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Integrated Groundwater Management of Mediterranean Coastal Aquifers

27-30 September 2022

Chania, Crete, Greece

Book of Abstracts

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PREDICTING SEAWATER INTRUSION USING ARTIFICIAL INTELLIGENCE-BASED MODELS FOR THE OPTIMAL AND SUSTAINABLE USE OF GROUNDWATER IN COASTAL AQUIFER: Case of Monastir, Tunis.

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Knowing the temporal and spatial evolution of the fresh water-salt water interface is significant for groundwater development and prevention of seawater intrusion and for understanding the vulnerability of a coastal environment. Many hydrogeological studies have discussed and used models describing a sharp interface between fresh water and salt water in coastal areas, especially in coastal aquifers. In the 21st century, Seawater intrusion is posing a serious threat to humanity throughout the world, particularly in developing nations. Tunisia being one of the largest consumers of groundwater in the world, dwindling groundwater storage has emerged as a serious concern in recent years. Consequently, the judicious and efficient management of vital groundwater resources is one of the grand challenges in Tunisia. This study demonstrates a pragmatic framework for predicting the yearly evolution of seawater intrusion at a country scale using real-world data. In addition, groundwater and seawater processes exhibit a high degree of spatial and temporal variability within a coastal aquifer as well as among coastal aquifer system, which renders the evolution of seawater intrusion a challenging task for the researchers. The extent of data and information required for developing process-based groundwater-flow/transport and seawater interactions are enormous; many of these data and information are usually expensive and/or difficult to obtain, particularly in developing countries. Under such circumstances, machine learning (ML) techniques such as Artificial Neural Network (ANN) and linear autoregressive (AR) were employed for predicting using in situ annual exploitation of groundwater, flow water and pertinent meteorological data of 1996–2020. It was developed for Monastir (MAS) coastal aquifer systems in Tunisia and their efficacy was evaluated using suitable statistical and graphical indicators. MAS vary significantly in terms of climatic settings, topography, land use/land cover, soil, agricultural activities, hydrogeologic settings, hydrologic regimes, etc. In addition, the availability of groundwater-monitoring sites, continuity of field data, duration of field data, and the quality of available field data vary

considerably for MAS, which render the preprocessing of country-scale field data cumbersome and arduous. The findings of this study revealed that the AR model is more proficient in predicting yearly evolution of seawater intrusion than ANN. Such applications can be very useful in developing a computationally feasible linked Simulation /Optimization (S/O) methodology for regional scale management of saltwater intrusion in coastal aquifers. ML has emerged as a promising scientific tool to help decision-makers develop sustainable management strategies for the efficient utilization and protection of this vital resource. It is recommended that groundwater monitoring network and data acquisition systems be strengthened in Tunisia to ensure efficient use of modeling techniques.

Keywords saltwater intrusion; coastal aquifer; prediction model; MAS.

Indirect methods for defining the hydrodynamic response of a complex coastal karst aquifer.

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Keyword: groundwater level, meteorological drought, time series analysis
Conference topic: Tools and methods for groundwater monitoring at coastal aquifers (ICT tools, multi-probe sensors, web-GIS applications, integrated telemetric observatories)

Salento is a regional coastal karst aquifer located in Southern Italy with a highly complex geological, geomorphological, and hydrogeological structure. Groundwater is affected by high and unruly exploitation from licensed and unlicensed wells for irrigation and drinking purposes, resulting in its qualitative and quantitative status degradation. Furthermore, the increasing frequency of meteorological drought events exacerbates the already compromised situation.
The analysis of the relation between climate indicators and groundwater levels (GWLs) in nine monitoring wells outlines direct and statistically significant correlations between the time series, providing useful qualitative information about the response time with which this aquifer reacts to precipitation and temperature variability. Pearson's correlation coefficients range from 0.6 to 0.8, with a time lag varying from 16 to 23 months. Moreover, decreasing trends in GWL are far consistent with the trend in meteorological indicators during dry periods.
Long response time is also confirmed by implementing short time-series analyses between daily groundwater levels and precipitation in both the time and frequency domain. These methods highlight the presence of baseflow as dominant hydraulic behaviour and a great storage capacity, suggesting a poor degree of aquifer karstification and dominance in the permeability structure of not well-developed hierarchical karst networks. This behaviour is occasionally bimodal with quick flow and baseflow simultaneous presence. Finally, results from both approaches describe the Salento aquifer as a slow filter with a notable inertial behaviour in response to meteorological events.
Under data scarcity and in relation to the complexity of such aquifer (in terms of scale, intrinsic properties, and boundary conditions), similar methodologies revealed significant interest and reliable general application. The capability to predict the aquifer response in relation to a meteorological drought period allows for identifying priorities in terms of water resource use. Thus, continuous recording of precipitation, air temperature, and GWLs are relevant for the correct management and safeguarding of groundwater.

Evaluation of spatio-temporal changes in groundwater quality of Tarsus Coastal Aquifer (Mersin, Turkey) using GIS techniques and water quality indices

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The work described here, conducted within the scope of the MEDSAL project, aims to evaluate the spatio-temporal variation of groundwater quality in the Tarsus Coastal Aquifer (TCA) located in Mersin, SE Turkey. The spatial distribution of groundwater quality in this anthropogenically disturbed coastal area was investigated for both dry season (September 2020) and wet season (June 2021) using GIS techniques and water quality indices. The physico-chemical properties of the groundwater samples collected from the wells (n = 87) were compared with the World Health Organization (WHO) guidelines for drinking-water quality and evaluated based on the Water Quality Index (WQI) and Heavy Metal Evaluation Index (HEI) calculations.

In this study, the parameters used for calculation of WQI included pH, total dissolved solids (TDS), total hardness (TH), Na^+, Cl^-, SO_4^{2-}, F^- and NO_3^-, whereas the calculation of HEI considered eleven potentially toxic trace elements (i.e., As, Ba, Cd, Cr, Cu, Fe, Mn Ni, Pb, Sb and Zn), which may pose risks to environmental and human health. The spatial distribution maps of individual groundwater quality parameters, as well as the thematic maps of calculated WQI and HEI values display remarkable similarities for both dry and wet season sampling campaigns. The comparison of WQI and HEI values with the land use/land cover (LULC) map produced using satellite imagery from Google Earth Engine reveals the main sources of pollution as industrial and agricultural activities (waste water discharges, excessive use of agrochemicals and fertilizers). The groundwater quality in the vicinity of Kazanlı (western part of the study area) seem to be the most affected by the anthropogenic pollution, which has been exacerbated by the active seawater intrusion (SWI) along the coastal zone due to excessive pumping of groundwater to meet ever increasing water demands of the industrial and agricultural economic sectors.

Keywords: Groundwater, Pollution, Water Quality Index, Heavy Metal Evaluation Index, GIS, Tarsus.

Acknowledgement
This study is fully funded by the grant from TÜBİTAK (Scientific and Technical Research Council of Turkey, No: 118Y366), supported under the European Union's PRIMA (Partnership for Research and Innovation in the Mediterranean Area) Programme.

Deciphering factors governing salinization of Tarsus Coastal Aquifer (Mersin, SE Turkey) using an integrated data analysis approach combining multivariate statistics, GIS and hydrogeochemical modelling techniques

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The work described here, conducted within the scope of the MEDSAL project, aims to decipher factors governing salinization of Tarsus Coastal Aquifer (Mersin, SE Turkey) using a sequential methodology combining multivariate statistics (i.e., factor analysis (FA) and hierarchical cluster analysis (HCA)), geographic information system (GIS) and hydrogeochemical modelling techniques. In order to characterize the surface water and groundwater chemistry of the site, two sampling campaigns were conducted in the dry season (September 2020) and wet season (June 2021) from identical locations (n = 98). Q-mode HCA method divided dry and wet season data sets into two major groups and revealed the presence of six subgroups for dry season and five subgroups for wet season. R-mode FA method extracted four latent factors, which explained 77.17% and 80.28% of the total variance in the dry and wet season data sets, respectively. The processes elucidated by R-mode FA and end-member water types defined by Q-mode HCA methods were validated by sequential inverse hydrogeochemical models developed along the groundwater flow paths using PHREEQCI. The inverse geochemical modelling demonstrated that relatively few phases (e.g., $CO_{2(g)}$, calcite, dolomite, gypsum, halite, quartz, plagioclase, chrysotile, muscovite, saponite-Na, illite and kaolinite) and ion exchange are required to derive observed changes in water chemistry and to account for the geochemical evolution of groundwater in the area. In a broad sense, the reactions responsible for the geochemical evolution of the groundwater fall into six categories: (i) silicate hydrolysis reactions; (ii) dissolution of evaporites; (iii) dissolution/precipitation of carbonates; (iv) precipitation of clays; (v) ion exchange with clays, and (vi) mixing with seawater. In the region, groundwater salinization is multifaceted and governed by a wide variety of processes. Besides that groundwater resources at the site is subject to anthropogenic pollution from diverse sources, among which agricultural and industrial sources are the most important ones.

Keywords: Groundwater, Salinization, Multivariate statistics, GIS, Hydrogeochemical modelling, PHREEQCI.

Acknowledgement
This study is fully funded by the grant from TÜBİTAK (Scientific and Technical Research Council of Turkey, No: 118Y366), supported under the European Union's PRIMA (Partnership for Research and Innovation in the Mediterranean Area) Programme.

Pollution Vulnerability Assessment of Arborea Coastal Aquifer (Sardinia, Italy) by Modified AHP-DRASTICLu Model Using GIS

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The purpose of this study was to evaluate the vulnerability of groundwater to contamination in the Arborea Coastal Aquifer (ACA) on the Sardinia Island (Italy), which is a part of the Mediterranean basin, using the modified AHP-DRASTICLu method based on the Geographical Information System (GIS). In this context, in addition to the criteria, namely; depth to water table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I) and hydraulic conductivity (C), used in the classical DRASTIC method, the land-use class (Lu) criterion has been added. Pairwise comparisons of these main criteria and their sub-criteria were made using the Analytical Hierarchy Process (AHP) method and the weight values of each sub- and main criteria were calculated. Weighted criteria layers were created by assigning these weight values to the cells in the relevant raster layers in the GIS environment. Finally, these layers were combined in the GIS environment with the Weighted Linear Combination (WLC) method and the final vulnerability map was created. Eventually, the final map was reclassified into five classes namely "Very low", "Low", "Moderate", "High" and "Very high". These classes occupied 5%, 11%, 32%, 40%, and 12% of the study area, respectively. Areas of very high vulnerability are mostly irrigated crop areas. Considering the fertilizers used in agriculture, integrated water management needs to be more careful, especially for these highly sensitive areas.

Acknowledgment
This study is fully funded by the grants from TÜBİTAK (Scientific and Technical Research Council of Turkey, No: 118Y466) and ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale, Italy), both supported under the European Union's PRIMA Programme.

Investigation of the Pollution Vulnerability of Malia Coastal Aquifer (Crete, Greece) by Modified AHP-DRASTICLu Model Based on GIS

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This study aims to determine the vulnerability of the Malia Coastal Aquifer (MCA), which is one of the Mediterranean basins where vulnerability to pollution risk is increasing due to climate and anthropogenic pressures. For this purpose, a modified AHP-DRASTICLu model based on Geographic Information System (GIS) was used. In this model, the layers representing the DRASTICLu, namely; D (Depth to the water table), R (Net recharge), A (Aquifer media), S (Soil media), T (Topography), I (Impact of vadose zone), C (Hydraulic conductivity), and Lu (Land Use Classes) were compared in pairs using the Analytic Hierarchy Process (AHP) method, which is a multi-criteria decision-making method. After the AHP calculations, the weight values of each criterion and the sub-criteria belonging to these criteria were determined. These weight values were assigned to the relevant cells in raster layers containing their sub-criteria created using the GIS. Afterwards, all layers were combined using the weighted linear combination (WLC) method in the GIS environment, and the final vulnerability map was created. Finally, the vulnerability map of the MCA was divided into five classes namely "Very low", "Low", "Moderate", "High", and "Very high", which covers 17%, 33%, 26%, 23%, and 2% of the study area, respectively. Groundwater in the coastal areas of the MCA has a very high potential for contamination, especially along the east coast. In contrast, the potential for groundwater contamination in the western part is mainly in the “Low” and “Very low” categories. Considering the intense touristic activities in the coastal areas of MCA, it is necessary to adopt water management practices to minimize the impact and to maximize beneficial use of groundwater resources.

Acknowledgment
This study is fully funded by the grants from TÜBİTAK (Scientific and Technical Research Council of Turkey, No: 118Y476) and GSRI (General Secretariat of Research and Innovation, Greece), both supported under the European Union’s PRIMA Programme.

Variable density flow modelling in coastal aquifers of Greece and Tunisia

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Physical-based models for groundwater flow and contaminant transport are compiled for 3 of the porous medium aquifer systems of MEDSAL'S pilot sites: Rhodope and Samos in Greece and Bouficha in Tynisia. Each of the three compiled models shares the same principles of salinization front geometry and evolution; that of a transition zone between fresh and salt water masses, through the adoption of the variable density flow approach. Two well-known and highly documented and scientifically justified modelling suites of codes that both offer numerical solutions, have been used for this exercise: the finite element code FEFLOW for Rhodope pilot and the coupled finite difference MODFLOW-SEAWAT suite for Samos and Bouficha pilots.

Despite the varying degree of sophistication and detail of the three compiled models, all performed satisfactory and successfully simulated the major evolution mechanisms that are dominant in each of the studied systems. All three models were capable to replicate the seawater intrusion and furthermore provide hints to identify the existence of additional mechanisms that affect the salt content evolution in the aquifer systems. Depending on the data availability and the capability to approximate the sources of salinity based on these, additional salinization processes could be represented to a higher or lower degree. In any case however, the existence of such mechanisms will become apparent either quantifying them, or through partial divergence of field data to modelled results.

A significant conclusion of the modelling exercise is that a single and complete simulation of complexed systems with multiple salinization mechanisms is not easy to be performed and requires considerable effort that needs to be based on data availability, detailed knowledge of the structure and evolution of the system, as well as, deciphering well the controlling mechanisms before attempting to compile the model.

Re-thinking social complexity throughout the stakeholder mapping. A sociological approach to water governance analysis

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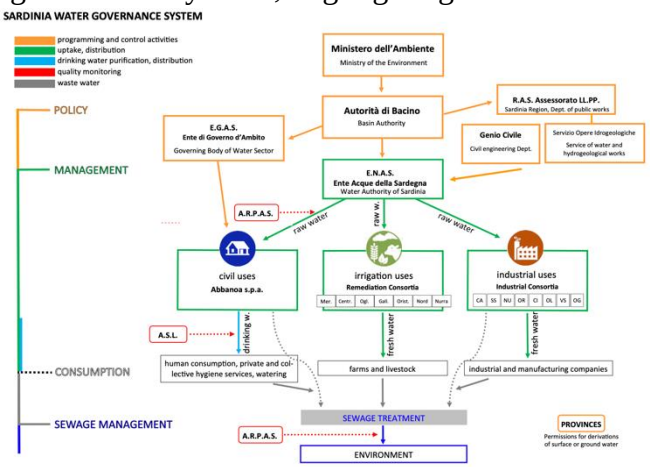
Water governance has gained increasing resonance in the international arena. Integrated and holistic water governance approaches have emerged in the scientific literature (Jiménez et al., 2020; Pahl-Wostl, 2009), going beyond technology-driven management approaches and with a growing focus on effective stakeholder engagement (Barquet et al., 2022; Raum, 2018).

The PRIMA-funded project SUSTAIN-COAST explores governance approaches for the sustainable management of groundwater resources in Mediterranean coastal aquifers, starting from the effective mapping of local stakeholders. This work illustrates the results of one of the four case studies of the project: Arborea (Sardinia, Italy), a rural coastal district specialized in the dairy sector and a nitrate-vulnerable zone. The water governance analysis is rooted in a stakeholder mapping process. Results show conflicting perceptions about groundwater-related issues, and the perceived ineffectiveness of top-down measures for limiting groundwater pollution. Results also show that including neglected stakeholders in the debate unveils conflicting narratives about the future.

Adopting a sociological approach to water governance analysis allows an increased understanding of the social dynamics that emerge between local communities and water governance systems, highlighting the factors that enable or prevent the success of water governance measures and policies (Lienert et al., 2013). Stakeholder mapping has fundamental methodological relevance in any research related to rapidly changing and complex social systems, where stakeholders have diverging interests but face interconnected problems, as it can be used to generate knowledge about the behaviours, perceptions, relations, and influence of the actors who have a stake in a process (Reed et al., 2009). This information can then be used to improve understanding of the social, technical, and political feasibility in relation to specific decisions and in turn guide future policy directions (Aligica, 2006; Zingraff-Hamed et al., 2020). Ultimately, effective stakeholder mapping can contribute to promoting innovative governance structures, empowering neglected actors and co-creating shared solutions for the sustainable management of groundwater resources.



Keywords: water governance; stakeholder mapping; sociology; social complexity; sustainable development

Acknowledgements:
We gratefully acknowledge the support of our colleagues Alberto Carletti and Gianni Ragaglia, who assisted the research by facilitating outreach to local authorities and economic actors. We would also like to express our gratitude to all the participants who agreed to be interviewed, for contributing so thoroughly to the research through their insights and experiences. This work was supported by the Sustain-COAST project. Sustain-COAST was funded by the Italian Ministry for Universities and Research (MUR) (CUP number: J84D18000180005) under the EU PRIMA 2018 programme.

Analyzing the dynamics of groundwater salinization in coastal aquifers through statistical and hydrogeochemical approaches: strengths and future outlooks

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Keywords: Coastal aquifers, MVSA, HFE-D, groundwater salinization, 3D density distribution

Coastal aquifers in highly urbanized areas, in particular those in arid/semi-arid regions, are much prone to groundwater salinization because of the impact of natural and man-made drivers. Salinization negatively affects groundwater quality and causes cascading effects on its depending systems and ecosystems. Determining the spatial and temporal evolution of salinization phenomenon in coastal aquifers might help policymakers, decision makers and stakeholders to better understand the dynamics of such worrying phenomenon, as well as to act towards implementing structural and non-structural mitigation and adaptation strategies in the short, medium and long terms. During the last decades, researchers implemented several methodological approaches based on statistical and hydrogeochemical techniques in groundwater studies for the assessment of groundwater salinization dynamics. By dealing with the case study of a karstic coastal aquifer in the Mediterranean basin prone to groundwater salinization (Salento aquifer, Southern Italy), this study aims at evaluating the dynamics of groundwater salinization through multivariate statistical analysis (MSVA), as well as through a hydrogeochemical approach based on facies evolution (HFE-D). The study applies Hierarchical Cluster Analysis and Factor Analysis, and HFE-D on a set of groundwater samples collected from the regional groundwater monitoring network of the Salento aquifer during six consecutive monitoring surveys, carried out at the end of each wet and dry season from 2016 to 2018. The results of such applications highlight the vulnerability of some coastal and inland zones to groundwater salinization and can decipher its spatial and temporal evolution. Both methodological approaches show comparable results, which provide a mutual validation of both outcomes. The study also advances some general critical remarks on the influence of the 3D groundwater density distribution as far as the groundwater sample collection methods and well equipment: the related issues concern monitoring reliability in coastal aquifers and consequently the results of the application of both techniques.

Presentation preferred

Invited

Acknowledgements

This research has been conducted in the context of MEDSAL Project© (www.medsal.net), which is part of the PRIMA (Partnership for Research and Innovation in the Mediterranean Area) Programme supported by the European Union's Horizon 2020 Research and Innovation Programme and funded by the national funding agencies MIUR (Ministry of Universities and Research of Italy) (Grant No: 1421) and TÜBİTAK (Scientific and Technical Research Council of Turkey) (Grant No: 118Y366).

Monitoring of Saltwater intrusion in the Chtouka aquifer (Agadir - Morocco)

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In the groundwater contract established in 2016, a continuous monitoring network of the saltwater intrusion is recommended to follow its evolution and to inform the local authorities on the degradation of the groundwater quality.

In this context, the ABHSM (Souss Massa Water Basin Agency) wished to carry out a high frequency and continuous monitoring of the saltwater intrusion on several levels of the aquifer by new instruments measuring the electrical conductivity of the water (SMD - Subsurface Monitoring Device) on two different locations: northern part of the aquifer, south of Agadir at about 6 km from the coast (Mzar), and central part of the aquifer, near Tifnit, at about 1 km from the coast (Tif).

The two autonomous SMDs measured several daily water conductivity profiles on the vertical of the aquifer continuously over two years and the analysis of all the data in Mzar (northern part of the aquifer) allows us to establish:

- near the Oued Souss (Mzar), the dynamics and evolution of the saltwater intrusion observed are alarming for the exploitation of the Lmzar well field located only about three kilometers to the east.
- the shape, dynamics and advance of the saltwater intrusion are strongly correlated with the water table level (constantly below the ocean level). In the year 2020, the transition zone (freshwater/salt/saline) is globally diffuse and spreads over more than 50 m in height (between 20 and 70 m in depth)
- an increase of nearly 5000 m3 per month in extractions from the catchment area located 3 km away results in a drop of nearly 4 cm per month in the water level table, an advance of the saltwater (salinization of the groundwater on all levels of the aquifer of + 113 µS/cm per month and a rise in the saltwater interface - arbitrary limit of 17000 µS/cm - of 52 cm per month)

These initial results show that the impact of the drinking water supply operation to the north of the aquifer on the advancement of the saltwater wedge is significant and is beginning to be evaluated. The intrusion in the central coastal area (at the monitoring point) does not seem to be changing much.

Barriers to the application of "Adaptive Management" to coastal aquifers

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The term "adaptive management" describes management approaches that involve structured monitoring and investigation used to underpin changes to project operations in response to new knowledge about the stresses to the system and the associated impacts. Where the impacts of a proposed project are uncertain, adaptive management is often proposed as a technique that allows proponents to delay investigations until the project is approved and initiated. A recent review of adaptive management applied to groundwater-affecting projects (Thomann et al., 2020) concluded that in many cases, there was a lack of substantive mitigation measures and/or assessment of the potential for remediation. Although adaptive management guidelines exist (e.g., Williams & Brown, 2012), these are usually neglected in devising adaptive groundwater management strategies, even where court cases have focused on the validity of the adaptive aspects of disputed project proposals.

This presentation will build on the review of adaptive groundwater management by Thomann et al. (2020) by highlighting some of the key challenges in applying adaptive groundwater management to coastal aquifer settings. Issues in assigning trigger level conditions (i.e., thresholds in hydrogeological variables that lead to management intervention) are addressed where these depend on processes accompanying seawater intrusion in coastal aquifers. Finally, recommendations are offered for the application of adaptive management to coastal aquifers to avoid common pitfalls that arise from their complex behavior.

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Assessment of the impact of including hydrological information in the classification of groundwater quality data

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The Tarsus coastal plain (TCP) is an economically important region situated between the fertile fluvio-deltaic plains of two rivers, Deliçay and Tarsus (Mersin, SE Turkey), where anthropogenic activities (e.g., domestic, agricultural and industrial) are very intense. Thick clay-silt layers or lenses are present in the TCP, resulting in semi-confined as well as confined aquifer systems. Several factors are threatening the sustainability of the groundwater system, such as excessive groundwater abstraction and salinization. Furthermore, the local ecocystems are under pressure due to the construction of large dams and extensive emissions of greenhouse gases. However, the impact of the natural and anthropogenic processes on these complex systems is not yet fully understood.

Within the framework of the MEDSAL project (www.medsal.net), groundwater samples were collected for the characterization of physico-chemical state of the aquifer. Additionally, 208 in-situ measurements of the saturated hydraulic conductivity were also used to build hydrogeological constraints for enhancing the above physico-chemical characterization.
In particular, this study aims at addressing the classification of groundwater quality data into salinization-related clusters through the inclusion of hydrological information. The fuzzy *c*-means algorithm was initially applied to selected physico-chemical data, and the resulting membership values wrere used as surrogates of the probability that a sampling location belongs to a particular cluster. Hydrological controls were incorporated in the clustering process based on hydraulic connectivity and geographical proximity considerations. Preliminary results demonstrate the ability of these controls to modify initially low cluster membership values, shifting sample data to different clusters to enhance the spatial connectivity of the resulting salinization categories.

Keywords: Fuzzy clustering, spatial connectivity, salinization categories

Acknowledgements
This research is conducted in the context of MEDSAL Project© (www.medsal.net), which is part of the PRIMA Programme supported by the European Union's Horizon 2020 Research and Innovation Programme and funded by the national funding agencies of RIF (grant number 0318-0031), and TÜBİTAK (grant number 118Y366).

Inclusion of hydrological information for classifying groundwater quality data

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The Rhodope (RHO) pilot site of project MEDSAL (www.medsal.net) is located in north-eastern Greece and is mainly composed of agricultural land occupying more than 65% of the study area. Several lagoons at the southern part of RHO interact with the sea and possibly with the local aquifers. Regarding groundwater salinization, it is evident that RHO is affected at its SW boundaries by seawater intrusion due to overexploitation. However, the complex stratigraphy and the hydrogeochemical evidence denote that additional potential sources might exist, whose overall intensity and impact are not yet fully understood.

Water quality parameters for RHO were surveyed at 54 groundwater sampling sites during the summer of 2020. The objective of this study is to address the problem of classifying sample geochemical data into salinization-related categories by accounting for hydraulic controls. Particularly, dissimilarity among any two vectors of geochemical elements at each pair of sample locations was enhanced based on hydraulic connectivity and geographical proximity considerations. Sample locations were initially grouped into three clusters, using the K-means clustering algorithm based only on the hydrogeochemical data. Probabilities of class membership for any sample location were computed based on the dissimilarity of the geochemical vector of that location from the geocmemical vector corresponding to the centroid of each cluster. Hydraulic and geographical information were subsequently incorporated into the process of clustering. Preliminary results showed that the inclusion of this information within the classification process resulted in sample locations shifting clusters/categories. On-going work involves the inclusion of additional geological features into the clustering process to better tailor that process to the postulated complexity of the subsurface composition.

Keywords: clustering, groundwater quality, spatial proximity, hydraulic connectivity

Acknowledgements
This research is conducted in the context of MEDSAL Project© (www.medsal.net), which is part of the PRIMA Programme supported by the European Union's Horizon 2020 Research and Innovation Programme and funded by the national funding agencies of RIF (grant number 0318-0031), and GSRT (grant number 2018-7).

Identification of suitable regions for intentional recharge of aquifers through multi-criteria decision analysis and stakeholders' involvement

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Mediterranean basin is considerered to be one of the most vulnerable region in terms of climate changes, being subjected to severe summer droughts, intense agriculture and the high frequency of intense seasonal rainfall events. Achieving water security in the Mediterranean region is undoubtedly a major challenge, requiring an open social debate and the establishment of new water governance to balance a demand that is currently unsustainable.

Within the framework of the AGREEMAR project (www.agreemar.inowas.com), an adaptive framework will be proposed for the identification of suitable regions within the Mediterranean basin for implementing Managed Aquifer Recharge (MAR) through the strong involvement of stakeholders' across multiple sectors. Suitability maps will be complied by considering biophysical, technological, social, economic, environmental, hydrological, institutional and financial indicators through multi-criteria decision analysis. The relative importance of these indicators will be determined through the continuous interaction with key stakeholders, leading to a comprehensive multi-sectoral matrix of indicators aligned to Integrated Water Resources Management pillars (IWRM). This matrix will be used as input to construct feasibility maps by combining the intrinsic suitability, recharge water availability and water demand for selected pilot regions. The validity and societal acceptance of the suitability and feasibility maps will be ensured through the strong stakeholders' involvement across multiple sectors, thus preventing conflict between water users, while supporting a safeguarding sustainable use of water resources. The applicability of the AGREEMAR approach will be demonstrated at selected case study areas of different scale, complexity, subsurface and climatic conditions to a) ensure social equity by harmonizing the interests and avoiding conflicts between water users, b) guarantee economic efficiency by the integration of social-economic components in technical MAR planning, and c) support environmental sustainability by safeguarding sustainable use of water resources and the associated positive impacts on the other aquifer-dependent services.

Keywords: groundwater, managed aquifer recharge, multi-sectoral approach, feasibility mapping, AGREEMAR

Acknowledgements
This research is conducted in the context of AGREEMAR Project© (http://www.agreemar.inowas.com/), which is part of the PRIMA Programme supported by the European Union's Horizon 2020 Research and Innovation Programme and funded by the national funding agencies of RIF (grant number 0321-0024), BMBF (grant numbers 02WPM1649A and 02WPM1649B) and MESRS, Tunisia.

Groundwater Recharge Time Series Estimation Supported by Earth-Observation Data: A Case Study of the Gediz River Basin Alluvial Aquifer

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Abstract

Groundwater recharge is one of the critical components of the hydrological cycle, and consequently also one of the key parameters in the mathematical modeling of groundwater flow. As it cannot be directly measured, there are numerous approaches available for estimating recharge. One method that is appealing is based on the water balance method using remotely sensed earth observation data, where groundwater recharge is determined as the residual of relevant water balance components.

The objective of this study is to develop an alternative approach to estimating the spatial and temporal distribution of recharge. It relies on the water balance method where net recharge can be calculated as the difference between precipitation and the sum of actual evapotranspiration, runoff, and changes in soil water content. Precipitation is obtained from ground measurements and runoff time series are estimated using the SCS curve number method. The recently increased availability of remotely sensed data lead to the development of satellite-based evapotranspiration (ET) products, which provide ET at different scales. The MODIS Global ET product (MOD16A2) is a collection of 500-m resolution data layers that provide PET and AET distributions based on an improved Penman-Monteith equation and inputs of daily meteorological reanalysis data. Soil moisture time series were retrieved from the ERA5-Land reanalysis dataset.

The approach is demonstrated on an over-exploited alluvial aquifer in the Gediz River Basin (Turkiye). Monthly time series of net recharge raster layers for the period of 2013-2020 are obtained by executing an automated sequence of GIS operations on data sets through a script developed for ArcGIS. Given that the monthly total precipitation ranges from 0 – 123.2 mm, monthly net recharge fluctuates between an average minimum of 2.9 and an average maximum of 46.0 mm month^{-1}. On an average basis, 53% of precipitation recharges the aquifer.

Keywords
hydrogeology, satellite remote sensing, soil water, evapotranspiration, data analysis

Presentation preferred
Invited

The subsidence of the coastal aquifer of Comacchio: an interesting challenging

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Keywords: coastal aquifer, land subsidence, remote sensing, Comacchio

The phreatic coastal aquifer of Comacchio is located in the coastal floodplain of the Po River in northern Italy. The Comacchio area is characterised by a brackish lagoon, reclaimed lands below the mean sea level, intensive agriculture inland and tourism along the coast during summer periods. The hydrographic system includes the Po River, its tributaries, and a dense network of channels and drainage and irrigation ditches which supply an important volume of fresh water for crop production and to control saltwater intrusion. The whole coastal area has been affected by land subsidence since the last World War with values that changed significantly over time and in space posing a serious issue to local structures and infrastructures. Here, the loss of land elevation is caused by the superposition of various processes: natural consolidation, peat oxidation, surface loading due to new structures and infrastructures, groundwater withdrawals, and hydrocarbon production from deep reservoirs. Disentangling the contribution to land subsidence due to aquifer exploitation from the other factors is a difficult effort due to the lack of specific extensometer stations. In the framework of the PRIMA project RESERVOIR (Sustainable groundwater RESources managEment by integrating eaRth observation deriVed monitoring and flOw modelIng Results) the spatial and temporal evolution of land subsidence was analysed using Advanced Differential Interferometric Synthetic Aperture Radar A-DInSAR techniques in order to process Sentinel SAR images. The Geohazards Exploitation Platform (GEP) developed by the European Space Agency (ESA) and the Coherent Pixels Technique (CPT) have been used. The data were compared to previous ERS-1/2 (1992-2000), ENVISAT-RADARSAT (2002-2006), RADARSAT (2006-2016) ground deformations obtained through PSInSAR™ and SqueeSAR™ techniques. Historical measurements provided by levelling have been considered too. Land subsidence evolution in space and time is post-processed by several methodologies (PCA, GMA, fastICA, wavelet analysis…) to detect possible relathinships with hydrogeological and meteoclimatic data.

Initial results from the development and operation of a sensor-based groundwater salinization monitoring network in Rhodope, Greece

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For semi-arid areas such those located in Mediterranean, groundwater is considered as the primary and sometimes the only freshwater source. Groundwater salinization constitutes the major threat for coastal aquifers, while it constitutes a highly complex phenomenon involving a wide range of mechanisms that might co-exist, such as seawater intrusion or upconning due to excessive abstractions of groundwater and existence of trapped seawater or connate saltwater. The technological advancements in electronics and telecommunications over the last decades resulted in the development of robust sensors that can efficiently monitor parameters in groundwater with high frequency, while they present low energy consumption and their data can be transmitted via a wide variety of alternative routes directly in the office. Therefore, sensor-based groundwater monitoring networks constitute a valuable tool not only for enlightening the complex groundwater salinization processes, but also for the operational protection of groundwater resources. Considering the above, a sensor-based network was developed in Rhodope aquifer system in the context of MEDSAL project (https://medsal.eu/) located in northeastern Greece in which electrical conductivity (EC), water temperature (T) and groundwater depth are recorded. The network comprises 3 sensors installed in carefully selected monitoring wells according to a detailed protocol developed for all the 5 test sites of MEDSAL project. Each of the 3 monitoring wells is considered to be representative of different states of groundwater salinization, namely: 1) seawater/brackish water intrusion, 2) transition between fresh and medium salinity groundwater and 3) geogenic factor and alternative salinization sources.

After almost 2.5 years of monitoring, the results demonstrate the high hydrogeological complexity of the aquifer system and consequently of groundwater salinization evolution. More specifically, EC variation during the irrigation period (May to September) reveal the existence of aquifer layers of significantly different groundwater potential and salinization levels. From the operational perspective, the evolution of EC is critical since groundwater is applied in crops with different tolerance in groundwater salinity and may also lead to soil degradation. The EC and T variation patterns under non-pumping conditions (from October to April) are complex but very well reproduced between the 2 hydrologic years of monitoring, thus indicating that the groundwater system has well-defined response in hydrological mechanisms like groundwater recharge. All the above results can only be efficiently captured with high-frequency monitoring, thus illustrating the value of sensor-based groundwater monitoring networks.

Keywords: groundwater salinization, electrical conductivity, sensors

Assessment of groundwater contamination and salinity sources in the Bouareg and Gareb aquifers (northeast Morocco)

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Because of their agricultural and industrial activities as well as their geographical location in the Mediterranean, the interconnected aquifers, Bou- areg, and Gareb, represent an important zone for Morocco. Situated in the Neogene basin, these plains host an aquifer system constituted of sediments dating back to the Messinian and continuing to the early Quaternary. The Messinian gypsum marl provides the substratum. The objective of this study was to evaluate the source of water salinity and to reveal the processes of the different sources of pollution using a variety of chemical and isotopic indicators (δ^{2}H-H_2O, δ^{18}O-H_2O, δ^{34}S-SO_4, and δ^{18}O-SO_4). The results of the chemical tracers proved extremely high salinity levels (EC up to 22000 µS/cm). Accordingly, compositions of waters are determined by the availability of easily soluble minerals like gypsum and calcite. According to the environmental isotope (δ^{34}S-SO_4, and δ^{18}O-SO_4) analyses, there are three potential processes affecting sulfate concentration: Evaporites (Gypsum); sewage; and fertilizers. These results are an added value for decision-makers to improve the sustainable management of groundwater in Mediterranean water-stressed regions, especially by using this knowledge of hydrogeochemical variations.

Keywords: Salinization, pollution, stable isotope, coastal aquifer, Bouareg-Gareb aquifers

Assessment of groundwater quality in Pinios Hydrologic Observatory, central Greece

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Pinios Hydrologic Observatory (PHO) was established in the year 2015, it belongs to the International and the Greek Long-Term Ecosystem Research (LTER) sites and it is located in the Agia watershed in central Greece. Covering an area of 55 km^2, PHO belongs to the Pinios river basin, which is considered one of the most productive basins in Greece, in terms of agricultural production. Agricultural activities are widely developed in PHO and their sustainability is crucial for the local socio-economic stability because of the significant fruit production (mainly apples, cherries and chestnuts) supplying Greek and foreign markets. Groundwater constitutes the dominant source of water to satisfy the irrigation needs and therefore groundwater quality is crucial for maintaining sufficient quality of agricultural products and also conservation of the environment and the ecosystems. The present work is based on hydrochemical data from 121 water samples collected on a biannual basis over five years. The monitoring network includes 18 monitoring points, 13 of which are groundwater wells, 5 are springs and 1 monitoring point is located in the creek crossing PHO. The parameters measured in situ or analyzed in the laboratory are the following: pH, EC, K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, NO_3^-, NO_2^-, NH_4^+, and B. The results demonstrate the effects of agricultural activities on groundwater quality with NO_3^- concentrations reaching values up to 101 mg/L. Higher NO_3^- concentrations were observed after the end of the irrigation period, resulting from irrigation return flow with increased NO_3^- loads. Moreover, the high correlation (R^2=0.8) between electrical conductivity and NO_3^- shows that the increased groundwater salinization levels can be attributed to agricultural pollution. Hierarchical Cluster Analysis (HCA) was applied to the dataset, and it revealed three distinct groups of water samples. The 1st group includes samples collected from springs, the 2nd group includes samples collected from groundwater wells located mainly in talus screes/cones which serve as a transition zone and the 3rd group includes groundwater samples from southern part of the alluvial aquifer. Finally, Principal Component Analysis (PCA) was implemented and the results indicated 4 principal components, the majority of which are related to the anthropogenic influence on groundwater quality and mainly to the irrational application of fertilizers.

Keywords: Hydrogeochemistry, nitrate pollution, multivariate data analysis

Development of a groundwater map for the Mediterranean region combining global models and in-situ data

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Groundwater represents a strategic freshwater reserve in the Mediterranean region. However, its status remains poorly characterized, and its total water budget is increasingly uncertain. Modelling at a larger scale has offered new insights into groundwater assessment, especially in areas with limited direct measurements.

This study aims to quantify the steady-state groundwater levels at the Mediterranean continental scale by combining global gradient-based models and in-situ observations. First, the capabilities of three groundwater models to predict the steady-state level in one of the most monitored groundwater systems in the Mediterranean region, the Iberian Peninsula, were tested. Results showed that the three groundwater models could consistently reproduce the observed steady-state groundwater level of the Iberian Peninsula (R^2 ranges from 0.70 to 0.74). Model outputs are comparable in the low-land areas, while discrepancies increase with topography. The ensemble model that combines models' results with observations showed reasonable performance in replicating the groundwater levels for shallow groundwater, but performance deteriorated with increased depth. Furthermore, the agreement of the combined product with observed values becomes better the more observations we use.

Overall, this study describes a benchmark approach of combining multiple model simulations and observations to deliver improved mapping of groundwater resources which can serve as a baseline for groundwater users and managers in the Mediterranean region.

Aknowledgements
This work was supported by the German Federal Ministry of Education and Research (BMBF, Germany, Grant 01DH19015) under the Project Sustain-COAST, co-funded by EU PRIMA 2018 programme.

Evolution of pollution sources at last decade of wadi el Bey watershed area

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Comparative analysis was carried out of the evolution of groundwater quality over ten years (2010–2021) by source focus and spatial distribution of several activities. The shallow groundwater in a groundwater resource area was studied using conventional monitoring analysis and HRMS (high-resolution monitoring sensor) was performed especially for surface water quality assessment. The relationship between surface activities and potential polluting uses, hydro-chemical composition, and the quality of groundwater trend were demonstrated, and hotspots are identified as results. The analytical methods used are IC, COD titration, and all results showed an interaction between agricultural land use and fertilizer application rate, and essentially the industrial wastewater release and their respect of standards. The monitoring of nitrates, salinity, and COD confirmed that pollution hotspots are more important throw the last ten years of several activities, which were indirectly responsible for the evolution of contamination in the groundwater essentially in hotspot points. The main potential pollution sources that could represent a considerable effect on the groundwater quality index in future were classified into three pollution sections: heavy metals (Cr), Nitrogen compounds (ammoniacal nitrogen, and nitrates) and salinity and organic pollution (chemical oxygen demand). The results proved that a salinization gradient exists following the main aquifer flow direction to Sebkhat El Maleh from South to North and from East to West reaching more than 3g/L. The high salinity and high nitrate concentration in the region between Grombalia, Soliman, Beni Khalled, and Menzel BouZelfa can both be attributed to increased agricultural activity, fertilizer use, and irrigation water returns, the Cr and COD parameter didn't show an alarming value in the aquifer. However, hotspot points are identified in the river according to recent monitoring campaigns. To avoid the pollution transfer to the groundwater, prevention actions concerning polluting activities are undertaken within Sustain-COAST project activities.

Acknowledgment
Sustain-COAST project is funded by the national agencies mentioned below under the PRIMA section II Programme. PRIMA is an Art.185 initiative supported and co-funded under Horizon 2020, the European Union's Programme for Research and Innovation.

Aposelemis Projects: the largest hydraulic project of the region of Crete

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In this article will be presented the Aposelemis Projects, which is the largest hydraulic project of the region of Crete. The supervision and direct control of the design and construction, as well as the management and operation of the water supply projects of Heraklion to Agios Nikolaos from the Aposelemis Dam (Aposelemis dam, Water Treatment Plant, pipelines, tunnels, and other parts of the work), were transferred, in its entirety, to O.A.K. S.A. Aposelemis projects consist of the following sub- projects: the Aposelemis Dam (reservoir capacity 25.3 million cubic meters of water), the Water Treatment Plant (maximum installation capacity of 110,600 cubic meters of water per day), the pipeline system (77 km), the Lasith Plateau Tunnel. Aposelemis projects have been operating since September 2015 and until today have supplied over 65 million cubic meters of water in the areas of Heraklion, Hersonissos and Agios Nikolaos. Aposelemis projects cover spatially the northern front of the entire eastern Crete. From 2015 until today the water produced is of excellent quality water for human consumption, covering all the standards of the Greek and European legislation on drinking water. The water in the reservoir, in the four different stages of water treatment (ozonation, flocculation- precipitation, filtration, chlorination) in the water treatment plant, along the entire length of the pipeline system as well as in the points of water distribution to the final recipients, is checked daily by the Aposelemis Water Quality Control Laboratory, which is a modern water quality control laboratory of basic physicochemical and microbiological parameters.

A numerical flow and transport model for sustainable groundwater management of the coastal aquifer system of the Arborea plain, Sardinia (Italy)

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Coastal areas around the Mediterranean basin concentrate population, multi-sector economic activities and agricultural activities. This induces an important need in fresh water and high solicitation of coastal aquifers, which can lead to salt water intrusion. This issue, added to contaminated surface water percolating towards the aquifer, and along with climate change show the urge for innovative groundwater management, especially in coastal areas. The PRIMA Sustain-COAST European project aims at exploring innovative governance for sustainable coastal groundwater management and pollution reduction in the context of a changing climate by involving researchers, local populations, water stakeholders and policy makers.

The Arborea plain in Sardinia (Italy) is characterized by an intense agricultural activity based on dairy cattle farming (approximately 31.000 livestock units in the district). The area, reclaimed from a lagoon in the 1920s, is intensely used for fodder crops to feed the cattle. Thus, an important drainage network has been developed to maintain the soil in suitable conditions for agriculture. Heterogeneous nitrates contamination of the aquifer system has been highlighted through soil sampling and groundwater monitoring in the Arborea plain in previous studies and the zone is classified as a Nitrates Vulnerable Zone (following Directive 91/676/CEE). The hydrogeology of the study site is characterized by two main aquifers: the upper one, unconfined, hosted in a sandy unit (SHU), separated from the second aquifer, hosted in an alluvial formation (AHU), by lagoon deposits aquitard.

In the present study, we show the individual work steps to get from the existing 3D hydrogeological model to a 3D numerical groundwater model using the interactive finite-element simulation system Feflow 7.4. The developed partially unstructured steady-state flow model takes into account the recharge of the aquifer system by surface water, the drainage and irrigation network and the seasonal variation of water volumes drained and spread on the land. Also accounted for are water pumped by farms for technical use and livestock, groundwater flow between the different units and interactions with seawater. Results show the influence of groundwater management, especially for agricultural activities, and interaction with surface water, which is highly impacted by anthropic networks (irrigation and drainage). Ongoing research is aimed at quantifying the spatio-temporal distribution of nitrate in the SHU aquifer

under transient groundwater flow conditions to compare different water management, climate change and contamination scenarios.

Acknowledgements

The project is funded by the General Secretariat for Research and Technology of the Ministry of Development and Investments under the PRIMA Programme. PRIMA is an Art.185 initiative supported and co-funded under Horizon 2020, the European Union's Programme for Research and Innovation. We also acknowledge funding from the Italian Ministry of University and Research CUP no. J84D18000180005.

Quantitative groundwater modelling of the Wadi El-Bey watershed (Tunisia)

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The PRIMA Sustain-COAST European project aims at exploring innovative governance for sustainable coastal groundwater management and pollution reduction in the context of a changing climate. Four study sites have been selected, among them the Wadi El-Bey watershed in Tunisia, located about 40 km south of Tunis. The study area is the Grombalia aquifer whose size is approximately 391 km². It is boarded to the north by the Gulf of Tunis and the Tekelsa Hills, to the east by the Abderrahman Mountain and the oriental coastal highlands, to the south by the Hammamet Hills, and to the west by the Bou Choucha and the Halloufa mountains. The Grombalia aquifer constitutes a complex aquifer system formed by shallow unconfined, semi deep, and deep aquifers with different exploitation levels. The interest of the study relies on the upper aquifer. Surface flow occurs mainly in 5 wadis toward the north, reflecting regional topographic gradients.

During the last few decades, the Grombalia shallow unconfined aquifer had been under stress by groundwater pumping due to the increasing population and development of agricultural and industrial activities. Recently, it has been noticed in some wells a rise in the level of the water table due to the abandonment of the exploitation of surface wells and to the irrigation by the water transferred from the north of the country, and considerable deterioration of groundwater quality due to saltwater intrusion and increased nitrate contamination as well as the organic matter in terms of COD.

A groundwater numerical model for the Grombalia aquifer has been developed using Feflow 7.4 to simulate groundwater level changes under steady state and transient conditions. The steady state flow calibration was carried out using the water levels measured 1972 in 35 observation wells and then used as initial state of the Grombalia aquifer system. The groundwater model constitutes a solid basis for further studies under transient flow and transport conditions to compare different water management, climate change and contamination scenarios, and is part of the calibrated multi-criteria decision supporting system developed in the PRIMA Sustain-COAST project context.

Acknowledgements
The project is funded by the General Secretariat for Research and Technology of the Ministry of Development and Investments under the PRIMA Programme. PRIMA is an Art.185 initiative supported and co-funded under Horizon 2020, the European Union's Programme for Research and Innovation.

The PRIMA programme is an Art.185 initiative supported and funded under Horizon 2020, the European Union's Programme for Research and Innovation.

Modelling the Water-Energy-Food-Ecosystem Nexus in the JRC

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The origin of the Water Energy Food and Ecosystems Nexus in the Joint Research Centre (JRC) came after the acknowledgement we had to move away from sectorial approach in 2019. This is the reason why in the JRC, we started combining the expertise in the fields of Water Resources modelling and management, with energy modelling that both depend on climate projections, and assess how agriculture and ecosystems will fare.

The latest version of our in-house developed hydrological and water resources management model, LISFLOOD, has incorporated a fully coupled crop growth model (EPIC). Using the new model, we can make assessments, on different types of water saving measures, like irrigation efficiency, water reuse, desalination, urban distribution systems improvement, etc. We can also assess the impact of different scenarios to the crop growth, and subsequently our food security. For example, with the new model, we can estimate the yield loss if we decide to go for deficit irrigation, or to see how the groundwater is expected to be depleted if we pump from there to cover the need for full irrigation.

The Water Exploitation Index (WEI+), i.e. consumption over availability, is our preferred index for our analyses, as it is a good index to show water scarcity. It shows how much of the available water is consumed, without returning to the water systems. Even for current climate, there are river basins, considered to be water stressed (WEI+>0.2). At a country level, we can see that at least two Member States would be considered under ‘severe’ water stress, and two more under water stress.

The preliminary assessment of four water efficiency measures on WEI-abstraction, as estimated with the LISFLOOD shows that although it is obvious that all these measures help, reducing abstractions, we see that the proposed measures, so far, might not be able to counter the effect of climate change. If we see the combined effects, for most of the countries, the effect is less than 15% and, in many countries, it is close or less than 5%. More ambition is needed on water efficiency in the Mediterranean to keep water scarcity at bay.

Modeling the groundwater flow of the Malia, Crete, Greece, coastal aquifer under climate change scenarios.

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The location of the Mediterranean region can lead to crucial changes. The increase of greenhouse gases makes the Mediterranean region particularly vulnerable to climate change (1). In this work we are referred to an area on the island of Crete in Greece. Specifically, for the region of Malia, Crete a study was performed about the projections of Regional Climate Models (RCMs) regarding the mean temperature and precipitation which showed a negative trend during the period 2010-2040 (2). For the period 2040-2098, the situation appears to be worse with a greater decrease in the average precipitation and also an increase in temperature (3). Because of the increasing demands for water and the decrease of precipitation this work aims to assess the impact of the future climatic scenarios on the groundwater resources.

This work presents the simulation of the Malia aquifer system with the use of the numerical simulator FEFLOW which is an advanced Finite Element subsurface FLOW and transport modelling system (4). The simulations are based on data in the study area for the period 2000-2012. The data that are used are obtained either from the literature or from field measurements that are available on different databases.

The climate scenarios that were used in this work were produced in collaboration with the University of Parma. The climate projections were produced by 17 RCMs based on two Representative Concentration Pathways (RCPs 4.5 and 8.5). The period 1976-2005 consists of the historical data and the period 2006-2098 is the scenario period.

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Acknowledgements
This work is part of the Sustain-COAST project and is funded by the General Secretariat for Research and Technology of the Ministry of Development and Investments under the PRIMA Programme. PRIMA is an Art.185 initiative supported and co-funded under Horizon 2020, the European Union's Programme for Research and Innovation.