ARISTOTLE UNIVERSITY OF THESSALONIKI
DEPARTMENT OF GEOLOGY
Laboratory of Engineering Geology and Hydrogeology

Research Project (Code 97824)

Groundwater depletion. Are Eco-friendly Energy Recharge Dams a solution?

FINAL PROJECT REPORT / (WP6/D6-3)

GroundwateR DePLETION

PRINCIPAL INVESTIGATOR:
KAZAKIS NERANTZIS
Dr. HYDROGEOLOGIST

Funding: Hellenic Foundation for Research & Innovation H.F.R.I.

February 2024

Table of Contents

Summary of the Project

Groundwater is a primary source of drinking water for up to 2 billion humans worldwide. Moreover, it is critically important for energy, food security, human health and ecosystems. Yet, depletion of groundwater reserves is a common phenomenon in both humid and semi-arid regions of the world. Although non-sustainable groundwater exploitation has been documented on both regional and global scales, specific spatiotemporal characteristics need to be further studied and quantified. The phenomenon of groundwater depletion occurs when extraction from an aquifer exceeds the recharge, with the extent of the depletion effects being also determined by the aquifer type. The main cause of groundwater depletion is the excessive extraction for irrigation especially in cases the aquifer is only replenished in a slow manner, while climate change could potentially exacerbate the challenge in some regions. Vertical distribution and seasonality of snow coverage, drought events, and rainfall and temperature variation are some of the climate parameters which influence groundwater depletion. Additionally, the aquifer type, land use, population density, availability of surface water for groundwater artificial recharge constitutes important aspects in the study of groundwater depletion. Effective strategies to mitigate groundwater depletion built on effective groundwater modeling incorporating land use, climate and water management scenarios. Artificial groundwater recharge through treated wastewater or surface water could aquifer replenishment and reverses its depletion. However, artificial recharge is a complex and high cost option, and groundwater simulation models should evaluate it before its large scale in situ application.

In Greece, groundwater is an almost ubiquitous source of fresh water and covers about 60% of the water demand. Indisputably, preserving groundwater reserves is of outmost importance to support economic activities (food, tourism, industry, energy) as well as to ensure human health and ecosystems. Due to its importance, the phenomenon of groundwater depletion needs to be further studied, adopting cutting edge methods and innovative approaches. The first attempt is dated in 2013 through the development of Water Resources Management Plans of Water Districts of Greece. Nevertheless, these plans are limited to qualitative descriptions regarding groundwater quantity and quality.

The present research project aims to quantify groundwater depletion in representative aquifers of Greece and determine those parameters that have exacerbated this phenomenon. Moreover, various model-based strategies will simulate scenarios to inverse groundwater depletion. On the core of the scenarios will be the use of small recharge dams, while their transformation to mini-scale hydropower facilities and will benefit clean energy production, save CO2 emissions and lead to an economically feasible strategy against groundwater depletion. Accordingly, the project will create interdisciplinary approaches building on a team that cross-cuts different scientific fields.

The main output of the GRecoDAM project can be summarized below:

- The comparison of climatic/non-climatic highlighted that mis-management is the main factor of groundwater depletion, while climatic parameters will influence groundwater reserves in the future.

- Snowfall modeling and analysis for 60-year period showed an increased trend during the periods of 2000 and 2013; however, decreasing trends starting from 2013 occurred.
- Groundwater depletion occur in the three sites of Greece influencing the quality of groundwater in the coastal aquifers due to seawater intrusion.
- The pumping cost is tripled in groundwater depletion zones.
- The transformation of small dams and apply MAR with injection wells can significantly decrease or eliminate in some cases groundwater depletion zones.
- The optimization code and software for dam operation revealed that the hydropower can reach up to 1683.19 MWH/year.
- The use of small dams for hydropower generation requires improvements in existing relevant legislation. The main issue constitutes the bureaucracy and the numerus involved agency in order to get the final licence.

Additionally, specifying the conclusions to groundwater depletion the project resulted to the following:

- High drought events can influence groundwater decline.
- Rainfall events during the summer period slightly contribute to groundwater recharge.
- Mis-management of groundwater constitute the triggering factor of groundwater depletion occurrence.
- Small dams can store the water from extreme summer rainfall events and increase groundwater reserves during the summer period by applying MAR.
- The energy production and groundwater recharge quantity can reach up to 1500 MWV/year and 5×10^6 m^3 per year in the studied aquifers.

The phenomenon of groundwater depletion occurs at 27%, 22.8%, and 11% in the Eastern Thermaikos Gulf, Marathonas and Mouriki basin, respectively. The depletion zone will extend until 2030 if the pumping rates remain the same under the RCP 4.5 scenario. The transformation of dams to mini-scale hydropower facilities and applying MAR will benefit clean energy production, save CO_2 emissions, and lead to an economically feasible strategy against groundwater depletion. In the Upper Volturno basin, the quantity of groundwater is not affected by the phenomenon due to the high dynamic of the surrounding karst aquifers and the lateral inflow.

On balance, eco-friendly energy recharge dams can contribute to groundwater sustainability. However, detailed monitoring of all hydrological parameters and regular updates of the simulation process are essential for the integrated management of water resources in the Mediterranean environments.

1 Introduction

Within this report are presented the results of the project, a summary of the methodological approach and the main dissemination actions. The dominant target of the project was the mapping of groundwater and simulate scenarios to inverse groundwater depletion. On the core of the scenarios will be the use of small dams for the application of managed aquifer recharge. Additionally, the dam suggested to transform into mini-scale hydropower facilities in order to benefit clean energy production. This report is divided into four (4) main chapter. The first one provides an overview of the literature, methodology, results and discussion of the project. The next one shows the policy suggestions, while it follows the main dissemination actions and the list of the publications of the project. The final report of all work packages are available on the website of the project (https://groundwater-ecodams.web.auth.gr/) including the data that produced within the project.

The main output of all project method applications can summarize below:

- The comparison of climatic/non-climatic highlighted that mis-management is the main factor of groundwater depletion, while climatic parameters will influence groundwater reserves in the future.
- Snowfall modeling and analysis for 60-year period showed an increased trend during the periods of 2000 and 2013; however, decreasing trends starting from 2013 occurred.
- Groundwater depletion occur in the three sites of Greece influencing the quality of groundwater in the coastal aquifers due to seawater intrusion.
- The pumping cost is tripled in groundwater depletion zones.

- The transformation of small dams and apply MAR with injection wells can significantly decrease or eliminate in some cases groundwater depletion zones.
- The optimization code and software for dam operation revealed that the hydropower can reach up to 1683.19 MWH/year.
- The use of small dams for hydropower generation requires improvements in existing relevant legislation. The main issue constitutes the bureaucracy and the numerus involved agency in order to get the final licence.

With this report the work package 6 fulfilled the 12th and last milestones of the project which is the **Project end (M6.3)**. The data is available in the web-site of the project. It is necessary to have the permission of principal investigator if someone want to re-publish this data, while there are not available for commercial reasons.

2 Overview of literature, methodology and main conclusions of the project

Groundwater is a primary source of drinking water for almost two billion people worldwide (Gleeson et al., 2010). Moreover, it is critically important for energy, food security, human health, and ecosystems (Gleeson et al., 2015). Yet, depletion of groundwater reserves is a common phenomenon in both humid and semi-arid regions of the world. Although non-sustainable groundwater exploitation has been documented on both regional and global scales (Gleeson et al., 2012), specific spatiotemporal characteristics need to be further studied and quantified. The phenomenon of groundwater depletion occurs when extraction from an aquifer exceeds recharge, with the extent of the depletion effects being also determined by the aquifer type. Several research challenges prevail, the most significant being the quantification of factors triggering groundwater depletion. Inevitably, depletion leads to increased pumping costs and the reduction of groundwater discharge to streams, springs, and wetlands affecting ecosystems (Sophocleous, 2000). Additionally, lowered water tables induce groundwater flow, which can lead to salinization by seawater intrusion in coastal aquifers (Konikow et al., 2005). Eventually, groundwater depletion can even lead to dry wells. The main cause of groundwater depletion is excessive extraction for irrigation especially in cases where an aquifer is only replenished gradually, while climate change could potentially exacerbate the phenomenon in some regions (Weider and Boutt, 2010; Pranjal et al. 2021). Global food production has increased dramatically since 1970 due to advances in well-drilling equipment and electrical pumping (UNESCO, 2009), and numerous wells have been operated in a largely unregulated manner, often replacing surface-water resources. Over-irrigation may lead to crop evapotranspiration levels above those of aquifer inflow (Kendy, 2003). Accordingly, in some areas, groundwater levels have declined at rates even exceeding 1 m per year (Kendy et al., 2004). On the other hand, climate-related changes might also influence recharge rates and aggravate groundwater depletion (Bates et al., 2008) as recharge rates are influenced by the distribution and seasonality of snow coverage (Schneider and Molotch, 2016) as well as drought events (Mavromatis, 2009). Projecting the effects of climate change on groundwater is a challenging task with uncertainties in all the steps of the process (Crosbie et al., 2011). So far, the impact of climate change on aquifer depletion has only moderately been compared with non-climatic drivers (Kundzewicz et al., 2007). Such a comparison although complex, can potentially divulge unknown aspects of groundwater depletion.

Effective strategies to mitigate groundwater depletion can be built on effective groundwater modeling incorporating land use, climate, and water management scenarios (Aeschbach-Hertig and Gleeson, 2012). Nonetheless, groundwater modeling requires detailed hydrogeological and hydrological knowledge of a studied system to develop a robust conceptual model and increase reliability (Anderson et al., 2015). Managed aquifer recharge using treated wastewater or surface water could offer aquifer replenishment and reverse its depletion (Foster et al., 2004). However, managed aquifer recharge is a complex and high-cost option, and groundwater simulation models should evaluate it fully before its large-scale in situ application (Pliakas et al., 2005). Managed aquifer recharge faces certain limitations regarding location, timing, available water, and its distance from the area to be recharged. Dams can store surface water in periods of abundant precipitation, protect lowlands from flooding, and provide periods with increased water demands. Recent studies have shown that groundwater depletion may be offset if more surface water is stored in reservoirs behind dams (Wada et al., 2012). Additionally, these dams can be transformed into mini-scale hydropower facilities - multi-scope dams – and produce clean energy (Patsialis et al., 2017). For instance, in Greece, small hydroelectricity applications have a very good techno-economic performance and, therefore, a promising future (Kaldelis, 2007). In Mediterranean countries, groundwater is an almost ubiquitous source of fresh water and covers about 60% of the water demand. Indisputably, preserving groundwater reserves is of utmost importance to support economic activities (food, tourism, industry, energy) as well as to ensure the health of humans and ecosystems. Due to its importance, the phenomenon of groundwater depletion needs to be further studied, adopting cutting-edge methods and integrated approaches. In Greece, the first attempt to study groundwater depletion dates back to 2013, and this was updated in 2018 through the development of the Water Resources Management Plans of Water Districts in Greece. These plans are limited to qualitative descriptions regarding only groundwater quantity and quality; however, they do provide unequivocal evidence that in certain regions of Greece, groundwater is being depleted (Gemitzi and Lakshmi, 2018). For instance, since 1980 the decline in groundwater level recorded in the coastal area of the Eastern Thermaikos Gulf has reached a rate of over 1 m per year and has caused salinization of the local aquifer up to 5 km towards the mainland (Kazakis et al., 2016). Similar problems have also been recorded in other Mediterranean countries. Especially in coastal areas, the mismanagement of groundwater systems can lead to the drying-up of rivers and the deterioration of groundwater quality. According to global practices, model-based strategies are an efficient tool to mitigate groundwater depletion (Hutchison, 2010). Mathematical models require several parameters to be measured and quantified before being introduced into the model. Vertical distribution and seasonality of snow coverage, drought events, and rainfall and temperature variations, are some of the climatic parameters that influence groundwater depletion. Additionally, the aquifer type, land use, population density, and availability of surface water for artificial groundwater recharge, all constitute important aspects in the study of groundwater depletion. The critical step of every simulation process is the model validation and verification.

2.1 Study sites

Four representative areas have been selected in Greece (three sites) and Italy (one site) (**Figure 2.1**) with different hydrogeological, climatological, and socio-economic characteristics and required data availability to accomplish the goals of this article. The characteristics of the study areas are briefly described below:

Study area 1: Study area 1 is the coastal area in the eastern part of Thermaikos Gulf located in Northern Greece. The mean annual rainfall is 451 mm, and the mean annual temperature is 15.1°C. Groundwater is the area's main source of drinking water. Agricultural, livestock, and industrial water demands are also met with groundwater. Porous-medium aquifers occur in sedimentary deposits, metamorphic and igneous rocks contain localized fractured-rock aquifers, whereas karst aquifers are found in areas underlain by limestones. The quality of groundwater is influenced by seawater intrusion in the coastal area of the site, geothermal fluids occur in the center of the site (Kazakis et al., 2016). The site contains five small dams which were built in the past to protect populated areas and farmlands from flooding.

Study area 2: The second area is Perdikas basin located north of Kozani city in northern Greece. The mean annual precipitation in this area is 636.5 mm and the mean annual temperature is 11.2°C. The main aquifer system is developed in alluvial formations with a mean thickness of 70 m. Significant fractured rock aquifers occur locally in areas underlain by crystalline basement rocks. Agricultural and livestock activities are mainly located in the lowlands, whereas mixed forest constitutes the land cover of the mountainous part. Nitrate pollution due to intensive agricultural activities has been reported in previous studies (Patrikaki et al., 2012). One small dam which was also built for flood mitigation and agriculture is located within the study area.

Study area 3: The Upper Volturno in Campania Plain, central Italy, is the third study area. The mean annual precipitation recorded here is 800 mm with a mean annual temperature of 18°C. The main aquifer system is developed in alluvial formations with a mean thickness of 60 m (Busico et al., 2017). Important karst aquifers occur in the mountainous part of the study area. Agricultural and livestock activities are mainly located in the lowlands, whereas mixed forest constitutes the land cover of the mountainous part. Nitrate pollution due to intensive agricultural activities has been reported in previous studies. Campania Plain contains one small dam that was originally built for flood mitigation.

Study area 4: Study area 4 is the basin of Marathonas, located in central Greece, near Athens. It has a recorded mean annual rainfall of 380 mm and a mean annual temperature of 17.4°C. A porous aquifer is located in the coastal area of the site, whereas karstic aquifers are found in areas underlain by marbles (Zavridou et al., 2018). Groundwater is mainly used for domestic use and irrigation in the sub-urban coastal zone. Both aquifers are subjected to intense pumping due to extensive agricultural activities, with an extended irrigation period (greenhouses) in most of the plain. As a result, groundwater depletion and seawater encroachment have occurred in both formations, the unconsolidated formation being more widely affected. In this study area, one small dam was built to protect downstream areas from flooding also in view of the 2004 Olympic Games Athens' Marathon Route.

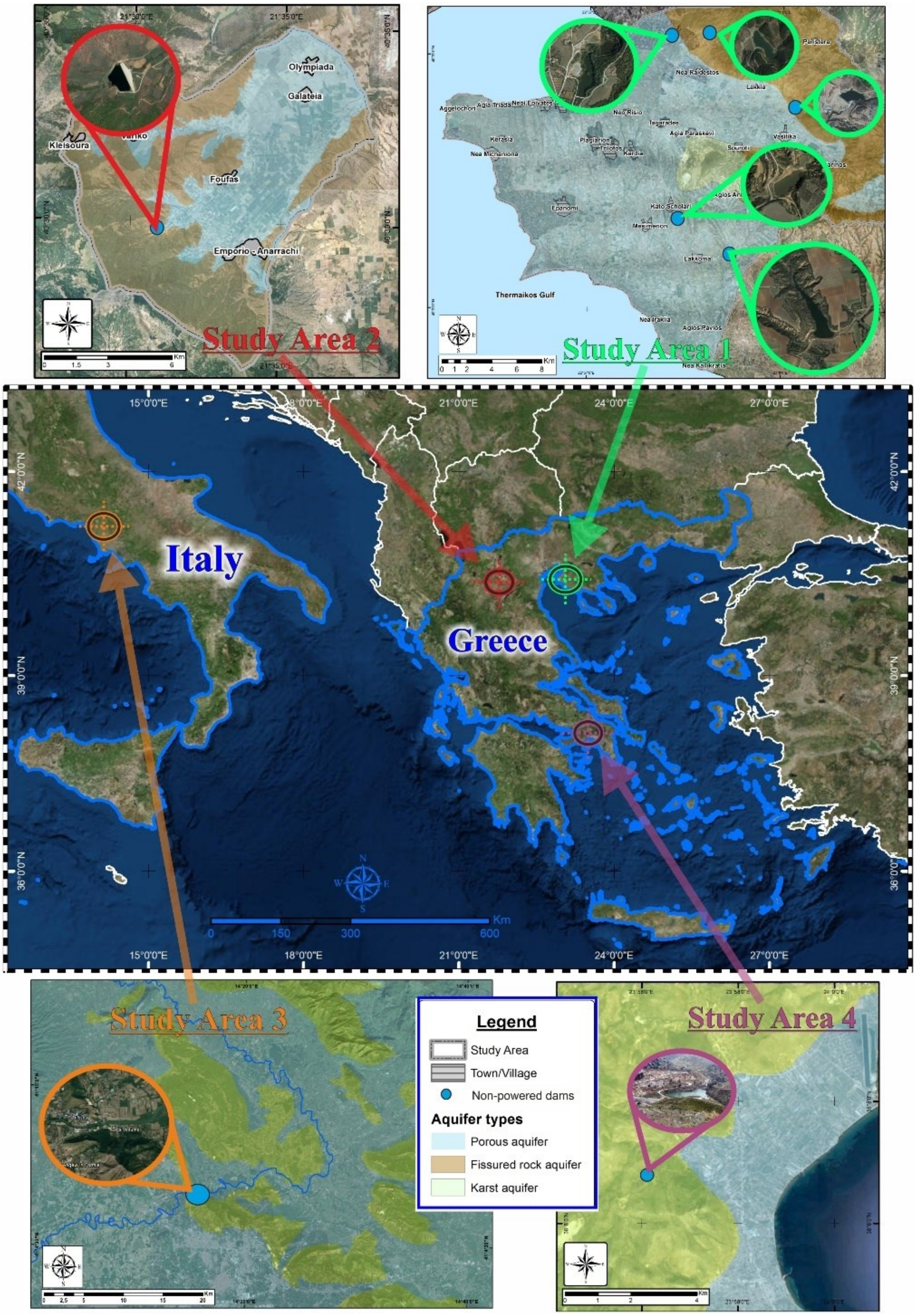


Figure 2.1 Study areas and non-powered Dams.

2.2 Methodology

The methodology of this study is based on the interdisciplinary approach of analyzing atmospheric parameters such as rainfall variation and intensity, snow variability, and drought. The next step was the modeling of surface runoff with the ArcSWAT model using climatological data. Dam operation was simulated for hydropower generation, while the output water was destined for managed aquifer recharge. The final step was the simulation of groundwater dynamics with Modflow code applying scenarios for the application of managed aquifer recharge using dam water for this purpose. A flow chart of the methodological approach is shown in **Figure 2.2**. The determination of the optimal codes for the simulation of the interaction between groundwater and surface water as well as the MAR methods was initially obtained resulting in Modflow and ArcSwat constituting the dominant approaches in existing literature. A detailed analysis is presented by Ntona and Kazakis (2022) and Ntona et al. (2022c). Within this project the modeling process coupled with the DPSIR management – policy model is also provided in Ntona et al. 2023c. Snowfall and spatial distribution were also determined to supplement the modeling process and correlate with groundwater depletion in the study areas (Voudouri et al., 2021; Voudouri et al., 2023). The simulation of ArcSWAT obtained in the Eastern Thermaikos Gulf, Upper Volturno basin, Marathonas basin and Mouriki basin are presented in Busico et al., 2021, Ntona et al., 2023c and in the final deliverable of work package 5 (D5-4). Hence, the input of the dams was available, in order to be used in the code for the hydropower optimization as presented in Karakatsanis et al. (2023) and in the final report of work package 3. The results of dam simulation were presented in work package 5, as well as the simulation of groundwater, mapping of depletion zones, and simulation of future conditions under the application of MAR. A critical question for the application of MAR constitutes the quality dam water which was studied and concluded that be suitable for MAR application (Kalaitzidou et al., 2023). Additionally, the quality of groundwater was detailly studied and introducing new methodological approaches as presented in Ntona et al. 2023a, Ntona et al. 2023b and Ntona et al. 2023d.

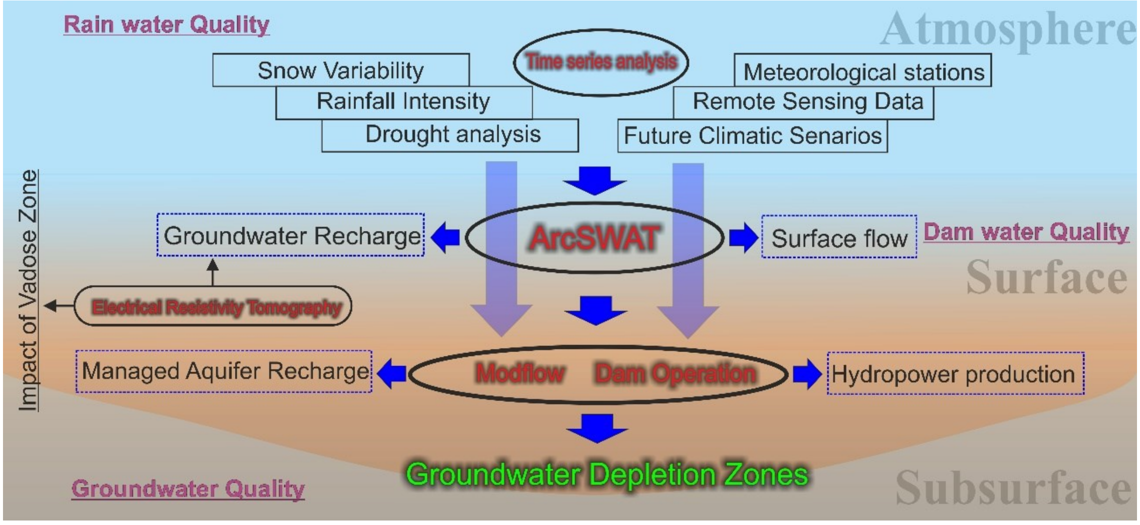


Figure 2.2 Flow chart of the methodological approach.

2.2.1 Geophysical research

The concept of the electrical resistivity measurements (ERT) within this study was to determine the recharge regime in Eastern Thermaikos Gulf. Hence, an array of 24 electrodes with 2 acquisition protocols was established including the Dipole-Dipole protocol with 195 stations (measurements) and the Multiple Gradient protocol with 442 stations (measurements). A data set, consisting of those 2 protocols, was measured at 4-hour intervals, providing until now 4.757 dated apparent resistivity data sets (more than 3 million measurements) from the period of September 2021 to December 2023. The data were collected weekly in situ and transferred from the electrical resistivity device to the laptop’s memory. Each apparent electrical resistivity measured protocol of the data sets was inverted with Geotomo “res2Dinv” software using standard constraints on the data and the model. The inversion process is based on a 2.5D finite-element routine that solves the forward resistivity problem with an iterative least-squares algorithm with active constraint balancing for the reconstruction of the actual subsurface resistivity model. The ERT measurement was supplemented with a meteorological measurement with a small meteorological station and a probe for soil moisture and temperature measurements.

2.2.2 Estimation of Drought – SPEI index

The Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) was applied to identify the drought severity in the study areas. SPEI drought index was chosen due to the limited input data needs. Monthly values of precipitation and minimum and maximum values of temperature were used. The drought index was calculated for different aggregation periods (1, 3, and 6 months) in the R programming code. The 6-month time scale had the optimum results, and the drought events were classified based on SPEI values (Table 2.1). Forecast SPEI was calculated based on REMO2009 data with projections based on Representative Concentration Pathway 4.5 (RCP 4.5) for the period 2020-2040.

Table 2.1. Drought categories based on SPEI values.

SPEI	**Category**
>2.00	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
-0.99 to 0.99	Mild drought
-1.00 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
≤-2.00	Extreme drought

Meteorological data from the Makedonia station were collected to classify SPEI in Eastern Thermaikos Gulf. In Mouriki basin, meteorological data were collected from Aristotelis meteorological station, while in Marathonas basin, data from the Climate Forecast System Reanalysis (CFSR) model was used for the climatic information due to gaps in the existing datasets from nearby stations. The CFSR provides the best estimate of the state of coupled atmosphere-ocean-land surface-sea ice system domains in high resolution (Dee et al., 2013). The detailed draught analysis and time series analysis of meteorological parameters present in the final report of work package 3 and in Ntona et al. 2022a and Ntona et al. 2022b.

2.3 Summary of the main project results

In Eastern Thermaikos Gulf seven drought periods of more than 15 months are recorded according to the SPEI index between 1958 to 2040 (Figure 2.3). These drought periods are observed in 1958-1959 (16 months), 1977-1978 (15 months), 1984-1985 (17 months), 1992-1994 (17 months), 2011-2014 (35 months), 2021-2028 (82 months of extreme drought) and 2038-2040 (39 months). In the same period of 1958-2040, six long wet periods with a duration of more than 15 months are noted. Fifteen wet months are noted during the years 1964-1965, 1966-1967, and 2002-2003, while during the years 2014-2016, 2019-2021, and 2033-2034 there are 25, 22, and 21 continuously wet months, respectively. In Mouriki basin, five drought periods with a duration of more than 15 months occur (Figure 2.4). The long drought periods are noted during 2000-2002 (18 months of moderate drought), 2006-2008 (26 months), 2011-2012 (15 months), 2025-2028 (33 months of moderate to severe drought), and 2039-2040 (24 months). Two long wet periods are noted during 2002-2003 (15 months) and 2036-2038 (19 months).

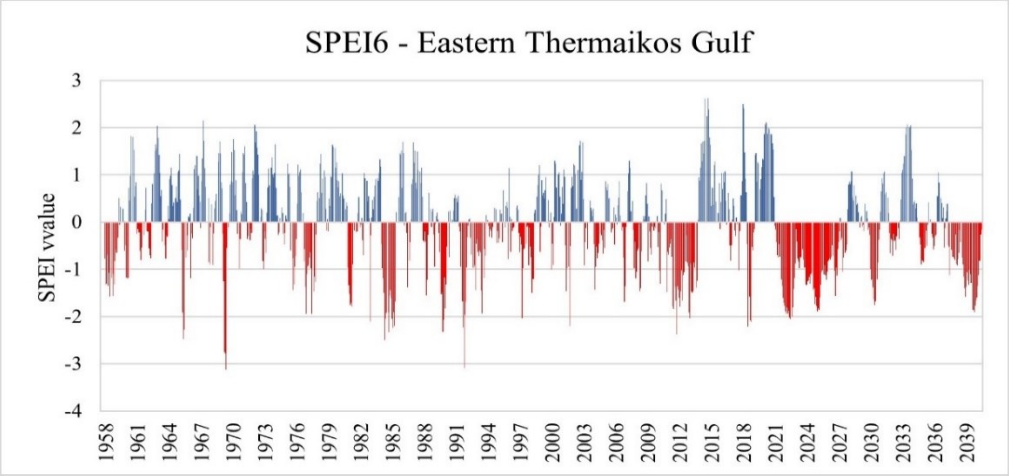


Figure 2.3 Past and forecast SPEI in the period 1958-2040 for Eastern Thermaikos Gulf.

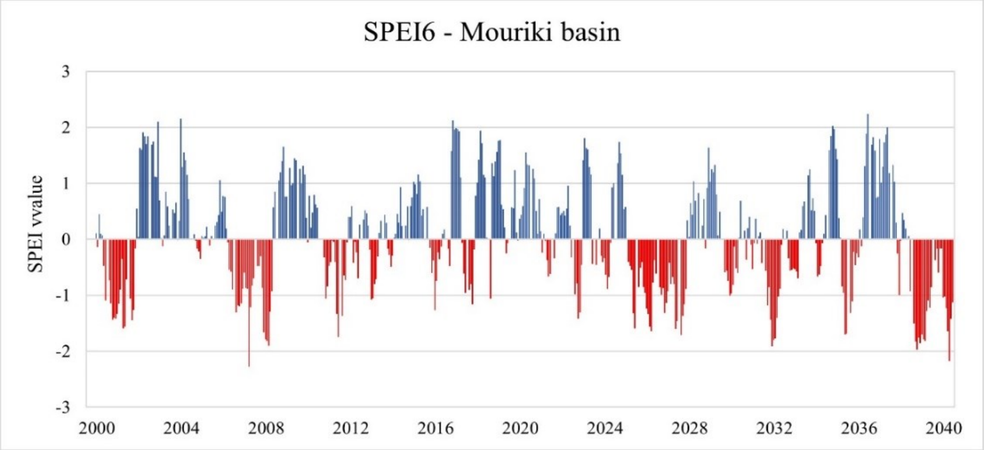


Figure 2.4 Past and forecast SPEI in the period 2000-2040 for Mouriki basin.

In Marathonas basin, the maximum long period of drought is 13 months (Figure 2.5). Three drought periods are observed during 2007-2008 (12 months of severe drought), 2024-2025 (13 months) and 2035-2036 (12 months). Three long wet periods are observed in Marathonas basin of a maximum of 12 months duration in 2003-2004, 2017-2018, and 2020-2021. In Upper Volturno basin, four long periods of drought are observed (Figure 2.6) during the years 2003-2004 (15 months), 2006-2008 (20 months), 2032-2034 (25 months of severe drought), and 2035-2036 (17 months of severe drought). Three long wet periods are noted during 2009-2011 (32 months), 2012-2014 (26 months) and 2023-2024 (18 months). In all studied sites is obvious that future projection is characterized by long periods of draught. In the Eastern Thermaikos Gulf, such periods occur from 2009.

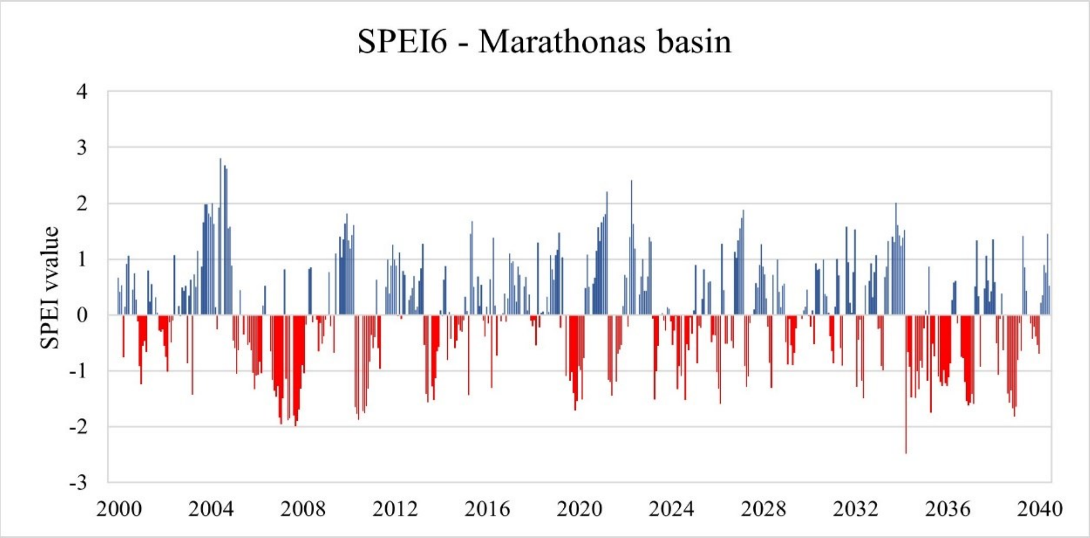


Figure 2.5 Past and forecast SPEI in the period 2000-2040 for Marathonas basin.

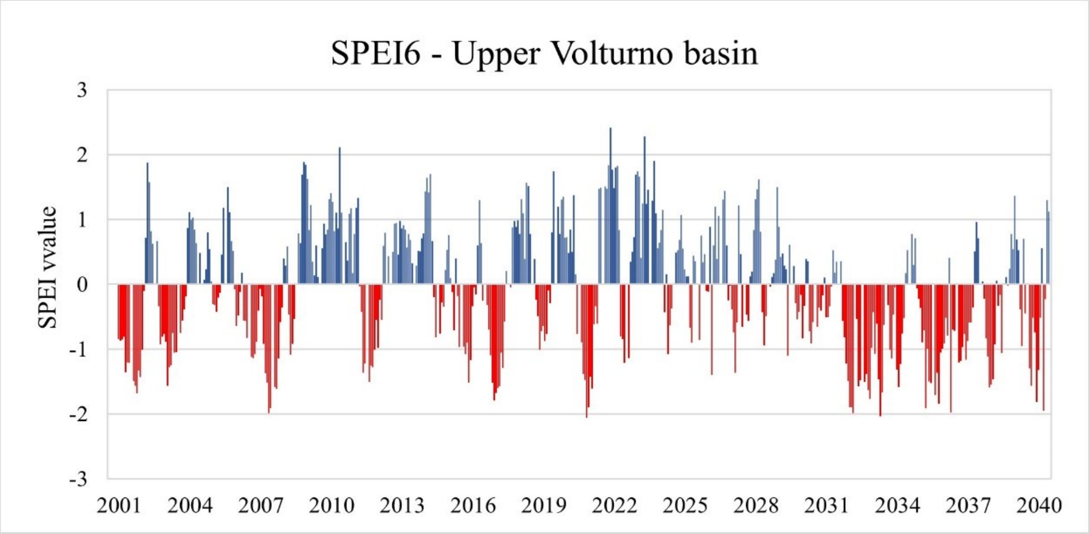


Figure 2.6 Past and forecast SPEI in the period 2001-2040 for Upper Volturno basin.

The monitoring parameters ad ERT median vales in the upper vadose zone of Eastern Thermaikos Gulf are shown in Figure 2.7. These data were analysed for all precipitation events and an example is shown in Figure 2.8. The analysis resulted that during the period between June to October the recharge from precipitation is neglected or zero. Additionally, the recharge rates are variable and might reach up to 30 days per meter to penetrate from the upper vadose zone to deeper zones.

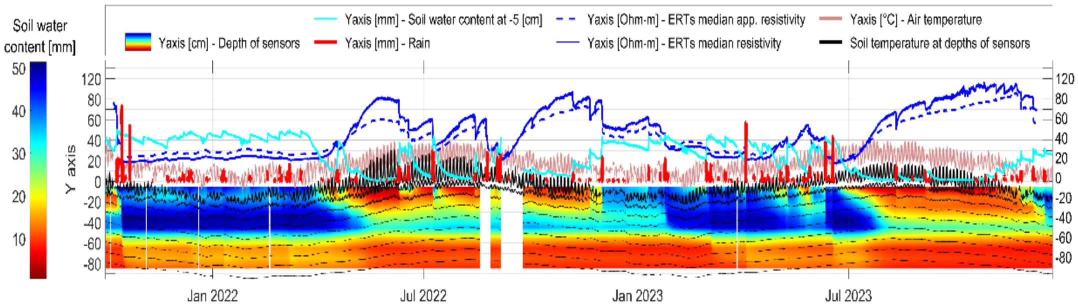


Figure 2.7. Monitoring parameters of the vadose zone.

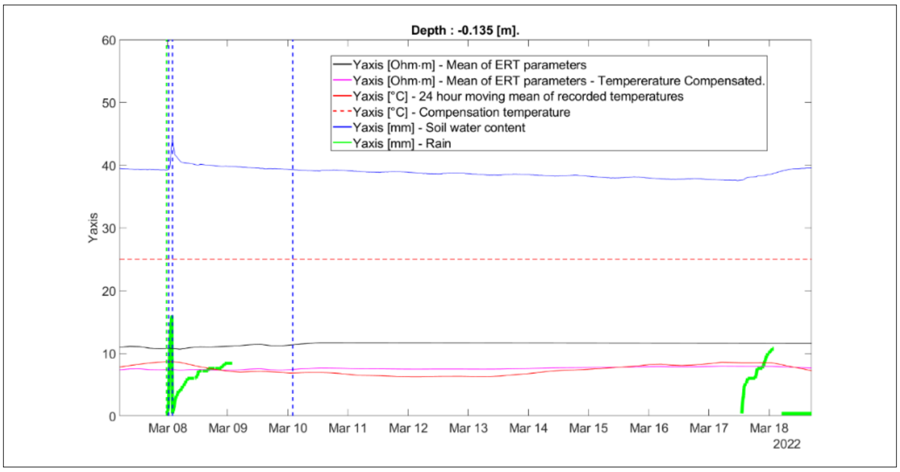


Figure 2.8. Time points selection for precipitation incident of 8 March 2022.

The simulation of groundwater revealed that in Eastern Thermaikos Gulf, Marathonas and Mouriki basin groundwater depletion occurs. Contrawise, in the Upper Volturno aquifer the phenomenon does not occur due to the surrounding karst aquifer and the later recharge of the aquifer.

In Eastern Thermaikos Gulf, the piezometric head has negative values up to – 6 m near the coastline for the period of 2020 (Figure 2.9), while up to 2030 groundwater decline will lead to a negative piezometric head up to -13.6 m (Figure 2.10). Toward the mainland, the piezometric head reaches up to 62 m, while a dropdown to 55 m occurs in the simulation of 2030. During the year 2020 groundwater depletion extended in 27.7% of the porous aquifer (Table 2.2). The simulation forecast that the groundwater depletion zone will extend up to 42 % of the aquifer until 2030 (Table 2.3).

Table 2.2 Statistics of groundwater depletion zones in studied aquifers.

Study Area	**Model area**		**Groundwater Depletion 2020**		**Groundwater Depletion 2030**		**Groundwater Depletion 2040 after MAR application with existing Dams**		**Groundwater Depletion 2040 after MAR application with extra Dams**	
	Km^2	**%**	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**
Mouriki	30.66	100	3.4	11.09	15.3	49.90	4.48	14.61	0.15	0.49
Anthemountas	387.12	100	107.32	27.72	163.25	42.17	69.94	18.07	35.85	9.26
Marathonas	35.92	100	8.21	22.86	15.72	43.76	8.53	23.75	4.28	11.92

Table 2.3 Statistics of negative piezometric head zones in the studied aquifers.

Study Area	**Model area**		**Negative Piezometry 2020**		**Negative Piezometry 2030**		**Negative Piezometry 2040 after MAR application with existing**		**Negative Piezometry 2040 after MAR application with extra Dams**	
	Km^2	**%**	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**
Anthemountas	387.12	100	86.32	22.30	118.05	30.49	16.44	4.25	14.96	3.86
Marathonas	35.92	100	4.01	11.16	10.68	29.73	3.59	9.99	2.63	7.32

The scenario with the application of MAR by using the water of the existing small dams in the site from 2030 to 2040 is depicted in the negative piezometric which decreased up to -0.84 m (Figure 2.11), while the depletion zones decline to 18% (Table 2.2). The scenario with the construction of extra small dams (Figure 2.12) in the site and the application of MAR using in total of 14 dams will lead to a significant deterioration of groundwater depletion zones covering 9.2% of the aquifer (Table 2.2). The spatial distribution of the different scenarios of groundwater depletion zones is shown in Figure 2.13, while the zones with negative piezometric heads are shown in Figure 2.14. The extent of the negative piezometric zones is similar to the depletion zones (Table 2.3).

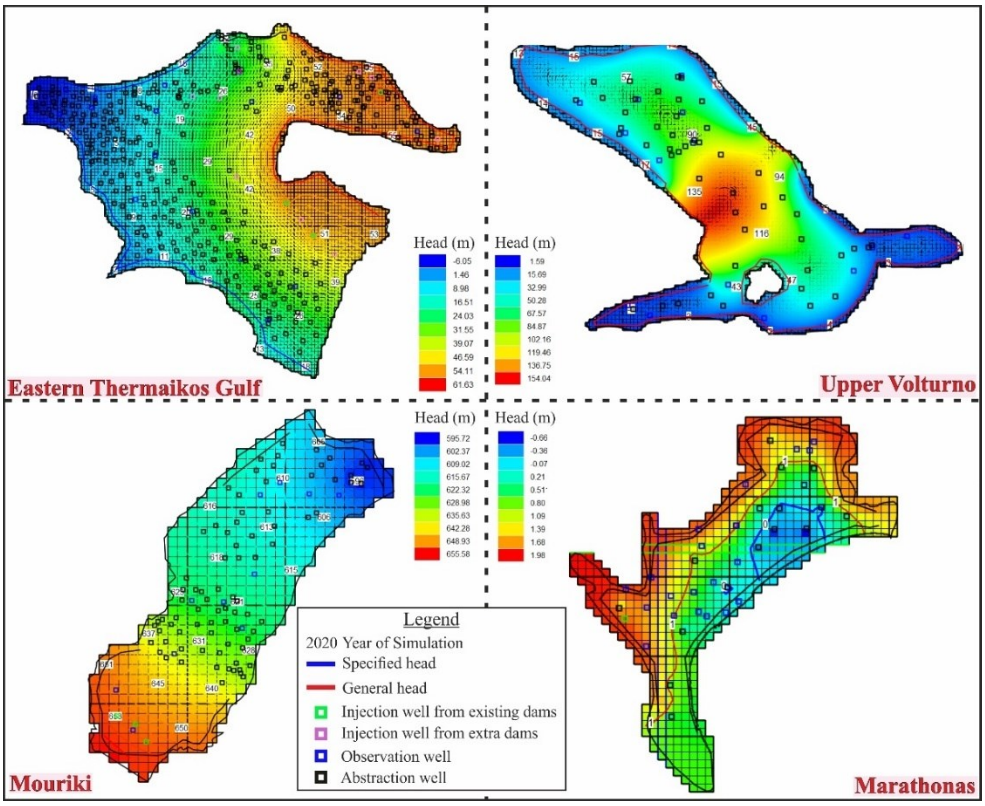


Figure 2.9. Simulation Result for the year 2020.

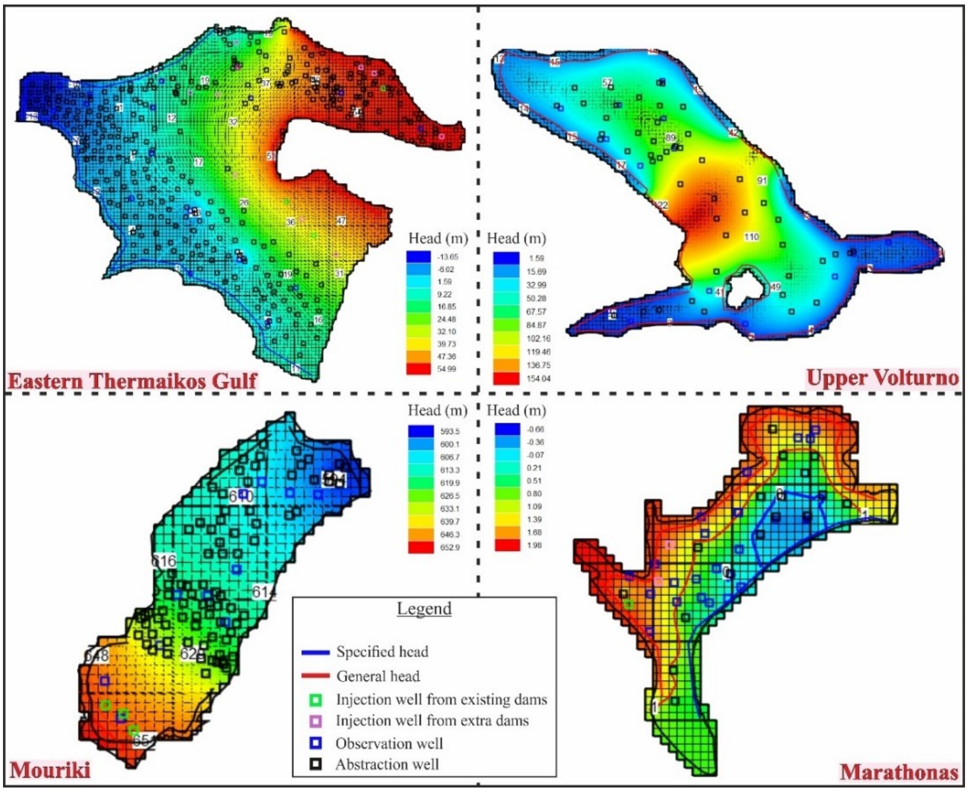


Figure 2.10. Simulation Result for the year 2030.

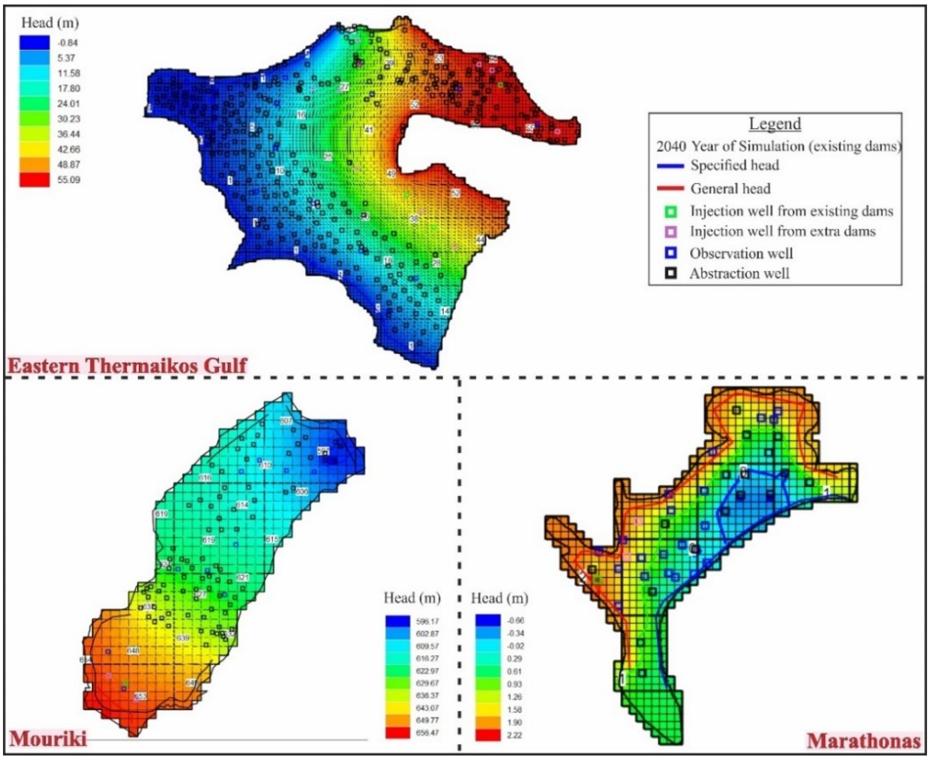


Figure 2.11. Simulation Result for the year 2040 with MAR application using the existing Dams.

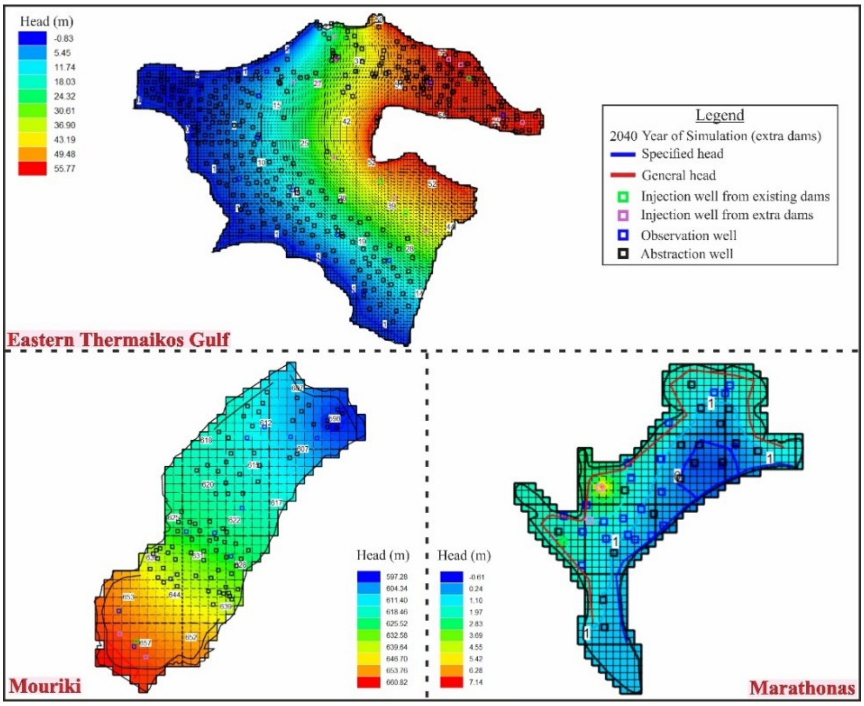


Figure 2.12 Simulation Result for the year 2040 with MAR application using extra Dams for MAR application.

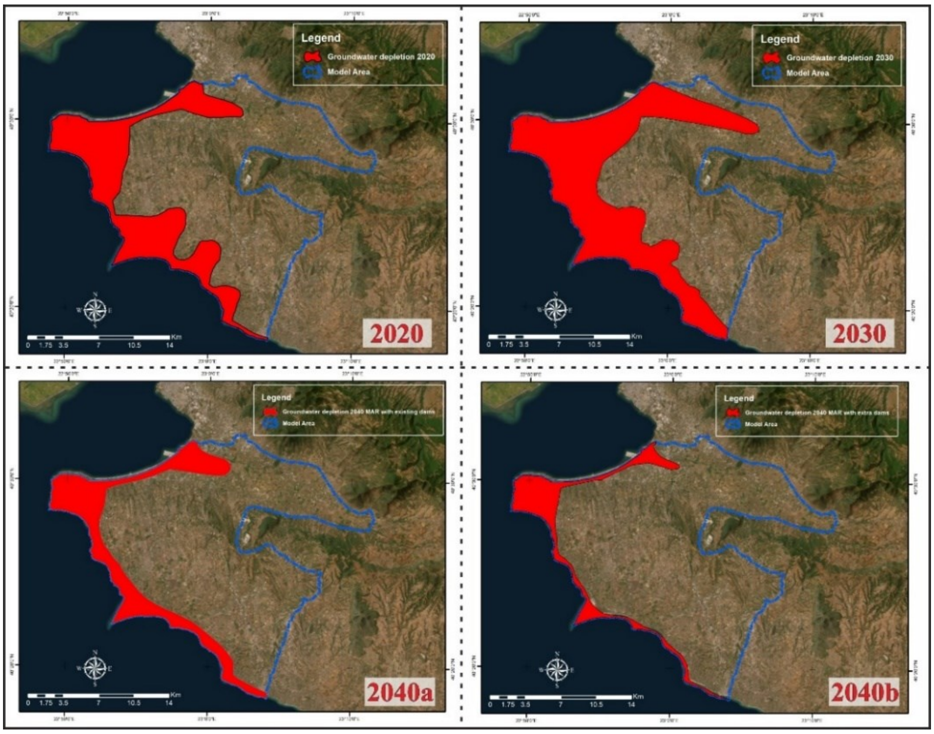


Figure 2.13 Groundwater depletion zones in the coastal aquifer of Eastern Thermaikos Gulf.

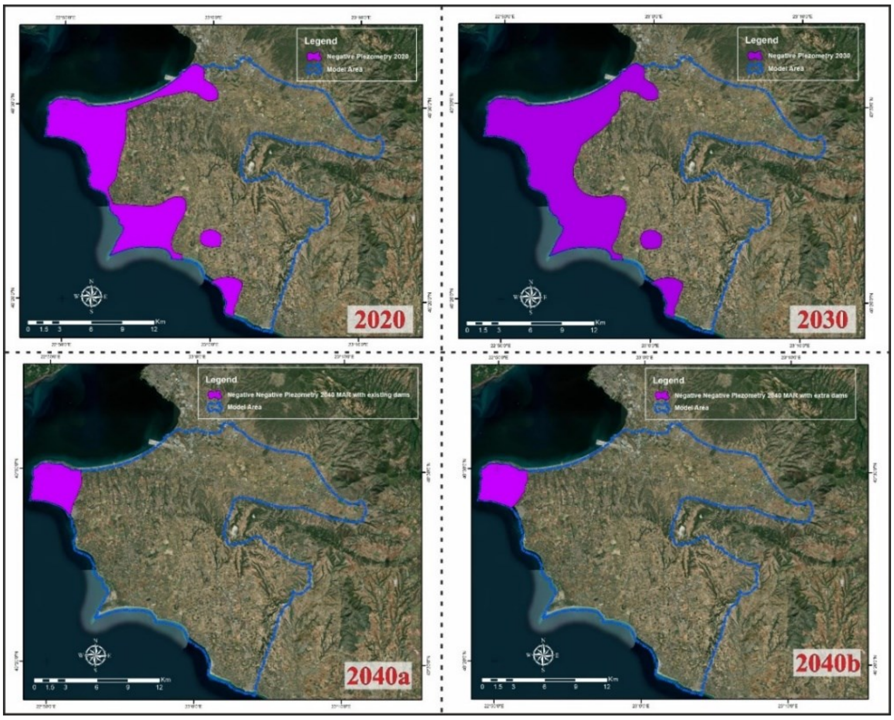


Figure 2.14 Negative piezometric head in the coastal aquifer of Eastern Thermaikos Gulf.

In Marathonas coastal aquifer, the piezometric head has negative values up to – 0.6 m near the coastline for the period of 2020 (Figure 2.9), while up to 2030 groundwater decline will lead to negative piezometric head up to -0.7 m (Figure 2.10). Toward the mainland the piezometric head reaches up to 2 m, while the maximum piezometric head is similar in the results of the simulation of 2030. During the year 2020 groundwater depletion extended in 22.8% of the porous aquifer (Table 2.2). The simulation forecast that the groundwater depletion zone will extend up to 43.7 % of the aquifer until 2030 (Table 2.2).

The scenario with the application of MAR by using the water of the existing small dams in the site from 2030 to 2040 is depicted in the maximum piezometric head with an increase to 2.2 m (Figure 2.11), while the depletion zones decline to 23.7 % (Table 2.2). The scenario with the construction of extra small dams (Figure 2.12) in the site and the application of MAR using in total 3 dams will lead to a significant deterioration of groundwater depletion zones covering 11.9% of the aquifer (Table 2.2). The spatial distribution of the different scenarios of groundwater depletion zones is shown in Figure 2.15, while the zones with negative piezometric head are shown in Figure 2.16. The extent of the negative piezometric zones is similar to the depletion zones (Table 2.3).

In the aquifer of Mouriki basin, the piezometric head varies from 595 to 6555 for the period of 2020 (Figure 2.9), while up to 2030 groundwater will vary between 593.5 to 652.9 (Figure 2.10). During the year 2020 groundwater depletion extends to 11 % of the porous aquifer, while the zone will extend up to 49 % until 2030 (Table 2.2). The scenario with the application of MAR by using the water of the existing small dam in the site from 2030 to 2040 is depicted in the maximum piezometric head with an increase to 656 m (Figure 2.11), while the depletion zones decline to 14.6 %

(Table 2.2). The scenario with the construction of extra small dams (Figure 2.12) in the site and the application of MAR using in total 3 dams will lead to a significant deterioration of groundwater depletion zones covering 0.49% of the aquifer (Table 2.2). The spatial distribution of the different scenarios of groundwater depletion zones is shown in Figure 2.17.

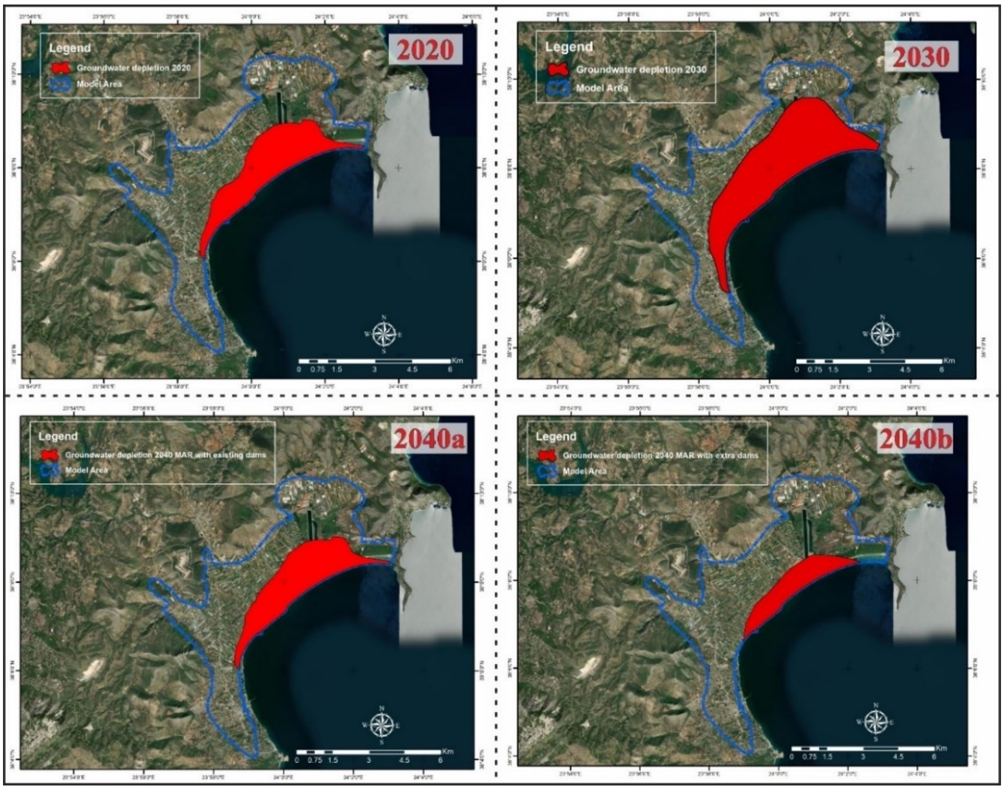


Figure 2.15 Groundwater depletion zones in the coastal aquifer of Marathonas.

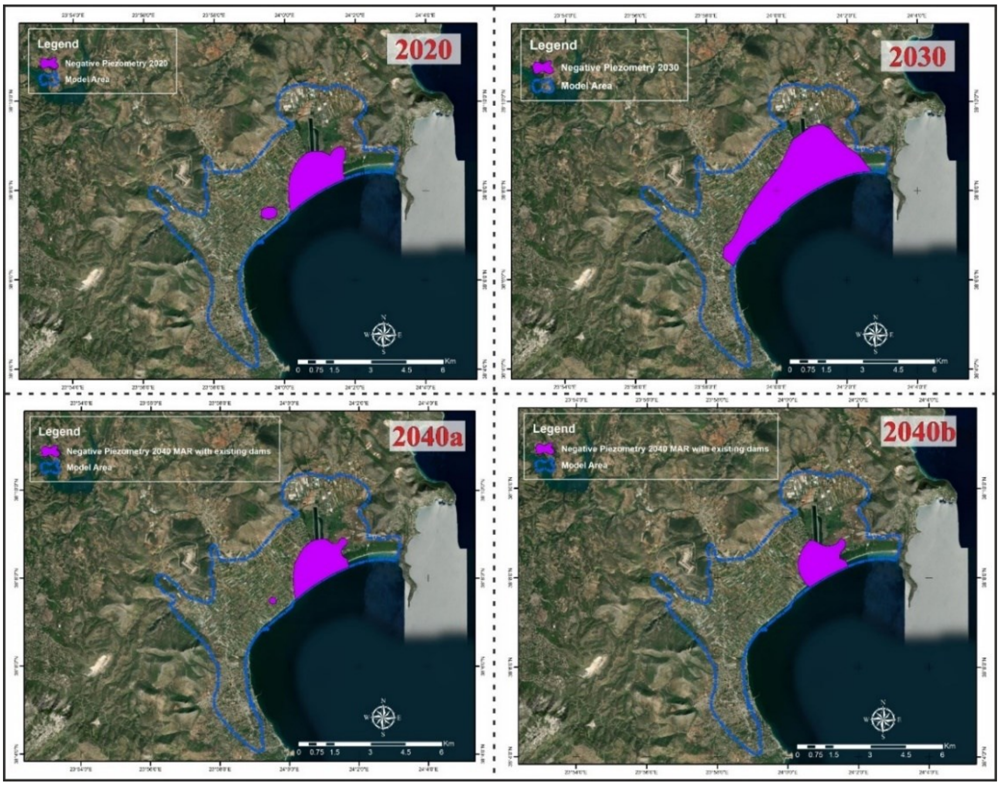


Figure 2.16 Negative piezometric head in the coastal aquifer of Marathonas.

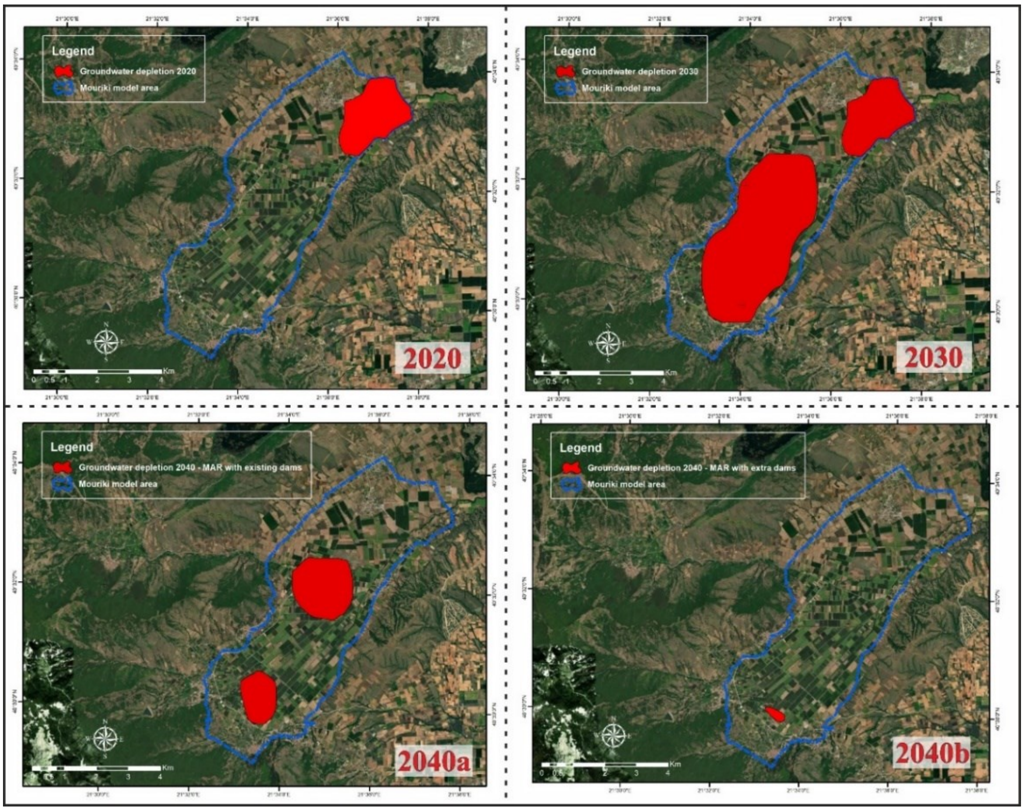


Figure 2.17 Groundwater depletion zones in the aquifer of Mouriki.

Beyond the benefits of groundwater replenishment, the transformation of the dams into small hydropower generation units will contribute to energy production. In the Eastern Thermaikos Gulf, the dams can yearly generate 832.40 MWH/year. While in Marathons and Mouriki basin, the dams can generate 1683.19 MWH/year and 132.36 MWH/year respectively. Figure 2.18 shows the mean yearly hydropower dynamic of the studied dams, while the hydrodynamic of all dams are presented in the final report of work package 5.

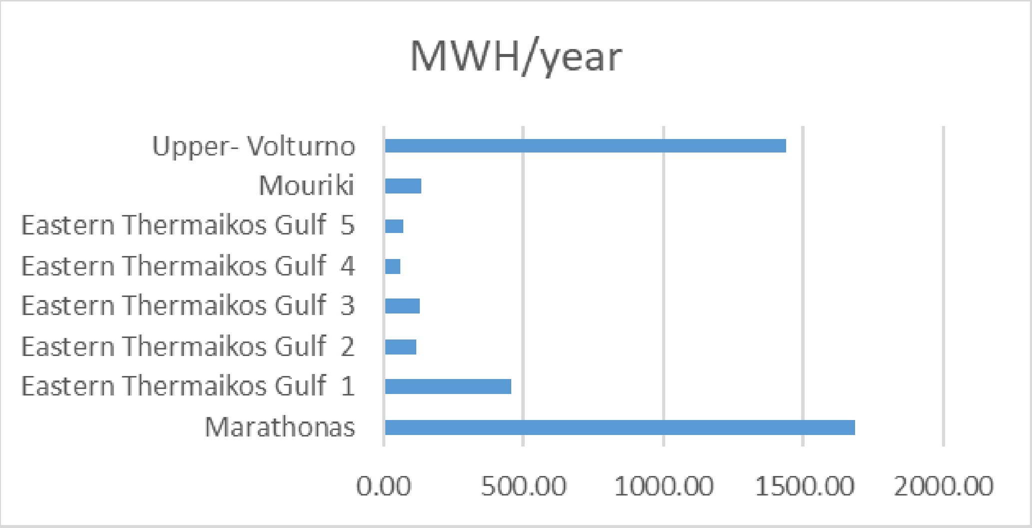


Figure 2.18 Mean annual energy production from the dams.

2.4 Discussion

Groundwater depletion constitutes a multidisciplinary phenomenon that is influenced by both climate and non-climatic parameters. Within this study, we used the tool of groundwater simulation which has been suggested in such cases (Aeschbach-Hertig and Gleeson, 2012). The core of the idea was to transform small dams that only serve for flood protection into small hydropower units and after the energy production to apply MAR to the depleted aquifer. The use of small dams is severely suggested due to the several drawbacks of using large dams for water supply (Di Baldassarre et al., 2018). The methodology was based on a future moderate climate scenario (RCP 4.5) to have input for 20 years. Additionally, on the base of realism, it was assumed that the dams can be transformed and be ready for use in 2030. Moreover, a second scenario was applied including, more theoretical, dams for MAR application. The application of MAR and construction of small dams are in accordance with the suggestions of previous studies on the sites (Voudouris et al., 2006; Kazakis, 2013; Patrikaki et al., 2012) as well as with the official management plans. In the Eastern Thermaikos Gulf since 1978 Papageorgakis and Koumantakis (1978) have reported the necessity to protect groundwater reserves. Unfortunately, the monitoring of the authorities was obtained for short periods, while the last decade has limited water level measurements only for two periods per year, while the monitoring of surface runoff is missing. Hence, the driving factor of groundwater depletion in the studied aquifers is mismanagement, including limited monitoring, overexploitation of groundwater, and absence of groundwater replenishment actions such as MAR application.

Nevertheless, this study highlights also the impact of climate variability. Draught periods have already occurred with longer duration, while future projections forecast that such periods will have an extreme duration of up to 90 months (McKee et al., 1993; Feng et al., 2024). The alternation of long wet-draught periods also influences groundwater level variation as it is shown in Figure 2.19. The groundwater level drawdown started in 1980 mainly due to over-pumping. Between 2013 and 2016 occurred a recovery period due to the long-wet period. Obviously, climatic drivers influence groundwater depletion, however, even a long-wet period couldn’t replenish the depleted quantities from the aquifer at the natural levels (Figure 2.19). These findings are in accordance with Ashraf et al. (2021) which studied the impacts of drought in groundwater depletion in Iran.

Additionally, precipitation events during the dry period of May to October do not favor the recharge of groundwater. This argument is supported by this study from the ERT analysis. The ERT data from the vadose zone will be analytically presented in a future article. Nevertheless, this supports the argument for the utilization of small dams to store surface runoff and the use of MAR to limit the evaporation from the dam reservoir.

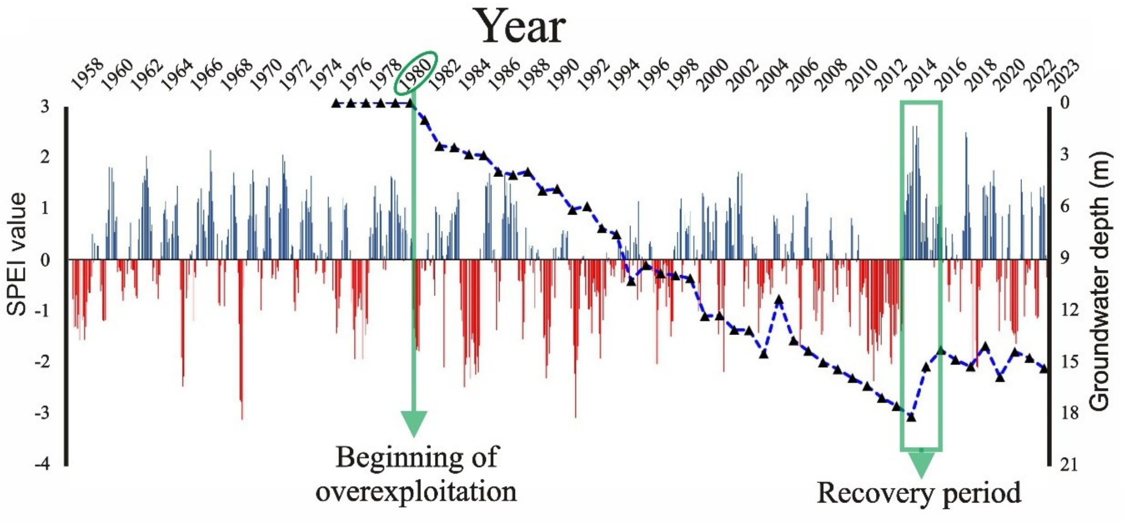


Figure 2.19 SPEI and groundwater depth diagram of Eastern Thermaikos Gulf.

However, despite the important results of this study, there are still issues that should be addressed. For instance, in Marathonas basin, the application of MAR in the margin of the aquifer might transferred to the center of the basin. The simulation in Mouriki basin should be obtained in monthly time step, rather than in wet and dry periods as it was obtained within this study. Additionally, the depletion zones in Mouriki basin extend in a significant part of the aquifer, however, the aquifer can recover in one decade. In Eastern Thermaikos Gulf a further step of this study is to simulate the aquifer more discredited using hydro units.

Assessment of groundwater depletion is of great concern and hydrological models have been used to estimate groundwater depletion rate on a global scale (Doll et al., 2014). Within this study we focused on smaller aquifers, illustrating that such approaches can suggest lower-scale solutions. Additionally, groundwater quality deterioration has been reported due to groundwater depletion in large aquifer systems (MacDonald et al., 2016). This argument has been also verified in the studied aquifers by Ntona et al. (2023b).

Based on the results from the hydropower generation of the existing reservoirs it is shown that the Mouriki potential corresponds to small-scale hydropower, while for the other two sites, there is a discrete potential indicating hydropower potential medium-sized power plants can be caused by several factors (Oliver Paish et al., 2002). Mouriki is expected to have significant hydropower potential due to geological characteristics such as a small water table and relatively small reservoir size. These factors limit the ability to exploit large amounts of energy from the dam. Despite this limitation, a small hydroelectric plant can still provide valuable electricity to communities, helping to sustain their energy needs.

In contrast, the remaining areas exhibit favorable conditions for medium-sized hydropower projects, characterized by the presence of large water bodies and differences in elevations. These factors generate substantial energy production is weaker compared to Mouriki. While environmental assessment is an important consideration, the small size and versatility of these reservoirs minimize significant environmental disturbance (Dudhani, 2006). Considering how energy production and consumption in the area, the generated electricity can be used to meet immediate needs. Furthermore, the development of hydroelectric power systems in these areas can stimulate economic growth and create employment opportunities, thereby promoting sustainable development. (Česonienė et al., 2021; Zhang et al., 2021). The allocation of small dams can be optimized to achieve the maximum hydrodynamic (Kontos et al., 2018).

The study of groundwater depletion constitutes a global issue and newer studies reveal the extent of the problem. Jasechko et al. (2024) studied groundwater depletion on a global scale suggesting among other actions the application of managed aquifer recharge on a global scale. Another issue that should be included in the forecast of groundwater depletion is land use/land cover change and population growth (Olivares et al., 2019). Unfortunately, the unbalanced population growth and land cover change led to opportunistic solutions to cover water demands such as deeper well drilling (Perrone and Jasechko, 2019). The abstraction from deeper zones can also lead to sedimentary condensation of the upper layers and decrease the water capacity of the aquifer. Inevitably, the runoff coefficient increased, and flood events might occur. This phenomenon however requires holistic research and hence we suggest researchers correlate groundwater depletion zones with flood events.

On balance, this study provided a spatial distribution of groundwater depletion in the present and forecast the phenomenon. Additionally, highlighted that specific hydrogeological conditions in the mountainous part can balance the overexploitation of groundwater in the lowlands. Nonetheless, monitoring of groundwater reserves and prevention actions should be taken to protect groundwater reserves.

3 Policy recommendations

The exploitation of the small hydro potential of streams and springs in Greek mountains is the solution for distributed energy production in Greece, which can be directly connected to the grid network, offering stability and reliability throughout the year. Within this project a detailed analysis provided, while the results are included in Patsialis et al. (2022). Despite the country's knowledge and available hydro potential, the hydroelectric plants have not been developed yet according to the European Union's expectations and objectives. According to the European Energy Institute, in the last 25 years there have been no initiatives by the state for the rationalization of the institutional framework and the more efficient management and exploitation of the country's small hydropower, as manifested in other countries. In Greece, the growth rate of four small hydropower stations (SHPS) per year is disappointing and it will take many years to reach satisfactory levels.

Due to the morphology and the climate of Greece, hydroelectric plants deliver high performance indicators with very good techno-economic analyses. Today, most of the world's renewable energy comes from water. The advantages are many and in combination with the increasing demands for more energy they become even more important.

3.1 Licensing Legislation

The legislation in Greece for the licensing of a hydroelectric project follows the same procedure as other renewable energy sources and the total duration of licensing varies between 4 and 10 years. The steps for licensing a SHPS are described below:

3.1.1 Energy Production License

It is the first license that the investor must have and the competent agency for issuing it is the Energy Regulatory Authority (RAE). The submission file includes technical, financial and business elements of the project. RAE examines the legal status of the applicant, the administrative and organizational structure as well as the financial data of the last 3 years. It also checks the feasibility of the project and the financial planning that will provide the projected cash flow. Applications to the RAE are accepted in the first ten days of each quarter and its results are ideally posted within a year.

3.1.2 Installation License

It is the largest in terms of studies and licensing and includes many license approvals from several services. For a typical MHP to have an installation permit, at least 10 agencies must approve its construction. The most critical service that will give an opinion is DEDDIE, which will initially accept to connect the project in question to its network and then, through the connection offer, will indicate the method and the cost. In Greece, due to the construction of the network and the geomorphology of the country, many projects are unable to connect to the grid or the connection costs are not sustainable and their development stops.

3.1.3 Environmental License

It is the result of the approval of the Environmental Impact Study (EIA) and includes all the environmental, technical and economic elements of the project.

3.1.4 Water Use License

The Water Directorate of the respective area is the competent agency responsible for the water use permit. It will examine the project study and based on the criteria and specifications it sets, it will issue or not the water use permit. Great importance is given to the presence of fish fauna and the way to protect it during the operation of the project.

3.1.5 Operating License

It is the final licensing stage of the project, where they are accompanied by all the individual approvals and licenses from all the previous services. Now, the licensing of the project has matured and the MYIS can be built and operate based on the specifications and limitations that have been set. The operating license also includes building permits, road construction, fire safety, network construction and other infrastructure projects as well as responsible declarations of the mechanical supervision and owners.

3.2 Technical and License Problems

Undoubtedly, licensing a MUIS is not one of the easiest procedures. There are problems and obstacles that appear which are due to either technical or bureaucratic issues. Such issues are presented below:

3.2.1 Connection to the Grid

It is the biggest and most critical obstacle in developing a power plant. WWTPs are developed in streams and rivers with a large water supply or large elevation differences, or ideally both. These areas are located in the mountainous mass of Greece, where the existing electrical network is unable to accept the produced amounts of energy. The DEDDIE obliges the investor to construct a new network route of many kilometers or a new voltage substation. The cost of the investment rises, and the project is deemed unsustainable. The result of the process is the freezing of the licensing until a solution is found. There are cases where DEDDIE has proposed to 5 prospective investors, where their projects are adjacent, the joint construction of a substation at their own expense.

3.2.2 Environmental License

It is an equally important problem, similar to connecting a project to the network. The environmental problems that arise are difficult to overcome and many times can completely stop the development of a project. In this phase, there are many delays of a bureaucratic nature, as the issuance of EPO requires approval from at least 10 (maybe more) independent agencies. RAE, on its own initiative, has started procedures to simplify licensing procedures and remove network saturation, in collaboration with DEDDIE. The most important problems faced by licensing based on progress reports shows at the table below.

Table 3.1 Major problems in the development of small hydropower (based on progress reports).

Delays in service approvals	7,80%
Lack of environmental licensing	25,50%
Problems with funding	2%
Problems with neighboring Projects	2%
Problems with securing a position	9,80%
Problems with the connection terms	25,50%
Appeal cancellation of licenses from STE	23,50%
Spatial planning problems	2%
Problems with local community	2%

3.3 Policy recommendations that could trigger improvements in existing relevant legislation.

3.3.1 Licensing process. Simplification and faster.

Very small hydroelectric projects face the same licensing process as larger ones. Given that the intervention in the environment is much smaller, the competent services should simplify and completely delete certain stages of the licensing.

3.3.2 Grid priority and instant connection response.

The connection of a RES project to the DEDDIE network is one of the most critical stages for the development of the project. For the development of very small hydroelectric projects, DEDDIE should secure space in the grid and give priority to these projects.

3.3.3 Increased energy sales price.

DAPEEP's compensation for each MWHr amounts to 100 euros. The price would have to rise for such a project to be attractive to prospective investors. Considering the environmental importance of the use of small dams for energy production the funding should not be based only to investors. To our opinion the state should lead the funding for the use of small dams for hydropower generation.

The table below shows the policy recommendations that emerged from the research project.

- Simplification of the licensing process
- Exemption from environmental licensing
- Exemption from water use permit

- Securing space on the DEDDIE network
- Priority in connecting to the DEDDIE network
- Exemption from operating license and accompanying projects
- Exemption from building permit
- Increase in the selling price of energy

Note that the above proposals have already been implemented in the small photovoltaic and wind farms and there has been an increase in the development of these projects.

4 Dissemination and data

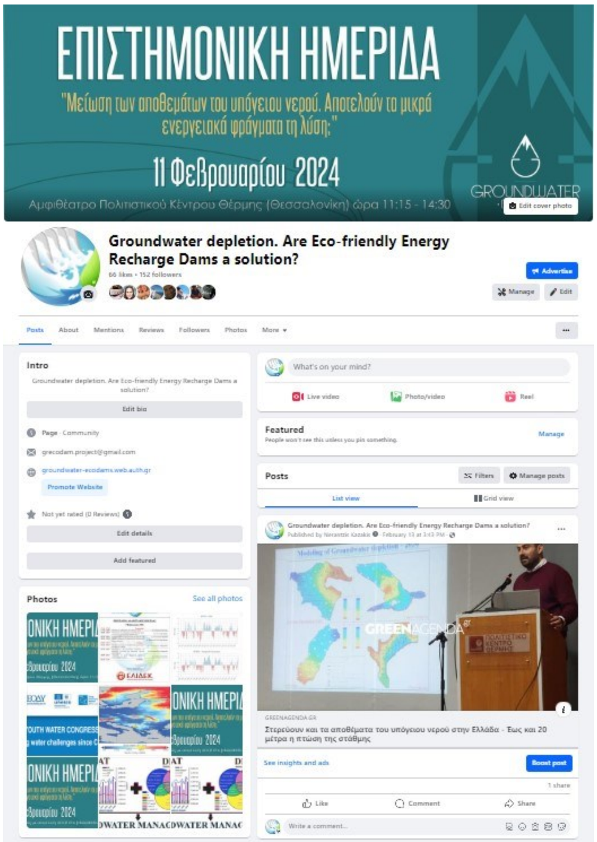
The funding of the project is open accessible in many sources such as open access journal, the web-site and you tube. The dissemination plan included social media, participation and presentations in conferences, article publication in journals, a You tube channel and a web-site. A brief analysis of the action is presented below, while the material will be online after the end of the project.

4.1 Social media

In the framework of the project developed pages in Facebook (**Figure 4.1**), Instagram (**Figure 4.2**) and LinkedIn (**Figure 4.3)**. The impact of the pages is presented in Table 4.1. In the media obtained announcements of the project events and the publications.

Table 4.1 Impact of GRecoDAM pages on social media.

Social media	Connections	Post Impresions	Profile Views
LinkedIn	53	414	102
Facebook	152	719	-
Instagram	22	-	-



ΕΠΙΣΤΗΜΟΝΙΚΗ ΗΜΕΡΙΔΑ

"Μείωση των αποθεμάτων του υπόγειου νερού. Αποτελούν τα μικρά ενεργειακά φράγματα τη λύση;"

11 Φεβρουαρίου 2024

Αμφιθέατρο Πολιτιστικού Κέντρου Θέρμης (Θεσσαλονίκη) ώρα 11:15 - 14:30

Groundwater depletion. Are Eco-friendly Energy Recharge Dams a solution?

66 likes • 152 followers

Intro

Groundwater depletion. Are Eco-friendly Energy Recharge Dams a solution?

Page · Community

grecodam.project@gmail.com

groundwater-ecodams.web.auth.gr

Not yet rated (0 Reviews)

Featured

People won't see this unless you pin something.

Groundwater depletion. Are Eco-friendly Energy Recharge Dams a solution?

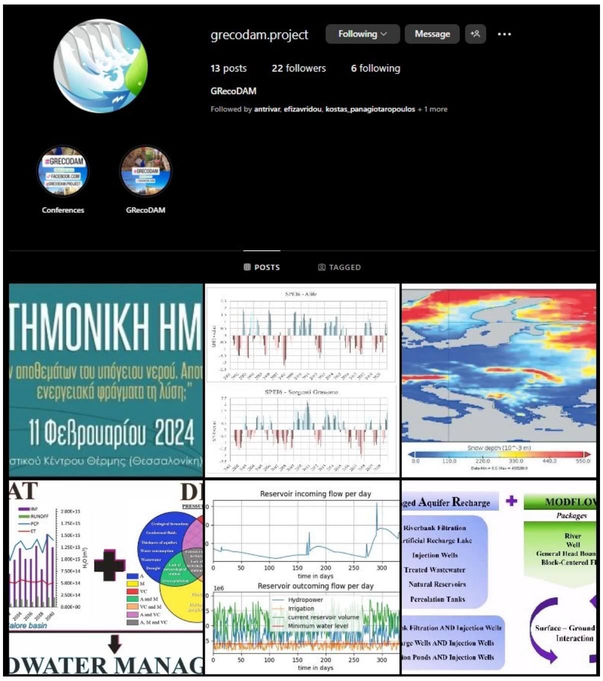
Published by Nerantzis Kazakis · February 13 at 3:43 PM

GREENAGENDA.GR

Στερεύουν και τα αποθέματα του υπόγειου νερού στην Ελλάδα - Έως και 20 μέτρα η πτώση της στάθμης

1 share

Figure 4.1 Page of GRecoDAM in Facebook.



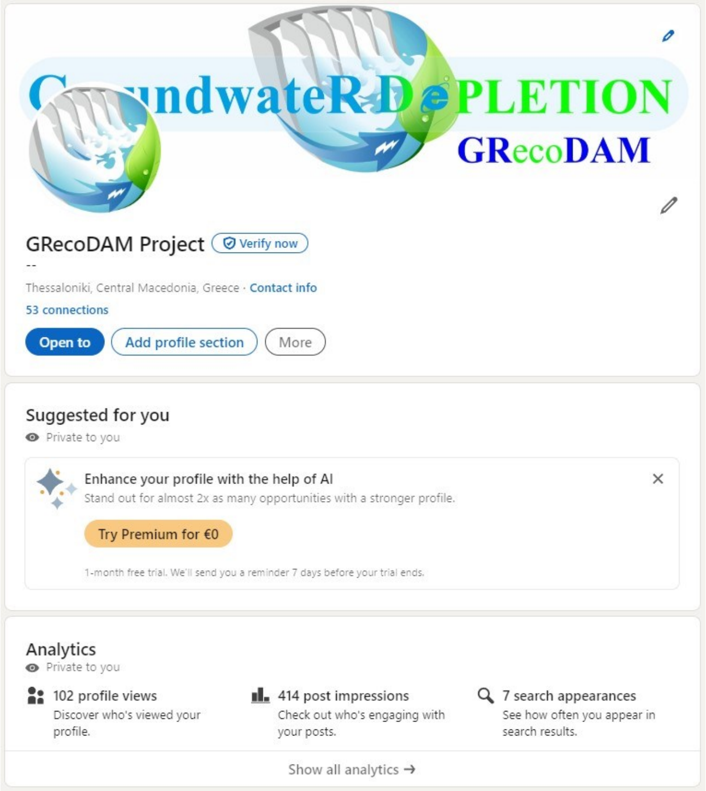
grecodam.project

13 posts 22 followers 6 following

GRecoDAM

Followed by antrivar, efizavridou, kostas_panagiotaropoulos + 1 more

Figure 4.2 Page of GRecoDAM in Instagram.



GRecoDAM Project

--

Thessaloniki, Central Macedonia, Greece · Contact info

53 connections

Suggested for you

Private to you

Enhance your profile with the help of AI

Stand out for almost 2x as many opportunities with a stronger profile.

1-month free trial. We'll send you a reminder 7 days before your trial ends.

Analytics

Private to you

102 profile views
Discover who's viewed your profile.

414 post impressions
Check out who's engaging with your posts.

7 search appearances
See how often you appear in search results.

Figure 4.3 Page of GRecoDAM in LinkedIn.

4.2 Workshop

The workshop was organized online as well as in person. The online workshop obtained on 5th February 2024 in which 80 people was registered, while the maximum number of viewers was 67 during the workshop (Figure 4.4). The in-person Workshop obtained on 11th February in the cultural Center of Thermi and the participated were more than 70 persons including students, stakeholders, citizens, researchers and professors (Figure 4.5). The in-person workshop is online in the Open Hydrogeology channel of You Tube in the following link: https://www.youtube.com/watch?v=LecmArUSFTM&t=42s

WORKSHOP

"Groundwater depletion. Are Eco-friendly Energy Dams a solution?"

5 February 2024

Online workshop. Register via email (nkazakis@upatras.gr)

GROUNDWATER
· DEPLETION ·

Figure 4.4 Flyer of the online workshop.

ΕΠΙΣΤΗΜΟΝΙΚΗ ΗΜΕΡΙΔΑ

"Μείωση των αποθεμάτων του υπόγειου νερού. Αποτελούν τα μικρά ενεργειακά φράγματα τη λύση;"

11 Φεβρουαρίου 2024

Αμφιθέατρο Πολιτιστικού Κέντρου Θέρμης (Θεσσαλονίκη) ώρα 11:15 - 14:30

GROUNDWATER
· DEPLETION ·

Figure 4.5 Flyer in Greek of the via person workshop.

4.3 Publication – Participation in Conferences

In the framework of the project published until 21 of February sixteen (16) articles, one chapter is under minor revision and one article in a Journal is under review. The list of publications is presented below:

4.3.1 Conferences

The research team have been participated in six (6) conferences and published nine (9) articles until February 2024 (**Table 4.2**). The conferences and the article titles are presented below, while the full publications are within the web-site.

Table 4.2 List of conferences and corresponding publications.

A/A	Month from GRecoDAM	Journal - Conference	Article
1	8	15th International Conference on Meteorology, Climatology and Atmospheric Physics-COMECAP	Voudouri K. A., Ntona M. M., Kazakis N. (2021) Investigating the snow water equivalent in Greece. 15th International Conference on Meteorology, Climatology and Atmospheric Physics-COMECAP, Ioannina, Greece, 26-29 September 2021, pp. 315-319.D7
2	14	12th International Hydrogeological Conference	Karakatsanis D., Patsialis T., Kougias I., Ntona M.M., Theodosiou N., Kazakis N. (2022). Simulation software for small eco-friendly energy recharge dams. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022, pp. 115-119.
3	14	12th International Hydrogeological Conference	Patsialis T., Karakatsanis D., Kougias I., Theodosiou N., Kazakis N. (2022). The small hydropotential in Greece. Current projects and future challenges. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022, pp. 378-381.
4	14	12th International Hydrogeological Conference	Ntona M.M., Kazakis N. (2022). An Overview of managed aquifer recharge applications using simulation models. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022. pp. 177-180.
5	14	12th International Hydrogeological Conference	Ntona M.M., Busico G., Kazakis N., Mastroccico M. (2022). Simulating historical, actual and future water balance in mountainous watershed. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022, pp. 172-175.
6	15	Online Youth Water Congress: "Emerging water challenges since COVID-19"	Kazakis N. (2022) Strategies to mitigate the phenomenon of groundwater depletion in the Mediterranean region. Youth" in the forefront: before and after World Water Forum. Online Youth Water Congress: "Emerging water challenges since COVID-19". pp. 79-80, 6-8 April 2022.
7	21	16th International Congress of the Geological Society of Greece	Ntona M.M., Busico G., Mastroccico M., Kazakis N. (2022) The impacts of drought on groundwater resources in the Upper Volturno basin, Southern Italy. 16th International Congress of the Geological Society of Greece. Patra, 17-19 October.
8	29	6th Edition of FLOWPATH	Ntona M.M., Busico G., Kalaitzidou K., Mitrakas M., Kazakis N., Mastroccico M. (2023). Identification of major sources controlling groundwater quality under different hydrogeological regimes in Mediterranean catchments. 6th Edition of FLOWPATH, Malta, 14-16 June 2023.
9	30	12th World Congress on Water Resources and Environment (EWRA 2023)	Ntona M.M., Kalaitzidou K., Mitrakas M., Busico G., Mastroccico M., Kazakis N., (2023). Anthropogenic sources and hydrogeochemical characteristics of groundwater in Mediterranean regions. 12th World Congress on Water Resources and Environment (EWRA 2023), "Managing Water-Energy-Land-Food under Climatic, Environmental and Social Instability", Thessaloniki, Greece, 27 June - 1 July 2023.

4.3.1.1 15th International Conference on Meteorology, Climatology and Atmospheric Physics -Comecap 2021, Septembber 26th-29th, Ioannina Greece

- Voudouri K. A., Ntona M. M., Kazakis N.. (2021) Investigating the snow water equivalent in Greece. 15th International Conference on Meteorology, Climatology and Atmospheric Physics-COMECAP, Ioannina, Greece, 26-29 September 2021, pp. 315-319.

4.3.1.2 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022

- Ntona M.M., Kazakis N. (2022). An Overview of managed aquifer recharge applications using simulation models. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022. pp. 177-180.
- Ntona M.M., Busico G., Kazakis N., Mastroccico M. (2022). Simulating historical, actual and future water balance in mountainous watershed. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022, pp. 172-175.

- Karakatsanis D., Patsialis T., Kougias I., Ntona M.M., Theodosiou N., Kazakis N. (2022). Simulation software for small eco-friendly energy recharge dams. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022, pp. 115-119.
- Patsialis T., Karakatsanis D., Kougias I., Theodosiou N., Kazakis N. (2022). The small hydropotential in Greece. Current projects and future challenges. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022, pp. 378-381.

4.3.1.3 Online Youth Water Congress: "Emerging water challenges since COVID-19"

- Kazakis N. (2022) Strategies to mitigate the phenomenon of groundwater depletion in the Mediterranean region. Youth" in the forefront: before and after World Water Forum. Online Youth Water Congress: "Emerging water challenges since COVID-19". pp. 79-80, 6-8 April 2022.

4.3.1.4 16th International Congress of the Geological Society of Greece

- Ntona M.M., Busico G., Mastroccico M., Kazakis N. (2022) The impacts of drought on groundwater resources in the Upper Volturno basin, Southern Italy. 16th International Congress of the Geological Society of Greece. Patra, 17-19 October.

4.3.1.5 6th Edition of FLOWPATH

- Ntona M.M., Busico G., Kalaitzidou K., Mitrakas M., Kazakis N., Mastroccico M. (2023). Identification of major sources controlling groundwater quality under different hydrogeological regimes in Mediterranean catchments. 6th Edition of FLOWPATH, Malta, 14-16 June 2023.

4.3.1.6 12th World Congress on Water Resources and Environment (EWRA 2023)

- Ntona M.M., Kalaitzidou K., Mitrakas M., Busico G., Mastroccico M., Kazakis N., (2023). Anthropogenic sources and hydrogeochemical characteristics of groundwater in Mediterranean regions. 12th World Congress on Water Resources and Environment (EWRA 2023), "Managing Water-Energy-Land-Food under Climatic, Environmental and Social Instability", Thessaloniki, Greece, 27 June - 1 July 2023.

4.3.2 International Journals

The research team have been published seven (7) articles and submitted one (1) in scientific journals until 21 February of 2022 (**Table 4.3**). The article titles and journal names are presented below, while the full publications are within the web-site.

Table 4.3 List of Journals, the title of the articles and the corresponding citations.

A/A	Journal	Article	Citations (1 February 2024)	
			Scopus	Google Scholar
1	**Water Resource Management**	Busico G., Ntona M.M., Carvalho S.C.P., Patrikaki O., Voudouris K., Kazakis N. (2021) Simulating future groundwater recharge in coastal and inland catchments. Water Resource Management. 35(11), 3617-3632 https://doi.org/10.1007/s11269-021-02907-2	36	44
2	**Science of the Total Environment**	Ntona M.M. Busico G., Mastrocicco M., Kazakis N. (2022) Modeling groundwater and surface water interaction: an overview of current status and future challenges. Science of the Total Environment. 846:157355. https://doi.org/10.1016/j.scitotenv.2022.157355	26	41
3	**Remote Sensing**	Voudouri K.A., Ntona, M.M., Kazakis, N. (2023) Snowfall Variation in Eastern Mediterranean Catchments. Remote Sens., 15, 1596. https://doi.org/10.3390/rs15061596	2	2
4	**Journal of Environmental Management**	Ntona M.M. Busico G., Mastrocicco M., Kazakis N. (2023) Coupling SWAT and DPSIR models for groundwater management in Mediterranean catchments. Journal of Environmental Management 344, 118543. https://doi.org/10.1016/j.jenvman.2023.118543	3	3
5	**Water**	Karakatsanis, D., Patsialis, Th., Kalaitzidou, K., Kougias, I., Ntona, M.M., Theodossiou, N., Kazakis, N. (2023) Optimization of dam operation and interaction with groundwater. An overview focusing on Greece. Water, 15, 3852. https://doi.org/10.3390/w15213852	3	3
6	**Water**	Ntona, M.M., Chalikakis, K., Busico, G., Mastrocicco, M., Kalaitzidou, K., Kazakis, N. (2023) Application of judgmental sampling approach for the monitoring of groundwater quality and quantity evolution in Mediterranean catchments. Water, 15, 4018. https://doi.org/10.3390/w15224018	1	1
7	**Water**	Kalaitzidou, K., Ntona, M.M., Zavridou, E., Tzelatas, S., Patsialis, Th., Kallioras, A., Zouboulis, A., Virgiliou, Ch., Mitrakas, M., Kazakis N. (2023) Water quality evaluation of groundwater and Dam reservoir water. Application of water quality indices in study sites of Greece. Water. 15, 4170. https://doi.org/10.3390/w15234170		

4.3.2.1 Water Resources Management

- Busico G., Ntona M.M., Carvalho S.C.P., Patrikaki O., Voudouris K., Kazakis N. (2021) Simulating future groundwater recharge in coastal and inland catchments. Water Resource Management. 35(11), 3617-3632 https://doi.org/10.1007/s11269-021-02907-2

4.3.2.2 Science of the Total Environment

- Ntona M.M. Busico G., Mastrocicco M., Kazakis N. (2022) Modeling groundwater and surface water interaction: an overview of current status and future challenges. Science of the Total Environment. 846:157355. https://doi.org/10.1016/j.scitotenv.2022.157355
- Kazakis et al. (2024) Groundwater depletion. Are Eco-friendly energy recharge dams a solution? (under review)

4.3.2.3 Remote Sensing

- Voudouri K.A., Ntona, M.M., Kazakis, N. (2023) Snowfall Variation in Eastern Mediterranean Catchments. Remote Sens., 15, 1596. https://doi.org/10.3390/rs15061596

4.3.2.4 Journal of Environmental Management

- Ntona M.M. Busico G., Mastrocicco M., Kazakis N. (2023) Coupling SWAT and DPSIR models for groundwater management in Mediterranean catchments. Journal of Environmental Management 344, 118543. https://doi.org/10.1016/j.jenvman.2023.118543

4.3.2.5 Water

- Karakatsanis, D., Patsialis, Th., Kalaitzidou, K., Kougias, I., Ntona, M.M., Theodossiou, N., Kazakis, N. (2023) Optimization of dam operation and interaction with groundwater. An overview focusing on Greece. Water, 15, 3852. https://doi.org/10.3390/w15213852
- Ntona, M.M., Chalikakis, K., Busico, G., Mastrocicco, M., Kalaitzidou, K., Kazakis, N. (2023) Application of judgmental sampling approach for the

monitoring of groundwater quality and quantity evolution in Mediterranean catchments. Water, 15, 4018. https://doi.org/10.3390/w15224018

- Kalaitzidou, K., Ntona, M.M., Zavridou, E., Tzelatas, S., Patsialis, Th., Kallioras, A., Zouboulis, A., Virgiliou, Ch., Mitrakas, M., Kazakis N. (2023) Water quality evaluation of groundwater and Dam reservoir water. Application of water quality indices in study sites of Greece. Water. 15, 4170. https://doi.org/10.3390/w15234170

4.3.3 Book Chapter

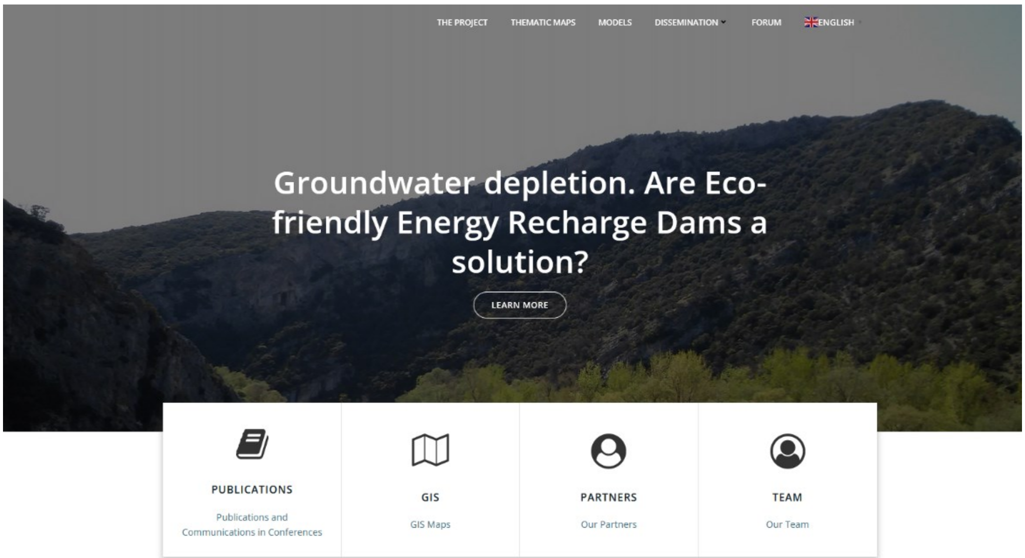
The research team submitted one (1) article in a Book chapter until February 2024. The article accepted after minor revisions and currently is under revision. The Book names is presented below.

4.3.3.1 Handbook of Hydrosystem Restoration

- Voudouris K., Kazakis N., Kolokytha E. (2024) Classification Methods for Ranking the Appropriate Locations for Groundwater Artificial Recharge with Conventional Water. Handbook of Hydrosystem Restoration (resubmitted after minor revisions - under revision)

4.4 Website

In the framework of the proposed research activity, a website was developed in order to host the project. The website is accessible from the link: https://groundwater-ecodams.web.auth.gr/. The first page is shown in the following figure (**Figure 4.6**). The page content is structured on smaller sections for easy navigation. The website is also translated in three languages including Greek, Italian and English. Within the web site are the final reports of all work packages including all project's data.



Groundwater depletion. Are Eco-friendly Energy Recharge Dams a solution?

Figure 4.6 Start page of the Projects website.

5 Conclusions of the project

Groundwater depletion constitutes a global issue, especially in the Mediterranean area. Within this study, the phenomenon was studied in four study sites in Greece and Italy. The phenomenon is influenced by different climatological, hydrological, and socioeconomic factors depending on the site even within the same country. The main conclusion for groundwater depletion can be summarized below:

- High drought events can influence groundwater decline.
- Rainfall events during the summer period slightly contribute to groundwater recharge.
- Mis-management of groundwater constitute the triggering factor of groundwater depletion occurrence.
- Small dams can store the water from extreme summer rainfall events and increase groundwater reserves during the summer period by applying MAR.
- The energy production and groundwater recharge quantity can reach up to 1500 MWV/year and 5×10^6 m^3 per year in the studied aquifers.

The phenomenon of groundwater depletion occurs at 27%, 22.8%, and 11% in the Eastern Thermaikos Gulf, Marathonas and Mouriki basin, respectively. The depletion zone will extend until 2030 if the pumping rates remain the same under the RCP 4.5 scenario. The transformation of dams to mini-scale hydropower facilities and applying MAR will benefit clean energy production, save CO_2 emissions, and lead to an economically feasible strategy against groundwater depletion. In the Upper Volturno basin, the quantity of groundwater is not affected by the phenomenon due to the high dynamic of the surrounding karst aquifers and the lateral inflow.

To conclude, eco-friendly energy recharge dams can contribute to groundwater sustainability. However, detailed monitoring of all hydrological parameters and regular updates of the simulation process are essential for the integrated management of water resources in the Mediterranean environments.

6 References

Abbaspour, K.C., Vaghefi, S.A., Yang, H., Srinivasan, R., 2019. Global soil, landuse, evapotranspiration, historical and future weather databases for SWAT Applications. Sci. Data 6, 26. https://doi.org/10.1038/s41597-019-0282-4

Aeschbach-Hertig, W., Gleeson T., 2012. Regional strategies for the accelerating global problem of groundwater depletion. Nat. Geosci. 5, 853–861.

Anderson, M.P., Woessner, W.W., Hunt, R.J., 2015. Applied groundwater modeling: simulation of flow and advective transport, 2nd edn. Academic, San Diego.

Ashraf, S., Nazemi, A., Agha Kouchak, A., 2021. Anthropogenic drought dominates groundwater depletion in Iran. *Sci. Rep.* 11, 9135.

Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P. (eds), 2008. Climate Change and Water (IPCC Secretariat).

Busico, G., Kazakis, N., Colombani, N., Mastrocicco, M., Voudouris, K., Tedesco, D., 2017. A modified SINTACS method for groundwater vulnerability and pollution risk assessment in highly anthropized regions based on NO_{3}^{-} and SO_4^{2-} concentrations. Sci Total Environ, 609, 1512-1523.

Busico, G., Ntona, M.M., Carvalho, S.C.P., Patrikaki, O., Voudouris, K., Kazakis, N., 2021. Simulating future groundwater recharge in coastal and inland catchments. Water Resource Management 35(11), 3617-3632. https://doi.org/10.1007/s11269-021-02907-2

Busico, G., Ntona, M.M., Carvalho, S.C.P., Patrikaki, O., Voudouris, K., Kazakis, N., 2021. Simulating future groundwater recharge in coastal and inland catchments.

Water Resour. Manag. 35, 3617–3632. https://doi.org/10.1007/s11269-021-02907-2

Crosbie, R.S., Dawes, W.R., Charles, S.P., Mpelasoka, F.S., Aryal, S., Barron, O., Summerell, G.K., 2011. Differences in future recharge estimates due to GCMs, downscaling methods and hydrological models. Geophys. Res. Lett. 38(11), 1–5.

Česonienė, L., Dapkienė, M., Punys, P., 2021. Assessment of the Impact of Small Hydropower Plants on the Ecological Status Indicators of Water Bodies: A Case Study in Lithuania. Water 13, 4, 433. https://doi.org/10.3390/w13040433

Dee, D.P., Balmaseda, M., Engelen, R., Simmons, A.J., Thépaut, J.M., 2013. Toward a consistent reanalysis of the climate system. Bull. Am. Meteorol. Soc. 95, 1235–1248.

Di Baldassarre, G., Wanders, N., AghaKouchak, A., Kuil, L., Rangecroft, S., Veldkamp, T.I.E., Garcia, M., van Oel, P.R., Breinl, K., Van Loon A.F., 2018. Water shortages worsened by reservoir effects. Nature Sustainability 1(11), 617-622

Dudhani, S., Sinha, A.K., Inamdar, S.S., 2006. Assessment of small hydropower potential using remote sensing data for sustainable development in India. Energy Policy 34, 3195-3205. https://doi.org/10.1016/j.enpol.2005.06.011

Doll, P., Muller Schmied, H., Schuh, C., Portmann, F.T., Eicker, A., 2014. Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites, Water Resour. Res. 50, 5698–5720.

Feng, S., Hao, Z., Zhang, Y., Zhang, X., Hao, F., 2023. Amplified future risk of compound droughts and hot events from a hydrological perspective. Journal of Hydrology, 617, C. https://doi.org/10.1016/j.jhydrol.2023.129143

Foster, S., Garduno, H., Evans, R., Olson, D., Tian, Y., Zhang, W., Han, Z., 2004. Quaternary aquifer of the North China plain–assessing & achieving groundwater resource sustainability. Hydrogeol. J. 12, 81–93.

Gemitzi, A., Lakshmi, V., 2018. Evaluating Renewable Groundwater Stress with GRACE Data in Greece. Groundwater, 56(3), pp. 501-514.

Gleeson, T., Befus, K.M., Jasechko, S., Luijendijk, E., Cardenas, M.B., 2015. The global volume and distribution of modern groundwater. Nat. Geosci. 9, 161–167.

Gleeson, T., Vander Steen, J., Sophocleous, M.A., Taniguchi, M., Alley, W.M., Allen, D.M., Zhou, Y., 2010. Groundwater sustainability strategies. Nature Geosci. 3, 378–379.

Gleeson, T., Wada, Y., Bierkens, M.F., van Beek, L.P., 2012. Water balance of global aquifers revealed by groundwater footprint. Nature, 488 (7410), 197–200.

Hutchison, W.R., 2010. The use of groundwater availability models in Texas in the establishment of desired future conditions. GSA Annual Meeting 2010 (Geological Society of America).

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R.G., Fallatah, O., Kirchner, J.W., 2024. Rapid groundwater decline and some cases of recovery in aquifers globally. Nature 625, 715–721. ttps://doi.org/10.1038/s41586-023-06879-8

Jacob, D., Elizalde, A., Haensler, A., Hagemann, S., Kumar, P., Podzun, R., et al., 2012. Assessing the Transferability of the Regional Climate Model REMO to Different COordinated Regional Climate Downscaling EXperiment (CORDEX) Regions. Atmosphere, 3(1), 181–199. https://doi.org/10.3390/atmos3010181

Kalaitzidou, K., Ntona, M.M., Zavridou, E., Tzelatas, S., Patsialis, Th., Kallioras, A., Zouboulis, A., Virgiliou, Ch., Mitrakas, M., Kazakis N., 2023. Water quality evaluation of groundwater and Dam reservoir water. Application of water quality indices in study sites of Greece. Water 15, 4170. https://doi.org/10.3390/w15234170.

Kaldelis, J., 2007. The contribution of small hydropower stations to the electricity generation in Greece: technical and economic considerations. Energy Policy 35, 2187-2196.

Karakatsanis D., Patsialis T., Kougias I., Ntona M.M., Theodosiou N., Kazakis N. (2022). Simulation software for small eco-friendly energy recharge dams. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022, pp. 115-119.

Karakatsanis, D., Patsialis, Th., Kalaitzidou, K., Kougias, I., Ntona, M.M., Theodossiou, N., Kazakis, N., 2023. Optimization of dam operation and interaction with groundwater. An overview focusing on Greece. Water 15, 3852. https://doi.org/10.3390/w15213852.

Kazakis, N., Pavlou, A., Vargemezis, G., Voudouris, K., Soulios, G., Pliakas, F., Tsokas, G., 2016. Seawater intrusion mapping using electrical resistivity tomography and hydrochemical data. An application in the coastal area of eastern Thermaikos Gulf, Greece. Sci Total Environ, 543: 373-387

Kazakis N. 2022. Strategies to mitigate the phenomenon of groundwater depletion in the Mediterranean region. Youth" in the forefront: before and after World Water Forum. Online Youth Water Congress: "Emerging water challenges since COVID-19". pp. 79-80, 6-8 April 2022.

Kendy, E., 2003. The false promise of sustainable pumping rates. Ground Water 41, 2–4.

Kendy, E., Zhang, Y. Q., Liu, C. M., Wang, J. X. & Steenhuis, T., 2004. Groundwater recharge from irrigated cropland in the North China Plain: Case study of Luancheng County, Hebei Province, 1949–2000. Hydrol. Processes 18, 2289–2302.

Konikow, L.F., Kendy, E., 2005. Groundwater depletion: A global problem. Hydrogeol. J. 13, 317–320.

Kontos, Y.N., Bampekos, I., Katsifarakis, K.L., 2023. Multi-criteria optimization approach to the design of small dams' systems along mountainous stream beds. Journal of Hydroinformatics 25(3), 685–705. https://doi.org/10.2166/hydro.2023.118

Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, P., Jiménez, B., Miller, K.A., Oki, T., Sen Z., Shiklomanov, I.A., 2007. Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 173-210.

MacDonald, A., Bonsor, H., Ahmed, K., Burgess, W., Basharat, M., Calow, R., Dixit, A., Foster, S., Krishan, G., Lapworth, D., Lark, M., Moench, M., Mukherjee, A., Rao, M.S., Shamsudduha, M., Smith, L., Taylor, R., Tucker, J., van Steenbergen, F., Yadav, S., 2016. Groundwater depletion and quality in the Indo-Gangetic basin mapped from in situ observations. Nat. Geosci. 9, 762–766.

Mavromatis, T., 2009. Use of drought indices in climate change impact assessment studies: an application to Greece. International Journal of Climatology 30 (9), 1336–1348.

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration of time scales. Eighth Conference on Applied Climatology, American Meteorological Society, Jan17-23, 1993, Anaheim CA, pp.179-186.

Neitsch, S., Arnold, J., Kiniry, J., Williams, J., 2000. Soil and Water Assessment Tool Theoretical Documentation 2000. Grassland, Soil and Water Research Laboratory, Agricultural Research Service, 808 East Blackland Road, Temple, Texas, 76502:506.

Ntona M.M., Busico G., Kazakis N., Mastroccico M. 2022a. Simulating historical, actual and future water balance in mountainous watershed. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022, pp. 172-175.

Ntona M.M., Busico G., Mastroccico M., Kazakis N. 2022b. The impacts of drought on groundwater resources in the Upper Volturno basin, Southern Italy. 16th International Congress of the Geological Society of Greece. Patra, 17-19 October.

Ntona M.M., Kazakis N. 2022. An Overview of managed aquifer recharge applications using simulation models. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022. pp. 177-180.

Ntona, M.M., Busico, G., Mastrocicco, M., Kazakis, N., 2022c. Modeling groundwater and surface water interaction: an overview of current status and future challenges. Sci. Total Environ. 846, 157355. https://doi.org/10.1016/j.scitotenv.2022.157355

Ntona M.M., Busico G., Kalaitzidou K., Mitrakas M., Kazakis N., Mastroccico M. 2023a. Identification of major sources controlling groundwater quality under different hydrogeological regimes in Mediterranean catchments. 6th Edition of FLOWPATH, Malta, 14-16 June 2023.

Ntona M.M., Kalaitzidou K., Mitrakas M., Busico G., Mastroccico M., Kazakis N., 2023b. Anthropogenic sources and hydrogeochemical characteristics of groundwater in Mediterranean regions. 12th World Congress on Water Resources and Environment (EWRA 2023), "Managing Water-Energy-Land-Food under Climatic, Environmental and Social Instability", Thessaloniki, Greece, 27 June - 1 July 2023.

Ntona, M.M., Busico, G., Mastrocicco, M., Kazakis, N., 2023c. Coupling SWAT and DPSIR models for groundwater management in Mediterranean catchments. Journal of Environmental Management 344, 118543. https://doi.org/10.1016/j.jenvman.2023.118543

Ntona, M.M., Chalikakis, K., Busico, G., Mastrocicco, M., Kalaitzidou, K., Kazakis, N., 2023d. Application of judgmental sampling approach for the monitoring of groundwater quality and quantity evolution in Mediterranean catchments. Water, 15, 4018. https://doi.org/10.3390/w15224018

Ojeda Olivares, E.A. et al., 2019. Climate change, land use/land cover change, and population growth as drivers of groundwater depletion in the central valleys, Oaxaca, Mexico. Remote Sens. 11, 1290.

Paish, O., 2002. Small hydro power: technology and current status, Renewable and Sustainable Energy Reviews, Volume 6, Issue 6, Pages 537-556, ISSN 1364-0321. https://doi.org/10.1016/S1364-0321(02)00006-0.

Papageorgakis, I., Koumantakis, I., 1978. Hydrogeological research of Anthemountas basin and the coastal area of Chalkidiki. Ministry of Agriculture (unpublished technical report).

Patrikaki, O., Kazakis, N., Voudouris, K., 2012. Vulnerability map: A useful tool for groundwater protection: An example from Mouriki basin, North Greece. Fresenius Environmental Bulletin, vol. 21, No 8c:2516-2521.

Patsialis, T., Kougias, I., Kazakis, N., Theodossiou, N., Droege, P., 2017. Supporting renewables' penetration in remote areas through the transformation of non-powered dams. Energies, 9 – 1054.

Patsialis T., Karakatsanis D., Kougias I., Theodosiou N., Kazakis N. 2022. The small hydropotential in Greece. Current projects and future challenges. 12th International Hydrogeological Conference, Cyprus, 20-22 March 2022, pp. 378-381.

Perrone, D., Jasechko, S., 2019. Deeper well drilling an unsustainable stopgap to groundwater depletion. Nat. Sustain. 2, 773–782.

Pliakas, F., Petalas, C., Diamantis, I., Kallioras, A., 2005. Modeling of groundwater artificial recharge by reactivating on old stream bed. Water Resources Management, 19(3), 279–294.

Pranjal, P., Kadiyan, N., Chatterjee, R.S. et al., 2021. Interpreting land subsidence impacts due to groundwater depletion using remote sensing-based GRACE gravity anomaly and DInSAR technique: a study on north-western parts of India. Environ Earth Sci 80, 596. https://doi.org/10.1007/s12665-021-09905-y

Running, S., Mu, Q., Zhao, M., Moreno, A., 2019. MOD16A2GF MODIS/Terra Net Evapotranspiration Gap-Filled 8-Day L4 Global 500 m SIN Grid V006. NASA EOSDIS Land Processes DAAC. https://doi.org/10.5067/MODIS/MOD16A2GF.006

Schneider, D., Molotch N.P., 2016. Real-time estimation of snow water equivalent in the Upper Colorado River Basin using MODIS-based SWE Reconstructions and SNOTEL data. Water Resour. Res., 52, 7892–7910.

Sophocleous, M., 2000. From safe yield to sustainable development of water resources — the Kansas experience. J. Hydrol. 235, 27–43.

UNESCO, 2009. World Water Assessment Programme. The United Nations World Water Development Report 3: Water in a Changing World. Report No. 978-92-3-104235-5, 407.

USGS, 2022. ModelMuse: A Graphical User Interface for Groundwater Models.

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A Multi-scalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index – SPEI. Journal of Climate, 23, 1696-1718.

Voudouri K. A., Ntona M. M., Kazakis N. 2021. Investigating the snow water equivalent in Greece. 15th International Conference on Meteorology, Climatology and Atmospheric Physics-COMECAP, Ioannina, Greece, 26-29 September 2021, pp. 315-319.

Voudouri, K.A., Ntona, M.M., Kazakis, N., 2023. Snowfall Variation in Eastern Mediterranean Catchments. Remote Sens., 15, 1596. https://doi.org/10.3390/rs15061596

Voudouris, K., Sotiriadis, M., Pavlou, A., Hatziliontos, C., 2006. Groundwater quality in the coastal aquifer system of eastern Thermaikos Gulf, North Greece. Journal of Environmental Protection and Ecology 7, 2, 269-279.

Wada, Y., van Beek, L.P.H., Sperna, Weiland, F.C., Chao, B.F., Wu, Y.H., Bierkens, M.F.P., 2012. Past and future contribution of global groundwater depletion to sea-level rise. Geophys Res Lett 39: L09402.

Weider, K., Boutt, D.F., 2010. Heterogeneous water table response to climate revealed by 60 years of ground water data. Geophys. Res. Lett. 37, L24405.

Zavridou, E., Markantonis, K., Argyrokastritis, I., Voudouris, K., Kallioras, A., 2018. Preliminary results from unsaturated zone studies in unconfined unconsolidated coastal aquifers. MDPI Proceedings *2*(11), 642. doi.org/10.3390/proceedings2110642

Zhang, Y., Tang, W., Duffield, C.F., Zhang, L., Hui, F.K.P., 2021. "Environment Management of Hydropower Development: A Case Study" Energies 14, no. 7: 2029. https://doi.org/10.3390/en14072029