Book of abstracts

Flowpath 2025 - Torino

June 11-13, 2025 Torino - Italy

Event organised by

Politecnico di Torino
Department of Environment, Land and Infrastructure Engineering

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UNIVERSITÀ DI TORINO

CONSIGLIO NAZIONALE DEI GEOLOGI

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Preface

The Italian Chapter of the International Association of Hydrogeologists (IAH) is pleased to present you the proceedings of the abstracts submitted to the 7th Edition of FLOWPATH, the National Meeting on Hydrogeology. The congress took place on 11th-13th June 2025 in Turin.

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

The objectives of the conference are:

- To ensure that hydrogeology can play an important role in supporting the development of groundwater management and protection policies.
- To strengthen knowledge and research initiatives on emerging challenges to the groundwater environment
- 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:

- Session A: Groundwater and climate change: impact and opportunity
- Session B: Groundwater modelling: development and application
- Session C: Hydrogeological system and processes: from local to regional scale
- Session D: Groundwater quality and protection

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, 128 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 (61) or poster (82) presentation. The Authors come from Universities, Public Bodies, Private Companies of Italy and some other countries.

In summary, this congress, with 198 internation participants, testified the interest in groundwater resources and their protection with a view to future challenges in the hydrogeological sciences.

The Organizing Committee

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Identification and Mapping of groundwater Potential Recharge Areas in the Dosso region (Southwestern of Niger) by using Multicriteria Analysis Method

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Groundwater is the main source of water supply in the Dosso region which is located in the southwestern part of the Iullemmeden Basin in Niger republic (West Africa). Despite the arid to semi-arid climate that characterizes this region, groundwater recharge is occuring mainly through rainfall. This recharge of water which is an essential element in the hydrological cycle is prefentially done according to zones which can also be vulnerable to groundwater pollution. The main objective of this study is to identify and mapped the potential recharge areas. A methodology based on a multicriteria analysis integrating GIS and remote sensing was used to map the potential recharge areas. After processing the Landsat satellite images of Dosso region, all the parameters influencing the hydrological recharge processes were obtained and integrated into GIS.

These parameters are: soil types, land cover, fracture density, drainage density, lithology and slope. The map of potential recharge areas obtained shows that the majority of the study areas has great recharge potential. According to this study, this great potentiality could be linked to: the sandy nature of the soil, the cultivable areas, the presence of fractures and density of hydrographic network. This map also confirmed that areas with high recharge potential are located in the beds of ponds and "dallols" (wide dry valleys), which thus become more vulnerable areas. This map of potential recharge areas constitutes therefore a tool for decision makers.

Profiling salinity in a coastal shallow aquifer near the Venice lagoon

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The Venice coastal plain and its surroundings is suffering of soil and surface water salinization due to seepage of saline groundwater into drainage canals of agricultural lands and soil salinization due to irrigation water quality. To study this phenomenon, two agricultural fields experiencing crop yield decrease in the last years were selected. The fields are located in a reclaimed area at approximately 2 m below sea level in the Venice province, 2.5 km from the Venice Lagoon (Site 1) and in Rovigo province, 10.5 km from the Venice Lagoon and 18.5 km from the Adriatic Sea (Site 2). To delineate the salinity gradients, 9 high resolution vertical profiles of soil cores were collected with an electrical auger corer and analysed in the field via a Meter® TDR for porewater salinity, volumetric water content (VWC), and temperature, and in the laboratory for sedimentary organic matter (SOM) gravimetrically, major ions and trace elements (TEs) via IC and ICP-EOS, respectively. The composition of porewater's leaching fraction (LF) was gained via deionized water batch extraction with solid liquid ratio 1:5, while the plant available water (PAW) was obtained via microwave hot water extraction in three selected profiles. Stratigraphical cores were almost homogeneous with the most permeable layers constituted by organic sandy layers. An average porewater salinity of 2.2 g/l with an upward increasing trend was found in Site 1, while an average porewater salinity of 3.5 g/l with a downward increasing trend was found in Site 2. Vertical profiling highlighted the strong connection among some trace elements and the saline organic horizons in Site 2, characterized by paleo-seawater upward fluxes. Conversely, Site 1 was mostly affected by evapoconcentration processes of irrigation waters. The PAW salinity was up to two times the LF, highlighting that organic layers are the major saline source in these reclaimed lands and they can release large amount of solutes as well as TEs.

Multiscale and multidisciplinary approaches to assess groundwater vulnerability to agrochemicals of alluvial aquifers

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Groundwater management requires detailed aquifer characterization, especially in alluvial aquifer systems, where the occurrence of intense agricultural and industrial activities represents a high risk for groundwater contamination. In this context, a challenging task toward the goal of zero-pollution and sustainable agriculture is to assess groundwater vulnerability related to the use of agrochemicals in the farming practices. In the framework of PNRR AGRITECH project, a multiscale and multidisciplinary approach has been applied to the Torre Lama farm, located in Bellizzi (Campania, southern Italy), managed by the University of Naples, which has been selected as a representative site of alluvial aquifers. It belongs to the alluvial plain of Sele River, which is characterized by an articulated stratigraphic and hydrogeological setting favoring the formation of a multilayered aquifer system. The research focused on the application of a multimethodological approach at different scales and on the monitoring and modeling of transport and attenuation processes of agrochemicals toward the groundwater. At the local scale, corresponding to that of an experimental plot, a detailed stratigraphic and hydrogeological characterization, based on drillings and soil laboratory analyses, has allowed the reconstruction of the physical setting. This has been used for designing a monitoring station based on suction lysimeters to be used for sampling capillary water and detecting the transport of agrochemicals through the unsaturated zone. Moreover, considering soil hydrological and meteorological time series, a 1D and 2D numerical model based on HYDRUS code has been set. At the scale of the whole farm area, the stratigraphic and hydrogeological settings were recognized through Vertical Electrical Soundings (VES), which allowed to identify resistivity horizons with different hydrogeological properties. Results obtained at the local scale were extended at the scale of the whole farm area.

Flow model of a drainage trench used for irrigation

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The landscape of Cuneo Plain (Piedmont, NW Italy) is characterized by the presence of drainage trenches, known as fontanili. Along these channels the groundwater resurfaces naturally from the unconfined aquifer and is made available to the local agrozootechnical activities. The fontanili were constructed starting from the 11th century with the aim of reclaiming swamps, by lowering the water table, and to provide water for irrigation and drinking purposes. Their configuration was later improved by adding screened boreholes, known as tubi calandra, along the furrows, as they enhance the groundwater flow towards the surface.

The aim of this study is the development of a conceptual and numerical model capable to describe the drainage capacity of such structures. The model was calibrated using monitoring data of a fontanile located in the municipality of Beinette (Italy).

The flow model was developed in Hydrus (PC-Progress), solving the Richard's equation and allowing to model the water flow also in the vadose zone. The 2D model of a transversal section of the trench was implemented to study the hydraulic connection to the phreatic aquifer, whereas, the 3D model was used to estimate evolution of the drainage capacity, and therefore of the discharge, along the furrow. Afterwards, a sensitivity analysis was conducted to determine the drainage capacity of the trench under different scenarios of aquifer hydraulic conductivity, upstream hydraulic head and, finally, length and radius of the tubo calandra.

The numerical model allowed to have a clearer picture of the mechanisms controlling the discharge in the fontanili, both in terms of their connection directly to the water table, as well as the contribution of the tubi calandra. The results are particularly meaningful as they contribute to the sustainable management of water resources in the area, coupling groundwater and surface water, so that a careful planning of the resource to meet the irrigation demand can be developed

The influence of the hydrogeological setting for the definition of the optimal spacing between vertical borehole heat exchangers

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The use of low-enthalpy geothermal energy through vertical borehole heat exchangers (BHE) represents a low-impact solution, based on a renewable energy source that is widespread worldwide. This study focuses on studying the most significant parameters that influence the energy performances and the environmental impact of vertical borehole heat exchangers (BHE) installed in different geological contexts.

The aim of the study is to develop a design guide for designers indicating the optimal distances between a row of BHE arranged perpendicular to groundwater flow and varying operational condition of the energy system, geometry of BHE and the hydrogeological parameters of the aquifer. The study was performed through the implementation of synthetic numerical models into MODFLOW-USG code. The vertical U-shape pipes of BHE were implemented into the model adapting the Connected Linear Network (CLN) Package, such as discussed in Antelmi et al., 2021. Specific flow and thermal boundary conditions were introduced to reproduce the real operation of a vertical BHE and various physical and hydrogeological properties of the aquifer were set to simulate a wide range of porous materials characteristics (from clay to sand and gravel).

Starting from numerical models representing a single BHE, having the aim to determine operating conditions without interferences, different borefield of 3 and 5 BHE were implemented to study in detail how their closeness can influence the energy performance of the central BHE and the extension of the thermal plume. Fixed a threshold (95%) of acceptance related to the heat rate exchanged reduction between BHE and surrounding subsoil, the optimal distances between geothermal exchangers were carried out for each parameter combination: results show an optimal distance ranging from 8 meter for fine materials and low groundwater flow velocity to 2 meters for coarse materials and higher groundwater flow velocity.

Evaluation of recharge sources and nitrates origin in a karst spring: a case study from the F.na Nurighe spring (NW Sardinia, Italy)

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Miocene limestones and calcarenites from the Mores Formation outcropping in the Logudoro basin (NW Sardinia, Italy), host a karst aquifer that gives rise to several springs. One of these, the F.na Nurighe spring, supplies the municipal aqueduct of Cheremule. Results of the hydro-geochemical monitoring carried out by ARPAS since 2013 have highlighted continuous exceedances of the nitrate threshold value (50 mg/l) in the spring waters.

Based on the available information, a preliminary ZVN has been defined, which currently constrains over a wide area. The aim of the present research is to deepen the hydrogeological knowledge of the study area and to provide useful information for the re-delimitation of a more effective ZVN. The study includes i) a review and interpretation of chemical analysis from the ARPAS monitoring, ii) the collection of new samples from springs located in the nearby area, and iii) a new monthly monitoring of flow rates and the sampling of the spring waters since June 2023 for the determination of nitrates, major ions, trace elements, and water isotopes.

Multi-temporal geochemical analyses from ARPAS show that chemistry of the F.na Nurighe spring is characterized by a bicarbonate alkaline-earth type during the winter/spring period and a chloride-bicarbonate alkaline-earth type during the summer-autumn period. Compared to nearby springs, which are also fed by marls and basalt formations, the compositional ratios of the F.na Nurighe waters indicate significant mixing processes, and therefore possible lateral recharge from other hydrogeological units, especially during the dry season.

Flow rate measurements collected so far span from a minimum of 2,9 l/s to a maximum of 18 l/s. Nitrates show a progressive increase during the dry season, followed by an abruptly collapse in the wet season. Such preliminary results have provided useful information about the possible alimentation sources of the spring, but further investigations and monitoring are required.

Geochemical and Isotopic Characterization of the Quality of Groundwater in the Jeffara Coastal Aquifer, Tunisia

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The Groundwater resources studied here are located in Jeffara coastal plain, southeast of Tunisia, which is 5500 km² in area and characterized by a semi-arid climate. The groundwater is the main source of water supply, and the region is facing increasing needs in drinking water, agriculture and tourism activities. The salinity measured in groundwater samples from this area is rather high; the values range between 1 and 10 g/l. Geochemical and stable (18O, 2H, 87Sr/86Sr, 3H) isotopic determinations were applied to characterize the groundwater shallow aquifer and using the results to specify the origin of the salinity, the hydrodynamic of the groundwater and the origin of the recharge area. To this end, groundwater samples were taken from hundred (130) of survey of wells during sampling campaign carried out in 2020 and 2021 and reported in this work. Observed slight changes of the chemical composition of the water after a rainy period have been attributed to rainwater infiltration into the groundwater. The ⌾18O values of the individual water samples vary from –6,39 ‰ to – 3,11 ‰ while the ⌾2H values range from –44,6 ‰ to –24,5 ‰. The deuterium excess of the majority of the samples is remarkably constant; the individual values cluster round 5,8 ‰, the deuterium excess value characteristic for palaeo-groundwater in northern Africa. The 87Sr/86Sr ratios allow to distinguish two poles of water mixtures in the aquifer: A saline pole corresponding to the dissolution of the evaporites and seawater. The contribution of seawater in the aquifer has been estimated to be between 10 to 25 % depending on the location transposing heterogeneity from the salinization process in this region. The salinity of groundwater appears to originate from water rock interaction with dissolution of evaporites (gypsum and halite minerals), by seawater intrusion and partly derived from human activities (agriculture flowback and urban pollution from sewage water).

Rising Groundwater Temperatures: Risks and Rewards in Times of Global Warming and Urban Expansion

Benz Susanne

Karlsruhe Institute of Technology

The keynote is talking about the Rising Groundwater Temperatures: Risks and Rewards in Times of Global Warming and Urban Expansion

Groundwater systems are increasingly affected by the dual forces of global climate change and urbanization. Even under a medium emissions scenario, shallow groundwater temperatures could rise significantly by 2100. Urban areas exhibit even more pronounced subsurface warming due to the urban heat island effect, with groundwater temperatures in city centers exceeding those in surrounding rural areas.

This talk will delve into the mechanisms driving groundwater warming, including the roles of surface temperature increases and anthropogenic heat sources. It will explore the potential implications on water quality, ecosystem health, and the potential for geothermal energy utilization. Only by examining both global trends and localized studies, challenges and opportunities presented by rising groundwater temperatures in the context of sustainable urban development and water resource management can be highlighted.

A Novel Approach for Unlocking the Geothermal Potential of Urban Aquifers

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[1]*Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino*

Low-enthalpy geothermal energy has been identified as a sustainable solution for urban heating and cooling, with open-loop systems efficiently harnessing aquifer resources. This study introduces a novel methodology that integrates Geographic Information System (GIS) tools with classical hydrogeological equations to assess the potential of geothermal aquifers in urban environments. A comprehensive bibliographic analysis underpins the approach, drawing on fundamental models such as Darcy's Law, the Thiem-Dupuit formulations, and the Cooper & Jacob method. These established equations are combined with high resolution spatial data to evaluate groundwater flow, aquifer transmissivity, and well interference parameters. The methodology produces geothermal potential maps that identify zones with optimal water availability and adequate well spacing, providing a reliable preliminary assessment tool before engaging in complex numerical simulations. A case study in an urban environment demonstrates the effectiveness of the method in delineating suitable areas for open-loop geothermal applications, thereby addressing challenges related to spatial constraints and resource variability. Preliminary results indicate that the approach can estimate flow rate extraction and water thermal power, providing valuable quantitative insights. This innovative approach not only enhances the understanding of aquifer behaviour under low-enthalpy conditions, but also offers essential decision-making support for urban planners, policymakers, and energy stakeholders. By combining classical hydrogeological theories with modern GIS capabilities, the framework significantly contributes to the strategic development of low-carbon energy solutions and the sustainable deployment of open-loop geothermal systems.

Modelling of hydrodynamic behaviour in the Bossea aquifer system through natural radon concentrations: results and applications.

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Bossea Cave (Western Ligurian Alps) is affected by the presence of natural radon, originating from the radioactive decay of uranium and thorium isotopes contained in the Permian meta-volcanic basement of the karst aquifer. The non-chemically reactive Rn-222 concentrations have been investigated since 2003 by Bossea Underground Karst Laboratory: the diffusive and advective processes allow the reconstruction of the paths related to the inflowing water from the surface into the fractured network. Hence, radon fluctuations are cross-correlated with hydrodynamics: the transfer of gas from underground water flows is lagged behind the discharge peaks. The 45 hour delay in the upper meta-carbonate canyon and the 66 hour delay in the collapse chambers (located at the contact with the meta-volcanics) exclude the influence of external meteorological factors and confirm the double convective cell model describing the hypogeal atmospheric circulation. Different radon concentrations in water can also be detected between the main creek (Torrente Mora) and a secondary inflow (Polla delle Anatre). Although both are subjected to a piston flow hydrodynamic response, the former shows an increase in Rn during floods (with a lag of 46 hours), due to the mobilization of long-resident water volumes in karst fractures. In the latter case, there is a dilution of water in contact with radioactive elements of the impermeable basement (delayed by 6 hours and caused by volumes of neo-infiltration). In agreement with these results, radon proves to be an innovative tool to study the hydrodynamics of a karst aquifer and suggests a wide range of further cross-disciplinary applications, such as in the field of seismology.

Open source tools for collecting, managing and processing hydrogeological data: Python libraries and predictive algorithms for data analysis

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The amount of data generated in hydrogeological studies has increased significantly in recent last years, especially for contaminated sites monitored over long periods of time: reasons include the increasing use of continuous automated sensors for several variables (mainly piezometric levels and flows) and the higher frequency of discrete monitoring, but above all the large amount of analytical data generated by regular groundwater sampling surveys, as well as other management data related to remediation technologies (such as piezometric levels, volumes of water or NAPL extracted, operating flow rates of barrier wells, inlet/outlet flows of treatment plants).

This requires more efficient and reliable tools for data processing, analysis and storage: geospatial and relational databases. Collected data can be checked and corrected before being loaded into databases.

All data can be geo-referenced. Good design of conceptual and logical models allows the creation of a reliable database, capable of storing huge amounts of information, powerful query for data selection.

Python algorithms can be used to analyse large datasets, generate automated reports, highly customisable graphs and predictive analysis.

Some professional experience with large hydrogeological datasets from contaminated sites led to the development of a methodology ranging from data collection to analysis and publication of results, using Python libraries such as Numpy, Pandas, Scipy, Matplotlib and SK-Learn. The main possibilities are discussed with the help of some application examples.

These data analysis tools require deeper knowledge and specialised expertise, but ensure higher quality data control, faster and more sophisticated processing and targeted reporting, enabling for better and faster decision support.

Spatially-varying anisotropy allows the realistic interpolation of groundwater levels in complex settings

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Groundwater surface maps are a useful way to represent the distribution of groundwater levels and flow directions, as well as the effects of elements that disturb the natural flow.

Ordinary kriging is the standard method used to interpolate measured groundwater levels. It requires information on the spatial correlation of the data to be interpolated, typically represented by a variogram, along with an anisotropy factor and the direction of maximum correlation if necessary. When a preferential direction is expected, a polynomial plane is fitted to the measurements, and interpolation is performed on the residuals. These approaches assume second-order stationarity and therefore lack the ability to represent non-stationary cases where the regional trend, given by the principal groundwater direction, is influenced by other factors such as surface water bodies, faults, or hydraulic barriers.

An alternative approach, which considers the covariance structure of groundwater levels as location-dependent, has been applied at an industrial site bounded by an L-shaped hydraulic barrier. In this approach, the parameters defining the variogram and the preferential directions of groundwater level correlation are assigned at several points within the interpolation domain, with values reflecting the influence of local disturbances on regional groundwater flow. The resulting interpolated groundwater surface realistically represents the effect of withdrawal in each section of the hydraulic barrier, yielding results comparable to those of a numerical groundwater model while honoring the measured levels. Cross-validation statistics indicate performance comparable to stationary kriging. Real-world case studies demonstrate that this approach provides a more accurate depiction of groundwater conditions, improving the reliability of piezometric reconstructions.

Groundwater salinization processes and reversibility of seawater intrusion in coastal industrial

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The industrialization of many areas, especially close to the coastline, causes intensive exploitation of groundwater, with negative consequences on water quality due to saltwater intrusion. This is the case of the industrial area of Catania, in the eastern part of Sicily (Italy), where numerous pumping wells caused water quality issues, leading to a significant increase in salinity due to marine intrusion, as well as pollution from chemicals used in agriculture and leaching from industrial waste. This study develops a density-dependent groundwater flow model using the FREEWAT-Q3 platform and the SEAWAT code to study the seawater intrusion phenomenon. The implemented model consists of fourteen model layers, each five meters thick, representing the hydrogeological units of the study area: an upper unit of recent alluvial deposits with different permeability values and an underlying unit of sandstone and gravel. The industrial zone's aquifer receives inflow from hills on the northern and southern edges and groundwater, flowing from west to east, discharges into the Ionian Sea. The source and sink terms are represented by pumping, recharge from rainfall and the Simeto river. We calibrated the model using measurement of water electrical conductivities, taken in different years, by converting them to chlorides values. This allowed us to analyse the evolution of saltwater intrusion over time and to develop forecasting models. The results highlight the critical impact of groundwater overexploitation causing saltwater intrusion and emphasizing the need for sustainable water management strategies. The developed model provides a valuable tool for predicting future scenarios and supporting decision-making for groundwater protection in coastal industrial areas.

Assessing Groundwater Vulnerability to Nitrate Pollution and Chloride Salinization using Gaussian Simulation in the Campania Region, Italy

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The purpose of this study is to evaluate the likelihood of nitrate (NO3-) pollution and chloride (Cl-) salinization using the Sequential Gaussian Simulation (SGS) approach and to prioritize the hydrological parameters affecting the target probability in three areas of the Campania Region in Italy: Lower Volturno River Plain (LVP), Garigliano River Plain (GP), and High-middle Volturno River (HVP). Three different approaches such as Decision Tree (DT), Random Forest (RF), and Information Gain Ratio (IGR) were applied to rank the parameters.

Regarding the LVP for the NO3- probability map, the areas close to the Volturno River, have a notably low probability while for Cl- salinization the highest probability is located 15 to 20 kilometers from the coast. For the GP, the areas showing exceeding of NO3- threshold are some hot spots in the center of the plain while the highest probability for Cl- is located in the Garigliano River mounts. In the HVP only the NO3- probability exceed was detected especially around the agricultural areas. Then, the probability maps obtained from SGS (i.e., the probability of exceeding the threshold values) were compared with the probability of exceeding the same threshold limits of NO3- and Cl- measured at regional groundwater quality monitoring wells for model validation. The results show a significant correlation with coefficients of 0.97 for NO3- and 0.67 for Cl-, highlighting the accuracy of the sequential Gaussian simulation results. Finally, the results of the prioritization of parameters show that recharge, hydraulic conductivity, water depth, and crops fertilizer request are the responsible for NO3- pollution, while hydraulic head, recharge, hydraulic conductivity, distance from inland water, and soil fine sediment are in charge in determining Cl- salinization.

Strengthening the hydrogeological conceptual model of a small karst island of Vis (Croatia) by combined groundwater and precipitation hydrochemical research

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Vis is a remote island in the Croatian part of the Adriatic sea. It is a popular summer tourism destination, meaning its water supply needs are extremely high when the recharge is extremely low. A karst aquifer ensures the water supply of the island, so it is paramount to provide a solid scientific basis for its long term sustainable utilisation. To this end, all previous research is being systemised and new investigations are conducted in the scope of SIS-VIS project, with the final aim to produce the basic hydrogeological map of the island with explanatory notes.

To increase the understanding of the island's water cycle we included hydrochemical investigations of precipitation, the only source of groundwater recharge, into the existing groundwater monitoring scheme. Three rainwater samplers were placed at different altitudes on the island: close to sea level, in the central part of the island at 150 m a.s.l., and in the highest point of the island at 587 m a.s.l. (the zonal groundwater divide on the island, according to the most recent findings). The samplers are specially designed to disable re-evaporation, so there is no need to use medicinal paraffin oil, which can create various problems for laboratory analyses. Groundwater and precipitation samples were collected with a monthly resolution, and principal ion content and stable water isotopes were analysed. After one year of monitoring the preliminary results will be presented, while the monitoring will continue in the next three years to strengthen our interpretation.

Acknowledgment: This research was conducted in the scope of the internal research project SIS-VIS of the Croatian Geological Survey, funded by National Recovery and Resilience Plan 2021–2026 of the European Union – NextGenerationEU and monitored by the Ministry of Science, Education and Youth of the Republic of Croatia, and PACT-VIRA project of the Croatian Science Foundation (IP-2024-05-9190).

Reconstruction of the hydrogeological structure of the Po river basin for modeling purposes

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Hydrogeological modeling is a key instrument for groundwater resource management and for its qualitative and quantitative protection. This study presents a methodological framework for reconstructing the subsurface geology of the Po Plain within the MidAS-Po project. Coordinated by the Po River Basin District Authority (ADBPO), the project aims to develop a basin-scale hydrogeological model that enhances the understanding of aquifer systems. The resulting model comprises 12 layers that integrate, and adapt, regional hydrogeological surfaces either with chronological or managerial significance, not always consistent with each other. Aquifer units, including shallow unconfined and confined aquifers, range from 14 to 100 m in thickness, while aquitards typically measure from 7 to 12 m. Layer reconstruction was achieved by harmonizing heterogeneous regional datasets via GIS-based interpolation and stratigraphic correlation. Critical steps involved a) the introduction of median surfaces to resolve conflicting boundaries and b) extending data to Veneto by using analogs from adjacent regions. Hydraulic parameters zonation (horizontal/vertical conductivities, storage coefficients, and effective porosity) were estimated through lithological zonation. Horizontal conductivities were calculated and adjusted for lithological heterogeneity (e.g., gravel/sand vs. clay fractions), from these, the vertical ones were calculated by a variable reduction factor to allow interlayer water exchange in recharge areas. Results reveal marked spatial variability in aquifer properties, highlighting the need for a district-wide modeling approach to support sustainable water management. This integrated method enhances predictive capabilities and provides a robust basis for future groundwater management strategies.

Acknowledgements

Modello idrogeologico delle Acque Sotterranee del distretto idrografico del fiume Po-MidAS-Po (Fondo per lo Sviluppo e la Coesione 2014-2020).

Hydrogeological water balance in the high and middle venetian plain defined through a regional-scale numerical model (NE, Italy)

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In the AMARONE project, funded by the Cohesion and Development Fund (FSC 2014-2023), a regional-scale numerical model was developed to comprehensively assess the hydrogeological water balance in the High and Middle Venetian plains. The partnership between the Department of Geosciences of the University of Padova and the Eastern Alps River Basin District Authority aimed to develop a valuable tool for water management to support public authorities, in accordance with the European Community's Water Framework Directive (WFD) that promotes sustainable water use and its long-term protection.

The implemented numerical model extends from the Mincio River to the Tagliamento River, covering an area of about 6100 km2 crossed by a dense network of alpine rivers, spring rivers and artificial channels. This area is characterized by the transition from the unconfined aquifer system on gravelly materials of the high plain to the multiaquifer system of the low plain, primarily composed of gravelly-sandy confined aquifers separated by silty-clayey aquitards. The transition between these hydrogeological provinces is marked by a plain spring belt and the groundwater exploitation in the region is a crucial factor for both social and economic reasons, as evidenced by the abundant extraction through pumping wells estimated at 2351.4 M m3/year, primarily used for drinking, domestic, irrigation and industrial purposes.

This complex situation was simulated using a three-dimensional finite-difference numerical model based on the MODFLOW-NWT code, implementing and calibrating a steady-state simulation to represent the average behavior of the system in the period 2010-2022, based on the results of the previously developed monodimensional water balance. This approach allowed the integration of hydrogeological data into the balance, such as hydraulic heads and hydraulic conductivity, resulting in a numerical model useful for performing balances on the water bodies of the Veneto region.

Forested infiltration Area (FIA) as Nature-based Solution to mitigate groundwater nitrate contamination in the Nitrate Vulnerable Zone (NVZ) of Arborea (Sardinia, Italy)

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Managed Aquifer Recharge (MAR) technique based on the Forested Infiltration Area (FIA) is being tested to mitigate groundwater nitrate contamination, due to intensive agricultural activity, in a sandy aquifer within the Nitrate Vulnerable Zone of Arborea (central-western Sardinia). The research is being carried out within the NATMed project (https://natmed-project.eu/) (2023-2026), funded under the EU PRIMA Programme.

The FIA system is implemented in a pilot site of around 0.4 ha and it is supplied by drainage water with an average nitrate concentration of 70 mg L-1, coming from a nearby dewatering pumping station. The infiltration process occurs through six recharge trenches, with a total length of 300 meters and one meter deep, placed between rows of Eucalyptus and Poplar trees. The recharge water is treated before infiltration by a Passive Treatment System (PTS) installed within the trenches. It consists of a mixture of Eucalyptus wood chips (50% of volume) and inert material, whose function is to promote the denitrifying bacteria action, reducing nitrate (NO3) to atmospheric nitrogen (N2). Eventually, when the PTS effectiveness is reduced and the planting is fully developed, denitrification will be sustained by symbiotic bacteria residing on the tree root systems.

In two years of hydrogeochemical monitoring, a noticeable reduction of nitrates up to 85% in the infiltrating water and a significant decrease in groundwater nitrate concentration have been observed. These results suggest that the FIA technique is an efficient Nature-Based Solution for decontaminating waters polluted by nitrates. However, a considerable amount of soluble phosphate is released by the PTS, leading to an increase in the concentration of this pollutant in groundwater. Laboratory and field tests on some materials able to remove phosphate before infiltration are ongoing, with promising results

Feasibility of Managed Aquifer Recharge (MAR) in the Cuneo plain: experiences from the SeTe-ALCOTRA project

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Managed Aquifer Recharge (MAR) has emerged in recent years as a climate change adaptation measure to increase water availability in dry seasons and, in coastal aquifers, also to contrast the seawater intrusion.

The SeTe (Sécheresse et Territoires) project, funded by the EU programme Interreg ALCOTRA, involves the feasibility study and demonstration of MAR in the Cuneo plain, a large shallow alluvial aquifer at the south-western edge of the Po Plain. In this area, the availability of water for irrigation during summer has diminished in recent years, sparking the initiative for testing MAR as an environmentally and economically sustainable countermeasure.

The three project pilot sites identified in the project - Beinette, Tetti Pesio-Morozzo and Tarantasca-Centallo - are characterized by the presence of "fontanili", i.e. drainage trenches dug since the Middle Ages to reclaim marshy land by lowering the groundwater level. Flow rates up to 1400 l/s are extracted by fontanili, which therefore represent an important irrigation water source but are very sensitive to groundwater level declines.

The activities and the results of the first half of the SeTe-ALCOTRA project, which started in October 2023 and lasts 3 years, are hereby summarized.

Historical meteorological, geological, and hydrogeological data were collected to reconstruct the climate impacts on water resources and to characterize the shallow aquifer.

Three monitoring networks were implemented in the test sites to measure groundwater levels and flow rates in the fontanili. Field tests were performed to characterize the aquifer in the experimental recharge sites, such as Lefranc tests, pumping tests, and grain size distribution analyses on samples from core drillings and shallow excavations.

Three infiltration structures have been designed, with two configurations (two sites with a shallow trench and one with a vadose zone well), and their installation and first weeks of operation will be presented.

A bird(hawk)'s eye view of Northern Apennines hydrogeology for a quantitative assessment and mapping of sedimentary and ophiolitic fractured aquifers

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Over the past 20 years, the perception of groundwater resources in the Northern Apennines has shifted significantly. Once considered a region of "poor hydrogeology" compared to the Alps and Central-Southern Apennines, now some of their main aquifer units are recognized as a high-quality, climate-resilient strategic resource. This renewed interest has been driven by scientific research along with the support from public water companies (Gruppo Hera, Montagna 2000) and direct hydrogeological observations from railway and highway tunnel excavations, providing new insights into groundwater flow systems active within the main fractured aquifers: shallow marine Miocenic arenites, foredeep silico-clastic or calcareous Paleogenic and Neogenic turbidites and Jurassic ophiolites (peridotites and basalts). This communication presents a synthesis of quantitative aquifer parametrization, covering both intrinsic properties (hydraulic transmissivity and conductivity, specific yield, spring recession behaviour, effective groundwater velocity and kinematic porosity derived from tracer tests) and climate-related parameters including direct recharge and discharge per unit area. It's relevant, for example, the higher value of specific discharge (per unit outcropping area of the aquifer) of Pantano calcarenitic formation, in the range 5-7 L/s on km2, around twice respect to turbiditic deposits, in the range 2-4 L/s on km2. These parameters serve as critical inputs for hydrological modeling to determine sustainable withdrawal rates during droughts. Furthermore, the findings and associated conceptual models will contribute to the development of new guidelines for quantitative hydrogeological mapping, coordinated and financed by ISPRA and applied to "Hydrogeological Sheet n°218 Castelnovo ne'Monti" which is being carried out under the scientific supervision of the Hydrogeology group at the University of Bologna in collaboration with the Geological Survey of Emilia-Romagna region.

Groundwater Monitoring and the POA Acquacentro Project - State of the Art and Future Perspectives in Lazio

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In 2022, ARPA Lazio started the "POA-ACQUACENTRO" project, defined in agreements with the Environmental Directorate of the Lazio Region and the Central Apennine Basin District Authority, addressing the following actions (translation from the original agreement):

-Action A.1.2.1: Implementation of the surface and goundwater monitoring network of the Lazio Region within the Central Apennine Basin;

-Action A.2.1: Analysis of pressures and impacts on carbonate groundwater bodies in the Lazio Region within the Central Apennine District.

The POA project will be completed by the end of 2025. ARPA Lazio is carrying out surveys and monitoring activities:

-implementation of the monitoring network with an additional 360 representative points (springs and wells);

-define the chemical status of the GWBs according to the EU WFD;

-deepening the large-scale hydrogeochemical aspects related to: hydrochemical facies of all regional groundwater bodies; saline intrusion assessment in 5 coastal sectors; monthly flow surveys carbonate springs, investigation of emerging contaminants such as perfluoroalkyl chemicals and microplastics.

The main goals are the implementation of the monitoring network and by 2025 they will lead to the assessment of the chemical status of GWBs at regional scale, the determination of the dynamics between different GWBs and the exchange between surface waters, including coastal marine waters; the assessment of the anthropogenic impact on 12 carbonate GWBs through key indicators such as the volume used by municipalities, the presence of emerging contaminants such as microplastics and perfluoroalkyl substances.

The results of the activities will be presented at the end of the project and will include a regional scale analysis of the above objectives and the drafting of technical references on how to proceed with future monitoring plans.

Natural geochemical background levels in groundwater of large-scale contaminated sites

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Groundwater environmental objectives in Europe are defined by the Water Framework Directive (2000/60/EC) and the Groundwater Directive (2006/118/EC), based on contaminant thresholds and considering Natural Background Levels (NBL) when appropriate. NBL represents the boundary between natural processes and anthropic impact, and defines the targets for remediation in polluted sites.

The Sacco River Basin (1530 km², Latium, Italy) includes a contaminated "Site of National Interest", 72.35 km² wide. Anthropic pressures are widespread within the basin (e.g. industrial sites, transport infrastructures, landfills). Geogenic arsenic (As), iron (Fe), and manganese (Mn) can be mobilized in anoxic conditions into groundwater by biogeochemical processes.

This research aims to define the NBL for As, Fe, and Mn in the different lithologies (alluvial deposits, volcanic rocks, travertines) using a multidisciplinary approach. The currently ongoing groundwater sampling targets the low-impact areas to get a set of concentration values associable exclusively to geogenic processes. Groundwater levels, chemical-physical parameters, inorganics, dissolved organic carbon, isotopes (δ18O, δ2H, δ13C, and 87Sr/86Sr), and microbial properties were analyzed.

Preliminary results show that the highest Fe (201-1988 μg/L), As (38-55 μg/L), and Mn (55-406 μg/L) levels are related to reducing conditions in peat-rich alluvial sediments and, to a minor extent, to volcanic formations. Cell abundance is in the range of 10^3-10^4 cells/mL with predominance of cells with low nucleic acid content, as reported in oligotrophic environments. Furthermore, microbial respiration suggests higher metabolism and functional diversity of microbial communities in the alluvial facies. Our findings contribute to a more accurate assessment of natural versus anthropogenic influences, ultimately supporting the development of effective groundwater management and remediation strategies in contaminated sites.

Exchanges between deep and shallow aquifers in the Piedmont Po Plain (NW Italy): a hydrochemical approach with groundwater chemical trends analyses

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The Piedmont Plain (NW Italy) is characterized by a shallow phreatic aquifer, overlying a deep confined/semiconfined aquifers, the latter are essential for the supply of drinking water.

The aim of this study was to analyze the trends (period 2000–2021) in the main physicochemical parameters (electrolytic conductivity (EC), pH) and main ions (Ca, Mg, HCO3, Na, Cl, NO3 and SO4) in 70 wells in the deep aquifers in order to identify the ongoing processes. The temporal distribution of threshold exceedances for the sum of pesticides was also evaluated. The interaction with shallow aquifers was evaluated comparing the average concentrations for the main ions between shallow and deep aquifers and evaluating the trends of the Saturation Index (SI) of calcite. Additionally, the temporal trends of ion exchange (Ca+Mg/Na index) were evaluated to highlight the contribution from silty-clayey layers, which represent the less permeable portions of the deep aquifers.

Results highlight relevant increasing trends for EC, Ca, Mg and Cl in 57-69% of the monitored wells, and increasing trends for HCO3 and Na in 41-46% of the monitored points. Decreasing trends exist for 3-10% of the monitored points. SO4, NO3 and pH show heterogeneous trends. The sum of pesticides shows greater exceedances of the threshold values in the most recent period compared to the previous one. The temporal trends of ion exchanges reveal the presence of trends in 61% of monitored wells.

Average concentrations in shallow aquifers show higher values than in deep aquifers. The decreasing trends of Calcite SI confirm the interaction between aquifers.

These results suggest an increase in the flows from the shallow aquifers to the deep aquifers and an increased contribution from silty-clayey layers of the deep aquifers. These processes are consistent with excessive withdrawal from deep aquifers.

In conclusion, the existence of impacting and worrying processes at a regional scale were defined.

Estimating low-enthalpy geothermal potential of alluvial-pyroclastic aquifers of the Phlaegraean Fields area (Campania, southern Italy)

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Low-enthalpy geothermal energy is a renewable and sustainable source of heat extracted from either groundwater or vadose zones. It provides important advantages: energy saving with reduced environmental impacts as well as constant availability, if compared to other renewable sources. The present research regards the theme of energy saving (Goals 7, "Affordable and Clean Energy", and 11, "Sustainable Cities and Communities", of the ONU 2030 Agenda) in the Campania region (southern Italy), where the use of low enthalpy energy is still underdeveloped.

The study aims to characterize the low-enthalpy geothermal potential of shallow alluvial and pyroclastic aquifers, which extend over densely urbanized and industrialized areas. The selected study area, the Phlegraean Fields, lies across and beyond the caldera. Given the volcanic activity of the central part of the caldera, this area was considered unique for the comparison of different groundwater temperatures (80-16 °C), from the inner to the outer part, and the assessment of effects on heat exchange potential.

The pyroclastic and alluvial aquifer was characterized for its hydrogeological features based on stratigraphic data and in situ tests. The thermal properties were determined by associating thermal conductivity values with lithotypes recognized in stratigraphic columns retrieved from boreholes. These data were interpreted and integrated to form thematic maps: geothermal gradient map (air and groundwater temperatures); thermal conductivity map (stratigraphic data of the saturated zone); groundwater velocity map (based on water table elevation, hydraulic conductivity, effective porosity, hydraulic gradient). The overlay of these maps led to a low-enthalpy geo-exchange potential map, highlighting suitable areas for exploitation.

Preliminary results and future research developments aim to foster low-enthalpy energy use in Campania's alluvial-pyroclastic aquifers, promoting its role as a sustainable energy resource.

Design of an open-loop geothermal system for heating and cooling a cultural and university centre

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According to the aim of achieving the highest level of environmental sustainability, an open-loop geothermal system has been planned for thermal needs (warming and cooling) of a large public building that will host a bibliotheque, a theatre and many civil buildings for universitary studies.

The system is located into the shallow (phreatic) aquifer hosted into alluvial Pleistocenic deposits drained by the river Po; initially designed for a supply < 100 l/s, it will be up-graded in order to cover the whole needs of the thermal station of the complex of buildings called "To-Expo", with a nominal discharge of 160 l/s.

The test-site is located into a wider analysis area, in which existings data sets concerning stratigraphic and hydrogeological pattern have been collected and updated also by groundwater levels measurements, toward the end of an extraordinary recession period (2022), fixing the minimum reference conditions of flow into the aquifer.

The project has been supported by an exaustive ground survey that has been set up into the test-site area, by geophysical investigations (ERT, MASW, HSVR profiles), direct sampling (boreholes, piezometers) and hydraulic and laboratory testing.

The simulation numerical model (finite element model – FeFlow with supermesh grid) has been implemented to reproduce the present-state but above all flow and heat transport scenarios, considering 4 extraction and 4 inflowing wells and a piezometric control network too. The model covers a wider area discretized with 6 computations layers, settled around and inside the open-loop system, determining external and internal boundary conditions and sink/source terms, both flow and thermal, in transient conditions, estimating the evolution of the thermal plume in exercise mode referred to a 20-years scenario.

The whole plant has been approved by the Local Authorities, and the wells drilling program is currently ongoing.

Quantification of driving redox reactions potentially induced by managed aquifer recharge in the suburban environment of Brescia (IT)

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The Po River plain is experiencing groundwater resources decline since the last two decades, due to diminished recharge rates and groundwater overexploitation. Additionally, the elevated anthropogenic pressures increase the likelihood of groundwater contamination. For instance, Brescia with more than 200k citizens and a widespread industrial area, hosts many potential sources of groundwater pollution. The managed aquifer recharge (MAR) technique is well-known to mitigate groundwater contamination and to replenish groundwater resources; although MAR could trigger unwanted redox reactions, like pyrite oxidation, that must be evaluated before to establish a MAR scheme. To quantify possible interactions among recharge waters and the aquifer, 2 cores were drilled in a sub-urban area to capture the lithological variability of the unconfined aquifer. To delineate redox gradients within the aquifer, vertical profiles of sediment cores were collected via Rhizon® samplers and analysed for TDS, pH, DOC, major ions, and trace elements. In addition, 3 batches with 160 g of sediment and 800 ml of deionized water were set-up and monitored for 3 months. Pre- and post-experimental characterisation of mineral phases was done via sequential extraction (SE). Stratigraphical cores were similar but not homogeneous, with the most permeable layers constituted by sandy gravel layers. Depth profiles of selected species delineated possible pollution sources from urban leakage, although below admissible limits. SE suggested a >50%±25 increase of Fe-oxides at shallow depths, while no significant increase at the base of the aquifer. The batches and SE demonstrated that no significant release of heavy-metal(loid)s was induced by the recharging water and the already present contaminants were diluted below admissible limits. The proposed framework could be employed to assess the feasibility of MAR to assist tailored design solutions.

Observing a climate change adaptation solution's linkages with groundwater dependent ecosystems: a modeling and field based approach

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Groundwater plays a crucial role in the water cycle and in sustaining life and human activities, and can help alleviate hydrological drought periods serving as a buffer reservoir. Groundwater sustainability, however, relies on a delicate balance between recharge and discharge, in which humans play an important role, with influences on groundwater dependent ecosystems. Agricultural Managed Aquifer Recharge (Ag-MAR) can be an adaptation measure to drought periods and expected climate change effects on water resources. As part of the Interreg CE project MAURICE, an off-season irrigation practice is proposed in Lombardy as a climate change adaptation strategy, storing surface water into aquifers in periods of exceedance (autumn/winter) using the existing irrigation network's canals as a "natural" infiltration system.

In the case study area, a great number of typical Northern Italy lowland springs, called "fontanili", is present, used since the XIV century to irrigate fields while generating biodiversity hotspots right in a urbanized area. In the past decades, they have been largely abandoned and endangered by infrastructures and decreasing groundwater levels. Their relationship with groundwater still holds some uncertainties related to their interaction with the aquifer along their course and their influence on the surrounding groundwater system, which could hinder the performance of measures like the proposed Ag-MAR.

This work presents numerical models in MODFLOW that, with increasing complexity, reproduce a single lowland spring's behavior based on in-situ observations and literature, considering pros and cons of the different methods. Then, the lowland springs have been implemented in a larger scale model, to simulate scenarios assessing their response to the implementation of off-season irrigation. Results bring more light to these unique systems' behavior and show concrete and successful possibilities of modeling them and applying Ag-MAR also in their presence.

Investigating the north-eastern Adriatic basin and coastal plain, through hydrogeological modeling: insights on potential offshore freshwater aquifers.

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The Venetian-Friulian Plain (VFP) hosts a complex confined aquifer system that is both highly productive and heavily exploited even within its lagoonal areas. Approximately 50.000 water wells, of which a large part extract water 24h/day, are currently estimated to be present in the region, and water table level monitoring since the 70s highlight a declining trend up to 10 cm per year.

In this study we investigate the onshore groundwater dynamics of VFP and the related potential offshore freshened groundwater availability in the adjacent North Adriatic Basin (NAB) through geological and groundwater numerical modeling. The aim of this study is to investigate: 1) whether and how permeable units that host freshwater onshore extend offshore, and 2) the extent to which onshore-sourced groundwater contributes to the offshore groundwater budget. Geological models were developed using multi-approach techniques, including geostatistics, to build a 3D onshore-offshore framework extending ca. 250 m below sea level and 15 km into the NAB. e model confirms the presence of offshore permeable formations which are connected to the onshore aquifer bearing formations.

A preliminary groundwater model, built in MODFLOW-2005 and calibrated with PEST using data from 180 monitoring wells, simulates 2000–2023 conditions. The simulation is performed with and without active well extraction to assess the impact that such significant extractions have on water table declining rates. Groundwater model results indicate the existence of an offshore-directed flux of freshwater toward the NAB (ca.4 m3 sec-1), suggesting that offshore permeable formation might be freshwater saturated. The results also show an onshore-directed flux (0.5 m3), suggesting the risk of saline intrusion in coastal aquifers. Moreover, the model highlights that current well extraction rates accelerates water table declining rate up to 10 times, suggesting the potential need to adopt more sustainable management practices.

Data from Law 464/84 as support for groundwater management

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The law 464 of 4 August 1984 requires the Italian Institute for Environmental Protection and Research (ISPRA) to collect information related to underground investigations (wells, excavations and drillings) with a depth greater than 30 metres below ground level or a length greater than 200 metres in the case of tunnels. The hundreds of thousands of stratigraphic and hydrogeological data received, following formal checks, are progressively made available on the website of the Geological Survey of Italy or Polo Strategico Nazionale (https://legge464webgis.isprambiente.it/views/VisualizzatoreLegge464).

Currently, the database collects approximately 150,000 practices. Most of these are referred to drillings for water supply purposes (wells), while a smaller amount refers to other aims, such as piezometer, vertical geothermal probe, anodic disperser, environmental survey, inclinometer, drainage well, etc. For each drilling information is provided regarding: region, province, municipality, type, depth, altitude, year of construction, number of diameters, presence of water, maximum flow rate, operating flow rate, number of aquifers, number of filters, number of piezometers, stratigraphy, coordinates.

Given the amount of information provided, these data can constitute a scientific basis for addressing the environmental challenges related to water resources and in particular to the management of groundwater. Indeed, they can support municipalities and other public institutions to deepen the knowledge of their territory in relation to both the hydrogeological structure and the potential possibilities of water supply aimed at different uses. More generally, these data can be useful for the management of water resources and therefore also of groundwater.

Efficient history-matching of a complex groundwater model using Ensemble Space Inversion

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In groundwater modeling, uncertainty in parameters and predictions can be reduced by history-matching the model against observations of groundwater levels. When observations span different periods or come from pumping tests, complex calibration schemes may be required, potentially making optimization unfeasible. In such cases, the modeler may choose to lose information by reducing or simplifying the observation set in exchange for a manageable process.

This study employs the Ensemble Space Inversion (ENSI) methodology for history-matching a groundwater model of a complex site against a large number of observations. ENSI estimates "super parameters" instead of native model parameters, using an ensemble of random samples from prior parameter probability distributions. A key advantage of this method is that it requires far fewer super parameters than model parameters, reducing the number of model runs needed to calculate parameter sensitivities.

ENSI was applied to a site characterized by heterogeneous pyroclastic and volcanic deposits, with three distinct aquifers. Various hydraulic tests were conducted to determine site-specific hydrogeological parameters, assess vertical conductance, derive pumping well characteristics, and collect piezometric data. A six-layer numerical model was developed using MODFLOW-USG. Hydraulic parameters were calibrated via pilot points, with values interpolated through kriging.

Compared to history-matching the same model using a standard GLM method applied to model parameters, ENSI provided several advantages: fast convergence to low objective function values, significantly reduced execution time, and natural parameter field distributions.

Though ENSI does not perform uncertainty estimation, it offers a fast and effective way to obtain a single history-matched model, which could serve as a starting point for ensemble-based uncertainty assessment.

Groundwater-surface water interaction in the Farfa River Valley (Central Italy): implications for the assessment of ecological flow and water quality

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The Farfa River is one of the most important tributaries on the left bank of Tiber River, upstream Rome in Central Italy. The final part of its course is part of the Nazzano-Tevere-Farfa Regional Nature Reserve, a ZPS zone (IT6020018 and IT6030012) and part of UE Natura 2000 network. This part is also the most interesting but, at the same time, the least studied in terms of hydrogeology and hydrology, characterized by a marked heterogeneity, important artificial modifications along the river and a high groundwater - surface water interaction. The ever-increasing need to assess the quantitative and qualitative status of watercourses and the new legislation on ecological flow promoted by the EU in the water framework directive (WFD), requires an increasingly greater attention on monitoring plans. In this sense, quantitative assessment on ungauged water resources and a proper evaluation of groundwater-surface water interaction can be helpful for institutions and stakeholders to define a standard ecological flow of rivers, often lacking in water protection plans but required for the water exploitation concession. A first quali-quantitative evaluation of water resources and the identification of groundwater-surface water interactions along the watercourse of the Farfa River is the main goal of this study. To achieve this discharge measurements carried out in specific cross-sections, together with on-site measurements of the main physico-chemical parameters and results of laboratory analyses on water samples have been carried out in May and September 2024, allowing to study the system in recharging and discharging phases of the hydrological year.

Recharge estimation from groundwater level fluctuations in a coastal unconfined aquifer in Campania Region (southern Italy)

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This study estimates the recharge dynamics in an unconfined porous coastal aquifer by means of a time-series approach. Two water wells were selected in the Volturno Plain (Campania Region, southern Italy), respectively located in a wetland area close to the coastline (Pz1) and in an agricultural not irrigated field at 10 km inland close to the Volturno River (Pz2). A multiparameter probe was installed in each water well to measure: water depth, temperature and electrical conductivity. Data were collected every 24 hours from February 2016 to December 2017 in Pz1, and every 12 hours from October 2022 to the present in Pz2. Rainfall data collected at the meteorological station closest to each monitoring point were considered in the analysis. The recharge rate was estimated using the Water Table Fluctuation (WTF) method. Six and five single recharge events were identified at Pz1 and Pz2, respectively.

At Pz1, the recharge ratio (RR, ratio between recharge amount and precipitation amount) remains constant throughout the year (average RR = 45%), likely due to the presence of marshy land, which limits groundwater recharge during heavy rainfall. At Pz2, RR shows seasonal variations with average values of 104% in autumn-winter and 351% in spring-summer, probably related to the agricultural practises (bare land, planting, growing and harvest phases). The results indicate that recharge decreases as precipitation increases due to greater pore saturation during the infiltration process. In both sites, we observe that precipitation events exceeding 50 mm in 24 hours result in a decrease in both electrical conductivity and temperature, highlighting the influence of infiltration dynamics on groundwater chemistry. Lastly, recharge amounts calculated using the WTF method are compared with those obtained through a classical hydrogeological balance, showing a good correlation.

This study highlights how groundwater recharge varies in response to seasonal changes and soil conditions.

A comparative study of physics-based and machine learning approaches for sustainable groundwater management in the Emilia-Romagna region (Italy)

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The Emilia-Romagna region (Italy) hosts extensive agricultural and industrial activity, and densely populated urban areas. Groundwater serves as a crucial freshwater source, particularly during droughts, which are expected to become more frequent and intense.

This study estimates the evolution of groundwater conditions in part of Emilia-Romagna, considering climate change and human impacts, to assess the resilience of the regional multi-layered aquifer system to droughts and outline potential guidelines for long-term sustainable groundwater management. A numerical groundwater flow model and a random forest algorithm, implemented in MODFLOW 6 and R respectively, are applied to compare the performance of a physics-based and a machine learning method in simulating past and future groundwater levels, and to explore the benefits of their combination. Input data are sourced from the regional groundwater model by Arpae (Regional Agency for Prevention, Environment and Energy of Emilia-Romagna) and publicly available datasets on the Emilia-Romagna Region and Arpae repositories.

Both techniques are then used to analyze scenarios of reduced precipitation and altered pumping, focusing on their combined effects on the aquifer system. Results show the aquifer system's vulnerability to future droughts. Increased pumping amplifies precipitation reduction effects, while lower abstraction partly mitigates them. Critical hotspots are identified, emphasizing the need for multi-scale approaches to develop effective mitigation and adaptation strategies.

The random forest algorithm provides insights into factors influencing groundwater head distribution, enhancing the groundwater model results interpretation and potential improvement. However, its lack of physical grounding limits its generalization potential. These findings highlight the value of integrating physics-based and machine learning methods to improve their performance, making a significant contribution to groundwater modeling.

Investigating the Sustainability of Groundwater Resources in the Friuli High Plain: A Modeling Approach

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The Friuli-Venezia Giulia Region hosts one of the largest hydrographic basins in Italy, composed of multiple layered confined aquifers in its lower plain and a thick phreatic aquifer in the upper plain. Groundwater in the Region is crucial, approximately 50,000 water wells serve the population for agricultural, industrial and drinking use. Monitoring of the upper plain phreatic aquifer highlights a water table decline rate of up to 10 cm per year, raising concerns about the status and future availability of water resources.

This project focuses on the sustainable management of the groundwater resource in the Friuli High Plain, and the potential impact of climate change. The project is in its early stages. The first step involves the development of a geological model of the study area, built using stratigraphic data from approximately 1,500 wells surveyed in the Region. For this purpose, the Petrel software has been used which, through interpolation techniques and geostatistics, allows the creation of a cell-based geological model. The model extends vertically for the entire Plio-Quaternary sequence. Once the geological structure has been defined, the focus will shift to the creation of a groundwater numerical model to investigate how exploitation and climate change impact the water resources. For this phase, MODFLOW 2005, will be employed in conjunction with the ModelMuse graphical interface. The hydrogeological model will allow the analysis of groundwater budgets under different future climate scenarios, evaluating how the system responds to extreme drought or wet periods.

Interpreting chemical and biomarker patterns with reactive transport modeling to assess chlorinated ethene biodegradation in groundwater

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Biomarkers associated with the biodegradation of chlorinated ethenes (CEs), such as RDase functional gene DNA, mRNA, and enzymes, are increasingly monitored in contaminant plumes to assess reductive dechlorination (RD). These biomarkers provide direct proof of RD and are used to evaluate biodegradation potential and possibly infer degradation rates. However, aquifers are inherently heterogeneous, and local hydrodynamic and biogeochemical conditions likely influence the behavior and efficiency of organohalide-respiring bacteria. Moreover, identifying the key factors shaping the observed spatiotemporal patterns of chemicals and biomarkers remains a challenge.

At the Grindsted site (Denmark), a 1500-m long CE plume has developed from a former pharmaceutical factory. Extensive monitoring of both chemicals and biomarkers has been conducted at this site. To aid in the data interpretation, we developed new enzyme-based kinetics linking the reductive dechlorination of cis-1,2-dichloroethene to vinyl chloride and ethene with the expression of the vcrA and bvcA genes in Dehalococcoides. These kinetics were integrated into a 1D reactive transport model simulating the Grindsted plume, also including the estimated variable flow rates. Fitting the observed chemicals and biomarkers (i.e., functional gene DNA and mRNA) required to calibrate the kinetic parameters with a zonal approach.

As a result, the model pointed out different ecological strategies of vcrA- and bvcA-carrying Dehalococcoides, which affected the RD efficiency within the plume core. Moreover, CE biodegradation efficiency appeared further decreased under high flow rate conditions, because of the shorter residence time.

This modeling endeavor is the first attempt of field application and allowed enhancing the mechanistic interpretation of observed chemical and biomarker patterns in the CE plume. Consequently, it proved to be a reliable support for designing of future monitoring and remediation strategies.

Evaluating the snowfall influence on the hydrological balance of Apennine mountain aquifers in Central Italy

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Accurate knowledge of groundwater availability and its variations is essential for sustainable groundwater management. Within this framework, the water balance serves as a valuable tool for assessing water resource availability. Currently, management authorities require more precise evaluations of groundwater resources to address the growing demand for freshwater.

In this study, the water balance was determined for the main hydrogeological structures in the Central Apennines (Italy). The calculated outflows were compared with spring discharge data sourced from existing literature. Inflow data were collected over a six-year period (2018–2023), accounting for both rainfall and snow contributions. Unlike many previous studies that focused only on liquid inflows from rainfall, this research properly evaluated snowmelt contributions using data from a recent network of snow gauges. These contributions were incorporated into total precipitation estimates to achieve more accurate results.

For each hydrogeological structure, monthly inflow datasets from rain gauges were interpolated using regression equations and subsequently applied to the water balance assessment. An initial comparison of water balances, estimated with and without snowmelt data, revealed that excluding snow contributions can lead to significant underestimations of infiltration rates. Moreover, a comparison between calculated outflows—including snowmelt—and measured spring discharges demonstrated strong agreement for each investigated hydrogeological structure.

Integrating Field, Meteorological Data and GIS for Hydrogeological Mapping of Carbonate Aquifers in Central Apennines

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The maps related to Central Apennines hydrogeological bodies are a useful tool to understand the circulation inside them, for administering the groundwater exploitation and for sustainable water management. The measuring campaign from the POA Acquacentro project has allowed to update the already existing hydrogeological maps for the Abruzzo Region area, like Celico and CAMEZ (1983), Boni et al. (1986),PTA Regione Abruzzo (2008), and Desiderio et al. (2011).

Six carbonatic water bodies were considered (~ 2800 km2), from a hydro-geological point of view they are mostly fractured and karstified limestones, with high conductivity that overlap marls or clay deposits almost impermeable. The aquifers, within the limestones, emerge mostly through basal springs with minimum discharge over 50 L/s. Most of this water is exploited for drinking, hydroelectric power, irrigation, and fisheries.

These springs were monitored both seasonally and continuously: in the first case, at least four field campaigns were needed for full annual monitoring, while in the second they are observed using permanent measuring stations.

In addition to the field work, monthly water balance was calculated for all the hydrogeological bodies considering six years (2018-2023); precipitation and evapotranspiration were spatialized through regression lines. The total outflow and infiltration were completely estimated in QGIS environment for each hydrostructure, and maximum, minimum and mean values were inferred for each monthly map.

Field work and water balance estimation were summarized in six hydrogeological schemes where springs' discharge, flow direction, hydrogeological complexes and water balance results are represented for a full water body characterization.

Integrated approach to evaluate the ecological flow: results from the experimentation in a river fed by carbonate aquifer in Central Italy

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Estimating Ecological Flows (EF) is essential in rivers to achieve the objectives defined by the Water Framework Directive (WFD) 2000/60/EC. In the framework of an agreement with Autorità del Bacino distrettuale dell'Appennino Centrale (AuBAC), an integrated approach is developed that considers different factors involving the fluvial system (hydrologic, hydrobiological, hydrogeological, hydro-morphological, and hydrochemical). Different fluvial sections in the Umbria Region (Central Italy) are analyzed (25 sections), the underlying catchments of which include hydrogeological systems with different lithological characteristics. The present study focuses on the Nera River, mostly fed by groundwater from limestone aquifers (Base Flow Index higher than 0.9), at the Torre Orsina section (1360 km2, with mean natural discharge of about 33.60 m3/s). The river catchment hosts strategic water resources that are key in providing drinking water and sustaining aquatic ecosystems. Moreover, river water is used for hydropower, fish farming, and river-based recreational activities. The Ecological Status resulted very high considering the New Index of the Ecological Status of Fish Communities (NISECI) combined with the physicochemical characterization of river water as criteria for its definition. Thanks to a geostatistical regional model developed for brown trout, the minimum EF was set at approximately 2.98 m^3/s. Based on flow-duration curves, the average and maximum EF values were also identified as 3.90 and 5.27 m^3/s, respectively. Given the sufficient value of the Morphological Quality Index (MQI) of the river stretch, an increase in the average EF is proposed (from 3.90 to 4.28 m3/s), considering a new approach based on MQI, channel-forming discharge, and mean discharge. The Water Exploitation Index Plus (WEI+) application showed moderate stress over the catchment; thus, further planned withdrawals should carefully consider the minimum EF needed not to reach severe stress.

Investigating groundwater-surface interactions and constraining the water budget in a carbonate hydrogeological system of Central Italy

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Carbonate aquifers host strategic water resources that sustain river discharge during no-recharge periods, provide drinking water, ensure ecological flow, and modulate solute exchanges related to physical-chemical weathering processes. Overall, hydrogeological systems of the Apennine Ridge in Central Italy are minimally influenced by human activity; thus, understanding the groundwater circulation feeding mountain rivers offers insights into the hydrogeological system properties that are often difficult to quantify due to the complexity of geological and structural features. Within the framework of the PRIN22 Hydro4C project, the Ussita catchment (44 km²) has been selected to investigate groundwater-surface water interactions and to collect data to constrain the water budget, a critical issue in mountain regions. Since 2019, several hydrological and hydrogeochemical parameters have been continuously monitored, including river discharge data at two stream sections, weather data, and electrical conductivity of stream water. Additionally, two thermal drone surveys carried out in January 2024 and January 2025 helped identify river stretches fed by groundwater. Seasonal geochemistry stream water sampling, electromagnetic device discharge measurements, and tracer tests were also carried out. This information was used to calibrate baseflow values derived from river discharge through a one-parameter recursive digital filter. The Base Flow Index increased along a 1 km river stretch from about 0.80 to 0.90 due to substantial groundwater inflows. Aside from uncertainties regarding estimating the recharge amount due to snowmelt, the water budget computed over the 2019-2024 period and results from tracer tests indicated that the extent of the hydrogeological system feeding the Ussita stream slightly exceeds its catchment area. The integrated approach can effectively manage water resources and be adapted to similar systems in the Mediterranean Region.

Evaluating transmission loss between surface water and groundwater within the Cornia Alluvial River plain

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Surface water and groundwater are interconnected in the hydrologic cycle as they exchange mass and energy. As this exchange is also impacted by human activities, understanding the spatial and temporal variation of this interaction is essential for effectively managing water resources. This study presents and discusses experimental discharge flow data, measured in baseflow conditions, from the groundwater recharge area of the Cornia alluvial aquifer in Tuscany (Italy).

The aquifer consists of unconsolidated gravel deposits, with silt and clay lenses at varying depths, forming the main aquifer system, with a maximum thickness of 40 m. We measured the river discharge with OTT-ADC at three following river cross-sections on November 12 and December 2, 2024, detailing the interaction along two river segments, 3 km and 2.7 km long, respectively. On the monitoring days the river level at the last measurement point was -0.73 m and –0.77 m above datum, respectively.

Discharge at the inflow point in November was 0.548 m3/s, and in 0.265 m3/s in December. Notwithstanding the discharge difference, results show two loosing segments. In November, we measured a total loss of 0.176 m^3/s, with the first segment loosing 0.061 m^3/s and the second segment 0.115 m^3/s. By December, the total loss was 0.158 m^3/s, with first segment loosing 0.111 m^3/s and second 0.047 m^3/s.

Changes in hydraulic head in the aquifer in the upstream segment area (about 0.15 m drop) may justify the increase in transmission losses at the first segment. On the other hand, reduction in transmission on the second segment could be related to diminished areal hydraulic contact at riverbed level.

This study highlights the need to monitor discharge at different sections to quantify aquifer recharge in baseflow conditions throughout the whole year.

Acknowledgement

This research is funded within the PhD Programme in Agrobiosciences (39th cycle), Institute of Crop Science, Scuola Superiore Sant'Anna.

Groundwater level prediction based on deep learning

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Deep learning paradigms are widespread approaches for manifold environmental applications. Their strength consists in the possibility of processing massive quantities of data as well as performing complex tasks, with unsupervised procedures. The use of deep learners, based on neural computing, proved its effectiveness for data classification, data generation, time series prediction, etc.. In particular, recurrent neural networks are suitable for time series prediction. Here, recurrent neural networks are used to model groundwater levels of the large shallow porous aquifer of Brindisi. This is an aquifer with a catchment of approximately 1000 km2 located in the upper east Salento peninsula, in southeast Italy. It is hosted by the shallow Quaternary deposits consisting of weakly cemented sands, which diffusively outcrops in its catchment. This aquifer is recharged by local rainfalls, which do not significantly change across the catchment, in terms of volumes and time distribution. This shallow aquifer was monitored by the former National Hydrographic Bureau, whereas piezometric wells were used to acquire groundwater level measurements with a frequency of one measure every three days. However, these time series, available for 6 wells between 1952 and 2002, are not complete, since several gaps, i.e. missing data exist. These time series, together with the time series of rainfall data are used to train a recurrent neural network, which is able to predict average monthly groundwater levels as well as reconstructing missing data, whereas time series are incomplete. Differently from machine learning approaches, multiple well groundwater time series, as well as multiple rain gauge time series will be used together, in order to train the deep learner.

The Role of Women in Hydrogeology Research in Italy (IAH Members)

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This research on gender and hydrogeology examines the representation, barriers and experiences of women in the field. Statistical data reveals clear gender inequality. In 2010, the IAH in Italy had 67 male members (M) and only 7 female members (F) (9%). By 2024 IAH membership had grown to 231, with 32% being F, indicating progress, but persistent underrepresentation in senior academic roles.

Among academic members, few F have achieved full professorships. Compared to 12 M full professors and 6 retired M full professors, there is only 1 F full professor and 1 retired F full professor in IAH Italy. Bibliometric indices for F associate professors are the same as those of their M counterparts, with a median H-index value of 16. For researchers, median H-index values for M are higher than the F median (16 vs 10). However, the 2 F full professors in the association have H-indexes significantly higher than the M median, highlighting the greater contribution required to achieve the same position. Indeed, the underrepresentation of F in senior academic positions remains a pressing issue that needs attention.

Women in geological research face challenges including: discrimination in securing employment; discrimination throughout their career progression; prejudice linked to motherhood affecting visibility and participation of younger F researchers. Their absence from the workplace and lower participation in activities like field trips and/or summer schools is often tied to societal expectations and family responsibilities. Instead of receiving support during these crucial career phases, F researchers may find M colleagues using these opportunities to advance their own careers.

F hydrogeologists are often overlooked, marginalized or ignored, despite their significant contributions. To close the gender gap, it is crucial to recognize and highlight the valuable input that women bring to the field of hydrogeology, ensuring they receive deserved acknowledgment and opportunities.

Groundwater droughts in Piedmont region

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Growing water demands and climate change raised up concerns on groundwater drought, that is prolonged periods of below normal piezometric levels. During meteorological droughts, when aquifer recharge diminishes, groundwater systems are threatened by overexploitation, and it is important to understand their recharge dynamic and apply an efficient water management that links actions on surface water with those on groundwater.

This work examines the relationship between meteorological and groundwater drought for the shallow aquifers of the Piemonte Plain (Italy), where agricultural irrigation practices are important. For the analysis piezometric levels and gridded precipitation data, obtained from regional monitoring network, were used to compute trends, response times and drought propagation also through the Standardized Precipitation Index (SPI) and the Standardized Groundwater Index (SGI).

The outcomes displayed a spatial variability in groundwater trends, with evident negative trends in the southern and central areas of the plain. An attenuated and delayed response of groundwater drought to meteorological drought was found. SPI-SGI correlations were higher for SPI computed over time windows of 3-6 months, nevertheless these relationships came out to be influenced by irrigation practices.

Results showed that during irrigation (April-September), SPI-SGI correlations are weak especially in rice cultivation areas where flooding irrigation technique impacts piezometric levels. Irrigation, in fact, disrupts the expected propagation of meteorological deficits to groundwater, masking groundwater drought conditions. Outside the irrigation period, the precipitation role prevails, leading to stronger correlation and shorter delays.

From the analysis the role of irrigation on the piezometric levels of the shallow aquifers of the region came out to be evident so that possible change in the irrigation practices should consider their impact on the groundwater recharge.

SentinelSpringS: Springs as Sentinels of Climate Change and Sustainability of Aquatic Ecosystems

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Springs are a natural interface between groundwater (GW) and surface water, supporting ecosystems (ES) and they are sentinels of environmental stress. Yet, despite their importance, they are still overlooked in European water policies. The SentinelSpringS project aims to fill this gap by developing a robust framework to assess the health of springs and their role in sustaining biodiversity.

The project brings together six European countries to tackle local challenges and develop a unified monitoring approach. Portugal focuses on methods to identify GW-dependent ES and evaluating the impacts of contamination and land use. Denmark leads the implementation of real-time water data into the European Geological Data Infrastructure, upgrading GW monitoring digital tools. Italy studies the status of lowland springs with hydrogeological and ecological monitoring. France applies hydrogeochemical and hydrological modelling to forecast the behaviour of karst springs in relation to climate change (CC) and human impact. Poland focuses on ecological evaluations, integrating biodiversity data with remote sensing to analyse and model processes at local and landscape scales. Malta pursues citizen science activities, while monitoring GW flow from perched aquifers and investigating possible conservation approaches for small island ES.

Through the integration of data from all partners, this project will institute standardised monitoring protocols. Moreover, this project will assess the impact of CC and human activities on springs in different European landscapes. The project also fosters citizen science involvement and stakeholder partecipation, making sure that local communities both contribute to and benefit from it.

Acknowledgement: SentinelSpringS is a funded research project by the Water4All Partnership-Water Security for the Planet (Water4All/0010/2023) which is co-funded by the European Union within the frame of the Horizon Europe programme.

Hydrogeological aspects of the water supply of Benevento town

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The historical evolution of the water supply systems of the city of Benevento (southern Italy) has been described. Some main historical periods, namely the Roman, Lombard and Papal times, and the recent-present times, have been analysed. During this long historical time (about 2000 years), the water supply amount and quality have changed many times, and this has probably affected the well-being and growth of the city.

In this current state, two main aquifer systems supply the town: the Matese karst aquifer and the local alluvial aquifer. The latter represents a system connected with a stream network, where we performed numerical simulations to investigate the specific contributions of aquifer-river interactions, effective meteoric recharge, and pumping to groundwater circulation. The simulations showed that the pumped groundwater comes partially from the river and that the latter represents a strong hydrological boundary, which limits the expansion of the cone of depression induced by wells.

Nowadays, the drinking water management of Benevento is still a matter of debate. In the near future, the water from a dam-reservoir (Campolattaro dam, Tammaro River) will be exploited to guarantee the water needs of the city, and water-supply systems will undergo further changes . The knowledge about the historical evolution of the water supply of Benevento represents an essential requirement for consciously analyzing the future planning and management of water resources.

Modeling Groundwater Flow in Intensive Agricultural Area: The Case of El Carracillo aquifer, Spain

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The management of groundwater resources in areas at high agricultural intensity is a critical challenge for ensuring environmental and economic sustainability. In the El Carracillo region (Spain), known for its highly specialized horticultural production, irrigation depends heavily on groundwater, exposing the aquifer overexploitation risks. Additionally, teh use of fertilizers increases the likehood of nitrate contamination, affecting groundwater quality.

This study developed a numerical model of the El Caracillo area using the FREEWAT-Q3 platform to analyze the interactions between water resources and agricultural practices. It simulates the groundwater flow with the MODFLOW-2005 code and nitrates transport using MT3DMS, based on a version developed by the TRAGSA Group in 2000.

The study area covers about 240 km² with a shallow phreatic aquifer in Quaternary sandy deposits, averaging 25-30 m thick. The aquifer lies on an impermeable substrate of Tertiary clays and marls. The Quaternary aquifer is simulated as a single layer. Three scenarios were simulated: 1) alternating extractions and managed aquifer recharge (MAR) cycles based on current water permissions; 2) extended MAR periods; 3) withdrawals without MAR. Results show that scenarios 1 and 2 sustain withdrawals without significant depletion, while scenario 3 leads to considerable drawdown, showing the need for MAR.

The numerical model developed with the FREEWAT-Q3 platform provides a valuable tool and easy way for sharing data and information among different stakeholders.

Acknowledgement

This contribution is presented within the framework of the NEXUS-NESS project. The NEXUS-NESS received funding from the PRIMA Programme, an Art.185 initiative supported and funded under Horizon 2020, the European Union's Framework Programme for Research and Innovation.

Numerical groundwater flow model in a data-scarce coastal area in western Sicily.

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The Marsala-Mazara del Vallo area (western Sicily, Italy) faces increasing pressures on groundwater due to intensified withdrawals and climate change, exacerbating seawater intrusion. This study developed a density-dependent groundwater flow numerical model to analyze groundwater dynamics and salinization of the coastal aquifer.

The conceptual model was built by collecting, archiving, and analyzing soft and hard data from previous studies and field monitoring campaigns. The study area features a calcarenitic-sandy aquifer hosted in terraced Tyrrhenian deposits and the Marsala Calcarenite formations, both of Quaternary age. The aquifer thickness ranges from a few meters to over 70 m, resting on an impermeable clayey-marly substrate (Marnoso-Arenacea Formation of the Belice Valley).

The numerical model was implemented using the SEAWAT code integrated with the FREEWAT-Q3 interface to simulate seawater intrusion. It covers about 320 km². Results show a decline in the piezometric level due to pumping activities, leading to the advancement of the saline wedge inland. However, the scarcity of available data limits the robustness of the simulation results throughout the whole domain. In particular, the lack of hydrodynamic parameters across the whole domain and information on temporal variability leave the door open to local different representations of the conceptual model.

However, the implemented model constitutes a useful tool for a first attempt to define the groundwater budget and to estimate the rate of seawater encroachment. A solid data acquisition strategy will allow refining of the model and developing effective mitigation strategies, thus contributing to the preservation of water quality and availability over time.

Acknowledgement

This contribution is presented within the framework of project Servizi di modellistica idrogeologica applicata funded by Autorità di Bacino del Distretto Idrografico della Sicilia (CUP: F62G16000000001).

DRASTIC application with open data

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Nowadays, the concern regarding groundwater vulnerability evaluation, particularly in coastal regions characterized by high population density, socio-economic development, and intensive agricultural activities, is increasing worldwide. Achieving sustainable water resource management in these areas requires comprehensive evaluations; however, such assessments are often hindered by financial, social, and environmental constraints, as well as limited data availability. To address this challenge, the presents study aims to critically evaluate the suitability of open global database in assessing groundwater vulnerability assessment across various coastal basins worldwide, representing all five continents using the well-known DRASTIC methodology. A new geodatabase was created gathering data from different open sources providing geological, hydroclimatic, hydrogeological, pedological and hydrological parameters. Moreover, each database has been downscaled in resolution, homogenized and then classified to ensure consistency for each chosen site. The DRASTIC index was applied using standard ratings and weights, without modifications and the results were compared with previous applications, within the chosen basins, already available in literature to validate the global database effectiveness in assessing groundwater vulnerability remotely. This approach could offer a broad perspective on groundwater pollution, offering guidelines to how correctly use some of existing open data to enable hydrogeologists to remotely assess the initial state of groundwater quality in diverse aquifers worldwide without field investigations.

Surface-groundwater investigations to support ex-ante evaluations of water withdrawals

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Effective groundwater management in coastal areas requires a detailed understanding of surface-water and groundwater interactions, particularly in alluvial plain affected by seawater intrusion. This study focuses on the Muravera alluvial plain, where both a phreatic and a partially confined aquifers are present. The research aims to refine the conceptual model of recharge sources and the hydrogeological balance by systematically integrating hydrogeological and hydrological data, supporting ex-ante evaluations of water withdrawals.

This work was conducted under the collaboration agreement between the University of Cagliari (DSCG), the Sardinian Hydrographic District Agency (ADIS), and with the collaboration of the Regional Environmental Protection Agency (ARPAS).

Between January and May 2024, extensive field campaigns were conducted, including piezometric surveys, geochemical analyses, and river-aquifer interaction assessments. The results reveal significant spatial variability in the hydrogeological properties of the phreatic aquifer, strongly influenced by prolonged drought conditions that have led to a decline in piezometric levels. This has activated previously undetected drainage axes, modifying local flow dynamics. The Flumendosa River alternates between recharge and drainage phases depending on location and hydraulic conditions. The partially confined aquifer remains less characterized due to limited data availability, requiring further investigation.

This study provides a comprehensive dataset and interpretation framework to improve groundwater resource management, mitigate seawater intrusion risks, and optimize water use strategies in the region.

Groundwater levels in the Po plain: current trends and insights on future variations

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The Po Plain is home to approximately 20 million people and serves as Italy's most important economic region. Beneath its surface lies a complex multi-aquifer alluvial system that supplies 87% of the region's drinking water and plays a crucial role in industrial, agricultural, and general production demands. Beyond the pressures of groundwater extraction, climate-related stressors have altered recharge rates, with drought events becoming increasingly frequent and severe in recent years. However, the impact of these stresses on groundwater has never been systematically studied in the Po River Basin.

As part of the MIDASPO project*, piezometric data were collected over 13 years (2010–2022) at various depths across the Po Plain, ranging from ground level to several hundreds of m a.s.l. This period was chosen as it provides sufficient coverage for piezometric monitoring across the studied area.

Data homogenization and an in-depth evaluation of temporal coverage allowed for the selection of several hundred of high-quality time series from an initial dataset of over 1000. These series were then analyzed to identify long-term trends, seasonal variations, and potential change points.

The analysis provided a comprehensive overview of piezometric dynamics at different depths across the Po Plain. Some trends were consistent across the entire study area, while others varied by geographic region or depth. By examining these patterns in relation to key anthropogenic and natural stressors, the study offers valuable insights into potential future groundwater behavior.

*This work was funded by "Fondo per lo Sviluppo e la Coesione (FSC) 2014-2020 - Piano Operativo Ambiente - Interventi per la Tutela del Territorio e delle Acque - Sviluppo di modellistica idrogeologica e delle conoscenze di supporto al piano del bilancio delle acque sotterranee (Modello idrogeologico delle Acque Sotterranee del distretto idrografico del fiume Po – MidAS-Po)".

Assessing water resources availability using the water balance in four basins of the Southwestern Alps (Italy)

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Assessing water availability is crucial for regions susceptible to climate change impacts. Severe droughts in 2022 exposed the vulnerability of both surface and groundwater resources in the province of Cuneo (Piedmont, Italy). These events emphasised the need to understand hydrological dynamics to achieve effective management of water supplies. This study explores the hydrological behaviour of four basins in the SW Alps using the water balance in the last 15 years, with a particular focus on aquifer storage to stream discharge.

Data for the Varaita Valley, Maira Valley, Gesso Valley, Stura di Demonte Valley basins regarding temperature, precipitation (P) and river runoff (Q) was taken from ARPA Piemonte's database. Potential evapotranspiration (PET) was calculated with the Thornthwaite method (1948), and actual evapotranspiration (AET) with the Fu equation (1981) to represent the Budyko curve. Measured river runoff was assumed to be equal to the sum of baseflow and surface runoff. Our goal is to discriminate the surface and the subsurface terms of the water budget at a monthly scale. Groundwater storage or discharge are usually neglected in long-term analysis but become relevant when the water balance is conducted at a monthly basis, especially during dry periods.

Results indicate that in most months Q is larger than the monthly available resources given by the difference between P and AET, which means that stored groundwater contributes to surface discharge; such subsurface contribution increases with larger aridity conditions (i.e. with larger PET/P ratio). This analysis helps quantifying the loss of stored resources using the water balance and plotting tendencies that contribute to depict the evolution of available water resources.

Funding: 1) PhD project funds (39th cycle), University of Turin, supported by the Italian Ministry of University and Research (MUR); 2) Project TREASURE (PCI2024-153494) - 2022 EU Partnership 101060874- Water4All.

Insights on the near-field effects of the 2016-2017 Central Italy seismic sequence on groundwater resources within the High Valley of Tenna River (Sibillini Mts. Range, Central Italy)

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The High Valley of Tenna River is located at the central-eastern part of the Sibillini Mts., Central Italy. Hydrogeological surveys aimed to characterize the study area and evaluate the near-field effects of the 2016-2017 Central Italy seismic sequence on the local groundwater resources started in June 2018 and were performed by monthly monitoring frequency until July 2020. Stream discharge and hydrochemical in situ measurements were carried out.

The built hydrogeological conceptual model suggested that Capotenna sector acts as a groundwater recharge area. There was a post-seismic groundwater depletion, along with that already induced by recent snow-rainfall decrease, within Capotenna spring area. It occurred especially in charge of the Scaglia Calcarea Aquifer, which contribute by overflow to the feeding of groundwater supply works dug within the underlying Maiolica Aquifer. During monitoring time, the Scaglia Calcarea Aquifer at Capotenna had seldom sufficient hydraulic potential for allowing to bypass the marly low permeability threshold of Marne a Fucoidi Formation. The groundwater resource located at less elevated Tenna River sectors, on the contrary, had a little and sudden post-seismic increase, nearly reestablished to its pre-seismic regime situation after summer 2020. Along Tenna streambed, at 1175-990 m a.s.l., groundwater inputs from the Calcareo Basale Aquifer and Maiolica Aquifer were evidenced, this latter by overflow on the low permeability Marne di Monte Serrone Formation. At lower elevation (985-845 m a.s.l.), in a sector featured by the Calcareo Basale Aquifer, a complex situation of hydraulic exchange between groundwater and surface water was found, likely due to the quite thin aquifer sustained by the basal low permeability layer (Evaporitic Unit) and/or to tectonic fragmentation of hosting rocks. The Pisciarelle Spring Group waters (925-845 m a.s.l.) come from the Scaglia Calcarea Aquifer with a likely contribution of Maiolica Aquifer.

Cross comparison of groundwater fluxes and dissolved salts in the Volturno and Po River coastal aquifers via SEAWAT model budgets

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Groundwater (GW) and surface waters (SW) salinization is affecting coastal aquifers, and this phenomenon, exacerbated by climate change (CC), is altering water cycle in transitional coastal environments. To compare GW fluxes and salinity origins, two coastal unconfined aquifers of Italy, the lower Po River lowland and Volturno River, were selected. A density-dependent numerical model was realized (SEAWAT4.2) with the same grid resolution (200x200m) and time steps (monthly, 2010-2020), to enhance the comparison. The models allowed to quantify GW flow directions changes and salinity evolution and to compare GW and saline fluxes within the aquifers. Both models were used to underpin SW-GW interactions and the CC impact. Each model was calibrated versus GW heads observations and high-resolution salinity profiles with good model performance.

The Po River aquifer simulation highlighted a salinity increase in the deeper aquifer layers due to increased upward GW fluxes triggered by decreased recharge rates and a "Polder" like situation. Shallow layers experienced both increasing and decreasing salinization trends depending on irrigation. The salinization of the drainage network is increasing during the modelled period, despite the seasonal and interannual variability.

The Volturno aquifer simulation highlighted an increasing GW salinization pattern due to seawater intrusion from the Volturno riverbed, induced by the decreased discharge rate. This salinization mechanism is complicated by salt leaching from peaty and silty-clay lenses deposited during the Late Holocene, when the coastal area was an inner bay.

The model budget intercomparison suggested that the classical mechanism of seawater wedge intrusion from the coastline is limited to the first km inland in both aquifers. While large inland portions of the model domains are characterized by high salinity due to remnant paleo seawater in aquitards, driving the GW salinity evolution and the salinity exchange with SW.

Groundwater flow in fractured bedrock: prior information from pumping tests, RQD and Earth tides

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Low-permeability fractured rocks constitute the bedrock of many regions worldwide. Due to the extreme heterogeneity and anisotropy, these rocks show very complex and varied drawdown-time trends when subjected to pumping. Understanding these trends is crucial for operational decisions, such as utilizing wells for water supply or managing dewatering operations in mining sites. This study examines nine pumping tests in an andesitic bedrock formation. The tests were carried out in wells of varying depths (30 - 260 m) in a region where groundwater circulation is not always continuous in the network of discontinuities. The tests lasting between 9 and 68 hours were generally carried out at constant flow rate (0.4-6 L/s) with measurements of drawdown in the pumping well and, in some cases, in an observation well. The drawdown data versus time have been analyzed through semi-log plots, the smoothed time series' have then been represented on bi-log plots together with the first derivative of the drawdown. The trends of the drawdown and its derivative have been compared with theoretical curves, and interpretation was refined using flow dimension sequence analysis. The results show very different responses of the aquifer to pumping, which are affected by the interconnection of discontinuities, the presence of multiple hierarchical networks of discontinuities and of dykes that bisects a country-rock aquifer.

Data from pumping tests was integrated by earth tides groundwater response from 6 piezometers and by additional information deriving from RQD available for 400 boreholes to obtain a probability distribution of the hydraulic parameters to be used as prior information in numerical modelling.

Salt migration and export via subsurface irrigation in a saline reclaimed landscape of the Po River lowland (Italy)

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Upward saline groundwater (GW) seepage is provoking surface water (SW) canals to be salinized in a large, reclaimed area of Po River lowland (Italy), particularly in tile drained agricultural fields embodying shortcuts among SW and shallow GW bodies. To identify salinization causes, a continuous monitoring network of SW channels, saturated and vadose zone (VZ) was established in two adjacent agricultural fields: the A1 field plot, mildly saline cultivated with maize and crossed by a paleochannel; and the A2 field plot, saline, uncultivated and covered by salt tolerant weeds.

The VZ continuous monitoring allowed to identify capillary rise as major driver of soil salinity in A1 field; in A2 additional salt is released by roots decomposition after the mow. These findings were integrated with remote sensing data on vegetation health (SAVI) and water requirement (NDMI).

Piezometers and drainage ditch continuous monitoring allowed to identify SW-GW relationships and saline sources in the aquifer/aquitard lenses.

Frequency domain analysis highlighted internal salinity dynamics, such as increased porewater salinity after mowing salt tolerant vegetation that increased temporary the EC up to 20 mS/cm.

Finally, measurements of water discharge and salt concentration at the outlet enabled a reliable estimation of salt fluxes from tile drained agricultural fields, showing that 70% of the total annual salt export (21±1.9 t/ha/yr) occurred during sub irrigation periods.

The upward saline flux from GW, together with the presence of halophilic vegetation fragments that slowly release salts into porewater and help to maintain elevated concentrations in GW and SW, pose a serious threat for the SW resources that are used for irrigation in these reclaimed lands, especially considering the ongoing climatic change that are already stressing the Po River lowland.

Unravelling the Hidden Lifeline of the Verlorenvlei Estuarine Lake: Groundwater Modelling of the Verlorenvlei Catchment

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The Ramsar Verlorenvlei Lake located along the West Coast of South Africa, faces increasing water scarcity due to rainfall variability, rising temperatures, and water-intensive agriculture. The Lake is an important habitat for rare species and is dominated by top conservation priority vegetation, however, the lake is drying up more frequently. Despite its international significance, no regional numerical groundwater model has been developed to simulate the region's groundwater flow dynamics or determine the groundwater dependency of the Verlorenvlei Lake.

A framework was developed to construct a steady-state numerical hydrogeologic model using a three-dimensional geological model, followed by the MODFLOW-NWT code in Visual MODFLOW Flex. The groundwater flow model enabled the estimation of global and zonal groundwater flow budgets, delineation of water resource areas, and simulation of hydraulic head responses due to various stress scenarios. The most significant water source sub-catchment was the Bergvallei sub-catchment, which has the highest groundwater recharge. The groundwater flow and recharge areas for the tributaries flowing into the Lake mainly occur in the mountainous regions, while the recharge to the Lake is only from the immediate surrounding area. Stress scenario simulations showed that a prolonged drought had a greater impact on groundwater availability than halting all groundwater abstraction. However, if groundwater abstraction is reduced in a drought, particularly near key tributaries near the headwaters, it can increase groundwater discharge and ultimately increase freshwater inflow to the Lake. Therefore, the groundwater discharge into the tributaries is a crucial freshwater source for the longevity of the Verlorenvlei Lake.

DATASET: social and communication strategies

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Coastal areas are vital ecosystems that provide essential resources for economic and societal development. However, the salinization of freshwater resources—driven by both natural and human-induced factors—represents one of the most pressing and widespread challenges in coastal regions, both in Europe and globally. Recent studies indicate that these issues will be further intensified due to ongoing climate change and the increasing frequency of extreme hydroclimatic events. The DATASET project (GrounDwater sAlinizaTion and pollution AsseSsmEnt Tool) seeks to develop an effective tool for protecting, regulating, and sustainably managing coastal aquifers. To ensure broad dissemination of its findings, the project's Communication and Dissemination Plan (CDP) outlines strategies to maximize impact, enhance visibility, and engage key stakeholders through targeted communication and suitable media. For recognition, DATASET has a dedicated logo, that features the project acronym, with colors symbolizing different vulnerability-related work packages: green for "safe zones," yellow for "caution areas," and red for "hazard zones". A fourth color, grey, has been incorporated to enhance the communication strategy, ensuring clarity and accessibility for a wide audience. The shield is divided into four sections, representing the project's four core Work Packages (WPs). The project's official website serves as the primary platform for presenting project developments and results. In addition to showcasing research findings, the website functions as an internal networking hub, facilitating the exchange of documents and research materials. To further extend its reach, DATASET actively shares research activities and updates through social media platforms such as Facebook, Instagram, YouTube, and LinkedIn. These channels allow for broader audience engagement by providing updates, project details, and announcements about upcoming internal and external events.

Hydrogeological Monitoring for Assessing Spring Discharge Variability: Case Studies from the Aosta Valley

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The sustainable management of mountain water resources is increasingly challenged by climate change, land use modifications, and evolving water demand patterns. These factors influence precipitation regimes, groundwater recharge processes, and seasonal water availability, affecting the quantity and quality of stored groundwater resources. Consequently, understanding how groundwater storage mechanisms are changing has become crucial for predicting future water availability scenarios in such areas. To achieve this, new automated tools and standardized approaches must be applied to continuously monitor hydrogeological variables that affect the spring recharge system. Since 2019, within the framework of the RESERVAQUA project (Interreg V-A Italy-Switzerland Cooperation Program), the Applied Geology Research Group at Politecnico di Torino has been conducting extensive spring monitoring activities in the Aosta Valley Region (northwestern Italy). Data collected from multiparametric water probes, which record water level, temperature, and electrical conductivity values at hourly intervals, have been analyzed to estimate discharge volumes in selected alpine springs over multiple hydrogeological years. Temporal variations in these parameters for the Cheserod, Entrebin, Gabiet, Mascognaz, Promiod, and Promise springs have been examined, providing insights into how recharge and discharge mechanisms are evolving under changing environmental conditions. To perform this analysis, a new software tool, SOURCE (a semi-automatic tool for Spring mOnitoring data analysis and aqUifeR CharactErization), was developed and applied. SOURCE enables the automated hydrogeological characterization of spring aquifers by processing input data from springs and associated meteorological stations. These data, uploaded into a formatted Excel file, are processed to generate graphical outputs and compute key hydrodynamic parameters of the studied aquifers.

Assessing groundwater recharge events through natural springs under extreme climatic conditions

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Springs are the transition from groundwater to surface water, serving as a direct indicator of the condition of the aquifers that sustain. For this reason, springs have been used as key indicators of aquifer hydrologic dynamics, as well as pollution occurrence (e.g. Boy-Roura et al., 2013, Weber and Kubiniok, 2022).

The aim of our study is to analyze the aquifer recharge processes, using natural springs as early warning indicators of severe climatic events. Our initial hypothesis is that spring's main hydrochemical characteristics remain constant throughout the year, in contrast to stable water isotopes and organic matter, which may be particularly sensible to both important rainfall events and severe droughts, being thus a good indicator of recharge processes.

The Brugent River Watershed (NE Spain) has an extension of 103,3 km2 with mean temperatures of 13,6 ºC and precipitations of 800 l/m2. It presents a Mediterranean climate, determined to be particularly sensitive to the impacts of climate change: high deterioration of river ecosystems, decrease in water security and intensification of flood and drought episodes (IPCC Sixth Assessment Report, 2022).

We have selected 12 springs, considering their geology (springs in shales, sandstones, limestones and in quaternary sediments), the human pressures in their catchments, and their distribution across the watershed. We have been conducting monthly sampling campaigns (May 2024-April 2025) to determine spring discharge, physicochemical parameters, major ions, organic and inorganic nutrients, as well as stable water isotopes. Additionally, in two campaigns, dissolved metals were also analyzed. The hydrochemical results have been analyzed considering region's climate (precipitations, temperatures) and hydrologic data (springs flow) to analyze their relation and dynamics.

By analysing this local case we want to identify which lessons can be learned towards a more global framework of the hydrogeological dynamics.

Analysing the effects of meteorological and hydrological droughts on Mediterranean coastal lagoons

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Climate change and anthropogenic pressures, such as land-use changes, can significantly alter hydrological processes. The Baix Ter region (NE Spain), characterized by a Mediterranean climate, is highly vulnerable to droughts, which threaten groundwater resources sustaining coastal wetlands. This study assesses the hydrological status of the Baix Ter by analysing drought events. Meteorological, hydrological, hydrochemical, and ecological data were integrated using multiple drought indices: the Standardized Precipitation Index (SPI); the Standardized Precipitation Evapotranspiration Index (SPEI); and the Streamflow Drought Index (SDI) to assess flow variations in a local stream (the Daró River). In addition, the Standardized Water-level Index (SWI) was applied to groundwater data, and production and respiration data from two coastal lagoons with distinct hydrological regimes to evaluate drought impact and lagoon adaptation. These regimes included the Ter Vell lagoon, which receives surface water from an intermittent stream, and the Fra Ramon lagoon, dependent on groundwater inputs. Results indicate an increasing trend in temperatures and significant decline in precipitation over the studied period (1950-2024) leading to more frequent and intense droughts over the past 25 years. Correlations between drought indices and biological and hydrochemical data confirm the direct influence of hydrological stress on the coastal ecosystems analysed. These findings underline the vulnerability of groundwater-dependent coastal lagoons, where hydrological stress is altering oxygen levels, salinity and biological productivity, with potential long-term consequences for aquatic biodiversity.

This study has been realized within the framework of the collaborative international Project consortium TREASURE (PCI2024-153436) - Joint Transnational Call of the Water4All European Partnership 2022, and by the AquiPondSys grant (PID2023-147186OB-I00), funded by MCIN/AEI/10.13039/501100011033.

SUITED: A Novel GIS Framework for Soil and Irrigation Suitability Assessment Under Salinization Risk

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With a growing global population, agriculture is facing increasing challenges in meeting rising food demands while minimizing environmental impacts. The United Nations' Sustainable Development Goals highlight the urgent need for innovative tools to evaluate soil suitability for agricultural use. In response, this study proposes a novel framework based on an Analytical Hierarchy Process (AHP) integrated with Geographic Information Systems (GIS) to assess soil suitability under complex and dynamic environmental conditions. Soil salinization is one of the most significant threats to global agriculture, affecting over 900 million hectares worldwide. To account for this issue, the proposed index integrates a remote sensing-based salinity index and a tailored Water Quality Index (WQI) to evaluate irrigation water suitability inside the canonical soil suitability assessment. This approach will also enable the preliminary evaluation of treated wastewater as a non-conventional water source for sustainable crop irrigation for those area suffering water scarcity. The methodology was tested in a section of the coastal floodplain of the Campania region, an area characterized by intensive agriculture and persistent water salinity issues. Soil chemical and physical properties (e.g., pH, texture, bulk density) were combined with climatic, hydrogeological, remotely sensed, and water quality data to ensure a holistic assessment that considers both soil characteristics and irrigation water salinity contributions. The compiled geodatabase was processed using a rating methodology to determine soil suitability for agricultural use. The index was calculated by considering multiple soil depth ranges and implementing a weighted system to account for both parameter significance and depth variations. This framework provides a scalable and adaptable tool for soil suitability assessment, supporting sustainable land management and water resource optimization in vulnerable agricultural regions.

Characterizing flow and transport in porous media: challenges of model and parameter uncertainty

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Flow and transport processes in porous media encompass a diverse range of physical and (geo)chemical phenomena. While these take place across multiple spatial and temporal scales, their quantification is fraught with significant challenges. Their inherent complexity naturally leads to multiple interpretations that are rendered through diverse conceptual models and mathematical formulations. As we navigate the complexities of process formulation and parameterization, addressing uncertainties is then increasingly critical. Key challenges include managing spatial heterogeneity of model parameters, such as, e.g., permeability, porosity or reaction rate parameters, and tackling our limited knowledge of the detailed characteristics of the porous medium. In this context, we delve into the uncertainties associated with process and system formulation, as well as parameterization. We evaluate their impact on critical model outputs of environmental significance, including solute concentrations, source protection areas, and reaction rates. Our discussion encompasses experimental studies, characterization of spatial patterns and heterogeneities within porous media, global sensitivity analysis, and stochastic inverse modeling. We explore these uncertainties through illustrative scenarios that range from regional- to laboratory- scales. We consider complex aquifer systems, the dynamics of a pharmaceutical compound at the laboratory scale, and nanoscale observations of mineral dissolution under continuous flow conditions.

Towards a European sentinel springs information platform with real-time monitoring of groundwater quantity and quality

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The SentinelSpringS project aims to establish cost-effective, inclusive, and sustainable monitoring and modelling solutions to preserve the crucial role of springs in supporting vulnerable ecosystems that depend on groundwater. Key research questions include addressing the lack of long-term and real-time monitoring data through standardised data collection protocols and characterising the sustainability of spring-dependent ecosystems. Here we introduce efforts toward a new European onshore and offshore spring information platform and map viewer enabling open access to real-time monitoring data on spring quantity and quality potentially including geogenic elements and relevant pollutants such as nitrate and pesticides. The information platform can encompass data on the impacts of emerging contaminants, water over-abstraction, land use change and invasive species on spring water chemistry and the characteristics of biological communities. Additionally, it contributes to assessing the influence of climate change on spring discharge and nutrient loadings, highlighting critical knowledge gaps in understanding climate-related vulnerabilities in spring-dependent aquatic and terrestrial ecosystems. The spring information platform will enhance our understanding of the hydro-ecological functioning of springs and aquatic ecosystems and their vulnerability to temperature changes and the broader impacts of climate change.

Hydrodynamic and heat transport modelling for the sustainable management of the Budapest Thermal Karst

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This study presents a model-based analysis of hydrodynamic flow and heat transport in the Budapest Thermal Karst System, including future production scenarios and the impact of newly planned facilities. It emphasizes the need for sustainable management of the region due to overlapping exploration requests—many of which are geographically close to vulnerable karst spring areas—following regulatory changes. In response, the Geological Survey of Supervisory Authority for Regulatory Affairs initiated the Budapest Geothermal Research Programme.

Numerical modelling was conducted using extensive geological and geophysical data, improving the reliability of the geological model for the covered karst aquifer and tectonic features, mainly on the Pest side. A high-resolution 55 km 2D seismic network, gravity data, data from more than 300 deep and approx. 30,000 shallow boreholes, and 2D/3D seismic interpretations contributed to a new 3D geological model. This includes six geological time-horizon models, six geologic formation maps, seven geological-geophysical sections, and a Pre-Cenozoic basement geologic and tectonic map.

The region contains cold and hydrothermal karst systems, including hypogene caves and springs that supply Budapest's thermal baths. To prevent significant changes in hydraulic heads, temperatures, and water composition due to new geothermal facilities, protective zones must be delineated. A harmonized water chemistry and isotope hydrology database was developed, interpreting main chemical components, discharge temperatures, and isotope data.

Both convective and conductive heat transport were simulated using FEFLOW® software with density-dependent heat transport. A regional (approx. 4477 km²) model with refined mesh around spring areas identified critical karst water supply zones and vulnerable regions through visualized maps, supporting decision-making processes.

The CARG thematic hydrogeological sheet n. 374 – Rome, and its innovation.

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The CARG project is the national initiative of Italian geological cartography at 1:50,000 scale. Its goal is to provide complete coverage of the Italian territory, not only through geological base mapping but also by developing thematic maps in areas where the geological base map is already available. Among the various thematic maps within the CARG project, hydrogeological maps remain underrepresented, with only a few sheets completed so far. However, in recent years, several Italian Regions and research groups have launched new surveys and initiatives to expand hydrogeological mapping efforts. One such efforts includes Sheet No. 374 – Rome.

The Rome hydrogeological sheet is currently being developed in-house by ISPRA. It is based on the hydrogeological informations gathered for the Hydrogeological Map of Rome (2015), which covers the entire municipal area. The project is ongoing, with a primary focus on collecting new data to update and refine the hydrogeological framework of the region.

A key innovation of this sheet is the instrumentation of Rome's existing groundwater monitoring network, improved with the installation of 50 probes capable of continuously measuring and transmitting water level and temperature. Additionally, 10 of these probes are also equipped to monitor electrical conductivity. The adoption of real-time recording of hydrogeological parameters at monitoring points represents a significant enhancement in the requirement for at least monthly data collection for two years envisaged in CARG hydrogeological guidelines. This experimental advance will enable real-time sharing of hourly groundwater data on the ISPRA website, providing a dynamic representation of groundwater behavior in the mapped area. As a pilot project, it aims to serve as a model for future hydrogeological sheets, enhancing groundwater monitoring and management across Italy.

A new participatory Hydrogeological Map of Italy 1:500,000 scale

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The Hydrogeological Map of Italy at 1:500,000 scale represents a significant advancement in the national hydrogeological knowledge framework.Positioned between the European Hydrogeological Map (IHME1500) and regional maps, it provides a comprehensive and standardized reference for groundwater assessment across Italy.This initiative integrates existing geological and hydrogeological datasets from multiple scales, ensuring consistency and accuracy. The project employs a geospatial overlay technique to harmonize regional hydrogeological information at 1:250,000 scale with national geological data at 1:500,000 scale. This process allows for the classification of hydrogeological complexes based on relative permeability, ensuring a coherent national representation of subsurface hydrodynamics.

The map includes various thematic layers, developed also in collaboration with Istat, such as productivity, piezometric data, cold and thermal springs, representative monitoring stations defining the current regional state of the art on groundwater resources in Italy.

An innovative aspect of the project is the participatory approach, facilitated through a WebGIS platform. This system enabled the Italian hydrogeological scientific community to provide feedback, suggest modifications, and updated geospatial data, ensuring a high-quality and widely acknowledged result. he digital version of the map is intended as a dynamic product, open to continuous updates as new information becomes available.

The new hydrogeological map provides policymakers, researchers, and water resource managers with a unified tool for groundwater assessment, improving legislative and management decisions. Its adherence to ISPRA's guidelines makes it a reference framework for future thematic hydrogeological maps.It represents a fundamental step in national-scale groundwater knowledge, bridging gaps in previous cartographic efforts and establishing a homogenous baseline for future research and resource management.

Groundwater resources diminishing in mountain areas: only climate change or also a "hidden" consumer? An example from Central Apennines (Italy)

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In recent years, the evaluation of water resources is acquiring ever greater importance mainly due to the world population growth, especially in areas like the Mediterranean region where rainfall has shown a generally negative trend, also characterized by shorter and even more intense events. Furthermore, the ever-increasing demand for high-quality drinking water highlights the importance of correct monitoring and careful management of the resource. The area of the Sibillini Mountains National Park, located in the central Apennines (central Italy), proves to be particularly suitable for a quantitative study of the water resource due to the excellent water quality widely exploited for drinkable uses. This sector of the Apennine ridge is characterized by suspended aquifers, even of large dimensions, and by a deep basal aquifer hosted within fractured and karstied micritic limestones. The monitoring, in some cases for decades, of the discharges emerging from some important spring systems and of some river reaches that drain the waters circulating within the basal aquifer has highlighted a constant and progressive decrease in stored water resources. This phenomenon, as mentioned, is certainly linked to the rainfall trend recorded in recent decades which, especially concerning the time of residence of the snowfalls on the ground, has shown a marked decrease. However, the role played by the strong increase in forest cover along the recharge areas within the carbonate ridge over the last 50-60 years is underestimated. The lower inltration linked to the consumption of trees, especially in the summer season, combined with the amount of precipitation lost through interception or evapotranspiration phenomena, has been shown to reach values in places higher than 25-30%.

A machine learning model trained on data from sites under remediation to predict geogenic arsenic distribution in shallow groundwater

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Geogenic arsenic (As) contamination is a known issue affecting groundwater quality worldwide. In heterogeneous aquifers, As mobility results from complex physical and geochemical interactions. Extensive monitoring data are required to reliably assess these underlying processes and the natural As heterogeneity. However, effective groundwater characterization is often hindered by limited data availability, high monitoring costs, and resource constraints. This study exploits an alternative source of geochemical information, aggregating data from monitoring wells of sites under remediation, a pervasive network widespread in urbanized areas. We previously demonstrated that, when properly processed to remove anthropogenic influences, these data can provide meaningful insights into groundwater's pristine composition. We developed a random forest model to predict the probability of As concentrations exceeding the 10 μg/L regulatory threshold. The method was applied to the shallow aquifer of Ferrara province in the Po Valley (northern Italy), a highly anthropized region with known geogenic As issues. Here, local assessments of As natural background levels are often required to distinguish geogenic from anthropogenic source of contamination in remediation procedures, since provided regional-scale assessments lack sufficient resolution. Our model identified areas with high probability of As exceeding 10 μg/L, mostly close to the Po River delta. As mobilization was linked to natural processes driven by the stratigraphic architecture of the area: widespread peat deposits promote redox reactions associated with organic matter degradation, leading to the reduction of Fe/Mn oxides originating from Apennine sediment sources. This study provides a useful tool for groundwater management, improving chemical composition knowledge through an integrated approach, relevant for both local-scale decision-making and large-scale groundwater quality assessments.

Terzaghi's Effective Stress Principle and Hydrological Deformation of Matese Karst Aquifers detected by GNSS and inSar

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Hydrological components in the time series of the horizontal and vertical ground displacements measured by Gnss (Global navigation satellite systems) and insAr (interferometric synthetic Aperture radar) have been analysed for the Matese karst massif. In particular, contraction and dilatation phases appear associated with the lowering and rising of the groundwater levels, respectively. This phenomenon has been explained combining the Terzaghi's effective stress principle (Skempton's generalization) and linear elasticity. The hydrological deformation of karst massifs is similar to the thermal expansion of solids, and it is primarily due to pore water pressure variations occurring in the aquifer saturated zone, which are associated with water table oscillations. The elastic properties of the rock mass and the coefficient of earth pressure at rest, Ko, control the magnitude of the deformation, which also depends on the aquifer geometry and thikness of the epiphreatic zone.

Hydrogeological conceptual model and multi-method approach for groundwater recharge estimation of the Monti Lattari karst aquifer (southern Italy)

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Coastal karst aquifer of Lattari Mts. (~280 km2) supports drinking water supply of the Sorrento Peninsula and Capri Island, an over densely populated area in summer, economically strategic for Campania region (Italy) and outstanding environmental and cultural value. Based on in-depth literature review and a GIS and R-based analysis of hydrological data, this study aims to reconstruct a novel conceptual hydrogeological model and update the water balance to prevent excessive groundwater exploitation and deterioration from potential saline intrusion due to intensive withdrawals. A multi-method approach was used to assess a multi-scale groundwater recharge, integrating geological, land use, soil type, cover type, vegetation cover type and thermo-pluviometric data recorded with monthly and daily frequency by 24 meteorological stations over the period 2000–2023. In order to estimate the groundwater recharge, three methodologies were applied, two using the same water budget approach but different evapotranspiration calculation methods (e.g. Thornthwaite-Mather and MODIS data), and a third independent approach based on the SWB (Soil Water Balance) model. Subsequently, a comparison of groundwater recharge with natural outflow (Qoutsw) and withdrawals (Qoutw) was conducted using a geodatabase of 650 water point. At the aquifer scale, the mean annual groundwater recharge estimated with Thornthwaite-Mather formula (5.21 m^3/s) and MODIS (4.88 m^3/s) exceed those evaluated with SWB model (3.91 m^3/s). The mean annual groundwater recharge remains higher than water withdrawals in all cases, although at the basin scale the current water withdrawals may be unsustainable in the long term in some cases, especially considering the interannual variability of recharge. Results obtained can support decision-makers and stakeholders in promoting sustainable groundwater use and enhancing water system security in Campania's strategic economic area.

Comparative assessment of groundwater recharge rates and transit time through the unsaturated zone for groundwater protection

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The intensification of human activities, particularly in agriculture, has resulted in the over-exploitation and depletion of groundwater resources leading to widespread contamination.

This study aims to evaluate and compare different methodologies for estimating groundwater recharge rates and transit times through the unsaturated zone, for enhancing the understanding of water percolation dynamics in the vadose zone.

The study area is in the Arborea plain in Sardinia (Italy), an area designated as a nitrate vulnerable zone since 2005, where groundwater is severely affected by diffuse nitrate contamination.

Three distinct approaches were employed to estimate groundwater recharge: (i) the peak-shift method based on isotopic profiles of soil pore water within the vadose zone, (ii) the water balance concept incorporating the results from the application to the one-dimensional flow and transport model FLOWS to simulate water balance in the unsaturated zone, and (iii) the Soil Water Balance code, which employs a modified version of the Thornthwaite-Mather soil-water balance approach at a daily resolution, integrating spatially distributed soil, meteorological, and land cover data.

The recharge estimates obtained from these methodologies show agreement with each other and with previous studies, demonstrating the consistency of these approaches as simplified and effective tools for quantifying net water infiltration.

The assessment of percolation times within the unsaturated zone is crucial for evaluating aquifer vulnerability and optimizing agricultural management practices. Accurate quantification of the spatial and temporal distribution of groundwater recharge contributes to improving land and water resource management, enabling the implementation of targeted mitigation measures to minimize groundwater pollution and enhance long-term protection strategies in similar hydrogeological settings.

From meteorological to groundwater drought in the Tanagro river basin in the perspective of climate change

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The baseflow is the slow streamflow component related to groundwater outflows from shallow and deep aquifers. In a context where climate change is increasingly evident, it is crucial to study how it is potentially affected by climate (Longobardi and Van Loon, 2018). Focusing on a water scarcity context, drought effect produces impacts for long periods even beyond its duration and, as they appear after its onset, an effective monitoring system can support the prediction of phenomena with a view to mitigation actions planning (Panu & Sharma, 2002). The research contributes to drought propagation studies, from meteorological to hydrological systems, in the perspective of climate change. The Tanagro river basin is an approximately 660 km2 catchment located in southern Italy, Campania region, featured by a typical mediterranean climate. The Tanagro river freshwater is characterized by a conspicuous spring contribution and is mainly used for irrigation purposes and for the production of energy from renewable sources. Meteorological and hydrological droughts are respectively assessed by the assessment of the Standardized Precipitation Index SPI and the Standardized Groundwater Index SGI, from monthly scale precipitation and discharge for the period 1918-2019 (McKee et al., 1993). A correlation analysis is proposed to assess the lag between meteorological and hydrological drought as well as the drought propagation rate is computed as the ratio between hydrological and meteorological drought events. The results will contribute to a methodological proposal for the quantification of the resilience of hydrological systems to climate change and the possibility for meteorological drought forecasting affecting hydrological systems. The activity falls within the objectives of the WaterWise project “Water Management Strategies and Climate Change Adaptation in Southern Italy” (SPOKE VS1 “Acqua” Project “Multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate - RETURN).

Hydrogeological Dynamics and Sustainable Management of Fractured and Karstified Aquifers: The Gran Sasso Case Study (Italy)

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Karst aquifers represent complex systems where groundwater flows at different velocities through a network of secondary porosity structures such as fractures and conduits. Their complexity comes from the interplay between geological and climatic factors, as well as human activities, like tapping springs and drilling tunnels, which can significantly change flowpaths and discharge regimes.

The Gran Sasso aquifer, one of the largest fractured and karstified aquifers in the central Apennines, offers a unique opportunity to study these phenomena thanks to the presence of drainage in highway tunnels, drilled in the 1970s. These tunnels tapped approximately 2 m^3/s of groundwater directly under the preferential recharge zone, providing access to peculiar hydrogeochemical conditions within the aquifer. Recently, to obtain information about hydrodynamic aspects of the natural drainage and an updated hydrodynamic setup of groundwater flow related to recharge mechanisms, the structural characterisation of both surface and tunnels has been carried out, integrating hydrogeochemical and isotopic data from 27 drainage points along the tunnels.

The study reveals a complex mix of recharge mechanisms influenced by fractures and lithology permeability. Major ions show minimal variation, while isotopic results identify four distinct flowpaths. These include fast infiltration via fault zones, the arrival of old water into the tunnel drainage, representing the slow-flow aliquot, interaction with Quaternary deposits, and rapid groundwater movement through karst systems. The findings also highlight the role of Campo Imperatore's endorheic basin and fault zones in groundwater recharge dynamics. The Gran Sasso aquifer can be used as a model for understanding fractured-karst systems under climatic and tectonic conditions similar to those in the Mediterranean, offering insights into strategies for conserving high-quality drinking water in the context of climate change and anthropogenic pressure.

Groundwater Modelling for Open-Loop Geothermal Heat Pump Systems Management

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Installation of open-loop geothermal heat pump (GSHP) systems for heating and cooling of buildings requires detailed planning in order to maximize management efficiency and minimize unwanted impacts. Failure to do so can induce a decline in public acceptance of these systems.

Groundwater modeling is essential for extracting management and impact salient information from site data, quantifying the repercussions of data insufficiency, and providing a basis for effective acquisition of further data. We exemplify a workflow for use in heterogeneous hydrogeological environments using a synthetic model based on a real-world setting. Simulation employs the MODFLOW 6 Groundwater Energy (GWE) model. The simulator is parameterized with stochastic hydraulic property fields based on nonstationary variograms. This type of parameterization can express hydrogeological conditions that prevail in complex aquifers such as those that exist near rivers, or are affected by faulting/fracturing. The numerical burden of assimilating borehole head and thermal data in order to quantify and reduce uncertainties of predicted GSHP efficiency and impact is minimal, as this is implemented using data space inversion (DSI). This eliminates the need for history-match-adjudicated parameter adjustment, while associating realistic uncertainties with management-critical predictions. Use of DSI offers the additional benefit of allowing rapid assessment of the ability of as yet unacquired data to reduce the uncertainties of key system performance and impact predictions, at the same time as it allows continuous assimilation of new data that emerges through GSHP operation.

Despite its outward complexity, this approach to open-loop GSHP system management is relatively easy to implement and incurs only a minimal numerical burden.

Education and Capacity building for Groundwater Management in Developing Countries

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While many research groups employ advanced hydrogeological data processing and numerical modeling tools, their full potential remains largely unknown in professional practice. This gap between research and practical application is even more pronounced in developing countries.

Academic training provides essential concepts, and the natural continuation would require real-world applications, crucial for professional expertise. This work presents the outcomes of SYMPLE (School of Hydrogeological Modelling and Project-Related Strategies), an initiative started in 2021 that now counts over 600 users of the e-learning platform from 78 countries, primarily developing countries which can attend all the courses for free.

With 40+ international trainers, the initiative combines recorded lessons, live sessions, self-evaluations, and group discussions to enhance learning. Achievements over the first 3 years of activity are presented, including learning progress, new employment opportunities, and collaborations among participants. A growing community of 100+ active members engages through social platforms, facilitating professional support, knowledge exchange, and job opportunities.

Participants have worked on real-world case studies, including:

- Contaminated site assessment in Milan
- Hydrogeological characterization of a landfill site
- Well protection zone delineation
- Geoexchange system impact assessment

SYMPLE has expanded collaboration networks with nonprofits and educational initiatives, including Aid for Life, Spring to Life, the Groundwater Project, and the European INUX initiative, supporting open-source training materials and projects such as water well drillings in refugee camps in Chad and in a hospital in Tanzania.

Suitable aquifers for MAR projects in the Emilia-Romagna Region according to current Directive and hydrogeological setting

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Managed Aquifer Recharge (MAR) could be a crucial strategy for addressing the impacts of climate change. Specifically, infiltration ponds may help to replenish depleted aquifers, thereby mitigating the effects of drought or groundwater overexploitation. Additionally, it may contribute to reducing the risk of flooding by utilizing river waters. This research aims to identify water bodies (WBs, deriving from DQA "Direttiva Quadro acque") suitable for MAR following Italian directives. The Emilia-Romagna Region's database includes 453 Surface Water Bodies (SWBs), such as rivers and other watercourses, along with 135 Groundwater Bodies (GWBs). An evaluation system to identify the optimal combinations between SWB and GWB to design infiltration ponds has been developed, focusing on alluvial fan systems along the Apennine foothills. First, GWBs were selected due to their poor quality and critical quantity issues, whereas SWBs were chosen based on their quality and ecological requirements (DM 100/2016). Forty-two combinations were identified between SWGs and GWBs. A quantitative and empirical evaluation was conducted involving a systematic combination assessment of key factors; each assigned a rating and weighting. The sum of these factors results in a global index for each combination of SWG and GWB. This allows for the establishment of a ranking for the WBs combinations, from the most to the least favorable. Key factors include river discharge rate, flood hazards, and the presence of non-active quarries near SWB. GWBs are evaluated considering lithology, permeability, and water table level. Our results enable to select all WBs suitable for MAR as permitted by Italian legislation and to rank SWB-GWB combinations specifically focused on infiltration pond MAR. Future research will focus on the best combinations identified in this study to characterize the optimal sites for implementing infiltration ponds MAR.

Assessing groundwater depletion in a changing climate through the vadose zone monitoring and a novel extreme rainfall index

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During the last few decades, climate change has led to an increase in heavy rainfall events in the Mediterranean basin, affecting groundwater resource availability (García-Ruiz et al., 2011). In this scenario some studies suggest shifting the monitoring focus from the saturated zone to the vadose zone, as its heterogeneity influences infiltration and runoff processes, making it a key layer for characterizing groundwater recharge mechanisms. This study investigates the vadose zone's response to rainfall in the Monte Conero Regional Park using an integrated monitoring system, which includes a thermo-pluviometric station, three soil moisture probes placed at different depths, and a piezometer. Rainfall trends over the last 30 years were analysed using the Standard Precipitation Index (SPI) and a newly proposed index designed to assess the impact of heavy rainfall events on annual cumulative precipitation. The aquifer recharge mechanisms were examined from multiple perspectives following the approach of Berthelin et al., 2023. Particular attention was given to analysing the wet front propagation associated with heavy rainfall events and their impact on groundwater recharge. Findings support the hypothesis that a declining recharge rate, driven by an increase in heavy rainfall events, is a primary factor contributing to groundwater depletion. This study highlights the importance of continuous vadose zone monitoring to improve the understanding of recharge mechanisms in heterogeneous media, particularly in the context of increasing hydrogeological extremes.

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Practical Application of Advanced LNAPL Multi-Phase Modeling in Groundwater Remediation

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Groundwater remediation of LNAPLs (Light Non-Aqueous Phase Liquids) has advanced with improved models for multi-phase flow and contaminant transport, essential for mapping out contaminant plumes and formulating remediation plans. While LNAPL models simulate how LNAPL interacts with water, air, and soil, their use is limited by specific site conditions, data access, and expertise level. Geological variations, like confining layers and barriers, must be considered as they affect LNAPL flow.

Accurate subsurface evaluation is pivotal, with LNAPL transmissivity measurement proving superior to traditional monitoring for assessing contamination and predicting remediation systems' efficacy. New refined computational techniques in modeling offer a precise representation of complex interactions between LNAPL, water, and air and pinpoint the boundaries between these fluids and improve parameter estimation through data integration. Moreover, joining geostatistical methods with physical models has made simulations of LNAPL spread more realistic, and the integration with Geographic Information Systems (GIS) enhances the analysis and depiction of contamination over time.

While sophisticated models offer detailed predictions, their utility in practice is contingent on validating assumptions through field data, simplifying model complexities for interpretability, and ensuring stakeholders' comprehension of model outputs. Environmental professionals must navigate the trade-off between model sophistication and operational feasibility, ensuring that the application of such models ultimately serves the goal of effective and sustainable LNAPL remediation.

This abstract advocates the need for regulatory acceptance of LNAPL transmissivity as a closure criterion, and for elaborating on best practices that can bridge the gap between theoretical modeling and field application. By doing so, it furthers our collective capacity for informed decision-making in LNAPL-impacted site management.

Evaluating Emerging Contaminants in the Atlantis Aquifer's Managed Aquifer Recharge Scheme, South Africa

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Managed aquifer recharge (MAR) using treated effluent and stormwater (TES) as source water is a vital strategy for sustaining urban aquifers used for potable water supply in water-scarce regions. However, concerns exist about the adverse impacts on groundwater quality due to the introduction of emerging contaminants (ECs) typically present in TES. This study aims to assess the impact of MAR on groundwater quality in the Atlantis Aquifer by investigating the occurrence and spatial distribution of ECs, including pharmaceuticals, pesticides, and industrial chemicals. Twenty samples from MAR source water, groundwater, and surface water were collected and analysed for 289 ECs. Preliminary results showed the detection of 120 compounds, with MAR source water having the highest number of detections, followed by MAR-impacted groundwater, while naturally recharged groundwater had the fewest. This pattern suggests that ECs are introduced into the aquifer through MAR, that some ECs may be attenuated, and that there is a baseline level of contamination in naturally recharged groundwater. Further analysis involving a three-tiered health risk assessment revealed that fewer than 10% of detected compounds pose potential health risks (RQ >1). To assess the aquifer's capacity to naturally attenuate (via biodegradation) ECs that pose potential health risks, conventional water quality indicators (e.g., nitrate, dissolved oxygen, manganese, sulphate) collected between 2018 and 2024 will be analysed. The findings will contribute to the development of an EC monitoring framework for the Atlantis Aquifer, and by integrating EC monitoring into existing management practices, this will enhance protection of both the resource and communities that depend on it.

Numerical Model Development and Application to Nuclear Waste Storage: Freeze & Thaw over Glacial Time Scales

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Deep geological repositories (DGRs) for isolating nuclear waste must be designed to last hundreds of thousands of years. Relevant processes needing consideration over such time scales include density-dependent flow, glacial loading, permafrost formation and thaw, and heat and brine transport. Host geological media can be complex and heterogeneous, including discrete fractures or fracture zones and depth-dependent hydraulic conductivity. Numerical modelling can provide much needed insight into the behavior of these non-linear systems.

In this context, the finite element model HEATFLOW/SMOKER has been further developed and applied to predict the effect of glacial cycles and permafrost freeze/thaw on deep groundwater flow systems relevant to a DGR. Simulations are based on a 2D conceptual model of the recently-approved Revell storage site in northern Ontario, Canada.

Driven by future projections of historic air temperatures, glacier base temperatures and glacier thickness, the 120,000-year simulations show how permafrost can extend hundreds of metres deep, potentially isolating deep flow systems. Unfrozen zones (or taliks) potentially forming in discharge zones, remain a concern as pathways to surface.

Long-Term Trend Analysis on the Bagnara Spring Flow Rates (Umbria-Marche Apennines, Italy): The Impact of Climate Change

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This study investigates the temporal variability of discharge from the Bagnara spring, located in the Umbria-Marche Apennines (Central Italy, 630 m a.s.l.), highlighting potential impacts of climate change on its hydrological regime. Analyzing 50 years (1973-2023) of daily discharge data, advanced statistical methods, including Mann-Kendall non-parametric tests and regression analyses, were employed. The historical record was divided into two 25-year intervals, revealing a significant reduction in spring discharge in the recent period (Mann-Kendall test; Mann-Whitney U test). Further analyses at different temporal scales, specifically focusing on annual, five-year, and ten-year averaged minimum flows, consistently indicated statistically significant decreasing trends, particularly strong in the ten-year window (R^2=0.5876). Results suggest climate change primarily impacts minimum flow conditions, potentially due to altered precipitations, increased evapotranspiration, and prolonged drought periods. The declining trend in minimum discharges poses critical implications for water resource management and ecosystem sustainability, highlighting the urgency for adaptive groundwater management strategies to mitigate future impacts.

Testing different fertigation water types performance in two different soils via batch experiments

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By 2030 agricultural sustainability will face critical challenges due to increasing freshwater scarcity and demand that will exceed the availability of natural water resources. The use of treated wastewater is a viable strategy for irrigation, providing an alternative source of water and essential nutrients through fertigation, thus optimizing the use of available resources. To evaluate the interaction between fertigation water and soil, batch experiments were conducted with three types of synthetic fertigation water sourced by leachates, domestic wastewater, and reclaimed water. The experiments were carried out with a 1:1 soil:water ratio (50 g of soil and 50 mL of solution), using loam and sandy loam soils. Key parameters were monitored for 30 days: electrical conductivity (EC), pH, concentration of chloride (Cl-) and nitrate (NO3-). At the end of the experiment, cations, anions, and trace metals were analyzed. The results showed that EC varied significantly according to the water source and soil type, with initial increases in leachates and reclaimed waters, followed by stabilization or decrease, thus suggesting soil ion adsorption and/or salts' precipitation. The initial pH drop is due to the microbial degradation of the organic dissolved solids in anaerobic conditions, then the subsequential increase of pH is due to the degradation of the organic acidic intermediates.NO_3^- showed an initial increase attributable to its release from the soils based on biotic and/or abiotic factors. Then, it showed a progressive decrease, likely due to microbial denitrification. Inversely, Cl- remained stable showing slight variations. These results are crucial to underline the strengths and weaknesses of using treated wastewater as fertigation water giving interesting insights about its interaction with soil. This study is pivotal for designing future experiments in mesocosms, macrocosms, and open field applications.

Surface mountain-front recharge promotes nitrate transfer from streams to groundwater in the Franciacorta area (N Italy)

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High groundwater nitrate concentrations are known to have adverse effects on human health. Nitrate concentrations close to or above the regulatory limit of 50 mg/L have previously been found in Franciacorta (Lombardy region, N Italy), which includes the moraine hills south of Lake Iseo, at the transition between the Alps and the Po Plain. The aim of this work is to understand the causes of these high nitrate concentrations in wells tapping the alluvial Po Plain aquifer in the piedmont area.

A one-year monitoring was performed collecting bi-monthly water samples from 5 mountain streams and six-monthly groundwater samples from 10 piedmont wells, 1 mountain well, and 1 mountain spring. In addition, rainwater samples were collected continuously during the same year. Tracers of recharge (water stable isotopes and Cl/Br ratio), major ions, and nitrate and boron stable isotopes were measured in the collected samples.

Ternary end-member mixing models based on δ2H in water and Cl/Br showed that piedmont wells are recharged by a) local precipitation, b) surface mountain-front recharge (sMFR) from Alpine streams and c) surface-water-irrigation. The nitrate-rich wells are mainly recharged by local precipitation and sMFR, with irrigation playing a minor role. sMFR represented between 10% and 50% of total recharge in these wells. The findings of a) high nitrate concentrations in streams (mean concentrations ranging between 14 and 28 mg/L) and b) a positive correlation between the percentage contribution of sMFR to recharge and the groundwater nitrate concentrations, together with c) a low nitrogen load in soils from agricultural activities, suggests that the groundwater nitrate pollution in the Franciacorta area is likely caused by the transfer of nitrate from streams to the piedmont aquifer by sMFR. Nitrate and boron isotopes revealed that the source of nitrate within streams is domestic sewage.

This work was funded by the European Union – Next Generation EU – PRIN 2022

Predicting discharge in complex karst aquifers through the ensemble smoother with multiple data assimilation: the case of Bossea aquifer.

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In a scenario of climate changes forecasting the availability of water from springs is desirable to prevent shortage in water supply to the connected utilities like aqueducts and irrigation systems. That is, it would be useful to know the "signature" response of the aquifer.

This work focuses on the application of the ensemble smoother with multiple data assimilation (ES-MDA) to build a hydrological model for flow rate prediction in a karst aquifer using the well-known instantaneous unit hydrograph method and the rational formula. The aquifer studied is the Bossea-Artesinera karst aquifer, located in northwest Italy in the Maritime Alps with an infiltration basin of around 6 km2. The input data are observed discharge flow rates, daily precipitations, and temperatures. Some of the challenges that have been addressed in this research are the modelling of infiltration as a time-varying infiltration coefficient, the classification of precipitation into snowfall and rainfall, and the transformation of snow into water equivalent infiltration. Others parameters of the hydrologic model such as base flow, infiltration coefficient, or snow melting contribution were estimated.

As first step, individual events were examined and the ES-MDA produced excellent results with values of Nash-Sutcliffe efficiency never below 0.9. Then on the basis of 27 such events, two average models were identified: one to be applied in spring months when the impact of snow melting is important and the other during autumn months. These average models used for predictions did not work as remarkably as the individually fitted models: fall model performances were better that those of the spring model suggesting that the snow equivalent calculation has to be improved, being the main difference between the two seasons. It is difficult to conclude whether a signature exist for Bossea, still it is clear that the ES-MDA is a powerful tool to investigate single event and give insights on the aquifer dynamics.

Influence of stratigraphic-structural setting on the yield of perched carbonate aquifers: Insights from the Monti Lattari Range, southern Italy.

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Karstified carbonate rocks constitute highly heterogeneous aquifers due to their stratigraphic and structural settings, and the presence of primary, secondary, and tertiary rock porosity with associated permeabilities. The heterogeneity of karstified carbonate aquifers also gives rise to perched aquifers, which represent a source of local water supply. The investigation concerns a sector of the Monti Lattari Range (Campania Region) where multiple levels of perched aquifers are located at high altitudes, in addition to a continuous and extensive basal groundwater system. This study aims to examine the origin and yield of these high-altitude groundwater circuits. Existing measurements and surveys, complemented by new investigations, were interpreted using the updated geological maps (CARG Project F 466-485, 2014). The different levels of perched aquifers in this carbonate hydrostructure appear to have various origins. Some springs, characterized by limited and highly variable flow rates (<1 L/s) and sometimes ephemeral nature, are attributable to high-altitude karst conduits. Perched aquifers with higher groundwater yields (up to 8 L/s per km 2) result from the overthrust of two carbonate tectonic units that comprise this sector of the Monti Lattari Range. In these cases, the leakage rate of the perched aquifers depends both on the degree of fracturing along the overthrust plane and the presence of siliciclastic lenses between the two tectonic units. Other high-altitude springs are associated with a marl layer within the Cretaceous Limestone. The flow rate and variability of these springs depend on the continuity of the marl aquitard, or its disruption due to late Pliocene-Pleistocene tectonic phases. Interpretating hydrogeological data in light of new geological knowledge of the area has allowed for a better definition of high-altitude groundwater.

Experimental investigations of the effect of biofilm growth on heat transport in fractured media

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The Heat transport in the subsurface is a very important process not only in the geothermal systems but also in industrial applications and environmental protection. Heat transport can be influenced by several factors. For instance, the effect of physical and chemical processes are already partially discussed in the literature. Besides, the effects of biological processes on heat transport, such as biofilm growth, are still unclear. In geothermal systems, fracture networks provide preferential pathways due to their lower hydraulic resistance compared to the host rock and transport most of the thermal energy. It is well known that in fractured media local thermal non-equilibrium phenomena may accur, and heat transfer between the fluid flow in the fractures and the surrounded host rock must be described explicitly. In this context, an experimental laboratory setup has been developed to study the effect of biofilm growth on heat transport in fractured media. The experimental setup comprises a block of fractured limestone of parallelepiped shape (0.08 m x 0.040 m x 0.060 m) crossed by 14 fractures, saturated with groundwater coming from the industrial area of Bari. The work contributes to the advancement of knowledge on biogeochemical dynamics in fractured aquifers subject to thermal stress, improving the prediction of temperature distribution in geothermal systems and enabling a more sustainable design and management of such systems.

The quantitative monitoring network of groundwater bodies within the Southern Apennine River Basin District. A comparison between past and present

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The implementation of the Water Framework Directive (2000/60/CE) and the Groundwater Framework Directive (2006/118/CE) aims to achieve a good environmental status of water bodies, both in chemical and quantitative terms, in order to ensure their sustainable management. The member states of the European Union carry out the status assessment by setting up monitoring networks and programmes. According to the European Directives, the Southern Apennines River Basin District Authority has identified the enhancement and standardisation of wells and springs monitoring systems as one of the priority measures to be undertaken to update the Water Management Plan. Groundwater monitoring is of primary importance for the Mediterranean region, a critical area for climate change, as decreasing effective rainfall and the increasing frequency and severity of droughts have been observed over recent decades. A robust assessment of the climatic effects on groundwater flow systems is necessary to evaluate the resilience of aquifers to climate change, and only a comparison between historical and contemporary detailed monitoring programmes can achieve this goal. The results of the most detailed hydrogeological monitoring of springs ever performed in Italy, organized in the regional-based monographs Le Sorgenti Italiane (conducted by the National Hydrographic Service between the 1920s and 1960s), have been compared, after a spring-by-spring matching, with contemporary field surveys and tests of drinking water supply springs. Preliminary findings, concerning the Calabria and Basilicata Regions, reveal a non-homogeneous decline in groundwater discharge, related to the lithology of the aquifer and geographic location, while some springs still maintain a significant flow. This highlights the urgent need for the implementation of discharge monitoring networks to support early warning systems and drought mitigation strategies.

Assessment of the Ag-MAR potential of rice flooding practices through a groundwater flow model in the Piedmont–Lombardy rice basin in Northern Italy

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Agricultural managed aquifer recharge (Ag-MAR) techniques involve intentional enhancement of groundwater recharge through agricultural practices to increase water availability in aquifers which can be used to support irrigation. Successful implementation of Ag-MAR requires thorough hydrogeological understanding and can be supported by mathematical models to quantify infiltrated volumes and to evaluate aquifer contamination risks. Ag-MAR could be relevant for long-term sustainability of rice production in the Piedmont–Lombardy regions, where 92% of the national rice production is concentrated. Our study focuses on the Lomellina area (1250 km2), a sub-region of the Piedmont–Lombardy rice basin, bordered by the Sesia, Po and Ticino rivers. This region is an alluvial plain with flat topography (elevations between 52–133 m asl), where the phreatic aquifer is very shallow and crucial for rice production. Recently, groundwater levels are declining due to changes in climate and rice irrigation management, and the question is whether Ag-MAR can reverse this trend. In this study, to estimate the recharge from the agricultural area and the extensive irrigation channel network, a modeling framework based on a semi-distributed application of the SWAP model (https://www.swap.alterra.nl/) was implemented in QGIS and completed with a simple model simulating the percolation from the irrigation network. Then, MODFLOW-6 was used to develop a transient model which includes surface recharge and the main natural and artificial streams and canals exchanging water with the aquifer. The groundwater flow model was calibrated using groundwater level time series from 22 monitoring wells in the study area. This study was carried out in the context of the PROMEDRICE project (https://promedrice.org/; PRIMA-Section2–2022) funded, for the Italian partners, by MUR (Italian Ministry of University and Research).

Factors controlling the distribution and dynamics of high-altitude springs in the karst system of Asiago plateau (NE Italy)

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Karst mountain plateaus are characterized by unique landscapes, but they face significant challenges due to water scarcity particularly during peak tourism seasons. Despite their importance, mountain systems remain poorly understood and this makes difficult planning new water supply solutions.

In this context, multidisciplinary investigations were performed in the Asiago Plateau (Eastern Alps, IT) to gain a comprehensive insight of the factors controlling the distribution and the dynamics of mountain springs in carbonate rocks.

Geophysical and structural analyses indicate the presence of a conjugate system of sub-vertical strike-slip faults (NW-SE and NNE-SSW) with an associated fracture network predominantly oriented ~N-S. The strike-slip faults have 10-20 cm thick cataclastic fault cores that, in some cases, impede groundwater flow. This complex fault setting gives rise to 23 small springs along Val Renzola Valley (1230÷1490m asl). These springs have a total flow rate ranging from 10 to 25 l/s and their regime shows a strong correlation with precipitation, indicating rapid circuits and high hydraulic transmissivity, likely imparted by high degree of fracturing. Chemical and isotopic analysis reveal that the groundwater primarily circulates within the Dolomia Principale Fm. and that the recharge area is located on nearby reliefs (mean recharge altitude ~1700 m asl). Several of these springs flow out along the major fault zones, highlighting the strong structural control on groundwater flow in the area.

Thus, preliminary results suggest that the conjugate system of strike-slip fault, together with their associated fracture network, may permit the formation of a substantial perched aquifer. This system is characterized by strong compartmentalization which results in distinct hydrogeological-geochemical dynamics within each compartment. Further investigations will be conducted to assess the potential of this aquifer as a supplementary water supply for the Asiago Plate

Sustainable groundwater management in a local transboundary karst aquifer using a multiscale approach

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Transboundary aquifers (TBAs) are large groundwater basins that cross national administrative boundaries and involve two or more states (IGRAC, 2021). Their sustainable groundwater management is an important challenge that requires coordinated and collaborative efforts between neighbouring countries and institutions. In Italy, water management is based on administrative/hydrographic and non-hydrogeological boundaries involving numerous regional (RTBAs) and local transboundary aquifers (LTBAs).

The Avella karst aquifer (southern Italy), extending 370 km2, was selected as a representative case study of LTBA for the southern Apennines, whose hydrogeological boundaries cross the administrative borders of all five provinces of the Campania region. Its water balance is increasingly threatened by prolonged periods of drought and the uncontrolled growth of groundwater abstraction for different uses (drinking, irrigation, domestic and industrial) by numerous water managers, companies and individuals (Petrone et al., 2024). A multiscale recharge estimation was performed using the soil water balance code for the period 2010-2021 (Westenbroek et al., 2010). At the aquifer scale, the average recharge is 244.40 Mm3/y, with an interannual variability of about ⊚45% and +73%. At the basin scale, the average recharge varies between 29.64 Mm3/y and 100.28 Mm3/y. A first inventory of springs and a registry of authorized wells were implemented to validate the water balance and assess the sustainability of current water withdrawals. At the aquifer scale, the outgoing groundwater volume is 252.30 Mm3/y, while at the basin scale, between 6.30 Mm3/y and 97.76 Mm3/y, exceeding the recharge in some basins. These results highlight significant groundwater stress, which is projected to worsen in the future due to climate change. They demonstrate the urgent need to adopt sustainable groundwater management strategies and reform existing water governance models in the Campania region and elsewhere.

Hydrochemical and isotopic study of recharge area of an alpine spring: the Montellina Spring case study (Piedmont, NW Italy)

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This study aims to evaluate the groundwater flow pathways in an alpine basin feeding a spring characterized by a high discharge (between 50 and 180 L/s).

The Montellina Spring, placed at 380 m a.s.l. and 100 m up the valley floor of the Aosta Valley, feeds the local water supply system and it is one of the drinkable water springs with highest discharge in the Turin Metropolitan City. The Renanchio Stream Basin (RSB), on the right of the main valley, in which the Montellina spring is located, shows peaks with an average altitude of 2000 m a.s.l.

Spring is fed by aquifers comprising fissured eclogite bedrock with thin layers of dolomitic marble and thick covers of glacial sediments; moreover, RSB is involved by deep-seated gravitational slope deformations (DSGSD) phenomena.

Precipitation, surface water and groundwater were sampled along the RSB in three different seasons (autumn 2017-winter 2017/2018-spring 2018), at different altitudes (from 380 m to 1460 m a.s.l.).

Chemical analyses of major ions revealed a bicarbonate alkaline-earth facies. Water stable isotopes (δ18O and δ2H) were also analysed. Waters referred to Montellina Spring, compared to the Renanchio Stream and its tributaries, are mostly enriched in major ions (especially Mg++, Ca++ and HCO3- due to the dissolution of bicarbonate minerals). Higher major ions concentrations and similar isotopic content indicate a significant circulation in the bedrock and in the glacial sediments.

Finally, chemical and isotopic data indicated that: i) the spring recharge area is located about 1500 m a.s.l.; ii) the spring is partly supplied by precipitation and inflow from the Renanchio Stream; iii) the DSGSD and glacial sediments, which also fill a buried and abandoned glacial incision, play a key role in the Montellina Spring recharge.

Highlighting the hydrogeological setting of the Renanchio Stream Basin can provide a new tool to safeguarding water resources in this alpine context.

Assessing groundwater storage in the plain area of Metropolitan City of Turin (NW Italy) to evaluate water supply resilience

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The resilience of drinking water supply and distribution systems has become a key aspect of climate change (CC) adaptation. For this reason, the national authority for network services (ARERA) has recently defined a set of indicators for the quality of water service.

The aim of this study is to propose a methodology to estimate the movable groundwater (GW) stored in the subsurface. The method was applied in a case-study focused on the plain area of Turin, which is characterized by a shallow aquifer hosted in a fluvial complex, overlying a fluvial-lacustrine and marine complex containing deep confined/semiconfined aquifers.

The volumes of these two main aquifers were estimated identifying the following boundaries, from top to bottom: the water table of the shallow aquifer; the base of the shallow aquifer, corresponding to the boundary between shallow and deep aquifers; and the interpolated surface of the bottom of the SMAT active wells. The volume of each aquifer system was estimated using QGIS 3.34 by discretizing the area into square cells (250 x 250 m) and calculating the elevation of each layer. The volume of movable GW was estimated considering the permeable fraction of each layer, considering the variability of aquifers granulometry at different depths. Based on literature values of effective porosity, the volume of movable (and, hence, effectively available) GW was estimated to be in the range 3.84 – 11.52 km3 for the shallow aquifer and 8.78 – 26.35 km3 for the deep aquifers.

Moreover, the trends in the GW level of the shallow aquifer were analyzed to assess the impact of CC on the estimated GW stock. This study allowed a simple, yet rigorous evaluation of available GW volumes.

Funding:

Research contract “Determinazione della capacità di accumulo dei corpi idrici sotterranei al fine di valutare la resilienza idrica di SMAT in accordo all’introduzione del nuovo macro-indicatore di qualità tecnica M0 introdotto da ARERA” between DST-UniTo,DIATI-PoliTo and SMAT.

Interaction between large lakes and multilayer aquifers: a multidisciplinary study on Garda Lake

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Understanding how large lakes interact with multilayer aquifers is crucial for managing water resources, especially where groundwater and surface water are closely connected. These interactions, found in many regions worldwide, are shaped by complex geological formations and dynamic groundwater flows. Investigating them requires a multidisciplinary approach that integrates (i) detailed 3D geological modeling, (ii) hydraulic characterization of the subsurface, and (iii) natural tracers to track water (and groundwater) movements and refine hydrogeological processes. This study examines the connection between Garda Lake and the surrounding Prealps and moraine-alluvial aquifers, a essential water reservoir for northern Italy. Spanning the provinces of Brescia, Mantova, and Verona, this area plays a key role in recharging the Po Basin aquifer system, making groundwater monitoring and protection necessary. To explore these dynamics, a hydrogeological conceptual model has been developed using geological surveys, official maps, and water well stratigraphy, supported by isotopic and microbiological tracer analysis. The results confirm a strong hydraulic link between the lake and aquifers. The moraine aquifer, composed of highly permeable sediments, is directly connected to the lake bottom and banks, allowing continuous water exchange. Below it, the alluvial multilayer aquifer, with alternating coarse and fine sediments, also interacts with the lake. These aquifers, in turn, connect to the fractured Prealps formations, forming a continuous hydrogeological system at the regional scale. By integrating geological, hydraulic, and tracer-based analyses, this study provides new insights into lake-aquifer interactions in complex settings. Beyond its relevance for the Po Plain, the approach offers a valuable framework for managing groundwater in similar regions worldwide, where lakes and aquifer plays fundamental function in the storage of this vital resource.

Spatiotemporal analysis and quantification of groundwater withdrawals in the Po basin: methodology and data homogenization within the "MidAS-Po" project

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Developing groundwater numerical models at basin scale is essential for sustainable water resource management but also challenging. Data collection is in fact often critical, as information is rather fragmented, inconsistent, or incomplete due to the different administrative and geological character of different sub-areas within the basin. As part of the project Modello idrogeologico delle Acque Sotterranee del distretto idrografico del fiume Po (MidAS-Po), coordinated by Autorità di Bacino Distrettuale del Fiume Po, which aims at developing a groundwater numerical model of the Po Plain, a methodology to quantify and spatialize all the groundwater withdrawals was adopted. Data provided by Environmental Agencies, Regional authorities and Water Suppliers have been gathered, resulting heterogeneous and incomplete for modelling purposes. A gap filling procedure was thus developed to homogenize and integrate incomplete data: a) missing coordinates (14% of wells) were assigned by randomly spatializing these wells within their municipality based on well type (e.g., industrial, irrigation) and land use; b) missing screen positions (81% of wells) were inferred as elevations from the closest well of the same type or as model layers if the exploited aquifer was known; c) missing well elevations (21% of wells) were determined by extracting the corresponding DTM value; d) missing flow rates (73% conceded + 13% unknown), were respectively filled using the conceded data modulated with a type-specific coefficient derived from the ratio of the conceded to the measured, when both of them are available, and with the average calculated by use type. The gap filling procedure was pivotal to create the first homogenized dataset of groundwater withdrawals for the entire Po plain, including 158000 wells divided into 14 typologies. These results evidence how homogenizing data collection among different institutions could aid the realization of basin-scale groundwater models.

Multidisciplinary hydrogeological reconstruction of carbonate thermal aquifer (Daruvar, Croatia)

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Thermal springs with water temperature up to 50 °C occur in the town of Daruvar feeding the local spa and tourism industry. This research detailed the geological subsurface reconstruction and the hydrogeological parameterization of the thermal aquifer through multidisciplinary investigations. Geological and geophysical investigations highlighted that the Triassic carbonate aquifer is deformed by a fault system cogenetic with the regional Daruvar anticline. The extensional relaxation in the anticline hinge zone increases the local permeability field. The hydrogeological parametrization was conducted through: i) pumping tests and well logging in a 190 m deep well, and ii) structural and photogrammetric analyses in an outcrop analog of the aquifer. Hydrogeological investigations quantified porosity of 0.03-9.1 % and permeability of 7.4-122.8 D. Structural analyses in the outcrop analog depicted two dominant systems of discontinuities (241/65 and 296/75). Their geometrical parameters calculated through a photogrammetric reconstruction of the outcrop were used as input for a discrete fracture network model. Employing the average porosity value for model calibration, a fracture aperture value of 3 mm was obtained resulting in a permeability of 1.5×10^5 D. This high value was interpreted as connected to the porosity value used for calibration, which represents the total porosity. However, fluid flow and permeability are influenced by effective porosity, which is an order of magnitude lower than the total porosity in carbonate aquifers. This difference was accounted for by testing a porosity of 0.2 % obtaining a fracture aperture of 0.22 mm and permeability of 60.5 D, in the range of measured values. This research highlights the importance of an integrated approach to characterize a fractured thermal aquifer for its sustainable exploitation.

Acknowledgment: This research was funded by the HyTheC project of the Croatian Science Foundation, grant number UIP-2019-04-1218.

The use of groundwater dating and isotopic analysis to characterize a coastal aquifer affected by saline intrusion

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This study investigates the critical issue of salinity intrusion within the Muravera coastal plain aquifer, located in Sardinia (SW), Italy, through a comprehensive hydrogeological investigation. An integrated approach, combining groundwater dating techniques, multi-isotope analysis (including ^{3}H, He, CFCs, SF6, noble gases, Sr, and B), and traditional hydrogeological monitoring, was employed to delineate distinct recharge sources and groundwater flow paths. To mitigate errors associated with seawater mixing, age tracer and noble gas concentrations were calculated specifically for the freshwater fraction, utilizing estimated concentrations for the saltwater component of each sample. Freshwater component concentrations were derived through saltwater component estimations, and subsequent analysis using PANGA and TracerLPM software, assuming a bimodal mixing model, yielded noble gas-derived recharge parameters and mean freshwater ages, respectively. The combined tracer results revealed that several samples were influenced by a geogenic source of SF6 (potentially fluorite mineralization) and possible CFC contamination introduced during sampling. Furthermore, reliable $^{3}H/^{3}He$ ages could not be determined due to elevated terrigenic helium concentrations and/or apparent loss of tritiogenic ^{3}He for undetermined reasons. Despite these challenges, the age tracers still provided valuable insights. The study identified four distinct recharge sources, including the previously uncharacterized Flumini Uri River, which was found to be a significant contributor. Analysis of the premodern seawater component revealed a high terrigenic helium-4 concentration, exceeding 4×10^{-7} ccSTP/g, consistent with groundwater ages exceeding 1000 years, indicating extensive mixing with modern freshwater. These findings offer crucial information for developing sustainable water resource management strategies within this vulnerable coastal aquifer.

Interference between geothermal systems in urban areas: a numerically based tool for sustainable city-scale development

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Shallow geothermal energy is a low-carbon and energy-efficient solution for heating and cooling buildings in urban areas, contributing significantly to the transition toward sustainable cities.

However, the shallow geothermal potential relies on the amount of heat that can be transferred to and from the ground which, in densely built environments, might be restricted due to competing applications. Hence, the maximum thermal power and the total extractable energy are directly influenced by the spatial density of geothermal installations and their respective operational regimes.

This study presents a comparative analysis of analytical and numerical approaches to quantify geothermal well interferences and develop a comprehensive feasibility assessment framework. The internal interference between extraction and reinjection wells (thermal short-circuiting) and the external interference from reinjection wells (thermal plumes) were numerically evaluated under diverse hydrogeological conditions and operational scenarios.

The comparison with analytical estimations, neglecting seasonal energy demand variations, and with the actual geothermal wells distribution in the city Milan city area highlighted the need for a quantitative tool to assess the available geothermal potential considering the interferences between systems. Hence, a machine learning-based surrogate model was trained on the numerical simulations to predict the space requirement for a dataset of geothermal wells active in the Milan city area. The proposed approach bridges the gap in evaluating the spatial footprint of shallow geothermal systems, supporting the sustainable development of new applications in urban areas.

Validation of a Machine Learning tool for preliminary quantification of the hydrogeological interference risk of tunnels.

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The hydrogeological connection between tunnel excavation and springs is a key aspect to be assessed during the preliminary design phase, both for environmental and socio-economic reasons. Based on a preliminary hydrogeological survey and environmental monitoring of the springs, the need to anticipate potential impacts at an early stage influences both the feasibility of the project and the design of mitigation measures in more critical areas.

A data-driven Machine Learning (ML) approach, designed to incorporate the complexity of the relationships between various physical and hydrogeological parameters contributing to the risk of spring impact due to tunneling, was calibrated using a dataset from detailed hydrogeological monitoring conducted alongside the excavation of two major tunnels in the Apennines (Italy), involving sedimentary and carbonate karst aquifers.

The approach shows good scores for model evaluation, and here we present the results of a further validation against datasets from two additional sites: one in the Alps (Brenner Base Tunnel, within a crystalline aquifer) and another in the Apennines (Bologna-Florence highway pass variant, within a turbiditic sedimentary setting). The application of the method to these new sites—one of which features a geological setting different from the original validation dataset— shows good scores again, demonstrating its potential for broader generalization.

The results were compared with those of the Drawdown Hazard Index (DHI), demonstrating that both methods can effectively identify risk while also highlighting the sensitivity of the latter. Specifically, by adjusting the various thresholds, highly accurate results can be achieved. Conversely, the ML models generate outputs that are not subject to modification or classification into discrete categories.

Isotopic composition of bottled mineral waters in the Mediterranean area

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As water moves through the water cycle the isotopic composition of hydrogen and oxygen reflects the hydrological cycle's natural processes and the isotopic ratio of fresh water varies substantially and systematically across the globe due to the spatially and temporally variable climatic patterns that govern the delivery of precipitated water to geographic regions.

In the frame of this research, 133 bottled water samples were collected from different countries in the Mediterranean region and analyzed in terms of chemistry and 18O and 2H isotopic composition. Also, data were collected from 138 IAEA-GNIP stations monitoring rainwater. The interpretation of the isotopic data available for the considered bottled waters proved to be a useful tool for better understanding the feeding source and the evolution processes of selected aquifers. It may also assist in determining the origin of the bottled water, the natural conditions of the parent water, and the production process that transports water from the capture zone to the bottle. These characteristics are a result of the fact that water isotopes may serve as tracers of water's ultimate source, reflecting the site of water evaporation rather than extraction. In addition, post-precipitation events, such as evaporation, can alter the isotopic signature of the source.

Hydrogeology of Skydra volcano-sedimentary multi-aquifer system (northern Greece)

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The aim of the present study is to define the conceptual hydrogeological model of a complex confined multi-aquifer system characterizing the volcano-sedimentary deposits of the Skydra area, northern Greece. In particular, the architecture of the hydrostratigraphic units, the hydraulic parameters and the hydrodynamic behaviour of the multi-aquifer system were analyzed.

The geological, geomorphological, and structural evolution affecting the area has influenced the geometric and hydraulic characteristics of the aquifer, and consequently its productivity. The thickness of the multi-aquifer system varies between 25.0 and 94.5 m and the hydraulic conductivity, calculated through the analysis of data from 72 pumping tests, and the application of empirical methods (42 wells), ranges between 2.2·10−6 and 2.5·10−3 m/s. Higher hydraulic conductivity values are calculated in areas where tuffaceous formations are fractured and/or interlayered with sandy layers; while lower values occur where tuffs present only primary porosity and are interspersed with frequent clay layers. Based on transmissivity and specific capacity values of the volcano-sedimentary multi-aquifer system, two potentiality classes could be distinguished, namely a) a dominant one (84% of the investigated sample) characterized by moderate productivity, and b) a statistically minor class (16%) showing high productivity. The latter, prevails in the northern sector of the study area. In the central area due to overexploitation of the aquifer, an annual piezometric level drop of approximately 6 m has been recorded.

The information acquired could serve as the basis for the sustainable development of groundwater resources in the test area and could also be applied in other similar hydrogeological settings.

Hydrogeological characterization of the complex hydrogeological system of the Brescia metropolitan area (N Italy) in the framework of Water Safety Plan

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The Water Safety Plan (WSP) is an integrated approach to ensuring drinking water quality, based on detailed risk assessment and management throughout the water supply chain. Mandated in Italy by Legislative Decree 18/2023, the WSP requires the identification of all processes affecting water quality, which for groundwater can be achieved by integrating hydrogeological, hydrodynamic, and hydrochemical data of the tapped aquifers. This study presents the hydrogeological characterization of the Brescia metropolitan area (N Italy) based on geological information, high-frequency water level measurements, and routine chemical monitoring data of 72 wells and 14 springs, provided by the water supplier A2A Ciclo Idrico SpA. By combining the results of a cluster analysis on major ions with the time series analysis of groundwater levels and the available hydrogeological cross-sections, 8 zones with different features were identified: 1) Central Val Trompia and 2) Nave valley, where recharge inputs mainly come from fractured bedrock and run-off; 3) Southern Val Trompia, with the same recharge processes as zones 1 and 2 but less vulnerable to anthropogenic impacts due to the local geology; 4) Northern Brescia, where the recharge comes mainly from the mountain karst system, the upgradient zones 2 and 3, and local infiltration, which determine a higher anthropic impact than northern areas; 5) Piedmont Area, showing intermediate conditions between mountain springs and plain area groundwater; 6) Western Plain Area, with different conditions from the rest of the plain due to differences in land use, recharge sources, and groundwater flow direction; 7) Central Plain Area, where the reduced water table depth and the recharge from upstream zones and local infiltrations determine the highest anthropic impact, and 8) Eastern Plain Area, where recharge is mainly due to excess irrigation water sourced from the Chiese River, with chemistry similar to zones at the mountain-plain interface.

Climate Change and Groundwater on Azores Islands

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On small oceanic islands such as the Azores, water resource management plans increasingly need to incorporate the effects of global climate change to accurately predict future water supplies for populations and agricultural activities, particularly farming.

The expected changes in temperature and precipitation on the Azores islands have important implications for all components of the island's hydrological cycle, altering the amount of evapotranspiration, surface runoff and infiltration into groundwater systems.

Groundwater is the only source of water supply on the Azores islands, with around 236,413 inhabitants (2021 census), 1,000,000 tourists per year and 2,000 km from the mainland, without the capacity to import large quantities of freshwater. The exploited aquifers are of the perched type, with a low storage capacity and flows with large seasonal variations, and basal with salinization problems due to marine intrusion.

This article discusses some effects of climate change on the groundwater of this island, especially in the basal aquifer, the likely main source of freshwater in the future on this island.

Rare Earth Elements as tracers of hydrogeochemical processes in Los Azufres geothermal field, Mexico

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Rare Earth Elements (REE) are promising tools for understanding hydrogeochemical processes in geothermal systems, although their application in high-temperature environments remains limited. This study assesses REE as tracers of water mixing, water–rock interaction, and water origin in the Los Azufres geothermal field in Mexico. This area has a large diversity of rocks (rhyolites, dacites, and andesites) and waters that vary from acidic to neutral environments, making it a complex system to study.

Ten spring samples and 4 solid samples (2 rocks, 1 soil, and 1 hydrothermal alteration crust) were analyzed. Scanning electron microscopy (EPMA and ESEM-EDS) and X-ray diffraction were used for mineralogical analysis, complemented by ionic chromatography, ICP-MS, and ICP-OES for chemical analysis. Updated databases adapted to hydrothermal environments and REE were used to perform the geochemical modeling using PHREEQC.

Significant variations in REE concentrations were detected in both water and rock samples, with the highest levels in sulfate-rich waters. The REE patterns of the springs have similar characteristics to the patterns of the aquifer rocks that contain them. Lanthanides (Ln) display a strong correlation with sulfate, Fe and Al, suggesting preferential transport as sulfate complexes ($Ln(SO_4)^+$), and possible coprecipitation with Fe/Al oxyhydroxides. Positive Eu anomalies in springs may indicate reducing conditions in deep waters, whereas negative Ce anomalies in cold springs point to oxidizing environments. Geochemical modeling highlighted a relationship between sulfate complexes under oxidizing/acidic conditions and free ions (Ln^{3+}) or chloride complexes under reducing/neutral pH conditions.

Overall, REE have shown to be effective hydrogeochemical tracers in Los Azufres, enhancing the understanding of complex geothermal systems and offering innovative tools for sustainable geothermal resource exploration and management in Mexico.

Defining boundary conditions and sink/source terms for the groundwater flow model of the Po River district (MidAS-PO project)

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This work presents the definition of boundary conditions and sink/source terms for the implementation of a large-scale groundwater flow numerical model supporting the definition of the groundwater budget for the Po River district.

The definition of boundary conditions required a detailed analysis of the available piezometric surfaces, distinguishing between shallow and deep aquifers. Various types of conditions were implemented, including specified head, specified flow, head-dependent flow, and no-flow conditions.

Regarding sink and source terms, we focused on main losing/gaining rivers, losing irrigation canals, and lowland springs (the so-called "fontanili"). The natural/highly modified river network was classified based on its interaction with aquifers, discretized into segments, and assigned geometric/hydraulic parameters from geomorphological/hydrographic analyses. Irrigation canals were selected based on the diverted flow rate, with seasonal loss estimates to reflect temporal variations. We modeled the fontanili as drainage elements with standardized geometric characteristics, in the absence of specific data.

We ran the entire process within the QGIS environment to maintain spatial consistency and to ensure data accuracy, producing .shp/.csv files for implementation in the FREEWAT-Q3 modeling platform, using MODFLOW-2005.

We produced data for building a model in a somehow “scarce data domain”, however a long-term data acquisition and archiving plan is needed for the development of a robust and widely accepted conceptual model, and to facilitate the creation of modeling datasets. This plan should aim to: a) improve the spatial distribution of the monitoring network and increase the frequency of hydrological parameter acquisition, b) establish an infrastructure for data storage/management at the district scale.

Acknowledgment

Modello idrogeologico delle Acque Sotterranee del distretto idrografico del fiume Po–MidAS-Po (Fondo per lo Sviluppo e la Coesione 2014-20

Assessing Alpine and Apennine mountain-front recharge to Po Plain alluvial aquifers: the AMBRA project

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A quantitative assessment of mountain-front recharge from Alpine and Apennine areas to Po Plain alluvial aquifers has often been overlooked in previous studies and is therefore addressed in this research project through the study of two pilot piedmont areas (Brescia and Bologna).

The recharge assessment is performed using 1) endmember mixing models based on conservative tracers of water (water stable isotopes) and salinity (Cl/Br ratio) and 2) water balance calculations based on discharge measurements of mountain rivers. A one-year monitoring of 41 wells tapping the alluvial piedmont aquifers, 17 mountain springs/wells, 11 mountain rivers/streams and 3 rainwater collecting stations was carried out.

Results showed that the sources of groundwater recharge vary in the different areas and sub-areas depending on the hydrogeological features and the land and water uses. More specifically, in the moraine of Lake Iseo in the Brescia area (Franciacorta), recharge is given by the mixing of 1) surface mountain-front recharge (sMFR) from minor streams coming from the moraine hills, 2) local (plain area) precipitations and 3) surface-water-irrigation return flow. In the piedmont urban area of Brescia recharge is due to 1) focused mountain-block recharge (fMBR) from the Alpine alluvial aquifer of Val Trompia, 2) diffuse mountain-block recharge (dMBR) from the karst Alpine aquifer and 3) sMFR from the Mella River. In the carbonate area of Carso Bresciano recharge is mainly due to 1) dMBR from the karst Alpine aquifer and 2) surface-water-irrigation return flow. Concerning the Apennine area of Bologna, the alluvial fan aquifers of the Reno, Savena and Idice Rivers are recharged by (1) sMFR from the rivers and (2) local precipitations. Recharge from MBR appears negligible in most cases. Mixing models also showed that a relevant source of water for pumping wells in Bologna is deep fossil groundwater.

This project was funded by the European Union – Next Generation EU – PRIN 2022

Hydrochemistry statistical analysis as support for the correct setup of hydrogeological model: A case study of the lower Magra Valley

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Protecting the quality of water bodies from human activities and climate change is a crucial issue. This study was conducted in the lower Magra Valley, along the northern Italian coast. The Magra River flows through the Apennine valleys and feeds an important coastal aquifer system. Since the late Miocene, the region has been subjected to an extensional tectonic regime that led to the development of the lower Magra graben. Upper Pleistocene and Holocene coarse sediments represent the Magra aquifer, carved into consolidated older Pleistocene sediments and rock formations. The aquifer is overexploited for drinking water purposes and is vulnerable to pollutants and seawater intrusion. The research aim is to validate the hydrogeological model using hydrochemistry statistical analysis for the implementation of groundwater protection measures. The hydrogeological model was reconstructed using more than 150 core logs and 15 geophysical surveys. A normal fault perpendicular to the Magra graben, divides the valley into two sectors with varying thicknesses of alluvial deposits. Northern (upper) sector is characterized by an unconfined aquifer, about 25 meters thick, while the south (lower) sector has two distinct aquifers. A layer composed of fine sediments divides a shallow and unconfined aquifer from a deep and confined aquifer. Subsequently, hydrochemical methods (PIPER), geostatistical techniques (PCA and HCA), and machine learning algorithms (SVM) have been employed. A database containing over 30’000 measurements of major and trace elements, collected from 2000 to the present, was analyzed. The water in the area was categorized into five clusters with different recharge sources. The hydrogeological model is validated by their spatial distribution. Finally, applying electrical conductivity and chemical data to the validated hydrogeological model we were able to identify areas vulnerable to seawater intrusion.

Flow and reactive transport modeling of a sandy aquifer subjected to agriculture in Eastern Netherland

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Evolution of groundwater chemistry is a natural phenomenon based on duration of contact, and the physical and chemical composition of subsurface geology. In addition, there are several pathways such as agriculture, waste disposal and leaching from urbanized area that triggers further enrichment of organic, inorganic, pharmaceuticals and emerging contaminant compounds in groundwater and make them unfit for usages. Therefore, avoiding contamination and improving the water resources are of utmost importance. Agriculture is a widespread practice in The Netherlands and their main irrigation water supply comes from surface water networks and shallow groundwater wells. An average of 1643 MCM of groundwater is abstracted every year for drinking and other purposes. The surplus rainfall helps to replenish both the surface water and groundwater resources. Despite the abundance of water resources in The Netherlands, intensive practices of farming has led to a complex nexus of surface water-groundwater interactions. The compounded effects of prolonged water usage and extreme climatic events, such as the drought in 2018 degrade the water quality and quantity in the region. The objective of the present study is to gain insight in recent groundwater contaminants through a numerical simulation of nitrate concentration in Baakse Beek Basin, in the eastern part of The Netherlands. The total area of Baakse Beek basin is 284 sq.km having a very dense surface water network. The terrain slopes gradually from southeast to northwest into the direction of IJssel River, with elevations varying from 5 to 40 meters above NAP. The model domain covers the entire Baakse Beek basin and thus the model domain area is 936 sq.km. The research is focussed vertically up to the depth of the first impermeable aquitard formation called the Breda formation. There are seventeen flat horizontal layers that reflect the physical, chemical, and depositional environments. The model domain is discretized into grid

The Simplified Separation Pumping Technique: a cost-effective system for multilevel groundwater sampling in fully screened monitoring wells

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Monitoring of long-term concentration trends at contaminated sites is often performed using fully screened monitoring wells because of their lower cost and a greater adaptability to other uses (e.g., pump and treat). However, monitoring data from long-screened wells flux integrate stratification and mix potentially incompatible chemistries. This may introduce random variability as these monitoring wells are not able to capture the vertical hydrochemical stratification that characterizes a contaminant plume.

To limit this loss of information, a new cost-effective sampling method for fully screened monitoring wells is proposed, called Simplified Separation Pumping Technique (SSPT). It involves the simultaneous use of a high-flow pump and a low-flow pump, operating at 10-15 L/min and 0.5 L/min, respectively. This creates a water divide near the low-flow pump, hydrodynamically reducing the screen length tapped by the low-flow pump, providing a depth-specific groundwater sample. Initially, the low-flow pump is placed one meter below the water table, and the high-flow pump one meter above the bottom of the piezometer. In this configuration the sample collected by the low-flow pump is representative of the first meter of aquifer below the water table. Then, by switching the two pumps, another sample can be collected, that effectively originates from the last meter of the screen length. Hence, this method provides information on the vertical concentration distribution.

To validate the SSPT, results for 22 monitored parameters (total hydrocarbons, BTEX, redox-sensitive species, field parameters) at 3 monitoring wells were compared with those obtained at the same depths using a packer system, considered a benchmark. The median percentage discrepancy between the concentrations obtained by the two methods at the same depths, among all wells and parameters, was 4.73%. This shows the comparability of the samples collected by both methods, demonstrating the validity of the SSPT.

Natural and anthropogenic factors affecting the hydrogeological variations of the Somma-Vesuvius volcanic aquifer (Southern Italy) in the last decades

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Groundwater in volcanic areas can be influenced by spatial and temporal hydrogeological variations due to natural and anthropogenic factors. In highly urbanized and active volcanic regions these variations are linked to changes in land use, pumping, recharge, deep hydrothermal fluids rise.

This study analyzes the factors influencing groundwater changes in the Somma-Vesuvius volcanic aquifer over the last decades. Hydrogeological trends have been evaluated by analyzing groundwater level variations from 1978 to 2022 estimating water balance, natural outflow, groundwater withdrawals and land-use changes.

Distinct trends were identified at the basin scale: from 1978 to 1994, piezometric levels decreased significantly with reductions of 9.90 m and 13.60 m for Somma and Vesuvius basins, respectively, mainly due to excessive water withdrawals; conversely, from 1994 to 2022 piezometric levels rise of 13.40 m in the Somma basin and 13.13 m in the Vesuvius basin attributed to reduce of pumping and deactivation of several drinking-water well fields.

The water balance estimates indicate a mean annual recharge of 0.54 m^3/s and 0.83 m^3/s for Somma and Vesuvius basins respectively. Changes detected in precipitation, actual evapotranspiration and recharge compared to previous balances highlight the impacts of land use and climate change at the decadal scale.

Groundwater withdrawals and natural outflow were estimated at 0.44 and 0.38 m^3/s for Somma basin, and 1.18 and 0.47 m^3/s for Vesuvius basin, respectively. Consequently, the Somma basin appears to have reached hydrogeological equilibrium, as indicated by rising piezometric levels, but the Vesuvius basin shows a water deficit of 0.35 m^3/s due to continued human pressure.

The results highlight the importance of continuous multi-parametric monitoring as a decision support tool for sustainable groundwater management and for distinguishing natural and anthropogenic influences, especially in surveillance of high-risk volcanic areas.

Assessing the effects of drought periods on the undeterred aquifer of Castelporziano Natural Reserve (Rome, Italy).

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The assessment of drought duration, severity, and its impact on groundwater resources can be achieved through the integrated analysis of climatic indices and groundwater level fluctuations. This study investigates the effects of drought periods on groundwater within distinct sectors of the Castelporziano Estate aquifer. Utilizing data from two meteorological stations and the Estate's piezometric monitoring network, a comprehensive analysis was conducted. The availability of extensive thermo-pluviometric and piezometric records (1995-2024) facilitated the computation of the Standardized Precipitation-Evapotranspiration Index (SPEI) and the Standardized Groundwater Index (SGI), enabling the evaluation of their variations over the past 30 years.

Prior research has established the presence of a main aquifer, exhibiting seasonal fluctuations primarily driven by local meteoric inputs, with base flow sustained by contributions from the regional aquifer. The Coastal and Central sectors, mainly recharged by local precipitation, show a different decline in piezometric levels. Comparative analysis of the SPEI calculated for two weather stations, one situated along the coast and the other in the inland sector of the Estate, revealed significant variations, which prove decisive in the recharge processes of these sectors. The Coastal sector exhibited a consistent pattern of alternating wet and dry periods until 2016, followed by a sustained drought period extending to 2023. These fluctuations are reflected in groundwater levels, as evidenced by the SGI, which has registered continuous negative values since 2016, reaching its minimum values in 2024. In the Central sector, the SPEI indicates a protracted drought from 1999 to 2008, resulting in a persistent reduction of piezometric heads. Consistent negative SGI values since 2008 corroborate the enduring water deficit in this sector, with a discernible exacerbation observed in the last three years, correlating with the SPEI trend.

Application and comparison of traditional and modified DRASTIC methods for assessing nitrate groundwater vulnerability in the Arborea coastal plain (Sardinia, Italy)

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Non-point-source nitrate contamination of agricultural origin represents one of the most widespread forms of groundwater pollution, and within the current framework of climatic changes and water scarcity especially in the mediterranean area, the safeguarding of both surface water and groundwater resources constitutes a topic of paramount importance. The Arborea plain, located in the central-western coast of Sardinia (Italy), is an intensive farming district based on dairy production and agricultural activities. This plain, formerly an unhealthy swamp, was reclaimed in the 1920s, and a complex network of drainage channels and pumping stations were constructed to lower the piezometric level and intercept runoff waters. Since 2005 it is classified as a Nitrate Vulnerable Zone (ZVN - 91/676/CEE) because of the high nitrate concentration in groundwater caused by excessive fertilization and manure production (Biddau et al., 2019). According to the hydrogeological model of the coastal plain, a phreatic multi-layer aquifer is hosted within the Holocene littoral sands superimposed to a deeper alluvial aquifer hosted in Pleistocene continental deposits. The aquifers are separated by a thick silty clay layer quite continuous northward but locally connected in the southern part of the plain because of the gradual thinning of the clay lenses (Ghiglieri et al., 2016). This study was conducted with the objective of evaluating the specific nitrate vulnerability of the hydrogeological system under study and to assess the risk of nitrate contamination through the application of rating methods. Specifically, the traditional DRASTIC method and the DRASTIC-PAN method (Kazakis and Voudouris, 2015) designed for the evaluation of nitrate contamination in porous aquifers, were selected and implemented. The results of this study will allow a detailed assessment of the status of the aquifer and will provide new insights for refining the agricultural practices and targeted mitigation actions.

Estimating Geothermal Exchange Efficiency: Enhancing Geothermal Energy Extraction through Laboratory and Numerical Modeling

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Geothermal exchange efficiency in porous media is crucial for optimising borehole heat exchangers (BHEs). However, assessing heat transport remains challenging due to the complex interplay of variables like geological factors, porosity and porous structure, water content and degree of saturation, and flow velocity. Thermal conductivity is fundamental in determining the efficiency of geothermal systems such as BHEs, as it directly affects the amount of energy that can be extracted/delivered from the subsurface, and the presence of groundwater flow significantly enhances this potential due to advective transport. This study aims to investigate the impact of advection, the dominant heat transfer mechanism in aquifer-influenced systems, on geothermal exchange. It was combined modified Thermal Response Tests (TRTs) with warm water injection with Finite Element Method (FEM) numerical modeling to analyse hydraulic and thermal properties under controlled conditions. By comparing results from both Infinite Line Source (ILS, conduction-dominated) and Moving Infinite Line Source (MILS, conduction-advection dominated) models, was developed theoretical nomograms to estimate both apparent thermal conductivity and groundwater flow velocity. These nomograms provide a novel tool for characterizing heat exchange in high-flow environments, enabling improved design and optimization of BHEs for enhanced geothermal energy extraction.

Merging hydrogeological and geophysical integrated approaches to optimal detection of submarine groundwater outflow

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The growing gap between water availability and strong demand, including risks of severe droughts, are leading to increased efforts to make the best use of the large quantities of water that coastal aquifers discharge into the sea, or to search for offshore resources.

The hydrogeological potential and economic factors linked to the coastal groundwater are the starting point of the two-year Italian Research Project of National Relevance (PRIN-2022) SUBGEO (funded by the EU-NextGeneration, Mission 4, Component 2, INVESTMENT 1.1, CUP H53D23011270001) where the University of Bari (UNIBA) and the two Institutes (IMAA and IRPI) of the National Research Council are involved. The project purses an innovative and integrated geophysical approach based on the use of electrical and electromagnetic methods, with the dual objective of non-invasively characterising the coastal underground freshwater reservoirs and obtaining useful management tools.

This study describes the hydrogeological research carried out to select the optimal site to apply the integrated geophysical approach, and the efforts to validate this choice by assessing the amount of discharge. The numerical modelling was based on a large dataset of hydrogeological data and water balance. A systematic literature review was conducted to synthesise geological, hydrological and hydrogeological data relevant to coastal aquifers, seawater intrusion and subsurface heterogeneity. Based on this review, a test site in Apulia was selected, characterised by stratified Holocene sands, Pleistocene calcarenites and Cretaceous limestones. The region's karstified and fractured formations create highly permeable pathways that facilitate rapid groundwater movement, making it an ideal case study for evaluating geophysical methods. To enhance the robustness of the analysis, a multi-source dataset was implemented and processed using a density-dependent 3D numerical modelling approach (MODFLOW-SEAWAT).

Assessment of Groundwater Quality for Drinking Purposes Using a Water Quality Index (WQI) and Multivariate Statistical Analysis: A Case Study in Seriana Region, Batna Province, Algeria

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Groundwater is widely regarded as a safe and reliable drinking water source in many regions of Africa. However, human pressures have led to its quality deterioration and degradation. This study evaluates groundwater suitability for human consumption in a semi-arid region using a Water Quality Index (WQI) and applies multivariate statistical analysis to identify key hydrogeochemical processes.

The area of interest is the Seriana region (Batna Province, Algeria), an inner alluvial plain, constituted of Quaternary aeolian-alluvial deposits. The plain is surrounded by Cretaceous and Jurassic limestones and dolostones of the Saharan Atlas. Sabkhas and salty deposits are widely present in the plain. Water samples were collected from twelve wells in June 2019, and their physicochemical parameters were analysed. The measured parameters are generally below the threshold values set by the World Health Organization for drinking water quality. Exceptions are observed for Ca2+, Mg2+, Na+, K+, HCO3–, Cl–, SO42–. These parameters exceed the thresholds in 10, 12, 1, 1, 9, 3, and 1 sample(s), respectively. Three hydrochemical facies are identified: mixed cations, Mg-HCO3 and Na-Cl. Samples are classified into three water quality classes based on WQI: good (5/12), poor (6/12) and very poor (1/12) quality. Rock-water interaction, mainly dominated by Mg2+ and SO42– and secondarily by Ca2+ and HCO3–, and evaporation processes or evaporites dissolution, dominated by Na+ and Cl–, are the main hydrogeochemical processes. Nitrates affect groundwater quality, despite concentrations below the drinking-water guideline value.

In conclusion, over half of the groundwater in the region is of poor quality and unfit for human consumption without treatment, presenting potential health hazards. We recommend treating groundwater at the household or community reservoir level before distribution, alongside organising public health awareness campaigns to promote the use of proper sanitation technologies.

Comparison of electrical resistivity tomography and frequency domain electromagnetic methods for mapping seawater intrusion in shallow aquifers

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Seawater intrusion into coastal aquifers is a growing global concern, driven by climate change, sea-level rise, and intensive groundwater exploitation. Effective assessment and monitoring strategies are crucial for sustainable water resource management. Traditional hydrogeological investigations, such as borehole measurements, provide point-source data but lack the spatial resolution necessary for comprehensive regional assessments. Geophysical techniques, in particular Electrical Resistivity Tomography (ERT) and Frequency Domain Electromagnetics (FDEM), offer non-invasive alternatives with distinct advantages and limitations.

This study presents a comparative evaluation of ERT and FDEM techniques for mapping shallow seawater intrusion at four test sites along the northern coastal margin of Friuli Venezia Giulia, Italy, each with different salinity levels, lithological conditions, and seasonal variations. ERT surveys provided high-resolution subsurface conductivity data, used as the reference dataset. The FDEM measurements were carried out using two different instruments: a multi-depth, constant-frequency system and a single-offset, multi-frequency system, both of which allow rapid and extensive data acquisition.

To ensure robust comparability, FDEM-derived apparent electrical conductivity (ECa) values were normalized against ERT-derived conductivity data. The results indicate that, despite its rapid acquisition capabilities, FDEM can provide reliable estimates of subsurface conductivity without site-specific calibration, using appropriate data normalization techniques.

This research underscores the potential of FDEM as a cost-effective and scalable solution for monitoring seawater intrusion, providing valuable insights into groundwater salinization dynamics and advancing methodologies for large-scale environmental and water resource management.

Hydrogeological Assessment of an Aggregate Mining Area in the Danube Alluvial Plain, Hungary

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In the last three decades, Hungary has undergone significant infrastructural development, especially around Budapest, which puts great pressure on nearby agglomerate reserves, including the excellent sand and gravel resources of the Danube Alluvial Plain, south of Budapest.

The surface mining of aggregates has led to an increasing number of open pit lakes in the region, with mining activities intensifying considerably in the 21st century. Meanwhile, the substantial decline in groundwater levels in the Danube-Tisza Interfluve (east of the area) has raised serious concerns. It is suspected that one of the contributing factors may be the enhanced evaporation of groundwater through the water surface of the open pit lakes. To assess the impact of aggregate mining, a comprehensive study was initiated in the area.

A geological model was developed, and appropriate hydrostratigraphic units were identified for the area using well log and facies correlation. The (near) natural hydrogeological conditions of the area were investigated by analysing archive water level and water chemistry data in 3D, constructing distribution maps and cross sections. Temporal changes were examined through time series analysis of shallow groundwater levels and by conducting sampling campaigns of groundwater and surface water to measure both main and trace elements.

These analyses and their results form the basis for building a conceptual model and help in assessing the impact of mining through numerical modelling. The water balance of Hungary is negatively affected by climate change therefore the sustainable management of surface water and groundwater is becoming increasingly important, which highlights the significance of this research.

The contribution of river infiltration to the recharge of the Northern-Apennine alluvial fan aquifers: the pilot case of the Reno, Savena, and Idice Rivers

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The Po Valley is the largest alluvial basin in Italy, supplying 87% of the drinking water demand from its underlying aquifers. In the Emilia-Romagna Region, which occupies the southern portion of the Po basin, 70% of the groundwater is extracted from aquifers hosted within the Northern Apennine foothill alluvial fans. These aquifers are primarily recharged by local precipitation and streambed infiltration, though the relative contributions of these sources remain poorly defined.

To address this knowledge gap, we studied a pilot area encompassing three alluvial fans formed by the Reno, Savena, and Idice Rivers in the Metropolitan City of Bologna.

Streambed infiltration was assessed through differential flow measurements taken every two months over the course of a year. These measurements revealed a linear relationship between infiltration and river discharge, a pattern consistent across all three rivers. This relationship allowed us to estimate the total annual volume of streambed infiltration for each alluvial fan and for the entire pilot area. When compared with estimated vertical recharge, the results clearly indicate that river infiltration is the dominant recharge mechanism.

Surface water (rainfall and rivers) and groundwater (production wells and piezometers in the fan aquifers) were sampled and analyzed using end-member mixing models, confirming the relative recharge contributions of precipitation and streambed infiltration. The analysis also revealed a significant decline in river recharge with increasing distance from the streambed. Additionally, it highlighted a substantial intra-basin contribution of deep fossil groundwater to the pumping wells, despite the total annual recharge volume exceeding the groundwater extraction in the pilot area.

This work was funded by the European Union – Next Generation EU – PRIN 2022.

Idrogeochemical assessment of groundwater resources under a growing urbanization in Douala Cameroon

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The groundwater is the main water resource in Douala for most households leading to constant stress and vulnerability of the resources. Developing the hydrogeochemical to assess the impact of the land use dynamics in relation to its characteristics and highlight the potential recharge areas that constitute the protected resources are thus essential. The hydrochemical parameters indicated that for the groundwater does not exceed WHO standards except nitrate for streams and springs whose mean values are above the threshold. This could be explained by the morphological variation in the study area where the flow direction is from the NE to SW. the numerous watercourses are thus making the amin collectors. The centre of the city, which consists of mostly popular and populous neighbourhoods, is characterized by much more acidic groundwater (pH < 7) than on the outskirts. The waters in the study area are mainly chlorinated with a dominant Na-Cl facies, not necessarily due to any pollution, but is derived from the various ion and anionic exchanges. The dynamics of land use reveals a significant increase (68%) in urbanization from 1990 to 2023. It should be noted that the infiltration of water into the locality will become increasingly difficult because it is conditioned in large part by growing urbanization. The water quality in the study area is currently good for consumption and irrigation.

The role of hydrogeochemistry and isotopes in understanding the karstic system in Budapest and its surroundings

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As part of a complex geological-hydrogeological survey, the karst system in Budapest and its surroundings has been investigated including its hydrogeochemical and isotopic characterisation. Additionally, the aim of this work was to support the 3D hydrodynamic flow and heat transport modelling by interpreted hydrogeochemical data which could be used for the verification of the models.

This karst system is characterised by the presence of different flow systems, from local to regional and with hypogenic karst developments shaped by discharging thermal karst waters. Based on major chemical parameters and outflowing water temperature we could distinguish two main clusters. Wells and springs mainly west of the Danube (Western group), contain mainly CaMgHCO3 type waters, with higher sulphate concentrations in the south. Wells and springs along the Danube and to the east (Eastern group), have higher water temperatures and TDS, and in some cases higher sodium and chloride concentrations, which show the presence of regional flow systems. The Western group could be further divided into 4, while the Eastern group into 6 subclusters.

Based on stable oxygen and hydrogen isotope data the karst water is mainly of meteoritic origin, although a very small brackish or seawater component cannot be excluded. Based on radiocarbon data the residence times of these karst waters are at least 20 to 30 ka. The thermal component is of Pleistocene origin, while the cold karst waters infiltrated during the Holocene. Some of the springs and wells contain detectable tritium, showing that these waters contain a modern precipitation component detected in the cold karst waters and in the discharge zones.

Analysis of groundwater samples from a recently finished campaign including a wide range of stable and natural radioactive isotopes will contribute to a better characterization of these karst waters enabling a better understanding of their mixing in the discharge zones.

Numerical modelling for sustainable mine water management

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There is currently no standardized approach to the numerical modelling of groundwater flow in the mining environment. Generally, three approaches are used: the equivalent porous media (EPM), which considers the rock mass and its discontinuities as a continuous, the discrete fracture network (DFN) that relates to the hydraulic characteristics of discontinuity, natural and/or anthropic of the rock mass, and the hybrid, a combination of the two approaches. To evaluate the best approach, a selected mine located in the Metalliferous Hills (Colline Metallifere; GR), in the Tuscany region, Italy, is used as case study. The mine is part of a complex of five, joined by a level at -200 m asl. It was active until 1981 and it was mined for pyrite extraction. From the closure data, natural and managed flooding events occurred to the actual level of -95 m asl. The choice of this specific mine as case study is related to the availability of enough data that cover a period of almost 100 years, from around 1920 to 2024. A three-dimensional numerical model, with the hybrid approach, was realized in FEFLOW 7.01, to simulate the progressive mine flooding, in transient state, occurred between 1995 and 2010. In this simulation, the rock mass is represented as EPM and it is composed by 31 slices, each with 33924 nodes. Faults and mining infrastructure, like tunnels, shafts, and wells, are represented as discrete elements. In the future, starting from the data obtained from the calibrated model, a forecast simulation will be realized to reproduce the effects of the level rise to +70 m asl, where a drainage tunnel will allow water to flow out by gravity.

Hydrogeological reconstruction of Baranja region (NE Croatia) as a key input for sustainable water management

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Preserving the chemical and quantitative status of a groundwater resource requires a detailed management plan based on the reconstruction of the hydrogeological setting and the assessment of resource utilization. This work details the hydrogeological setting of the Baranja region (NE Croatia) bordered by Drava and Danube rivers to the S and E. Baranja shows a steady growth of tourism capacities (33% in the last 5 years) causing an increasing demand for water. Agriculture industry is well developed with several farms feeding one of the biggest food industry in Croatia. Despite the natural and economic appeal, the population density is low and three well fields with a total exploitation of 50 L/s cover the need for drinking water. Local wells supply the water demand of farms. Furthermore, water flow in irrigation canals is regulated by pumping stations. These conditions result in an unevenly distributed anthropic pressure on the surface water-groundwater system that could cause localized overexploitation or pollution.

This research collected and digitalized approximately 200 stratigraphic logs of wells in a geodatabase, including the interpretation of well testing and chemical analyses. These data are the basis for a detailed reconstruction of the hydrogeological setting that will be used to plan a monitoring network of the water level and periodic groundwater sampling. These results will provide key inputs for a comprehensive understanding of the surface water/groundwater interaction and the reconstruction of geochemical processes in the aquifer.

Acknowledgment: This research was conducted in the scope of the internal research project BAKA at the Croatian Geological Survey, funded by National Recovery and Resilience Plan 2021–2026 of the European Union – NextGenerationEU and monitored by the Ministry of Science, Education and Youth of the Republic of Croatia, and PACT-VIRA project of the Croatian Science Foundation (IP-2024-05-9190).

Large scale groundwater modeling for drafting the groundwater budget in the Po River district

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Unlike surface water modeling, large-scale groundwater numerical modeling has rarely been conducted in Italy, leading to a weaker understanding of aquifers compared to river dynamics. As part of MidAS-Po project, Po River District Basin Authority started a scientific collaboration involving academic and institutional experts to analyze and discuss the current knowledge on Po Plain aquifers. The goal is to bridge the gap and initiate a process to enhance awareness of water resources.

Over two years, the first conceptual model was developed under the guidance of six scientific groups, focusing on 3D reconstruction and parametrization, boundary condition, withdrawals, aquifer recharge, calibration boreholes, and modeling coordination.

The first groundwater numerical model of the Po Plain is currently underway. To summarize with a few key figures, it includes: 12 model layers, over 30,000 active grid cells per layer, more than 4,000 km of river network, over 150,000 well points, more than 1,000 calibration boreholes, and nearly 60,000 head measurements, spanning 148 monthly stress periods. Recharge has been estimated using a soil water balance model that takes into account meteorological data, land use, pedology and irrigation practices.

Although the project is still ongoing, some preliminary findings can already be drawn. Despite the vast amount of collected data, much more remains to be obtained. Stakeholder involvement is crucial in a region spanning four different local government institutions, approximately 60 water companies, and 60 irrigation districts. Therefore, future project development must include strategies to collect missing data and ensure its effective management for future applications. Once refined, the model will serve as a tool to understand groundwater dynamics, monitor the system, and design

new measures for water protection.

Acknowledgment

MidAS-Po-Modello idrogeologico delle Acque Sotterranee del distretto idrografico del fiume Po-FSC 2014-2020

Density-dependent groundwater numerical modelling to meet Sustainable Development Goal 6 in a coastal area of north-western Egypt

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In many coastal areas of North Africa, access to clean and good quality water is limited, requiring the development of safe and reliable water supplies. In Wadi Naghamish, northwestern Egypt, rainwater is harvested in storage tanks during wet periods, but no pipeline-based water supply exists. Groundwater with varying salinity levels is available in a phreatic and a deep aquifer, while local communities rely on subsistence rainfed agriculture.

This study develops a density-dependent groundwater flow model using the FREEWAT-Q3 platform and the SEAWAT code to support water supply, addressing UN Sustainable Development Goal 6. The implemented model consists of ten heterogeneous layers representing three hydrogeological units: an upper unit of recent limestone and calcareous sand deposits, an intermediate unit of shale forming the shallow aquifer bed, and a deep unit of fossiliferous limestone. Inflows come from the tableland and meteoric precipitation, while outflows discharge into the sea. Simulations assess saline intrusion under different recharge conditions and after wells activation. Hydrodynamic parameters were estimated using UCODE_2014 based on hydraulic head observations in the deep aquifer, despite data scarcity.

Then, we evaluated the impact of a potential irrigation well for a 60-hectare area and a drinking water well for local communities, both pumping 12 L/s. After 10 years of continuous pumping under simulated rainfall conditions (2011-2022 data), results show a saline wedge advancement of about 500 meters from its 2011 position. The model demonstrated the reliability of groundwater as a solution for water supply in Wadi Naghamish, enhancing local communities' quality of life.

Acknowledgement

This contribution is presented within the framework of the NEXUS-NESS project. The NEXUS-NESS received funding from the PRIMA Programme, an Art.185 initiative supported and funded under Horizon 2020, the European Union's Framework Programme for Research

Analyses of decreasing productivity of groundwater wells in confined aquifers of the lower Po Plain (Ferrara, Italy)

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In the confined aquifers of the lower alluvial plains the fine grain size of the sediments (sands and silts) and the chemical-physical characteristics of the groundwater (reducing environment with high levels of dissolved iron and manganese) have important consequences on the service life and efficiency of water wells; these are often affected by clogging phenomena of the well screen, caused by physical, chemical, and biochemical (biofouling) processes. Typical symptoms are the progressive lowering of dynamic level and operating flow rate, with a consequent reduction of the specific capacity parameter. Occlusion of the gravel pack and well screen causes a progressive reduction in the efficiency and productivity of the well, with negative effects on the quantity and quality of the produced water.

The work analyses a case study in the lower Po Plain (Province of Ferrara) where the presence of a drinking water well field has allowed the collection of a significant hydrogeological data set, especially in recent years, thanks to continuous flow rate and groundwater level measurement systems. In particular, the temporal evolution of the specific capacity parameter is evaluated, analysing the possible dependencies on the construction characteristics of the wells, the boundary conditions and the local geochemical characteristics of the aquifer, in order to formulate hypotheses on the physical, chemical and biochemical processes involved and to obtain useful indications for the management and scheduled maintenance of the wells.

Systematic literature review on the role of groundwater in the Water-Energy-Food-Ecosystem NEXUS

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Human and the planet face numerous challenges due to global changes, including freshwater scarcity and rising demand for food and energy. Groundwater, supports life, ecosystems, and human activities, making it a key freshwater source in many regions.

The Water-Energy-Food-Ecosystem (WEFE) Nexus highlights interactions among these four sectors, aiming for integrated management of essential resources. Within this framework, groundwater plays a key role. However, its interdependencies with food and energy, particularly in an ecosystem context, and their synergistic impacts are rarely evaluated.

This study addresses this gap through a systematic literature review (using Scopus and Web of Science databases), covering articles published up to December 2024. Our search identified 477 papers. After analysis, 282 were deemed relevant, with 15 more added through snowballing.

We present a matrix detailing the complex interactions among food, energy, and groundwater within the ecosystem framework, integrating various factors such as economic and social dimensions, alternative water sources, and land types. The food sector is further categorized into crop production, livestock, aquaculture, and food processing to capture sector-specific dynamics.

Notably, groundwater is locally limited, intensifying food-energy competition. Its use across sectors can also be mutually beneficial, such as when groundwater-fed crops support bioenergy. Its role in food and energy also impacts ecosystems, influencing carbon emissions and water quality. Nature-based solutions may enhance groundwater storage in Managed Aquifer Recharge with low energy consumption.

Finally, we evaluated the impacts of various technologies and strategies developed, such as virtual water, offering insights and recommendations for future research and policy development.

Acknowledgement

This research is funded within the PhD Programme in Agrobiosciences (39th cycle), Institute of Crop Science, Scuola Superiore Sant'Anna.

Impact of past mining activities on water quality: the case of the Pestarena and Crocette gold mines (Piedmont, Italy)

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Extraction and processing of gold (from ore deposits) is often linked to long-term environmental impacts, with contamination persisting even after mine closure. The main issue to face is acid mine drainage (AMD) from underground mines and extractive waste that flows into streams and soils, mobilising potentially toxic elements (PTEs). This study investigates surface (SW) and groundwater (GW) contamination at the former gold mines in Crocette and Pestarena mining area (Western Alps, Piedmont, Northern Italy), active until 1961. Previous studies have shown that several PTEs in soil exceed the limit set by Italian legislation (e.g. As, Hg, Sb, Pb) and that As in SW also exceeds the limit. However, the quality of GW has not been assessed. To investigate the current contamination, three field campaigns were carried out in 2024 (May, July, September), collecting 32 SW and GW samples, 14 from Crocette and 18 from Pestarena for physico-chemical analysis. Results showed arsenic contamination in 75% of SW and GW samples, exceeding Italian regulatory limits. GW near Pestarena tailings deposits showed high concentrations of As (279 μg/L), Al (7266 μg/L), Fe (1785 μg/L), Mn (276 μg/L), Ni (86 μg/L) and Pb (25 μg/L). pH values of samples collected in the first field campaign were acidic (3.2-4.9). Oxidation of sulfides in the mineralised ore-veins and hence in the tailings produced by the ore processing may be responsible for the acidity of these waters. Furthermore, the high electrolytic conductivity and sulfate content found in the Pestarena GW suggest a link between contamination and mining activities. This study highlights the persistence of contamination more than 60 years after mine closure and underlines the need for continuous monitoring and mitigation strategies to protect water resources in areas affected by mining activities. Future studies will focus on gathering information on soil and water contamination to assess environmental and human health risk.

Groundwater Vulnerability to Salinization and Agricultural Leaching A Systematic Review of DRASTIC and GALDIT Applications

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ABSTRACT

Groundwater resources are under increasing pressure because of rapid population growth, agricultural practices, industrial activities, and environmental hazards especially in coastal areas. The over-exploitation of groundwater can lead to water salinization through seawater intrusion, while agricultural leaching further exacerbates water quality due to excessive pesticide and fertilizer uses. In this study, two systematic reviews were conducted to evaluate the screening of salinization processes (SP) and agricultural leaching (AGL) within the framework of vulnerability assessment methods, focusing on the widely used GALDIT index for SP and DRASTIC index for AGL with the aims i) to identify all factors associated with SP and AGL used in previous applications, ii) outlined the weights assigned to each factor based on their relative impact on groundwater vulnerability, and iii) to spotlight the models used to weight assignment. To analyse the results of the two literature reviews, statistical measures such as maximum (Max), minimum (Min), mean (M), and median (Mdn) were utilized. The results indicated that the most used impacted factors for assessing SP were groundwater elevation above sea level and the distance from the shoreline, while groundwater occurrence and the impact of existing seawater intrusion had the lowest impact on the vulnerability assessment for coastal aquifers. Depth to water, topography, recharge, and hydraulic conductivity were obtained as the most impacted factors for assessing AGL, while the factors of aquifer media, soil texture, and the impact of the vadose zone have the lowest impact. The reviews identified the critical factors for aquifer vulnerability assessment, trying to provide new insights into the influence of different factors on SP and AGL.

Key words: DRASTIC, GALDIT, Systematic Review, Groundwater, Vulnerability

Groundwater Flow Dynamics in Seismically Perturbed Aquifers: Insights from the 2016 Mw 6.5 Norcia Earthquake

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It is well known that earthquakes induce pseudostatic and dynamic changes in hydrogeological systems due to the instantaneous elastic strain release and the stress transfer between the solid crust and the fluid phase. Water level fluctuations, discharge variations, and hydrogeochemical changes are the most observed phenomena, interpreted as the aquifer's response to ground deformation and shaking. However, these hydrogeological perturbations can persist for months or even years, posing significant challenges for groundwater resource management. Such long-lasting effects are typically observed when surface faulting occurs. Seismogenic fault dislocation results in a permanent deformation of the crust. Moreover, when surface rupture occurs, the fault rupture propagates within the aquifer, further altering its hydrogeological equilibrium.

This work proposes a methodology based on conceptual and numerical modeling of complex hydrogeological systems to qualitatively and quantitatively assess earthquake-induced variations. The proposed method is applied to the 2016 Mw 6.5 Norcia earthquake, which caused a significant surface rupture along the Vettore Mt. and led to considerable discharge variations in the Sibillini Mts. carbonate hydrostructure (Central Italy). Following a parsimonious modeling strategy, we developed a robust yet simplified hydrogeological conceptual model constrained by pre- and post-earthquake hydrogeological data. We implemented two modeling approaches: a semi-lumped and a distributed model. With a specific focus on the critical role of seismogenic faults, we simulate groundwater flows before and after fault rupture, assuming a hydrogeological barrier effect of faults on groundwater flow dynamics. Modeling results reveal that the disruption of the fault barrier induces a co-seismic rupture of the pre-existing hydraulic gradient, triggering a transient response in the aquifer system as it gradually re-equilibrates in the post-seismic phase.