Key words:** geological modelling, hydrostratigraphy, hydrochemistry, forecasting scenarios, groundwater resources.

The protection and management of groundwater resources, as well as the elaboration of forecasting scenarios responding to climate changes, need reliable three-dimensional hydrostratigraphic and hydrogeological models as support. In mountainous regions, building these models is particularly challenging. They must reconstruct the complex geological-structural architecture of rock aquifers, but they need to be simple enough to allow the set-up of a conceptual stratigraphic and structural input model for further hydrostratigraphic parameterization and numerical computations.

We apply this approach to 3D modelling of the complex stratigraphic, structural, and hydrogeological setting of the Lombardy Alps (N-Italy), a more than 10.000 km<sup>2</sup> wide study area. The study aims to:

- evaluate the present ground- and surface water availability;
- evaluate future scenarios for groundwater availability, in the framework of local and global climate changes;
- identify areas of specific interest for implementing groundwater monitoring networks;
- identify recharge areas of the most relevant springs, to implement protection strategies of the resource.

Along the Insubric Line, the poly-deformed, fractured crystalline basement nappes of the Central-Northern Alps join the Southalpine fold-thrust belt, which hosts the most productive porous karstified carbonate aquifers, thrust over less pervious clastic and crystalline rocks. The “IDROMONT” hierarchic Geodatabase was built *ad-hoc*, to store and integrate all the available 2-D geological maps and cross-sections, hydrological, hydrochemical, and meteorological data. The preliminary 3D geological model was computed based on the potential field interpolation method (3DGeoModeller®).

After porosity - permeability parameterization, Hydrogeological Units (HU) were identified through the hierarchy of tectono-stratigraphic units. Springs discharge and the available hydrochemical facies were then related to the spatial distribution of the HU. The 3D model allows comparing the outcomes of the hydrological balance computation with estimates of storable water volumes, considering alternative scenarios of runoff, infiltration and aquifer saturation, and checking the consistency of the expected groundwater storage.

# Investigating the feasibility of using precipitation measurements from weather radar to estimate recharge in regional aquifers: the Majella massif case study in central Italy

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**Keywords:** Rainfall, Weather radar, Aquifer recharge, Water balance, Majella massif.

The measurement of precipitation, based on traditional rain gauges, exhibits many limitations due to the spatial and temporal high variability of atmospheric precipitation. In the past decades, the use of ground-based microwave weather radar has greatly improved the quantitative rainfall estimation by providing spatially continuous estimates of rainfall, at high temporal (i.e., few minutes) and spatial resolution (i.e., hundreds of meters). Furthermore, weather radar data have also proved to be relatively reliable in mountainous areas (Vulpiani et al., 2012). These paramount features of radar-derived precipitation data could definitely improve the estimation of recharge of aquifers, which generally rely on geospatializations (e.g., Thiessen polygons) of rainfall data, collected by a sparse rain gauge network. In regional aquifers, the rain gauge network is often lacking at high altitude (i.e., recharge areas), introducing additional uncertainty in the inflow volumes. Indeed, weather radar rainfall estimation is also affected by various sources of error, comprehensively discussed in literature (Collier, 1996), that can be reduced by proper post-processing; however, uncertainties still remain, especially for surface rain rate estimations.

Based on these considerations, this study is aimed at evaluating the feasibility of using radar-based precipitation data to estimate aquifer recharge and calculate a detailed water balance in the areas characterized by high elevations, such as the Majella massif (Nanni and Rusi, 2003). To address this objective, the Majella aquifer water balance has been calculated in the 2017-2018 period using both radar-based precipitation data and rain gauge data as well as adopting different methods (i.e., Turc, and Thornthwaite). Although intrinsically uncertain, the radar-based precipitation data provided robust results, pointed out by the comparison with water balance, obtained by rain gauge data, and the Majella aquifer total discharge. This interdisciplinary work may pave the way for continuous monitoring of aquifer recharge at very high temporal and spatial resolution.

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Nanni T., Rusi S. (2003) Idrogeologia del massiccio carbonatico della Majella (Abruzzo). Boll. Soc. Geol. It. 122 (2), 173-202.

Vulpiani G., Montopoli M., Delli Passeri L., Gioia A., Giordano P., Marzano F. (2012) On the Use of Dual-Polarized C-Band Radar for Operational Rainfall Retrieval in Mountainous Areas. Journal Of Applied Meteorology And Climatology, 51, 405-425.

## Transmissivity estimates by specific capacity data of fractured carbonate aquifers (Umbria Region, Central Italy)

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**Key words:** pumping test, carbonate aquifers, transmissivity, specific capacity.

Transmissivity estimates can be obtained by different approaches, mainly analytical and empirical. The application of analytical methods requires corrections for non-linear well losses due to turbulence and vertical flow related to partial penetration. The empirical approach relates transmissivity ( $T$ ) values to specific capacity ( $S_c$ ) data measured in the same well. Several studies in the literature presented  $T = f(S_c)$  relationships for different aquifer types (fractured rocks, sandstones, alluvial, etc.). Among these, Fabbri (1997), Mace (1997), and Hsu and Chou, (2019) analyzed fractured and karst rocks. As reported by Mace (1997), the  $T = f(S_c)$  relationship for the carbonate karst aquifer in Central Texas can be probably used for carbonate aquifers located in other regions. In this framework, the present work collected about thirty  $T$ - $S_c$  data from pumping test in limestone aquifer hosted in limestone formations of Umbria-Marche Sequence. A new relationship to estimate  $T$  by  $S_c$  data is proposed and compared with other relationships for similar aquifers worldwide. Results can improve the knowledge of fractured-karst aquifers, considering also data from Central Italy.

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Mace, R.E. 1997. Determination of transmissivity from specific capacity tests in a karst aquifer. *Groundwater*, 35(5), 738-742. <https://doi.org/10.1111/j.1745-6584.1997.tb00141.x>

Hsu, S.M., Chou, P.Y. 2019. Applicability of method to estimate transmissivity based on yield-drawdown analysis in mountainous fractured-rock aquifers: A case study in Taiwan. *Engineering Geology*, 262, 105315. <https://doi.org/10.1016/j.enggeo.2019.105315>

## **The hydrogeological role of some slip surface in a roto-translational landslide: the case study of Case Pennetta (Northern Apennines)**

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**Key words:** Roto-translational Slide; Hydrogeological Behaviour, Slip surface, Northern Apennines.

The hillslope of Northern Apennines is characterized by widespread occurrence of complex landslides due to the specific geological setting. Several authors (e.g. Di Maio et al., 2020) recognized the role of discontinuities, and particularly of sliding surfaces, as preferential flow and thus as a factor predisposing the slope to failure.

The aim of this research is to analyse through hydrogeological and isotopic investigation the role of slip band on groundwater circulation at “Case Pennetta” landslide. Piezometric data coming from two multilevel monitoring systems show a different groundwater regime: piezometers located in the landslide body show a fast infiltration of precipitation along preferential flow paths such as macropore, cracks, ect. followed by less rapid infiltration processes along the joint and fracture network in the matrix. In this portion of the landslide, variation over time of EC and  $\delta^{18}\text{O}$ - $\delta^2\text{H}$  composition of springs, drains and groundwater is wide and strictly related to the mixing processes between rain- and groundwater; the tritium content is not far from those found in rainfall. Conversely, the piezometer registering the pore pressure along the slip surface shows only a seasonal trend according to the rainfall regime, but is weakly related to the single precipitation events. The smoothed groundwater level variations suggests well-organized flowpaths. Moreover, the constant values over time of high EC and stable isotope composition, joined with the absence of tritium content, underline that inside the sliding surface the groundwater flowpaths are long and slow. Probably this is due to the continuous displacement along the slip surface that can cause changing in the clay minerals, given a very low permeability characteristic of the band.

Thus, pore water pressure and geochemical/isotopic data demonstrate that, in this case study, sliding surface behaves as an aquiclude where, differently to the finding of other Authors, the groundwater shows ultra long lived transient condition.

Di Maio, C., De Rosa, J., Vassallo, R., Coviello, R., Macchia, G. 2020. Hydraulic conductivity and pore pressures in a clayey landslide: experimental data, *Geosciences* 10 (3), 102 doi:10.3390/geosciences10030102

## The application of the TFM-ext model for the evaluation of the pesticide transport along the unsaturated zone.

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**Key words:** groundwater vulnerability assessment, extended transfer function model, pesticides, S-DSS.

This work presents the extended transfer function model (TFM-ext) which allows to simulate the spatio-temporal distribution of nonpoint-source pollutants, e.g., pesticides, along the unsaturated zone (Bancheri et al., 2021). The model is based on the transfer functions approach (Jury and Roth, 1990), i.e., on the travel time probability density functions (TT pdfs). Despite the two important assumptions on i) time-invariant TT pdfs and ii) steady-state input fluxes, the strength of TFM-ext is that it derives the TT pdfs from a physical quantity, i.e., the unsaturated hydraulic conductivity function  $k(\theta)$ . Where information on the hydraulic properties is not available, the model assumes a lognormal travel time pdf, whose parameters are derived according to the generalized transfer function model (Zhang R., 2000). In the case of reactive solutes, such as pesticides, it considers both the mass decay and the retardation factor. The TFM-ext was validated using 4 large soil columns, comparing the simulated and measured breakthrough curves of a non-reactive solute. Results were really good, with the best agreement with  $R^2=0.97$ ,  $RMSE=0.11$  and  $ME=-0.01$ . Moreover, forty-six soil profiles sampled in Valle Telesina, Italy, completely characterized from the hydrological point of view, were used to evaluate the mean travel times and the breakthrough curves at the groundwater depth and then compared with the results of a physically based model, Hydrus 1D. Results gave very high  $R^2$  (above 0.8), a MAE of around 40 days and a PBIAS of -16%. Eventually, a comprehensive sensitivity analysis to evaluate to which parameters the TFM-ext is more sensitive, was performed. Results shown that  $\tau$ ,  $n$  and  $\theta_s$  parameters related to the slope of the  $k(\theta)$  are those affecting more the travel time. The model was implemented as an operative tool for the specific groundwater vulnerability assessment within the geospatial Decision Support System developed for LANDSUPPORT H2020 project.

Bancheri, M., Coppola, A., & Basile, A., 2021. A new transfer function model for the estimation of non-point-source solute travel times. *Journal of Hydrology*, 598, 126157.

Jury, W.A., Roth, K., et al., 1990. Transfer functions and solute movement through soil: Theory and applications. Birkhäuser Verlag AG.

Zhang, R., 2000. Generalized transfer function model for solute transport in heterogeneous soils. *Soil Science Society of America Journal* 64, 1595–1602.



## **A comprehensive geodatabase to supporting the management of the coastal carbonate aquifers of Adriatic and Ionian Seas**

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**Key words:** Coastal Carbonate Aquifer, seawater intrusion, geodatabase, Ionian Sea, Adriatic Sea.

The increasing groundwater exploitation and contamination risks due to the progressive population growth in coastal areas are emphasised in the case of carbonate coastal aquifers (CCAs), the peculiarities of which, especially in the Mediterranean basin, constitute a scientific matter of worldwide relevance.

The CCAs of the Adriatic and Ionian coasts not only ensure the socio-economic development of the populations but feed with their spring waters valuable wetland and coastal environments with relevant and highly positive effects on ecosystems. The groundwater resources of CCAs are highly vulnerable, especially if affected by karstic phenomena, to the quality and quantity degradation phenomena, not only for the increasing water demand and the decreasing recharge due to climate changes but also in relation to the sea level changes and the pollutant loads due to the contamination occurred in the whole hydrogeological basins.

The aim of this study is to offer a systematic and synoptic view, useful for knowledge, management and forecast purposes, contributing to assure enduring availability of high-quality groundwater, conciliating water demand satisfaction with the ecological needs of coastal Adriatic and Ionian environments in which the role of groundwater is very important. A geodatabase, collecting information for all carbonate aquifers present along the Adriatic and Ionian coast, have been created. At the core, there is a Geographic Information System, in which are placed the spatial information regarding the geology of aquifers, hydrogeological and geochemical features, together with specific information concerning groundwater use of CCAs. The added value of this database is the availability of a wide bibliography related to CCAs, together with a schematised summary of key information realised considering available information in the whole geodatabase.

## **Analysing long time-series of groundwater levels in a paddy field area (Piedmont region, NW Italy): preliminary results**

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**Key words:** water table, groundwater hydrodynamic behaviour, trend, paddy fields.

The analysis of the time-series of groundwater level is extremely important to observe the behaviours of groundwater over time and to identify any critical situations (Lasagna *et al.*, 2020).

The studied area is an agricultural district characterised by paddy fields, located in the eastern part of Piedmont, on the border with Lombardy. In this area long time-series of groundwater level, starting from the 1960s, have been collected in 20 wells.

Water table data have a good continuity (in the majority of the cases >90%).

Firstly, the groundwater hydrodynamic behaviour, based on water table levels, was investigated to highlight the response of groundwater to the irrigation. A basic statistical analysis was performed (mean, median, standard deviation, maxima, minima), and then trends of water table levels were evaluated in order to better observe the long-term behaviour of groundwater.

Trends were performed on average and maxima annual data, and also on the minima annual data, which are, most likely, the data less influenced by the watering of the paddy fields.

These analyses allowed us to observe a groundwater hydrodynamic behaviour characterised by a repeating annual pattern (minimum in February/March and maximum in August/September) clearly linked to the phases of irrigation.

Moreover, trend analysis highlighted the presence of both wells with a decreasing water table (with maximum lowering of 4.3 m in 60 years) and wells with an increasing water table (with maximum rises of 2.8 m in 35 years). Furthermore, in most cases, it can be observed that all three trends analysed agree on being positive or negative.

Future insights will be the comparison of these long time-series with the meteorological data, and the investigation of other factors (e.g. anthropic withdrawal, variations of cultivation practices and irrigation, geology of the subsoil) to better understand the causes of the water table fluctuations and trends.

Lasagna, M., Mancini, S. & De Luca, D. A. Groundwater hydrodynamic behaviours based on water table levels to identify natural and anthropic controlling factors in the Piedmont Plain (Italy). *Sci. Total Environ.* 716, 137051 (2020)

## New ISPRA Permeability Map of Italy for Nationwide Water Budget Estimation

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Key words: groundwater, water budget, permeability map.

In the context of water resources management the Italian Institute for Environmental Protection and Research (ISPRA) has developed the automatic “Nationwide GIS-based hydrological budget on a regular grid” procedure, named BIGBANG (Italian acronym of “Bilancio Idrologico GIS BAsed a scala Nazionale su Griglia regolare”) (Braca and Ducci, 2018) currently at version 4.0, to evaluate the water budget components at monthly and annual temporal scale and in spatially distributed approach, from 1951 until 2019. The groundwater recharge component has been estimated as a percentage (Coefficient of Potential Infiltration, CIP) of the term precipitation minus evapotranspiration in function of the permeability of the outcropping hydrogeological units based on Mouton map (Mouton et al., 1982).

In this study, the new and more detailed Permeability Map of Italy (<http://portalesgi.isprambiente.it/it>), produced by ISPRA, is used to estimate the groundwater recharge. In particular, the Permeability Map is available on the scale 1:100.000 and has been partly derived from the official lithological cartography of Italy and partly obtained from the information available in the Geological Map of Italy integrated with geological and hydrogeological knowledge. The rock formations, at a first level of definition, have been divided into four classes of high to low permeability. Within each class, the types of three permeability have also been distinguished: primary and porosity permeability, fissuration and karst, and mixed type. Each class combination has been assigned a guideline value for the coefficient of permeability and the CIP.

Braca, G. and Ducci, D., 2018, Development of a GIS based procedure (BIGBANG 1.0) for evaluating groundwater balances at National scale and comparison with groundwater resources evaluation at local scale. In *Groundwater and Global Change in the Western Mediterranean Area* (pp. 53-61). Springer, Cham.

Mouton J., Mangano F., Fried J.J., 1982, *Studio delle risorse in acque sotterranee dell'Italia*. Th. Schafer GmbH. D. 3000 – Hannover

## Structuring of a database of Campania springs (southern Italy) and regional hydrogeological analysis

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Key words: groundwater, climate change, spring, discharge.

The recognition and characterization of groundwater resources is an important task for a territorial planning aimed at their proper management and protection of groundwater-dependent ecosystems. This topic is particularly significant for the Campania region due the strong dependence of social, economic and environmental conditions on groundwater resources. The hydrogeological framework of the region comprises the most relevant aquifers of southern Italy, such as karst, alluvial, volcanic and terrigenous ones, the latter including flysch and basin series aquitards and aquicludes (De Vita et al., 2018). Therefore, this region is characterized by a high availability of groundwater resources, which is threatened by climatic changes.

In such a framework, the collection of data on springs and discharge measurements is crucial point for the assessment of groundwater availability and its temporal variability. A systematic recognition of all springs was carried out in Italy only in the 1930s and 1950s of the last century by the 'Ministero dei Lavori Pubblici', a technical government agency, and published in the volumes 'Le sorgenti italiane' (Italian springs) series (Ministero dei Lavori Pubblici, 1941, 1942, 1952a, 1952b). After this comprehensive recognition, only non-systematic discharge measurements were carried during 1970's and 1980's on major springs for their tapping. Moreover, data gathered in the first recognition has not been yet analyzed, thus still representing a valuable source.

In this work, identity data collected for each spring (name and position) during the first recognition in Campania region (Ministero dei Lavori Pubblici, 1942) were validated by a crosscheck with other sources of data. Moreover, in order to assess the variation of the spring discharge over time, first spring measurements were analyzed comparatively with those collected in the following years. Finally, a statistical analysis of spring parameters in relationship to the aquifer type was carried out allowing the characterization of groundwater circulation in different aquifers.

Results obtained represent new advances of hydrogeological knowledge of the Campania groundwater resources and provide useful informations for planning their future use, not excluding the discovery of new resources to be used in case of drought scenarios.

De Vita, P., Allocca, V., Celico, F., Fabbrocino, S., Mattia, C., Monacelli, G., Musilli, I., Piscopo, V., Scalise, A.R., Summa, G., Tranfaglia, G., & Celico, P. (2018). Hydrogeology of continental southern Italy. *Journal of Maps*, 14(2), 230-241. doi:10.1080/17445647.2018.1454352.

Ministero dei Lavori Pubblici (Consiglio Superiore). Sezione Idrografica di Napoli – Campania (1942). *Le Sorgenti Italiane. Elenco e descrizione*. Pubblicazione N.14 del Servizio Vol. VII. Libreria Istituto poligrafico dello Stato Roma.

## **Hydraulic head in riverbed under influence of infiltration intake. Case study from Oława River, SW Poland.**

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**Key words:** infiltration intake, riverbed hydraulic conductivity, surface- groundwater interaction.

Management of water resources has traditionally focused on surface water or groundwater as if they were independent components. While, river-groundwater interactions should be at the core of hydrogeological investigations. About main characteristics of this interaction decide: riverbed thickness and hydraulic conductivity, heads differences (Hdif) between river and aquifer nearby.

There have been many studies on the hydraulic conductivity, focusing mainly on its spatial variability or anisotropy. (i.a Ghysels at al. 2018, Chen 2000), while the hydraulic conductivity (K) spot measurement methodology does not sufficiently focus on the Hdif. The encountered head differences are a pivotal factor affecting the correctness of K assessment, and this determines the potential additional resources of the riverbank infiltration intake or the assessment of its operating conditions.

This article analyzes the riverbed head measurement in the Oława River, lowland river in SW Poland, under the influence of an infiltration intake, in complex conditions: low riverbed permeability, high water depth and significant Hdif.

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<https://doi.org/10.1007/s002540000172>

Ghysels, G., Benoit, S., Awol, H., Jensen, E.P., Tolche, A.D., Anibas, C., & Huysmans, M. (2018). Characterization of meter-scale spatial variability of riverbed hydraulic conductivity in a lowland river (Aa River, Belgium). *Journal of Hydrology*, 559, 1013-1027.  
<https://doi.org/10.1016/j.jhydrol.2018.03.002>

## **Sharp & smooth inversion strategies of the AEM data to reconstruct the geological context in granular aquifers and in rocky aquifers useful to the predisposition of the flow model - case study Province of Brescia, Italy**

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**Key words:** AEM Method, Smooth, Sharp, Hydraulic Transmissibility, Flow model.

In February 2021, the UdA of Brescia started a technical board with the water companies A2A Ciclo Idrico and Acque Bresciane to investigate an area of approximately 146,4 km<sup>2</sup> with the AEM Method. This method has been chosen for studying major depths and characterized stratigraphic sequences of boreholes in the east part of the province of Brescia.

AEM survey has allowed us to investigate an area of 300 km<sup>2</sup> in less than 20 days, acquiring 2,000 linear km of data equivalent to about 60,000 electromagnetic probes.

A fluvial deposition environment characterizes the study area; it is delimited to the east by glacial deposits and to the west by the bedrock.

Data have been inverted with two different strategies: i) Smooth offers a solution that establishes a gradual transition between two bodies defined by a contrast of electrical properties. This allowed identifying the geometries and structures of the resistive bodies, which are supposed to represent aquifers, and then to interpret the depositional model; ii) Sharp provides a 'blocky' solution, defining the passage between two bodies characterized by a sharp contrast of electrical properties. This allows to better define the limits of the electro-layers and to build easier the geological structure of the area. This methodology has proved useful for the realization of the geological model.

Moreover, it has been carried an acquisition survey of hydraulic parameters of the boreholes of the area. Thanks to them, it will be possible to extrapolate an empirical relationship between hydraulic transmissibility and transverse electrical resistance obtained from geophysical models. This will allow us to obtain a spatial hydraulic characterization of the water systems.

The findings of this study will be useful to implement a numerical flow model, which will help the water companies to locate new productive wells.

## **Improvement of hydrogeological knowledge by means of Airborne EM – A case study in Lower Saxony (Germany)**

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**Key words:** Airborne EM, Geological modelling, Glacial aquifers, Buried valleys.

Airborne Electromagnetics (AEM) has become a mature technology to support hydrogeologists in the groundwater mapping and geological-hydrogeological modelling. This project was leaded by LBEG (Landesamt für Bergbau, Energie und Geologie) and involved two areas located in Lower Saxony, close to the towns of Rotenburg and Zeven (Northern Germany). The AEM data were acquired by Skytem Aps, while Aarhus Geofisica (now Emergo) was in charge of the data processing and inversion. The advanced workflow we applied (Auken et al., 2009) started from the detailed processing of navigation data (altimeter and tilt corrections) and the removal of decoupling, that was necessary due to the high urbanization of the survey area. Then, a Spatially Constraint Inversion (Viezzoli et al., 2008) and a sharp modelling (Vignoli et al., 2015) provided a 3D distribution of resistivity that was subsequently interpreted from a geological point of view, by exploiting existing knowledge of the subsurface. This was represented just by some geological cross-sections based on sparse borehole stratigraphies and seismic lines. The comparison between the resistivity modelling and the expected geology, showed many accordances: good resolution of the resistive buried glacio-fluvial aquifers (generally located at the bottom of paleovalleys) and of the resistive sandy aquifers within the Pliocenic substratum, in good agreement with the intercepted aquifers by the existing wells. AEM also suggests that a) the geometry of most of the buried valleys would need a substantial refinement, and b) the stratigraphic data are insufficient in number. The resolution capability of AEM has been confirmed in the detection of those aquiclude-aquitards within the glacial cover. The final geological model was used as a starting point to achieve a hydrogeological model that will be used by LBEG for planning new productive wells and for a correct management of the groundwater resources.

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## Optimising groundwater monitoring to ensure the sustainable exploitation of a coastal aquifer system

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Key words: groundwater, coastal aquifer, interface, Ghyben-Herzberg.

The EU Water Framework Directive considers sustainable groundwater use as the “*available groundwater resource not being exceeded by the long-term annual average rate of abstraction*” and establishes the piezometric level as the metric through which the achievement of good status is determined.

In coastal aquifer systems, changes to the piezometric surface are reflected in an amplified response in the freshwater-saltwater interface. This is due to the floating nature of the groundwater body, as outlined by the Ghyben-Herzberg Principle. Hence the development of the interface is considered as a better metric for assessing changes in the status of these aquifer systems.

The piezometric level of the Malta Mean Sea Level aquifer has been monitored since the 1940's, when the aquifer was relatively unexploited. Available piezometric data show that by the 1990's when the aquifer system was extensively over-abstracted, the level had lowered by as much as 2m when compared to the 1940's. This had a significant impact on the quality of water being abstracted.

Monitoring of changes in the highly responsive interface is required to effectively understand the status of coastal aquifers. Malta is implementing a significant enhancement of the existing monitoring network which will enable the profiling of the freshwater column as it transitions to the underlying saline waterbody. The distribution of monitoring sites over the whole island will also enable a representation of the spatial variations of the freshwater column. The development of this monitoring network is being undertaken with the support of the British Geological Survey and the Geological Survey of Korea.

Through the network, the assessment of changes in the freshwater/saline interface will enable the early identification of impacts on local groundwater status, helping the identification of corrective management actions to ensure the continued sustainable utilization of groundwater in Malta.

Badon Ghijben, W. and J. Drabbe 1889. Nota in verband met de voorgenomen putboring nabij Amsterdam. Tijdschrift van het Koninklijk Instituut voor Ingenieurs 1888-1889: 8

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EWA, 2015. Second Water Catchment Management Plan for the Malta Water Catchment District 2015-2021. Energy and Water Agency. The Project for the upgrading of the National Hydrological Monitoring Infrastructure is co-funded by the European Union through the Cohesion Fund – Project CF.10.096



## **A multi-method approach for estimating groundwater recharge of a strategic karst aquifer in southern Apennines, Italy**

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**Key words:** Groundwater recharge, karst aquifer, southern Apennines.

Karst aquifers represent the main source of water supply in southern Italy, thus they play a strategic role for the economic development and environmental conservation of groundwater-dependent ecosystems. The modeling of the groundwater recharge, through the estimation of the water balance at different space-time scales, is a fundamental prerequisite for the optimal management and protection of groundwater resources.

The objective of this work was the estimation and modeling of groundwater recharge, on an average monthly scale, by a multi-method approach implemented in a GIS environment for Mts. Avella karst aquifer, a strategic groundwater resource for the Campania region.

The groundwater recharge estimate was carried out for the period 2000-2018, through the application of the water balance equation, integrating terrestrial hydrogeological and hydrological data with remote sensing information (MODIS data). The Thornthwaite-Mather (1951) and Penman-Monteith methods (Penman, 1948) were used to estimate actual evapotranspiration and subsequently the surplus water. In this way, six estimates of the groundwater recharge were obtained, using different infiltration and runoff coefficients deriving from AGRC and Curve Number methods (USDA, 1986), and integrating hydrogeological, slope, soil type, vegetation cover and land use data. The results show an annual groundwater recharge values between 8.28 m<sup>3</sup>/s and 6.92 m<sup>3</sup>/s, with an average value of 7.77 m<sup>3</sup>/s. The comparison with the groundwater outflows of the karst aquifer (on average equal to 8.6 m<sup>3</sup>/s) deriving from literature data, highlights, on the one hand, the goodness of some estimates and, on the other hand, underlines the need to investigate the potential scenario of imbalance in the water balance that could be envisaged for the karst aquifer studied.

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USDA, 1986. Urban hydrology for small watersheds. Technical release 55 (1986): 2-6.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences* 193.1032 (1948): 120-145.

## **Methodology for identifying groundwater-dependent ecosystems (GDE) and allowing the groundwater status assessment accordingly in Sardinia.**

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**Key words:** groundwater body (GWB), surface water body (SWB), (GDE).

The Water Framework Directive (WFD; 2000/60/EC) aims to establish a framework for protecting waters. Among the WFD's objectives, the achievement of a good groundwater status is required, including a good groundwater quantitative and chemical status. The ecosystems directly dependent on groundwater (terrestrial and aquatic GWDE) can affect the status of a groundwater body (GWB), where is causing significant damage to the GDE. In the framework of updating the River basin management plan of Sardinia, a methodological approach for identifying (SWBs) and terrestrial ecosystems directly dependent from GWB has been proposed. In the first step, a priority has been assigned to the SWBs with a "not good" status or being at risk of failing to meet the objectives set for each body under Article 4 according to their characterization (PdG, 2016). Springs and low-lying coastal areas were considered as potential terrestrial ecosystems in Sardinia, as internal wetlands are usually temporary and feed by rain (Bagella et al., 2010). The GIS-based methodology envisages a cross-referencing procedure of various thematisms, according to the following work-flow:

- 1- Identify fresh perennial, intermittent and ephemeral and transitional SWB according to their "not good" status or being at risk of failing to meet the objectives set for each body under Article 4 (PdG, 2016).
- 2- Select springs
- 3- Use the Special Protection Areas (SPAs), Sites of Community Importance (SCIs), and Special Areas of Conservation, SACs;
- 4- Use the Nature map (Camarda et al, 2015) to identify the Ecological data;
- 5- Select the groundwater (GW) with poor quantitative status.
- 6- Establish whether a connection between GWB and SWB occurs on the base of the hydrogeological information.

According to the schema, the potential GDE will be identified. Remotely satellite acquired data, morphometric and geological data, and field surveys will mainly support the identification, particularly where hydrogeological information is missing.

Bagella S., Caria M.C., Zuccarello V. (2010) Patterns of emblematic habitat types in Mediterranean temporary wetlands. C. R. Biologies 333, 694–700.

Camarda I., Laurenti L., Angelini P., Capogrossi R. (2015) Sistema Carta della Natura della Sardegna. ISPRA.

PdG (2016) Riesame e aggiornamento del Piano di Gestione del Distretto Idrografico della Sardegna, 2° Ciclo di pianificazione. Monitoraggio e classificazione delle acque superficiali. Regione Autonoma della Sardegna. Autorità di Bacino Regionale.

## **IAH recommendations and emerging trends for groundwater inflows and heat management in tunnels**

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Alessandro Boscaro<sup>1</sup>, Alessandro Gargini<sup>1</sup>, Maria Governa<sup>1</sup>, Fabrizio Grosso<sup>1</sup>, Alessandra Insana<sup>1</sup>,  
Marco Masetti<sup>1</sup>, Maria Elena Parisi<sup>1</sup>, Daniele Pedretti<sup>1</sup>, Paolo Perello<sup>1</sup>, Luca Ranfagni<sup>1</sup>, Guido  
Ruffinatto<sup>1</sup>, Riccardo Torri<sup>1</sup>, Sergio Vazzoler<sup>1</sup>, Valentina Vincenzi<sup>1</sup>.

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Key words: sustainability, tunnels, groundwater inflow, energy geostructures.

This paper was developed by members of the Working Group GESTAG (Sustainable Water Management in Tunnels) of the Italian Committee of the IAH. In 2020 the GESTAG published a guideline, which can be downloaded for free from the IAH website. Given the interest in the guideline, also international, the GESTAG decided to translate the guideline into English, to broaden its dissemination. A wide panel of experts contribute to the guideline. Universities', designers', contractors', and public authorities' representatives shared their experience on case histories to provide a view on the essential elements and emerging trends for planning and managing water and heat in tunnel projects and other geostructures. In the new English edition, the document has been enriched with the results of the latest works by GESTAG, adding a new section on energy recovery. All the phases prior to the tunnel construction, during construction and operation are considered. The following topics are covered: the use of existing databases, the return of experience from tunnels already excavated, the 3D geological and hydrogeological model development; the predictive impacts models on the environment and on the Groundwater Dependent Ecosystems; the Risk Management Tools; the grouting and waterproofing technologies and the compatibility of the grouting materials with the use of water; the recovering and enhancing the groundwater inflows and the geothermal energy through the ground source heat pump technologies; and the monitoring criteria and techniques suggested in the different underground conditions. The so-called non-technical issues are also addressed, such as communication, the inclusive involvement of stakeholder's engagement, and social acceptability, with the aim of improving the design choices and keeping time and cost under control. An overview of the environmental legislation is finally given.

Dematteis, A, Barla, M, Boscaro A, Gargini, A, Governa, M, Grosso, F, Insana, A, Marchionatti, F, Parisi, ME, Perello, P, Ranfagni, L, Ruffinatto, G, Torri, R, Vazzoler, S, Vincenzi, V. 2020. Linee guida per la gestione sostenibile delle venute d'acqua e del calore geotermico nelle gallerie, Comitato Italiano IAH, allegato alla rivista Acque Sotterranee - Italian Journal of Groundwater Vol.9 n°162 DOI 10.7343/as-2020-486 (<https://www.acquesotterranee.net/index.php/acque/article/view/as-2020-486/398>).

IAH\_GESTAG: <https://www.iahitaly.it/site/gruppi/gestag-studio-gestione-sostenibile-acque-gallerie>.

## Long-Term Annual Average Aquifer Recharge assessment for the island of Sardinia (Italy)

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**Key words:** LTAAR, inverse water balance, residual kriging.

Evaluation of Long-Term Annual Average Recharge (LTAAR) is a challenge for sustainable management of groundwaters. Despite many methods were developed based on different kind of input dataset, inverse water balance is one of the most effective approach when long term climatic data series are available. In this work, the inverse water balance for all the aquifers of the Hydrographic District of Sardinia (Arras et al. 2019) is presented. The proposed model adopts a geographically based integrated evaluation system. Daily precipitation and temperatures data from the official weather stations network of Sardinia was collected for the periods 1981-2010 and 2009-2018, while average precipitation and temperature maps, elaborated by the Sardinian Regional Agency for Environmental Protection (ARPAS: Hydro-meteoclimatic Department), were used for the period 1971-2000. Elevation data comes from the 10 m grid Digital Terrain Model (DTM) of Sardinia, downscaled to a 40 meters grid. Daily measurements were used to calculate climate Normal according to the World Meteorological Organization guidelines (WMO 2017). Spatial interpolation of punctual Normal was performed through the application of the ordinary kriging of residuals from linear regression between climatic data and elevation. The method provides good results in terms of accuracy in reproducing missing data for both the climatic dataset, as demonstrated in similar context (Di Piazza et al. 2015). The Turc modified method by Santoro (1970) was used to calculate the actual evapotranspiration term. Based on literature data and field measurements potential infiltration indexes were evaluated. Then, runoff was calculated as difference between effective precipitation and effective annual aquifer recharge. Results have shown that LTAAR for the whole hydrographic district of Sardinia ranges from 1600 (1971-2000) to 1540 (1981-2010) and 1690 (2009-2018) Mm<sup>3</sup>, representing 15% of the average annual precipitation; more than 65% of the annual available water is lost through evapotranspiration; the remaining 20% occurs as runoff.

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## **Interactions between loosing streams and coastal groundwater-dependent ecosystem: a case study from the Torre Guaceto natural reserve and the Canale Reale River (Brindisi)**

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**Key words:** wastewater effluent-fed river, wetland, coastal aquifer recharge, coastal aquifer salinization, groundwater dependant ecosystem.

The Canale Reale River originates nearby Villa Castelli municipality and flows for 48 km through the Brindisi plain, a flat area extending along a geological transition zone between two Apulian structural and hydrogeological domains, Murgia at NW and Salento at SE. Besides rainwaters drainage, the river collects effluents coming from four wastewater plants with a total discharge of 270 l/s and crosses the Torre Guaceto protected wetland before reaching the Adriatic Sea. The study area shows a complex geological setting. The combined effect of faults, evidence of the Apennine orogenesis during Pleistocene, karst processes following glacio-eustatic variations since Cretaceous and sea level oscillations since Late Pleistocene, strongly affected the path of Canale Reale, its catchment basin and the groundwater circulation both in the shallow aquifer and the deep carbonate Mesozoic aquifer. A hydraulic connection between the river, the underlying shallow aquifer hosted in Quaternary deposits and the coastal springs supporting the wetland system fed by the deep aquifer, is allowed to be supposed. The water exchange between the two aquifers may naturally occur through significant vertical discontinuities as suggested by the temperature distribution within the saturated zone of the deep aquifer [1] or locally through the imperfect casing of the over 3,000 drilled wells, distributed along the Brindisi plain for agricultural needs. Aquifer recharge may also occur through loosing stream infiltration, which is likely to be a source of groundwater recharge especially in arid areas [2]; moreover, the discharge of treated effluents into surface water bodies is becoming a widespread method for groundwater recharge [3]. Adopting a multi-disciplinary approach, our study investigates the potential hydraulic connections between the effluent-fed streamflow and the consequent saturated zone to possibly quantify the water volumes resulting from streambed infiltration, and their effect in contrasting seawater intrusion in the groundwater-dependent ecosystem of Torre Guaceto wetland.

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## **Integrated hydrogeological modelling for sustainable management of the Brindisi plain aquifer (Southern Italy)**

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**Key words:** groundwater, hydrogeological model, Brindisi plain.

The sustainable management of groundwater resources is one the greatest challenges faced by society today. Climate changes together with the increasing of the water demand impose a sustainable management where the budget between water availability and demand is positively closed.

An integrated hydrogeological modelling approach was developed in order to understand the hydrological and hydrogeological dynamics in a semi – arid region of the Mediterranean basin. In particular way, the present work focuses on the catchment areas of the Siedi, Foggia di Rau, Pigonati and Palmarini channels of the Brindisi plain, Southern Italy.

In the last decades in the Brindisi plain catchment, the anthropization processes as well as the industrial and agricultural development generated an intensive exploitation of both shallow and deep groundwater resources as well as they qualitative deterioration.

The results evidence a sensitive anthropological – natural system where the variability of the rainfall regime combined with the agricultural water withdrawal leads to a combined system that is vulnerable to anthropogenic stresses and climate change.

The developed integrated hydrogeological model represents an important tool in order to evaluate the effectiveness of cost-effective climate resilience actions for the management of the groundwater resources with respect to land-use practices and socio-economic aspects.

## Monitoring strategies to detect the impact of landfills activities on groundwater

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Key words: groundwater, landfills, monitoring, isotopes.

The management of modern urban landfills require appropriate monitoring practices to promptly report first signs of inefficiency of the protective barriers against the pollution of soil and groundwater. As regards groundwater, the approach is based on the comparison of the concentration of a pollutant or a parameter against a standard, which does not fully describe the geochemical and hydrogeological processes involved at the groundwater body scale. Innovative indicators of pollution such as environmental isotopes, can provide a new perspective towards a holistic approach.

The aim of this communication is to present some successful examples of isotope application to resolve doubts about the origin of high levels of inorganic compounds in groundwater, as well as traces of organic compounds, which are of concern as a possible sign of failure of the protective barriers of the plant. In two urban landfills in central Italy, one currently active and one that is now dismissed, traditional groundwater monitoring has been complemented with the analysis of environmental isotopes including tritium and 13-carbon. Monitoring was conducted within the two sites and in the surrounding territory. Tritium is an excellent tracer of landfills pollution because its concentration is particularly high in both leachate and landfills gas.  $^{13}\text{C}$  originates from a variety of inorganic carbon sources and may provide additional information on contamination processes.

Field parameters (T, EC, pH, DO, ORP) were measured with probes in a flow-through cell. Ammonia, nitrite, sulfur and cyanide were measured in the field (UV-VIS). Lab analysis were performed for major and trace elements, environmental isotopes ( $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ , Tritium,  $\delta^{13}\text{C}$ ), DOC, VOC with standard procedures.

The integration of hydrochemical, hydrogeological and isotope data indicates a modest groundwater contamination in the old plant, while in the active plant no indication of pollution was found. Some anomalous data regarding sulfur and chloride were provisionally ascribed to a geogenic origin.

# Advanced automated integration of Airborne Electromagnetic and drilling data

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Key words: Airborne, electromagnetics, geophysics, drilling.

Airborne electromagnetic (AEM) surveys are widely used for hydrogeological applications. In areas that present large quantity of good auxiliary information (e.g., lithology, resistivity logs), integrating the latter with the AEM data is a common goal. Whether done a-priori or a-posteriori, quantitative integration is often hindered by locally conflicting information. That is, the airborne data and the drilling data may not be reconciled everywhere. For example, some drillings may have been logged imperfectly. Conversely, the AEM data may have a bias that makes it inaccurate.

In this study we propose to use a generalization of the minimum support norm, namely the asymmetric generalized minimum support (AGMS) norm (Fiandaca *et al.*, 2015), for defining the data misfit in the objective function of an iterative reweighted least squared (IRLS) gauss-newton inversion (Farquharson and Oldenburg, 1998). The AGMS norm in the data misfit puts a cap on the weight of non-fitting data points, allowing for the inversion to focus on the data points that can be fitted. Outliers (either boreholes or AEM data) can be identified after the AGMS inversion, excluded and a classic L2 misfit can be applied to the final inversion model.

The applicability of this innovative approach is tested on both synthetic examples and large-scale real case studies with AEM data and drilling information in the form of lithological logs translated to resistivity. The AGMS uses the “good” drilling information to locally improve the sensitivity of the AEM to some model parameters, whilst ignoring the “bad” drilling data. It also automatically flags the bad borehole, for review.

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Fiandaca G., Doetsch J., Vignoli G. & Auken E., 2015. Generalized focusing of time-lapse changes with applications to direct current and time-domain induced polarization inversions, *Geophysical Journal International*, 203, 1101-1112. 10.1093/gji/ggv350



## High resolution flow models at basin scale with the support of airborne geophysics and multiple-point statistics

Alessandro Comunian<sup>1</sup>, Gianluca Fiandaca<sup>1</sup>, Andrea Viezzoli<sup>2</sup>, Daniele Pedretti<sup>1</sup>, Matteo Gisolo<sup>3</sup>  
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**Key words:** multiple-point geostatistics, airborne transient electromagnetic, heterogeneity.

High-resolution distributed models of regional aquifer systems based on a realistic representation of the subsoil heterogeneity are valuable tools that can integrate models developed at local scale and support water management systems. Nevertheless, at the present day, and in particular in Italy, very few attempts were made to model fluid flow at the scale of big alluvial plains. This is probably due to the complexity of the spatial distribution of the sediments hosting the main aquifers of the region. Nowadays, a big part of the tools that can tackle this issue are there: high performance computing flow simulation platforms, allow to run flow modeling on a computing cluster with the required high-resolution grids [1]; in addition, airborne electromagnetic (AEM) geophysical systems, tailored for hydrological characterization, provide large-scale high-resolution mapping capabilities and recent researches opened the possibility to link the electrical properties retrieved from AEM data to hydraulic properties making use of the Induced Polarization (IP) phenomenon [2]; finally, multiple-point statistics allows to fill in the gaps left in the AEM maps and to reconstruct realistic representations of subsoil heterogeneity [3]. In this work, a workflow based on these three components is demonstrated on a synthetic study, set up for an area of about 10 km<sup>2</sup> down to a depth of 300 m, mimicking an alluvial aquifer. The use of a synthetic aquifer allows to compare the results of flow and transport simulation performed on the “true” reference distribution of the hydraulic properties against distributions deduced from AEM inversions, carried out either in terms of electrical resistivity, either in terms of hydraulic conductivity through the use of petrophysical relations, allowing to explore strengths and weaknesses of the two approaches. This study is carried out within the project GeoPHydro – GeoPhysics for Hydrogeology, a research agreement among the Earth Sciences dep. of the University of Milan and A2A ciclo idrico.

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## How to restore an overexploited aquifer... hints and insights from coastal Tuscany (Italy)

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Federico Lazzaroni<sup>2</sup>, Alessandra Pei<sup>2</sup>, Valentina Menonna<sup>2</sup>, Marco Masi<sup>2</sup>, Mirko Brilli<sup>3</sup>, Claudio  
Benucci<sup>3</sup>, Franca Palumbo<sup>3</sup>, Roberta Maggiorelli<sup>3</sup>, Lorenzo Rotelli<sup>4</sup>, Alessandro Fabbrizzi<sup>4</sup>

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**Key words:** sustainable groundwater management, aquifer restoration, managed aquifer recharge, river restoration.

Several studies deal with description and causes leading to aquifer overexploitation, while relatively few face the challenge of reverting unbalanced situations. The lower Cornia valley aquifer system (Tuscany, Italy) provides the only source of water for drinking, irrigation, industrial purposes and it also contributes to the water needs of the nearby Elba island. Since 60 years, intensive exploitation of groundwater resulted in consistent head lowering and water balance deficit, subsidence, reduction of groundwater dependent terrestrial ecosystems, and salinization of freshwater resources. With this contribution, we present the main results achieved with the activities run within the EU funded LIFE REWAT project (*sustainable WATER management in the lower Cornia valley through demand REDuction, aquifer Recharge and river REstoration*; <http://www.liferewat.eu>) aiming at rebalancing the water budget of the Cornia river hydrologic system.

Five demonstration measures (river restoration works; Managed Aquifer Recharge; reuse of treated wastewater for irrigation; high irrigation efficiency scheme; leakage management in water distribution systems) are/have been in place for promoting sustainable groundwater resource management, along with capacity building and participatory actions starting since 2018.

Results show an increase in recharge/storage of about 2.5 Mm<sup>3</sup> per year, with noticeable effects related to the increase in natural recharge from the Cornia riverbed to the aquifer (accounting for about 1.5 Mm<sup>3</sup>/year) due to morphological restoration works. The experimental two-stage infiltration basin of Suvereto guaranteed an increase in recharge of about 0.5 Mm<sup>3</sup>/year. Additional storage increase is related to the reduction in leakage losses from drinking water network and thanks to a more careful use of irrigation water in farming. In about two years, thanks also to favorable hydrologic conditions, the groundwater head generally arose of about 2 to 3 m in the Cornia plain. The results achieved so far provide a clear trend (even in 2021) towards the Cornia aquifer restoration by means of low-impact and nature-based solutions along with a large involvement of the main stakeholders in creating a shared knowledge on the value of the groundwater resource.

### Acknowledgement

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# **Update of the framework for the availability of groundwater resources in the Norcia and Cascia Plains following the earthquakes of 2016**

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**Key words:** groundwater, seismic, isotope, radiocarbon, anthropogenic tracers.

The study covered geographically the territories of Cascia and Norcia, in the province of Perugia (Umbria). The focus of the project was to provide an update of the state of knowledge about the areas, in the light of the framework of the availability of groundwater resources that changed over the last decade, for climatic reasons and in relation to the seismic events that have affected the region. This update was supported by a specific on-site survey programme, based on deep geophysical prospections, isotope analysis and anthropogenic tracers, in addition to the classical hydrodynamic and geochemical monitoring techniques.

In the Norcia Plain, the geophysical investigation has allowed to recognize the role of active deformative structures and the high thickness power of the quaternary deposits. The local recharging of the fan conoid system, open to anthropogenic tracers, imposes itself on genetically older waters, with slowed outflow in the sequences of low permeability fluvio-lacustrine deposits, interconnected with the coarser fan deposits of conoid.

In the study area of Cascia (Padule Plain) was found a condition of critical production at the water system. The semi-confined aquifer in the marshy fluvio deposits expresses a marked dynamic imbalance, attributable to a reduction of the recharge and to a drainage component of seismic origin, with deep escape flows along the regional tectonic guidelines. The results of isotopic and dating analysis suggest a local recharge height, a recent component open to anthropogenic tracers and a radiocarbon age characteristic of a flow system with deep circulation components in medium-moderate permeability media.

In the light of these results it was possible to provide the Water Service Manager a support for the design of drinking water catchment works, in addition to the current equipment, able to meet a medium-time requirement long term, with an adequate safety factor against local climatic and seismic variability.

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## Session 3

# Geothermal, Urban and Contaminant Hydrogeology

### Keynote Lecture

*Groundwater resources in risk: Pollution threats under future stresses*

Xavier Sanchez-Vila (Universitat Politècnica de Catalunya)

### Conveners

Elisabetta Preziosi (IRSA – CNR)

Francesca Lotti (SYMPLE s.r.l.)

Diego Di Curzio (Università degli Studi "Gabriele d'Annunzio")

## KEYNOTE LECTURE

### **Groundwater resources in risk: Pollution threats under future stresses**

Xavier Sanchez-Vila (Universitat Politècnica de Catalunya)

*Climate and global changes will result in a multitude of effects upon groundwater resources. On one hand, aquifer heads will deplete, and together with meteorological changes will produce strong impacts in riverine ecosystems. Upon quantitative issues, we must superimpose the impact of groundwater depletion plus the impact of stressors upon groundwater quality as a function of time. In this talk we evaluate some of the (sometimes hidden) potential threats posed by groundwater, here including bacterial pathogens, viruses, genes that are resistant to antibiotics, and potentially carcinogenic emerging organic compounds (EOCs). We will present some of the present challenges regarding the study of the fate of all these threatening elements, as well as some modelling efforts, and the open challenges for the future involving a formal evaluation of the risk of wells to provide unsafe water and the way we can devise protocols to minimize it.*

## Soil conditioners effects on hydraulic properties, leaching processes and denitrification on a silty-clay soil

Maria Pia Gervasio<sup>1,2</sup>, Nicolò Colombani<sup>3</sup>, Giuseppe Castaldelli<sup>1</sup>, Dario Tedesco<sup>2</sup>, Micòl Mastrocicco<sup>2</sup>

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**Key words:** fertilizer leaching, denitrification, clay swelling, aquifer recharge.

The continuous decrease of the environmental quality due to agricultural activities has become an important issue worldwide, as fertilizers' use could cause harmful nutrients leaching through soil, reaching groundwater resources. Different agricultural practises are applied in agricultural landscape to increase soil organic matter content and to reduce nutrients leaching. In this study an experimental silty-clay soil column was monitored at laboratory condition to determine the amount of nutrients and heavy metals leached after the simulation of a storm events. Urea, straw residuals, and compost were applied on an undisturbed column in three different experiments. Column was flushed for two pore volumes in each experiment, except for compost (where six pore volumes were applied). All treatments presented aerobic condition and pH was circumneutral, while total dissolved solids decreased during the experimental time due to simulated rainfalls. Leachate samples were analysed to determine dissolved ions, heavy metals, and major gasses content (Blicher-Mathiesen et al., 1998). Nitrate and nitrite were leached in the urea application followed by compost and straw residuals. Denitrification rate was low and had a slightly increment after straw residuals and compost addition; also dissolved organic carbon slightly increase. Results confirm that urea treatment showed incomplete denitrification due to the lack of labile organic substrates, rather than to other inhibitors, as pH changes. Heavy metals concentrations were very low, except for lead in the urea application and at the beginning of the compost experiment. Finally, prolonged rainfall events caused the complete saturation of the column and the dispersion of sodium present in the compost, so clay swelling (Warrence et al., 2002) appeared at the middle of the column in the compost treatment after three pore volumes. Swelling factor calculation confirmed this phenomenon, that influenced hydraulic properties: porosity and hydraulic conductivity decreased, so the infiltration coefficient declined (Hanson et al., 1999).

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Warrence, N.J., Bauder, J.W., Pearson, K.E., 2002. *Basics of Salinity and Sodicty Effects on Soil Physical Properties*. Department of Land Resources and Environmental Sciences, Montana State University-Bozeman, MT, pp. 1–29. DOI: 10.1.1.464.1745.

The full paper is published on: [Colombani, N., Gervasio, M. P., Castaldelli, G., & Mastrocicco, M. \(2020\). Soil conditioners effects on hydraulic properties, leaching processes and denitrification on a silty-clay soil. \*Science of The Total Environment\*, 733, 139342.](#)

## **Formation of new solute plumes from buried industrial waste as a consequence of the regional increase of aquifer head levels in the Piana ad Oriente di Napoli**

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**Key words:** groundwater table rising; aquifer contamination; numerical modelling; MODFLOW; MT3DMS.

The steady increase of groundwater head levels as a consequence of the closure of large well fields is a common problem for many urban areas all over the world. While the socioeconomic effects of groundwater head level rising on subsurface infrastructures have been well documented, the environmental implications of groundwater head level rising remain less explored.

Little is known about the potential effects of groundwater head level rising on the formation of solute plumes from contaminant sources that lie in the vadose zone and that groundwater head level rising may mobilize with time.

In this presentation, we showed the main results of a recent research (Varisco et al., submitted) which evaluates the mobilization of buried contaminant sources in a stratified highly heterogeneous aquifer near Naples, Italy. A dismissed chemical factory caused a multicomponent solute plume contamination which was hydraulically confined by a pump-and-treat (P&T) system. Since 2011, concentrations of contaminants such as 1,1-dichloroethene (1,1-DCE) were found to exceed regulatory maximum concentration levels in monitoring boreholes outside the P&T.

It has been hypothesized that such occurrence was linked to the groundwater head level rising, as the P&T was correctly working before 2011. Using a combination of stratigraphic geological analysis, time series of monitoring head levels and concentration records and a numerical flow and transport analysis, the hypothesis was demonstrated as plausible. The model considers a contaminant source located above the position of the water table in 2011. The source was progressively saturated by the rising groundwater. This resulted in enhanced advective transport components at the source, which generated a simulated solute plume that scales in space and time according to the field measurements.

This work demonstrates the ability of the proposed methodology to quantify the potential implication of groundwater head level rising in similar settings, a phenomenon which is expected to become increasingly important in the future.

Varisco, S. et al. (in preparation) “Implication of groundwater rebound on contaminant transport in heterogeneous aquifers: model-based analysis of a former industrial area near Naples (Italy)”, to be submitted to *J. Contaminant Hydrology*.

## **Adaptation of the Connected Linear Network Process for borehole heat exchangers numerical modelling**

Sara Barbieri<sup>1</sup>, Matteo Antelmi<sup>1</sup>, Luca Alberti<sup>1</sup>, Sorab Panday<sup>2</sup>

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**Key words:** borehole heat exchanger, CLN package, MODFLOW-USG, heat transport .

The Connected Linear Network (CLN) is a specific package included in the hydrogeological software MODFLOW-USG reproducing one-dimensional hydrogeologic and hydrologic features that requires flow connections separated from those of the aquifer (wells, fractures, rivers, karts conduits, etc.; Panday, 2019). The study focuses on the adaptation of the CLN to simulate a borehole heat exchanger (BHE) and compare the new approach to a detailed and complex approach consisting of a model already validated by means of an analytical solution (Angelotti et al., 2014). Furthermore, the introduction of unstructured grids in MODFLOW-USG allowed the analysis of the results varying the spatial grid discretization through the innovative quadtree refinement technique. The CLN adaptation provides a new tool for BHEs modelling, overcoming the limitations of the classical approach adopted in the validated model (strong grid refinement) and allowing the simulation of several BHEs in one model. This innovation gives access both to the evaluation of thermal interference between BHEs belonging to the same GroundSource Heat Pump (GSHP) system and of thermal disturbance induced downstream of large borefields (Antelmi et al., 2021). Moreover, the new approach was applied to identify the thermal influence of a real GSHP system installed in Milan, consisting of 60 BHEs, towards the extraction wells for drinking use located downstream of it.

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## Natural and anthropogenic groundwater contamination in a coastal volcanic-sedimentary aquifer in the archaeological site of Cumae (southern Italy)

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**Key words:** coastal volcanic-sedimentary aquifer, natural and anthropogenic contamination, water isotopes, nitrate isotopes, Phlegraean Fields.

The archaeological site of Cumae extends for about 3.0 km<sup>2</sup> along the Tyrrhenian coast of the southern Italy, north-west of the active volcanic system of Phlegraean Fields, about 20 km north of Naples bay. The coastal plain is characterized by a complex volcanic-sedimentary sequence formed by sands, silts, silty clays and volcanoclastic sediments, resting on a substrate of yellow tuff and trachytic lavas, outcropping in the surrounding reliefs. The soil around the site is intensively cropped with large use of pesticide and fertilizers. A multidisciplinary investigation was conducted from December 2013 to February 2015. Thirteen domestic and agricultural wells were studied to characterise the groundwater flow and quality. The natural and anthropogenic processes affecting the hydrochemical and isotopic groundwater composition of the sedimentary aquifer and the spatial and temporal variations of the contamination sources by anthropic activities were determined. This might help to design proper management measures of the site avoiding any damage of the archaeological artefacts by salinized groundwater. The data from the hydrostratigraphic and piezometric survey confirmed the presence of a multi-layered aquifer, whereas the hydrochemical (major ions and trace elements) and isotopic ( $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ ,  $^{222}\text{Rn}$ ,  $\delta^{15}\text{N}-\text{NO}_3$ ,  $\delta^{18}\text{O}-\text{NO}_3$  and  $\delta^{11}\text{B}$ ) results showed that the overall quality of the groundwater was affected by: i) aquifer lithologies and localised rise of highly mineralized magmatic fluids, ii) freshwater-saltwater interactions (induced by groundwater pumping) and iii) contamination from non-point agricultural sources.

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# **Application of multivariate statistical techniques for groundwater spatio-temporal analysis: the case study of Milan metropolitan Area.**

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**Key words:** cluster analysis, time series analysis, urban groundwater management, Lombardy.

Urbanisation is constantly increasing, and this requires an adequate knowledge and management of the quality and quantity of groundwater resources. Parallely, the amount of monitoring data continuously increases, providing useful information if correctly investigated<sup>1</sup>. Multivariate statistical techniques have been widely applied to interpret groundwater quality datasets<sup>2</sup>, but few studies dealt with groundwater quantity<sup>3</sup>.

In this work, the use of hierarchical cluster analysis is tested on groundwater levels measured from the monitoring network of the shallow aquifer in Milan with a double aim: to provide insights into the general aquifer behaviour through space and time; to detect evidence of the impact of underground infrastructures (public car parks and subway lines) on groundwater flow.

The dataset consists of groundwater levels from 2005 to 2019 over 153 piezometers and is unevenly spaced over time. As a result, it was split in two subsets covering the periods a) 2005-2014, including the total number of piezometers, to investigate general groundwater behaviour, and b) 2005-2019, including fewer piezometers having the longest time-series, to investigate infrastructure impacts in most recent years. In both cases, two measures per year have been considered: March and September, the piezometric minimum and maximum, respectively.

Preliminary results enabled to detect a general different groundwater behaviour between the northern and the southern sectors of the domain, allowing also to distinguish the local stresses exerted by different land uses as agriculture, quarrying, etc. Indications of possible local impacts of the most recent underground infrastructures were identified.

Applying these techniques confirmed already-known aspects of local hydrogeology and provided new insights, proving their reliability also for the study of groundwater quantity. They could be further used as a valid support for other municipal administrations and stakeholders in urban groundwater management, detecting also critical areas to be analysed by groundwater numerical models.

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## Modeling groundwater/surface-water interactions in an industrial area (Mantua, Italy)

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**Key words:** heterogeneous aquifer, hydraulic barriers, 3D flow model, aquifer-river-lake water balance

The city of Mantua has developed historically a complex surface water management system allowing protection against flooding of the Mincio River. On the left side of lakes di Mezzo and Inferiore, lies the SIN "Mantua Lakes and Chemical Pole".

A scientific collaboration between DISAT and ARPA was developed to realize a groundwater/surface-water model for understanding the pumping well barriers (229 wells) effects on groundwater and its interaction with surface water within the SIN. To prepare the model, a method based on sharing and transparency was used, establishing a technical committee: all the local authorities and the companies within the SIN participated.

The aquifer system simulated consists of a multilayered aquifer characterized by an accumulation of cyclic depositional sequences of alluvial deposits forming aquifers with variable spatial extension. A total of 22 hydrogeological cross-sections were reconstructed and about 1800 well logs, loaded into the CASPITA database, encoded into the TANGRAM database, were three-dimensionally interpolated with GOCAD and converted in hydraulic conductivity and effective porosity values.

A transient numerical groundwater flow model (36 stress periods – 2016-2018) was built using MODFLOW2005; the following packages were used to simulate the BCs: LAKE for the lakes, SFR2 (Streamflow-Routing) for natural and anthropic channels (19 network segments), HFB (Horizontal Flow Barrier) for confinement barriers and defense systems between lakes and the city, WELL for pumping systems, RCH for recharge settings. The model area was 12x13 km, about 80m deep (from the ground level to -60m asl), with 25 layers of increasing thicknesses (< 2m near the surface, up to 12m); cells size ranges from 50x50m to 10x10m in the Industrial Area (SIN).

The model response was tested using 83 transient head targets (about 3000 data), with variable depths, using a trial-and-error calibration methodology, reaching a final RMSE value of 3.6%. A detailed water balance was developed by identifying gaining or losing river portions within the simulated period. The model is now available for the ARPA Agency, to support a regional water management of the SIN.

## **An unorthodox method for deriving natural background levels of arsenic at the meso-scale using site-specific datasets: the case of Ferrara**

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**Key words:** Natural Background Levels, arsenic, sites under remediation, site-specific data, Ferrara.

Arsenic is found in groundwater above regulatory limits in many countries and its origin is often from natural sources, making the definition of Natural Background Levels (NBLs) crucial [1]. NBLs are commonly assessed based on either dedicated small-scale monitoring campaigns or large-scale national/regional groundwater monitoring networks that may not grab local-scale heterogeneities. An alternative method is represented by site-specific monitoring networks in contaminated/polluted sites under remediation representing a pervasive and extensive source of information on groundwater chemical composition. As a main drawback, groundwater quality at these sites is most likely affected by human activities. The current (recently published) work explores the potential for groundwater data from an assemblage of site-specific datasets of contaminated/polluted sites to define NBLs of arsenic (As) at the meso-scale (order of 1000 km<sup>2</sup>). Common procedures for the assessment of human influence (e.g. preselection or component separation [2]) cannot be applied to this type of dataset due to limited data homogeneity. Thus, an “unorthodox” method is applied involving the definition of a consistent working dataset followed by a statistical identification and critical analysis of the outliers. The critical analysis is based on a conceptual model that includes information on geology, hydrogeology (type and depth of the aquifer involved, groundwater flow direction), and contamination/pollution at each site (chemical species and compounds involved, location of monitoring points with respect to the contamination/pollution sources). The study was conducted in a highly anthropized area (Ferrara, N Italy), where As concentrations often exceed national threshold limits in a shallow aquifer. Two different NBLs of 68 and 21 µg/L were defined in the area, pertaining to two distinct geological settings. The results highlight that site-specific datasets, if properly pre-treated, are an effective alternative for the derivation of NBLs when “conventional” regional monitoring networks fail to catch local-scale geological and geochemical variability.

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## **Assessment and potential of the groundwater urban heat island in the Milan metropolitan area**

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**Key words:** Groundwater heat island, Urban aquifers, Shallow geothermal energy, City-scale modelling.

The natural thermal regime of groundwater resources beneath big cities is jeopardized by their intense use as well as due to modifications of the surface/subsurface environment. This leads to the development of Urban heat Islands (UHI) in the subsurface whose impact on the groundwater quality and on the potential of shallow geothermal systems is of increasingly interest among drinking water suppliers, control agencies and energy planners.

This study demonstrates a more than 3°C intense UHI in the Milan metropolitan area (northern Italy), and through statistical analysis and modeling techniques aims to quantify the hydrogeological and thermal processes that are relevant at the city scale. To this aim, a 3D FEM groundwater flow and heat transport numerical model was developed. First, the variability of hydraulic and thermal properties as from borehole logs was spatialized in the domain by means of 3D geostatistical techniques to account for aquifer heterogeneities. Complex thermal boundary conditions were assigned to the model including the effects of the land covering, building foundations, tunnels, shallow geothermal wells, and surface canals. The thermal transport model was calibrated against time-lapse groundwater temperature profiles and continuous measurements to reproduce the current thermal regime of the shallow aquifers.

The modelling results are a valuable tool to assess the impact of specific natural/anthropogenic heat sources on the overall thermal regime and to test the long-term thermal potential of ground/groundwater heat exchangers in the Milan UHI. The proposed approach can support the sustainable development of densely populated areas and the optimization of low enthalpy geothermal resources.

## **Background contaminants values in groundwater: methodological analysis in the case studies of Turin and Biella plains (NW Italy)**

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**Key words:** background values, diffuse pollution, chlorinated solvents, nickel.

Background Values (BVs) of diffuse pollutants in groundwater are a very important information to the correct comprehension of contaminant phenomena and constitute an operative tool for local authorities. The aim of the study was to highlight the criticalities of the SNPA (Sistema Nazionale per la Protezione dell'Ambiente) BVs determination methodology in the Piedmont plain shallow aquifer considering different chemical parameters. More specifically, chlorinated solvents and nickel were considered at a local scale (two study areas in Biella and Turin provinces) and at a provincial scale (Metropolitan City of Turin).

Following the SNPA method, the conceptual model was built considering geological data, contaminants and contamination characterization. Then, a statistical procedure was applied for each area by imposing different conditions such as the subdivision of the area and the dataset. The concentrations data of the chemicals derived from the Regional Monitoring network (RMRAS) for the Metropolitan City of Turin and from local analyzes of Agenzia Regionale per la Protezione Ambientale (ARPA Piemonte) in the two local sites. The study highlighted numerous relevant criticalities. The utilized SNPA method was resulted not exhaustive due to the non-attendance of specific indications on various contaminants. Moreover, the “statistical informations” provided were resulted sometimes incomplete and inapplicable. The use of the RMRAS monitoring points was resulted inappropriate to define BVs in groundwater due to the low density of monitoring wells. On the contrary, the analyzes in the local study areas made it possible to understand and characterize correctly numerous specific aspects, recognizing the diffuse pollution and identifying new potential punctual contamination despite the complex situation linked to historical and current contaminations. In conclusion, the study made it possible to define the BVs in groundwater at a local scale and to propose possible improvements of analysis methodology.

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## Particles ending point location in constraining optimal pumping rate estimation

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Key words: inverse model, hydraulic barrier, pumping rate, optimization.

A constraining method is presented here as an alternative, simpler, way to estimate optimal pumping rates for groundwater remediation, using flow model in conjunction with particle tracking algorithm. Most of the research efforts concerning this topic (Sadeghfam et al. 2019; Becker et al. 2006), are based on genetic algorithm and differential dynamic programming or artificial neural networks and require the use of flow and solute transport models. The method presented here requires setting the variance of particles ending point locations as calibration target for the inverse problem. The observed variance is readily determined from the actual variance of the well array employed as hydraulic barrier. In order to test this method a synthetic model was developed using MODFLOW for the flow model and MODPATH for the particle tracking algorithm. The inversion was carried out using PEST (Doherty 2015). The flow field in the simulation was applied along the northing direction in between two constant head boundary conditions, while the hydraulic barrier was implemented in 12 nodes with specified flow in the lower part of the domain. The numerical test takes place in two subsequent stages. During the first stage, a synthetic set of pumping rates was chosen, and the backward tracking of the particles starting from the well nodes location was performed. The ending point locations of the first stage were used as starting points for the next one in forward tracking and employed for the inversion. The reliability of the method was then evaluated by comparison between synthetic and estimated flow rates. This method led to a good estimation for the cumulative flow rate while succeeding to let the barrier to capture all the particles. Further analysis showed that the resulting estimate is sensitive to the spatial discretization, tracking time constraints, number of particles involved, and perturbation factor used to approximate the Jacobian matrix of the model.

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## **Multi-isotopic investigation at regional scale in Lombardy Region: implication on groundwater management for Water Alliance stakeholders**

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**Key words:** regional scale, groundwater quality, isotopes, renewability

Groundwater represents the main and safest source of water, for drinking purposes for urban and rural communities all over the world. For this reason, a comprehensive knowledge of groundwater flow system in terms of quality, vulnerability and renewability of this precious resource is fundamental for a responsible use and management by different stakeholders. Thanks to the contribution of different members of Water Alliance in synergy with the Hydrogeology lab of Sapienza University, a multi-isotopic analysis at regional scale for a wide area of Lombardy region, aimed to improve knowledge about groundwater flowpath, aquifer vulnerability and renewable rate has been carried out. Based on results of a previous isotopic characterization performed at regional scale during 2017, each Water Alliance supplier selected wells and springs for a total of 121 samples, intercepting different aquifer levels and distributed along a possible regional N-S flowpath. Stable isotopes (<sup>18</sup>O and <sup>2</sup>H) analyses on water were performed on all the monitoring points, and tritium, nitrogen isotopes (<sup>15</sup>N and <sup>18</sup>O in nitrates), sulfates isotopes (<sup>34</sup>S and <sup>18</sup>O) and <sup>13</sup>C isotope in Dissolved Inorganic Carbon (DIC), were analyzed in a subset of monitoring wells selected based on previous data and major ions concentrations results. Groundwater isotopes and tritium highlighted the direct influence of meteoric recharge, the interaction between the shallow and deep aquifer and infiltration of surface water on different portions of the regional aquifer system. Nitrogen results point out the possible anthropogenic origin of nitrate in groundwater and the role of attenuation processes, while sulfates origin was ascribed both to marine origin and oxidation processes, partially influenced by human activities. Through the analyses of <sup>13</sup>C in DIC, a clear distinction between shallow and aquifers was not confirmed, suggesting a possible interaction among different aquifer levels. Therefore, results confirmed the key role of multi-isotopic approach in defining origin, ages, vulnerability, and renewability of groundwater resources, offering a useful tool for improving the sustainable management and the protection of tapped groundwater resources used by different water suppliers.

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## Opportunities and critical issues related to the use of amendments as remediation techniques

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**Key words:** groundwater remediation management, amendments, aerobic bioremediation, ISCO, surfactants.

This study aims to analyze the opportunities and criticalities related to the use of amendments as remediation techniques. The performance of amendments (Aerobic Bioremediation, ISCO and surfactants) was compared with the performance of other groundwater remediation technologies (Air Sparging, Pump&Treat, Multi-Phase Extraction, Pump&Reinjection, Monitoring Natural Attenuation) based on a dataset of 100 contaminated sites. The considered factors are: effectiveness of the remediation as contaminant mass extraction; applicability based on hydraulic conductivity; cost to remediate and operational time.

The occurrence and types of amendments-related issues were studied on the 40 sites where the amendments had been applied. Issues occurred in 20% of the 40 analyzed cases and consisted of: a) partial or total occlusion of the monitoring wells and by-product formation, for example heavy metals (37.5%); b) uncontrolled increase in contaminant concentrations and potential downstream migration (37.5%); c) by-product formation without well obstruction (25%). For each critical event, a detailed analysis was conducted to understand the processes (pH-Eh variations, contaminant desorption, hydraulic conductivity reduction), to highlight the design and procedural gaps (surplus of amendment, injection method selection, contaminant removal by purge). However, the issues can be avoided or mitigated with an accurate design, pilot tests performance, with the application of delivery and monitoring protocols, and at least with a prompt response adopting a corrective action plan, if necessary.

The use of amendments turns out to be an effective solution: in 60% of the analyzed sites it led to a significative reduction of the contamination within one year from the application. The cost is about one third if compared to other technologies. The operational time is about half the operational time of other technologies. Based on the results of sustainability analysis the amendments technologies reduce the production of waste, the energy and water use and they minimize air emissions.

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## **Sustainable Development Goals, natural risks and best practices for low enthalpy geothermal systems: Apulian experiences**

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**Key words:** Sustainable Development Objectives, best practices, geothermal system, heat pumps, Apulia.

The United Nations General Assembly of 2015 approved the 2030 Agenda for Sustainable Development, which is based on the 17 sustainable development objectives (SDGs, Sustainable Development Goals). These objectives were assumed as landmarks to define the route of the regional decision, orienteering the legislative activity and the regional planning to the global context. The described experience is focused on the objective 7, concerning the development of renewable energy sources.

The use of low enthalpy geothermal systems is part of a regional strategy for mitigating and adapting to climate change in Apulia. These systems allow reduction of energy consumption and emission by fossil fuels, offering the best thermal comfort, and lend itself to integration with other thermal renewable energy sources, using heat pumps. Many projects were developed as many geothermal systems are operating in Apulia, some of which can be classified as best practices, which deserve to be brought to the attention of the decision makers. At same time, as the diffuse realization of these systems calls for a systematic definition of optimal technical criteria, defined considering possible natural risks and potential negative effects.

The cooperation between the Apulian Regional Council and the CNR is part of an evidence-based legislation process and is focused on two main scopes. At global scale, the selection for sharing purposes of data and best practices at local, regional, national and international level, which are functional to progress related to the long-term implementation of the SDGs, was pursued. At detailed or regional scale, a research on optimal criteria to guide the approval of new geothermal system was realized. Effects of system installation and use, including underground temperature variations, are considered, assessing any kind of natural risks due to use of low enthalpy geothermal system.

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## Seasonal variability of pesticides in surface and drinking water wells in the annual cycle in western Poland, and potential health risk assessment

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**Key words:** pesticides, surface water, riverbank filtration, imidacloprid, risk assessment.

Drinking water wells on a riverbank filtration site are exposed to plant protection product contaminations infiltrating from the contaminated river. At the Mosina-Krajkowo well field in Poland pesticide contaminations of the Warta river and riverbank filtration water (wells and observation wells) in annual cycle were examined. 25 of the 164 tested pesticides were detected. The highest concentrations occurred in the river water and were reduced on the flow path from the river to the wells. Only the most persistent substances were detected at the farthest points from the river. During the study period, seasonal changes in pesticide concentrations, as well as, differences in the occurring substances were noticed. The most substances and the highest concentrations were detected in May 2018, the least substances and the lowest concentrations in February 2018. Based on the research, periods of increased exposure of water to pollution (mainly spring) were indicated. The periods were combined with increased chemical plant protection and more rainfall. The dominant group of pesticides was herbicides, which is in the line with the worldwide trend. In the highest concentrations in surface and riverbank filtration water occurred 7 pesticides: isoproturon, nicosulfuron, imidacloprid, terbuthylazine, chlorotoluron, S-metalachlor, and prometryn, mainly toxic and persistent. Some of the detected substances (isoproturon, prometryn and simazine are banned in the European Union. Pesticides are widely used in the research area, so the potential health risk assessment was performed. The values of hazard quotients (HQs) do not exceed 1, which does not mean a significant risk for human health. The highest values of HQs noted for common fungicide tebuconazole.

## The Permeability Map of Italy

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Key words: permeability map, Italy, land cover.

The Geological Survey of Italy (SGI) Department of ISPRA has prepared the Permeability Map of Italy on a 1:100.000 scale (<http://portalesgi.isprambiente.it/it>), drawn on the basis of a considerable amount of characterizing geological information.

The objective of the map is to provide a useful tool for the elaboration of hydrological and hydrogeological balances on a regional or hydro(geo)logical basin scale.

Based on the data collected, the degree and type of permeability of the rocks has been defined. The processed map is representative of but schematic, since the factors that influence the permeability (stratification, fissuration, karst, and porosity) are never uniformly spatially distributed at the rock formation scale.

The Permeability Map is based on the Geological Map of Italy at 1:100.000 scale which ensures coverage of the entire Italian peninsula, although prepared between the nineteenth and twentieth centuries and focused on the substrate, thus neglecting the Quaternary deposits. Subsequently, information about lithotechnical characteristics, deriving from the Lithological Map of Italy at 1:100.000 scale was as well considered.

Four classes relating to relative permeability degree of lithotypes have been identified: highly permeable rocks (1), intermediate permeable rocks (2), low permeable rocks (3) and very low permeable rocks (4). According to the classification just mentioned, the degree of permeability is substantially supported by the fissuration, stratification, porosity and karst features. Within each class, three types of permeability have also been distinguished: primary and porosity permeability (P), fissuration and karst (F) and mixed type (by fracturing and porosity) (M). Thus, 12 classes were obtained; each class has been assigned to an indicative range of permeability values (K) which expresses the infiltration speed (m/s) of the water through the rock formation.

Data from the ISPRA-SNPA National Land Consumption Map referred to 2019, which identifies sealed artificial surfaces in the Italian territory, implemented the Permeability Map.

## Urban Hydrogeology - The groundwater monitoring activities in Rome (Italy)

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**Key words:** urban groundwater, hydrogeology, monitoring network, Rome.

The Groundwater Monitoring Network of Rome (GMNR) was born in 2014 when the Environmental Protection Department of Roma Capitale (Municipality of Rome) decided to dedicate the more than 200 existing water wells (mainly developed for green areas irrigation) also to monitoring purposes. The GMNR considerably contributed to the development of the new Hydrogeological Map of Rome in 2015 (La Vigna et al. 2015, La Vigna and Mazza 2016) but after the first two years of activity the monitoring has been interrupted for several managing reasons.

Recently, by an agreement between Roma Capitale and ISPRA (Geological Survey of Italy) the monitoring activities started again; several new wells have been surveyed and all data are going to be viewed and managed by a web-GIS system and an interactive map.

Each monitoring station visible on the interactive map will have a link to a graph showing the trend over time of the measured parameters. In this regard, a system is being developed in order to allow the collection and the entry to the central database of investigated data even in real time by means of portable devices (tablet or smartphone), through a survey form. As a whole, this will allow the field workers to quickly transmit the measured data - piezometric levels and in situ chemical-physical parameters - from the hydrogeological data collection site to a single online central database.

With the described agreement related to the GMNR, the survey activities will soon lead to a systematic structuring of information relating to the groundwater of the city of Rome, probably developing the first dedicated urban example in Italy, and contributing to enhance the local groundwater resource knowledge and also to increase public awareness in this regard.

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## **Traditional phytoscreening coupled with PID analysis and detector tubes: a rapid in situ assessment of VOCs concentrations and plume delineation**

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**Keywords:** phytoscreening, CEs, PID, optimal conditions .

The technique behind this research is called phytoscreening. Parallel to the well-known phytoremediation, it consists of exploiting the absorbing potential of trees to delineate volatile organic compounds (VOCs) contamination plumes, especially chlorinated ethenes (CEs) (e.g., [1]). CEs are prevalent contaminants in groundwater due to their persistence. Their fate and transport in surface ecosystems, such as trees, are still poorly understood and constrain high variability. Besides, commercial acceptance of tree-coring is still limited in many countries. Among the reasons for this may be the lack of knowledge of the application opportunities. Tree-cores are analyzed with a closed-system purge-and-trap process, followed by a gas chromatography-mass spectrometry analysis. It is also possible to measure the gaseous phase concentrations of CEs directly on-site, inserting detector tubes in the tree-holes left by the coring tool [2]. We coupled the technique with the assessment of VOCs gaseous concentrations through a photoionization detector (PID). We tested the updated technique in six sites contaminated by CEs in Emilia-Romagna (Italy) to evaluate its effectiveness in different hydrogeological and seasonal settings. A significant correlation exists between tree-core and groundwater concentrations ( $r^2 > 0.6$ ) for most sites, being higher for sites with shallower and thinner aquifers. Concurrently, the correlation between tree-core and PID measured concentrations can be highly positive ( $r^2 > 0.7$ ), especially in sites with coarser aquifers. Conversely, the analysis via detector tubes reveals inaccurate concentrations ( $r^2 < 0.3$ ) but is functional in discriminating the occurrence of one solvent or another. The correlations were higher when precipitation rates and relative air humidity were lower and air temperature and net solar radiation were higher. These results indicate the opportunities of assessing in situ the occurrence, type, and concentration of solvents directly from the stem of trees. This can reduce the costs of characterization surveys, allowing rapid identification of hotspots and plume direction, optimizing the drilling of boreholes.

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[2] Luchetti, L. & Dilgenti, A., 2018. Protocollo operativo per le attività di phytoscreening. ARTA Abruzzo, SNPA, 15 pp.

# **A novel methodology for Groundwater Flooding Susceptibility assessment through Machine Learning techniques in a mixed-land use aquifer**

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**Key words:** Groundwater Level rising, Groundwater Flooding Susceptibility, Machine Learning algorithms, Ensemble methods, Metropolitan City of Naples.

Many areas around the world are affected by Groundwater Level rising (GWLr). One of the most severe consequence of this phenomenon is Groundwater Flooding (GF), with serious impacts for the human and natural environment. In Europe, GF has recently received specific attention with Directive 2007/60/EC, which requires Member States to map GF hazard and propose measures for risk mitigation.

In this paper a methodology has been developed for Groundwater Flooding Susceptibility (GFS) assessment, using for the first time Spatial Distribution Models. These Machine Learning techniques connect occurrence data to predisposing factors (PFs) to estimate their distributions. The implemented methodology employs aquifer type, depth of piezometric level, thickness and hydraulic conductivity of unsaturated zone, drainage density and land-use as PFs, and a GF observations inventory as occurrences. The algorithms adopted to perform the analysis are Generalized Boosting Model, Artificial Neural Network and Maximum Entropy. Ensemble Models are carried out to reduce the uncertainty associated with each algorithm and increase its reliability. GFS is mapped by choosing the ensemble model with the best predictivity performance and dividing occurrence probability values into five classes, from very low to very high susceptibility, using Natural Breaks classification.

The methodology has been tested and statistically validated in an area of 14,3 km<sup>2</sup> located in the Metropolitan City of Naples (Italy), affected by GWLr since 1990 and GF in buildings and agricultural soils since 2007. The results of modelling show that about 93% of the inventoried points fall in the high and very high GFS classes, and piezometric level depth, thickness of unsaturated zone and drainage density are the most influencing PFs, in accordance with field observations and the triggering mechanism of GF. The outcomes provide a first step in the assessment of GF hazard and a decision support tool to local authorities for GF risk management.

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## Assessment of Chloroethenes Enhanced Biodegradation in groundwaters by Compound-Specific Isotope Analysis (CSIA)

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**Key words:** chlorinated solvents, enhanced bioremediation, Compound-Specific Isotope Analysis, Landfill.

Chloroethenes are a class of organic anthropogenic contaminants widespread in aquifers all over the world. When these contaminants degrade, a shift in their carbon, chlorine and/or hydrogen stable isotope composition can occur due to isotope fractionation, whose magnitude is related to the nature and entity of the active degradation process(es). Compound Specific Isotope Analysis (CSIA) is an analytical technique that permits the isotopic characterization of individual compounds and thus detects their shifts in isotopic composition in time and/or along a flowpath. This results in a better assessment of the performance of remediation activities, permitting a better evaluation of the management options for a specific contaminated site.

The aquifer object of this study is located near a lagoon in Italy and subject to chloroethenes contamination (concentrations up to several tens of mg/l) derived from landfill leachate. An enhanced *in situ* bioremediation system is implemented in the site, which consists in two sequential 400 m long microbiological barriers (anaerobic and aerobic) designed to stimulate biodegradation of higher and lesser chlorinated ethenes by anaerobic reductive dechlorination (RD) and aerobic oxidation, respectively.

Carbon stable isotopes shifts in tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cis-1,2-DCE) and vinyl chloride (VC) have been measured by CSIA on groundwater samples collected along a 200-m long flowpath intersecting both barriers (a total of four sampling points located upgradient and downgradient of each barrier) in order to provide evidence of the ongoing degradation of the contaminants. A progressive increase of  $\delta^{13}\text{C}$  from PCE ( $-58.2 \pm 0.7\text{‰}$ ) to VC ( $-32.7 \pm 0.1\text{‰}$ ) was observed at the first sampling point, suggesting ongoing RD even before the anaerobic barrier. An enrichment of PCE ( $\delta^{13}\text{C} = 3.0 \pm 0.9\text{‰}$ ), TCE ( $\delta^{13}\text{C} = 2.4 \pm 0.3\text{‰}$ ) and cis-1,2-DCE ( $\delta^{13}\text{C} = 2.5 \pm 0.3\text{‰}$ ) was observed after the anaerobic barrier proving ongoing degradation by RD. A much more significant isotopic enrichment was observed in cis-1,2-DCE ( $\delta^{13}\text{C} = 14.9 \pm 0.6\text{‰}$ ) after passing through the aerobic barrier, suggesting the onset of degradation by oxidation. Further studies will be carried out in order to provide a more accurate interpretation of the data.

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## **Evaluation of Chromium pollution into an industrial remediation site, and its occurrence in reserve areas of deep aquifers**

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**Key words:** Chromium, vulnerability, groundwater age, stable isotopes.

An important industrial site with large chemical plants, with several decades of production history, has been involved in a remediation plan, with hydraulic barrier (pump and treat wells) and monitoring of the Chromium concentrations in piezometers filtered on three different depth intervals, into the fluvial deposits and in the upper unit of Villafranchiano fluvio-lacustrine sequences.

Inside the distance of 1 km from this plant, a strategic reserve zone has been identified through pilot-wells into a deep-seated (up to 180 meters below the ground) leaky to confined artesian aquifer; in this aquifer traces of Chromium were found, according to background values already defined in the same hydrogeological basin by the Regional Environmental Agency, due to dissolution of Chromide-rich ultramafic rocks in the recharge zone (serpentinites, lherzolites).

A series of hydrogeological (piezometric) and geochemical investigations have been set up thanks to the cooperation among the local water manager of the deep wells for drinking purpose, the public authority for water infrastructure planning (EGATO) and the manager of the remediation program of the chemical plant, including major ions analysis, radiocarbon (apparent) age and tritium content, stable isotopes analysis, in addition to Chromium distribution in selected representative wells.

The degree of vulnerability of the multi-layer aquifer complex has been defined, crossing the stable isotopic data with age estimation (both referred to “modern” and “ancient” age components). Finally, the degree of natural protection of the deep aquifer has been confirmed, helping the public decision-maker to define the security level of the future extraction center for drinkable use respect to the hazard related to the Chromium diffusion around the remediation site. An optimization of the monitoring piezometric network has been studied, in order to confirm the conclusions of the study and reduce the residual level of pollution risk.

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# **Identifying areas suitable for Sustainable Drainage Systems and Aquifer Storage and Recovery to mitigate stormwater flooding phenomena in Rome (Italy)**

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**Key words:** urban hydrogeology, SuDS, ASR, stormwater flooding management.

This study proposes a survey methodology for identifying areas for combined Sustainable Drainage Systems (SUDS) and Aquifer Storage and Recovery (ASR) (Dearden et al. 2013, Sharp Jr., 1997); these techniques exploit the hydrogeological and geomorphological characteristics of an area, to increase the natural infiltration capacity of water into the ground.

The target area is the city of Rome and the aim of such techniques is to solve the problems related to rainwater which, in case of extreme events, struggles to infiltrate the ground, overloads the undersized hydraulic systems and floods the urban space.

The proposed method involves GIS geospatial analysis of various data: the permeability of outcropping lithology, the piezometric level of the aquifer, hydrogeological units, geomorphology and land use.

To identify the suitable areas, areas characterised by high permeability and a piezometric level that would confer a volumetric capacity to possibly store even large quantities of water, without triggering possible problems associated with fluctuations in the water table, were identified.

The data were divided into classes and indexed in order to compare and overlap them. Finally, hydrogeological units were also taken into account (by analysing their depth trend) in order to identify areas with similar characteristics of permeability with respect to depth. The latter will also be compared with the previous data to identify the areas suitable for SUDS and ASR.

The final product of the suitable areas from a hydrogeological point of view, will be compared with the land use map in order to exclude those areas that, for administrative and other legislative reasons, cannot be destined to this kind of activity.

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## Groundwater Vulnerability Assessment in Areas with Intensive Agricultural Activities Through a DRASTIC-like method

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**Key words:** groundwater vulnerability, DRASTIC-like method, groundwater quality protection.

Intense agricultural activities in developed countries commonly determine a progressive degradation of the groundwater quality causing challenging management of groundwater resources, especially in shallow aquifers. Agricultural practices, such as amendment of soils by nitrate fertilizers or pesticides treatments, represent the principal origins of pollution in these areas. These are well recognized as one of the most severe environmental emergencies, so much as to have determined the issuing of specific European policies and legislations (European Parliament, 2000; 2006).

In the framework of the LANDSUPPORT project, a Horizon 2020 project funded by the European Community, results of a research aimed at assessing groundwater vulnerability by DRASTIC-like method are here proposed. Two representative areas with intensive agricultural activities were considered: the Telesina Valley (southern Italy) and the Marchfeld Region (eastern Austria). High spatial density and quality of available data allowed the reconstruction of detailed hydrogeological maps and the application of the SINTACS-R5 method (Civita and De Maio, 2000). Geological, hydrogeological, geomorphological, pedological, climatic and land use data were analyzed to define each of the seven parameters considered by the method. For such a scope, extended bibliographic research and consultations of unpublished archives of municipalities allowed to implement a comprehensive geodatabase. Instead, for the attribution of multiplying weights related to the five scenarios considered by the method, the following sources of data were taken into account: regional map of agricultural land use; flooding-prone areas; areas with water table depth less than 2 m; hydrogeological map and satellite images. The resulting groundwater vulnerability map of the study areas showed intrinsic vulnerability to pollution ranging prevalently between medium to high classes. Furthermore, highest values of vulnerability resulted coinciding with alluvial plains, where a shallower depth of the water table occurs. Results obtained were implemented in a geoSpatial DSS (S-DSS; [www.landsupport.eu](http://www.landsupport.eu)), a comprehensive decision-support tool for the planning of land use based on protection of groundwater quality.

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## **Reconstruction of the vertical thermal disturbance induced by a groundwater heat pump system (GWHPs): Potential of using a temperature-measuring chain as a monitoring tool**

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**Keywords:** Geothermal energy, Groundwater heat pump, Temperature-measuring chain, Thermally affected zone, Injection system.

Social and environmental impact analyses related to energy production strategies based on fossil fuels have favored an increase in the efforts aimed at the use of renewables and increasingly efficient systems. The increased implementation of geothermal heat pumps for heating and cooling buildings is a reflection of that trend. Groundwater Heat Pumps (GWHPs) can offer substantial improvements in terms of energy efficiency and reductions in CO<sub>2</sub> emissions. However, system performances are strongly dependent on the heating and cooling load, heat pump design and aquifer characteristics (Lo Russo et al. 2016). Among the technical aspects associated with GWHPs that need to be constantly controlled, there is the development of a thermally affected zone (TAZ) around injection points. The environmental impact is strongly influenced by the re-injected water flow rates and modalities. The process of setting up an adequate monitoring system is fundamental for the proper reconstruction of TAZ propagation modes (Gizzi et al. in press). With the aim to identify the stratigraphic intervals of the Turin shallow aquifer that are affected by the thermal disturbances produced during each heat exchange period, a temperature-measuring chain (type TT164/Pt) was installed in the 35m-deep piezometer of the Politecnico of Torino geothermal plant. The instrument, composed of 12 different temperature sensors, was settled to monitor the aquifer between the depths of 24 m and 38 m from the ground level. From the analysis of the water temperature data recorded, it emerged how the continuous monitoring of the thermal perturbation generated in the superficial levels during the days following the plant turning off remains fundamental. Besides, the implementation of temperature data in a 3D-conceptual hydrogeological model, performed by finite-element FEFLOW® 6.2 package, has allowed the understanding of the extent of the impact that such vertical temperature variations can have on down-gradient located geothermal users.

Gizzi, M. Taddia, G. Lo Russo, S. in press. Use of a temperature-measuring chain for the reconstruction of the vertical thermal disturbance induced by an open-loop groundwater heat pump system. *Italian Journal of Engineering Geology and Environment*

Lo Russo, S. Taddia G. Cerino Abidin, E. Verda, V. 2016. Effects of different re-injection systems on the Thermal Affected Zone (TAZ) modeling for open-loop Groundwater Heat Pumps (GWHPs) *Environmental Earth Sciences*, vol.75 (48) pp.1-14, DOI:10.1007/s12665-015-4822-8

# **Numerical investigation on the performance and sustainability of borehole heat exchanger system in fractured and karstic limestone aquifer for resilient and smart cities**

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**Key words:** borehole heat exchanger, fractured aquifer, numerical model.

Nowadays, the heating and cooling of water and air represent an important aspect of the energy consumption of urban and industrial settlements with enormous economic, environmental and social costs due to systemic inefficiencies.

In this work, a comprehensive numerical model was set up to analyze the efficiency of an innovative borehole heat exchanger system (BHEs) in the coastal area of the fractured limestone aquifer of Bari (Italy). The role of seawater intrusion on the BHE efficiency was investigated.

The geological surveys and aquifer tests were analyzed in order to determine the hydraulic parameters of the aquifer. Novel borehole heat exchanger solutions were validated experimentally through physical models.

The results show that that aquifer transmissivity and its variation along the depth play an important role in the borehole heat exchanger efficiency. The variability of the aquifer transmissivity governs the benefits due to the natural and forced heat convection which increases the heat exchange between the borehole heat exchanger and the aquifer.

## Geophysical estimation of hydraulic conductivity at contaminated sites and its integration into groundwater flow modelling

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Key words: hydraulic conductivity, geophysics, contamination.

The heterogeneity of hydraulic conductivity (K) plays a significant role in transport processes at contaminated sites. Traditionally, the spatial distribution of K is estimated by grain size analyses of samples from drillings or with in situ slug tests in screened boreholes. These methods are expensive, time consuming and punctual. As an alternative approach, geophysical methods have been increasingly used for K mapping. Recently, Time-Domain Induce Polarization (TDIP) has been successfully applied in the field for imaging Hydraulic Conductivity (Fiandaca *et al.*, 2018), using petrophysical relations derived in the laboratory without any calibration. This method has been further developed and validated on different 2D datasets acquired in five different European countries (Martin *et al.*, 2021), with an average agreement between geophysical and hydrological K estimates within one order of magnitude.

In this study, we present the results of TDIP K estimates along ten kilometers of 2D lines acquired around the Vallosa landfill, near Ospitaletto (Brescia, Italy), within the framework of the project GeoPHydro – GeoPhysics for Hydrogeology, a research agreement between the Earth Sciences dep. of the University of Milan and the company A2A ciclo idrico. The 2D K maps obtained from geophysics are used as training images to generate 3D multiple-point statistics simulations by means of sequential 2D simulations and conditioning data (s2Dcd method, Comunian *et al.*, 2012). These 3D simulations are used to populate the grid of flow and transport models for the investigated area. To enlighten the advantages of the proposed reconstruction of the spatial distribution of the hydraulic properties, the results of these models are finally compared against the results obtained with a modeling approach that does not incorporate such a kind of geophysical soft information.

Fiandaca G., Maurya P.K., Balbarini N., Hördt A., Christiansen A.V., Foged N., Bjerg P.L., Auken E., 2018. Permeability estimation directly from logging-while-drilling Induced Polarization data, *Water Resources Research*, 54 (4), 2851-2870. DOI: 10.1002/2017WR022411

Tina Martin, Pieter S. Pauw, Marios Karoulis, Alfredo Mendoza, Thomas Günther, Line Meldgaard Madsen, Pradip Kumar Maurya, Joseph Doetsch, Simon Reijkaer, Torleif Dahlin, Gianluca Fiandaca, 2021. Inversion of hydraulic conductivity from Induced Polarisation, Part B: field examples from five countries, *Near Surface Geoscience 2021, Extended Abstract*, 1-4.

Comunian, A., Straubhaar, J., Renard, P. (2012), 3D multiple-point statistics simulation using 2D training images. *Computers & Geosciences* 40 - DOI: 10.1016/j.cageo.2011.07.009

## Multidisciplinary Approach to Conceptual Modelling of Hydrothermal Systems, Topusko - Croatia

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**Key words:** hydrothermal system, natural thermal spring, multidisciplinary research, Croatia.

Natural thermal water springs, with temperatures up to 65 °C, emerge at two dozen localities in the Pannonian part of Croatia which has favourable geothermal characteristics. These waters have been used for millennia, and in the past fifty years they were a basis for the development of tourism and health care centres [1]. As their water demand increased, higher quantities were abstracted and additional intake structures and wells were constructed. A system-level understanding of the factors controlling these resources is necessary for their sustainable utilization. These thermal springs are generally part of intermediate scale hydrothermal systems which include: recharge areas in the mountainous hinterlands of the springs; geothermal aquifers mostly hosted in Mesozoic carbonate rocks [2]; and discharge areas in places with favourable structural characteristics increasing the local permeability field. In the scope of HyTheC project, funded by the Croatian Science Foundation, a multidisciplinary approach is used for the characterization of Daruvar, Hrvatsko zagorje, and Topusko hydrothermal systems in central and northern Croatia. Structural, hydrogeological, geothermal, hydrogeochemical, and geophysical investigations and remote sensing will be used to construct conceptual models. Their physical validity will be tested through numerical simulations supported by 3D geological reconstructions and local hydrogeological and thermal parameterisation of the hydrostratigraphic units. The emphasis is placed on the Topusko hydrothermal system with very scarce initial data. The available conceptual model will be refined based on researches which are currently underway.

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[2] Borović, S., Marković, T., Larva, O., Brkić, Ž. & Mraz, V. 2016 : Mineral and Thermal Waters in the Croatian Part of the Pannonian Basin. In: Papić, P., Ed., *Mineral and Thermal Waters of Southeastern Europe*. Cham: Springer, pp. 31-45.

# The particle size distribution as a key factor for hydrogeological investigations

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Key words: hydrogeology, permeability, particle size distribution, specific surface.

In the field of urban hydrogeology, it is often needed to define the permeability, as the most important hydrogeological parameter for interpretation of impact of pollutant on groundwater quality. Calculating permeability from grain size data is fast, relatively simple and cheap, and is often used for stated purpose. Causeless modifications of original methods for determination of hydraulic conductivity or permeability from grain size data have been, in the last three decades, widely disseminated in scientific and expert articles and published in numerous scientific journals. Modification of referential grain size, which is generally integrated in the calculations as square value, is especially a sensitive issue. Such and similar modifications strongly affect the results compromising the valuable utilization of grain size data for the permeability assessment in loose deposits and similar porous materials. This problem was demonstrated in this research through the presentation of original versions of four permeability calculation methods from grain size distribution: Hazen's, as a representative of extremely experimental method, USBR /USCRO (Urumović et al., 2020) as empirical method, and Slichter's and Kozeny – Carman (Urumović and Urumović, 2016) method as theoretical methods. Validity and proposal for corrections were demonstrated as their validity ceases to depend on the grading of the analyzed materials. This is especially important for Kozeny – Carman method that integrates formulation of specific surface area, making it widely applicable in soil science disciplines. In this research, samples of loess and loess-like sediments (Pola et al., 2020) were analyzed in laboratory within the ISSAH project (funded by Croatian Science Foundation), and later mathematically processed for hydraulic conductivity calculation. Statistical analyses show high accuracy of mentioned methods when properly used, opposed to recently (mis)used formulae.

Pola, M., Pavičić, I., Rubinić, V., Kosović, I., Galović, L., Borović, S., Wacha, L., Urumović, K. 2020. First results of multidisciplinary investigations for the hydrogeological conceptual modelling of loess deposits in eastern Croatia. *Acque Sotterranee - Italian Journal of Groundwater*, 9 (1), 43-49. doi:10.7343/as-2020-432.

Urumović K., Urumović K. Sr. 2016. The referential grain size and effective porosity in Kozeny-Carman model. *Hydrol. Earth Syst. Sci.*, 20, 1669-1680. doi:10.5194/hess-20-1669-2016.

Urumović, K., Borović, S., Urumović, K., Navratil, D. 2020. Validity range and reliability of the United States Bureau of Reclamation (USBR) method in hydrogeological investigations. *Hydrogeology journal*, 28 (2), 625-636. doi:10.1007/s10040-019-02080-2.



## Session 4

### Groundwater flow and hydrogeochemical features in volcanic, karst and coastal plain aquifers

#### Keynote Lecture

*Selected European research results, information products and map viewers of groundwater quality and quantity developed by the four GeoERA groundwater projects: HOVER, RESOURCE, TACTIC and VoGERA*

Klaus Hinsby (Geological Survey of Denmark and Greenland, GEUS)

#### Conveners

Alfonso Corniello (Università degli Studi di Napoli "Federico II")

Lucio Martarelli (ISPRA)

Stefano Viaroli (Università degli Studi Roma Tre)

## KEYNOTE LECTURE

### **Selected European research results, information products and map viewers of groundwater quality and quantity developed by the four GeoERA groundwater projects: HOVER, RESOURCE, TACTIC and VoGERA**

Klaus Hinsby (Geological Survey of Denmark and Greenland, GEUS)

*Selected research-based information products and highlights of the four GeoERA groundwater projects: HOVER, RESOURCE, TACTIC and VoGERA, and their contribution to improve our understanding of the evolution of groundwater quantity and quality at European and regional scale, are briefly presented. The presentation include demonstration of on-line map viewers developed for a common digital European subsurface information platform, the European Geological Data Infrastructure (EGDI) illustrating e.g. groundwater quality and quantity issues such as nitrate contents in the unsaturated zone moving towards European aquifers (incl. travel time through the unsaturated zone), and a new European groundwater recharge map compiled based on satellite measurements, national groundwater recharge studies and machine learning. Other information products include map viewers of relevance for human health impact assessments (e.g. maps of arsenic and fluoride distribution in European aquifers) or assessment of the volume of the available groundwater resources across Europe. Finally, selected results from regional or local studies published in research papers from the GeoERA projects e.g. investigating natural background levels, DRASTIC vulnerability, groundwater age distributions and saltwater intrusion are also shown. The provided data on groundwater quantity and quality in Europe contribute with valuable information for managing and protecting Europe's groundwater resources as well as groundwater dependent or associated terrestrial and aquatic ecosystems towards pollution from the surface, over-exploitation and competing uses. The GeoERA groundwater projects thereby contribute with important information for sustainable management of (ground)water and subsurface resources in general according to EU and UN policies such as the Water Framework Directive, the European Deal, UN SDGs and a new UN resource management system.*

*Please visit the GeoERA groundwater projects at: <https://geoera.eu/>*

# **Recharge assessment and water table variation over time in different areas of the Castelporziano Presidential Estate: possible implication on forest health**

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**Key words:** coastal aquifer, monitoring network, forest, Critical Zone.

The piezometric monitoring of the aquifer of the Castelporziano Presidential Estate is based on a network measuring the water table and the main chemical-physical parameters. Water table changes with time are limited, but different trends have been recognized in different areas of the aquifer, due to the distribution of rainfall and infiltration and to the soil permeability. On coastal area seasonal changes of the water table are limited and time trend shows a depletion. On central area oscillations with time are evident and a negative trend is also affecting the aquifer. On the northern and eastern areas, the recharge periods are able to hinder the depletion, resulting in a positive trend of water table, probably enhanced by groundwater flow coming from the regional aquifer of Alban Hills [1]. A winter semester of aquifer recharge is usually followed by a summer period of groundwater exhaustion. Increase of occurrence of drought years (like 2016-2017) caused an extension of the exhaustion phase, which both decreases the water table and causes stress and water scarcity in soil and unsaturated zone, in the so-called “Critical Zone”. Soils act as link among the rainfall, the forest and the groundwater table. The water content in the first meter of soil has been monitored by CREA Institute, recording different responses of outcropping sediments. In different periods of the year, the soils have a fundamental role in capturing rainfall water in unsaturated zone, in allowing deep recharge of the water table, but also in feeding the forest roots. These different conditions with time and space can obviously influence the forest health and consequently changes in recharge regime of the aquifer are to be considered one of the possible causes of critical stress shown by the forest during last years in the Castelporziano Presidential Estate.

1. Banzato Francesca, Marino Domenico Barberio, Andrea Del Bon, Alessandro Lacchini, Valentina Marinelli, Lucia Mastrorillo, Stefania Passaretti, Chiara Sbarbati, Marco Petitta 2019. Relationship between rainfall and water table in a coastal aquifer: the case study of Castelporziano Presidential Estate *Acque Sotterranee - Italian Journal of Groundwater*.- AS28- 379: pp. 27-33 DOI: 10.7343/as-2019-379

## **New insights on the groundwater-seismicity relationship: experiences from the hydrogeological network in central- southern Italy**

Francesca Gori<sup>1</sup>, Marino Domenico Barberio<sup>1</sup>, Maurizio Barbieri<sup>1</sup>, Andrea Billi<sup>2</sup>, Carlo Doglioni<sup>1</sup>,  
Stefania Franchini<sup>1</sup>, Marco Petitta<sup>1</sup>

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**Key words:** groundwater, earthquake-hydrology, monitoring, precursors, hydrosensitivity.

Earthquake-induced groundwater responses have been widely observed in seismogenic areas worldwide, before, during and after the occurrence of seismic events. In order to deepen our knowledge about the groundwater-seismicity relationship, since 2014 pilot sites for the research of seismic precursors have been installed in the central-southern Apennines (Italy), with the main aim of establishing new hydrogeological, hydrogeochemical, and gas-geochemical monitoring network. Through these years, we collected on a monthly basis data of groundwater major and trace elements, isotopic ratios and chemical-physical parameters. Additionally, we performed continuous monitoring of groundwater Radon activity and groundwater level by using multiparametric probes. Promising results were achieved and recently partially published. In detail, groundwater Radon concentrations were continuously measured between April 2017 and December 2019 in two springs emerging along active fault zones in the inner sector of the central-southern Apennines. We detected significant groundwater Rn anomalies for all monitored seismic events that were expected to influence the Rn concentration based on the strain radius of the effective precursory manifestation zone. The recorded preseismic signals could be explained as the result of contraction and expansion that fractured systems undergo. Besides, between July 2014 and December 2019 the groundwater level was continuously recorded in a 100 m deep monitoring well in central Italy. Impulsive groundwater level responses to worldwide  $M_w \geq 6.5$  earthquakes were observed, even over 18.000 km from the monitoring site. We interpreted the recorded groundwater level changes as oscillations driven by the passage of Rayleigh seismic waves through the aquifer. Detecting the water table variations induced by distant earthquakes is another step towards a correct identification of (preseismic) changes in groundwater due to near-field seismicity. Overall, the results of our ongoing research shed light on the hydrosensitivity of the study sites and on the characteristics of fractured aquifer systems to strain variations.

Barberio, M. D., Barbieri, M., Billi, A., Doglioni, C., & Petitta, M. (2017). Hydrogeochemical changes before and during the 2016 Amatrice-Norcia seismic sequence (central Italy). *Scientific reports*, 7(1), 1-12.

The full paper is published on: 1) Barberio, M. D., Gori, F., Barbieri, M., Billi, A., Casalati, F., Franchini, S., Lorenzetti, L., & Petitta, M. (2020). Optimization of dissolved Radon monitoring in groundwater to contribute to the evaluation of the seismic activity: an experience in central-southern Italy. *SN Applied Sciences*, 2(8), 1-12. 2) Barberio, M. D., Gori, F., Barbieri, M., Billi, A., Caracausi, A., De Luca, G., Franchini, S., Petitta, M., & Doglioni, C. (2020). New observations in Central Italy of groundwater responses to the worldwide seismicity. *Scientific reports*, 10(1), 1-10.

## Hydrogeochemistry and geothermometry of fractured carbonate aquifers controlled by deep-seated faults: two study cases from Central Italy

Marino Domenico Barberio<sup>1</sup>, Francesca Gori<sup>1</sup>, Maurizio Barbieri<sup>1</sup>, Tiziano Boschetti<sup>2</sup>, Antonio Caracausi<sup>3</sup>, Giovanni Luca Cardello<sup>1,4</sup>, Marco Petitta<sup>1</sup>

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**Key words:** Groundwater mixing, Deep fluids, Earthquake-Hydrology, Isotope, Geochemistry.

Expanding knowledge about the origin and mixing of deep fluids and the water-rock-gas interactions in aquifer systems can represent an improvement in the comprehension of crustal deformation processes. Indeed, fractured carbonate aquifers probably constitute the most important thermal water resources in non-volcanic areas. In this study we performed hydrogeochemical screenings of springs in two study areas in Central Italy affected by mixing of shallow groundwater flow with deep fluid rise: the San Vittorino Plain and the Pontina Plain. We carried out two conceptual flow models for both shallow and deep fluids. The application of Na-Li geothermometers, coupled with a comparison of major and trace elements and gas analyses allows us to understand the geochemical and structural processes driving the uprising of deep sealed fluids. The geothermometric approach has identified the greatest equilibrium temperature of the analyzed groundwater (>150 °C) and consequently the maximum depth of groundwater flowpaths driven by infiltration processes (by the application of local geothermal gradient). In addition, the gas-geochemistry analysis confirms the mixing between shallow and deep fluids identifying the presence of some traces of mantle derived He ( $\approx 1\text{-}2\%$ ). The obtained evidences in both study areas suggest a common genesis of mixing processes, influenced by recent tectonics. The occurrence of deep fluids is closely related to the presence of deep-seated faults which constitute pathways for the hydrothermal circulation. The study highlights the criteria to identify the most suitable sites for monitoring variations in groundwater geochemistry due to the deep fluids uprising modulated by fault activity, to be further correlated with crustal deformation and possibly with seismicity. Furthermore, for the management of water resources, changes in faults activity (e.g. increases of deformation rates) can modify the uprising flow and consequently the geochemistry of regional fractured carbonate aquifers with increases in dissolved heavy metal content (e.g. As, Fe, Cr).

Goldscheider, N., Mádl-Szönyi, J., Erőss, A., & Schill, E. (2010). Thermal water resources in carbonate rock aquifers. *Hydrogeology Journal*, 18(6), 1303-1318.

Barberio, Marino D.; Gori, Francesca; Barbieri, Maurizio; Boschetti, Tiziano; Caracausi, Antonio; Cardello, Giovanni L.; Petitta, Marco. 2021. "Understanding the Origin and Mixing of Deep Fluids in Shallow Aquifers and Possible Implications for Crustal Deformation Studies: San Vittorino Plain, Central Apennines" *Appl. Sci.* 11, no. 4: 1353. <https://doi.org/10.3390/app11041353>.

## Groundwater salinization assessment in the coastal area of Sozopoli (Northern Greece)

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**Key words:** groundwater, seawater intrusion, ERT, SWIM.

In the last decades, groundwater level reduction and groundwater quality degradation has been observed due to agricultural, residential and tourism development. The groundwater overexploitation is worldwide considered as one of the main causes of the salinization phenomenon (Kazakis et al., 2016; Mastrocicco et al., 2019). Additionally, the overuse of ammonium fertilizers in agricultural areas has become a main global environmental issue (Kazakis et al., 2020). This study deals with the pressures of agricultural activity on account of the uncontrolled use of fertilizers and the non-rational management of groundwater in the coastal aquifer of Sozopoli area in Northern Greece. The investigation of the seawater intrusion and groundwater chemical characteristics can provide important information for the effective application of groundwater protection measures. Therefore, a holistic analysis of groundwater samples, groundwater level measurements and electrical resistivity tomographies (ERTs) has been carried out to determine the hydrochemical water regime of the study area in regard to salinization phenomenon. A “Seawater Intrusion Map” (SWIM) has been produced according to the results of ionic ratios ( $\text{Na/Cl}$ ,  $\text{SO}_4/\text{Cl}$ ,  $\text{Mg}^{2+}/(\text{Mg}^{2+}+\text{Ca}^{2+})$ , and  $\text{Cl/HCO}_3$ ) underlying the zones affected by salinization. Additionally, two ERTs have been performed to confirm the seawater intrusion in the coastal aquifer. The ion ratio maps were classified into two categories: i) affected or ii) not affected by salinization through a numerical index. The results of the study revealed the correlation among seasonal water level fluctuation and groundwater overexploitation which controls the aquifer’s recharge process. Moreover, the quality of groundwater is controlled by salinization along the coast and by the use of fertilizers in agricultural areas inland. The geoelectrical measurements (ERTs) verify the salinization front and salinization layers in the study area while the combination of the classified ion ratios depicts how groundwater is highly influenced by the salinization phenomenon.

Kazakis, N., Matiatos, I., Ntona, M. -, Bannenberg, M., Kalaitzidou, K., Kaprara, E., Mitrakas, M., Ionnidou, A., Vargemezis, G., Voudouris, K. (2020). Origin, implications and management strategies for nitrate pollution in surface and ground waters of Anthemountas basin based on a  $\delta^{15}\text{N-NO}_3^-$  and  $\delta^{18}\text{O-NO}_3^-$  isotope approach. *Science of the Total Environment*, 724 doi: 10.1016/j.scitotenv.2020.138211.

Kazakis, N., Pavlou, A., Vargemezis, G., Voudouris, K., Soulios, G., Pliakas, F., Tsokas, G. 2016. Seawater intrusion mapping using electrical resistivity tomography and hydrochemical data. An application in the coastal area of eastern Thermaikos Gulf, Greece. *Science of Total Environment*, 543, 373-387. doi: 10.1016/j.scitotenv.2015.11.041.

Mastrocicco, M., Busico, G., Colombani, N., Vigliotti, M., Ruberti, D. 2019. Modelling actual and future seawater intrusion in the Variconi coastal wetland (Italy) due to climate and landscape changes. *Water (Switzerland)*, 11(7) doi: 10.3390/w11071502.

# Hydrogeological Behaviour and Geochemical Features of Waters in Evaporite-Bearing Low-Permeability Successions: A Case Study in Southern Sicily, Italy

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**Key words:** conceptual model; evaporites; bacterial community; stable isotopes; tritium.

Knowledge about the hydrogeological behaviour of heterogeneous low-permeability media is an important tool when designing anthropogenic works (e.g., landfills) that could potentially have negative impacts on the environment and on people's health. The knowledge about the biogeochemical processes in these media could prevent "false positives" when studying groundwater quality and possible contamination caused by anthropogenic activities. In this research, we firstly refined knowledge about the groundwater flow field at a representative site where the groundwater flows within an evaporite-bearing low-permeability succession. Hydraulic measurements and tritium analyses demonstrated the coexistence of relatively brief to very prolonged groundwater pathways. The groundwater is recharged by local precipitation, as demonstrated by stable isotopes investigations. However, relatively deep groundwater is clearly linked to very high tritium content rainwater precipitated during the 1950s and 1960s. The deuterium content of some groundwater samples showed unusual values, explained by the interactions between the groundwater and certain gases (H<sub>2</sub>S and CH<sub>4</sub>), the presences of which are linked to sulfate-reducing bacteria and methanogenic archaea detected within the saturated medium through biomolecular investigations in the shallow organic reach clayey deposits. In a wider, methodological context, the present study demonstrates that interdisciplinary approaches provide better knowledge about the behaviour of heterogeneous low-permeability media and the meaning of each data type.

The full paper is published on: [Rizzo, P., Cappadonia, C., Rotigliano, E., Iacumin, P., Sanangelantoni, A. M., Zerbini, G., & Celico, F. \(2020\). Hydrogeological Behaviour and Geochemical Features of Waters in Evaporite-Bearing Low-Permeability Successions: A Case Study in Southern Sicily, Italy. \*Applied Sciences\*, 10\(22\), 8177.](#)

## Hydrogeological Map of the Sibillini Mts. (Central Italy)

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**Key words:** Hydrogeological map, fractured aquifers, hydrogeological sections, tectonics, regional hydrogeology.

The results of regional hydrogeological studies are, usually, outlined in hydrogeological maps. The interpretation of geological units and tectonic elements, according to their hydrodynamic roles, supports the understanding of groundwater flow conceptual models, especially at regional scale.

Collection, standardization, and interpretation of the geological, tectonic, and hydrogeological data from literature, led to the realization of the hydrogeological map (1:50,000 scale) of the Sibillini Mts. carbonate system (Central Italy). The aim of the map is to illustrate a detailed pre-seismic hydrogeological conceptual model of the Sibillini Mts area which was struck by a prolonged seismic sequence up to Mw 6.5 in 2016, becoming reference for the comparison between the pre-seismic and the new hydrogeological conditions emerging from the post-seismic research.

With specific different colors the Map presents a classification of the hydrogeological complexes based on the effective infiltration rate. The Map, also, shows the location of the springs having a mean discharge equal or higher than 30 L/s and the tectonic elements with regional significance, selected by a careful review of the structural data known.

The hydrogeological map is supported in a pseudo-3D conceptual model defined by eleven hydrogeological sections at 1:50,000 scale. Eight sections are perpendicular (SW-NE) and three are parallel (NNW-SSE) to the main regional structural lineaments. The realization of the hydrogeological cross sections requested simplifications of the complexity of the structural elements and the thickness variability of each hydrogeological complex. This simplification highlighted the specific hydrodynamic roles of the considered tectonic elements. Generally, the thrust faults act as hydraulic barriers, whereas the normal faults do not necessarily correspond to a groundwater flow seal, because their permeability is controlled by the fracture network properties (connectivity, density, orientation, and length distribution of the fractures) of the fault zone.

Boni, C., Baldoni, T., Banzato, F., Cascone, D., & Petitta, M. (2010). Hydrogeological study for identification, characterization and management of groundwater resources in the Sibillini Mountains National Park (Central Italy). *Italian Journal of Engineering Geology and Environment*, 2, 21–39. <https://doi.org/10.4408/IJEGE.2010-02.O-02>

Pierantoni, P., Deiana, G., & Galdenzi, S. (2013). Stratigraphic and structural features of the Sibillini Mountains (Umbria-Marche Apennines, Italy). *Italian Journal of Geosciences* 132, 497–520. <https://doi.org/10.3301/IJG.2013.08>



# Groundwater resources and legacy mining: the usefulness of integrated approaches to investigate complex carbonate aquifer systems

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**Key words:** groundwater protection, karst aquifers, thallium, drinking water, Apuan Alps

Safeguarding and protection of groundwater resources is a major challenge for the present and future human society. Carbonate aquifers represent an essential source of water supply worldwide, although they generally have a high intrinsic vulnerability to contamination and short-term climatic fluctuations. An optimal management of complex karst systems is fundamental for their sustainable exploitation and protection from contaminants. This objective can be met through detailed surveys based on multidisciplinary approaches, in order to define groundwater flowpaths in terms of origin and evolution, including processes affecting the water resource quality. This work addressed the critical issues tied to the coexistence of abandoned mining activities and valuable karst groundwater in a past-mining district of the Apuan Alps (northwestern Tuscany, Italy), by means of an integrated approach based on hydrodynamics, hydrochemistry, and water isotopes. The local carbonate aquifers, hosting groundwater resources, are threatened by acid mine drainages and contaminated stream from potentially toxic elements (e.g. thallium) (Perotti et al. 2017; Ghezzi et al. 2019). The research focused on three major springs, outflowing in a restricted area adjacent to the stream-bed, among which only one is currently tapped for drinking use. Nine sampling fields were carried out on the contaminated stream and spring water from September 2017 to December 2018, along with a continuative monitoring of hydrologic-physical-chemical parameters. Chemical (major and trace elements) and isotopic analysis ( $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ) were performed on collected samples. Despite the proximity of the three springs, we recognized two different groundwater flow systems (Doveri et al. 2021). The first one is shallower and shows evidences of hydraulic connection with the contaminated stream, threatening the quality of groundwater resources. The second one, feeding the tapped spring, shows characteristics of a deeper and longer groundwater flow, which seems to be isolated from the former and protected from contamination.

Ghezzi, L., D'Orazio, M., Doveri, M., Lelli, M., Petrini, R., Giannecchini, R., 2019. Groundwater and potentially toxic elements in a dismissed mining area: Thallium contamination of drinking spring water in the Apuan Alps (Tuscany, Italy). *J. Geochemical Explor.* 197, 84–92. <https://doi.org/10.1016/j.gexplo.2018.11.009>

Perotti, M., Petrini, R., D'Orazio, M., Ghezzi, L., Giannecchini, R., Vezzoni, S., 2017. Thallium and Other Potentially Toxic Elements in the Baccatoio Stream Catchment (Northern Tuscany, Italy) Receiving Drainages from Abandoned Mines. *Mine Water Environ.* 37, 431–441. <https://doi.org/10.1007/s10230-017-0485-x>

The full paper is published on: [Doveri, M., Natali, S., Franceschi, L., Menichini, M., Trifirò, S., Giannecchini, R., 2021. Carbonate aquifers threatened by legacy mining: hydrodynamics, hydrochemistry, and water isotopes integrated approach for spring water management. \*J. Hydrol.\* 593, 125850. <https://doi.org/10.1016/j.jhydrol.2020.125850>](#)

## Defining dissolved species background levels in a complex heterogenic area through stochastic approach

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**Key words:** background levels, sequential Gaussian simulation, groundwater pollution

The aim of the study was the determination of the background levels of three pollutants potentially harmful for human health (NO<sub>3</sub>, F and As), dissolved in different groundwater bodies of the Campania plain (southern Italy). To achieve this purpose, the gaussian sequential simulation algorithm (sGs) was performed to process three hundred ninety-eight water samples collected during many field campaigns over the last two decades from springs and water wells (urban and agricultural). For the present study, one hundred simulations were realized for NO<sub>3</sub>, F and As and then post-processed to obtain two statistic rasters showing: (i) the median values of the simulated cumulative distribution, and (ii) the probability of exceeding a fixed threshold limits (WHO threshold) along the study area. The hydrogeological background was in agreement with previous characterization (Busico et al. 2018; Rufino et al. 2019). Subsequently, the Median values predicted by sGs were extracted for defining the background levels of those groundwater bodies. The NO<sub>3</sub> maps showed higher median values and higher probabilities of exceeding the WHO threshold (50 mg/L; WHO 2017) especially in those areas characterized by ignimbrite outcrops, while lower median values and probabilities in carbonate systems and alluvial plains were calculated. The F and As maps showed higher values and high probabilities of exceeding the WHO threshold limits (5 mg/L and 10 µg/L, respectively) especially in areas near volcanic edifices (Roccamonfina and Campi Flegrei) or in alluvial plains characterized by the presence of volcanic material (lavas and ignimbrite) and/or reworked volcanic material. The presence of peat lens and clay materials in the plain between the Volturno river and the Regi Lagni seems to play an important role both in limiting NO<sub>3</sub> concentration and in As releasing through the whole plain.

Busico G, Kazakis N, Colombani N, Mastrocicco M, Voudouris K, Tedesco D (2017) A modified SINTACS method for groundwater vulnerability and pollution risk assessment in highly anthropized regions based on NO<sub>3</sub>- and SO<sub>4</sub><sup>2-</sup> concentrations. *Sci Total Environ* 609:1512–1523. <https://doi.org/10.1016/j.scitotenv.2017.07.257>

Rufino F, Busico G, Cuoco E, Darrah TH, Tedesco D (2019) Evaluating the suitability of urban groundwater resources for drinking water and irrigation purposes: an integrated approach in the Agro-Aversano area of Southern Italy. *Environ Monit Assess* 191:768. <https://doi.org/10.1007/s10661-019-7978-y>

WHO, World Health Organization, 2017 Guidelines for drinking water quality, 4th ed. Incorporating the first addendum. WHO, Geneva, Switzerland, 145–220.

## **Designation of Nitrate Vulnerable Zones in northern Sardinia – Coupling geochemical data and geostructural mapping and modelling to enhance the understanding of groundwater flow**

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Key words: NVZ, Sardinia, Isotopes, 3D-model

Nitrate concentration exceeding the European limit of 50 mg/L in groundwater requires detailed investigation in order to delimitate Nitrate Vulnerable Zones (NVZ). The complex flow pattern in groundwater originating from the geological structure often leads to difficult predictions of the main flow paths and potential mixing of groundwater. The methodological approach consists in defining a hydrogeological model based on geostructural mapping and modelling, supported by hydrogeochemical and isotopic tools.

The Logudoro basin, within a Burdigalian half-graben in northern Sardinia, was considered as a test site. The area includes mainly subhorizontal continental to marine deposits such as conglomerates, sandstones, limestones and mudstones. The infill unconformably lies over an Oligo-Miocene volcanic succession. Pleistocene basaltic flows unconformably overlie both volcanic and sedimentary Miocene rocks.

The geological model was improved through detailed mapping (1:10.000). Outcrop geology and boreholes were used to constrain cross-sections. The subsequently created 3D-model validated the geological map and allowed to analyse water-volume potential, recharge areas and aquifers interconnection.

Water samples were collected from 13 springs, 28 wells, 3 surface waters and untreated and clean sewages. Geochemical features and isotopic analysis of  $\delta^2\text{H}$  -  $\delta^{18}\text{O}$  in water,  $\delta^{11}\text{B}$ ,  $\delta^{15}\text{N}$  -  $\delta^{18}\text{O}$  in dissolved nitrate, and  $\delta^{34}\text{S}$  -  $\delta^{18}\text{O}$  in dissolved sulphate were determined to investigate groundwater recharge, processes occurring during flow path and identify nitrate origin. Groundwater show a wide range of geochemical compositions. A weak variation of isotopic composition with depth was observed. Piezometric contour lines combined with hydrogeochemical analysis allow to classify water groups and identify interaction processes within aquifers.

Five hydrogeological units bounded by faults and aquitards, discontinuous in width and thickness, were outlined by coupling geochemical and geological modelling. The applied approach improves the groundwater flowpath comprehension leading to the delimitation of potential NVZ.

## Groundwater natural background levels in a densely populated valley plain along the Ligurian coast

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**Key words:** Coast; Porous aquifer; Hydrochemistry; Natural background levels; Ligurian coast;

The research aims to define the natural background levels (NBLs) (according to SNPA, Doc. 20/17) of an alluvial valley and marine coastal groundwater body in a densely anthropic and tourist area of the Levante Ligure, where Ophiolites rocks outcrops and may release heavy metals. The defined NBLs will help to recognize future groundwater anthropogenic pollution phenomena from the natural leaching of Ophiolites. The investigated area is the coastal alluvial plain of Levante. It is composed of coarse and fine alluvial deposits originated by Ghiararo stream and its minor tributaries, and coastal marine deposits. The extension of the alluvial plain is a few square kilometers and the maximum thickness of the deposits is 35 meters. The aquifer is a monolayer and it is unconfined in the medium-high portion of the plain and confined or semi-confined near the coast. In the plain, three group of wells are used for drinkable purpose. Levante plain is densely populated and it is a famous tourist hub (due to the proximity with the Cinque Terre). On the plain insist different anthropogenic activities (e.g., agricultural, industrial infrastructural and residential) that could potentially impact the groundwater quality. Historically, salt intrusion phenomenon isn't discovered in the aquifer and only two drinkable wells have been affected by a low presence of contaminants.

## Multiple-step numerical modeling to assist aquifer characterization: a case study from the south of Brazil

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**Keywords:** Groundwater flow, Coastal aquifer, FEFLOW, Conceptual model, Brazil

Management of coastal aquifers must take account of the complex hydrological processes and data uncertainties associated with this environment. In such conditions, regular evaluation of mechanisms, parameters and boundary conditions is required to understand groundwater flow and to develop a robust conceptual model. Information on transient recharge, tide-driven fluctuations of groundwater receptors (e.g. seas, rivers) and the activation status of drainage networks may need to be updated recurrently, as they affect the evolution of groundwater balance over time. In coastal tropical regions, due to the high intensity and variability of natural drivers (e.g. precipitation, evapotranspiration), a comprehensive hydrogeological characterization can be even too expensive or technically unfeasible. In those contexts, numerical models can be effectively applied at various phases of a hydrogeological investigation to elucidate preliminary conceptual models and to guide the field characterization. Models provide a quantitative framework for synthesizing field information and verifying mechanisms, readily contributing to a cost-effective decision-making process. Accordingly, this article presents a systematic hydrogeological characterization of a coastal basin in a tropical region of southern Brazil that is affected by intensive rainfall and ocean tides. Precipitation is the main process driving groundwater flow in the region, although high head variations at the boundaries affect spatiotemporal distribution of the water table and groundwater discharge. In the work, a set of numerical experiments is deployed to test the understanding of natural processes and to assist additional field campaigns. The hierarchy of hydrogeological processes is evaluated over different scales, to eliminate less sensitive mechanisms. By presenting the detailed setup information on model development, the applications are demonstrated and limitations are discussed in light of the available field data and specific research objectives. [Abstract obtained from a published paper]

## Hydrogeological properties of ignimbrites: two examples of pyroclastic flow deposits in central Italy

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**Key words:** ignimbrite, hydraulic properties, volcanic aquifer

Ignimbrites are aquifers also used for the supply of drinking water in the volcanic regions of central and southern Italy. However, little knowledge is available about these aquifers. This study reports the results of some experiments carried out on two ignimbrites in central Italy: the Cimino Ignimbrite of the Cimino Volcano (hereafter ICV) and the C Ignimbrite of the Vico Volcano (hereafter CIV). The ICV, erupted 1.3 Ma, is trachytic in composition, covering an area of about 300 km<sup>2</sup> with a volume of about 15 km<sup>3</sup> and variable thickness up to 150 m. The CIV, erupted 151 ka, is phonolitic in composition, covering an area of about 1250 km<sup>2</sup> with a volume of about 10 km<sup>3</sup> and variable thickness from a ten of meters up to 60-80 m.

Using a multi-scale approach, the hydraulic properties of the two ignimbrites were investigated through: i) laboratory measurements of porosity and hydraulic conductivity on rock samples, ii) discontinuity measurements of rock masses on some significant outcrops, and iii) pumping tests on a single well and in some cases also with observation wells.

The hydraulic conductivity measured in the laboratory on rock samples varies between 10<sup>-6</sup> and 10<sup>-7</sup> m/s, depending on the porosity and welding degree of the two ignimbrites. The transmissivity determined by pumping tests varies in a wider range of values (10<sup>-3</sup> to 10<sup>-5</sup> m<sup>2</sup>/s), depending on the fracturing degree of welded facies and the frequency of intercalations of non-welded facies, coarse lapilli deposits and agglomerate layers. A more developed fissure network characterizes the more densely welded ignimbrite, i.e. the ICV, compared to the less densely welded one, i.e. the CIV. All these factors have a significant influence on well yields (ranging from 0.5 to 5 L/s) and on the trend of the drawdown over time found during the pumping tests.

## Numerically enhanced conceptual modelling (NECoM) applied to the Malta Mean Sea Level Aquifer

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**Key words:** Data gap, Numerical modelling, Groundwater management, Seawater intrusion, Malta

Conventional hydrogeological practice is used for data to be collected to formulate a conceptual model, which often provides a basis for construction of a numerical model. The numerical model is then used to test groundwater management strategies before they are implemented in the field.

A new workflow is proposed employing the numerically enhanced conceptual model (NECoM) of the mean-sea-level aquifer (MSLA) in the island of Malta.

The Malta MSLA is affected by overexploitation and is under constant threat of salinization. In development of a conceptual/numerical model of the island, data of many different types, including heads, chloride concentrations, EC logs, tidal tests and qualitative data were assimilated into a fast-running numerical model. Simultaneously, strategies for optimal acquisition of further data were examined through the modelling process.

The model was delivered to the Energy and Water Agency, together with suggestions for flexible model deployment. These workflows will, hopefully, spawn improvements in the model through further revision of the concepts on which it is based. At the same time, the model provides the Agency with an ability to make predictions whose uncertainties are quantified and reduced through data assimilation as soon as new data is available.

The proposed NECoM approach can be generalized since it bases model usage on the premise that modelling should make maximum use of existing data by assimilating its information content, highlighting the uncertainties of decision-critical predictions that remain because of data insufficiency. Through pursuing this strategy, the presently disjointed process of modelling on the one hand, and data acquisition on the other can become better aligned with each other. Conceptual and numerical model development are seen as parallel, rather than as sequential, activities. Together, they endow the modelling process with an ability to make predictions of future system behaviour whose bias is reduced, and whose uncertainties can be quantified.

The full paper is published on: [Lotti, F., Borsi, I., Guastaldi, E., Barbagli, A., Basile, P., Favaro, L., ... & Sapiano, M. \(2021\). Numerically enhanced conceptual modelling \(NECoM\) applied to the Malta Mean Sea Level Aquifer. \*Hydrogeology Journal\*, 29\(4\), 1517-1537.](#)

## **Study for the realization of an expert system for continuous monitoring of turbidity in the water bodies of the Apuan area**

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**Key words:** marble powder, karst system, continuous monitoring.

Apuan area in north Tuscany is affected by intense marble mining, which continued since the middle age up to the present day. In the last 30-40 years the advent of new methods of cutting and processing of stone materials has produced a significant increase in the number of quarries, extraction rate and, consequently, of the produced waste.

The finest fraction, a marble powder known as “marmettola”, has significant impact in a large groundwater karst system that acts as drinking water reservoir of the highest quality.

Tuscany Region giving a mandate to the Tuscany Environment Agency (ARPAT) to promote necessary actions to improve the monitoring of the impact of marmettola and among various activities undertaken by ARPAT, focus was on river and springs of area through the creation of a network for continuously detection of discharge, turbidity, temperature, conductivity, chemical/physical parameters of environmental interest.

The OMNIA expert system, (Operative Monitoring Instant Alert) analyses data collected extrapolating attention and alarm thresholds for turbidity as a function of rains occurred.

OMNIA is a non-physically based system, an attempt has been made to build a valid method that can frame the natural characteristics from limited input series, less than two years. However, OMNIA has already proved to be of valuable support in the monitoring activity, following successful investigation by the authorities. When turbidity is higher than expected, the system warns and to confirm this conductivity was considered, a parameter closely related to meteoric events [1]. Increasing in turbidity, without changes in conductivity, confirming the anomalous nature.

Monitoring results are displayed on interactive maps, clicking on station icon will open the graph for the last seven days

The color of the icon indicates whether there has been overshoot in the last 24 hours compared to attention and alarm thresholds identified for station. Monthly graphics for the archive are produced.

[1] Drysdale R., Pierotti L., Piccini L., Baldacci F. Suspended sediments in karst spring waters near Massa (Tuscany), Italy Environmental Geology (2001) 40:1037–1050.



## **A coupled hydrogeological and multi-isotopic approach to investigate saltwater intrusion in a coastal groundwater (Sardinia, Italy)**

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**Key words:** groundwater, saltwater intrusion, isotopes

Saltwater intrusion is a crucial environmental issue in the Muravera coastal plain (south-eastern Sardinia). Since the early fifties, the natural hydrodynamic equilibrium between groundwater, surface-water and seawater has been deeply modified by construction of dams across the Flumendosa river and the development of agriculture, tourism and aquaculture activities along the coast. The aim of this work is to analyze the different salinization mechanisms and hydrogeological inputs in order to implement an integrated and sustainable management system aimed at slowing saltwater intrusion and, on the other hand, to meet human needs.

A total of 52 points were sampled among groundwater from different aquifers and surface water. Chemical and isotope analyses of  $\delta^{18}\text{O}_{\text{H}_2\text{O}}$  e  $\delta^2\text{H}_{\text{H}_2\text{O}}$  were carried out. To deepen the knowledge of salinization mechanisms and water evolution, analyses of  $\delta^{11}\text{B}$ ,  $\delta^{87}\text{Sr}$ , and  $\delta^3\text{H}$  were carry out at selected sampling sites.

The monitoring of water level and fresh-salt water interface in wells has been carried out in order to provide information on the groundwater response to the water level fluctuation induced both by withdraw and natural phenomena. Influence of the tide was also investigated.

This combined approach of environmental isotopes, chemical analyses and hydrogeological indicators is expected to provide useful information about the mechanisms and geochemical processes affecting groundwater in the plain and to plan measures for the correct management and protection of water resources from saltwater intrusion.

## Karst springs along the Murge Adriatic coastline (Apulia, southern Italy)

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**Key words:** karst, hydrogeology, coastal spring, Apulia

Apulia is an almost entirely karst region in southern Italy, being characterized by several thousand-meter-thick Mesozoic carbonate succession, diffusely outcropping in the Gargano (north), Murge (center) and Salento (south) areas.

It is surrounded by Adriatic and Ionian seas for most of its extent, with over 850 km of coasts and a significant, but not yet quantified, amount of freshwater gushing out along coastline or offshore. Mainly the coastal sectors of Apulian aquifers are then strongly exposed to seawater intrusion phenomena for both natural causes, due to the presence of fractures and karst forms, or human induced causes, such as sea level rise and over-exploitation.

Focusing on Murge area, the groundwater discharge to the sea typically occurs in a diffuse way, through groundwater fractures; locally it is concentrated where karst conduits reach the sea or coastal zones, that is where the hydraulic function of karst conduits for freshwater transfer prevails. Many thermal anomalies have been detected in the past thanks to multi-spectral aerial surveys (visible, infrared and thermal infrared), due to differences in temperatures between spring water and seawater.

In this work, we describe the Adriatic coast between the city of Monopoli and the Torre Canne place: in this area, the main known springs show average discharges ranging from 300-400 to 600 l/s, with maximum peaks slightly lower than 1.200 l/s. This is the coastal stretch where most of the thermal anomalies have been recognized as submarine springs. In addition, at several other locations, in the immediate proximity and along the coasts, there are proofs of water emergencies. To provide a contribution aimed at improving the knowledge about hydrogeology of this sector of Murge, we present new data on the karst coastal springs and a first attempt to link them with those coming out from the main inland recharge area.

Cotecchia, V. 2014. Le acque sotterranee e l'intrusione marina in Puglia: dalla ricerca all'emergenza nella salvaguardia della risorsa. Mem. Descr. Carta Geol. d'Italia, 92, 1228 pp.

Pisano, L., Zumpano, V., Liso, I.S. & Parise, M. 2020. Geomorphological and structural characterization of the "Canale di Pirro" polje, Apulia (Southern Italy). *Journal of Maps*, 16 (2), 479-487. doi: 10.1080/17445647.2020.1778550.

# Groutability of a rock mass evaluated by means of geo-structural surveys and in-situ tests

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**Key words:** hydraulic conductivity; jet grouting; sea arch; Campania

In order to strengthen rocks involved in engineering structures such as dams, tunnels or rocky cliffs, sometimes jet grouting is needed. In this regard, it is necessary to know the hydraulic conductivity ( $K$ ) along the joint sets affecting rock masses to assess the most suitable grouts. This paper aims to describe the assessment of hydraulic properties of the joint network characterizing the Natural Arch of Palinuro (Campania): a geotope of high environmental and landscape value (Budetta et al., 2019). Due to wave motion and gravity, the marine arch experienced several rock falls that progressively thinned the structure, making its complete collapse likely within a few decades. Based on photogrammetric and geo-structural surveys the reconstruction of the geo-structural and geo-mechanical setting was performed in detail. The aim was to detect the rock mass permeability in order to evaluate its groutability by means of cements or chemical resins. According to Scesi and Gattinoni (2012), hydraulic conductivity was evaluated on the basis of geo-structural data completed by results of injection tests performed in 10 horizontal boreholes located on both arch façades. The study highlighted the presence of three main joint sets which group the bedding planes as well as tectonic discontinuities with different orientation whose overall  $K$  values range between  $10^{-3}$  and  $10^{-2}$  m/s. Even though the strengthening could be performed by means of cement grouts, it was deemed more appropriate the use of silica gel slurries because the aggressiveness potential of the sea water could favor reactions such as carbonation of cements. Lastly, the study also allowed to assess that the strengthening of the marine arch cannot be obtained only by grouting, as the uncertain stability also needs reinforcement by means of fiberglass or carbon fiber bars.

Budetta, P. De Luca, C. Simonelli, M.G. Guarracino, F. 2019 Geological analysis and stability assessment of a sea arch in Palinuro, southern Italy *Engineering Geology*, Vol. 250, pp. 142-154, <https://doi.org/10.1016/j.enggeo.2019.01.009>

Scesi, L. Gattinoni, P. 2012 *Methods and Models to Determine the Groundwater Flow in Rock Masses: Review and Examples*. Springer, ISBN: 978-1-61942-690-0, pp. 1-165.

## **Analysis and mapping of the salinity distribution and water table level of the Emilia-Romagna coastal phreatic aquifer.**

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**Key words:** coastal aquifer, freshening, water table, salinization, geostatistical analysis.

Freshwater in coastal areas is crucial for life, but its availability at a sustainable quality and quantity is challenged by impacts from climate change, land subsidence, coastal erosion, land loss, saltwater intrusion, and environmentally damaging land use practices. This research assesses the distribution of water level and salinization at regional scale in the coastal aquifer of the Emilia-Romagna. Data from 35 wells distributed across the entire regional coastal area are used to establish temporal trends, as well as correlations between salinity, water table level, and rainfall during the period 2009-2018. The results show that the freshwater presence is mainly controlled by strong seaward-directed hydraulic gradients, good connectivity between aquifer and high discharge rivers, as well as by presence of a coastal dune systems without pine forests. The lowest water table level occurs in the western and northern parts of the study area, because of the semi-confined behavior of the aquifer. The existence of water table level below sea level and high salinity at the bottom of the aquifer suggest that the aquifer is in unstable hydrodynamic conditions and strong vertical seepage of saltwater from the bottom towards the aquifer top occurs. The limited rainfall, along with fine overbank deposits and heavy drainage result into small effective recharge of the coastal aquifer. Only in the northernmost and southernmost parts of the study area the groundwater remains fresh due to the Po and Marecchia river aquifer recharge, respectively. In the rest of the region, the freshwater lenses thickness, where present, is less than 4.5m. This study is the first to provide a regional overview of the state of groundwater level and salinization within the coastal aquifer of the Emilia-Romagna region. Overall, the aquifer salinization has not increased in the 10-year period under examination and there are some local encouraging signs of freshening.

## Hydrochemical, isotopic and microbiota characterization of telese mineral waters (Southern Italy)

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**Key words:** Telese springs, Italy, Mineral waters, Chemical and isotopic data, Microbiota

The study deals with the analyses of springs and wells at the base of Montepugliano Hill that represents the SE edge of the wide carbonate Matese massif (Campania, southern Italy). At the base of the hill, from west to east and for almost one kilometre, cold springs HCO<sub>3</sub>-Ca type (Grassano springs, ~4.5 m<sup>3</sup>/s; TDS: about 0.45 g/L) pass to hypothermal, HCO<sub>3</sub>-Ca type, sulphurous and CO<sub>2</sub>-rich springs (1 m<sup>3</sup>/s with TDS <1 g/L). Some of the latter are widely used in *Telese Spa and Centro Relax Spa*. Chemical and isotopic analyses carried out for this study support the hypothesis that all these waters (mineral and non-mineral) have the same catchment area, which is located in the Matese massif.

As regards the sulphurous springs, they receive both meteoric waters infiltration and uprising of deeper waters rich in endogenous CO<sub>2</sub> and H<sub>2</sub>S gases through important faults systems. Far from these faults, the chemistry of groundwater is scarcely (or not at all) affected by these deep fluid enrichment processes.

This scheme is very significant; in fact, when very important groundwater resources are present, it is possible to use both mineral waters in Spa and, in areas far from the faults, those not yet mineralized. Finally, at Montepugliano Hill, in the final stage of the flow path, groundwater is also affected by change in the microbiome: this could provide a basis for comparison between various mineral waters.

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# **The hydrological role of soil coverings on the groundwater recharge of representative Mediterranean karst aquifer: the case study of the Mt. Soprano-Mt. Vesole-Mt. Chianello aquifer (Campania region, southern Italy)**

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**Keywords:** karst aquifer, groundwater recharge, soil coverings, southern Italy.

For many countries, karst groundwater is a fundamental source of water for human, and irrigation uses as well as for sustaining natural groundwater-dependent ecosystems. In southern Italy, and especially in the Campania region, karst aquifers represent strategic resources of drinking water feeding several regional aqueduct systems. Therefore, the assessment of groundwater recharge and of the main hydrological variables controlling it is a major scientific challenge, especially considering the strategic relevance of karst aquifers for social and economic development in southern Italy.

The goal of this research is the assessment of effects of hydrological features and regime of soil coverings on groundwater recharge of Mt. Soprano-Mt. Vesole-Mt. Chianello karst aquifer (Campania region, southern Italy), coinciding with the groundwater catchment that feeds the Capodifiume spring (Capaccio, Province of Salerno). In this study, soil physical features, thickness and hydraulic unsaturated / saturated properties of soil coverings were characterized by field and laboratory activities. As principal results obtained, thickness of soils of representative land cover conditions, varying from wooded areas to bare ones with sparse outcropping rocks, were analyzed and characterized by a statistical approach. Values of soil thickness up to 1.5 m were related to an allochthonous origin derived by air fall deposition of pyroclastic soils erupted by the volcanic centers of the Campania region (Phlegraean Fields and Somma-Vesuvius volcanoes).

The coupling of field recognitions and the land cover map, obtained by a supervised technique applied to Google Earth orthophotos, allowed to assess the spatial distribution of soil thickness covering the karst aquifer. Moreover, Soil Water Retention Curves were determined by laboratory tests permitting the estimation of field capacity and allowable water content.

Finally, the installation of soil moisture sensors allowed to initiate a monitoring activity of soil moisture which is revealing the main patterns of soil hydrological regime that affects the groundwater recharge.

Data and characterizations obtained will be used in the assessment of the role of soil coverings on hydrological balance and then on groundwater recharge of karst aquifer. The approach proposed is conceived as being exportable to other karst aquifers of the southern Italy and of the world in all cases in which soil covering exert a relevant role on hydrological regime and groundwater recharge.

# **Study of dilution processes of sulfidic aquifer hosted by the “Fiume-Vento” karstic complex, Frasassi (Marche Region, Central Italy)**

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**Key words:** Cave Frasassi, Karst aquifer, Sulfidic springs, dilution processes

This study update and deepen the hydrogeological and geochemical knowledge about the complex underground water circulation system of the Frasassi karst area (Tazioli et al., 1990; Galdenzi et al. 2008; Galdenzi et al., 2017), especially about the dilution processes of the sulfidic aquifer hosted by the “Fiume-Vento” karstic complex, and the formation of freshwater layers above it. The mainly horizontal development of underground spaces and passages allows reaching the water table in the lower section of the cave, outcropping in the form of lakes, permitting the sampling and the study of its surface. From the chemical analysis emerged that each sampled lake, except Lago Verde, is superficially characterized by a layer of bicarbonate water of variable thickness, floating on the sulfidic one. Through the geochemical characterization of this water, and those coming from the Sentino river, the sulfidic springs and dripping, it was possible to attribute to the dripping water the responsibility of this phenomenon. It has not been excluded a possible feeding of the aquifer by the stream during flooding events in the outermost portions of the complex, before the touristic entrance of the Frasassi Caves. On the contrary, flow measurement carried out during a low discharge period along the Sentino river, excluded water leaks towards the internal karst aquifer downstream the sulfidic springs emerging along the water course not far from the caves entrance. On the contrary, a flow increase in the stream sector downstream the caves entrance has been recorded, testifying that in the easternmost part of the gorge the internal aquifer feeds the stream. This was also confirmed by the results of the geochemical study.

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## First results of infrared thermography applied to the evaluation of hydraulic conductivity in rock masses

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Key words: hydraulic conductivity, rock masses, infrared thermography

An innovative methodological approach using infrared thermography (IRT) provides a potential contribution to the indirect assessment of hydraulic conductivity of jointed rock masses. The hydraulic conductivity of a rock mass is a difficult parameter to define because it is a function of numerous factors (e.g. orientation, persistence, spacing, opening, shape and roughness of discontinuities) and of the uncertainty in rock mass properties (Silliman 1989). Numerous Authors suggested a methodology to empirically calculate the hydraulic conductivity of fractured rock masses using mathematical formulas, whose terms can be derived through a detailed mapping of the fractures.

Recently, some researchers have tested infrared thermography (IRT) for the study of rock masses, proving that their cooling behavior is related to their degree of fracturing (Pappalardo et al. 2016). With particular reference to rock masses, they established a Cooling Rate Index (CRI), which describes the cooling speed of the rock after a natural heating, highlighting that an intensely jointed rock mass cools down faster than a less fractured one. CRI correlates well to the main geomechanical features of the rock mass, such as the rock quality designation (RQD) and the joint volumetric count (Jv).

Inspired by such recent innovative outcomes achieved by IRT, which designate CRI as a suitable potential index for the study of the rock fracturing, this paper aims at looking for a useful application of CRI for the indirect estimation of rock mass hydraulic conductivity by means of IRT and the empirical methods above mentioned.

This technique proved a suitable tool to evaluate the degree of fracturing of rock masses along with their discontinuity systems, which expedite water flow within the rock mass itself. Such index was correlated with the assessed hydraulic conductivity and satisfactory regression equations were achieved. The interesting results show that hydraulic conductivity values are likely to be linked with the cooling behavior of rock masses, which, in turn, is affected by spacing, aperture and persistence of discontinuities.

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## **Hydrogeological characterization of Naples city's coastal volcanic-marine aquifer (southern Italy)**

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**Keywords:** coastal volcanic-marine aquifer, urban hydrogeology, seawater-freshwater interaction

The Historic Center of Naples, one of the oldest (about 2800 years) and the largest (about 17 km<sup>2</sup>) of Europe, has been declared since 1995 an UNESCO World Heritage Site due to the universal value of its urban fabric, which comprises a multitude of archaeological, cultural, historical-architectural values and geo-environmental beauties to be protected and enhanced.

By a hydrogeological point of view, it is part of a coastal volcanic-marine aquifer, characterized by a complex stratigraphic, geomorphological and structural settings, whose groundwater resources have been used from historic times until the end of the 19<sup>th</sup> century. In such a framework, advancing the knowledge on the hydrogeological features of this unique area is fundamental to assess the potential of groundwater resources, even for low-enthalpy geothermal uses, and to mitigate risks related to groundwater rising and flooding that can affect the socio-economic development of the city and prevent the fruition of its heritages and public utility services.

As part of the SNECS (Social Network delle Entità dei Centri Storici) and PAUN (Parco Archeologico Urbano di Napoli) research projects, developed by DATABENC District S.c.a.r.l. (High Technology Consortium for Cultural Heritage), various research activities were focused in recent years on the hydrogeological, hydrodynamic, hydrogeochemical and hydrogeothermal study of test areas located within the Historic Center of Naples. This study shows the main results of the abovementioned projects, which were based on the analysis of geological, stratigraphic and hydrogeological data found in the literature and collected by public and/or private bodies, as well as new hydrogeological surveys. Specifically, it was aimed at the production of thematic maps and the reconstruction of a 3D hydrogeological model that allowed to define a hydrostratigraphic and multitemporal groundwater flow models as well as to analyse the interactions between groundwater circulation, seawater intrusion and anthropic-archaeological structures, along the coastal sector.

The results obtained from hydraulic, hydrodynamic, hydrogeochemical and hydrogeothermal investigations have advanced the knowledge on groundwater circulation, chemical-physical response of the aquifer to the hydrodynamic stimulation and on the chemical-physical and thermal features of the hydrogeological system at the local scale, which are the basis for the design of low-enthalpy geothermal plants.

## Groundwater management through Forested Infiltration Area and hydrogeological numerical modeling of Arborea coastal plain (Sardinia, Italy)

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**Keywords:** 3D Hydrogeological numerical modeling, MAR, Forested Infiltration Area, Nitrate.

This research aims at developing an innovative approach and tools for groundwater management to mitigate nitrate contamination due to agro-zootechnical sources. The system will be tested in the 60 km<sup>2</sup> farming district of Arborea in central-western coast of Sardinia, Italy. This area is one of the most productive agricultural sites in the region, based on intensive dairy cattle farming, and on fodder production.

The Arborea district has been declared a nitrate vulnerable zone (NVZ) in 2005, following the Nitrate Directive 91/676/CEE caused by high level of nutrients found in the groundwater (Biddau et al., 2018).

According to the 3D hydrogeological conceptual model of the area, two main aquifers have been identified: the upper unconfined one which is hosted in sandy sediments and the lower multi-layer aquifer hosted in alluvial sediments. The occurrence of discontinuous clay layers and lagoon deposits, up to 10m thick, causes varying degrees of communication between the multi-layer hydrogeological units. (Ghiglieri et al., 2016).

One aim of the research (conducted within the frame of two European funded projects MENAWARA - <http://www.enicbcmcd.eu/projects/menawara> and Prima Sustain-COAST - <https://www.sustain-coast.tuc.gr/en/home>), is to test nitrate mitigation strategies for the sandy phreatic aquifer, especially through dilution processes, by implementing a Managed Aquifer Recharge (MAR) system based on Forested Infiltration Area (FIA). A second objective is to understand aquifer dynamics, evaluate the dilution effect of FIA and simulate aquifer response to different groundwater management strategies using a 3D Groundwater Numerical Model.

The model implementation will consider various information including drainage and irrigation schemes, recharge volumes, climate, groundwater withdrawal, land use, and data acquired during field surveys to assess the hydrogeological setting and groundwater quality, quantity, and flow paths prior and after FIA implementation.

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Ghiglieri, G., Carletti, A., Da Pelo, S., Cocco, F., Funedda, A., Loi, A., Manta, F., Pittalis, D. (2016). Three-dimensional hydrogeological reconstruction based on geological depositional model: A case study from the coastal plain of Arborea (Sardinia, Italy). *Engineering Geology*, 207, 103-114. <https://doi.org/10.1016/j.enggeo.2016.04.014>

## Ecosystem preservation of the Doberdò lake (Classical Karst)

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**Key words:** groundwaters, karst lake, sustainability, temporary thresholds, hydrogeology.

The karst lake of Doberdò, in the western sector of the Classic Karst (NE Friuli Venezia Giulia Region, NE Italy) represents a unique ecosystem for a territory where the absence of surface water is the distinctive feature. The typical hydrogeological context of a mature karst with sudden variations in groundwater levels has favored the development of plant associations that represent a *unicum* in the whole Dinaric Karst, so much that the territory has become a Nature Reserve and a Site of Community Interest. However, in recent decades, the progressive shortage of water due to both anthropic (drainages, withdrawals, dams, etc.) and natural (global warming and climate changes) factors, together with the lack of vegetation maintenance are leading the lake to a gradual burial with the consequent disappearance of the ecosystem. The Water Resources Management Survey and Geological Survey of the Friuli Venezia Giulia Region jointly with the Department of Mathematics and Geoscience of the Trieste University have developed a project aimed at saving this ecosystem. The hydrogeological studies carried out clarified the importance of the karst aquifer recharge by the Soča/Isonzo River leakages and highlighted how Doberdò waters in turn feed the Slovenian and Italian water supply systems. Analysis of the historical data demonstrated that in the past the lake remained full of water even during summer times, while in recent years only a small stream connects the spring system to the swallow hole area. To counteract the emptying of the lake, temporary thresholds around the swallow holes were installed. The experiment succeeded with thresholds having only 60 cm of elevation. With this new limit the lake was flooded for more than a third of its surface without changing its hydrogeology and the neighboring spring systems.

## 2002-2021: Twenty Years of Groundwater Quality Monitoring in Campania (Italy)

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Key words: groundwater, monitoring, Campania, nitrates.

In 2002 ARPAC carried out a study about groundwater quality, aiming at the creation of a regional monitoring network. About 400 sampling sites were examined and the chemical- physical parameters, requested by the Italian and European Union regulations (D.Lgs. n.152/99 All.1 EU Directive 2060/2000), were taken into account. The monitoring started in autumn 2002, sampling points, including major springs and significant wells were chosen looking at hydrogeological setting and priorities envisaged by River Basin Authorities. The network consisted of 120 monitoring sites for 40 major regional GWBs. The number of sampling points increased reaching 183 for 46 GWBs in 2012. Since 2012, according to D.Lgs. 152/2006, the network revision started, and in 2015 the Campania Region has been partitioned in 80 significant GWB: 10 % volcanic, 25 % alluvial, 30 % karstic and 35 % mixed with low-moderate permeability. Today about 200 sampling points are monitored. GWB quality data are processed in order to calculate the annual chemical status classification (D.lgs. 30/2009 and D.M. Env. 6 July 2016). During the evaluation and classification of the GWBs large variations in chemical composition occurred. The best quality has been recorded for carbonate massifs fractured aquifers of the Apennine chain, where water recharge occurs mostly in national and regional parks. Spectacular springs, with a flow exceeding 1-2 m<sup>3</sup>/s outpour from these zones and represent the most relevant portion of drinking water of the region. On the contrary, the Tyrrhenian coastal plains are affected by severe contamination, mostly by nitrates. Near the Sarno river and in the Regi Lagni basin nitrate concentrations sometimes exceed 200 mg/l, with local rising trend reaching 2-3 mg/l year, and hazardous substances have been detected. In volcanic GWBs, As and F of natural origin often exceed the drinking water and environmental thresholds.

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