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PILOT DESCRIPTION AND ASSESSMENT

Malta Mean Sea Level Aquifer, Malta

Authors and affiliation:

Manuel Sapiano
Henry Debattista



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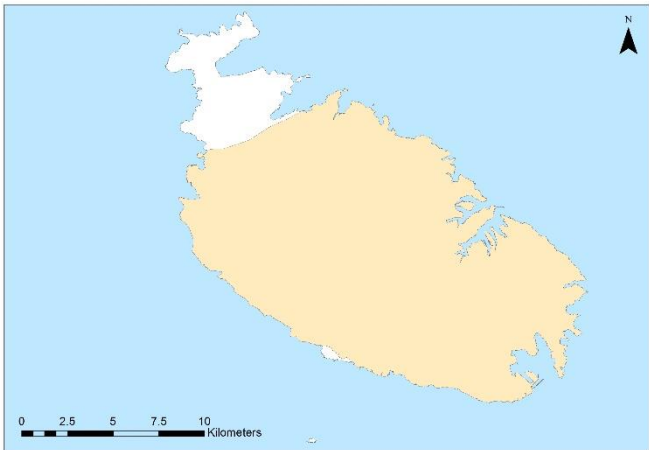
LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate Change
GHB	General Head Boundary
GL	Globigerina Limestone
GSO	Geological Survey Organisation
HFB	Horizontal Flow Barrier
EEA	European Environment Agency
ERA	Environment and Resources Authority
EWA	Energy and Water Agency
LCL	Lower Coralline Limestone
MSLA	Mean Sea Level Aquifer
RBMP	River Basin Management Plan
WFD	Water Framework Directive
WSC	Water Services Corporation

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1 EXECUTIVE SUMMARY

Pilot name	Malta MSLA	
Country	Malta	
EU-region	Mediterranean Region	
Area (km ²)	216.6Km ²	
Aquifer geology and type classification	Limestone (sedimentary-fractured aquifer)	
Primary water usage	Drinking Water, Agricultural Irrigation	
Main climate change issues	Increasing temperatures, Decreasing Recharge (both due to decreasing rainfall and changing rainfall patterns) and Sea-Level rise	
Models and methods used	Groundwater numerical models, water balance equations.	
Key stakeholders	Water Services Corporation, Environment and Resources Authority	
Contact person	Manuel Sapiano, Energy and Water Agency, manuel.sapiano@gov.mt	

The Malta Mean Sea Level Aquifer system is by far the most important groundwater body in the Maltese islands sustaining around 80% of the available renewable freshwater resources. The aquifer system sustains a groundwater body which takes the form of a lens of freshwater floating on the denser sea-water, and therefore an arrangement where freshwater is in lateral and vertical contact with sea-water. These aquifer systems are therefore highly vulnerable to sea-water intrusion in response to abstraction activities, and groundwater abstraction needs to be carefully managed to ensure the quality of the abstracted water. The level of sea-water intrusion depends on several factors including the rate of abstraction, the hydro-dynamic properties of the aquifer matrix and the distance of the bottom of the abstraction point to the freshwater-seawater interface. The position of the interface depends, in accordance with the Ghyben-Herzberg principle, on the piezometric levels. Therefore any lowering of the piezometric surface due to Climate Change impacts is construed as potentially contributing to an exacerbation of the sea-water intrusion levels arising under pumping conditions,

The study represented in this report models the impact on the piezometric levels of the Mean Sea Level aquifer system arising from the occurrence of three potential climate change scenarios entailing a reduction in rainfall, an increase in abstraction and a rise in sea-level respectively.



The study also undertakes a comparative analysis of the impact arising from these three Climate Change scenarios with that arising from due to anthropogenic activities such as different levels of overabstraction and recharge reduction.

The results of the numerical models show that the piezometric surface under the modelled Climate Change conditions is generally lower than that resulting when the aquifer is modelled under reference conditions. In general, however, the impact of climate change on the groundwater body seems to be of a lower concern when compared with modelled results for scenarios testing the application of poor groundwater management practices. However, the onset of Climate Change is expected to exacerbate the effects of poor aquifer management practices, due to an increase in the vulnerability of the new aquifer reference conditions. Hence the need to optimise existing groundwater management strategies to ensure a high level of protection for these vulnerable natural freshwater resources.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and has the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. In order to enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments the GSOs, in the framework of GeoERA, has established the project “Tools for Assessment of Climate change Impact on Groundwater and Adaptation Strategies – TACTIC”. By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infrastructure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (<http://www.europe-geology.eu>).

This report provides an outline of the studies carried out under the TACTIC project in the pilot area of Malta’s Mean Sea Level Aquifer system (MSLA). The MSLA extends over an area of 216km², south of the bounding Pwales Fault system. From a hydrogeological perspective the groundwater body is sustained in the Lower Coralline Limestone and is bounded by the Pwales fault in the North and the freshwater-saltwater interface at the coast.

The study concerns the development of the MSLA under three scenarios which assume potential climate change impacts related to reduced recharge (due to changing rainfall patterns), increased abstraction (due to increased irrigation needs as a result of higher temperatures and increased losses due to evapotranspiration) and sea-level rise. These assessments are important to guide the development of future management frameworks for this groundwater body, which is the most important natural freshwater resources in the Maltese islands. Malta’s 2nd River Basin Management Plan (2nd RBMP) identifies this aquifer system in poor quantitative status with the main abstraction pressures arising due to groundwater abstraction for municipal supply and agricultural irrigation purposes. The 2nd RBMP sets out the development of an abstraction management framework as one of the key measures to enable this groundwater body to progressively achieve good quantitative status – that is a balance between recharge and abstraction. Studies on the development of the groundwater body under climate change conditions are important to enable water management frameworks to be sufficiently flexible to effectively address future challenges.

The protection of the status of the Malta Mean Sea Level aquifer system is a central feature in Malta's water management strategies due to the strategic importance of this natural freshwater body for water supply purposes. The "floating-lens" typology of this groundwater body makes it highly vulnerable to the intrusion of sea-water in response to abstraction activities, in particular where sustainable abstraction rates are exceeded. This leads to the salinisation of the groundwater resource further constraining its use. Therefore, the results obtained under TACTIC will also support the development of the groundwater protection measures under Malta's 3rd RBMP, intended to secure the sustainability of this groundwater resources in the future. The results of this project will in particular contribute to the climate-proofing assessments of the 3rd RBMP's measures, thereby supporting the achievement of the EU's Water Framework Directive's (WFD) Environmental Objectives.

3 PILOT AREA

The Maltese archipelago consist of three inhabited islands: Malta, Gozo and Comino, located approximately 96km south of Sicily and 290km north of Tunisia. The total surface area of the archipelago is approximately 316km², with Malta and Gozo, the two largest islands occupying 246km² and 67km² respectively. The Malta mean sea-level aquifer system is located in the island of Malta south of the bounding Pwales fault, which juxtaposes the aquifer formation – the Lower Coralline Limestone with the impermeable Blue Clay formation creating a natural boundary condition. The MSLA develops over an area of 216km² and is primarily sustained in the Lower Coralline Limestone. The freshwater body takes the form of a lens dynamically floating on the more saline water, having a convex piezometric surface and conversely a concave interface, both tapering towards the coast.

The MSLA is by far the most important groundwater body in the Maltese islands, sustaining around 80% of the total groundwater yield. It is however, also under sustained quantitative pressures – with the analysis undertaken as part of Malta's 2nd RBMP qualifying the groundwater body to be under poor quantitative status conditions. The 2nd RBMP identifies groundwater abstraction for municipal and agricultural irrigation purposes as the two most significant quantitative pressures on this aquifer system. The MSLA's floating lens structure entails a direct relationship between quantitative and qualitative aspects, due to the intrusion of saline waters in response to over-abstraction events.

The effective protection of this aquifer system is of strategic importance for the Maltese islands due to the important contribution it provides to Malta's water production resource base. Groundwater abstraction from the MSLA contributes around 34% of the municipal water supply, whilst also sustaining around 40% of the water demand of the agricultural sector. The collapse of this aquifer system would therefore have social, economic and environmental repercussions on the country. Malta's 2nd RBMP introduces a water management framework intended to offer a high level of protection to groundwater resources by promoting the conjunctive use of water demand management and water supply augmentation measures. This management framework seeks to introduce alternative water resources to supplement groundwater supplies thus easing the pressures on these fragile natural resources.

The 2nd RBMP identifies Climate Change as another important factor which needs to be engrained in Malta's medium to long-term water management frameworks. The impacts of Climate Change are expected to lead to changes in rainfall patterns (lower rainfall depth and increased propensity of high intensity rain events) and increasing temperatures, both of which can potentially have a profound effect on groundwater resources. In the case of the MSLA, the impacts of these changes could be further compounded by impacts related to sea-level rise. The studies undertaken under the TACTIC project attempt to model the effect of these Climate Change impacts on the status of the Malta Mean Sea Level aquifer system, in order to enable these impacts to be considered during the development of current water management frameworks such as the 3rd RBMP.

3.1 Site description and data

3.1.1 - Location

The Mean Seal Level aquifer system is developed over an area of 216km² in the island of Malta. It is bounded by the Pwales fault (a natural impermeable boundary) to the North, and by the freshwater-saltwater interface at the coast. The groundwater body is sustained in the Lower Coralline Limestone formation and the Globigerina Limestone formation where this occurs at sea-level.

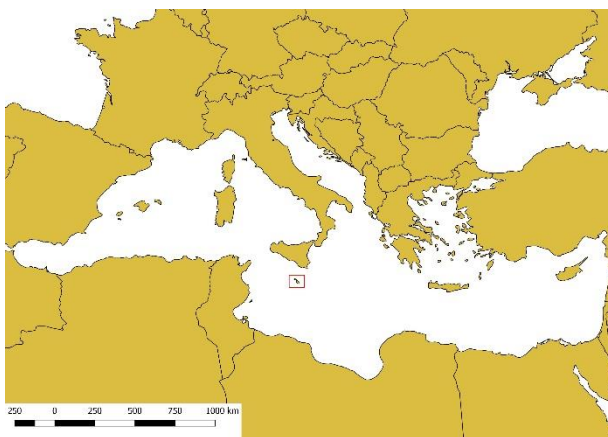


Figure 1 - Location of the Maltese Islands (marked in red)

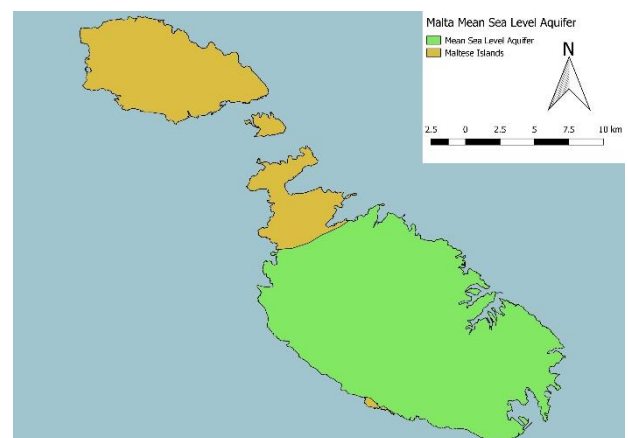


Figure 2 - Extent of the Malta Mean Sea Level Aquifer System

3.1.2 – Climate

The climate of the Maltese Islands is typically semi-arid Mediterranean with characteristic mild, wet winters and hot, dry summers. The average annual precipitation is of 550mm. Rainfall exhibits a high intra-annual variability with some years being excessively wet, whilst other relatively dry. The seasonal distribution of rainfall defines a wet period between the months of October and March (with around 85% of the total annual rainfall occurring during this period), and a dry period between April to September. Another important characteristic of the semi-arid climate is the high natural losses of water due to evapotranspiration. In fact the potential evapotranspiration rate (Penman Monteith) for the Maltese islands is estimated at 1391mm, whilst the effective evapotranspiration is estimated to exceed 60% of the mean annual rainfall. Evapotranspiration and losses due to surface runoff further limit the natural recharge to the aquifer systems.

The main climatic characteristics that are of particular relevance to water management include:

- high variability in interannual and intra-annual rainfall;
- high-intensity, short-duration rainfall events;
- seasonal scarcity of precipitation when the water requirements of the agriculture and tourism sectors are highest (normally from June to August);



- frequent occurrence of low rainfall years when groundwater recharge is likely to be low; and
- frequent occurrence of high rainfall years when runoff is likely to be high.

3.1.3 - Topography

The Maltese islands present a generally flat topography gently sloping from the highlands in the west to the coastal areas in the east. The highest elevations in the island, located on the Rabat-Dingli plateau reach around 250m above mean sea-level. Deep incised or broad dry-valley systems guide the flow of rainwater runoff in an eastern direction long this sloping terrain, the valley typology depending on the nature of the outcropping geological formations. These valley systems serve as the main natural drainage lines for the conveyance of rainwater runoff to the coastal zone.

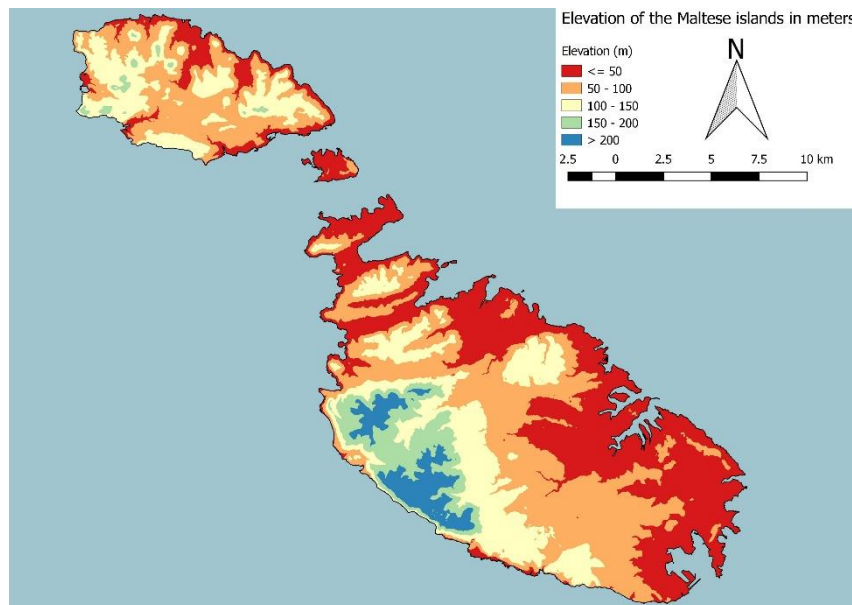


Figure 3 - Elevation Map of the Maltese Islands

3.1.4 – Land Use

The main land-use categories in the Maltese islands are Urban and Agricultural areas which account for around 25% and 50% of the total area of the Islands respectively. The Maltese islands thus present an uncharacteristically high rate of urban development, arising primarily due to the high population density of the island, which at around 1500 inhabitants/km² is by far the highest in Europe.

The high population density also leads to an intensive use of available land resources, which results in a mixed-land use scenario, which is not common in larger continental countries.



Various activities are thus commonly found operating side by side, and large areas of pristine land are generally lacking.

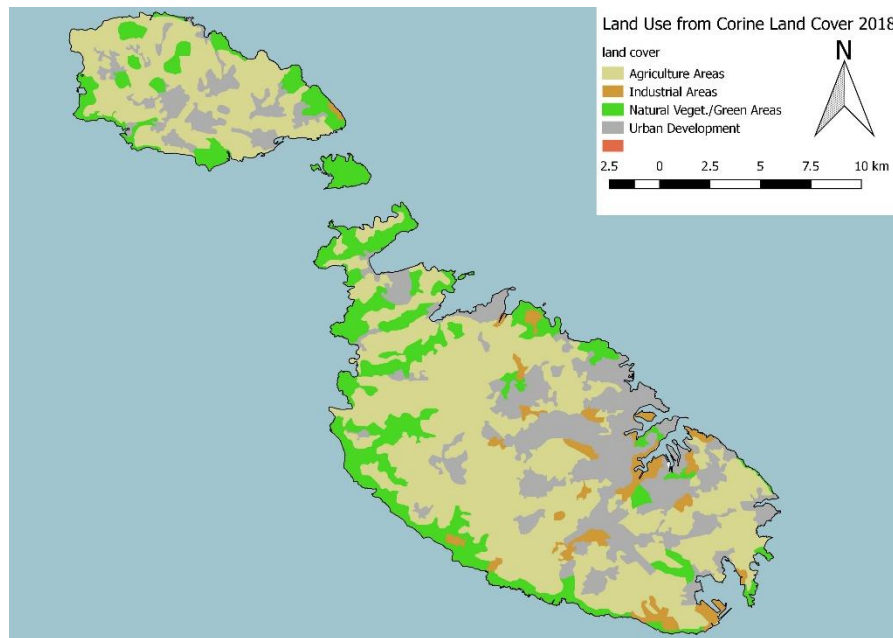


Figure 4 - Land-Use Map of the Maltese Islands (CORINE 2018)

3.1.5 – Soil Types

Maltese soils are derived from local geology, are highly calcareous and affected by cultural elements. D. M. Lang (1960) classified Maltese soils formations as Carbonate, Xerorendzinas, Terra and soil complexes, further subdivided into subtypes (series) named after the localities where the first examples were noted. The depth of the soil and soil material is very variable. On the ridges, plateau and plains (erosion surfaces), the soils are very shallow ranging in depth from less than 20cm to about 60cm. Deeper soils occur only in isolated pockets. In valleys, the soils are deeper (150cm), but patches of shallow soils are very common, especially near the valley edges.

3.1.6 – Geology and aquifer type

3.1.6.1 - Geology

The geology of the Maltese islands comprises a succession of tertiary limestones and marls with scarce Quaternary deposits. Essentially, the islands are geologically made up of a core of clays and marls, the Blue Clay and the Globigerina Limestone formations stacked between two coralline limestone formations known as the Upper and the Lower Coralline Limestone. The oldest formation, the Lower Coralline Limestone is chronologically dated to the Upper Messinian age and possibly extending into the early Pliocene.



The lithological different natures of these formations, together with their geological position enable the development of two broad aquifer typologies: the upper aquifers (perched), in the Upper Coralline Limestone and the lower (mean sea-level) aquifers in the lower limestone units (the Lower Coralline Limestone and where fractured the Globigerina Limestone).

The Upper and Lower Coralline Limestones are therefore considered to function as the main aquifer formations in the islands. The Globigerina Limestone functions only locally as an aquifer formation, only where it is fractured and/or is located at sea level, and is commonly expected to allow groundwater flow exclusively through fractures and fissures. The Blue Clay is normally impermeable and underlines the perched aquifer systems.

3.1.6.2 – Aquifer typology

The Lower Coralline Limestone formation represents the most important aquifer formation of the Maltese islands, sustaining the major sea level groundwater bodies, which by far are the primary sources of freshwater for the islands. As the formation is predominantly composed of algal limestone with sparse corals, it has moderate, irregular and channel-like permeability.

The largest and by far the most important of these sea level bodies of groundwater is the mean sea level aquifer system occurring in the island of Malta. This aquifer stretches across an area of 216km², primarily south of the bounding Pwales fault. The body of groundwater sustained by the Malta MSLA yields an estimated 66% of the total groundwater abstracted in the country and under optimum conditions, the aquifer system is estimated to be capable of storing up to 1.5 billion m³ of groundwater.

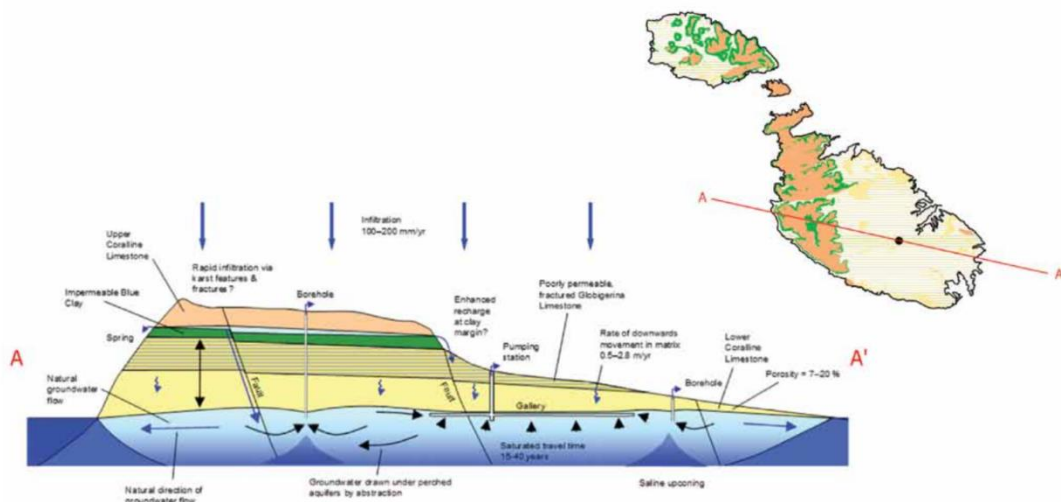


Figure 5 - Conceptual Understanding of the Malta Mean Sea Level Aquifer System

The groundwater body occurring in this sea level aquifer system is in lateral and vertical contact with seawater. Due to the density contrast of freshwater and saltwater a Ghyben-Herzberg system is developed. The outcome is a lens shaped body of freshwater that is dynamically



floating on more saline water, having a convex piezometric surface and conversely a concave interface, both tapering towards the coast where there is virtually no distinct definition between the two surfaces. Maximum hydraulic heads of 4-5m amsl were measured for the groundwater sustained in the Malta MSLA in the 1940s, when the system was largely unexploited. The lens sinks to a depth below sea level roughly 40 times its piezometric head at any point, fading into more saline water across a transition zone, the thickness of which highly depends on the hydrodynamic characteristics of the aquifer formation, and the dynamic effects of pumping. The limits of this transition zone are commonly defined by the surface of the 1% and 95% seawater context, based on the total dissolved solids, or chloride content.

3.1.7 – Surface water bodies

The small size and geomorphology of the islands precludes the development of economically exploitable surface water resources such as rivers and lakes. Inland surface water systems are generally very small and limited to specific areas in dry valley systems in the vicinity of perched aquifer springs.

3.1.8 – Abstraction/Irrigation

Groundwater abstraction, from all the groundwater bodies in the Maltese Water Catchment District, is estimated to reach around 38 million m³, or 61% of the total national water demand. The sector with the highest dependence on groundwater resources was the agricultural sector, which accounted for almost half of the total groundwater abstraction in the Maltese islands.

Groundwater abstraction tends to have a regional dimension, with the perched aquifer systems being important groundwater sources to sustain the traditional irrigated land-areas of the Maltese islands, whilst abstraction by the Water Services Corporation gains more relevance in the mean sea-level aquifer systems.

The assessments leading to Malta's 2nd RBMP classified the mean sea level aquifer system as being under poor quantitative status, namely that the mean annual abstraction is estimated to exceed the mean annual recharge. The 2nd RBMP identifies groundwater abstraction of municipal supply purposes as the most important groundwater abstraction typology from this aquifer system, followed by abstraction for agricultural irrigation. The water balance framework of the MSLA is presented in figure 6 below. The water balance assessment outlines the quantitative pressures on the aquifer system, with water outflows from the system being estimated at higher levels to water inflows in the system.

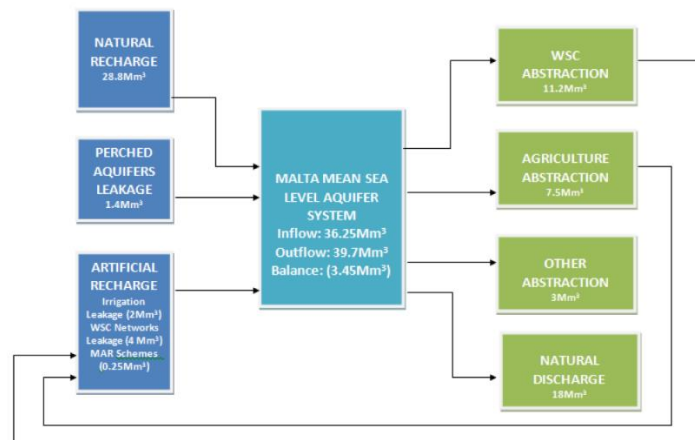


Figure 6 - Water Balance Assessment for the Malta Mean Sea Level Aquifer system (2nd RBMP)

3.2 Climate change challenge

In the Mediterranean region, climate change is expected to negatively affect water resources and current climate change studies outline the following expectations:

- An increase in air temperature in the range of 2.2 C° to 5.1 C° for the countries of the Mediterranean region by 2100 with respect to the period 1980 – 1999 (IPCC 2007, scenario A1B);
- A significant decrease in rainfall, ranging between -4 and -27 % for the countries of the Mediterranean region (IPCC 2007, scenario A1B);
- Extreme events, such as heat waves, droughts or floods, are likely to be more frequent and violent.
- An increase of the sea level which, according to specific studies, could be around 35 cm up to the end of the century.

In the case of the Maltese islands, Climate Change is thus expected to result in the gradual increase in temperature and the decrease in the mean annual rainfall. The increasing temperatures would also entail an increase in natural water losses due to evapotranspiration which would lead to increased irrigation requirements. Rainfall patterns are also expected to change, with a prevalence of more high intensity rain events and increased periods with less precipitation, both factors contributing to lower recharge rates to groundwater. These important changes would also be complemented by a rise in sea-level, which however is considered as being of less importance with regards to the development of the sea-level aquifer systems.

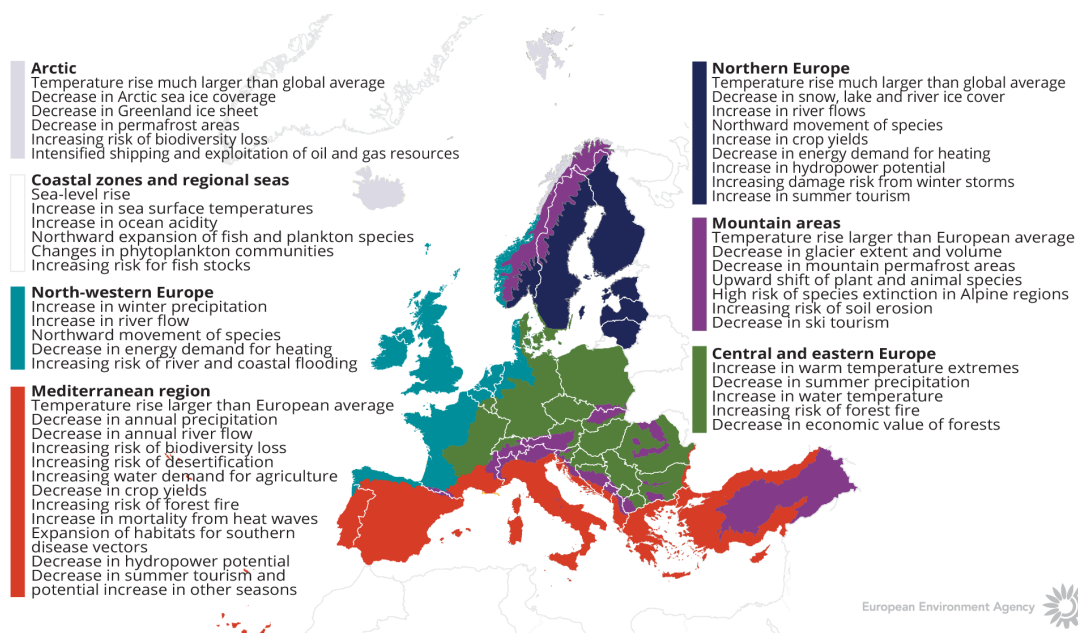


Figure 7 – EEA Projections for Climate Change Impacts in different regions in Europe

4 METHODOLOGY

4.1 Methodology and climate data

4.1.1 Tools/ model description

The numerical model of the Mean Sea Level aquifer system was developed using the MODFLOW-2005 numerical code (Harbaugh, 2005), mainly through the GIS-integrated user interface FREEWAT. A transient-state numerical model of the Mean Sea Level aquifer was developed, based on the conceptual model of the aquifer system. The development of the groundwater body was considered over a long-term period (1600 – 2018) to reflect its different exploitation scenarios throughout the years. The main result of the model presented the hydraulic heads (and interface) under reference conditions.

The availability of this baseline model enables the investigation of the development of the aquifer system under different scenarios. Scenario modelling is the activity that shows the usage of numerical models in a dynamic approach, namely the application of models as effective tools to assess future (or alternative) settings due to the variation of anthropic or natural conditions, such as management of water resources, abstraction policy, land use variation, climate change conditions, etc.

For the purpose of the TACTIC project, the baseline model was run on three scenarios which take into account the foreseen climate change effects on the water balance with reference to:

- (i) Scenario 1: This scenario assumes an estimated decrease in infiltration caused by the existing trends in rainfall decrease and temperature rise. Applying the estimated variation of the water balance term as a consequence of the Climate Change RCP8.5 scenarios for the central Mediterranean (Malta area) an overall reduction of about 10% of the reference recharge has been calculated for the year 2050;
- (ii) Scenario 2: This scenario projects an increasing abstraction for agriculture to compensate the demand due to higher losses by evapotranspiration. Whilst maintaining the recharge decrease of the 1st scenario, this second scenario increases agricultural abstraction with respect to the reference model by 10%; and
- (iii) Scenario 3: This scenario focuses on sea-level rise where the sea-level at the coast is gradually increased till it reaches an elevation of +0.40m over reference conditions.

The reference model of the mean sea-level groundwater body and the testing of different groundwater management scenarios were undertaken in the frame of the implementation of the LIFE 16 IPE MT 008 Project -LIFE-IP-RBMP-Malta - Optimising the implementation of the 2nd RBMP in the Maltese River Basin District.

4.1.2 Climate data

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5° global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (a.o. bias correction). Data selection and preparation included the following steps:



1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set were selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to simulate the future climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).
2. A reference period was selected as 1981 – 2010 and an annual mean temperature was calculated for the reference period.
3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature were calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means that the temperature changes are the same for all scenarios, while the period in which this occurs varies between the scenarios.
4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact in the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these endmembers often reflect outliers.
5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).
6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

Precipitation and Evapotranspiration projections were based on HadGEM2-ES data for the RCP8.5 scenario (3 degree global change – maximum), whilst precipitation projections were based on GFDL-ESM2M data for the RCP8.5 scenario (3 degree global change – minimum).

The tables below outline the estimated variation of the water balance term in the model as a consequence of the Climate Change data projections available for the Maltese islands, through the application of the foreseen variation of precipitation, temperature and evapotranspiration. The water balance terms were applied in the numerical model to develop the Climate Change scenarios.

Temperature (Deg C)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
Average temperature (1980-2010)	21.5	17.6	14.2	12.7	12.5	13.9	16.0	19.7	23.8	26.6	27.1	24.6
T change under 3 deg C global change (max)	2.0	1.8	1.9	1.7	1.7	1.7	1.8	2.0	2.1	2.3	2.1	2.1
Projected Temperature	23.5	19.4	16.1	14.4	14.2	15.6	17.8	21.6	25.9	28.8	29.2	26.7



(2050) scenario	for											
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Precipitation (mm/month)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
Average PR (1980-2010)	68.6	102.9	108.6	92.9	56.9	37.9	20.8	8.5	4.0	0.2	5.6	56.0
Change in PR under 3 deg global change (min)	0.924	0.814	0.683	0.686	0.503	0.745	0.930	0.677	0.500	1.000	0.762	0.701
Projected Precipitation for scenario (2050)	63.43	83.75	74.22	63.72	28.63	28.26	19.35	5.77	2.01	0.21	4.26	39.29

Potential Evapotranspiration (mm/month)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
Average PET (1980-2010)	97.6	66.9	46.0	36.0	29.5	37.2	44.5	64.2	87.6	116.6	131.3	114.4
Change in PET under 3 deg global change (max)	1.052	1.050	1.060	1.056	1.056	1.053	1.053	1.052	1.051	1.051	1.046	1.048
Projected PET for scenario (2050)	102.7	70.3	48.8	38.0	31.1	39.2	46.8	67.5	92.1	122.6	137.4	119.9

Table 1: Temperature, Precipitation and Evapotranspiration Projections for the water balance assessment of the Malta Mean Sea Level Aquifer System

4.2 Tool(s) / Model set-up

The main settings of the model are summarized in Table 2 below. In transient state, stress periods related to the abstraction of groundwater and other water losses and the temporal and spatial redistribution of natural recharge were included.

Domain	Width ~19 km (along the SW-NE direction), length ~27 km (along the NW-SE direction) with a rotation of 53°.
Horizontal discretization	Cell size 100x50m; total 105536 cells, 388 rows by 272 columns.
Active domain	1022386 cells.
Vertical discretization	1 model layer, representing the lithology Globigerina Limestone (GL) and Lower Coralline Limestone (LCL). The model top is set as the top of GL. The elevation of model bottom is firstly calculated as (TOP-180m), to mimic a constant saturated thickness. Where this returns a bottom elevation higher than -180 m, the value is lowered to -180 m, so that eventually almost the whole aquifer has a constant bottom equal to -180 m.
Boundary conditions	The sea level is represented by the third type condition (GHB – General Head Boundary package in MODFLOW). A value of 0.15 m is set to represent the sea level (slight larger than in the steady state model after an analysis of tidal variation over the years of interest). The conductivity of GHB is a value parametrized and object of calibration, with a starting value of 50 m ² /day. The



	main faults in the islands are accounted for by applying the HFB (Horizontal Flow Barrier) package of MODFLOW code. For all cells the same value of HFB input parameters is used, namely $K = 8.64 \text{ m/day}$ for fault hydraulic conductivity and 1 m as fault thickness. Estimation of the conductivity is done along the calibration process. Galleries, public boreholes and private wells are represented as WEL package, same as the water losses from pipes which inject water rather than extracting it from the system.
Hydrogeological parameters	Horizontal hydraulic conductivity values are object of calibration (with associated prior information from the data analysis). Vertical hydraulic conductivity is supposed to be 1/10 of the horizontal one. Storage coefficient and porosity are assumed to be constant all over the domain with the following values: porosity = 0.2; specific storage = $5\text{E-}6 - 1\text{E-}6 \text{ m}^{-1}$; specific yield = 0.05 - 0.1 (Freeze and Cherry, 1979)

Table 2: Main Characteristics of the numerical model for the Malta MSLA

4.3 Tool(s)/ Model calibration/ test

The calibration process was set to adjust the parameters not only to reproduce the observed heads, but also to respect the parameters' prior information, trying to find the agreement between hard and soft data along with the model behavior.

In order not to overfit the heads (i.e., calibrating "too well"), heads observations were provided a weight proportional to their reliability, and the measurement Objective Function was assigned a lower threshold, given the uncertainty of the original data. Elements that were taken into account in setting a threshold for the measurement Objective Function were:

- the geostatistical interpolation of heads which provided a RMSE of 0.43 m;
- the average SD of heads time series is about 0.2 m;
- the borehole elevation error, which can be higher than 1 m in places;
- the tidal oscillations which make the heads oscillate accordingly, with differences that range from a few millimetres to 0.2-0.3 m.

Considering the above list, the Objective Function was set to provide a RMSE related to heads residuals not lower than 0.43 m.

Besides heads, additional "parameter observations" were added to the calibration process in order to make the inverse problem solvable. The weight assigned to the prior information was iteratively adjusted to reach a compromise between respecting the head data given the above constraints, while limiting the overfitting with advantage of the parameter preferred value coherence.

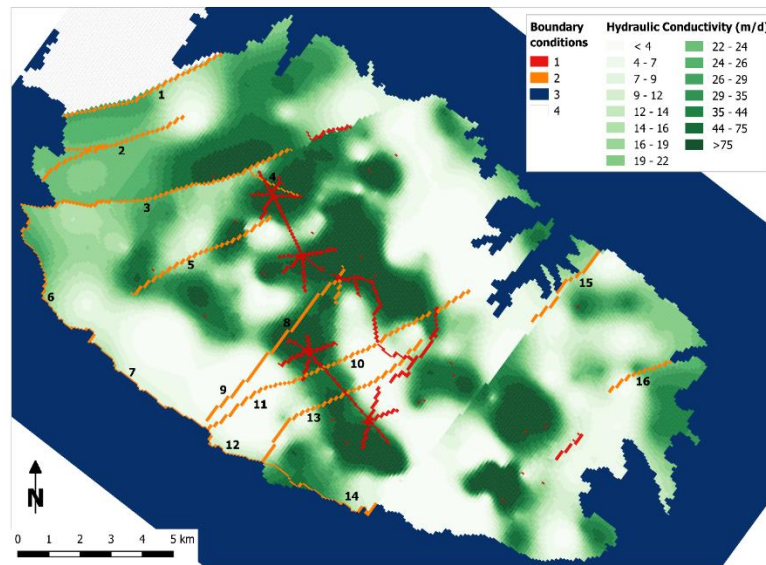


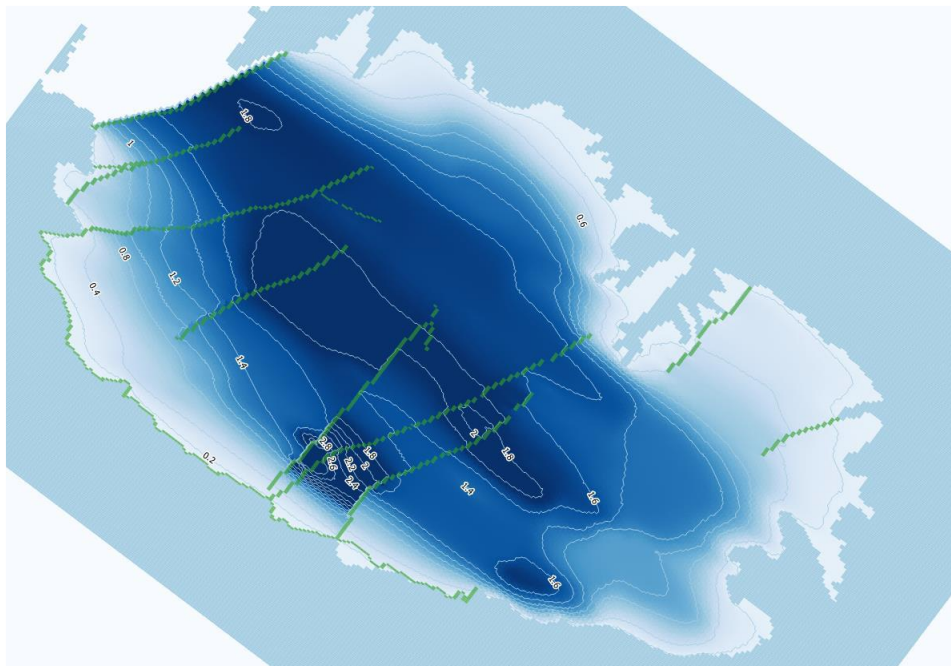
Figure 8 - One of the calibration process results outlining a possible spatial distribution of the hydraulic conductivity (m/d) that calibrates the MSLA head data.

5 RESULTS AND CONCLUSIONS

The application of the Malta-MSLA numerical groundwater body model to the climate change scenarios assessed under the TACTIC project portray the development of groundwater body piezometric (and interface) levels under the additional stresses induced by climate change, and enable a comparative assessment to the aquifer development under reference conditions. The main model outputs for the reference conditions and each of the three climate change induced scenarios are represented in the plots hereunder:

(i) Reference Conditions

Simulated heads (m asl) resulting from the application of the numerical model under reference conditions are presented hereunder. The reference year is 2012.



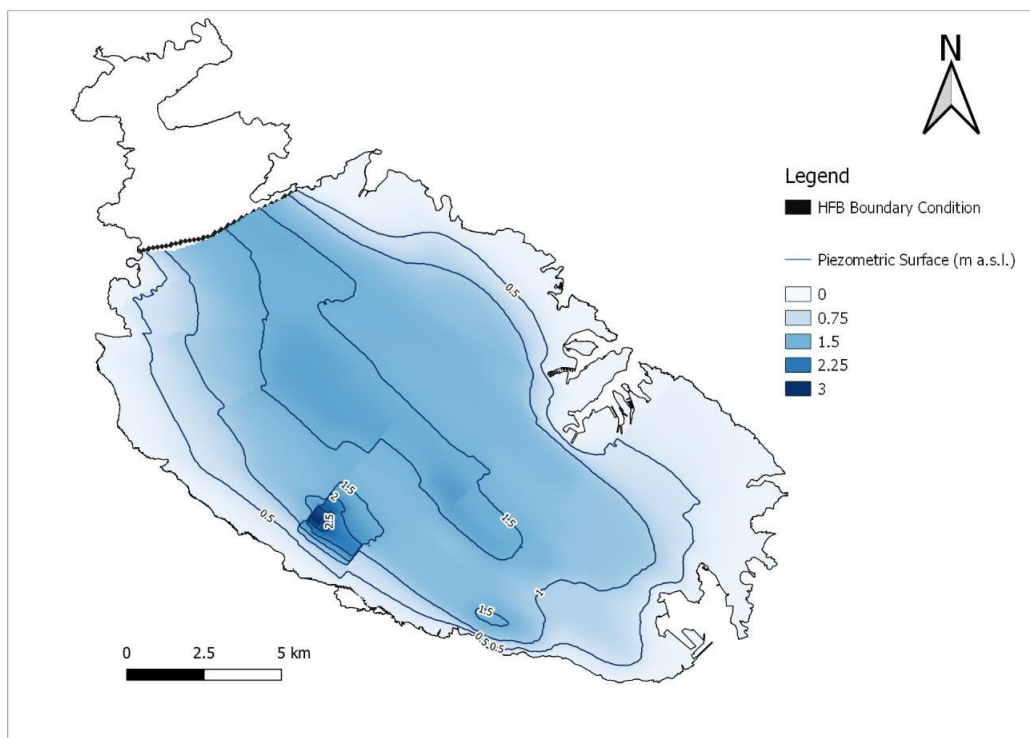


Figure 10 - Malta MSLA - Piezometric Surface under Climate Change Scenario 1 projections

(iii) Climate Change Scenario 2 – increase in agricultural groundwater abstraction
Simulated heads (m asl) resulting from the application of the numerical model under the second Climate Change scenario are presented hereunder.

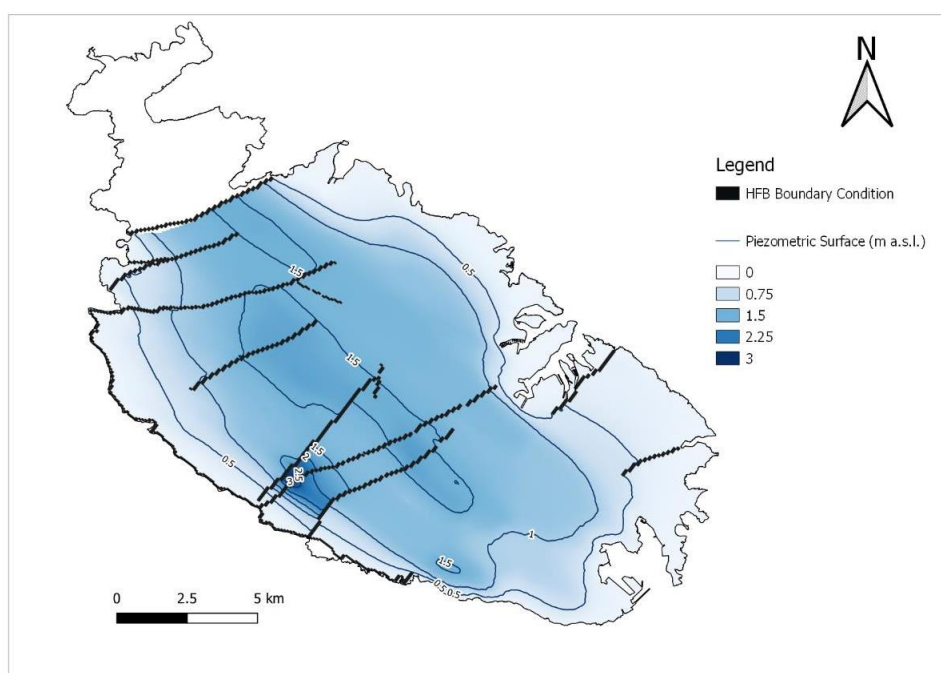


Figure 11 - Malta MSLA - Piezometric Surface under Climate Change Scenario 2 Projections

(iv) Climate Change Scenario 3 – sea-level rise

Simulated heads (m asl) resulting from the application of the numerical model under the third Climate Change scenario are presented hereunder.

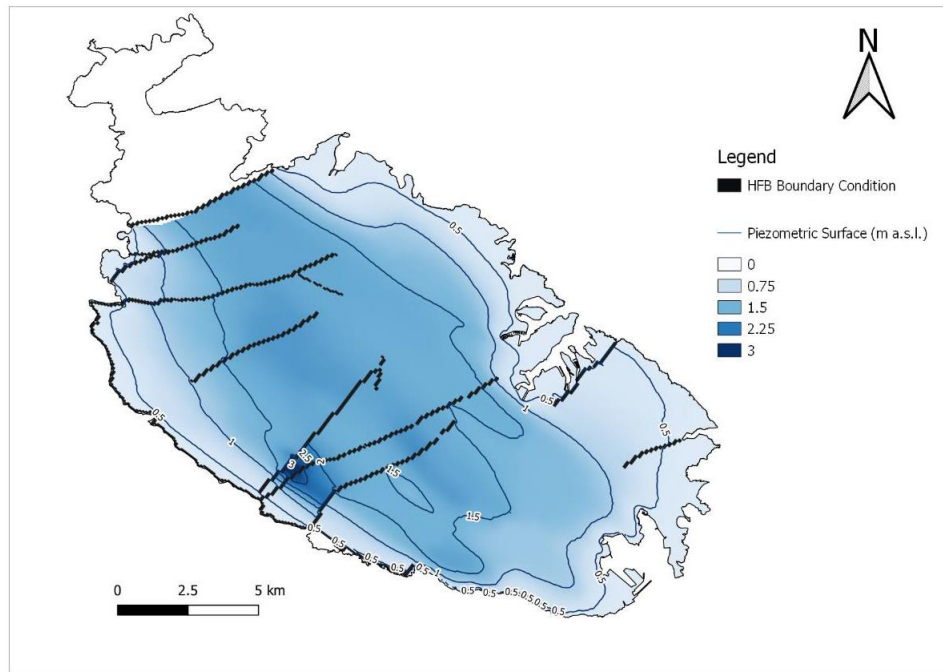


Figure 12 - Malta MSLA - Piezometric Surface under Climate Change Scenario 3 projections

5.1 Results of assessments

The projected piezometric levels emerging from the application of the three Climate Change scenarios to the numerical model of the Malta mean sea-level aquifer system are summarized hereunder:

(i) Climate Change Scenario 1: the resultant piezometric levels are lower than those under the reference situation, which is an expected outcome since the piezometric head is directly dependent on the long-term mean annual recharge levels. However, the reduction in the piezometric level is generally contained to the central regions of the island, where a decline in head of up to 0.5m occurs. However, it is important to note that compared to other water management scenarios, in general, the projected impact of climate change under these conditions seems to be extremely less threatening when compared to poor groundwater management practices such as high levels of over-abstraction.

(ii) Climate Change Scenario 2: in this scenario the resultant piezometric levels are similarly lower than those under the reference condition, but the projected deterioration is close to that registered under the first scenario. In fact this scenario projects the central region of the aquifer system to maintain hydraulic heads of the order of 1.5m amsl. This could be a resulting effect of the groundwater body settling into a lower steady state (under lower hydraulic heads) which



would enable the groundwater body to sustain the marginally increased abstractions. Similarly to the first scenario, therefore, the impact of climate change seems to be extremely less threatening when compared to the impact of poor groundwater management practices. It should be noted however, that these results do not preclude further deterioration in the status of the groundwater bodies should more marked Climate Change impacts occur.

(iii) Climate Change Scenario 3: The piezometric head projected under the sea-level rise scenario are practically of the same order of the levels projected under the reference situation. The only visible effect over the aquifer volume is a boundary reduction along the coast generated by the reduction of emerged land. Therefore, also under this third scenario, the impact of climate change seems to be less marked when compared to the impacts on the aquifer systems arising due to aquifer mismanagement scenarios.

The modelled results of the three Climate Change scenarios undertaken under the TACTIC project, outline the development of a highly resilient groundwater body under conditions of reduced recharge, increased abstraction and sea-level rise. The projections seem to indicate that the groundwater body would, under the Climate Change related conditions assumed in the respective scenarios, reach lower steady state conditions. Hence, the impact of Climate Change according to the assumed climate models would not be expected to result in a severe impact on the mean-sea level groundwater body.

However, the reduced piezometric levels registered under each scenario would make the groundwater body more vulnerable to aquifer mismanagement practices such as over-abstraction. The conditions prevailing under the three Climate Change scenarios would facilitate the occurrence of localized sea-water intrusion and the salinization of wells under abstraction conditions. Hence, the need for the development of sound aquifer management frameworks to enable the sustainable management of this groundwater body of strategic national importance.

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