Innovative and Sustainable Groundwater Management in the Mediterranean

D3.4 Report on the Results of the Analysis of Different Scenarios in the Case Studies

VERSION 1.0

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Executive Summary

The overall objective of the InTheMED project is to implement innovative and sustainable management tools and remediation strategies for MED aquifers (inland and coastal) in order to mitigate anthropogenic and climate-change threats by creating new long-lasting spaces of social learning among different interdependent stakeholders, NGOs, and scientific researchers in five field case studies. These are located at the two shores of the MED basin, namely in Spain, Greece, Portugal, Tunisia, and Turkey.

InTheMED will develop an inclusive process that will establish an ensemble of innovative assessment and management tools and methodologies including a high-resolution monitoring approach, smart modelling, a socio-economic assessment, web-based decision support systems (DSS) and new configurations for governance to validate efficient and sustainable integrated groundwater management in the MED considering both the quantitative and qualitative aspects.

This Deliverable, namely D3.4, is part of Task 3.4 "Analysis of Different Scenarios" (Lead: UNIPR/ participants: UPV, TUC, IST-ID, CERTE and BU). The aim of Task 3.4 is to simulate different scenarios considering the impact of climate and socio-economic changes on groundwater resources at the five pilot sites. At this aim, different surrogate models were developed for each case study, which are described in Milestone 3.2 (Tanda et al., 2022) and Deliverable 3.2 (Todaro et al., 2023). The surrogate models will support the implementation of the Fuzzy WebDSS tool (Deliverable 6.2; Varouchakis et al., 2023) aimed at assist decision makers in aquifer management. The definition of the scenarios and the description of the application of the surrogate models under these scenarios were presented in Milestone 3.4 (Secci et al., 2023). The D3.4 presents the results of the analysis of the most relevant scenarios in the demo sites.

1. Introduction

InTheMED aims to develop new easy-to-use smart models that enable the assessment of alternative scenarios with small computation time. The MED aquifers are facing a progressive depletion due to overexploitation and adverse climate conditions. Climate change can have significant impacts on groundwater systems in various ways. It can alter precipitation patterns, leading to changes in the amount, intensity, and distribution of rainfall. These changes can affect groundwater recharge, which is the process by which water infiltrates into the ground and replenishes aquifers. A decrease in rainfall or an increase in evaporation, due to higher temperatures, can reduce groundwater recharge rates and water availability for agricultural, domestic, and industrial use. Climate change can also influence the quality of groundwater. Higher temperatures and changes in precipitation patterns can affect the concentration of pollutants and nutrients in the soil, which can subsequently leach into groundwater. Increased frequency and intensity of extreme weather events, such as floods or droughts, can also lead to the mobilization of contaminants and impact groundwater quality. In costal aquifers, climate change can also exacerbate the problem of saltwater intrusion. Adapting to climate change impacts on groundwater requires effective management strategies. This includes sustainable groundwater extraction practices, implementing water-saving irrigation techniques, and promoting water conservation measures.

To address these issues and determine the most effective management strategies, monitoring and modelling play a crucial role. However, developing and running complete numerical models require substantial computational resources and specialized expertise. Moreover, stakeholders highlighted a key weakness in the groundwater management process—the lack of reliable and user-friendly information and tools for monitoring the condition of the aquifers. To address these issues, surrogate models can be employed. In short, they are simplified models that approximate the behaviour of more complex and computationally expensive models.

Within InTheMED, for Requena-Utiel (Spain), Konya (Turkey) and Tympaki (Greece) demo sites, surrogate models were developed based on the results of complete numerical models. In particular, random forest and artificial neural network algorithms were used for the first two case studies, respectively, while the third one employed a spatiotemporal geostatistical model.

For Grombalia (Tunisia) and the Guadiana basin (Portugal), where complete numerical models were not available, the surrogate models were developed using a statistical approach that relies on regression models. All the surrogate models are described in Deliverable 3.2 (Todaro et al., 2023).

The surrogate models developed for Requena-Utiel, Konya and Tympaki are used to analyse the effects of climate change and socio-economic scenarios on groundwater resources, while the ones designed for Grombalia and Guadiana basin take into account only the impacts of climate change. The scenarios are specifically tailored to each pilot site under investigation, enabling the provision of valuable information to policymakers and resource managers, aimed at mitigating the impacts of climate and socio-economic changes on local groundwater resources.

The surrogate models developed are integrated in the Fuzzy WebDSS tool (Deliverable 6.2; Varouchakis et al., 2023). The following sections of this report outline the objectives of the surrogate models for each pilot site, define the scenarios investigated, and present the main results obtained from the surrogate models, focusing on the most relevant scenarios for each demo site.

2. Case Studies

2.1. Requena-Utiel (Spain)

Introduction

The exploitation of the Requena-Utiel aquifer (Figure 1) over the past two decades has resulted in a constant decline in its water levels and a negative storage balance. This trend signifies the gradual depletion of the aquifer, a situation that could potentially worsen due to the adverse effects of climate change. Recognizing this challenge, the UPV team has leveraged a comprehensive numerical model to develop an innovative smart model using Random Forest (Breiman, 2001). The primary objective of this surrogate model is to replace the numerical model when predicting changes in groundwater levels resulting from variations in recharge and pumping.

The smart model represents a cutting-edge tool to analyse the potential impact of future climate scenarios and groundwater utilization on the aquifer water levels. By employing this model, stakeholders can gain valuable insights without relying solely on complex numerical simulations. It offers a more accessible and efficient means of evaluating the aquifer state and informing decision-making processes related to groundwater management.

Definition of scenarios

The future climate impact on the Requena-Utiel aquifer was assessed by considering changes in recharge, primarily influenced by precipitation. It was assumed that over a span of 36 years, the recharge rate could fluctuate by plus or minus 30% of the average recorded during the last ten years (named recharge factor – RF). The impact of groundwater use was accounted by incorporating changes in the pumping rate of all active wells. It was assumed that these pumping wells could fluctuate within plus or minus 25% of the average recorded over the last ten years (named pumping factor - PF). The reasons underlying the adoption of these scenarios were thoroughly explained in Milestone 3.4 (Secci et al., 2023).

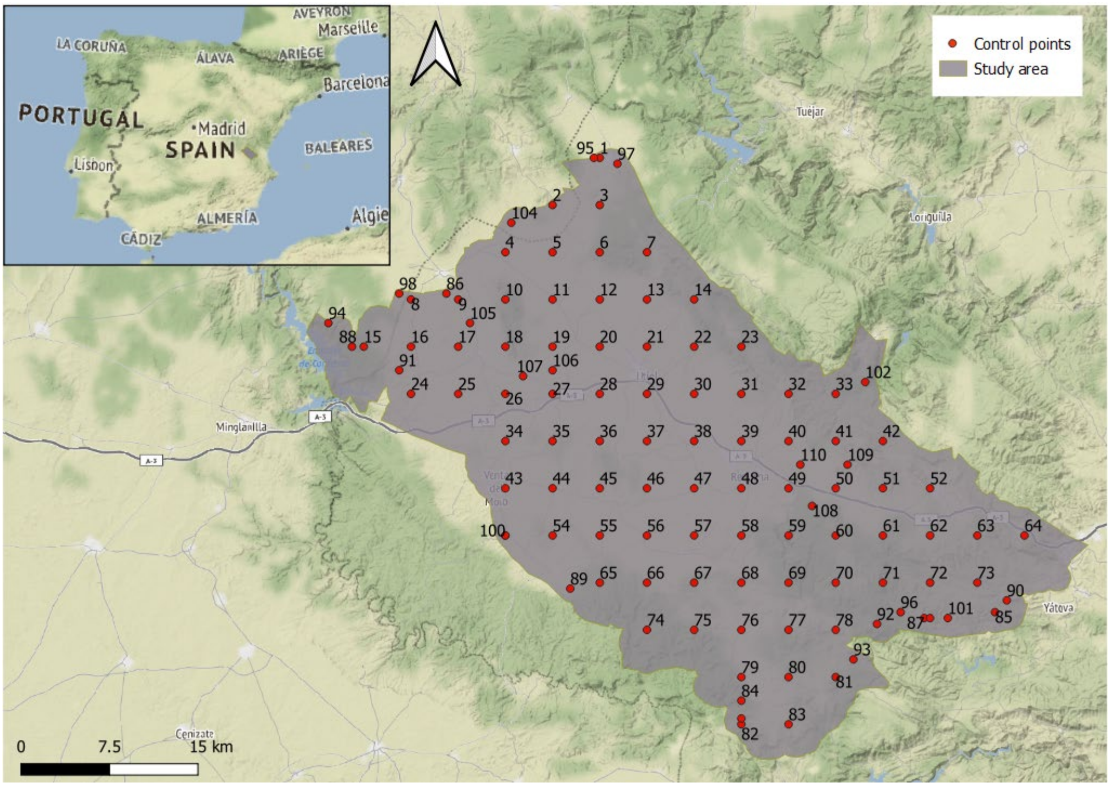


Figure 1. Spain: study area and control points for the surrogate model.

After establishing the ranges of variation for both the recharge and pumping rates, a total of 64 unique scenarios were generated which provide a comprehensive set of simulations that capture the possible outcomes resulting from different combinations of recharge and pumping rates. In this report, three pumping scenarios were considered as examples. The first scenario, labelled Pump -25%, assumes a 25% reduction in pumping of the average recorded during the last ten years, the second scenario, labelled Pump +25%, considers a 25% increase in pumping of the average recorded during the last ten years, and the last scenario, labelled Pump, considers pumping equal to the average recorded during the last ten years. For each pumping scenario, recharge is considered to fluctuate within a range of -30% to +30% of the average recorded during the last ten years. While the increase or decrease in pumping is assumed to occur suddenly on the first year of simulation and remains constant for the entire period, the recharge is assumed to vary linearly up to the specified factor since the effect of climate change is expected to materialize gradually.

The trained random forest model generates predictions of monthly piezometric heads at 110 monitoring points (Figure 1) taking four features as input: the month (from October 2016 to September 2052), the year (from 2016 to 2052), the recharge factor, and the pumping rate factor as defined in Milestone 3.4 (Secci et al., 2023). By designating as references four of the control points shown in Figure 1, the outcomes are presented in terms of variations in groundwater levels relative to the levels recorded in September 2016 (Figure 2).

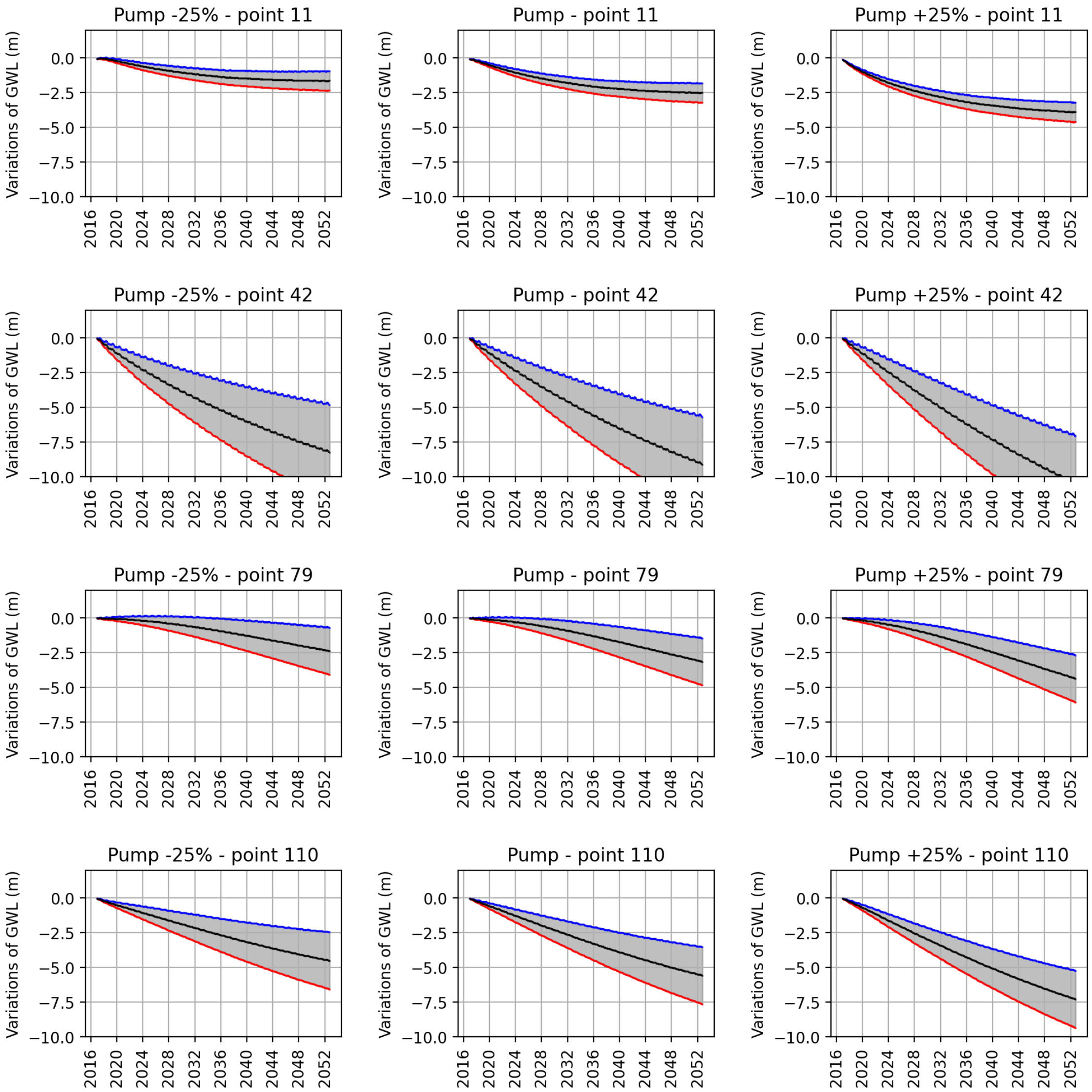


Figure 2. Spain: Groundwater level variations (relative to the September 2016 value) over time at fours control points for three pumping scenarios: - 25%, equal and +25% of the average pumping rate over the last ten years. The solid black line depicts the variation of groundwater levels considering the average recharge recorded during the last ten years. The grey band indicates the predicted groundwater level variability within a range of +/- 30% of the recharge. Red lines represent scenarios with 30% reduced recharge, while blue lines represent scenarios with increased recharge of 30%.

The observed decreasing trend in groundwater levels is consistent across all analysed scenarios and indicates that the aquifer is being overexploited. Specifically, in the unchanged scenario where recharge and pumping remain the same as the average recorded during the last ten years, a consistent decline in piezometric levels is observed. This decline serves as an indication of the ongoing stress on the aquifer system.

The reduction of 30% in recharge (red lines) has a highly significant negative impact on groundwater levels in all scenarios, and there are no indications of recovery over time. The lack of recuperation implies a sustained imbalance between recharge and extraction, exacerbating the adverse effects of overexploitation on the aquifer system. However, in the most optimistic scenario, which includes a 30% increase in recharge (blue lines) and a 25% reduction in pumping (first column), the decline in groundwater levels is less prominent, suggesting the possibility of mitigating the adverse effects of overexploitation under favourable conditions.

By employing a spatial interpolation technique, specifically radial basis function, we utilized the data collected from control points to interpolate and create piezometric maps for the entire aquifer. These maps provide a visual representation of the spatial distribution of groundwater levels. Figure 3 presents the baseline map, depicting the groundwater levels in September 2016. This map serves as a reference point for comparison to analyse the changes in groundwater levels over time.

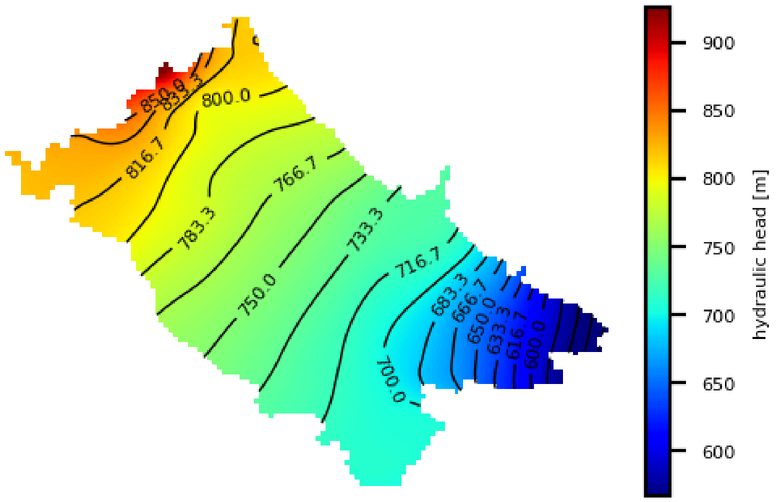


Figure 3. Spain: Piezometric map of groundwater levels (m) in September 2016

Figure 4 illustrates the maps that display the spatial patterns of piezometric differences for the analysed scenarios in October 2032 and 2052. These maps highlight regions where groundwater levels have decreased compared to the baseline map. They offer important insights into the variations occurring across the aquifer, aiding in the identification of areas where the decline in groundwater levels was more intense in response to the specific scenarios studied.

By examining these maps, one can gain a comprehensive understanding of the spatial dynamics and changes in groundwater levels within the aquifer. This knowledge is crucial for making informed decisions regarding water resource management and developing effective mitigation strategies.

It is noteworthy that the piezometric maps estimated for each month and year in the period 2016-2052 for all considered scenarios can be visualized using the DSS application (Deliverable D6.2; Varouchakis et al., 2023).

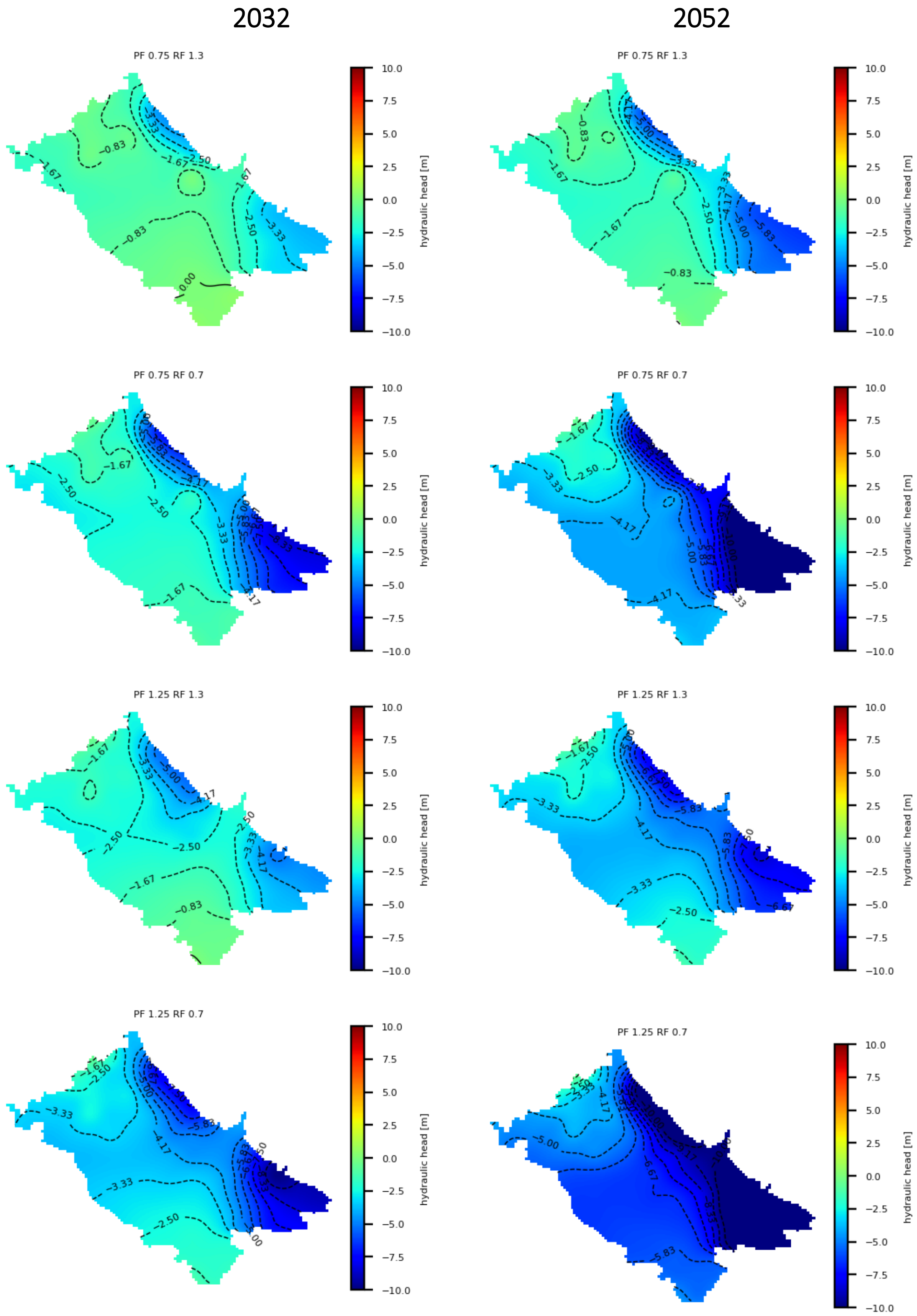


Figure 4. Spain: Piezometric differences in groundwater levels relative to the baseline map of September 2016. The recharge factor (RF) and the pumping factor (PF) define four scenarios: 25% reduction in pumping and a 30% increase in recharge (PF=0.75 and RF=1.3), 25% reduction in pumping and a 30% reduction in recharge (PF=0.75 and RF=0.7), 25% increase in pumping and a 30% increase in recharge (PC=1.25 and CP=1.3), and 25% increase in pumping and a 30% reduction in recharge (PF=1.25 and RF=0.7).

2.2. Tympaki (Greece)

Introduction

The Tympaki Basin (Figure 5) is a region located in Crete, Greece, known for its agricultural activities and groundwater resources. Climate change can have significant impacts on groundwater systems in the Tympaki Basin. Groundwater is a vital resource for irrigation in the region, and any decrease in availability or deterioration in quality can have significant implications for local communities and the agricultural sector. Monitoring and modelling groundwater resources can provide valuable data for decision-making and resources planning.

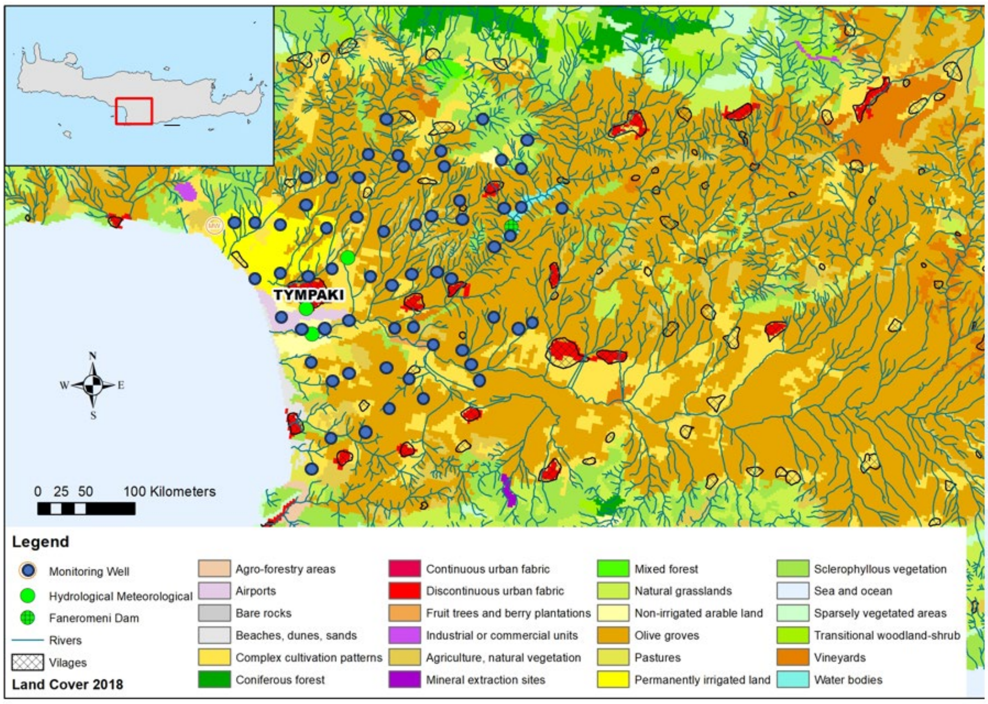


Figure 5. Greece: Tympaki basin and monitoring points used in the surrogate model

Specific studies and data analysis on the Tympaki Basin's groundwater and its response to climate change may provide more detailed insights and context. A numerical hydrogeological model and a more versatile surrogate model that can substitute the full model were developed to simulate groundwater conditions in the area. In particular, a space-time regression kriging (STRK) model, which is able to capture the complex spatiotemporal groundwater level patterns in the area, was developed as surrogate models. This model was applied, using auxiliary information, to estimate future groundwater level variations under variable management and policy scenarios and climate change impact. These points serve as a general understanding of the potential interactions between groundwater and climate change in the region.

Definition of scenarios

Achieving good water status requires the establishment and implementation of management plans at the river basin level. The Management Plans requirements are described in detail in Article 13 and Annex VII of Directive 2000/60/EC and include Programs of Measures for the Protection and Rehabilitation of Waters, in accordance with Article 11 and Annex VI of the Directive. The water resources directorate of Crete implements the Management Plans for the island (water district) of Crete in accordance with the requirements of Directive 2000/60/EC, pursuant to Law 3199/2003 and Presidential Decree 51/2007. Approved plans include all the detailed information required by Article 13 and Annex VII of Directive 2000/60/EC. The approved River Basin Management Plans were recently updated in accordance with the requirements of current Legislation. To this end, the Special Secretariat for Water has developed an extensive Consultation on the areas of high significance. Thus, the water resources directorate of Crete, considering the high importance of the Tympaki basin for the island's agricultural production, has closely monitored the current and future water resources availability in the area. Significant investments in infrastructure have been implemented in the area, including a reservoir and an extended water transfer network with an important target to reduce groundwater pumping and overexploitation. The basic aim is for the groundwater level to recover in the next 15 years. In the context of the revised water resources management plan in the area, they have suggested the following scenarios in terms of the current conditions and future climatic scenarios regarding overall groundwater level increase and pumping reduction due to the operation of a water reservoir in the case study area:

1. Optimistic scenario: 50% pumping reduction, 20% average groundwater level increase by 2027 (national/regional target).
2. Promising scenario: 80% pumping reduction, 50% average groundwater level increase by 2037 (national/regional target).

It is noteworthy that the surrogate model can also be used for comparison and sensitivity analysis to the effect of different combinations of climate and socio-economic scenarios on groundwater resources. The results of all considered scenarios can be visualized using the DSS application (Deliverable 6.2; Varouchakis et al., 2023).

Results of the analysis of different scenarios

The implementation of the suggested scenarios using the STRK method to address the challenges posed by climate change scenarios are presented below. The future scenarios are compared with the baseline map (Figure 6), which illustrates the groundwater levels spatial distribution in the area during the most recent hydrological year with available data (2021-22).

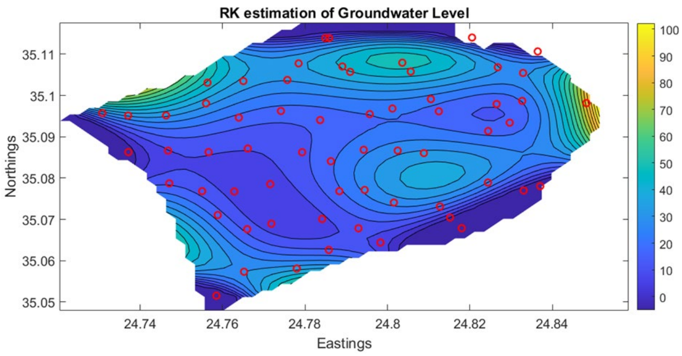


Figure 6. Greece: Groundwater levels spatial distribution (m a.s.l.) in the Tympaki basin during the hydrological year 2021-22.

The considered scenarios focus on pumping reduction and increasing average groundwater levels by specific timeframes. Let's discuss these scenarios results in more detail:

1. Optimistic Scenario: In this scenario, the target is to achieve a 50% reduction in pumping and a 20% increase in average groundwater levels compared to current conditions by 2027, as per national/regional targets. A 50% reduction in pumping implies a significant decrease in groundwater extraction for various uses such as agriculture, industry, and domestic consumption. This reduction aims to alleviate the stress on the groundwater system and allow for a gradual recovery of water levels. Achieving a 20% increase in average groundwater levels indicates a positive trend towards replenishing the aquifers. It is important to note that meeting these targets would require concerted efforts, efficient water management practices, and collaboration among stakeholders. Implementing the rainfall predictions of the RCP4.5 and 8.5 climate change scenarios, the piezometric differences in groundwater levels for the year 2027, relative to the baseline map of the hydrological year 2021-2022, is

presented in Figure 7. According to Figure 7, the groundwater level spatial distribution in the entire area has an increasing trend providing a slow aquifer recovery by means of both climate change scenarios assessed.

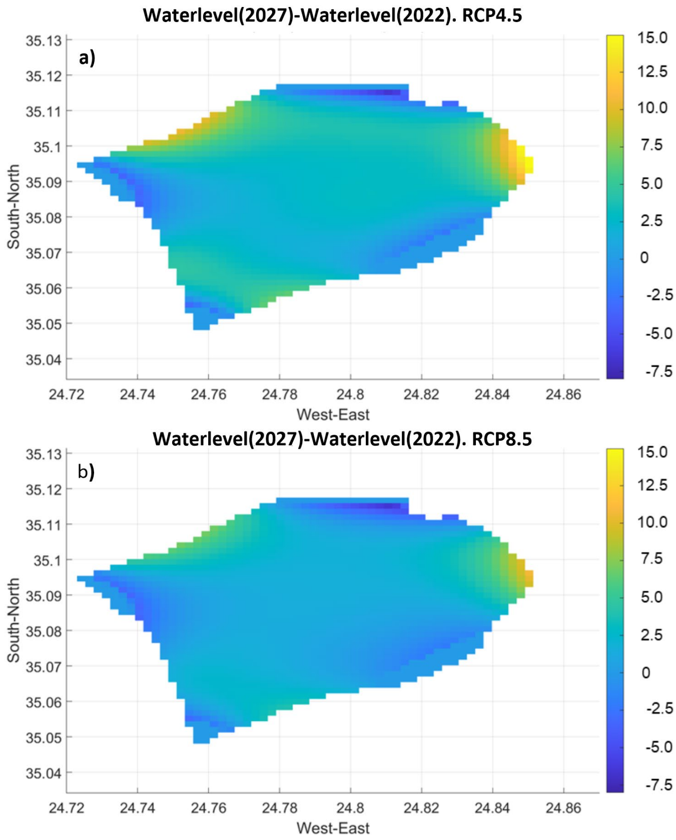


Figure 7. Greece: Groundwater level differences (m a.s.l.) for the year 2027 relative to the baseline map of the hydrological year 2021-2022 in Tympaki basin implementing the optimistic scenario and climate change scenarios a) RCP4.5, b) RCP8.5.

2. Promising Scenario: In this more ambitious scenario, the target is to achieve an 80% reduction in pumping and a 50% increase in average groundwater levels by 2037, as per national/regional targets. This scenario sets even higher benchmarks for pumping reduction and groundwater level increase. An 80% reduction in pumping would significantly reduce the demand for groundwater resources and necessitate the implementation of alternative water sources and conservation measures. The target of a 50% increase in average groundwater levels indicates a more substantial recovery and restoration of the aquifer system. Achieving these targets would require long-term commitment, sustainable water management practices, and the implementation of innovative approaches to reduce water demand and promote water conservation.

Figure 8 shows the piezometric differences in groundwater levels for the year 2037, relative to the baseline map of the hydrological year 2021-2022, implementing the rainfall predictions of the RCP4.5 and 8.5 climate change scenarios. According to Figure 8, a substantial increase in groundwater level spatial distribution is observed irrespectively of the climate change scenarios, which means that the pumping reduction can significantly affect the aquifer recovery.

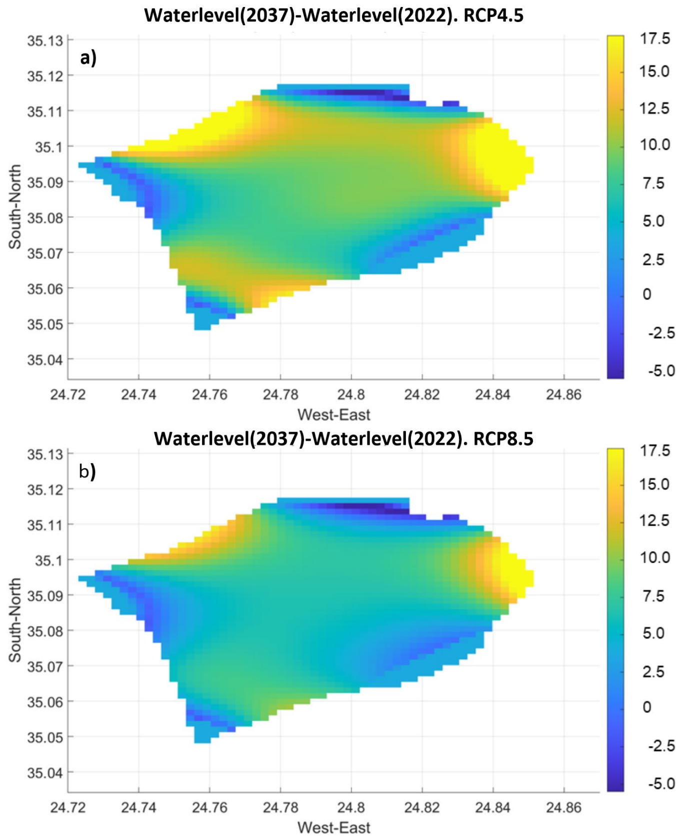


Figure 8. Greece: Groundwater level differences for the year 2037 relative to the baseline map of the hydrological year 2021-2022 in Tympaki basin implementing the promising scenario and climate change scenarios a) RCP4.5, b) RCP8.5.

Both scenarios highlight the importance of sustainable groundwater management and the need to address the challenges posed by climate change in the Tympaki Basin. It is crucial to consider the local hydrogeological conditions, identify the hotspots that require special attention, employ socio-economic factors, and stakeholder engagement when formulating and implementing strategies to meet these targets. Collaboration between government agencies, local communities, and relevant stakeholders is essential for effective water resource planning and management to ensure the resilience and sustainability of the groundwater system in the face of climate change. The most important outcome of this modelling approach is that the coastal part, which is more vulnerable to saltwater intrusion, is expected to recover following the suggested management scenarios to adapt to climate change effects.

2.3. Konya (Turkey)

Introduction

The Konya Closed basin, depicted in Figure 9, is an important agricultural area, where more than 50% of its flat surface is dedicated to farming. However, due to the absence of rivers and streams in the basin, farmers heavily rely on groundwater resources to meet their agricultural, especially during dry periods. Consequently, the groundwater reserves in the basin are facing significant pressure. In recent years, there has been a shift from traditional wheat farming to more profitable crops like sugar beets and maize, which require more water (Yilmaz et al., 2021). Moreover, the projected impacts of climate change are expected to worsen the situation, potentially compromising the sustainability of the basin due to aquifer overexploitation.

To promote the sustainable utilization of groundwater resources, the BU Team has developed a comprehensive numerical hydrogeological model for the Konya basin. The ultimate goal is to create a surrogate model that can replace the full model and simulate groundwater conditions in the Konya closed basin with minimal computational burden. This surrogate model will enable the evaluation of different climate and socio-economic scenarios. In particular, an Artificial Neural Network (ANN) has been implemented to provide predictions of future groundwater levels under various climate change and irrigation/crop scenarios.

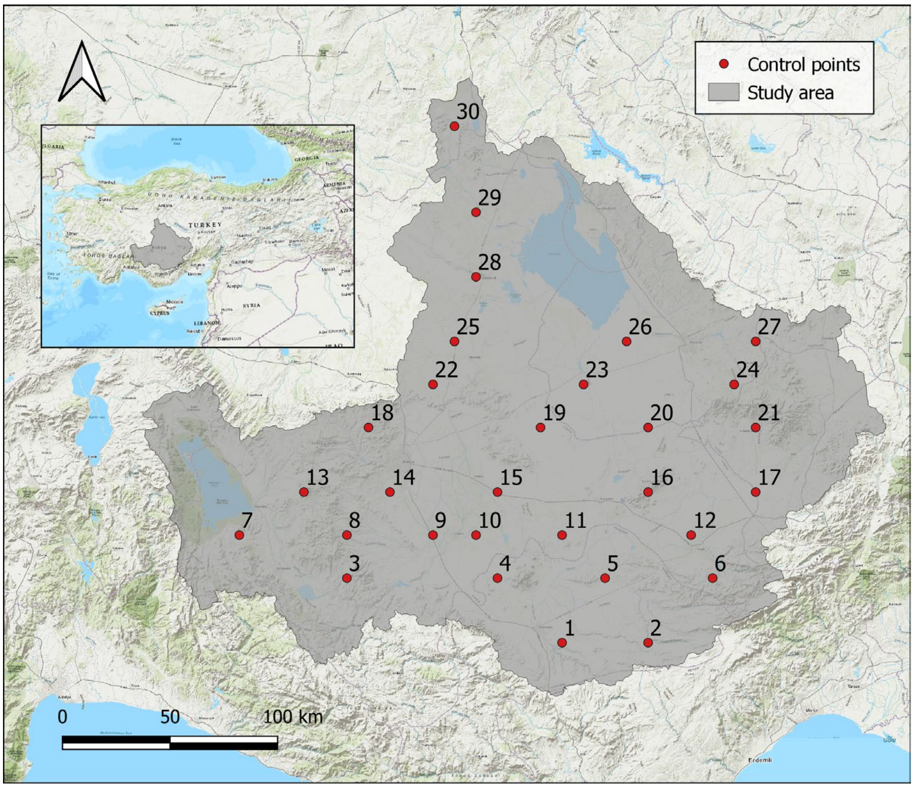


Figure 9. Turkey: study area and control points for the surrogate model

Definition of scenarios

The surrogate model is employed to examine the potential impacts of climate change and agricultural policies on groundwater resources. Different future precipitation scenarios (in terms of percentage decrease or increase of the historical precipitation) and water demand scenarios (in terms of percentage variation of the historical water demand) are taken into account as input variables.

The investigation focuses on the prediction period spanning from 2020 to 2039. As an example, in this report, three precipitation scenarios were considered. The first precipitation scenario assumes a 20% decrease in precipitation compared to the historical twenty-year period 2000-2019 (Prec. -20%). The second scenario maintains the historical precipitation pattern throughout the prediction period. The third precipitation scenario considers a 20% increase in precipitation compared to historical precipitation (Prec. +20%). The percentage variation is defined through a precipitation coefficient. For each precipitation scenario, the crop water demand is considered to vary within a range of -20% to +20% of the historical water demand; this percentage variation is defined through a crop coefficient.

The fully trained network, as already described in Deliverable 3.2 (Todaro et al., 2023) and Milestone 3.4 (Secci et al., 2023), generates predictions of monthly piezometric heads at 30 monitoring points (Figure 9) using as driven input the precipitation and crop coefficients and the time of the desired prediction.

By designating four control points (Figure 9) as references, the outcomes are presented in terms of variations in groundwater levels relative to the head value recorded in December 2019 (Figure 10 to Figure 13).

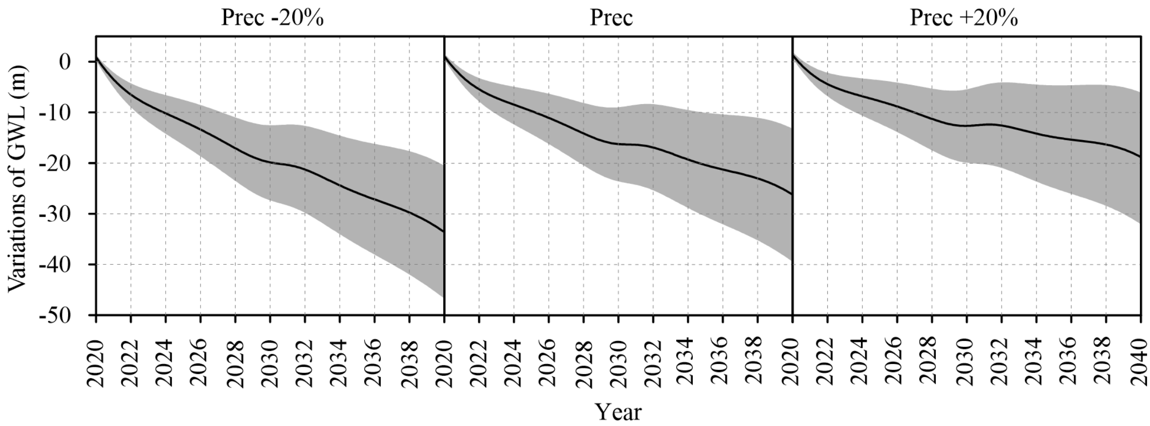


Figure 10. Turkey: Control Point 2. Groundwater level variations (relative to the December 2019 value) over time for different precipitation scenarios: observed (Prec) and -/+ 20%. The solid black line depicts the variation of groundwater levels considering the observed water demand. The grey band shows the variability of the predicted groundwater levels inside the range +/- 20% of the water demand

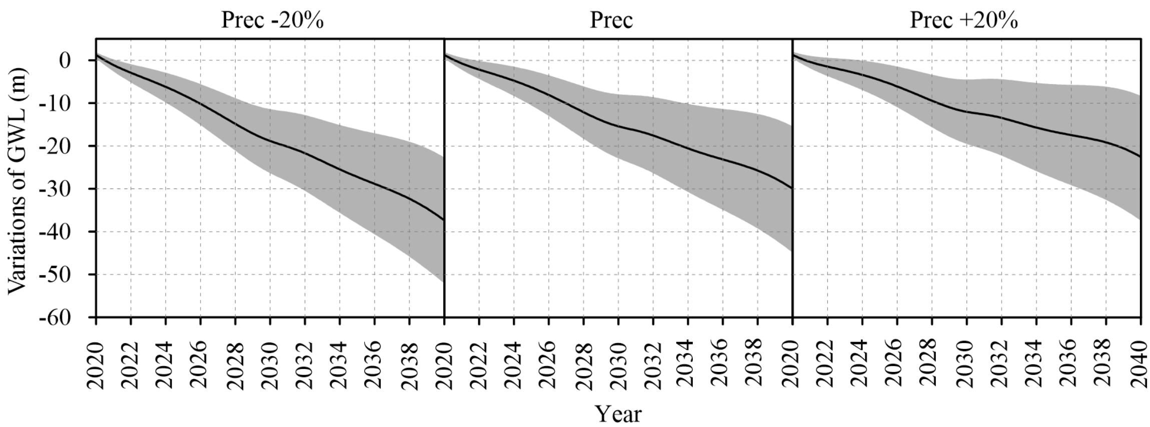


Figure 11. Turkey: Control Point 10. Groundwater level variations (relative to the December 2019 value) over time for different precipitation scenarios: observed (Prec) and -/+ 20%. The solid black line depicts the variation of groundwater levels considering the observed water demand. The grey band shows the variability of the predicted groundwater levels inside the range +/- 20% of the water demand

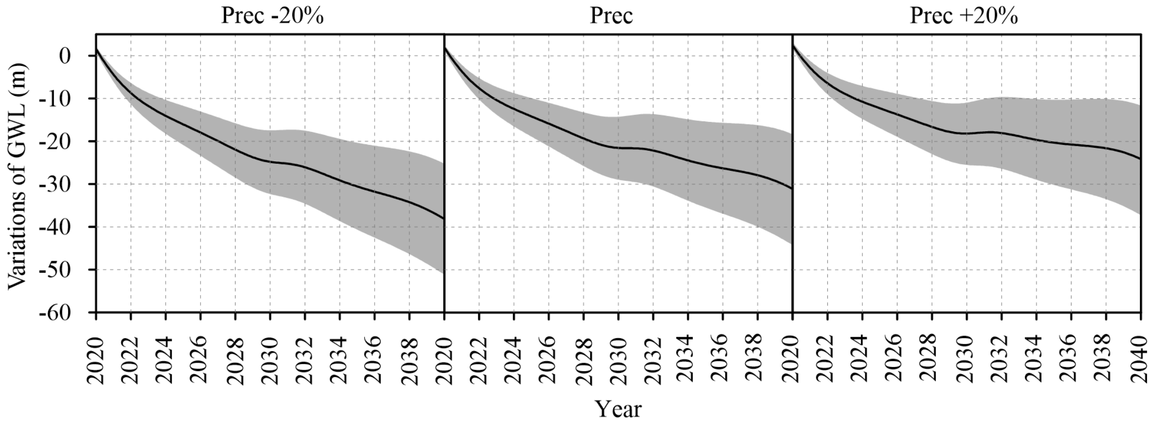


Figure 12. Turkey: Control Point 20. Groundwater level variations (relative to the December 2019 value) over time for different precipitation scenarios: observed (Prec) and -/+ 20%. The solid black line depicts the variation of groundwater levels considering the observed water demand. The grey band shows the variability of the predicted groundwater levels inside the range +/- 20% of the water demand

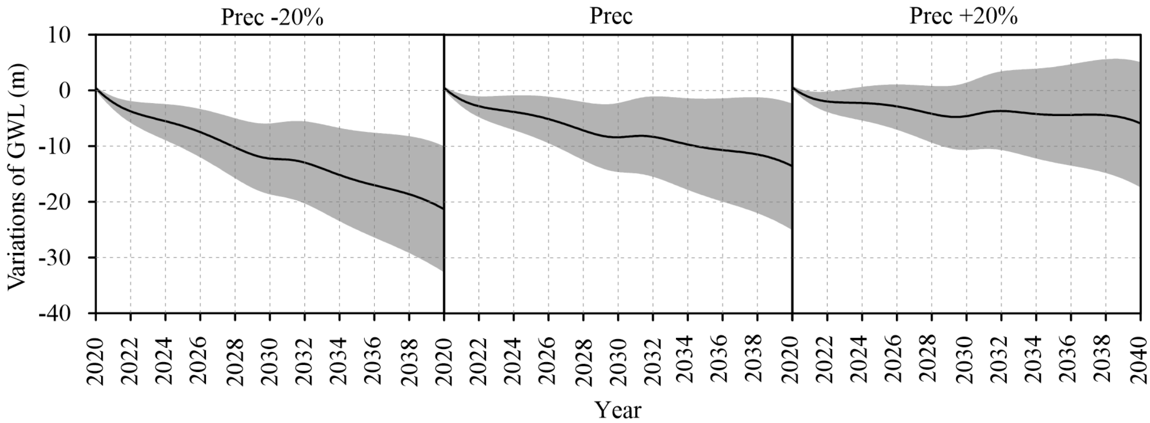


Figure 13. Turkey: Control Point 30. Groundwater level variations (relative to the December 2019 value) over time for different precipitation scenarios: observed (Prec) and -/+ 20%. The solid black line depicts the variation of groundwater levels considering the observed water demand. The grey band shows the variability of the predicted groundwater levels inside the range +/- 20% of the water demand

The results unequivocally suggest that the aquifer is experiencing a state of overexploitation. Specifically, in the unchanged scenario where precipitation and water demand remain the same as in the historical period, a systematic decline in piezometric levels is expected, clearly highlighting an ongoing stress of the aquifer system. This downward trend is also evident for all the other scenarios analysed; there is an exception observed at Control Point 30. In the most optimistic scenario, characterized by a 20% increase in rainfall and a 20% reduction in water crop demand, the variations in groundwater levels remain relatively constant during the initial period, followed by a slight increase. This outcome highlights the potential for mitigating the adverse effects of overexploitation under specific favourable conditions.

Using a spatial interpolation technique, such as inverse distance weighting, the data obtained at the monitoring points were interpolated to create piezometric maps across the entire basin. Figure 14 presents the baseline map illustrating the groundwater levels in December 2019. Based on this baseline map, Figure 15 reports maps that show the spatial patterns of the piezometric differences for the analysed scenarios, highlighting regions characterized by either an increase or decrease in groundwater levels.

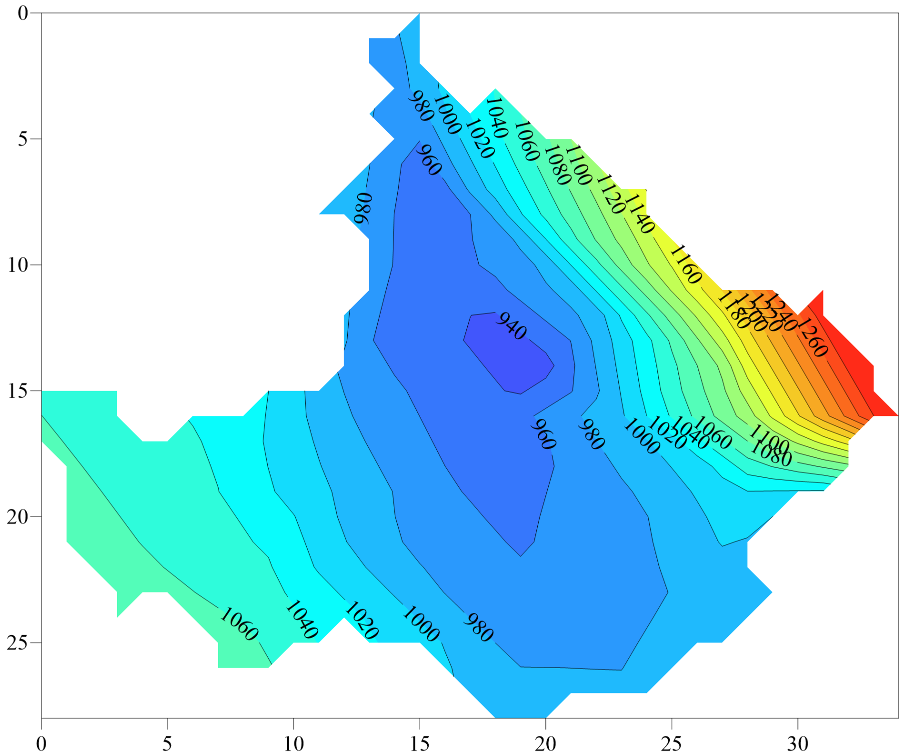


Figure 14. Turkey: Piezometric map of groundwater levels (m a.s.l.) in December 2019

Under the first scenario, where precipitation and water demand follow the historical period, the piezometric difference maps for December 2029 and December 2039 indicate a clear reduction of groundwater levels across the majority of the basin. This suggests an existent overexploited aquifer configuration. In the second scenario, with a 20% reduction in precipitation and a 20% increase in water demand, the maps reveal even more significant declines in groundwater levels, indicating a higher stress of the aquifer system. The third scenario, characterized by a 20% increase in precipitation and a 20% reduction in water demand, shows a slight increase in groundwater levels compared to the other scenarios. However, the piezometric difference maps still display negative differences, implying declining groundwater levels, albeit to a smaller extent, certainly due to the historical overexploitation.

These piezometric maps offer crucial information for hydrogeological assessments and water resource management within the basin. They assist in identifying areas of potential water stress or recharge, aiding in decision-making processes related to groundwater allocation, land use planning, and environmental conservation strategies.

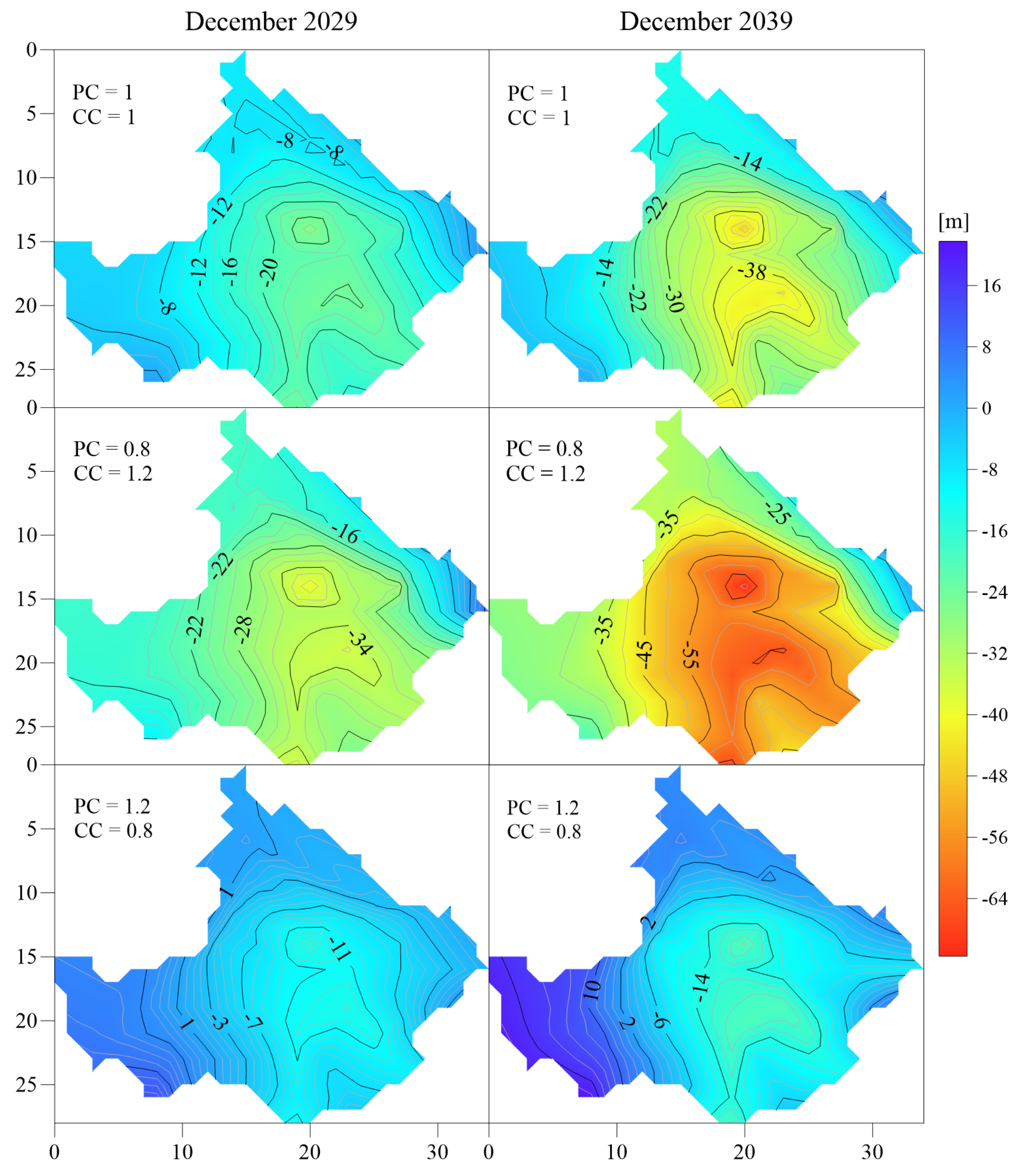


Figure 15. Turkey: Piezometric differences in groundwater levels relative to the baseline map of December 2019. The precipitation coefficient (PC) and the crop coefficient (CP) define three scenarios: precipitation and water demand remain unchanged from historical ones (PC=1 and CP=1), 20% reduction in precipitation and a 20% increase in water demand (PC=0.8 and CP=1.2), 20% increase in precipitation and a 20% reduction in water demand (PC=1.2 and CP=0.8)

It is noteworthy that the piezometric maps estimated for each month and year in the period 2019-2039 for all considered scenarios can be visualized using the DSS application (Deliverable D6.2; Varouchakis et al., 2023).

2.4. Grombalia (Tunisia)

Introduction

The Grombalia groundwater system faces a higher risk of depletion. One of the main factors contributing to the depletion of groundwater in Grombalia is the overexploitation of water from the aquifers. The increasing demand for water, especially for agriculture, has led to a significant increase in the number of wells and pumping stations in the region. In addition to overexploitation, climate change is exacerbating the problem in Grombalia (Todaro et al., 2022). The region is already characterized by a semi-arid climate with low rainfall, and climate change is projected to lead to further declines in groundwater levels.

The surrogate model developed for the Grombalia aquifer aims to provide a useful tool for evaluating the impact of future climate scenarios on groundwater resources. Since a complete numerical model is not available for the study area, a data-driven surrogate model has been developed based on historical groundwater levels and a meteorological index, namely the Standardised Precipitation Evapotranspiration Index (SPEI), which is related to the precipitation and temperature data. The proposed method employs simple and fast statistical techniques to assess the possible effects of climate change on the quantitative status of groundwater, combining historical relationships between meteorological and groundwater data with future climate scenarios (Deliverable 3.2; Todaro et al., 2023). If hydrological processes will not change over time, the surrogate model can make predictions about how the aquifer will respond to changes under different climate scenarios (Milestone 3.4; Secci et al., 2023). Figure 16 displays the investigated area and the positions of the monitoring wells where the future changes in groundwater levels are assessed. Overall, the surrogate model provides a quick and efficient way to assess the potential impact of climate change on the Grombalia aquifer without the need for a complete numerical model.

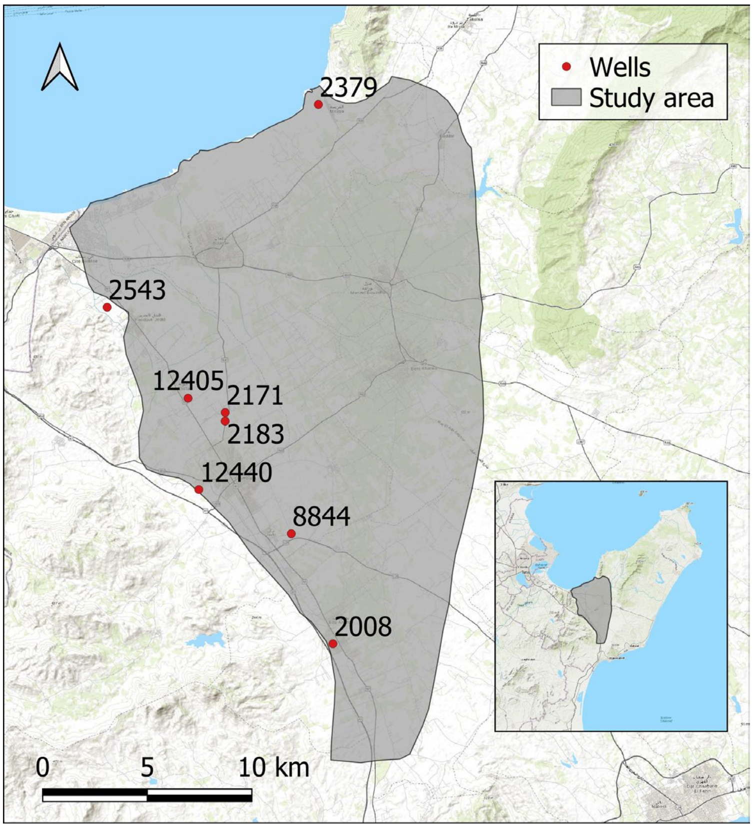


Figure 16. Tunisia: study area and location of monitoring wells

Definition of Scenarios

For this pilot site, the impact of climate change on groundwater resources is analysed under two climate scenarios: the Representative Concentration Pathways RCP4.5 and the RCP8.5. The RCP4.5 scenario assumes that greenhouse gas emissions will peak around 2040 and then decline, reaching a radiative forcing of 4.5 W/m^2 by 2100. This scenario assumes moderate emissions reductions and greater use of low-carbon energy sources. In contrast, the RCP8.5 scenario assumes that greenhouse gas emissions will continue to rise throughout the century, resulting in a radiative forcing of 8.5 W/m^2 by 2100. This scenario assumes a business-as-usual approach to emissions with little to no mitigation efforts. The evaluation of the impact of the anthropogenic actions cannot be considered as the surrogate model developed for Grombalia is driven by precipitation and temperature variations only. The groundwater levels until the end of this century are evaluated based on precipitation and temperature data provided by an ensemble of regional climate models (Deliverable 3.3; D'Oria et al., 2022).

The surrogate model has been developed based on late winter and early spring data (D3.2; Todaro et al., 2023). The future projections of groundwater levels (GWLs) were evaluated for the month of April, which was chosen as a representative timeframe to evaluate groundwater changes. The Figure 17 illustrates the outcomes for the eight wells during the period from 2005 to 2098. To ensure comparability across the different wells, the results are presented as GWL anomalies relative to the mean of the GWLs in April, inferred from the RCMs, in the period 1976-2005. To emphasize the impact of climate change on natural variability, Figure 17 displays the 10-year moving average of the predicted GWLs. A general decrease in groundwater levels is expected for all wells, which is more severe for the RCP8.5 scenario. According to the RCM ensemble median, the highest decreases in GWLs are expected for the wells 2008 and 12405, which present a decrease in the mean GWLs at the end of the century of about 2.5 m for the RCP4.5 and 4.5 m for the RCP8.5. Well 2379 denotes the lowest decrease, as well as the lowest uncertainty. The inter-model variability between the 17 RCMs is different for the eight wells, since the uncertainty associated with climate model predictions propagates differently for each well. This also underscores the importance of incorporating an ensemble of models to encompass for various climate realizations. It is noteworthy that the wells that exhibited the minimum decrease and low variability among the RCMs were associated with the smallest slope in the linear regression model, between the meteorological index SPEIs and groundwater levels, adopted as surrogate model (Deliverable 3.2; Todaro et al., 2023 - Milestone 3.4; Secci et al., 2023). This suggests that these wells are less sensitive to meteorological variability. In contrast, wells with the highest slopes indicate a greater sensitivity to climate change and are those associated with the most severe groundwater depletion.

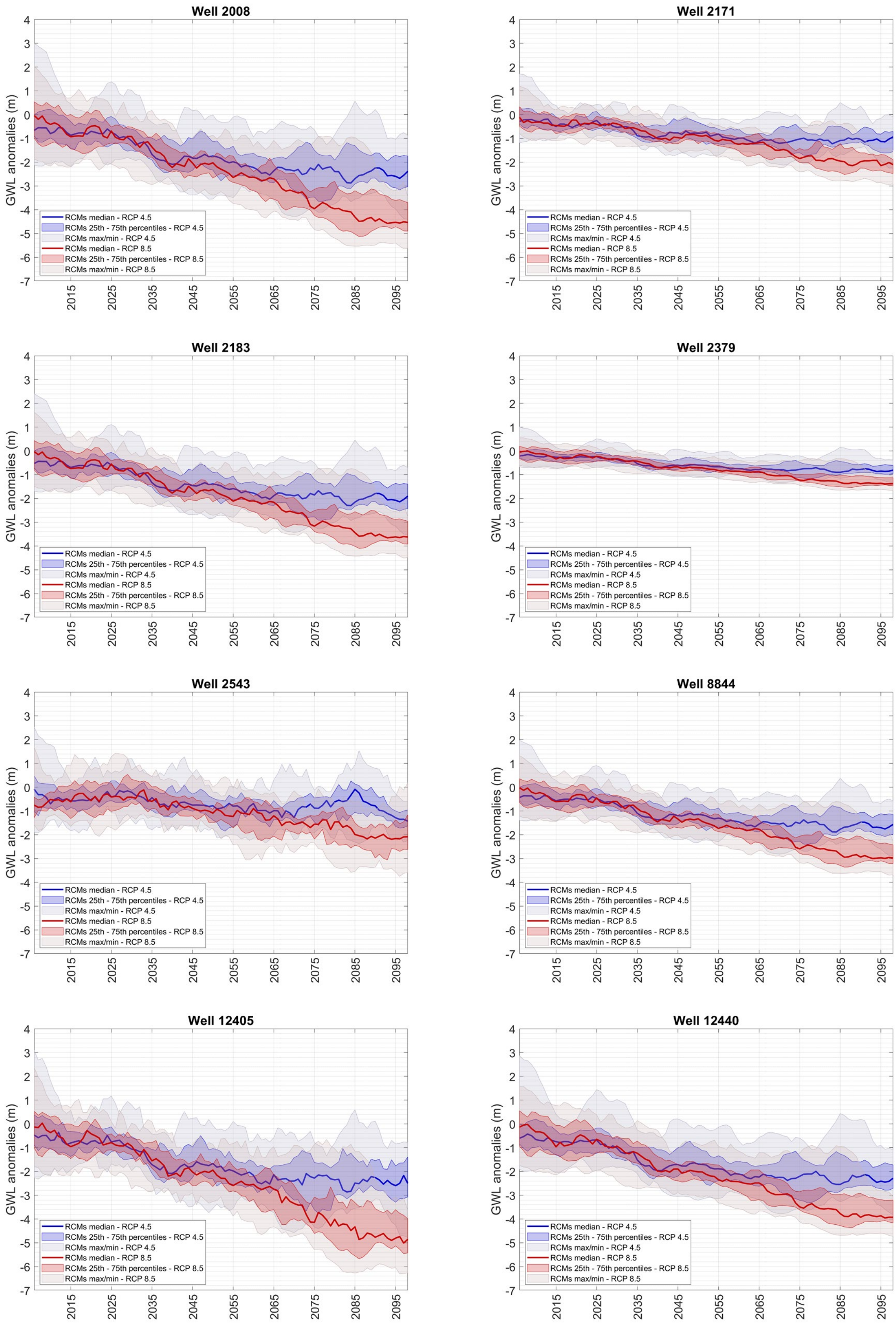


Figure 17. Tunisia: groundwater level anomalies in terms of 10-year moving average in the period 2005-2098, relative to 1976-2005, for the eight wells according to the RCP4.5 and RCP8.5 scenarios

2.5. Guadiana basin (Portugal)

Introduction

The study area involves the Portuguese South Zone of the Guadiana Basin groundwater system. The Guadiana Basin is heavily dependent on groundwater for agriculture, industry, and drinking water. The increasing water demand has led to a significant increase in the number of wells and pumping stations in the region. Climate change is also a significant factor affecting groundwater depletion in the Guadiana Basin (Todaro et al., 2022). The region is experiencing more frequent and severe droughts, reducing the amount of rainfall and surface water available for recharge. Higher temperatures also increase the demand for water for irrigation and other uses, exacerbating the problem of overexploitation.

The surrogate model developed for the Guadiana aquifer aims to provide a useful tool for evaluating the impact of future climate scenarios on groundwater resources. A data-driven surrogate model has been developed for the Guadiana aquifer, as a complete numerical model is not available for the study area. The surrogate model relies on historical groundwater levels and the Standardised Precipitation Evapotranspiration Index (SPEI), a meteorological index related to the precipitation and temperature data. The surrogate model uses a simple statistical technique to establish relationships between SPEIs and groundwater levels in the historical period. Combining these relationships between meteorological and groundwater data with future climate scenarios allows assessing the possible effects of climate change on the quantitative status of groundwater. If the hydrological processes, and the established relationships, will not change over time, the surrogate model can make predictions about how the aquifer responds to changes in climate variables. Figure 18 shows the investigated area and the location of the monitoring wells, where the future changes in groundwater levels are assessed.

Overall, the surrogate model provides a quick and efficient way to assess the potential impact of climate change on the Guadiana aquifer without the need for a complete numerical model.

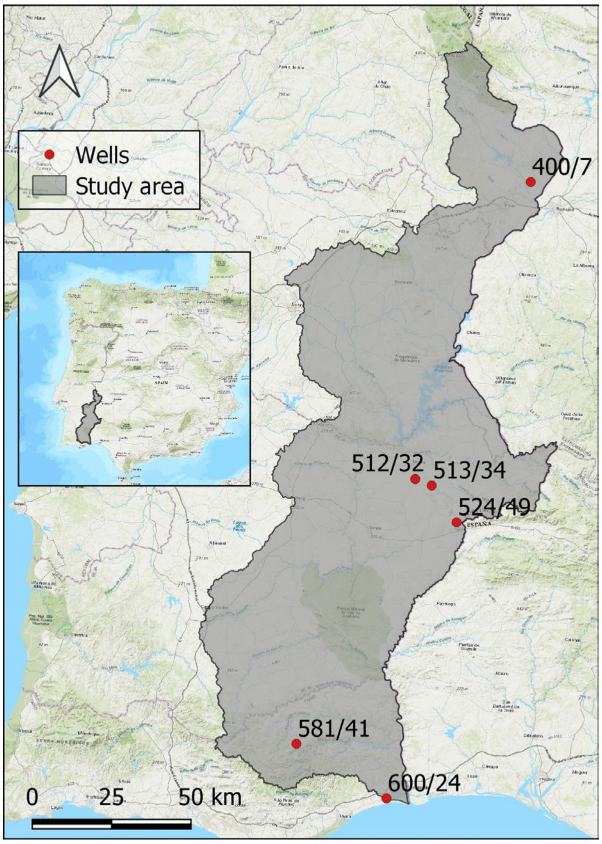


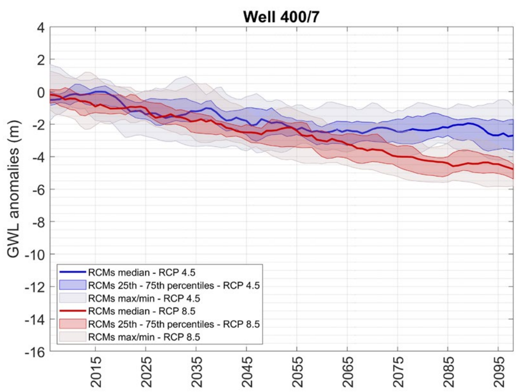
Figure 18. Portugal: study area and location of the monitoring wells

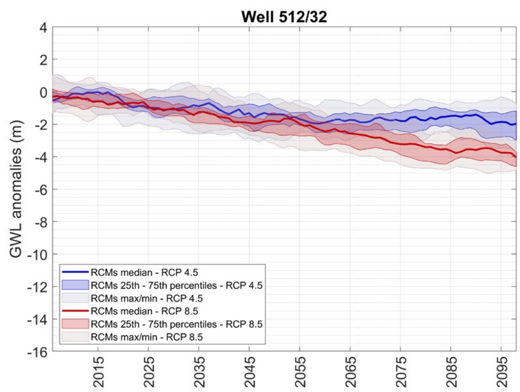
Definition of Scenarios

For this demo site, the impact of climate change on groundwater resources is analysed under two climate scenarios: the Representative Concentration Pathways RCP4.5 and the RCP8.5. The RCP4.5 scenario assumes that greenhouse gas emissions will peak around 2040 and then decline, reaching a radiative forcing of 4.5 W/m^2 by 2100. This scenario assumes moderate emissions reductions and greater use of low-carbon energy sources. In contrast, the RCP8.5 scenario assumes that greenhouse gas emissions will continue to rise throughout the century, resulting in a radiative forcing of 8.5 W/m^2 by 2100. This scenario assumes a business-as-usual approach to emissions with little to no mitigation efforts. The evaluation of the impact of the anthropogenic actions cannot be considered as the surrogate model developed for Guadiana basin is driven by precipitation and temperature variations only. The groundwater levels until the end of this century are evaluated based on precipitation and temperature data provided by an ensemble of regional climate models (Deliverable 3.3; D'Oria et al., 2022).

Results of the analysis of different scenarios

The surrogate model has been developed based on late winter and early spring data (D3.2; Todaro et al., 2023). To assess groundwater depletion, projections of groundwater levels (GWLs) were analysed for the month of April, selected as representative period to evaluate the future changes. The Figure 19 illustrates the outcomes for the six wells in the period 2005-2098. The results are presented as GWL anomalies relative to the RCM ensemble mean of the GWLs in April during the period 1976-2005; this allows comparability across the different wells. To emphasize the impact of climate change on natural variability, Figure 19 displays the 10-year moving average of the predicted GWLs. A general decrease in groundwater levels is expected for almost all wells, which is more pronounced for the RCP8.5 scenario. According to the RCM ensemble median, the highest decrease in GWLs is expected for the well 524/49, which presents a decrease in the mean GWLs at the end of the century of about 5 m for the RCP4.5 and 12 m for the RCP8.5. Wells 581/41 and 600/24 denote the lowest decreases, as well as the lowest uncertainties. The variability among the 17 regional climate models (RCMs) differs across the eight wells due to the varying propagation of uncertainty associated with climate model predictions for each well. This emphasizes the importance of incorporating an ensemble of models to encompass for various climate realizations. It is worth mentioning that the wells with the least decrease and minimal variability among the RCMs are associated with the smallest slope in the linear regression model adopted. (Deliverable 3.2; Todaro et al., 2023 - Milestone 3.4; Secci et al., 2023). This suggests that these wells are less sensitive to meteorological variability. In contrast, wells with the highest slopes indicate a greater sensitivity to climate change and are those associated with the most severe groundwater depletion.





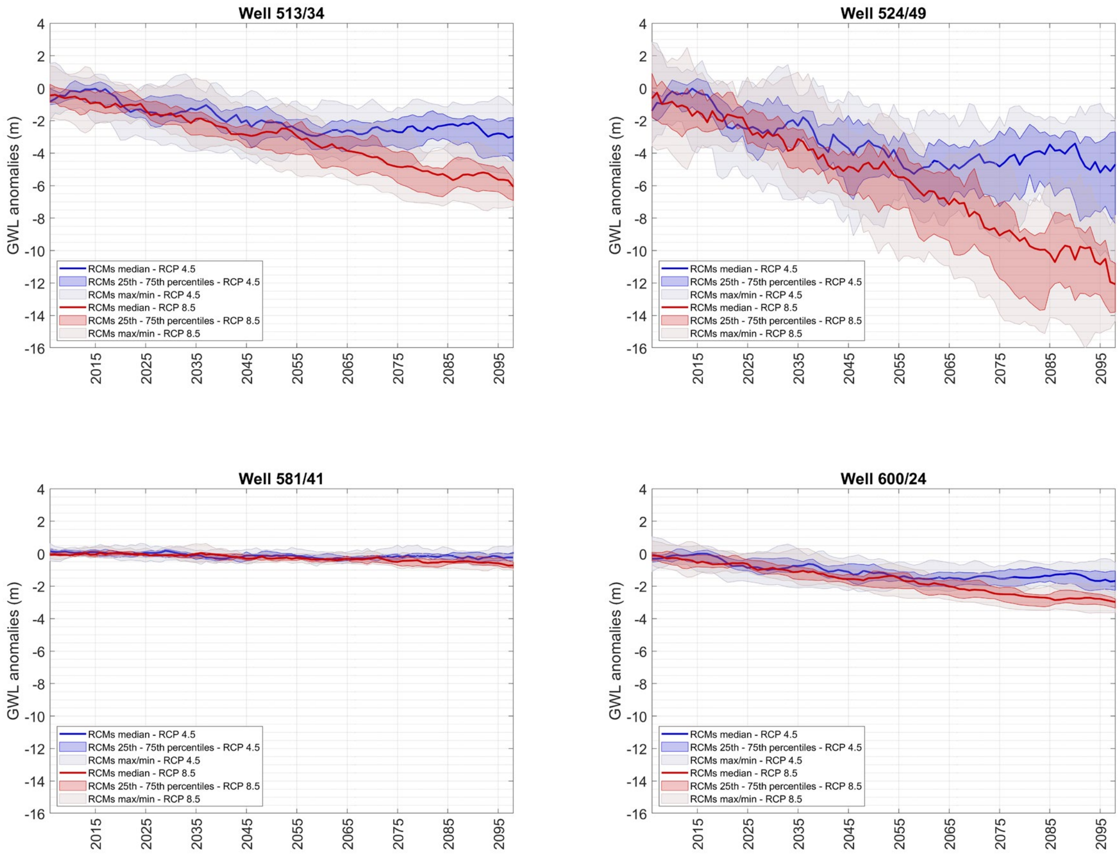


Figure 19. Portugal: groundwater level anomalies in terms of 10-year moving average in the period 2005-2098, relative to 1976-2005, for the eight wells according to RCP4.5 and RCP8.5 scenarios

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