Hydrogeological and Geochemical Modelling of a seawater intrusion barrier in a coastal/island groundwater body

Dissertation

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Declaration of authorship

I hereby declare that the presented dissertation is based on original research and is the result of my own work. I certify that this dissertation contains no material that has been accepted for the award of any other degree in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Publications associated with this thesis

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Abstract

The impact of Climate Change in the central Mediterranean Region is expected to result in a general reduction of the annual precipitation, coupled with an increased variability in precipitation events. This is expected to give rise to prolonged drought periods as well as reduced recharge levels to groundwater, increasing the existing pressures on these already stressed naturally renewable freshwater resources. On the other hand, an increased prevalence of high intensity rain events is expected to result in the over-availability of surface water resources during short time periods increasing the risk of flood events.

Ensuring a high level of resilience in the water sector is therefore increasingly becoming a priority for the Maltese islands, and this not only for ensuring security in the provision of water services but also in view of water's contribution to food production and ecosystems. Increased resilience is generally addressed through the application of traditional tools such as water demand management and water supply augmentation measures. But it can also be addressed through the restoration and augmentation of the capacity of existing natural freshwater resources.

Managed Aquifer Recharge is therefore one of the tools which can support a move towards a more water resilient management framework, improving the quantitative (and qualitative) status of groundwater whilst enabling the reservoir capacity of aquifer systems to be exploited for balancing water storage between wet and dry periods. In so doing, additional water resources during wet periods for which there would be no effective use can be stored, enhanced and made available during dry periods when water resources are scarce – thereby ensuring the sustainability of groundwater resources and ensuring their contribution to water security in the Maltese islands for the future.

This thesis assesses feasibility of the application of a Managed Aquifer Recharge (MAR) Scheme to the Malta Mean Sea Level Aquifer system, an island (freshwater-lens system) body of groundwater which is of strategic importance to the water supply of the islands, but which has suffered a deterioration in status over the years due to long term over-abstraction. The potential impact of a Managed Aquifer Recharge scheme in the central and southern regions of this aquifer system is assessed as a tool for improving the quantitative and qualitative status of the groundwater body with a view of guiding the development of policy considerations for the application of Managed Aquifer Recharge as a tool within Malta's future River Basin Management Plans for sustaining groundwater resources.

The evaluation of the suitability of a MAR scheme to halt further depletion of the Malta groundwater resources was based on the assessment of current social and local environmental settings. Due to fast urbanisation, water demand is rising rapidly while securing a safe drinking water supply becomes a challenge. Together with land consumption, high evapotranspiration rates typical of semi-arid regions compromise the implementation of typical MAR schemes such as infiltration spreading methods. To overcome the quantitative and qualitative challenges related to water management of the country, mitigation and adaption measures suitable for the site-specific conditions of Malta are needed to compensate the effects of groundwater exploitation associated to

saltwater intrusion into the freshwater lens system.

Zusammenfassung

Es wird erwartet, dass die Auswirkungen des Klimawandels in der zentralen Mittelmeerregion zu einer allgemeinen Verringerung des Jahresniederschlags, verbunden mit einer erhöhten Variabilität der Niederschlagsereignisse, führen werden. Es wird erwartet, dass dies zu längeren Dürreperioden sowie zu einer geringeren Neubildung des Grundwassers führen wird, was den bestehenden Druck auf diese bereits beanspruchten, natürlich erneuerbaren Süßwasserressourcen erhöht. Andererseits wird erwartet, dass eine zunehmende Prävalenz von Regenereignissen hoher Intensität zu einer Überverfügbarkeit der Oberflächenwasserressourcen in kurzen Zeiträumen führt und das Risiko von Überschwemmungen erhöht.

Die Gewährleistung einer hohen Widerstandsfähigkeit im Wassersektor wird daher für die maltesischen Inseln zunehmend zu einer Priorität, und zwar nicht nur zur Gewährleistung der Sicherheit bei der Bereitstellung von Wasserdienstleistungen, sondern auch im Hinblick auf den Beitrag des Wassers zur Nahrungsmittelproduktion und zu den Ökosystemen. Eine erhöhte Widerstandsfähigkeit wird im Allgemeinen durch den Einsatz traditioneller Instrumente wie Wassernachfragemanagement und Maßnahmen zur Verbesserung der Wasserversorgung erreicht. Es kann aber auch durch die Wiederherstellung und Erweiterung der Kapazität bestehender natürlicher Süßwasserressourcen angegangen werden.

Die verwaltete Wiederauffüllung von Grundwasserleitern ist daher eines der Instrumente, die den Übergang zu einem wasserresistenteren Managementrahmen unterstützen können, der den quantitativen (und qualitativen) Zustand des Grundwassers verbessert und gleichzeitig die Nutzung der Speicherkapazität von Grundwasserleitersystemen für den Ausgleich der Wasserspeicherung zwischen Nass- und Grundwasser ermöglicht Trockenperioden. Auf diese Weise können zusätzliche Wasserressourcen in Regenperioden, für die es keine effektive Nutzung gäbe, gespeichert, verbessert und in Trockenperioden, in denen die Wasserressourcen knapp sind, verfügbar gemacht werden – und so die Nachhaltigkeit der Grundwasserressourcen und ihr Beitrag zur Wassersicherheit in sichergestellt werden die maltesischen Inseln für die Zukunft.

In dieser Arbeit wird die Machbarkeit der Anwendung eines Managed Aquifer Recharge (MAR)-Systems auf das maltesische Grundwasserleitersystem auf mittlerem Meeresspiegel bewertet, einem Inselgrundwasserkörper (Süßwasserlinsensystem), der für die Wasserversorgung der Inseln von strategischer Bedeutung ist, aber dessen Status sich im Laufe der Jahre aufgrund der langfristigen übermäßigen Entnahme verschlechtert hat. Die potenziellen Auswirkungen eines Managed Aquifer Recharge-Programms in den zentralen und südlichen Regionen dieses Aquifersystems werden als Instrument zur Verbesserung des quantitativen und qualitativen Zustands des Grundwasserkörpers bewertet, um die Entwicklung politischer Überlegungen für die Anwendung von Managed zu leiten Grundwasserneubildung als Instrument im Rahmen der künftigen Flussgebietsmanagementpläne Maltas zur Erhaltung der Grundwasserressourcen.

Die Bewertung der Eignung eines MAR-Programms zur Eindämmung der weiteren Erschöpfung der maltesischen Grundwasserressourcen basierte auf der Bewertung der aktuellen sozialen und lokalen Umweltbedingungen.

Aufgrund der schnellen Urbanisierung steigt der Wasserbedarf rapide an, während die Sicherstellung einer sicheren Trinkwasserversorgung zu einer Herausforderung wird. Zusammen mit dem Landverbrauch gefährden hohe Evapotranspirationsraten, die für semiaride Regionen typisch sind, die Umsetzung typischer MAR-Systeme wie Infiltrationsausbreitungsmethoden. Um die quantitativen und qualitativen Herausforderungen im Zusammenhang mit der Wasserbewirtschaftung des Landes zu bewältigen, sind Abhilfe- und Anpassungsmaßnahmen erforderlich, die für die standortspezifischen Bedingungen Maltas geeignet sind, um die Auswirkungen der Grundwassernutzung im Zusammenhang mit dem Eindringen von Salzwasser in das Süßwasserlinsensystem zu kompensieren.

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A	Amplitude attenuation factor
AS	Aquifer Storage
ASR	Aquifer Storage and Recovery
b	Aquifer thickness
BC	Blue Clay
CBE	Charge Balance Error
CIS	Common Implementation Strategy
D	Diffusivity
DMB	Deep Monitor Borehole
EC	Electrical Conductivity
EIA	Environmental Impact Assessment
EPM	Equivalent Porous Medium
IDW	Inverse Distance Weighted
IBF	Induced bank infiltration
FFT	Fast Fourier Transform
GL	Globigerina Limestone
h_0	Amplitude of the sea tide
HDDW	Horizontal Directional Drilled Wells
HP	Highly Parametrized
K	Hydraulic Conductivity
LCL	Lower Coralline Limestone
MAR	Managed Aquifer Recharge
M	Maximum
m	Minimum
Md	Median
MSLA	Mean Sea Level Aquifer
OM	Operational Monitoring
QMRA	Quantitative Microbial Risk Assessment
RBCA	Risk/Based Corrective Action
WCMP	Water Catchment Management Plan
S	Specific yield
SAT	Soil Aquifer Treatment
SC	Specific Conductance
SP	Stress Period
SM	Surveillance Monitoring

STD	Standard Deviation
SWL	Static Water Level
T	Temperature
T	Transmissivity
TE	Tidal Efficiency
TD	Temperature-Depth
UCL	Upper Coralline Limestone
WHO	World Health Organization
WFD	Water Framework Directive
h_f	Freshwater head
ΔT	Time Shift
z	Freshwater/seawater interface depth
γ_f	Specific weight of freshwater
γ_s	Specific weight of seawater
α	Specific weight ratio
ω	Frequency of the oscillation
τ	Period of the oscillation
μ	Median
σ^2	Variance
n	Nugget
s	Sill
r	Range

1. General Introduction

Groundwater availability in coastal/island groundwater bodies is often threatened by excessive exploitation and lack of precautionary measures aimed at protecting the aquifer systems from quality depletion. This is the case of the Malta Mean Sea Level Aquifer (MSLA) facing a downtrend over time in both the qualitative and quantitative status. Population is growing rapidly in the Maltese Island while countermeasures to halt saltwater intrusion are tough to be applied given that relationships between increased overall abstraction and salinization impact are still equivocal.

The use of groundwater flow models is actually a standard approach used to solve groundwater flow problems and it is generally accepted that they give reliable predictions when provided with adequate data about the porous flow domain geometry, boundary conditions and spatial distribution of controlling parameters. On the other way around, numerical models can also be used for identifying data gaps to drive future water management decisions in terms of advanced monitoring techniques.

Although of qualitative issues, saltwater intrusion in freshwater lens system needs to be tackled with quantitative measures by means of restoring sustainable yields of the aquifer systems. When natural aquifer recharge is not sufficient to ensure sustainability of abstraction yields, Managed Aquifer Recharge (MAR) techniques can be deployed to increase net recharge. After running and calibrating the groundwater flow numerical model, several scenarios can be simulated in line with site-specific conditions for providing a technical support on the selection of the most feasible MAR scheme network. However, limited knowledge about salinization mechanisms may compromise the minimization of potential environmental impacts which may rise after the MAR implementation if its impact does not result properly monitored.

In this thesis, after an introduction of literature review linked to MAR and risk assessment analysis, the Malta MSLA groundwater flow numerical model is analyzed. This analysis led to the identification of major data gaps which may compromise the forecast of environmental risks associated to MAR techniques. The carbonate aquifer in its complexity can be simplified by estimating an Equivalent Porous Medium map of transmissivity by supplementing local pumping test results with tidal attenuation analysis. Furthermore, groundwater salinization mechanisms in the freshwater lens system are assessed through field data collected by means of Deep Monitor Boreholes.

Finally, a summary of the actual hydrogeological knowledge of the Malta MSLA is provided together with suggestions of further research topics to be carried on following this research activity.

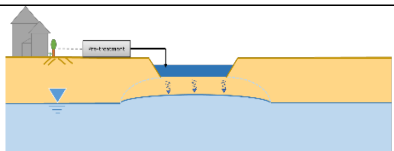
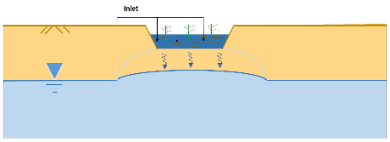
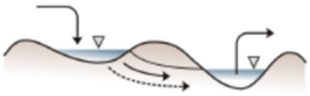
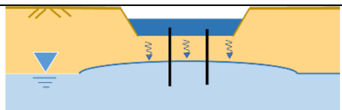
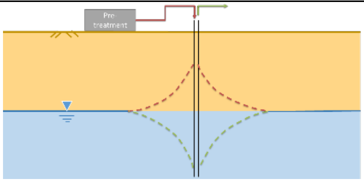
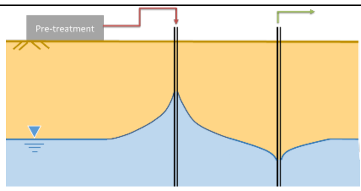
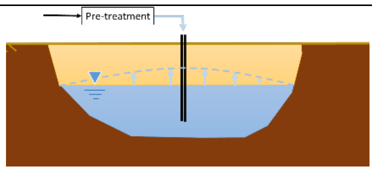
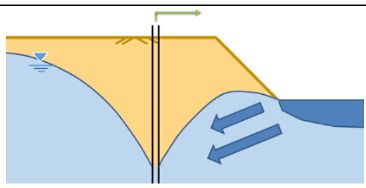
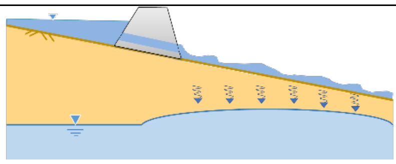
1.1. Managed Aquifer Recharge

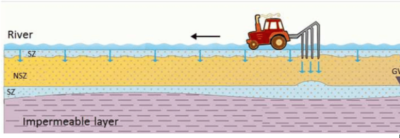
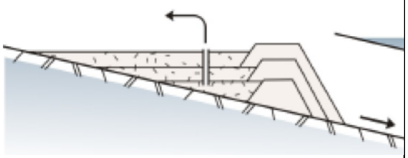
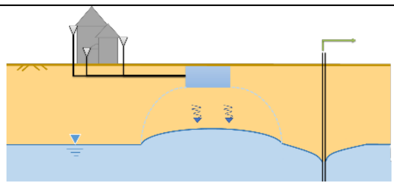
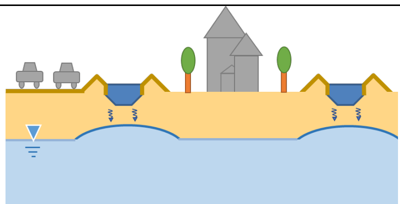
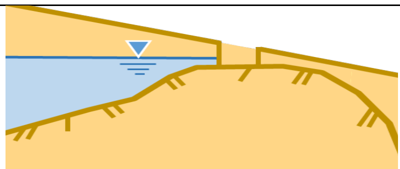
The availability of freshwater is a key factor in socio-economic development. Provisioning services for socioeconomic development are important hydrological ecosystem services that humans obtain from freshwater. The conflict between water scarcity and economic development in arid and semi-arid regions affects water utilization among different sectors (Zhou et al., 2018). The challenges of increased demand coming from an increased population in Mediterranean coastal areas provide an opportunity for the development of alternative water supplies which complement/supplement natural water resources. This necessitates the integrated management of all available water resources, including the management of groundwater abstraction together with seawater desalination and the consideration of stormwater runoff. In this context, groundwater is a vital water supply for humanity. Groundwater provides drinking water entirely or in part for as much as 50% of the global population and accounts for 43% of all of water used for irrigation (Poeter et al., 2020). Groundwater is threatened though by pollution and quantitative depletion resulting from human activity, generating chemicals leaked into the subsurface which challenge the sustainable usage of this resource.

In order to ensure that groundwater can keep play its role well in the future, Managed Aquifer Recharge (MAR) can be deployed to sustain and replenish groundwater supplies by guaranteeing sustainable yields and good status of quality. MAR is the process of intentionally increasing recharge into aquifer for subsequent recovery or for environmental benefits (Dillon et al., 2009). MAR can be used to store water from various sources, such as stormwater, reclaimed water, mains water, desalinated seawater, rainwater or even groundwater from other aquifers. With appropriate pre-treatment before recharge and sometimes post-treatment on recovery of the water, it may be used for drinking water supplies, industrial water, irrigation, toilet flushing and sustaining ecosystems. However, it is also worth to mention that MAR may cause adverse effects by displacing and redirecting natural groundwater flow if it is not correctly managed. For instance, MAR can lead to high groundwater mounds flooding crops (Fernández Escalante et al., 2020).

There are a large number and growing variety of methods used for MAR internationally, each specific MAR type is briefly introduced in Table 1. The feasibility of a MAR system depends largely on local hydrogeological conditions.

Table 1: Conceptual presentation of MAR techniques (modified after Dillon, 2005).

MAR technique	Illustration	Description
Infiltration ponds		Recharge water storage in ponds, above groundwater level to induce infiltration.
Soil Aquifer Treatment (SAT)		SAT have a similar design as infiltration ponds. The input of water is, however, of a lower quality. Water passes the biological active soil, a vadose zone to the saturated zone where the recharged water is recovered and reused.
Dune filtration		Infiltration of water from ponds constructed in dunes and extraction from wells or ponds at lower elevation for water quality improvement and to balance supply and demand.
Excess irrigation		Excess irrigation can be applied in irrigated land where water is deliberately spread by e.g. sprinkler or drop irrigation during dormant or non-irrigated seasons in order to increase water availability during dry seasons.
Well or borehole infiltration		Increased infiltration into groundwater via shallow boreholes or wells. This technique is used to increase infiltration in low permeable confining layers.
Aquifer Storage and Recovery (ASR)		This technique is used to overcome seasonal gaps in water availability by injecting water in a well for storage. When the stored water is needed the water is recovered from the same well. Often applied in saline aquifers.
Aquifer Storage, Transfer and Recovery (ASTR)		ASTR storage and recovery is regulated by different wells. This technique provides an extra water treatment to the recovered water.
Aquifer Storage (AS)		Permits the use of the groundwater environment as a sub-surface reservoir.
Induced Bank infiltration (IBF)		River water infiltration is induced by a pumping well close to a river or lake. This technique is commonly used to produce drinking water. The soil enhances the water quality of the extracted river or lake water.
Check dams		Check dams are a channel obstruction, to stagnate and infiltrate surface water into groundwater. Release wears can be used to regulate recharge downstream.

Riverbed scarification		Riverbed infiltration from the river is enhanced by perforation of the impermeable sediment layer.
Sand dams		Sand dams are usually small structures to accumulate sandy deposits in non-perennial streams, creating a small-scale artificial aquifer. In dry periods infiltrated water is extracted from this aquifer.
Rainwater harvesting for aquifer storage		Rooftop harvesting collects rain, and may store the water in settling tanks, before it is recharged through surface beds of sand / gravel or a well. Recharged water could subsequently be extracted from a downstream well.
Barriers and trenches		Barriers and trenches to reduce surface run-off and induce infiltration.
Subsurface dams		Technique to obstruct groundwater flow, therefore maintaining groundwater in certain aquifers. This technique is not applied in Europe (Sprenger et. al, 2017).

1.2. Regulatory Framework of MAR

Although MAR is recognized as a promising set of techniques to cope with a variety of water management-related issues, there are still some gaps in the scientific, economic and governance dimensions of MAR which need to be addressed. Fernández Escalante et al. (2020) reviewed a total of 18 guidelines, regulations and public operator rules distributed across the world providing a series of recommendations to help decision-makers in dealing with the complex task of formulating regulatory and operating framework entailing MAR. It is finally stated the need of including a risk assessment approach as part of the MAR policies.

At European level, the Water Framework Directive (WFD, 2000/60/EC) considers artificial recharge of groundwater as one of the Supplementary Measures that can be used by EU Member States for the achievement of good groundwater status as part of measures under their respective River Basin Management Plan. In order to ensure that the necessary regulatory controls are in place to guarantee that such practice does not compromise the achievement of the environmental objectives of good quantitative and qualitative status of the recharged groundwater body, Article 11(3)(f) requires the establishment of controls, including a requirement for prior authorization of artificial recharge (Sapiano et al., 2017) to ensure that the overall objectives set under Article 4 are in place. Article 4(1)(b)(i) of the WFD requires Member States to implement the measures necessary to prevent or limit the input of pollutants and to prevent further deterioration of the status of all bodies of groundwater. In this respect, the Groundwater Directive (2006/118/EC) recognizes that it is not technically feasible to stop all inputs of hazardous substances, in particular those hazardous substances which do not represent a risk to groundwater. In fact, in accordance with the CIS Guidance Document 17, under the Groundwater Directive, to "prevent" an input into groundwater means: taking all measures deemed necessary and reasonable to avoid the entry of hazardous substances into groundwater and to avoid any significant increase in concentration in the groundwater, even at local scale. Additionally, projects concerning artificial recharge above 10 million cubic metres a year are subject to Environmental Impact Assessment (EIA). For smaller rates of artificial recharge, Member States can determine individually whether EIA applies. The requirement for an EIA for proposed MAR projects enables the environmental impacts to be assessed and the necessary measures undertaken at the planning stage of the scheme to ensure alignment with the requirements of the EU environmental acquis.

1.3. Objectives

Despite the existence of a theoretical framework guiding the implementation of MAR to improve the qualitative and quantitative status of groundwater bodies in compliance with the WFD, a conspicuous lack of discussion exists regarding the safe implementation of MAR techniques in freshwater lens systems carbonate in type. This is the reason why the characterization of a coastal/island carbonate aquifer system at the levels required for the application of MAR projects is the main objective of this thesis. Instead of approaching this subject in a theoretical framework, the discussion of the different aspects related to this problem are based on a real case study: the Malta Mean Sea Level Aquifer (MSLA).

The general objectives can be expressed as the search for the answer to two questions:

(i) Does the current state of the art of the Malta MSLA allow the safe implementation of MAR projects in compliance with European Directives?

(ii) How can the existing MSLA monitoring network infrastructure be deployed to validate the positive impact of MAR schemes in Malta?

In addition to these questions, essentially related to conceptual issues, some particular aspects related to groundwater salinization need special attention. In fact, the use of Numerical Modelling and analytical approaches is often restrained to the analysis of an Equivalent Porous Medium when dealing with carbonate aquifers. However, taking into account the defined objectives, the complexity of the aquifer system must be considered. This is the case of the Malta MSLA where groundwater salinization mechanisms have not been clearly understood yet. Therefore, an additional challenge for the implementation of MAR in Malta consists in the evaluation of the impact of saltwater intrusion into the groundwater body.

Some practical results were obtained in this thesis by modelling MAR scenarios for identifying potential gaps in the conceptualization of the Maltese aquifer system. These data gaps need be tackled prior the implementation of MAR schemes in the MSLA for minimizing maximal risks of failure. Furthermore, analysis undertaken on tidally induced groundwater level fluctuations led us to generate an equivalent transmissivity distribution map at aquifer scale through geostatistical tools which can be used as a benchmark to calibrate flow models. Finally, salinization mechanisms affecting the qualitative status of this freshwater lens system were analysed through the measurement of temperature and salinity profiles in Deep Monitor Boreholes (DMBs). The objective of this field measurements was to characterize the hydrogeological dynamicity driven by the bouncy effect of the freshwater lens system floating on water of higher salinity.

2. Materials and Methods

2.1. Risk assessment of MAR projects

The main objective of risk assessment is to identify the risks and to evaluate scientific information that is available to decide whether a hazard exists and what the magnitude of that hazard may be (Rowe et al., 1995). The estimates calculated by the risk assessment method are used as a basis for deciding on actions to eliminate, reduce or otherwise manage the risk under consideration (Salgot et al., 2006).

In general, a standard risk assessment requires to undertake the following methodological steps (Moriarty and Nokes, 2014):

(i) **Hazard identification:** consists in the identification of hazardous substances which may create a burden to human life or the environment.

(ii) **Exposure assessment:** exposure pathways are identified as well as the estimation of possible levels of exposure to hazards arising from these pathways.

(iii) **Dose response:** allows an estimate of the probability of a health outcome (such as illness) given exposure to a known dose of a hazard.

(iv) **Risk characterization:** the phase that brings together the information from the three previous steps to estimate the probability of infection or illness.

The World Health Organization (2016) provides rigorous guidelines to the application of the above methodological steps of risk assessment based on the Quantitative Microbial Risk Assessment (QMRA). QMRA is a framework or mechanism that allows for a quantitative scientific data to be interpreted in the context of estimated health outcomes in order to support water safety management. The risk is therefore assessed using risk matrices which come with different levels of complexity in terms of the number of categories for assessing the likelihood of a hazard event occurrence and the severity of the hazard. This should aid in consistency in the assessment for all parts of the water supply system and over time.

When dealing with environmental issues raised by the presence of hazardous chemicals in soil and groundwater, reference should be made to the Risk-Based Corrective Action (RBCA). A brief description of the RBCA process follows (Brown, 1998):

(i) **Assess the site:** the first step in approaching any contaminated site is a scientific analysis of the condition of the site. This investigational step of the site requires site inspection, records review and physical testing aimed at developing data showing maximum concentrations of chemicals of concern and the points on the site where concentrations have been reduced to acceptable levels.

(ii) **Assess exposures:** the next step is to identify the potentially exposed population and its location and to determine how the chemical will reach the exposed population and how the population will be exposed. These four factors determine the nature of the risk.

(iii) **Calculate the level of risk:** using the techniques of quantitative risk assessment, risks to humans and environment caused by the exposure must be calculated. The results of the calculations will indicate if the exposures are within generally accepted levels and no further actions are required, or if some response is required.

(iv) **Analyse remediation alternatives:** this final step contemplates analysis of engineering and institutional controls that could replace a clean-up program or would permit less expensive program. Additionally, an analysis of remediation by natural attenuation should be done. The RBCA process often combines several remediation alternatives.

The Australian Guidelines for water recycling (Natural Resource Management Ministerial Council et al., 2009) are intended to give more certainty to risk assessments used in the approval process of MAR projects, speed up these assessments, prevent failure of MAR projects and uphold the confidence of investors and the public in future innovations. The Guidelines recognize that the level of risk associated with MAR projects cannot be fully understood until the project is implemented at full scale, due to uncertainties associated with the natural processes which take place in the unsaturated and saturated zones. However, it is outlined that with adequate system characterization and assessment, it is possible to adopt preventive measures and operational procedures which significantly reduce the associated risks. These measures and procedures allow the system to be implemented and protective measures to be validated, without compromising acceptable uses of recovered water or the environmental values of an aquifer beyond an attenuation zone (i.e., the area surrounding the zone of recharge where natural attenuation of contaminants such as chemicals and microorganisms takes place). For small scale MAR projects with low inherent risks a simplified assessment is possible. For all other projects the following four assessment stages apply:

(i) **Entry-level assessment** – this involves gathering information that is normally readily available at the local or regional authorities of the project area and performing a basic desktop assessment to determine whether the project is viable and the likely degree of difficulty. The results of this assessment provide an indication of the extent of the field investigations required in the subsequent step.

(ii) **Maximal risk assessment** – these baseline investigations and site-specific data reveal inherent risks associated with a checklist of key hazards. This assessment will reveal whether preventive measures are required (as is normally the case).

(iii) **Residual risk assessment (precommissioning)** – this assessment identifies proposed preventive measures and operational procedures that will ensure acceptably low residual risks to human health and the environment from constructing and commissioning the project this assessment also informs on hazards or aspects that require validation monitoring during commissioning trials.

(iv) **Residual risk assessment (operational)** – this is based on the results of commissioning trials and determines whether the ongoing operation of the project has acceptably low residual risks to human health and the environment. This assessment also informs the risk management plan including types and levels of verification and operational monitoring for ongoing operation of the project.

Basically, a maximal risk assessment assesses risk in the absence of preventive measures, whereas the residual risk assessment assesses risk in the presence of preventive measures. Residual risk assessment may also be applied to recharge activities that are already in operation but have not yet been assessed. Because they identify existing preventive measures and operational procedures, verification monitoring data may be evaluated to determine whether they demonstrate sufficient protection of human health and the environment. Figure 1 shows the above series of risk assessments that are designed to ensure protection of human health and the environment. These assessments allow decision points for investment, based on an informed understanding of the next required level of investigation.

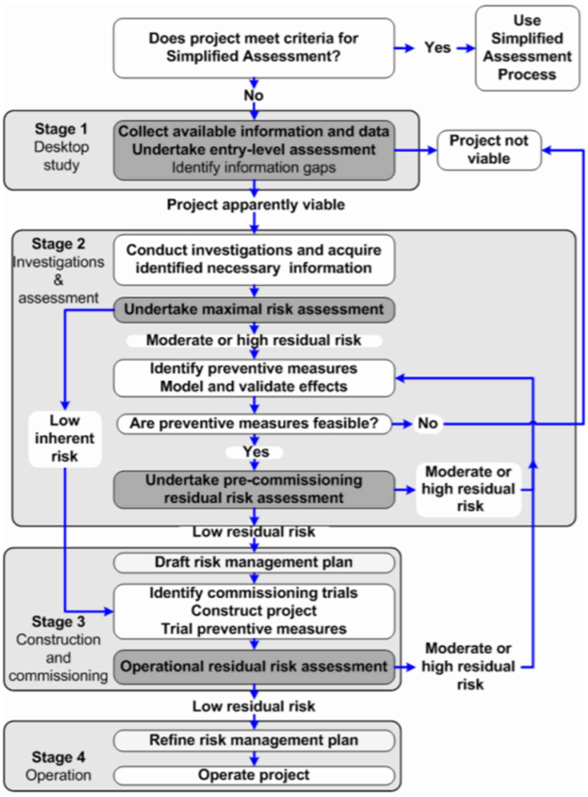


Figure 1: Risk Assessment Stages in MAR Project development (Natural Resource Management Ministerial Council et al., 2009).

The purpose of this thesis is to assess the feasibility of a MAR scheme aimed at halting saltwater intruding into the groundwater body. In this regard, groundwater salinization mechanisms need to be fully understood by undertaking preliminary risk assessment stages to assess whether proposed preventive measures and operational procedures such as those related to MAR identified within the 2nd Water Catchment Management Basin of the Maltese Islands (SEWCU & ERA, 2015) are adequate to ensure acceptably low risks to human health and the environment.

2.2. Groundwater hydrology of small islands

Small islands have particular hydrological and water resource assessment, development and management problems which distinguish them from medium and large islands. The definition of a "small island" is one where the area is not greater than 2,000 km^2 or where the width is not greater than 10 km (Falkland and Custodio, 1991).

Groundwater occurs on small islands as two main types of aquifers: perched and basal. Perched aquifers commonly occur over horizontal confining layers or aquicludes. Basal lenses can occur in the form of coastal aquifers or freshwater lenses overlying seawater. Between the freshwater lens and the underlying saltwater, a brackish water transition zone exists. The transition zone thickness depends on both natural conditions (permeability of the geological formation, tidal and recharge fluctuations and other factors) and artificial influences (man-induced extraction). Neither the freshwater nor transition zones are of constant thickness; they vary spatially and temporally.

Small islands have special physical, demographic and economic features. Their very reduced areas, shortage of natural resources, geological and orogenic complexity, and isolation make the hydrological and water resources problems of these islands usually very serious. High demographic pressures are also encountered which add to the natural problems in many small island states (Falkland and Custodio, 1991).

Permanent rivers and springs occur only where rainfall is relatively high and well distributed over the year, and where favourable topographic and geological conditions occur. From a hydrogeological point of view, the turnover time of groundwater systems on many small islands tends to be short. Thus, freshwater lenses and perched aquifer may deplete in dry seasons. The additional stress of pumping from such lenses can easily induce saltwater intrusion if care is not taken in the design and operation of extraction facilities. Seawater intrusion is a serious problem for the water quality of small islands, especially where over-exploitation occurs due to increasing populations and tourist, industrial or agricultural developments. In these cases, the natural water balance can be dramatically and adversely altered. Inorganic and organic contamination of drinking water wells is a frequent phenomenon in many small islands. Water pollution caused by uncontrolled use of fertilizers, herbicides and pesticides is prevalent in some islands particularly in carbonate islands where the vulnerability created by karstified features connected from the ground level to the surface water body is not negligible.

Carbonate islands are formed from limestone, dolomite, marl and combinations of these rocks. Two main types are considered: old carbonate islands and biogenetically constructed young islands. The latter can be described as coral reef islands or other bio-constructed islands. In carbonate aquifers, groundwater mainly flows according to preferential flow pathways and is often locally confined (Fidelibus et al., 2016). All of them have in common the easy dissolution of carbonate minerals in water under the action of soil CO_2. Then there is the possibility of enlargement of fissures and fractures by dissolution of carbonates due to water flow where karstification occurs. Karstification may result in only small enlargements of fissures or may cause the formation of large cavities and conduits. In the transition zone, dissolution provokes the increase of calcium and carbonate ion concentration generating a favourable situation to dolomitization (Aquilina et al., 2005). Dolomitization involves a redistribution of the porosity and generally causes a permeability increase.

Changes in sea level relative to an island's shore may result in perched or submerged karst formations. The karst may remain open or become clogged with debris and sediments. Infilling by redeposition of calcite is a minor process in young karsts but may have obliterated old karstified zones.

In an aquifer with a sea boundary, there is a direct contact between freshwater and marine saltwater (Figure 2). In a stable system, freshwater floats on saltwater and a landward sloping interface separates them. In small permeable islands the freshwater body takes the shape of a lens floating on saltwater. Since the freshwater flow zone thickness decreases towards the coast, the piezometric head is convex and the interface is concave in a homogeneous medium.

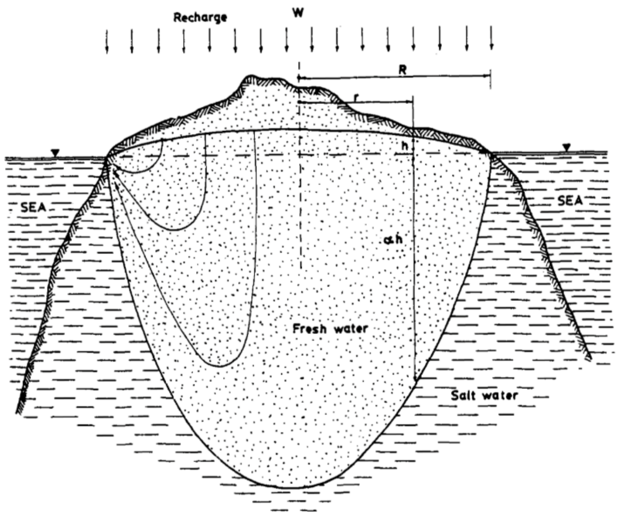


Figure 2: Idealised lens in a permeable oceanic island. Vertical scale is highly exaggerated (Falkland and Custodio, 1991).

The first quantitative observations of the saltwater depth in coastal aquifers were done independently by Ghyben (1889) and Herzberg (1901). They developed a hydrostatic approach based on the equilibrium of two stationary immiscible fluids of different density. At any one point of the sharp interface, the water pressure on both sides must be the same. Since these pressures are equal:

$$\left(z + h_f\right) \gamma_f = z\, \gamma_s \tag{2.1}$$

And thus:

$$z = \frac{\gamma_f}{\gamma_s - \gamma_f}\, h_f = \alpha\, h_f \cong 40\, h_f \tag{2.2}$$

Where h_f is the freshwater head above local mean sea level, z is the depth of the interface below mean local sea level, γ_f is the specific weight of freshwater (1,000 kg/m^3), γ_s is the specific weight of saltwater (normally selected as 1,025 kg/m^3), and α is the specific weight ratio which is normally selected equal to 40. As a first approximation, according to equation (2.2), the interface depth below mean sea level is about 40 times the water table elevation above mean sea level.

The Ghyben-Herzberg formula (equation (2)) has significant limitations. In fact, several authors (Glover, 1959; Bear and Dagan, 1964; De Josselin de Jong, 1965; Verruijt, 1969) attempted to identify robust equations for determining freshwater/seawater interface depths by reducing uncertainty while including more variables.

Taking into account the nonlinear nature of the boundary condition along the interface, Dagan and Bear (1967) developed the exact equations required for solving the problem of the moving interface based on the method of small perturbations while the range of validity of the analytical results was verified by means of experiments in a sand-box model. Isaacs and Hunt (1985) found an approximate analytical solution for a moving interface in a confined coastal aquifer by solving a nonlinear first-order partial differential equation with solutions coinciding with steady-flow solutions obtained from the Dupuit approximation. More recently, Masciopinto and Palmiotta (2013) examined the use of numeric flow solutions of the Navier-Stokes equations to improve flow modelling in fractured karst aquifers with simulation results which agreed well with the data collected during the test. Golshan et al. (2018) compared freshwater/seawater interface depths calculated through the Verruijt equation (1969) with geoeletrical and electromagnetic methods undertaken in a coastal island resulting in a good match in two study areas out of four. Notwithstanding the efforts of the scientific community to elaborate reliable analytical solutions for solving the problem of determining the freshwater/seawater interface depth through analytical solutions, the Ghyben-Herzberg equation still represents a quick and valuable formula to be applied to solve this type of environmental issues given its simple form and the widespread practice of monitoring groundwater levels in gauging boreholes.

2.3. Hazard identification: saltwater intrusion

Saltwater intrusion is one of the most wide-spread and important processes that degrades water-quality by rising salinity to levels exceeding acceptable drinking and irrigation water standards and endangers future exploitation of coastal aquifers. Human activities (e.g., water exploitation including industry and agriculture, reuse of wastewater) result in accelerating salinization (Bear et al., 1999) often leading to wells shut down.

In many coastal aquifers around the world, modern seawater intrusion commonly occurs because of natural flow controls or because of flows induced by extensive freshwater withdrawals. However, the source of salinity in coastal aquifers has been a subject of many studies, but in many cases is still equivocal. Custodio (1997) listed a number of saline sources that can affect water quality in coastal aquifers, but which are not directly related to seawater encroachment. These include entrapped fossil seawater in unflushed parts of the aquifer following invasion of seawater during relatively high sea levels (e.g., Fidelibus and Tulipano, 1986), sea-spray accumulation, evaporite rock dissolution, displacement of old saline groundwater from underlying or adjacent aquifers or aquitards through natural advection or thermal convection, leaking aquitards through fault systems and pollution from various sources including sewage effluents, industrial effluents, mine water, road de-icing salts and effluents from water softening or de-ionization plants. Additionally, agriculture return flows and leakage of urban sewer systems can contribute salts to phreatic coastal aquifers.

The chemical composition of waters resulting from a simple mixing would appear to be a matter of averaging the compositions of the waters that mix in proportion to their volume contributions to the mixture. While this situation is true for elemental concentrations of conservative solutes, such as sodium or chloride, it is not true where chemical speciation is concerned (Bear et al., 1999). These conditions in carbonate aquifers can be explained through figure 3 (a) which shows the solubility of calcite at different temperatures as to the content of dissolved sodium chloride in the water (Aquilina et al., 2005). The curves are concave downwards: this means that the mixing of two waters, both saturated as to calcite and at the same temperature, but containing different amounts of sodium chloride, causes under-saturation of the resulting solution. If kinetics allows and calcite is available, porosity will increase in the interacting rocks. The curves become nearly linear when temperature increases: this means that the diagenetic effect of mixing will decrease with increasing temperatures. Figure 3 (b) shows the solubility of calcium sulphate in water as to sodium chloride concentrations. The curves are concave downwards, showing a maximum at low temperatures. Mixing of waters A and B (or D and E as well) will produce under-saturated solution and cause calcium sulphate to dissolve. Therefore, the mixing of freshwater and sodium chloride waters in presence of limestone, gypsum and anhydrite, leads to under-saturation and porosity enhancement. In carbonate coastal/island aquifers, the re-activation of the karstification occurs therefore in the transition zone, right in relation to the disruption of the equilibrium due to mixing of different water bodies having different salt content, and hence ionic strength (Aquilina et al., 2005). According to its geological history, each carbonate formation shows a different extent of porosity evolution and, consequently, of permeability.

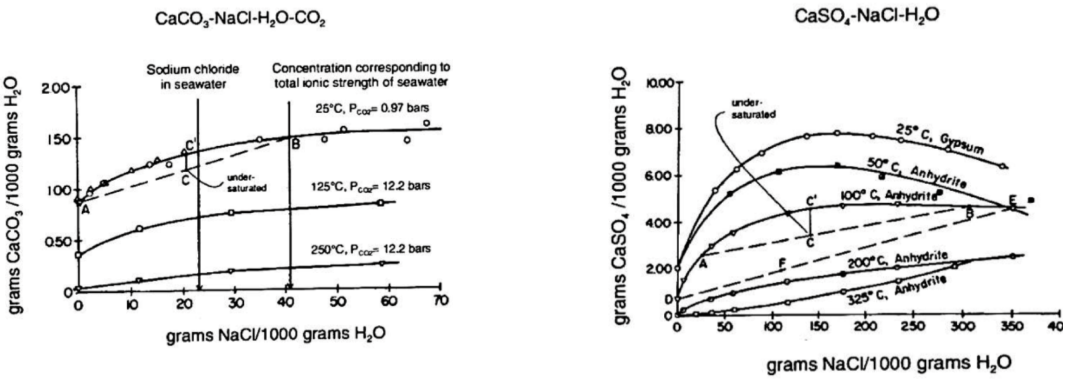


Figure 3. Solubility of (a) calcite as a function of the content of a neutral electrolyte (sodium chloride) in solution, and (b) of calcium sulphate minerals as a function of a neutral electrolyte (sodium chloride) in solution (Aquilina et al., 2005).

The water-rock interaction processes are clearly responsible for the evolution of Na-Cl type fluids towards Ca-Cl fluids. The more meaningful differences with respect to present seawater concern the concentrations of Ca and Mg and, consequently, the value of Mg/Ca ratio, ranging from 6 to 2 (Aquilina et al., 2005). Major reactions recognised as responsible of saltwater diagenesis are: (i) Ca-Mg exchange due to dolomitization, (ii) Na-Ca or Mg base exchange, and (iii) SO_4 reduction.

Although of qualitative impact, saltwater intrusion needs to be tackled through quantitative measures, namely by restoring groundwater quantitative status. Prior the implementation of MAR schemes aimed at halting saltwater intrusion, a thorough understanding of flow mechanisms and hydrogeochemical conditions at the aquifer scale need to be developed in line with the objectives of this thesis for the safe implementation of MAR projects in the Malta Mean Sea Level Aquifer (MSLA).

2.4. Monitoring network of freshwater lens systems

The problem of easy salinization of discharging wells and boreholes is often the result of an inadequate knowledge of groundwater behaviour or over-exploitation. The knowledge and correct assessment of groundwater resources require a sufficient understanding of the physical and chemical laws regulating their existence, an adequate and correctly operated observation network, and monitoring of abstraction rates (Falkland and Custodio, 1991).

In some small islands, the large volumes of water in storage and the slow movement of groundwater in aquifers dampen out short term fluctuations and obscure trends. Thus, groundwater abstraction volumes that do not produce clearly observable negative effects in weeks or months may be the cause of undesirable impacts if they continue for longer periods of time (Falkland and Custodio, 1991). Therefore, careful forecasting methods and continuous monitoring are needed, together with the ability to influence public and private management to adapt to observed or predicted simulations.

In accordance with Daniell and Falkland (1983), when dealing with coastal aquifers or freshwater lenses in small islands, such as the Malta Mean Sea Level Aquifer, special emphasis must be placed on the acquisition of data on:

- Areal variations of water salinity.
- Vertical distribution of water salinity, particularly the location of the freshwater/seawater interface or transition zone.
- Distribution of permeable or fractured zones and water heads at boreholes.
- Existence, importance and variability of discharge and water quality of coastal springs.
- Sea level both as a result of tides or other short-term changes and long-term processes.

Nonetheless, inventories of existing wells and boreholes, water levels, hydrometric and hydrometeorological data, abstractions and other pertinent information have to be periodically updated, otherwise they soon become obsolete.

2.4.1 Monitoring of groundwater quantitative and qualitative status

The monitoring of groundwater qualitative and quantitative status is undertaken through the drilling of exploratory boreholes. The number of monitoring boreholes is necessarily limited, and careful planning is required to provide the quantity and quality of information compatible with costs.

The monitoring system of piezometric heads is usually equipped with float-operated Shaft Encoder Thalimedes devices, although improvements have been made in the last decades by performing new submersible dataloggers for long-term uninterrupted, real-time water level monitoring using a pressure sensor measuring Electrical Conductivity, Temperature and Depth (CTD divers). This is the case of the Malta MSLA where an upgrade of water level devices was carried out in the last three years. The setting of acquisition frequency of these devices is of paramount importance, for example a frequency of acquisition of 1 measurement every 30 minutes would be sufficient to record time-series of short-term fluctuations of water levels induced by sea tides. Sea level states in Mediterranean coastal areas are data readily available online. Sea level gauges are managed by the Mediterranean regional subsystem of the Global Sea Level Observing System (MedGLOSS) which is a real-time monitoring network for systematic measurements of the sea level. It follows GLOSS requirements and methodology, aiming to provide high quality standardised sea-level data.

Groundwater chemical quality monitoring is generally done by collecting samples and analysing them in certified laboratory services. Sampling procedures are provided by USGS (2019). One of the most common methods of sampling groundwater is pumping the well with the installed pump. This yields a water that is a mixture of different layers. Very short pumping at low flow rates may produce only water stored inside the well, short pumping produces a mixture of the layers adjacent to the pump depth while long pumping produces water that tends to represent a weighted mean composition of the water in the aquifer. Sampling in static conditions at shallow depths of the groundwater body is possible using bailers consisting of a hollow tube with a check valve at the bottom and a handle at the top. Some parameters (e.g., pH, temperature and Dissolved Oxygen) should be measured directly in the field as soon as the water sample is collected, generally using a multiparameter probe.

2.4.2 Salinity and Temperature profiles

The special severity of saltwater contamination in coastal aquifers calls for a rigorous approach supplemented by up-to-date investigations of groundwater quality. Particularly useful are to this end the multiparameter logs which have to be executed along the water column of boreholes through the monitoring of temperature and salinity. This method allows to detect some typical trends of the parameters under study. These types, which are rather recurrent in space and time, allow an extensive use of this method which can be easily applied to the preliminary detection of the hydrogeological conditions which determine the chemical and physical nature of groundwater and the occurrence of human- or salt-related contamination (Cotecchia et al., 1999).

Monitoring the 50% mixing of salinity between freshwater and seawater in Deep Monitor Boreholes (DMBs) is useful to identify long-term trends in the movement of the transition zone (USGS, 2010). DMBs penetrate entirely through the freshwater zone and partly or entirely through the brackish-water transition zone that separates freshwater from underlying higher density saltwater in a freshwater lens system. Most of the multiparameter probes measure fluid Electrical Conductivity used as a proxy for salinity. All Electrical Conductivity profiles require conversion from Electrical Conductivity under ambient temperatures to Specific Conductance at 25 degC. The following equation has to be used for postprocessing (Clesceri et al., 1998, Hayashi, 2004):

$$SC = \frac{EC}{1 + 0.0191(T - 25)} \tag{2.3}$$

Where SC is the Specific Conductance in microsiemens per centimetre at 25 degC, EC is the measured Electrical Conductivity, in microsiemens per centimetre and T is the measured temperature in degrees Celsius.

By convention, the depth of the midpoint between freshwater and saltwater is the depth where the fluid Specific Conductance equals 25 mS/cm, however, this may not represent the true 50% mixing between freshwater and seawater salinity, because the measured Specific Conductance at the bottom of several DMBs exceeds 50 mS/cm (USGS, 2010). For the purposes of this thesis, saltwater is defined as having a Specific Conductance of 60 mS/cm, therefore, the definition of the midpoint is set at the conventional Specific Conductance of 30 mS/cm.

The monitoring of salinity profiles over time in DMBs allows the detection of typical patterns of fresh/sea-water interface fluctuations according to the occurrence of external driving forces like precipitation and/or local abstraction. The profiles can be correlated with aquifer characteristics such as, fractures and orientation of strata in the DMBs which are determined through high resolution images captured with an optical televiewer probe (MOUNT SOPRIS QL40-OBI-2G). For instance, in Malta these devices are deployed for characterizing saltwater intrusion mechanisms.

2.4.3 Groundwater multi-level sampling with depth

The analysis of water-rock interactions in the transition zone of DMBs require the collection of groundwater samples representative of the layers adjacent to the selected investigation depths. In this regard, bladder pumps can be deployed. When a bladder pump is lowered into a borehole, hydrostatic pressure allows formation water to enter the central chamber (the bladder) through the inlet filter, and fill to static water level. When compressed nitrogen gas is applied to the drive line it pressurizes the space around the bladder, causing it to collapse and pushes the water up into the sample line. Check valves ensure that no water flows back down through the pump or into the formation. When compressed gas is released, more formation water enters the bladder. When the pressure is reapplied, the fresh formation water is pushed up towards the surface. The pressure/vent cycles are repeated, providing a steady flow of water up the sample line without any stripping of volatiles from the sample. Turbidity is minimized due to the low flow rates and the gentle pumping action. Thus, a high quality groundwater sample is obtained (Solinst, 2022).

Bladder pumps can deliver low flow rates up to 1.5 l/min. In general, flow rates vary with depth of pump below the surface, depth below water level, size of drive and sample tubing, drive and cent cycle times, gas pressure applied and aquifer recharge.

2.5. Determining aquifer hydrogeological parameters from tidal attenuation analysis

The estimation of hydrogeological parameters has been extensively studied in coastal aquifers where tidal oscillations affect groundwater head measurements (Sánchez-Úbeda et al., 2016). The most commonly used methodology to calculate parameters through tidal influence was introduced by Jacob (1950) and Ferris (1951).

However, the original method assumes that measured head is a static level neglecting the effect of external driving forces which produce interference with the tidal oscillations. Sánchez-Úbeda et al. (2016) proposed a method based on Continuous Wavelet Transform (CWT), a technique widely used in tide studies (Flinchem et al., 2000), for filtering the groundwater head measurements and extracting the tidal influence. Srzić et al. (2020) carried out an extensive hydrogeological characterization of a coastal aquifer system by detrending procedures and using the Rahi method (2010); thus, enabling the use of tidal methods once only tidal components exist in groundwater level time-series.

Temporal variations of observed groundwater level signals are influenced by: (i) sea tides, (ii) barometric pressure, (iii) tectonic activity, (iv) human induced activities, (v) infiltration from the surface, (vi) high frequency noise. Sea tides induce significant periodic groundwater level fluctuations to those boreholes located near the coastline. The induced fluctuations are reduced as the distance from the coastline increases and/or the transmissivity decreases with the same period of oscillation of about 12 hours (figure 4). Barometric pressure can be explained as the result of the spatial displacement of air mass (Clark, 1967) and diurnal and semidiurnal barometric changes because of air heating and cooling following the transition from day to night (Turnadge et al., 2019). The groundwater response to Earth tides and atmospheric pressure changes can be used to understand subsurface processes and estimate hydraulic and hydro-mechanical properties (Rau et al., 2020) characterized using the concept of barometric efficiency (Turnadge et al., 2019). Although barometric and groundwater pressure records enable rapid assessment of subsurface processes and properties (McMillan et al., 2019; Clark 1967; Davis et al., 1993), the proximity to the Mediterranean Sea of the Maltese Islands leads us to assume that sea tides are more influential to groundwater level fluctuations than barometric response functions. Tectonic activity can induce changes in the hydraulic heads even if they are characterized by low magnitude fluctuations because of rock displacement. Human induced activities can be associated to two main factors: (i) withdrawal from nearby pumping wells laying within the radius of influence of the monitoring borehole, (ii) aquifer recharge that can be either intended if the source of water is intentionally injected into the aquifer system through MAR schemes or unintended such as leakage from freshwater distribution or sewerage system networks. Infiltration from the surface into the subsurface depends greatly on a number of factors including: variability of precipitation, baseflow originated either from the low permeability volume of the phreatic zone (Drogue 1971, Mangin 1975, Kiraly et al. 1979) or from the epikarst storage (Williams 1983; Sauter 1992; Klimchouk 2000), soil and vadose zone characteristics and saturation, land cover, slope of the land, and evapotranspiration. High frequency noise may be linked to errors of the gauging water level device.

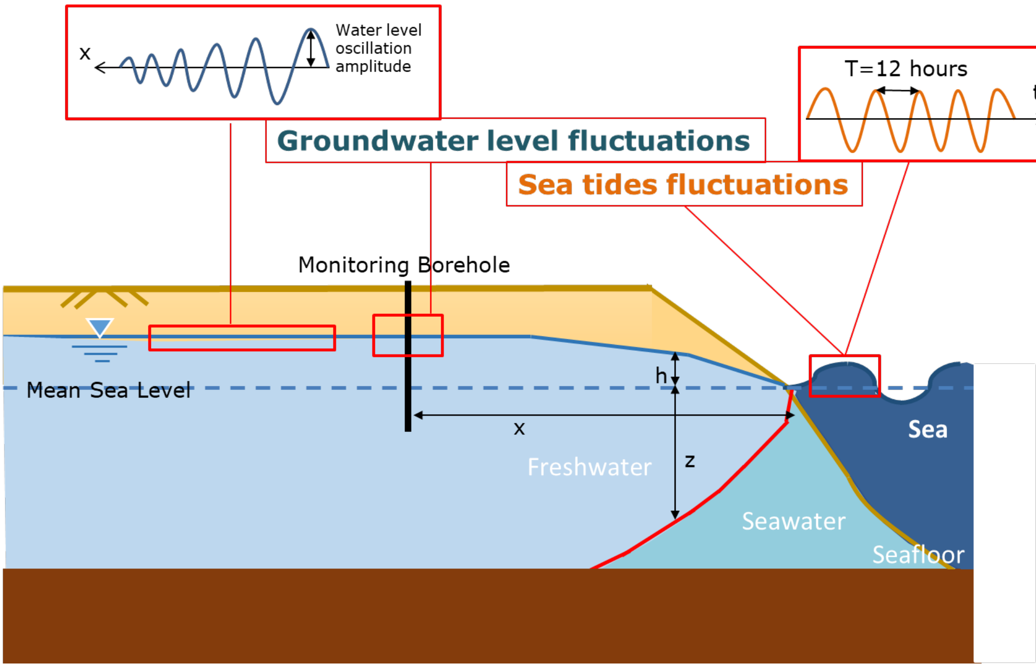


Figure 4: Conceptual diagram of tidally induced groundwater level signals over space and tide fluctuation over time in a schematic coastal aquifer.

Tidal methods to define coastal aquifer parameters were introduced by Jacob (1950) and Ferris (1951). Although techniques to analytically calculate tidally influenced groundwater levels have become more sophisticated (e.g., Guo et al., 2007; Rotzoll et al., 2008), the relatively simple Jacob-Ferris model remains useful for understanding aquifer hydraulic properties from measured groundwater level fluctuations if there is no interference from other factors (Rotzoll et al., 2013).

In highly populated coastal areas, external forces on piezometric fluctuations may be relevant and therefore they may be responsible for disrupting the undisturbed sinusoidal water level fluctuations induced over time by sea tides. These anthropogenic factors may make the tidal attenuation method difficult to apply and, depending on the nature of the disturbance, prone to uncertain estimations. This study proposes a methodology for improving the applicability of the Jacob-Ferris method by means of applying Fast Fourier Transform (FFT) filtering to the observed groundwater level and sea level fluctuations. The FFT reproduced signals allow the isolation of the component induced by sea tides thus eliminating short- and long-term variations of the water table induced by external driving forces.

In the MSLA of Malta the major component which induces water table fluctuations is sea tides. It is possible to detrend and scale the observed groundwater and sea level signals to zero, in order to obtaining fluctuations that can be analysed as explained hereunder.

The proposed method is based on a prior filtering process of observed groundwater level and sea tides signals so that the tidal oscillation reproduced from the original time series is compared with the tide oscillation that produced it. Observed groundwater level and sea tides signals can be modelled as a sum of windowed sinusoids. In theory, the number of sinusoids which represents the real potentiometric and sea-surface over time is infinite. In practice, by considering limited time-series, the observed signals can be expressed as the sum of a finite number of sinusoids having fixed amplitude and frequency in the spectral domain (Tomasicchio, 2015). In order to transform observed signals from the temporal to the spectral domain, a Fast Fourier Transform (FFT) algorithm is applied using Python's Numpy library. The original sea tides spectrum is characterized by high magnitudes in correspondence to the expected frequency of 2 waves/day with peaks usually occurring at midday and midnight. Afterwards, the frequency range is maintained at around 2 waves/day and cut off (i.e., turn to zero) higher and lower frequencies that correspond to the long-term variation of the signal and to aperiodic variations driven by external forces. The choice of selecting either a wider or tighter frequency range around 2 waves/day is arbitrary, and it is usually driven by the magnitude of driving forces disrupting the observed signal, i.e., the greater the magnitude of the external forces is, the lower the chosen frequency range might be. Finally, the Inverse FFT will return the reproduced signal over time, which is now clean of any trends and high-frequency effects. The same methodology can be applied to the sea level states.

Assuming a one-dimensional, homogeneous, isotropic, confined and semi-infinite aquifer with sharp boundary subject to oscillating force, it is possible to apply the Jacob-Ferris analytical solution (1950, 1951) to assess hydrogeological parameters. The solution reads:

$$h(x,t) = h_0\, e^{-x\sqrt{\frac{\pi S}{\tau T}}}\, sin\left(\omega\, \tau - x\sqrt{\frac{\pi S}{\tau T}}\right) \tag{2.4}$$

where h is the hydraulic head [m], x is distance to the sea [m], t is time [days], h_0 is amplitude of the sea tide [m], T is transmissivity [m^2/day] which is equal to hydraulic conductivity (K [m/day]) times aquifer thickness (b [m]), S is specific yield (or storage coefficient) [-], ω is frequency of the oscillation [day^{-1}] and τ period of the oscillation [days]. In Malta the aquifers bearing freshwater are of carbonate in type, consequently, the low permeability rock matrix forces the groundwater flow predominantly into fissures (Fidelibus et al., 2016); thus, the Jacob-Ferris method can be applied neglecting the hydrogeological role of the relatively low matrix porosity. Moreover, as the aquifer length over which tidal influence is long (kilometres), slope effects at the boundary can be negligible (Rotzoll et al., 2013). The equation for hydraulic diffusivity from amplitude attenuation, [m^2/day], can be expressed as:

$$D_{amp} = \frac{x^2 \pi}{(lnA)^2 \tau} = \frac{T}{S} \tag{2.5}$$

where A is the amplitude attenuation factor [-] given by the ratio of amplitude of the oscillation in a monitoring borehole to amplitude in the sea tides, T is transmissivity [m^2/day]. The latter parameter can be assessed in an island/coastal aquifer system by applying the well-known Ghyben-Herzberg formula (equation 2.2).

Groundwater level fluctuations induced by sea tides tend to remain sinusoidal with the period identical to the driving force (sea level) but with exponential decrease in Tidal Efficiency (TE) and linear increase of time lag (ΔT) (Jacob, 1950; Ferris, 1951). According to Srzić et al. (2020), TE can be calculated directly from the observed signals as the ratio of the standard deviations of piezometric head and sea level. By amplifying the reproduced water level signal and shifting the amplified signal by a time equal to ΔT, it is possible to fit sea level fluctuations and therefore verify that groundwater and sea level time series are comparable for tidal attenuation analysis.

The methodology we propose based on Fast Fourier Transformation leads to simplify the evaluation of peak-to-peak positions between sea tides and groundwater head time series reducing the uncertainty inherent in observed signals where external driving forces are not filtered. Hereby, the sought hydrogeological parameters (hydraulic diffusivity, transmissivity and hydraulic conductivity) are determined in Microsoft Excel with a manual peak-to-peak detection. The obtained results are therefore statistically analysed and the mean value of each dataset is assumed to be representative of the calculated hydrogeological parameters for each borehole exhibiting groundwater level fluctuations induced by sea tides.

Finally, the assessed transmissivity values are joined to the ones derived from pumping tests interpretation and then analysed by means of geostatistical tools for estimating uncertainty, correlation and variation in space, through the use of semi-variograms with the aim of generating a transmissivity spatial distribution map of the MSLA of Malta.

3. Characterization of the case study: Malta Mean Sea Level Aquifer (MSLA)

3.1. Hydrogeological and structural settings

The Maltese Archipelago is located in the central part of the Mediterranean Sea at a distance of about 90 Km South of Sicily (Italy), 300 Km East of Tunisia and 350 Km North of Libya. The archipelago consists of 3 main islands which are Malta, Gozo and Comino and a few other uninhabited islets (figure 5). The islands have a total land area of 316 Km^2 and a coastline about 190 Km long. The length of the whole archipelago is 45 Km; Malta being 27 Km long, Gozo 14.5 Km and Comino 2.5 Km (Magri, 2006).

Figure 5: Geographical location of the Maltese Islands.

The only exposed geological formations on the Maltese Islands are of Tertiary and Quaternary age. A brief description of the formations is given hereunder (BRGM, 1991):

(i) Plio-Quaternary; having little or no hydrogeological importance except possibly in alluvial valleys.

(ii) Upper Coralline Limestone (UCL); characterized by fissured aquifers associated with a porous matrix. The UCL is a porous massive formation which outcrops over the Western and Northern zones of the Island and forms the highest parts of the topography. Well-developed karst phenomena can be found with dolines, sinkholes, weathered and corroded on outcrops and fissures, dry valleys and dissolution figures.

(iii) Greensand; being a porous aquifer formation but of limited extent and usually very thin (less than 1 or 2 m).

(iv) Blue Clay (BC); which is an aquitard formation sustaining an aquifer in the Greensand and UCL with possible vertical leakage enhanced by fissuration and faulting.

(v) Globigerina Limestone (GL); which is generally a massive and porous formation which is rather homogeneous all over the island.

(vi) Lower Coralline Limestone (LCL); which is a fissured and fractured formation with a porous matrix. In the LCL the main water body is in equilibrium with brackish and seawater. If compared to the GL formation, LCL is more fissured and entails higher heterogeneity due to a different deposition environment.

Different members of the same formations can be found in borehole drillings. For instance, the Attard Member of the LCL formation is worth mentioning because of its extremely permeable properties developed under shoal conditions. The material of these reefal formations is indeed more porous than in the main part of this geological unit (Herbert, 1955). From a hydrogeological point of view, the heterogeneity they create in the aquifer must be kept in mind when assessing the results of hydrodynamic tests.

Furthermore, the quasi-horizontal attitude of the strata was literally broken up by two main direction fault systems whose orientations are N.50° - 70° for one system and N.120° - 130° for the second by earth movements that were probably initiated in the Pleistocene period and continue to the present time (Padley, 1989) (figure 6). Shearing produced breccia with a fine-grained matrix and which is clay-like in nature. The clay is derived from the marly composition of the limestones in small faults and from the BC formation in the large faults. Because clay is invariably present in the breccia, the faults act as water barriers which are partially or completely tight, depending on their openness (Newbery, 1968).

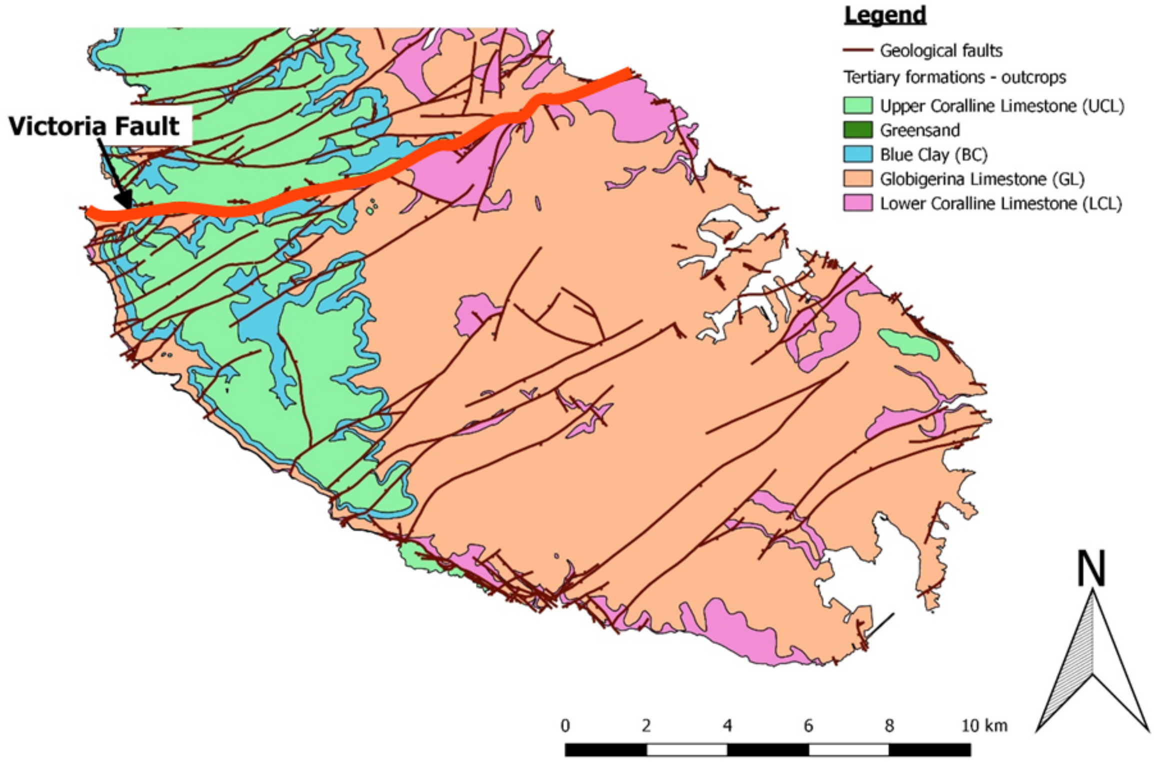


Figure 6: Simplified lithology and geological fault systems of the Maltese Island (modified after OED, 1993).

The Victoria Fault (figure 6) is the longest fault of the Maltese Islands and its displacement was responsible for dividing Malta into two distinct geomorphological parts: (i) the northern part which is a downthrown block characterized by horst and graben structures, and (ii) the southern part which is an upthrown block where the Perched Aquifer (PA) takes place. This aquifer is sustained by the BC formation in the West side of the island overlying the Mean Sea Level Aquifer (MSLA) developed throughout the extension of Malta South up to Victoria Fault when the latter is assumed as an impermeable barrier. A conceptual model of the MSLA system for a generic cross section oriented NW – SE is provided in figure 7.

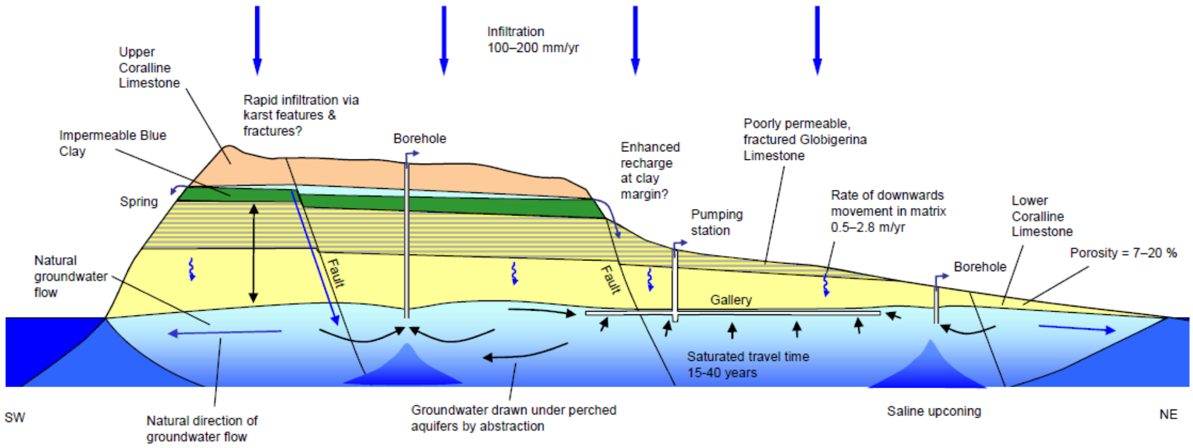


Figure 7: Conceptual cross-section of the Mean Sea Level Aquifer (MSLA) and the Perched Aquifer (PA) of Malta (SEWCU & ERA, 2015).

The MSLA is a carbonate aquifer system in bodily continuity with water of Mediterranean salinity marginally and at depth and its upper surface level is graded to the sea level round the coast. This body of freshwater owes its existence to winter rainfall adding more freshwater to the underground storage (BRGM, 1991). In karst aquifers, an important role is played by the epikarst zone, as it largely contributes to groundwater storage, distributing groundwater into vadose flow through fissures and conduits, and baseflow through rock matrix in the unsaturated zone (Perrin J., 2003).

After compiling all the geological data gathered in drilling reports (unpublished drilling report, Government of Malta, 1985) and technical literature, BRGM (1991) prepared the structural map of the top of the LCL formation (Figure 8) which is the main geological formation bearing freshwater in the Maltese Island. To the South of Victoria Fault, the map depicts clearly the general structure and slope of the LCL. Immediately to the South of the Victoria Fault and along it, two high structures can be depicted with a maximum elevation of more than 120 m. In the South Eastern part of Malta the main feature is the exact coincidence of the relative high elevation of the horst like structure defined by a fault system. The slope towards the North, i.e., to the Valletta graben, is gentle whilst the southern slope towards the South is steeper. The Valletta graben entails hydrogeological interest given the upward slope of the top of the LCL towards South-West until Maghlaq Fault (Figure 8). This was identified as the Hamrun syncline whose hydrogeological role within the MSLA groundwater flow is still equivocal.

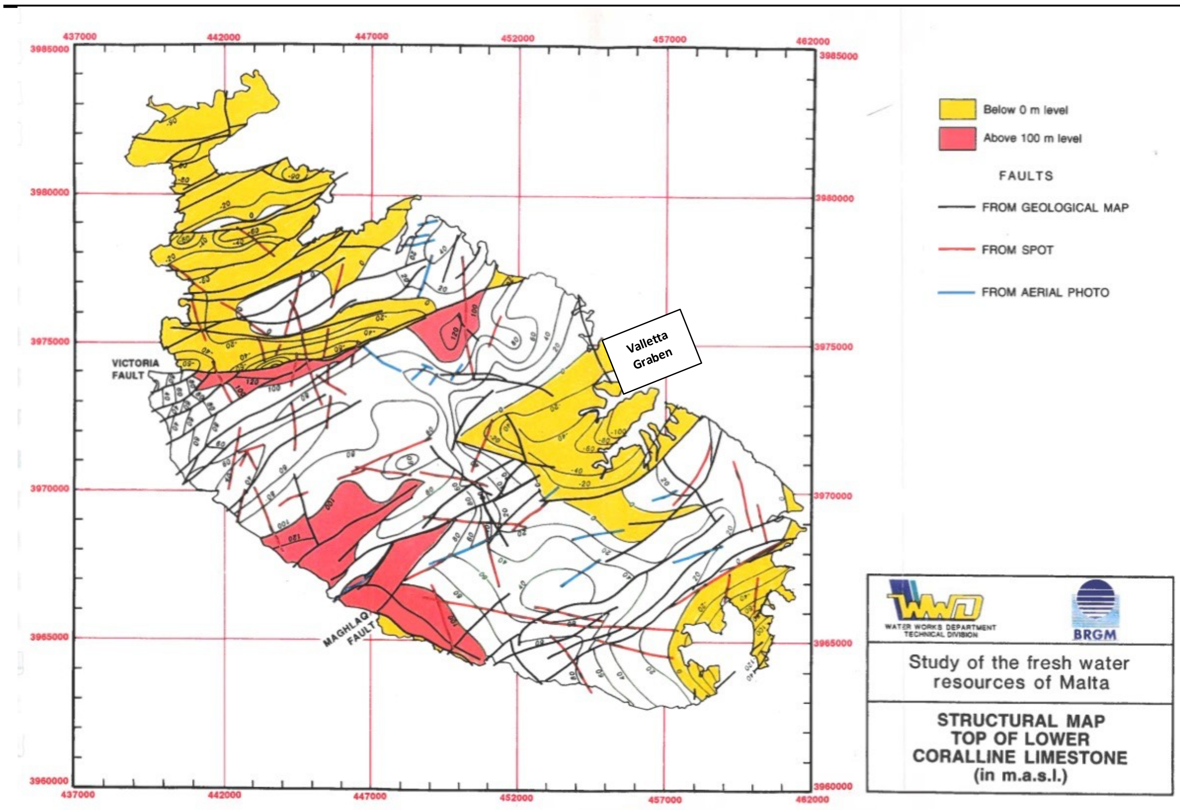
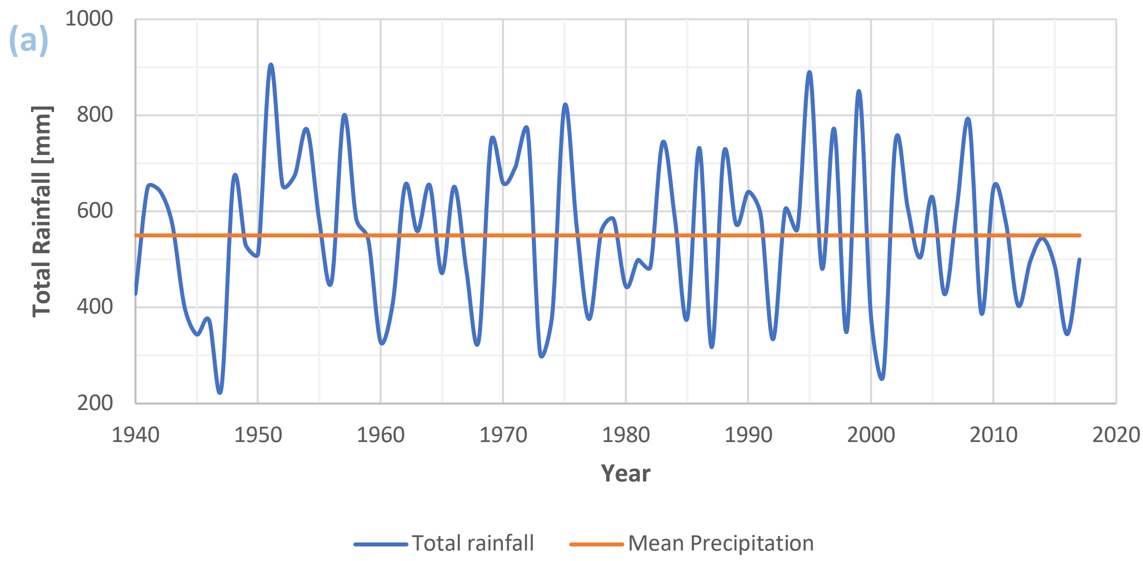


Figure 8: Structural map of the top of the Lower Coralline Limestone formation (BRGM, 1991).

The area has a Mediterranean climate, with strong inter-annual variability (figure 9.a) and a marked annual seasonality (figure 9.b). The mean yearly precipitation is 550 mm/year (SEWCU & ERA, 2015). Precipitation is distributed quite irregularly over the year, with peaks in winter seasons, whilst sporadic and intense precipitations occur during the arid summer seasons with a duration of a few hours.



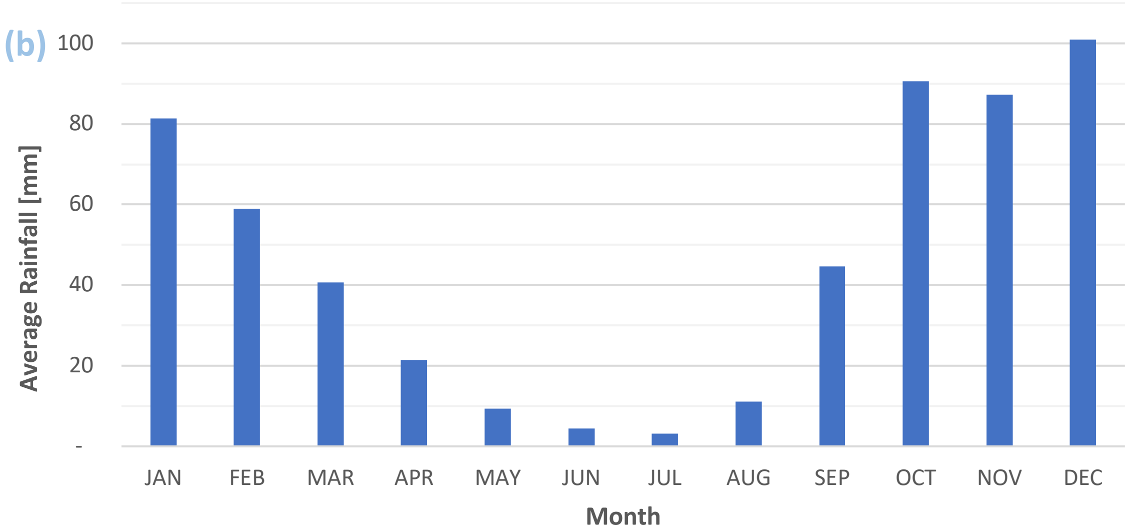


Figure 9: (a) precipitation inter-annual variability from 1940 till 2018, and (b) averaged precipitation from 1940 till 2019 showing intra-annual variability on a monthly basis. Data measured at the representative meteorological station of Luqa (Malta).

The long-term natural recharge to the aquifer systems is a measure of effective rainfall which is assumed to account for 35% of the mean annual rainfall, where losses due to evapotranspiration and runoff are estimated to account for 63% and 2% respectively. Nevertheless, the quantity of irrigation water that recharges groundwater is usually significant relative to recharge from precipitation. The return flow from irrigation is assumed at 20% of the net irrigation water applied over the surface catchment area of the aquifer system (SEWCU & ERA, 2015). In both cases groundwater recharge is expected to be highly seasonal and therefore not relevant to high frequency tidal fluctuation of groundwater table during the arid period.

Groundwater abstraction assessment was undertaken as part of the quantitative status estimate under the 2nd WCMP (SEWCU & ERA, 2015). Total abstraction, from all the groundwater bodies in the Maltese Water Catchment District, was estimated to reach around 38 million m^3, or 61% of the total national water demand (Figure 10 (a)). The sector with the highest dependence on groundwater resources is the agricultural one which accounts for almost half of the total groundwater abstraction. This indicated that cumulatively the Maltese aquifer system is being over-abstracted (Figure 10 (b)). Public boreholes abstraction flow rate data in the Malta MSLA was made available for this work. The majority of the public boreholes are accounted to withdraw a volume of groundwater ranging between 100 and 300 m^3/d in average with eight boreholes producing the highest amount of water from 300 to 500 m^3/d (Figure 10 (c)). Additionally to the about 11,250m3/d of freshwater abstracted from 51 public boreholes spread around the areal extension of the Malta MSLA, it is worth mentioning the role of pumping stations abstracting groundwater from a radial tunnelling system better described in chapter 4. Yearly abstracted volumes from pumping stations range from 8.6 to 11 million m3 (analysed data from 2009 till 2019) with an average volume of 10 million m^3/year (Figure 10 (d)).

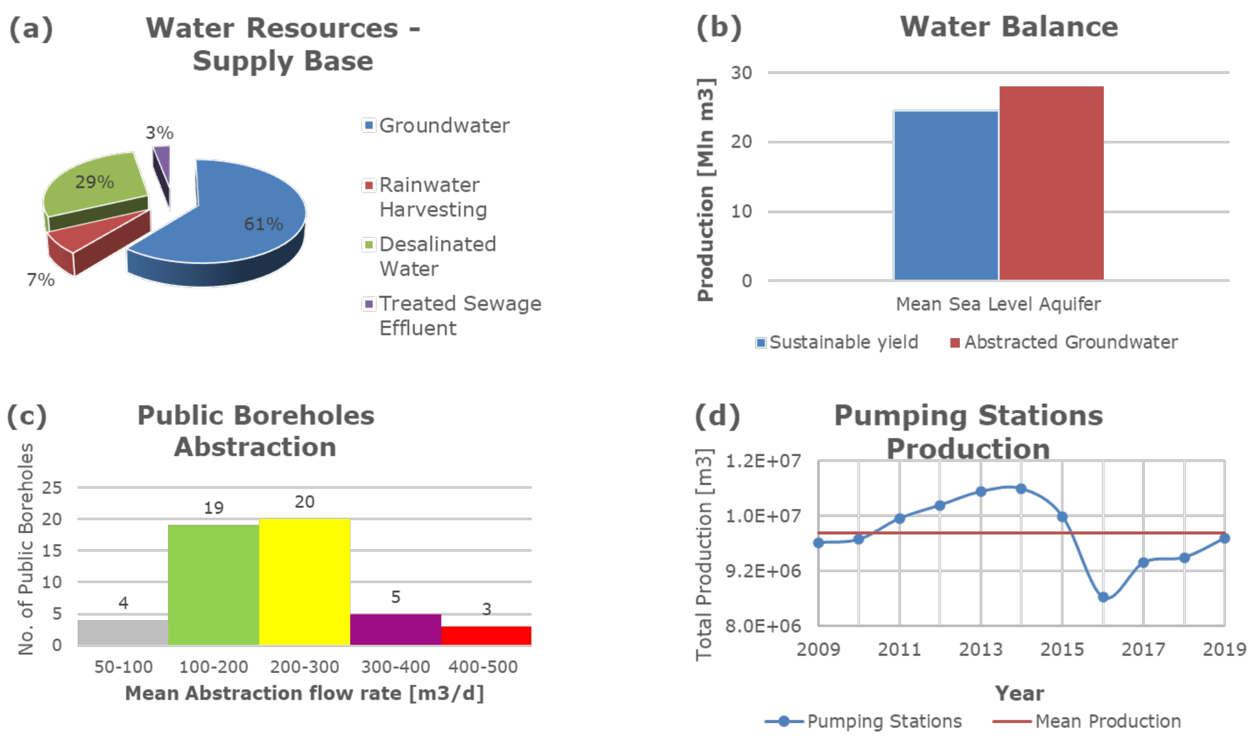


Figure 10: General summary of groundwater exploitation of the Malta MSLA showing (a) supply base of water resources for each groundwater dependent sector (modified after SEWCU & ERA, 2015), (b) water balance undertaken under 2nd WCMP (modified after SEWCU & ERA, 2015), (c) frequency distribution of public abstraction boreholes flow rates, and (d) yearly groundwater production from pumping stations (blue) with mean abstraction flow rate (from 2009 till 2019).

Although the pressure on the Maltese groundwater bodies is decreasing due to the increased efficiency use of non-conventional water resources (e.g., seawater desalinisation, water recycling and rainwater harvesting), the dependence to groundwater in Malta is still high. This induces further depletion of the quantitative and qualitative status as outlined through the national monitoring network.

3.2 Hydrogeochemical scheme

Through its national legislation and the transposition of European legislation, Malta is committed to ensure sustainability of water resources in a holistic manner. In compliance with the WFD, the qualitative groundwater monitoring strategy adopted in Malta is based on a six-year cycle through the Surveillance Monitoring (SM) while Operational Monitoring (OM) is carried out on six-monthly basis during the five-year periods between SM. SM is undertaken once every six years and entails a full set of chemical and physical parameters affecting the groundwater qualitative status. SM also identifies those parameters for which the more frequent OM is required to enable the assessment of long-term trends in natural conditions and in pollutant concentrations resulting from human activity. The OM list of parameters is specifically modified for each groundwater body following an analysis of the results of the SM programme and the pressures and impacts assessment undertaken in the lead-up to the formulation of the Water Catchment Management Plan.

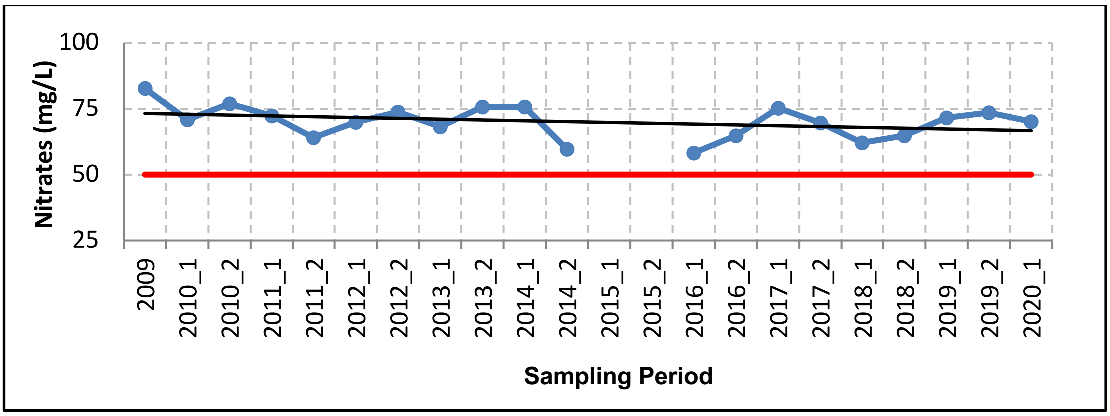
The available dataset corresponds to OM undertaken in 19 monitoring boreholes with samples collected twice every year from 2009 till 2020 except for the year 2015 when the OM was suspended. The oscillations in water composition are dependent of the period of data collection according to the evolution of the annual phase of the hydrological cycle. In order to illustrate the range of variation in water chemistry, Table 2 shows some statistical parameters characterising water composition of the main hydrogeochemical parameters object of this analysis.

Table 2: Statistic parameters obtained from OM undertaken through the MSLA monitoring network between 2009 and 2020. Legend: T – temperature, EC – Electrical Conductivity, Md – median, STD – standard deviation, M – maxim, m – minim. Total number of groundwater samples is 253.

	T [degC]	pH [-]	EC [mS/cm]	Chlorides [mg/l]	Boron [ug/l]	Sodium [mg/l]	Sulphates [mg/l]	Nitrates [mg/l]
Mean	20.2	7.4	2976.8	765.4	196.2	399.6	103.1	69.8
Md	20.0	7.4	2801.5	691.5	150.0	370.2	99.3	61.1
STD	1.2	0.4	1725.2	545.2	147.6	291.4	66.0	36.1
M	24.0	9.0	8450.0	2456.0	990.0	1482.6	338.0	201.0
m	17.7	6.8	918.0	96.0	0.5	76.5	2.3	18.6

By averaging nitrate and chloride concentration from all the groundwater samples it is possible to infer hypothesis related to the overall qualitative status of the Malta MSLA. Figure 11 (a) outlines that the MSLA qualitative status is cumulatively affected by a downtrend of nitrate pollution potentially linked to the good agricultural practices as part of the measures to improve the groundwater qualitative status within the 2nd WCMP (SEWCU & ERA, 2015). On the other hand, an upward trend of cumulative chloride concentrations Figure 11 (b) well above the threshold established by the Groundwater Directive is leading to infer an advancement of groundwater salinization into the MSLA.

(a)



(b)

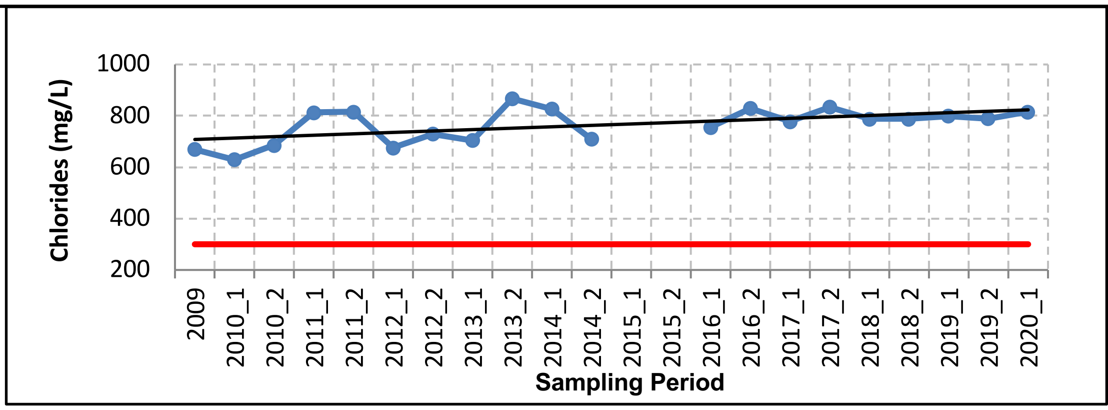
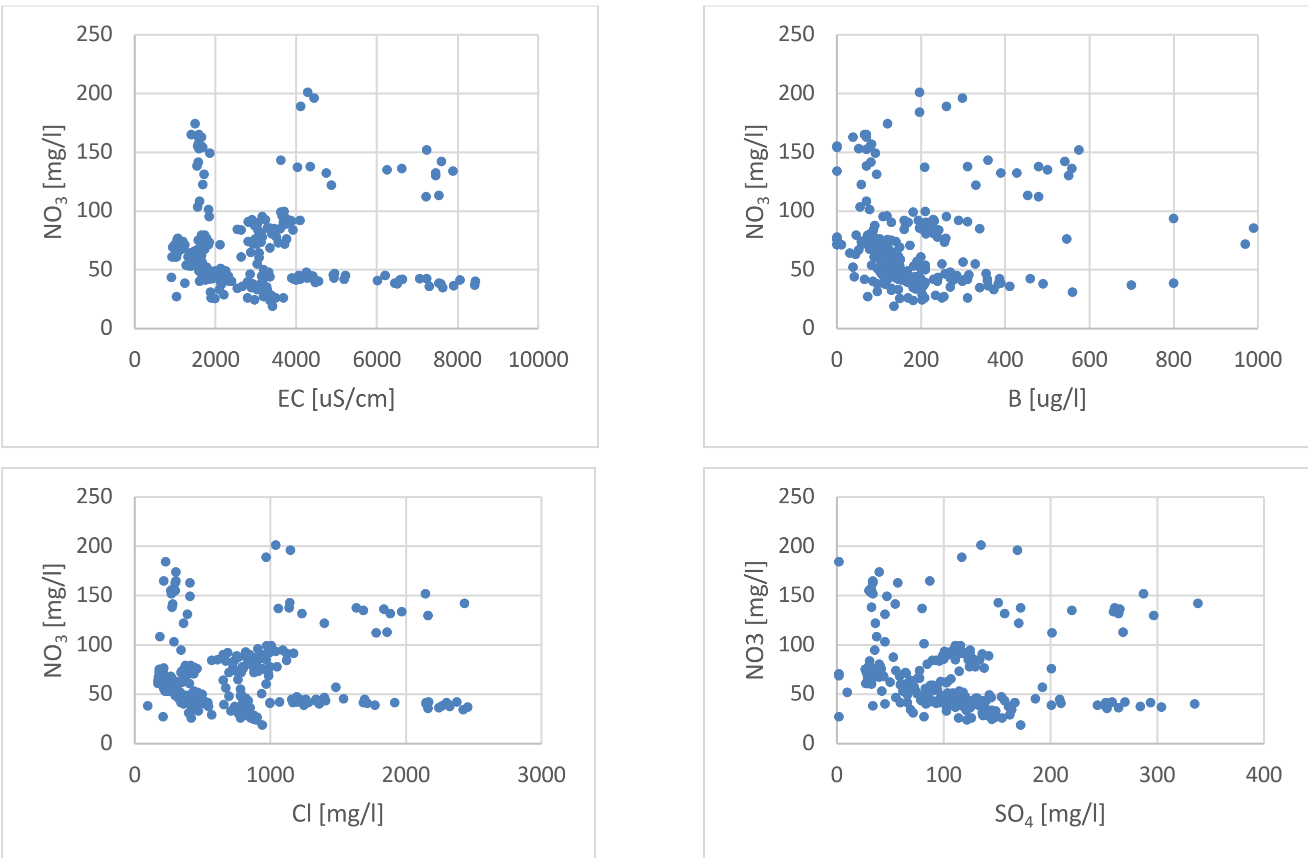


Figure 11: Averaged Nitrate (a) and Chloride (b) concentrations time series data obtained from OM undertaken through the MSLA monitoring network between 2009 and 2020. Legend: dataset trendline (black), threshold of nitrate (50 mg/l) and chloride (300 mg/l) established by Groundwater Directive for good qualitative status (red).

Bivariate correlations give a graphical representation of the likely impact of saline water mixing in the Malta MSLA. Visual inspection of figure 12 suggests that the majority of trace elements object of this analysis show little relationship to nitrate as all have some high values in samples with low nitrate. For all the other major components but nitrate it is possible to infer relationships with seawater encroachment given that most samples are close to the seawater mixing line ($Cl:SO_4=7.20$). However, it is worth to highlight that a clear linear relationship can be identified only through the relationship between Electrical Conductivity and Chloride.



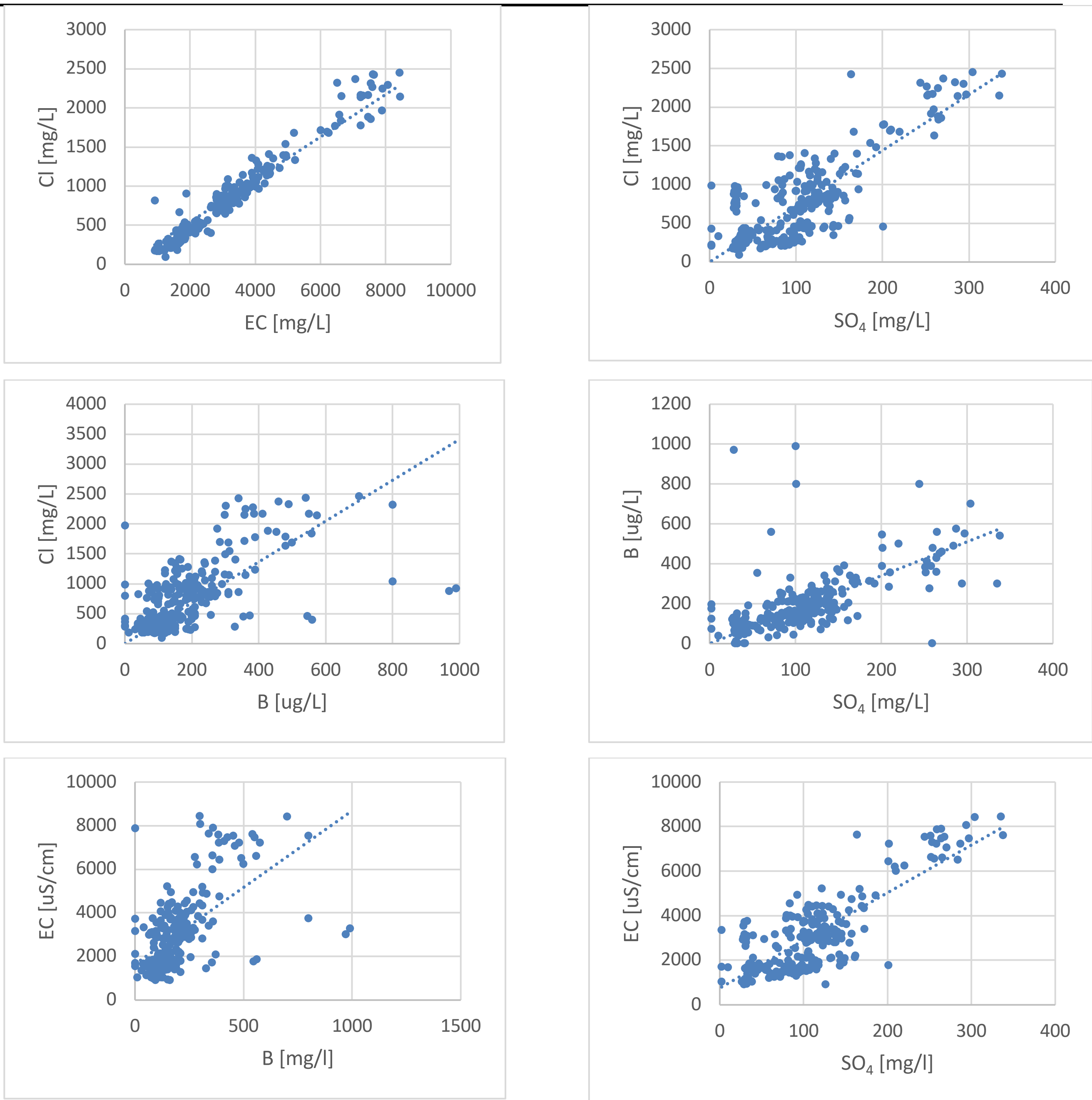


Figure 12: Crossplots of selected geochemical parameters with focus on groundwater salinization.

In accordance with BGS (2008), the spread of the samples around the trendline together with observed concentrations exceeding the value of seawater intrusion alone is likely to be due to a number of reasons:

- present in desalinated seawater used for water supply;
- present in infiltration affected by pollution;
- present in the aquifer matrix and mobilized over a long residence time.

The collection of historical and current quantity and quality data measured through gauging and monitoring boreholes in the Malta MSLA represent a valuable source of information which can be used to develop Numerical Models. Usually, such Numerical Models are deployed for identifying data gaps and/or develop scenarios of support for driving future water management decisions.

3.3 Two-dimensional flow model

The groundwater flow numerical model of the Malta MSLA was developed through the Life Project (LIFE 16 IPE MT 008) (Lotti et al., 2021) using the code MODFLOW-2005 by applying the modelling platform FREEWAT as user interface. Model calibration was performed through the highly parameterized approach coupling steady-state and transient stress periods. Highly parameterized (HP) groundwater models are characterized by having more parameters than those that can be estimated uniquely on the basis of a given calibration dataset, having more parameters than observations. With the advantage of obtaining a unique calibration from the HP family of calibrated models, regularized inversion was chosen. Regularized inversion problems are most commonly addressed by use of the code PEST in conjunction with pilot points as spatial parameterization device.

The Malta MSLA numerical model domain encompasses an area of about 500 Km^2 divided into about 105,500 cells of 50 x 100 m size and rotated by 53°. The model grid covers 216.6 Km^2 of aquifer surface (about 43,000 cells), 295.3 Km^2 of Mediterranean Sea (about 59,000 cells) while the northern area of the Island was defined as inactive in 15.8 Km^2 (3,150 cells). The main factor regulating groundwater flow in the case of the MSLA is defined by geometry of the aquifer and boundary conditions. The MSLA numerical model configuration can be presented as following:

(i) The net recharge was estimated applying the Thornthwaite method leading to the definition of a spatialized value of reference natural recharge represented by applying the RCH – Recharge package in MODFLOW. Enhanced recharge was applied where sinkholes and watercourses are present.

(ii) The sea level is represented by a third type condition (GHB – General Head Boundary package in MODFLOW). The conductance of GHB was subject to calibration leading to a value of 50 m^2/day.

(iii) The main faults in the MSLA are accounted by applying the HFB – Horizontal Flow Barrier package of MODFLOW. Conductivity was varied along the calibration process.

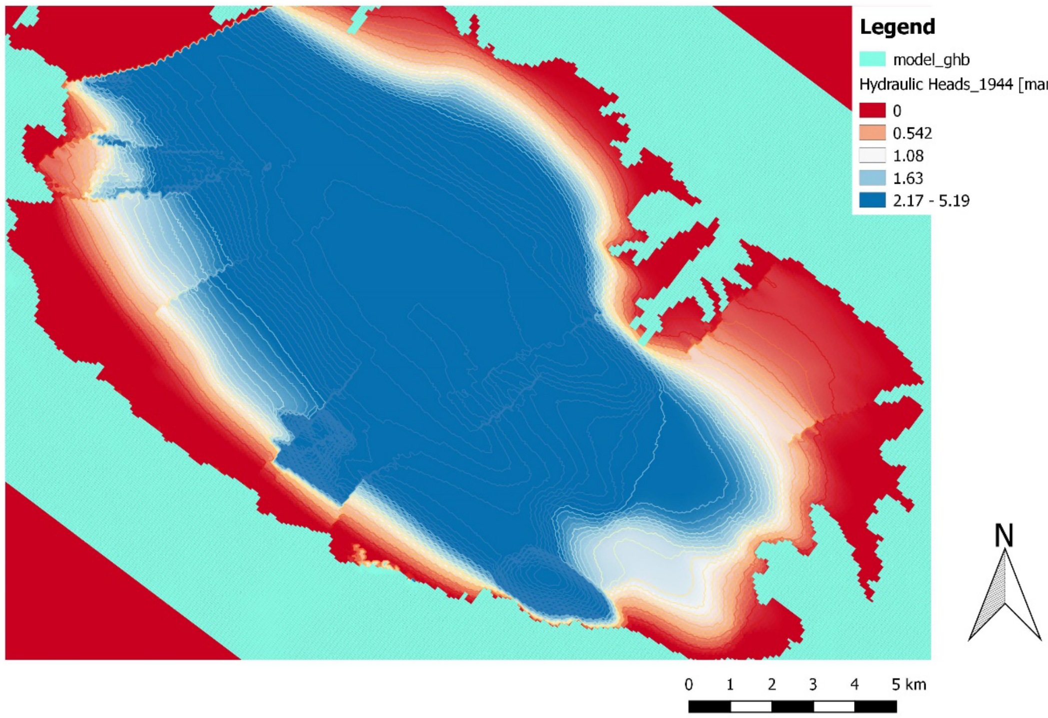
(iv) Water galleries, public abstraction boreholes and private wells are represented as the WEL package in MODFLOW.

(v) The water distribution network leakage (“water losses”) represents an additional amount of inflow and it was included as a series of injection wells, each one representing a cell that intersects with the water distribution network.

The availability of observed head and pumping data were taken into account for time discretization leading to a simulation approach based on 42 stress periods. The first group of stress periods (from 1 to 4) is simulated in steady-state conditions representing the unexploited conditions of the aquifer system, while the second group (from 5 to 18) and the third group (from 19 to 42) are simulated in transient conditions with a yearly and monthly frequency respectively.

Figure 13 shows the flow model outputs in terms of potentiometric maps of representative stress periods (SP1 (a), unexploited conditions and SP42 (b), current conditions). Results suggest a significant decrease of maximum hydraulic heads from 5.19 to 3.29 m amsl. The zones with low water level correspond to areas nearby the coastline approximately up to 2 km inland. Higher differences in hydraulic heads can be depicted in the centre of the Maltese Island likely due to the overexploitation of the groundwater body. Hydraulic mounds were simulated in two areas of Malta South-West. In any case, there are no reasons to infer that these regions are located in an area of preferential recharge and their anomalous levels can be explained by the stratigraphy logs of gauging boreholes drilled in these zones, where the presence of about 10m thick layer of clay laying at sea level was detected (unpublished drilling report, Government of Malta, 1985). Drilling investigations also indicated locally confined conditions of the aquifer system with groundwater levels first found at about 4.5 m below sea level and then balanced at about 8 m above sea level.

(a)



(b)

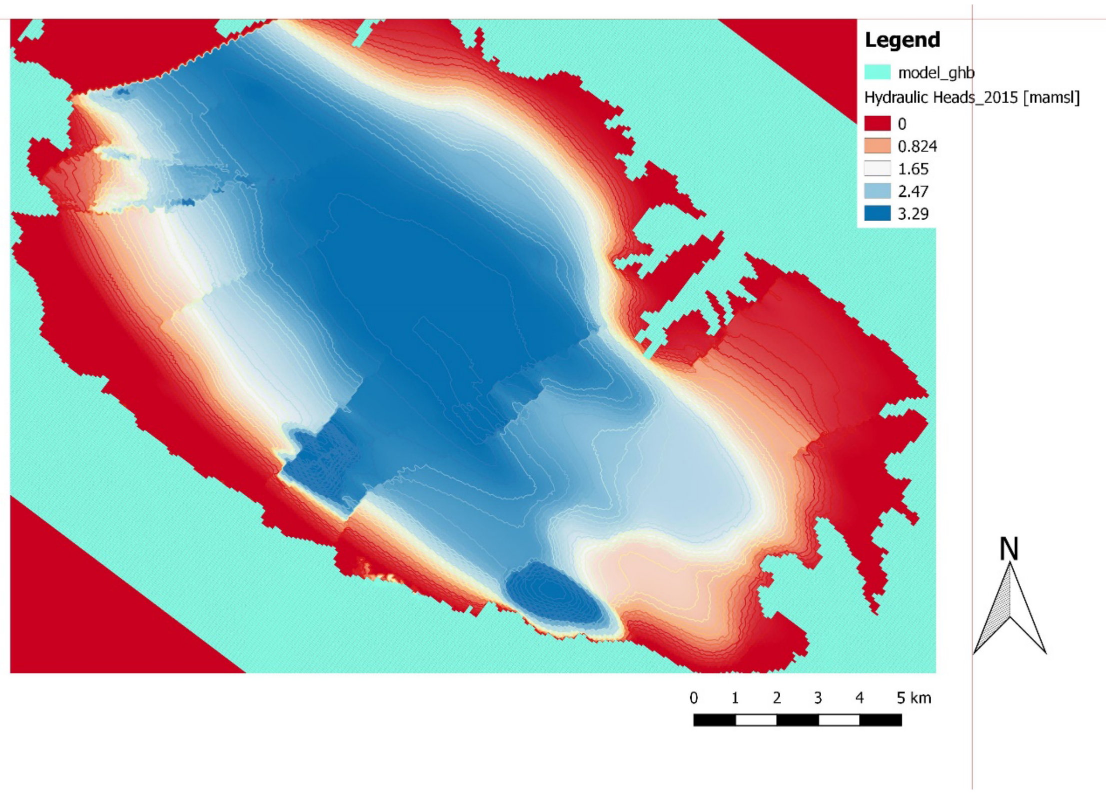
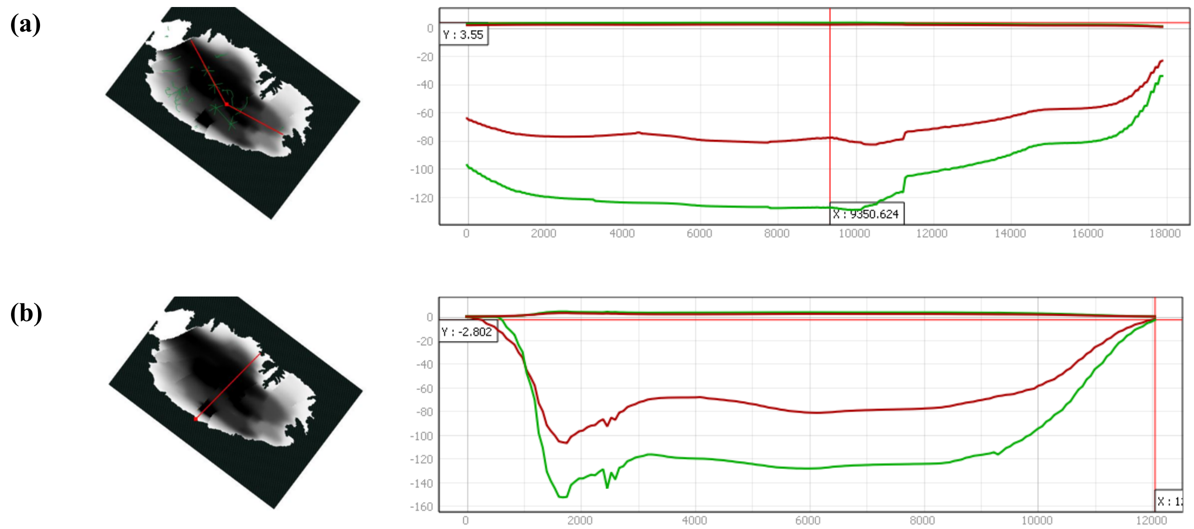


Figure 13: Simulated heads (m amsl): (a) stress period SP1 (till the 1940s), supposed to be the "unexploited condition" with no active pumping; (b) stress period 42 (till 2015). Potentiometric lines, equidistance = 0.1 m (m amsl) (modified after Lotti et al., 2021).

A first attempt to simulate the freshwater/seawater interface was performed using the code SWI2 (Bakker et al., 2013). The SWI2 package was coupled to the flow model and run. Results expressed a sharp interface were compared to the estimated position of the interface from four measured salinity profiles leading to a substantial difference with the simulated interface. This difference is so high to indicate a probable structural error of the model (Lotti et al., 2021).

A second attempt to model the third dimension of the MSLA flow model (i.e., the sharp freshwater/seawater interface of the freshwater lens system) was undertaken in this thesis by applying the Ghyben-Herzberg formula (equation (2)) which included a cell-by-cell calculation of the interface based on the transient results of the hydraulic head. This Semi-Analytical Approach seems to represent the best option to be used given frequent numerical instabilities of SWI2 in transient simulations and time-saving advantages of running times. Through figure 14 it is possible to infer a significant reduction of the groundwater availability equivalent to an average of the freshwater column loss of about 20 meters throughout the extension of the island/coastal aquifer if current conditions (Figure 14, red line, 2015) are compared to those corresponding to the simulated unexploited conditions (Figure 14, green line, 1940s).



Legend: 1940s fresh/sea-water interface; 2015 fresh/sea-water interface.

Figure 14: Cross sections (traces in left hand of this figure) with the comparison of SP1 (green) and SP42 (red) using the Semi-Analytical Approach.

Although of qualitative impact, saltwater intrusion needs to be tackled through quantitative measures namely by restoring sustainable yields of the groundwater body. The MSLA flow model offers opportunities to simulate preventive measures effects on the groundwater body. Nonetheless, modelling simulations can help to forecast undesired environmental impacts and therefore improving water management decisions in line with the thesis objective of assessing the feasibility of MAR implementation in the Malta MSLA.

3.3.1 Data gaps

Results of the MSLA flow model highlighted data gaps which need to be addressed and clarified. Data included quantitative and qualitative information, anomalies interpretation, ancillary information, narrations, etc., in the attempt to encapsulate all of them into the numerical model and maximize their information potential, according to the principle that evidence from independent and unrelated sources can converge towards the same conclusions.

In accordance with Lotti et al. (2021) a summary of the main relevant aspects to be considered is listed as following:

- The northern model boundary is assumed perfectly impermeable; this might not be true.
- SWI2 package (Bakker et al., 2013) revealed to have a high sensitivity to physical and numerical parameters included in its input data set. A proper process of calibration should include the available observation of piezometric heads, more information about Electrical Conductivity profiles and different hypothesis of domain aquifer bottom.
- More hydrodynamic tests shall be sought to recalculate the areal distribution of the hydraulic conductivity for calibration purposes (i.e., Jacob and Ferris, 1950 and 1951).
- The unconfined conditions should be better investigated, given that confined conditions could be generated by the fractured nature of the aquifer.
- Presently available data is missing the values of the bicarbonate anion (HCO_3^-) which precludes from performing any kind of processing such as ion balance, piper diagram, stiff diagram, etc., which are essential to check the quality of data and define the different water facies present in the Malta MSLA.
- Specific attention should be dedicated to the water galleries, which constitute the major source of water of the island; an appropriate monitoring network would include daily record of abstracted volumes, the correct geometry and elevations of the tunnels, record of hydraulic heads, Electrical Conductivity, and discharge at the end of each gallery, associated with a periodical monitoring of the punctual outflows from the main fractures along the tunnels.
- More head measurements in the Perched Aquifer, which plays a dominant role in recharge spatial distribution of the MSLA.
- In several groundwater level time-series it is possible to detect the sudden recharge operated by rainfall. Each impulse is composed by two shifted peaks, the first (high and thin) due to the fast flow through the fracture networks, the second (lower and wider) due to the water flow in the compact rock matrix. A method could be developed to perform a spectral analysis (e.g., Balacco et al., 2022), since the "footprint" of aquifer properties on water flow is reflected into hydrological signals, such as head variations.

The groundwater monitoring network can take advantages from the data collection and analysis for developing the flow model, together with the outcomes of the numerical model itself, to intensifying the future monitoring efforts on specific issues. This is in line with the thesis objective of optimizing the existing MSLA monitoring network to validate positive impacts of MAR schemes.

4 Hydrogeological modelling of a seawater intrusion barrier in the MSLA

4.1 Feasibility of MAR in the freshwater lens system

The evaluation of the suitability of a MAR scheme to stop further depletion of the Malta groundwater resources was based on the assessment of current social and local environmental settings. Due to fast urbanisation, water demand is rising rapidly while securing a safe drinking water supply becomes a challenge. This is the case of Malta where the urban area encompasses about the 33% of the 316km^2 islands areal extension due to increased land consumption in the last 40 years (SEWCU & ERA, 2015). Together with soil consumption, high evapotranspiration rates typical of semi-arid regions compromise the implementation of typical MAR schemes such as infiltration spreading methods (Table 1). To overcome the quantitative and qualitative challenges related to water management of the country, mitigation and adaption measures suitable for the site-specific conditions of Malta are needed to compensate the effects of groundwater exploitation associated to saltwater intrusion into the freshwater lens system.

Previous studies in the literature have proposed several countermeasures to prevent or mitigate seawater intrusion; among these, has been the installation of subsurface barriers, which can be of hydraulic or physical nature (Abarca et al., 2006; Oude Essink, 2001). In general, a hydraulic barrier works injecting freshwater into the aquifer to raise the water table, which impedes the inland motion of the saltwater (Abdoulhalik et al., 2017) (Figure 15).

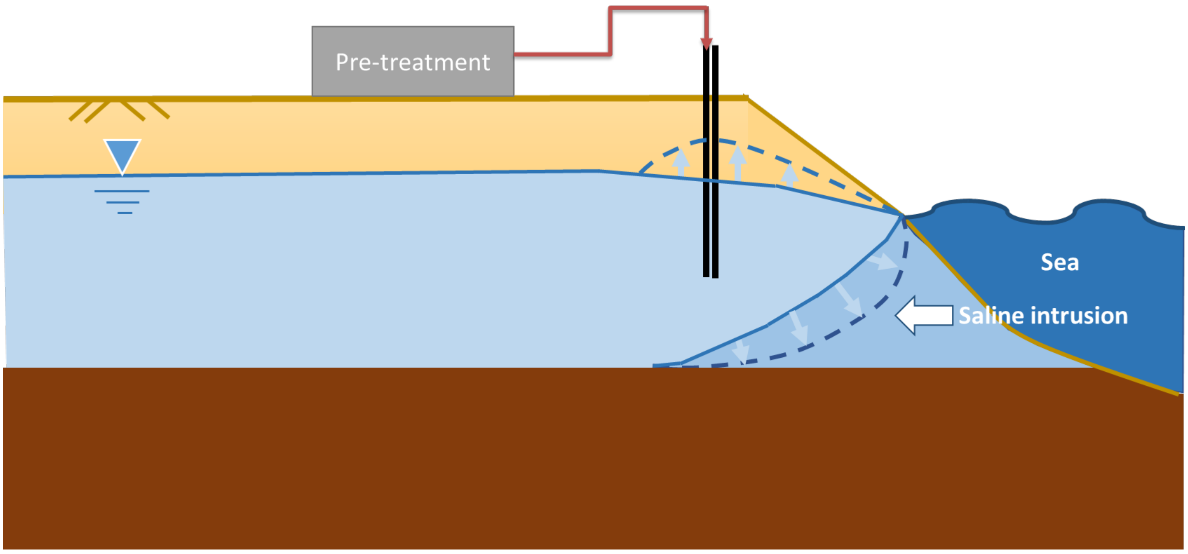


Figure 15: Simplified conceptual diagram showing an injection borehole hydraulic barrier in a schematic coastal aquifer.

To stop the advance of the seawater intrusion, a hydraulic barrier was constructed in 2007 in Llobregat delta aquifer (Spain) by injecting reclaimed water in 14 wells near the coast. Positive qualitative impacts were monitored in the surrounding of the aquifer which showed a progressive decrease in the amount of chlorides, sodium, calcium magnesium and ammonium, and a slight increase in nitrates, which are present in the injected water (Ortuño et al., 2010). Seawater intrusion barriers consisting of injection wells and using recycled water have protected the coastal groundwater basins in Southern California guaranteeing Orange County with a reliable, drought-resistant, locally controlled supply of water of the highest quality (Herndon and Markus, 2009). In the Ezousa coastal aquifer (Cyprus), the construction of a dam reduced natural recharge of the aquifer inducing the saltwater intrusion phenomena. Pollutants were attenuated recharging into the aquifer treated effluents from a wastewater treatment plant through a number of artificial ponds (Christodoulou et al., 2013).

More complex solutions to mitigate the impact of saltwater intrusion use subhorizontal designs. Subhorizontal tapping schemes have been realized using tunnelling and/or boring in combination with wide-diameter wells or shaft (Polemio and Zuffianò, 2020). In Malta, a total length of 36 Km has been bored at the centre of the MSLA in between 1940s and 1970s to improve the regulation of the discharge rate and of salinization due to control of tunnel water head (Micallef et al., 2004). These radial drainage galleries convey drained groundwater with a geodetical gradient towards pumping stations accounting for the production of about 10 million m^3/year of freshwater. However, pumping stations need to be shut down for some months when chloride concentrations in the withdrawal groundwater exceed threshold values established by the Water Services Corporation of Malta. With the aim of limiting evapotranspiration losses by preventing land consumption, a novel MAR network is proposed in this thesis for the site-specific conditions of the Malta MSLA. The MSLA MAR network (Figure 16) shall be implemented with an underground infiltration gallery located in the centre of the Island surrounding the drainage galleries and coupled with an injection boreholes array in Malta South-East. The infiltration galleries would be drilled through the aquifer's unsaturated zone using Horizontal Directional Drilled Wells (HDDW). In the construction of an HDDW, a filter pipe is introduced into an aquifer through horizontal directional drilling. The source of water for MAR shall be sought through highly treated wastewater, locally called New Water. New Water is treated wastewater thoroughly filtered using a tertiary treatment process. This results in the production of high quality water which is safe for the environment. New Water has been originally created for agricultural reuse purposes (SEWCU & ERA, 2015), therefore, the enhanced recharge to the aquifer shall be operated during winter seasons when water demand for agriculture is low. The effective impact of the hydraulic barrier consisting of an injection boreholes array can be maximized if the water is injected at the toe of the saltwater wedge (Luyun et al., 2011).

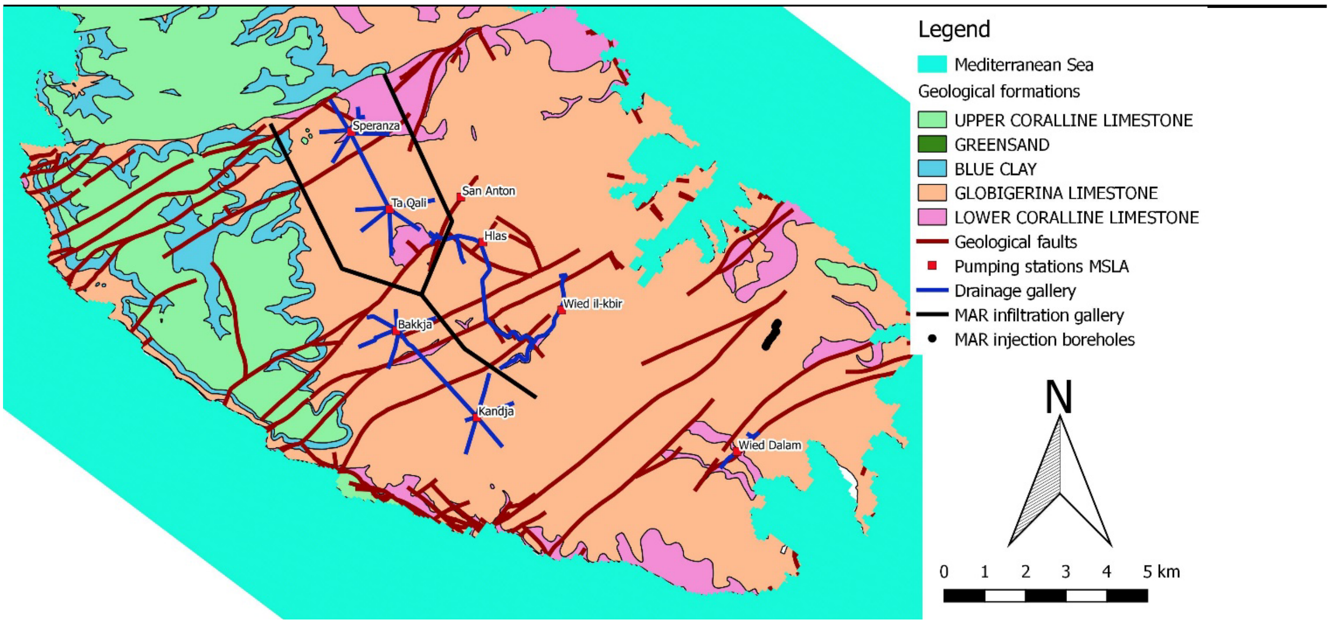


Figure 16: MSLA lithological map with operating pumping stations, drainage galleries, and proposed MSLA MAR network.

4.2 MAR network scenario

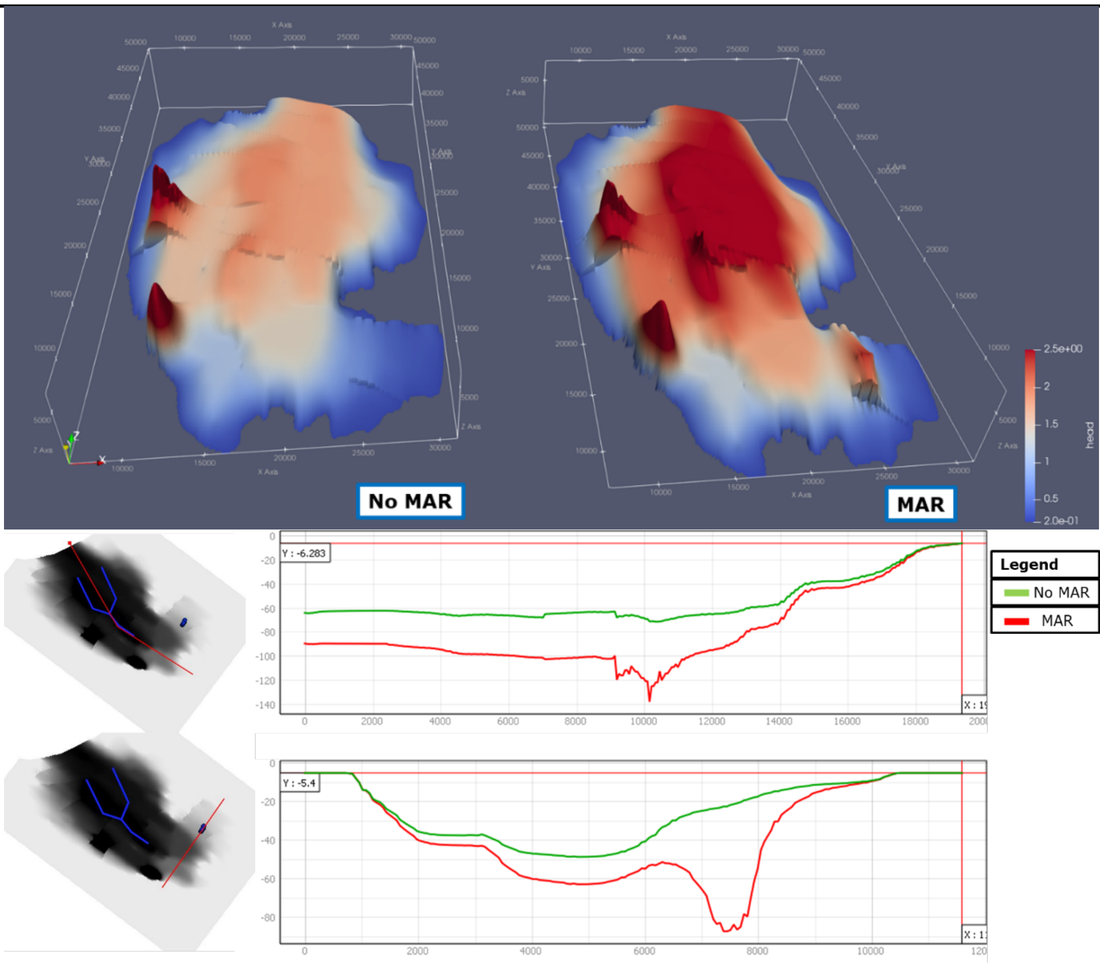
The feasibility of the MSLA MAR network was analysed by simulating the scenario of full implementation of MAR. After calibrating and running the model, several scenarios of MAR implementations and configurations were simulated leading to the following optimal MAR scheme configuration for the MSLA (figure 16):

(i) The underground infiltration gallery should be drilled in the middle of the Maltese Island with maximum injection flow rates of New Water equal to 29,000 m^3/day during the wet seasons. The enhanced recharge is represented by applying the RCH package simulating a specified flux distributed over the intersected cells and specified in units of length/time.

(ii) The injection boreholes array should be located in Malta South with maximum injection flow rates of New Water equal to 1,000 m^3/day into ten boreholes. The enhanced recharge is represented by applying the WEL package simulating the specified flux to defined cells in units of $length^3$/time.

Figure 17 (a) shows that the injection flow rates distributed along the infiltration gallery are adequate to restore unexploited conditions of the groundwater body by increasing hydraulic heads from 2.5 m amsl up to 5 m amsl, hence generating increased groundwater availability for the drinkable and agricultural supply of the Maltese Island. Nonetheless, the diffused infiltration occurring with this MAR design would generate benefits in terms of groundwater storage in a large area of the aquifer system. On the other hand, the localized injection of New Water in Malta South through the injection boreholes array would generate localized hydraulic mounds halting seawater ingression by pushing down the fresh/sea-water interface (figure 17 (b)). The location of the injection boreholes array is therefore suitable to repulse seawater intrusion from the Mediterranean Sea generating a hydraulic barrier protecting further depletion of the inland groundwater zones.

(a)



(b)

Figure 17: (a) Simulated heads (m amsl) comparing the "No MAR scenario" or current conditions (top left) with the "MAR scenario" or full implementation of MAR (top right). (b) cross sections (traces in bottom left hand) with the comparison of the No MAR scenario (green) and MAR scenario (red) in both longitudinal and transversal directions; with the latter crossing the injection boreholes array.

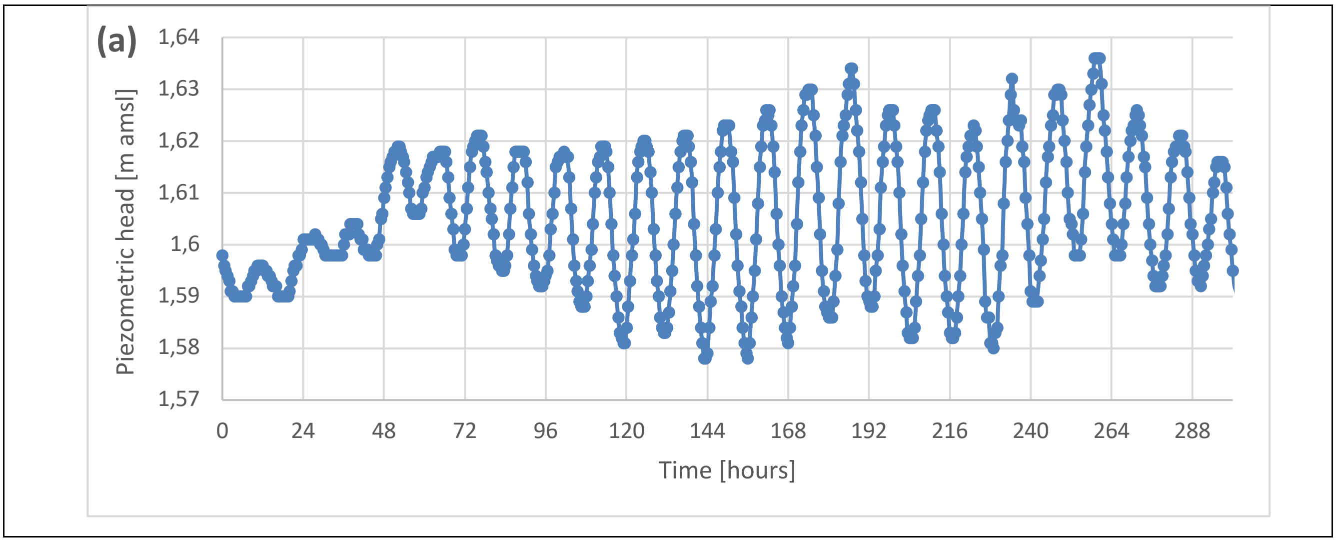
The preliminary assessment and modelling of the MSLA MAR network carried out as part of this research are indicative. It is recommended that these results are not considered as final given the presence of a number of modelling uncertainties and data gaps which are known to affect the performance of the simulated scenario. Therefore, it is proposed that additional modelling is carried out once the data gaps identified as part of this research are addressed to improve the conceptualization of the Malta MSLA. Data gaps need to be tackled and model predictions should be improved based on up-to-date monitoring data..

5 Estimation of equivalent transmissivity at the aquifer scale

5.1 Tidal attenuation analysis

With the objective of improving calibration tools through numerical modelling, the determination of additional hydrogeological parameters was sought by analysing tidally induced groundwater level fluctuations in those gauging boreholes in which hydrodynamic tests were never undertaken. The tidal attenuation method has been applied on groundwater levels recorded on nine boreholes monitoring the quantitative status of the MSLA exhibiting piezometric fluctuations induced by sea-tides for a 3 month period from 1st May until 31st July 2011. The analysed time period was chosen because it follows the summer season usually characterized by a lack of rainfall (figure 9 (b)). On the other hand, a number of monitoring boreholes were removed from the analysis because they were highly impacted by abstraction wells laying within their radius of influence. Only the analysis of Madliena borehole between the 1st and 13th of May 2011 (300 hours time-series) is shown in this work because of its low amplitudes, despite its position at short distance from the shoreline, compared to the other monitoring boreholes. The same considerations explained hereunder can be outlined for the other monitoring boreholes subjet of this study.

The Madliena dataset used for the purpose of this study is shown in Figure 18 (a) whilst the Portomaso sea tides dataset is shown in Figure 18 (b).



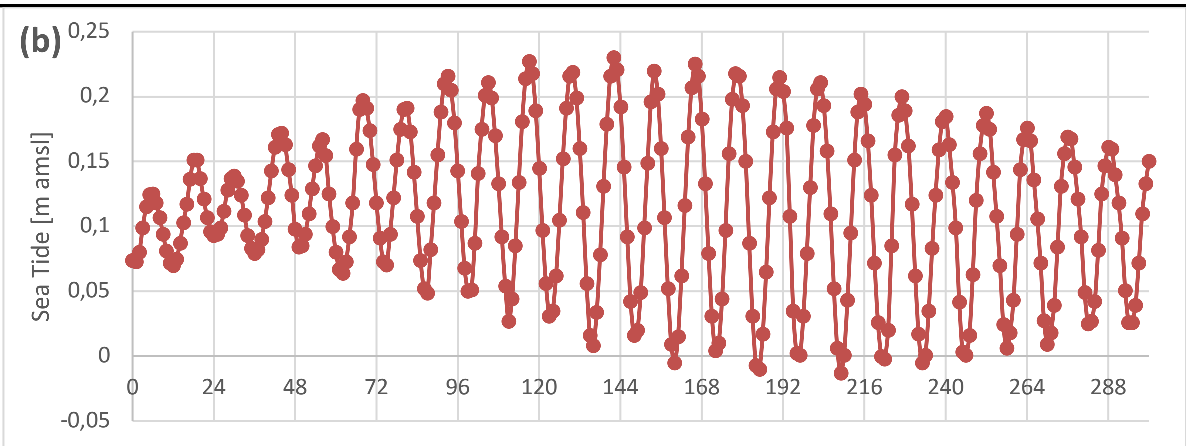


Figure 18: (a) observed groundwater level fluctuations in Madliena monitoring borehole; (b) observed sea tides in Portomaso sea gauge.

Although the observed piezometric signal is clearly affected by external driving forces, diurnal and semidiurnal fluctuations induced by sea tides can be inferred.

To enable separation of the effect of tidal components on the water table fluctuation from the available time series, FFT is applied and a cut-off range from 1.8 to 2.2 waves/day is selected (figure 19).

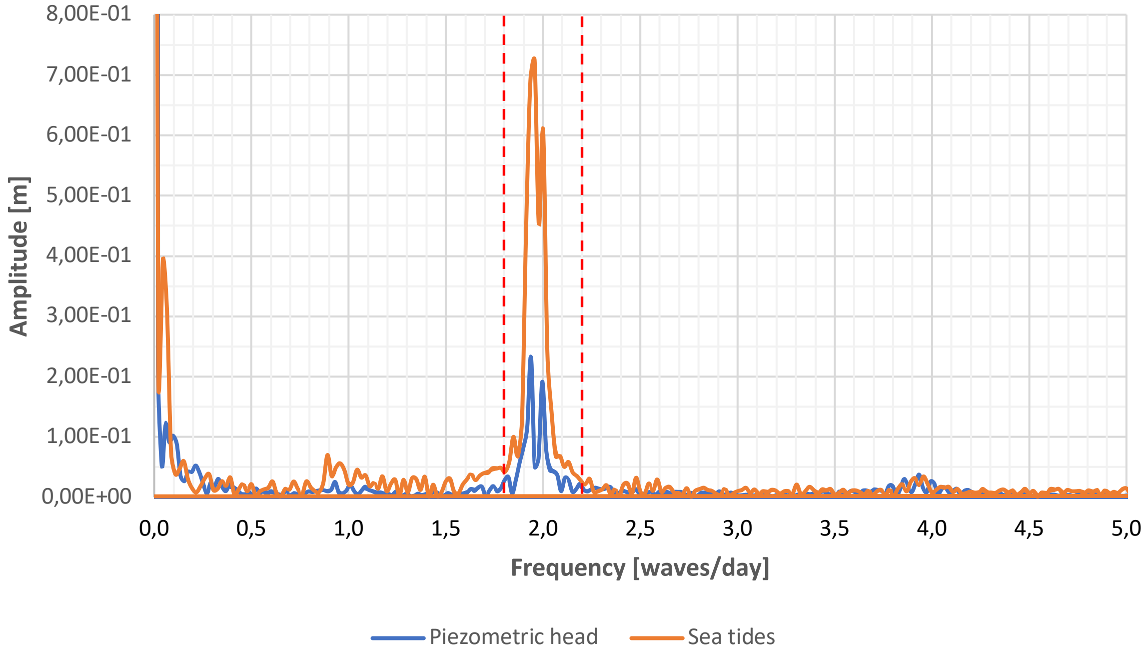


Figure 19: Plot of piezometric heads of Madliena borehole and sea tides in spectral domain; the cut-off frequency range is shown in red dashed lines.

Figure 19 highlights two peaks of amplitude in correspondence of the frequency of two waves per day of both the piezometric head and the sea tides dataset, thus, emphasizing the connection between the aquifer and the sea.

Subsequently, we obtain the detrended and scaled to zero signals for both hydraulic head and sea tides by applying the Inverse FFT (figure 20 (a)) and the reproduced water level signal amplified by the TE and shifted by a time equal to ΔT (figure 20 (b)).

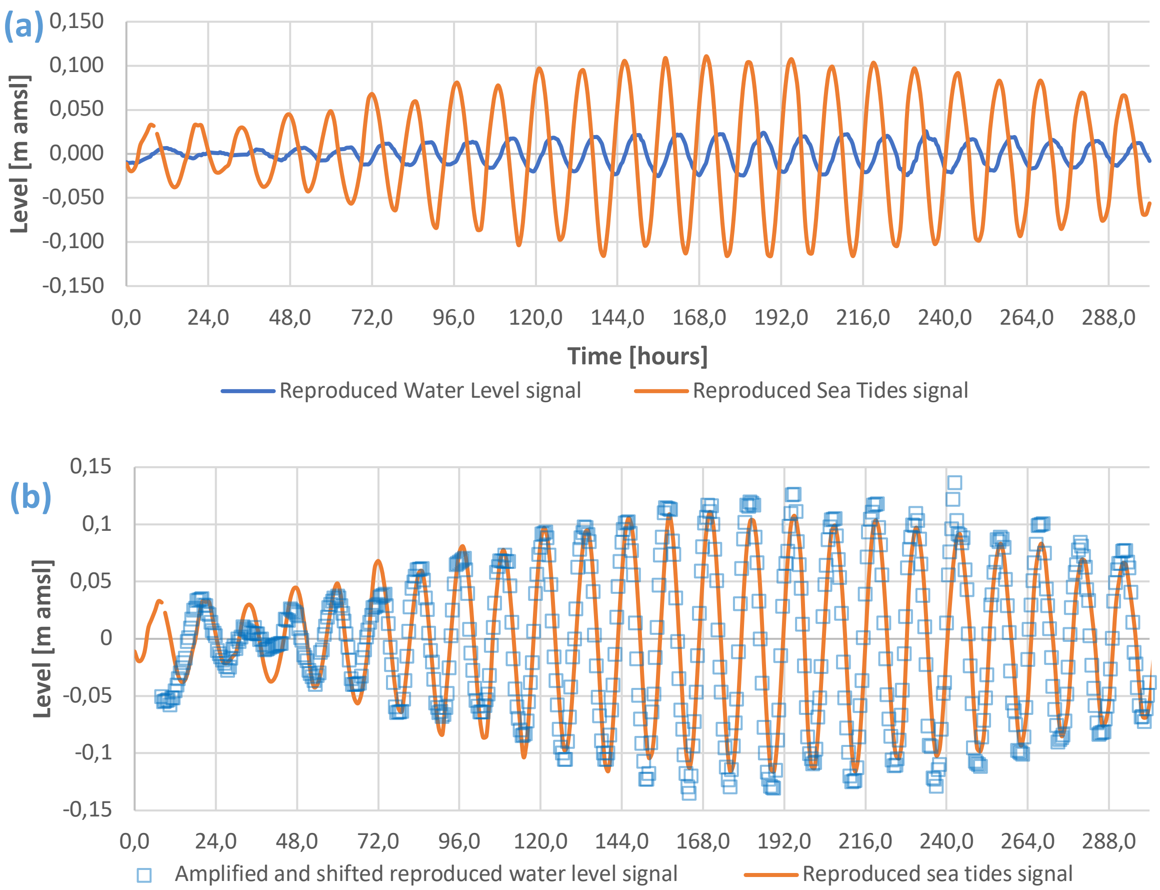


Figure 20: Reproduced water levels and sea tides signal obtained by applying the inverse FFT on the selected frequency range of the spectras from 1.8 to 2.2 waves/day (a) and reproduced sea tides signal plotted with the reproduced piezometric signal amplified by TE and shifted by ΔT (b).

Through figure 20.(a) we can notice the largest amplitudes characterizing the sea level and mixed semidiurnal character for both the reproduced signals. The 14-day envelope is retained in the reconstructed signals as it is encoded in the spectra seen in figure 8 as a splitting of the peak centred around 2 waves/day. Piezometric head observed in Madliena shows lower amplitude and temporal delay in peak values compared to the sea level signal. These two main differences can be explained as the aquifer diffusivity filtering effect to hydraulic heads observed inland from the sea level boundary condition. Moreover, it is possible to assess the time-lag by shifting over time-span the reproduced signal of piezometric head. The evaluation of this time-lag was conducted by observation and matching of the two signals. A more rigorous approach for the determination of the time-lag between the two signals was attempted using cross-correlation. The cross-correlation of the two signals was obtained and the result was then scaled using the autocorrelation of a rectangular signal of the same length. In theory, the maximal value of the scaled cross-correlation function should yield the time-lag between the two signals, as it occurs at the lag where the two signals are most similar. The results were inconclusive for the data analysed, and therefore, a result for the time-lag based on expert knowledge was considered as more appropriate.

Following reproduced signals of detrended and filtered sea level and hydraulic head, the Jacob-Ferris methodology is applied for each sine wave of the dataset characterized by specific amplitude and period with a manual peak-to-peak detection of sea tide and induced groundwater level oscillation. Tidal attenuation analysis undertaken on the three months time-series of Madliena water level fluctuations dataset leads us to calculate a number of 114 values of the sought hydrogeological parameters which is lower than the expected number of values within the three months time-series because of data gaps in both the groundwater level and sea tides dataset.

Average values of hydraulic diffusivity, transmissivity, saturated thickness and hydraulic conductivity for the analysed monitoring boreholes are shown in table 3.

Table 3: Average values of calculated hydrogeological parameters determined from the tidal attenuation method.

Borehole name	ID	Locality	Distance to the sea [m]	D [m2/s]	T [m2/s]	b [m]	K [m/s]
Noqra Lane	10240	Birzebbuga	260	7	2.8E-04	14	2.1E-05
Madliena	10093	Gharghur	1100	29	1.5E-03	61	2.4E-05
Halt Miem	10353	Zejtun	1680	78	3.9E-03	92	4.3E-05
Karwija	10097	Safi	2600	221	1.1E-02	57	1.9E-04
Wied Busbies	10371	Rabat	2675	139	6.9E-03	78	8.9E-05
Barrani	10366	Ghaxaq	4500	323	1.6E-02	72	2.3E-04
Wied Sewda	10225	Attard	4600	685	3.4E-02	77	4.4E-04
Mosta Road	10075	Mosta	5150	4,431	1.6E-01	72	2.2E-03
Buqana	10035	Mosta	7750	1,069	5.3E-02	86	6.2E-04

Due to the high anisotropy and heterogeneity entailed in the aquifer system, a relationship between hydrogeological parameters and distance to the sea cannot be identified except for hydraulic diffusivity. Indeed, the methodology considers the regional conditions of the aquifer encompassed within the distance between the sea and the monitoring borehole under investigation. On the other hand, pumping tests usually obtain local hydrogeological conditions and represent an expensive solution if compared to installing a water level device into a suitable well for tidal responses.

Hydraulic diffusivities estimated from tidal water level data in monitoring boreholes near the coast yielded one less order of magnitude values than those estimated in monitoring boreholes within 2 and 5 km away from the coastline and two lower than those located at a distance greater than 5 km from the shoreline.

In general, calculated mean transmissivity values range from 2.8E-04 to 1.6E-01 m^2/s. The wide range of variability of transmissivity was expected due to the different geological formations depicted in the MSLA of Malta and the numerous impermeable faults either sealing or reducing the bodily continuity between groundwater body and the Mediterranean Sea.

Finally, the calculated transmissivity values are joint to the ones derived from pumping tests interpretation (figure 21). This was done with the aim of spatially analysing the entire dataset and developing the transmissivity spatial distribution and its uncertainty map through the use of semi-variograms.

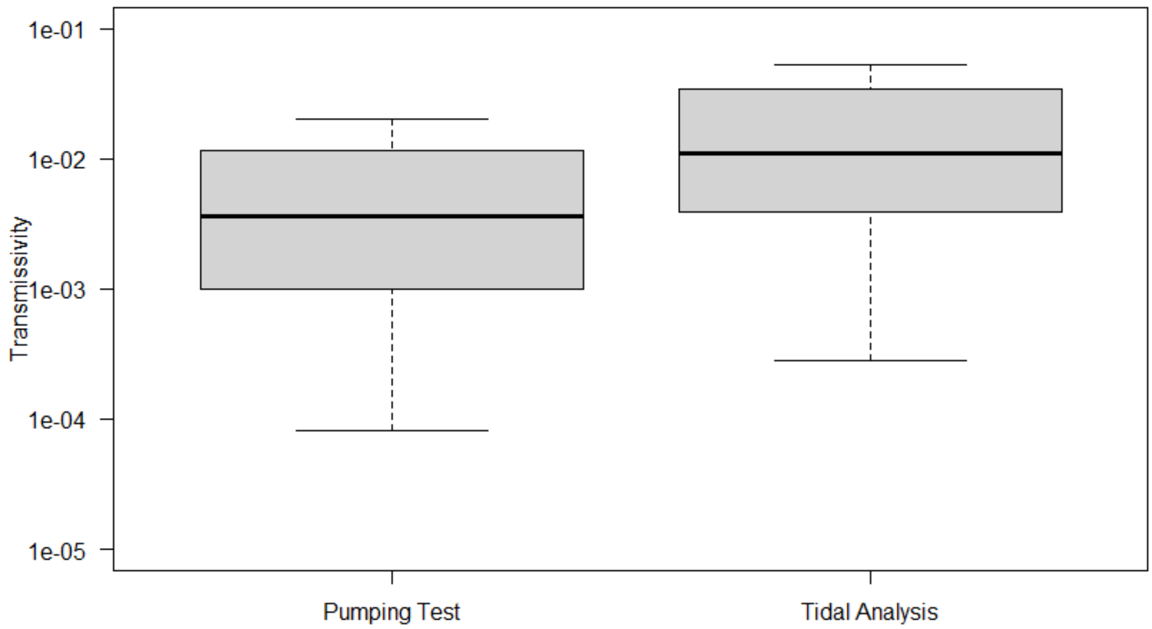


Figure 21: Comparison of calculated transmissivity values from pumping tests interpretations and tidal attenuation method through Box and Whisker plots.

Figure 21 highlights a shift equal to about half order of magnitude of average transmissivity between Pumping Tests and Tidal Attenuation method, the latter is slightly larger than Pumping Tests. This may be associated to two main reasons: (i) the Jacob-Ferris methodology assumes a sharp boundary subject to oscillating force, therefore, part of the energy transmitted from the sea boundary is naturally dissipated through the transition zone damping the actual signal recorded in monitoring boreholes; (ii) while Pumping Tests lead to an assessment of transmissivities in the area surrounding the borehole, the transmissivity values calculated with the Tidal Attenuation method represent an average value of the geological formations crossed from the coastline to the monitoring point.

5.2 Geostatistical analysis

Figure 22 shows frequency distribution and normal probability plot of transmissivity in real space and in normal space, with parameters listed in Table 4. The gaussianity of the Normal scores transformed transmissivity values was verified and the Normal score transform of the dataset is therefore acceptable.

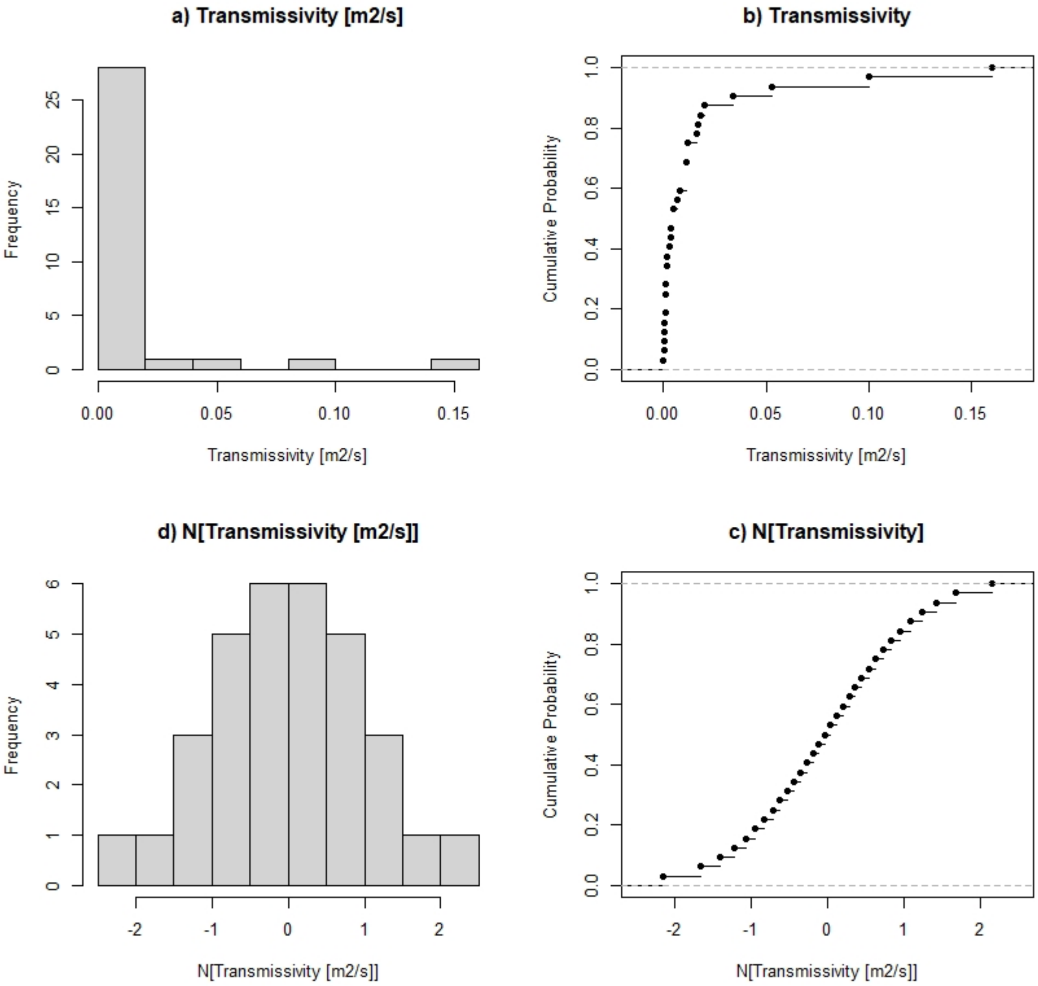


Figure 22: (a) Frequency distribution of transmissivity raw values; (b) cumulative probability plot of transmissivity raw values; (c) normal-probability plot of normal scores transformed values of transmissivity; (d) frequency distribution of normal scores transformed values of transmissivity.

Figure 22 shows omnidirectional empirical variograms of the normal scores transformed transmissivity calculated with a lag-distance of 1.3 Km through a spherical model. The figure leads us to understand that the dataset is not very autocorrelated and does not allow us to fit the variogram model with a small nugget which obviously generates relatively high levels of semi-variance.

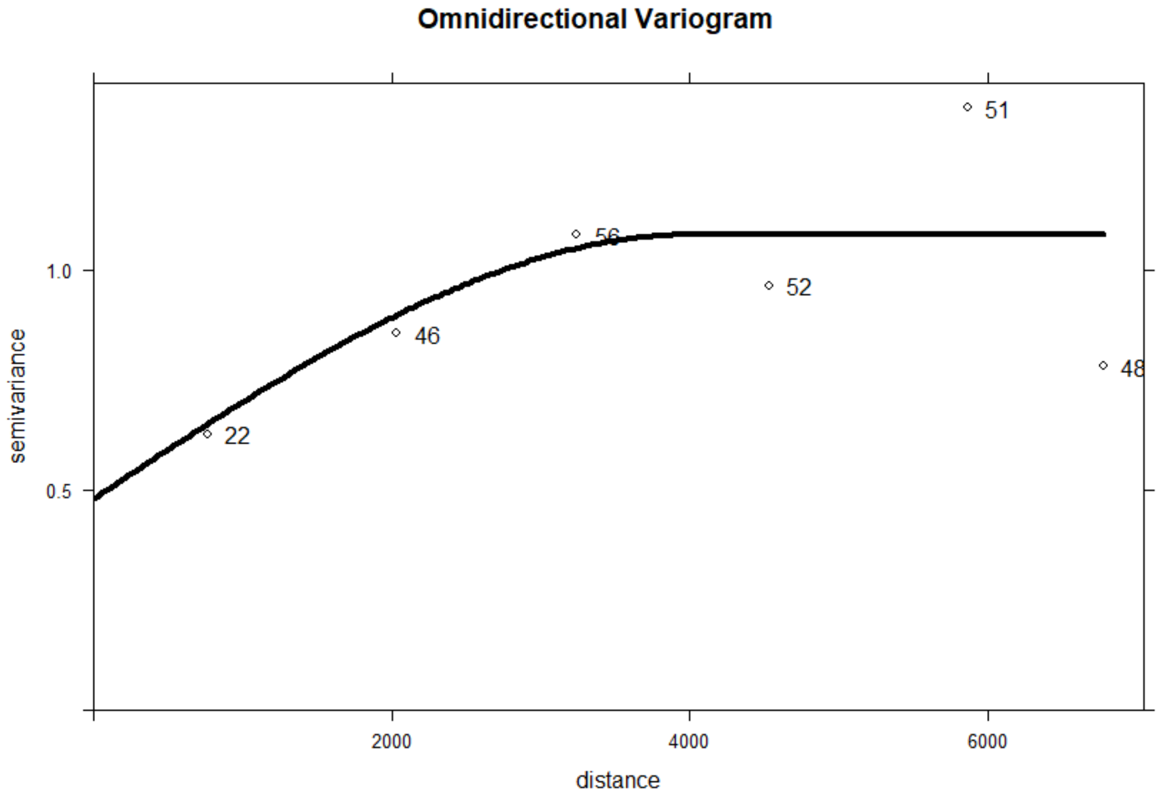


Figure 23: Omnidirectional variogram fitted with directional spherical model variogram by cross-validation.

A preferential isotropic direction (N135 or NW-SE) was assessed through hydrogeology expertise on the study area based on the main fault system strike and shape of the island. Afterwards, a directional variogram was calibrated. Restricted maximum likelihood was used to fit the directional variogram models resulting in model parameters as listed in Table 4.

Table 4: List of estimated geostatistical parameters of the transmissivity of the MSLA of Malta.

Parameter	Symbol	Units	Value
Mean	μ	m^2/s	0.016
Variance	σ^2	-	0.001
Nugget	n	-	0.48
Sill	s	-	0.60
Range	r	m	4005

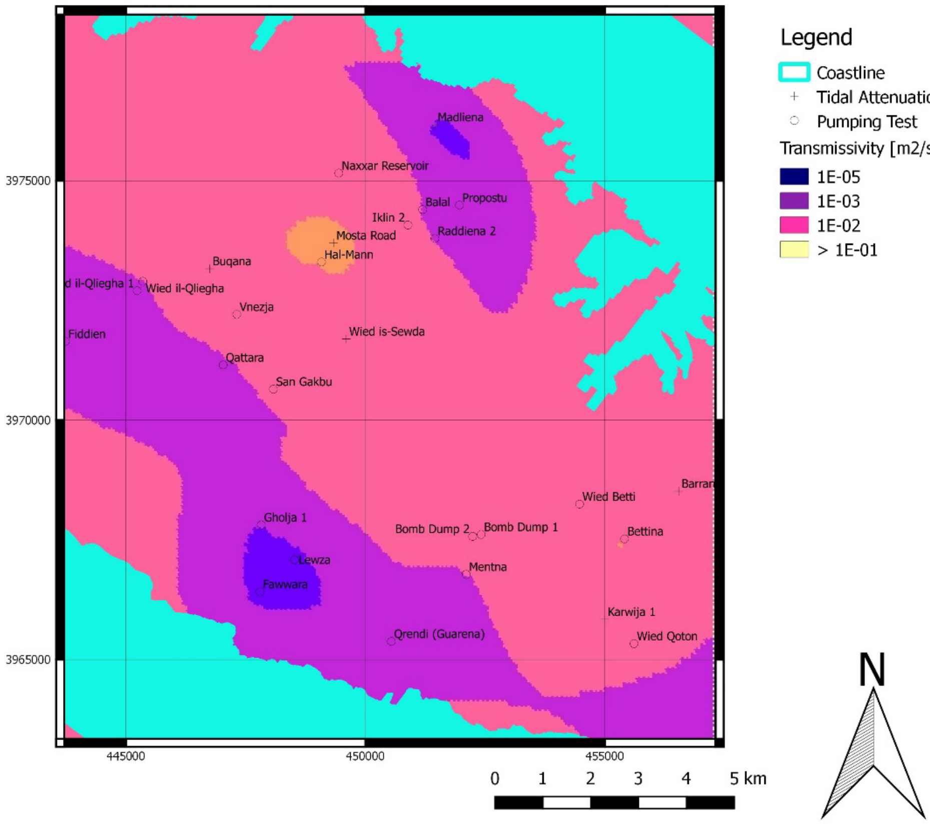
The range indicates that the transmissivity is spatially correlated over a distance of approximately 4 Km. The nugget represents about the 80% of the sill and can be attributed to measurement errors, high heterogeneity and anisotropy entailed by the aquifer system carbonate in type and inconstant sampling distance. The average of the standardized errors of the omnidirectional variogram is 0.052 and the variance is 1.029 which indicate the validity of the variogram model.

Figure 24 shows the spatial distribution map of the transmissivity of the Malta MSLA obtained by Ordinary Kriging interpolation and the associated error map with the spatial distribution of the kriging variance divided by the sample variance.

5.3 Equivalent transmissivity spatial distribution map

The geological structure of the aquifer system at the sea level shows the succession of two main formations: Globigerina Limestone (GL) and Lower Coralline Limestone (LCL). The LCL is found at the sea level in the middle part of Malta where the highest values of transmissivity are assessed.

(a)



(b)

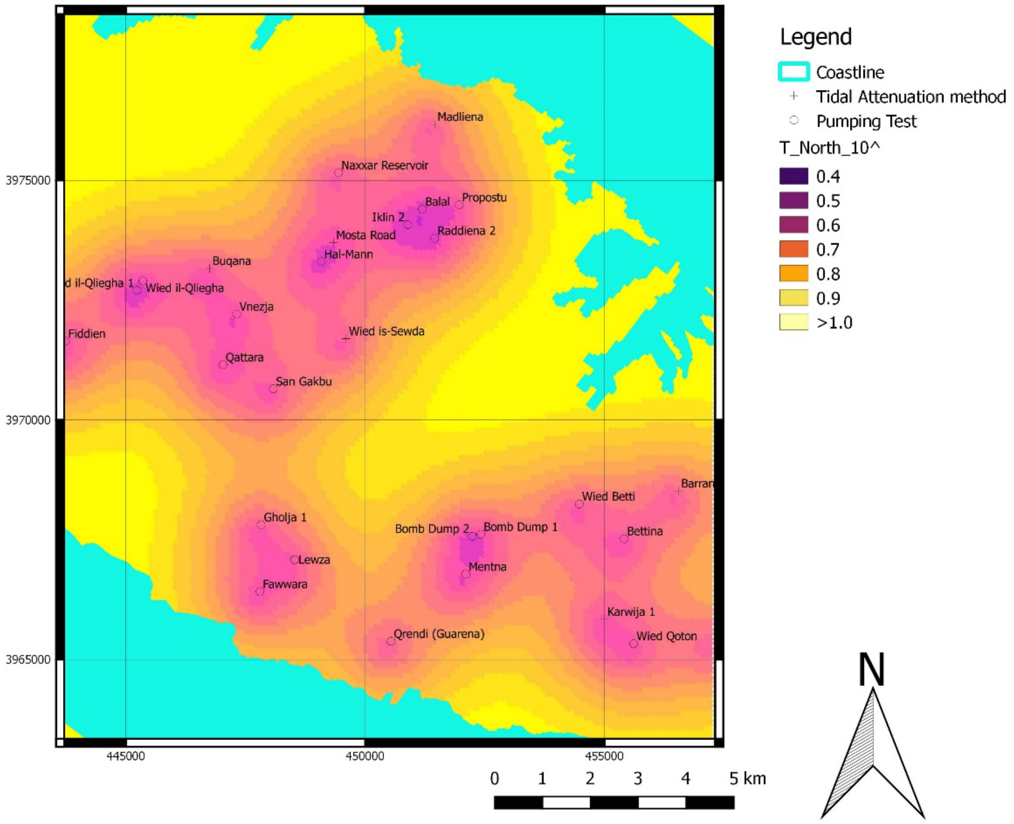


Figure 24: Map with the spatial distribution of the transmissivity of the Malta MSLA obtained by Ordinary Kriging interpolation (a) and the corresponding error map showing the spatial distribution of the estimated kriging variance divided by sample variance (b).

The LCL highly permeable formation dips below the sea level towards East (BRGM, 1991), therefore, the GL formation takes place at the sea level originating low transmissivity values typical of the compact limestone formation. The Western part of the island shows the lowest values of transmissivity despite the presence of LCL: this is because the overlying Blue Clay (BC) formation which gives birth to the Perched Aquifer (PA) allows a relative low infiltration to the MSLA. Hence, fine grain materials of BC fill the fissures of the LCL inducing a decrease of transmissivity. However, clay infilling is not only encountered under the PA but also to the East. The difference between the two regions may be explained by the fact that not all the fissures encountered in the Eastern side are filled with fine grain materials. Another theory that will be further investigated, is related to the origin of clay infilling. While the clay infilling on the west side originates from percolation through the BC layer, the one found in the East mainly originates from carbonate dissolution. Two high transmissivity regions can be identified; in the North where the Mosta Road borehole is located and, in the South, at the site of Bettina borehole. The latter suggests undertaking further analysis of transmissivity in this region might be useful, because the actual extension of this highly permeable area cannot be computed by geostatistical means due to lack of sampling data. The two individual high transmissivity peaks are separated by the Hamrun syncline which is responsible for the deepening of the top of the LCL below the sea level in the Valletta graben. In spite of the existence of the LCL above the sea level, in the middle part of the island and in between the two peaks of high transmissivity, the low transmissivity values may be either the result of faults acting as semi-pervious barriers or the result of a lack of data in this region. Moreover, the existence of numerous faults breaking the quasi-horizontal attitude of the formations in the West coast, lead to highlight potential permeable pathways leaving the aquifer, thus inferring that faults are not impermeable throughout their extension. The highest values of transmissivity found in Bettina and Mosta Road lead us to understand that the mentioned boreholes have been dug through the most permeable member of the LCL formation, locally called Attard member. However, since nothing is known of the vertical and horizontal extension of the Attard members of the LCL formation or about their interconnection (BRGM, 1991), more attention shall be dedicated to these values because they may compromise the quality of the regional scale of analysis.

Overall, the calculated transmissivity values are in the same range of variability of the ones obtained by pumping tests interpretation, suggesting that the simple Jacob-Ferris model is sufficient, but not exhaustive for a thorough hydrogeological characterization.

6 Groundwater salinization mechanisms

6.1 Temperature distribution in the freshwater lens system

Extensive drillings were operated in Malta during the end of 2021 and 2022 for improving the monitoring network of the saltwater wedge in the aquifer systems. The objective of this chapter is to draw a baseline condition assessment of heat distribution within the aquifer system which can be compared to future monitoring for inferring the advancement of groundwater salinization into the groundwater body.

The use of heat as a groundwater tracer is growing in popularity and it has been extended in a wide range of hydrogeological studies (Anderson, 2005). Heat sources for groundwater in coastal aquifers include surface water recharge, sea infiltration and geothermal heat (Blanco-Coronas et al., 2021). Recharge water temperature produces a surficial temperature zone that is highly variable throughout the year. Seawater temperature also produces a seasonal temperature oscillation within the saltwater domain.

With the aim of analysing heat spatial variabilities within the freshwater lens system of the Malta MSLA, a monitoring campaign based on the measurement of Temperature-Depth (TD) profiles was undertaken in April 2022. Given the high dynamicity of the aquifer carbonate in type, this monitoring campaign was undertaken in two days only with the assumption of elaborating an instantaneous picture of the temperature distribution within the groundwater body through the measurement of TD profiles in different boreholes (figure 25).

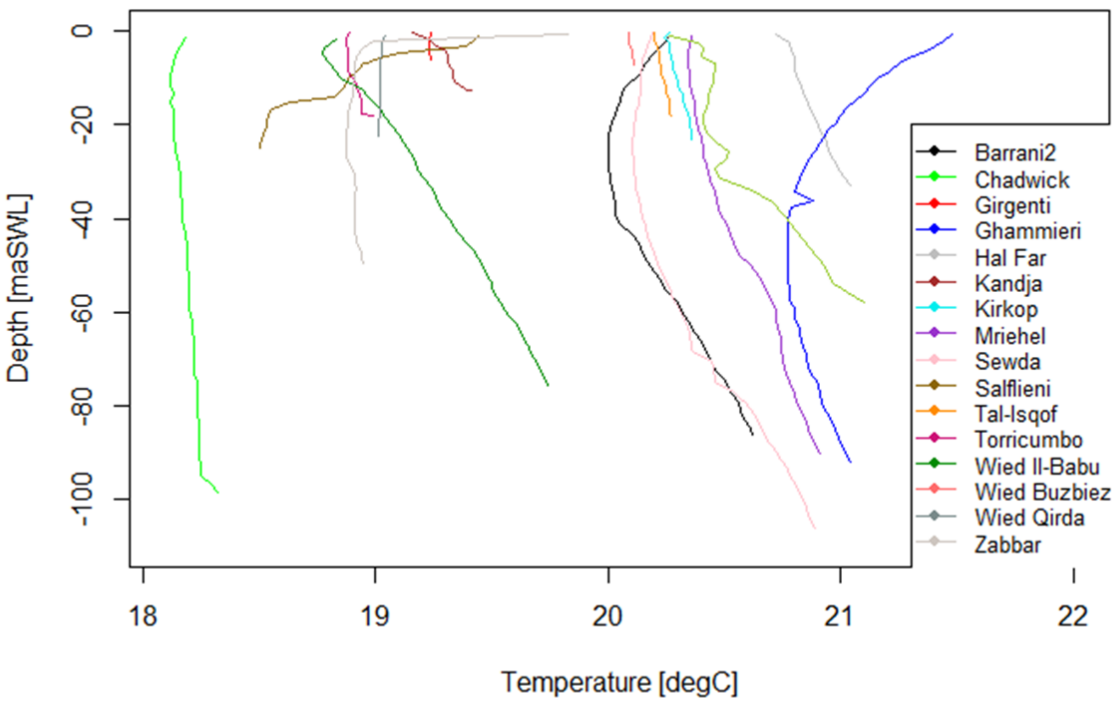


Figure 25: Observed Temperature-Depth profiles in monitoring boreholes.

Through figure 25, a first classification of the TD profiles can be inferred by analysing the shape of the profiles. In a 1D model, downward vertical movement of groundwater produces concave-upward thermal profiles, while upward movement results in convex-upward profiles (Bredehoeft and Papaopulos, 1965). Relatively high subsurface temperatures were detected in the discharge profiles and, vice-versa, relatively low subsurface temperatures were detected in recharge profiles.

To show the spatial relationship between the observed TD profiles and their classification, the observed profiles were interpolated to generate temperature distribution maps with depth using IDW Interpolation (figure 26).

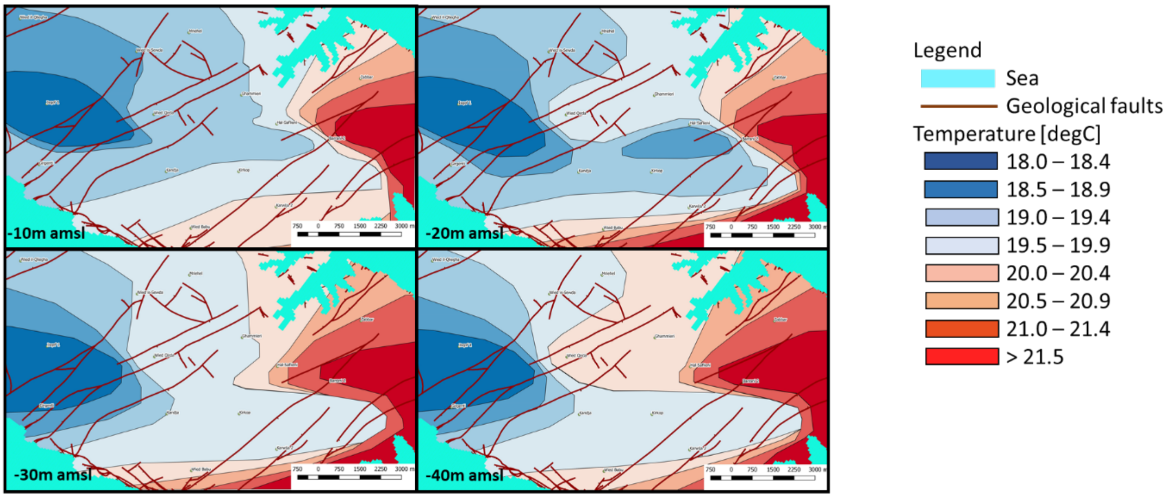


Figure 26: Temperature-Depth (TD) distribution maps of heat spatial distribution in the MSLA developed through IDW interpolation of TD profiles collected in two days during the wet season in 2022.

Visual examination of figure 26 reveals that most of the recharge profiles (cooler TD profiles) are distributed in the North-western part of the Malta MSLA, whereas the discharge types (warmer TD profiles) are located in the South-eastern coastal area. The thermal spatial distribution implies that groundwater flows from the Northwest to the Southeast in the MSLA, as indicated by the MSLA potentiometric surface (figure 13). Most recharge areas occur beneath the Rabat-Dingli plateau where the Perched Aquifer is sustained, while groundwater discharge in the study area commonly occurs in the Eastern coast where groundwater is mostly vulnerable to Mediterranean seawater intrusion (BRGM, 1991). Geothermal heat up-coning can be inferred through the progressive warming of the MSLA with depth. A tongue of cooler water connecting the recharge to the discharge zone and bypassing the Hamrun syncline responsible of lowering the top of the permeable LCL formation beneath the msl (figure 8) can be depicted at different depths. This observation can be related to the hydrogeological role of the Hamrun syncline protecting the inland groundwater body to seawater intrusion.

6.2 Spatial-temporal dynamics of Specific Cunductance profiles

The one-year field research undertaken on three DMBs of the Malta MSLA has highlighted that SC profiles clearly show aquifer salinization processes where anthropogenic activities have caused further degradation of the freshwater column. This study has provided useful information on the evolution of intruded saltwater inland with the subsequent gradual salinization of groundwater induced, to a large extent, by human agency.

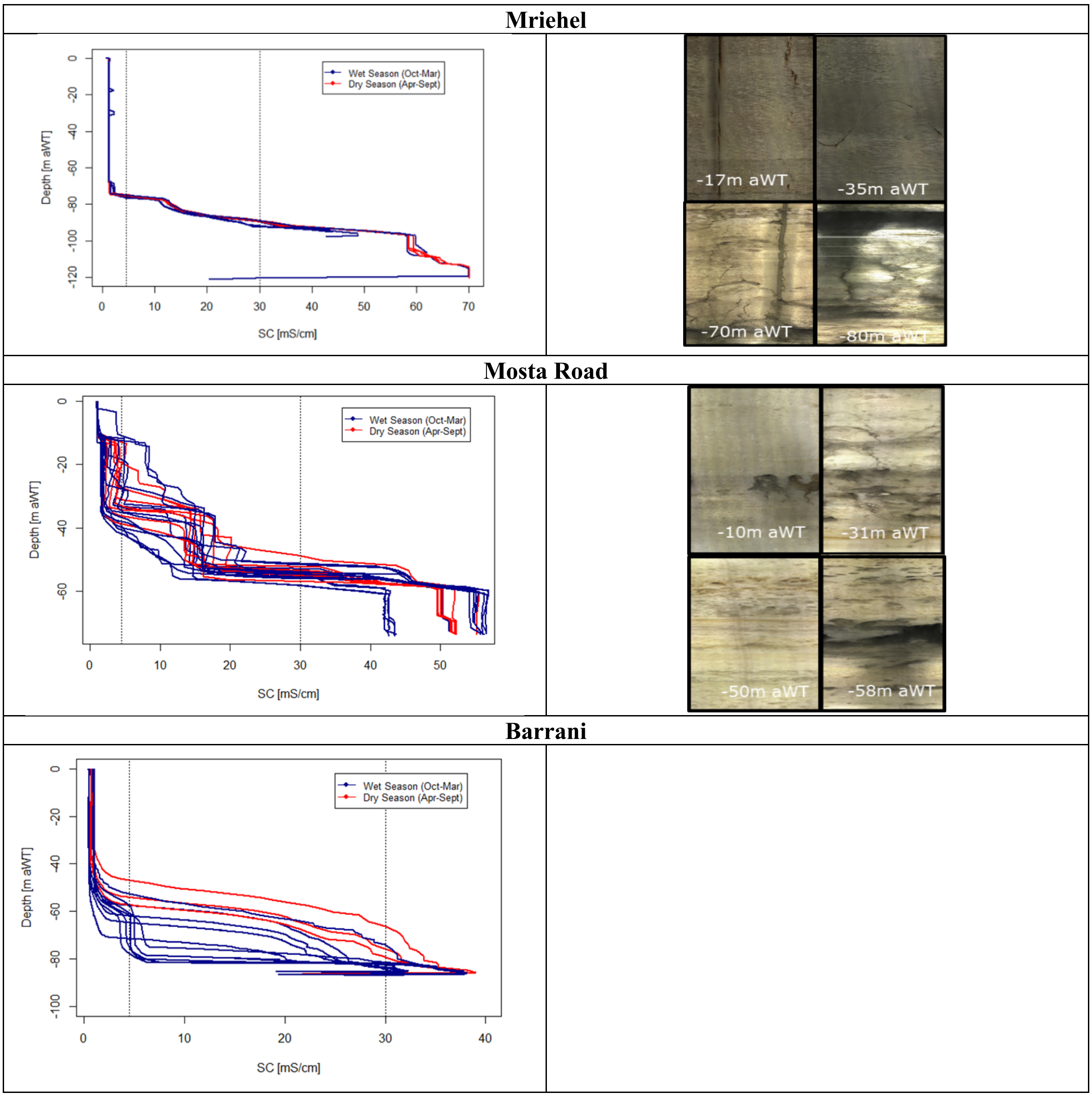


Figure 27: Specific Conductance (SC) logs measured in three Deep Monitor Boreholes (DMBs) over one year monitoring (left hand) and high resolution images of limestone dissolution features at specified depths (right hand).

Figure 27 (left hand) shows that the shift between freshwater and underlying saltwater is achieved through the transition zone whereas a layer of brackish water takes place. At the bottom of DMBs deposition of silt and/or clay is likely decreasing measured EC values, however, this phenomenon does not have any hydrogeological implications on preferential fluxes or groundwater management. In the absence of withdrawals in the surrounding of the DMB (e.g., Mriehel in figure 27) the brackish zone is thin. The finding of a thick transition zone is attributed to withdrawals occurring in the vicinity of the DMBs (Mosta Road and Barrani in figure 27) with shorter freshwater thicknesses if compared to thin transition zones. This scenario is worsened during the dry season when SC profiles have indicated a considerable upward expansion of the transition zone, with a significant reduction in freshwater column thickness. Moreover, step-like changes of SC through the freshwater column have been recorded in Mosta Road DMB. This may be due either to upward and/or downward movements of water within the borehole or some sort of anthropogenic pollution in terms of contaminants discharge. Further investigations are required.

High resolution borehole images captured in Mriehel and Mosta Road (figure 27 – right hand) lead us to infer that extensive dissolution features within the compact carbonate formations occur where kicks of SC are measured. Furthermore, significant dissolution features associated to enhanced tertiary porosity of the limestone matrix is observed in fresh/sea-water mixing zones. According to Aquilina et al. (2005), the mixing of freshwater and sodium chloride waters in presence of limestone leads to under-saturation and porosity enhancement. In carbonate coastal aquifers, the re-activation of the karstification occurs therefore in the transitions zone, right in relation to the disruption of the equilibrium due to mixing of different water bodies having different salt content (and therefore ionic strength).

Two typical transition zone shapes of Specific Conductance (SC) profiles have been identified. The shape of SC profiles around the fresh/sea-water interface could somewhat correlate with the abstraction conditions in the surrounding of the Deep Monitor Borehole (DMB):

(i) Sharp interface: Mriehel DMB transition zone exhibit a sharp SC gradient and maximum fluctuations of the 30mS/cm interface equal to about 3m while located in residential/commercial urban fabric where groundwater abstraction is absent.

(ii) Diffused interface: Barrani and Mosta Road DMBs are affected by strong fluctuations of the 30mS/cm interface up to 8m while low SC gradient are observed in the transitions zone. These DMBs are located in agricultural and industrial land respectively where variable groundwater discharge from nearby private abstraction sources occur.

The lack of abstraction sources within the radius of influence of Mriehel DMB induces short fluctuations of the analysed interfaces which remain quasi-steady over the monitoring period (figure 27). During the dry period, the 4.5 and the 30 mS/cm interfaces reach the minimum depth. After the Summer season, when the rainy period begins, these interfaces reach those depths measured during the beginning of the year. In general, the top of the transition zone of Mriehel is deepened when significant rainfall events (greater than 10 mm/week) increase regional aquifer recharge from the surface. During the year 2021 the Static Water Level (SWL) measured at the time the profile was collected ranges between 2.39m and 3.16m amsl while the top of the transition zone and the fresh/sea-water interface are affected by fluctuations of 2.21 and 3.34m respectively (table 5). These relatively short fluctuations are likely due to lack of abstraction wells surrounding Mriehel DMB leading to the development of a sharp transition zone between freshwater and seawater.

Table 5: Mriehel DMB statistical summary of Static Water Level (SWL), top of the transition zone and fresh/seawater interface.

Static Water Level (m amsl)			Top of the Transition Zone (m below SWL)			50% mixing fresh/seawater interface (m below SWL)		
Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
2.39	2.74	3.16	71.94	72.96	74.15	86.11	87.73	89.45

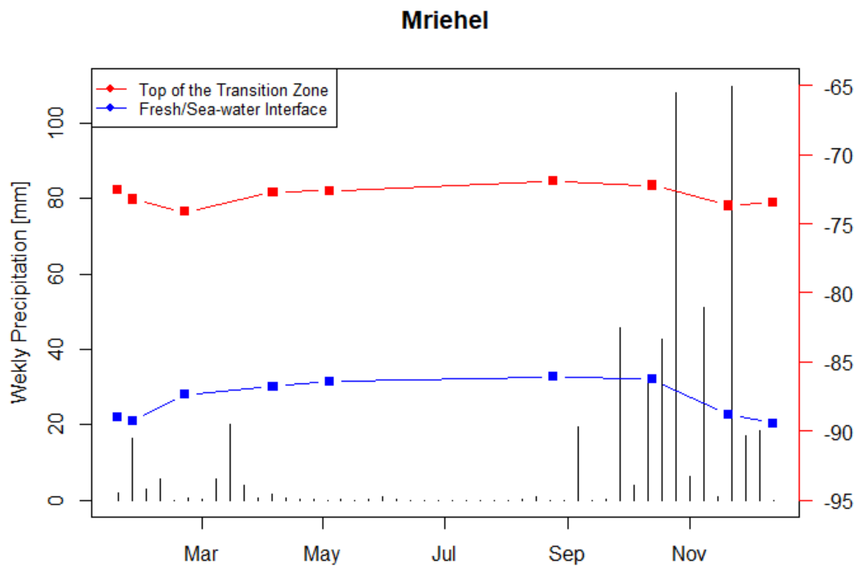


Figure 28: Plot of top of the transition zone and 50% mixing fresh/seawater interface measured in Mriehel DMB with precipitation.

Analysis undertaken on abstraction flow rates of a representative private abstraction well supplying local agricultural and laying within the radius of influence of Barrani DMB, allowed us to outline common agricultural practices adopted by farmers when irrigating their crops. The greatest weekly abstraction flow rates are observed during the dry season whilst minimum discharging rates are recorded when rainfall events magnitude is greater than 20 mm/week. Moreover, it is found that farmers are used to activate their own pump during the daylight with the aim of filling nearby water reservoirs for subsequent supply when required. These variable discharges affect the transition zone shape inducing typical diffused transition zone profiles between freshwater and seawater areas as documented by Falkland and Custodio (1991). Figure 28 shows large fluctuations of the Barrani DMB transition zone associated to both variable discharging flow rates of surrounding private wells and lack of recharge during the summer season. In particular, the transition zone thickness is significantly reduced up to 5.69m when the profile is collected immediately after the occurrence of meteorological events of exceptional conditions with magnitude of the rainfall event greater than 100mm/week. Moreover, freshwater thicknesses tend to decrease if regional recharge mechanisms decrease. Diffused interfaces are characterized by high fluctuations of transition zones between winter and summer seasons; in fact, maximum fluctuations of the 4.5 and 30 mS/cm interfaces are equal to 30.35 and 10.31 m respectively (table 6).

Table 6: Barrani DMB statistical summary of Static Water Level (SWL) measured at the time the profile was collected, top of the transition zone and fresh/seawater interface.

Static Water Level (m amsl)			Top of the Transition Zone (m below SWL)			50% mixing fresh/seawater interface (m below SWL)		
Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
2.32	2.63	3.05	44.55	58.85	74.90	71.55	78.72	81.86

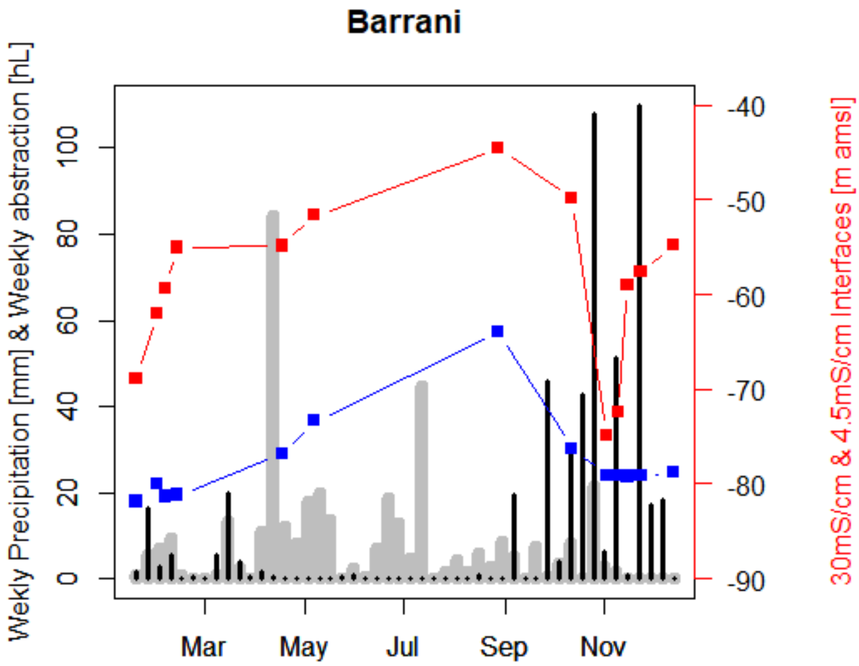


Figure 29: Plot of top of the transition zone and 50% mixing fresh/seawater interface measured in Barrani DMB with precipitation (black lines) and representative private abstraction flow rates (grey bars).

The Mosta Road DMB transition zone exhibits typical diffused conditions (figure 29). Although located in an industrial area, similar considerations to the abstraction conditions inferred in Barrani DMB can be outlined. The minimum transition zone thickness (5.69m) was measured during the rainy season when the maximum freshwater thickness (77.81m) was recorded. However, in this period the top of the transition zone is affected by strong fluctuations highlighting the influence of the abstraction and recharge conditions impacting freshwater availability. Maximum fluctuations of the 4.5 and 30 mS/cm interfaces between summer and winter seasons are equal to 70.35 and 17.87 m respectively (Table 7).

Table 7: Mosta Road DMB statistical summary of Static Water Level (SWL) measured at the time the profile was collected, top of the transition zone and fresh/seawater interface.

Static Water Level (m amsl)			Top of the Transition Zone (m below SWL)			50% mixing fresh/seawater interface (m below SWL)		
Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
2.32	2.61	3.05	4.55	58.85	74.90	63.99	77.59	81.86

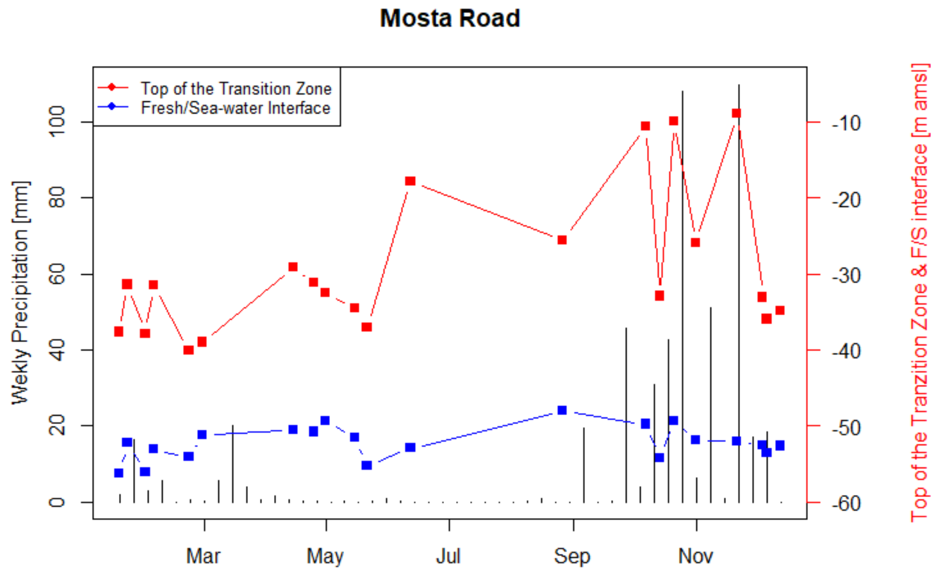


Figure 30: Plot of top of the transition zone and 50% mixing fresh/seawater interface measured in Mosta Road DMB with precipitation.

Analysis undertaken on three DMBs located in the Malta MSLA allowed us to identify occurrence mechanisms of sharp and diffused interfaces given considerations on withdrawal conditions and land use. Generally, the 50% mixing between freshwater and seawater is deepened during significant rainfall events which increase freshwater availability when hydraulic mounds are induced on the water table. On the other hand, the fluctuations of the top of the transition zone could be attributed to local abstraction.

The simple Ghyben-Herzberg mathematical formulation represents a useful equation to be applied when preparing quick plans for developing projects on DMBs investigation depths or numerical modelling calibration/validation steps. However, site-specific conditions are often neglected in this equation leading to substantial uncertainties when this formula is applied.

In this study the calculation of the experimental Ghyben-Herzberg alfa coefficient in equation (2.2) valid for the site-specific conditions of the Malta MSLA is attempted by applying ratios between water level heights measured at the time the profile was collected and interfaces depths measured in the three DMBs object of the study (figure 30). According to figure 30 (a), the top of the transition zone depth over water level height yields to a coefficient equal to 21.84 [-] with a correlation coefficient of 0.945 [-]. Notwithstanding the high correlation value, it is known that the fluctuations of this interface are significantly impacted by local external driving forces like withdrawals, therefore, this coefficient should be used with caution. By plotting the 30mS/cm interface depths with the water level heights (figure 30 (b)) the correlation coefficient slightly increases up to 0.994 [-] yielding to the following relationship:

$$\frac{fresh/sea\text{–}water\ interface\ depth}{water\ level\ height} = 30.11\ [\text{-}] \tag{6.1}$$

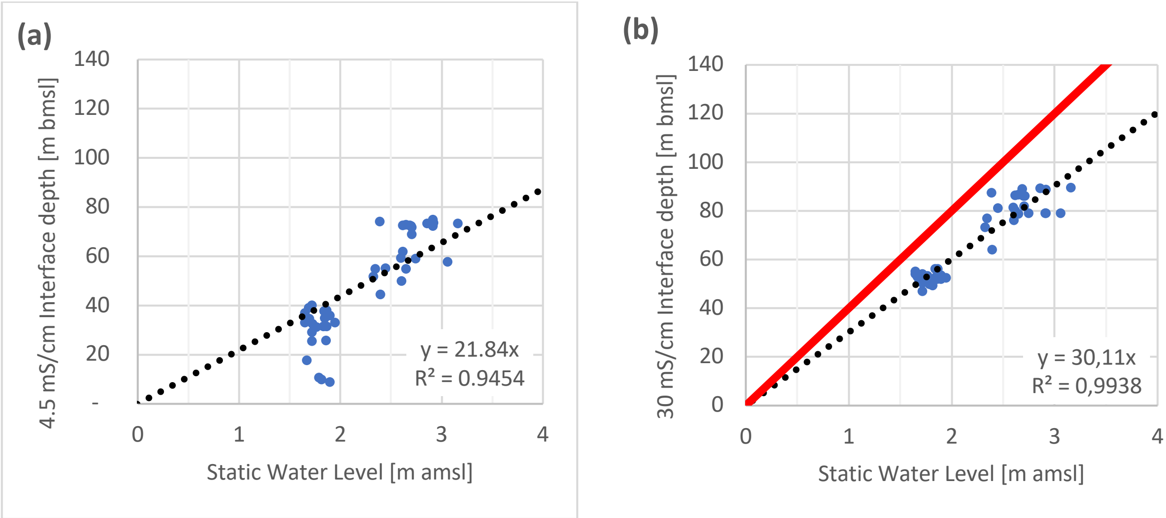


Figure 31: Cross plot between top of transition zone depths (a), 50% mixing between freshwater and seawater depths (b) and water level measured at the time the profile was collected with the red line being the theoretical Ghyben-Herzberg trend line with alfa coefficient equal to 40 [-].

It is important mentioning that equation (6.1) is affected by a maximum uncertainty of 10.70m according to the measurements undertaken during this monitoring period. However, it is still below the uncertainty entailed when using the theoretical Ghyben-Herzberg alfa coefficient whose application would generate an overestimation of the groundwater availability of the MSLA of about 25% (figure 31 (b)).

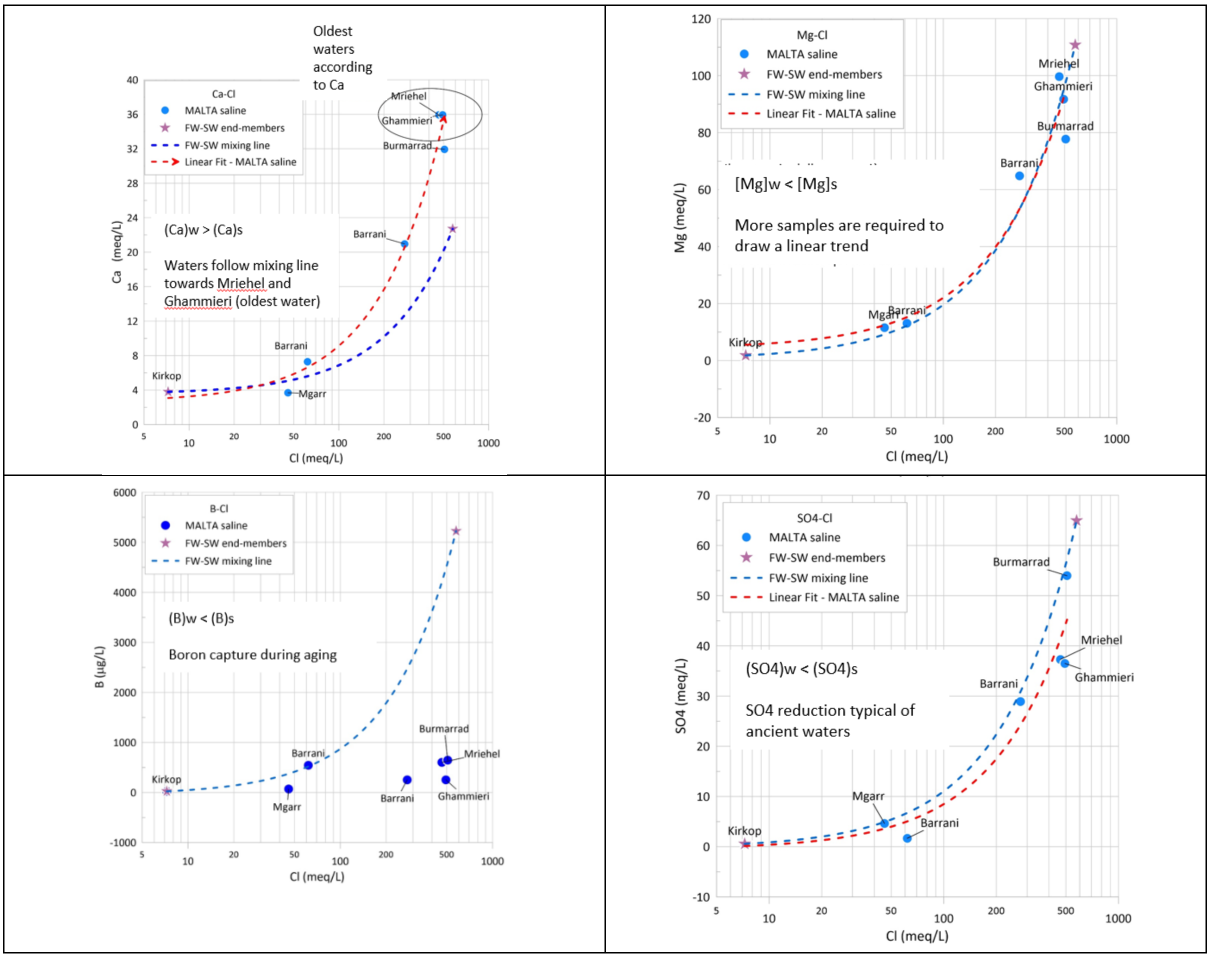
6.3 Water-rock interactions in the transition zone

With the aim of inferring the source of saltwater intruding inland, a number of saline samples were collected in the transition zone of DMBs located in the Malta MSLA. Investigation depths were selected according to short-term monitoring of salinity profiles while basic chemical and physical parameters were measured for depicting water-rock interactions. Table 8 shows a summary of geochemical parameters characterising water composition of the saline samples object of this analysis. The majority of the saline samples (four out of seven) are affected by a charge balance error greater than 5% while only one sample was estimated with a charge balance error greater than 10% (Ghammieri).

Table 8: Chemical parameters of saline samples collected through the transition zone of DMBs. The last column shows Charge Balance Error (CBE) of each sample while the last row represents the seawater sample collected 100m far from the coastline in Golden Bay (Malta).

BH	Sampling date	Ca [mg/l]	Mg [mg/l]	B [ug/l]	SO4 [mg/l]	Cl [mg/l]	CBE [%]
Barrani	17/01/22	146.0	158.8	545.5	80.5	2189.0	8.2
Barrani	04/02/22	420.0	787.9	252.8	1389.5	9747.0	-9.5
Mriehel	15/02/22	720.0	1212.1	601.4	1791.6	16495.0	-3.2
Burmarrad	07/02/22	640.0	945.5	646.9	2592.3	17994.0	-7.1
Mgarr	07/02/22	74.0	140.6	68.74	222.6	1622.0	1.7
Ghammieri	07/02/22	720.0	1115.2	253.8	1753.7	17495.0	-12.2
Kirkop	07/02/22	76.0	21.8	21.9	26.9	257.0	3.1
Seawater	26/09/21	449.0	1585.7	5667.0	2968.6	21356.2	4.0

In order to analyse water-rock interactions of the collected saline samples, a freshwater/seawater mixing line was assumed to be linear between the end members of the freshest saline water sample (Kirkop) and the seawater sample; any deviation from the freshwater/seawater mixing line is discussed as following prior a conversion of concentration of each analyte from mg/l to meq/l (figure 32).



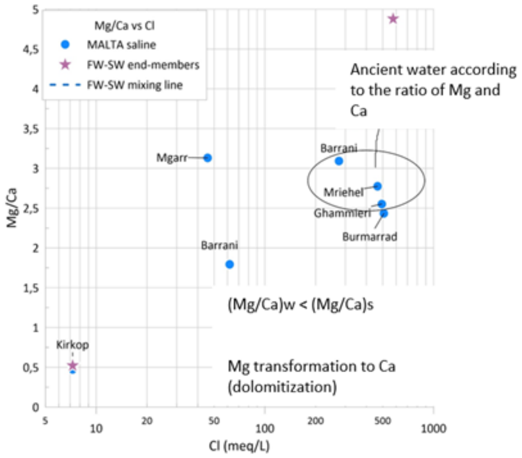


Figure 32: Crossplots of Calcium, Magnesium, Boron, Sulphate, and Magnesium and Calcium ratio with Chloride of saline samples collected in the transition zone of saline samples.

In general, saline samples collected in the transition zone of the Malta MSLA exhibit an enrichment in calcium

concentration if compared to the freshwater/seawater mixing line (figure 32). The oldest saline samples object of this study are Mriehel and Ghammieri. Further confirmation to this theory is found out when analysing magnesium and calcium ratios: given their high chloride concentration it would have been expected to observe this ratio close to the seawater sample, however, high residence times lead to magnesium transformation to calcium triggering dolomitization processes observed through televiewer images in Figure 28 of Mriehel borehole edge. Moreover, sulphate reduction typical of ancient waters is also detected in these DMBs while aging of these samples is inferred through capture of boron. However, up to date it is not possible to draw theories on magnesium/chloride patterns due to the low number of saline samples made available for this analysis which restrict the interpolation of a linear fit of Malta saline samples.

From a chemical point of view, the hydrochemistry of the brackish samples collected in the transition zone of DMBs result in a different chemical evolution if compared to present seawater; this is likely related to high residence time of this water within the carbonate aquifer system. The driving-force of flow which makes possible the circulation of salt waters within the MSLA still has not been perfectly identified, however, interpretations on water-rock interactions lead us to infer the existence of ancient salt waters sustaining the freshwater lens.

Further analyses are required to support this theory. It is recommended to undertake isotopes analysis for estimating an accurate age of the saline samples. Furthermore, the coastal discharge of brackish water might be object of future monitoring due to the likelihood that submarine groundwater discharge may transport to the sea saltwater components different from present seawater. However, it should be taken into account that extrusion of salt waters and intrusion of present seawater in the same aquifer at the same time may imply the existence within the aquifer itself of a regional saltwater flow system coexisting with the fresh groundwater flow system: both have to be recognised for the understanding of the global functioning of the aquifer.

The above analysis led us to infer that the source of saltwater intruding in the aquifer is therefore twofold:

(i) Present seawater intruding laterally from the Eastern coast of the Maltese Island.

(ii) Ancient saltwater upconing from the bottom of the freshwater lens system.

Following this preliminary conceptualization of saltwater intrusion dynamics into the freshwater lens system, the MSLA MAR network proposed in chapter 4 seems to be suitable for inverting the upward trend of chloride concentration endangering the sustainable usage of the fresh groundwater body for water supply of the Maltese Islands. In particular, the infiltration gallery through the unsaturated zone may generate diffused enhanced recharge throughout the centre of the Malta MSLA pushing downwards the freshwater/seawater interface. On the other hand, the sought hydraulic barrier in Malta South-East may be efficient to halt lateral seawater intrusion from the Mediterranean Sea.

7 General conclusions and further perspectives

7.1 General overview

The main objectives of this work were expressed in chapter 1 as the search for the answer to two questions:

(i) Does the current state of the art of the Malta MSLA allow the safe implementation of MAR projects in compliance with European Directives?

(ii) How can the existing MSLA monitoring network infrastructure be deployed to validate the positive impact of MAR schemes in Malta?

Despite the lack of conventional methods allowing the implementation of a sustainable MAR scheme for the site-specific conditions of the Malta MSLA, the results presented in this work seem to show that, at least according to Numerical Modelling simulations, the answer to the first question is positive. The main difficulties in identifying the actual impacts of the MSLA MAR network are related to the difficulties in forecasting the hydrogeological effect of the infiltration gallery to generate the hydraulic barrier to halt saltwater intrusion. The Semi-Analytical Approach introduced in the 2D MSLA flow model to model the freshwater/sea-water interface was defined by a cell-by-cell calculation of the interface depth assuming the validity of the Ghyben-Herzberg formula. With the aim of forecasting the impact of a seawater intrusion barrier, the obtained outcomes following this strategy yielded good results in the present case-study. Therefore, it is tempting to suggest that the steps defined for the preliminary risk assessment, followed in this work, are valid for the implementation of a seawater intrusion barrier in freshwater lens systems. However, it must be taken into account that, without detailed field studies focused on the same objectives in other coastal/island aquifers, it is not possible to assess to which extent the results obtained in the present case study can be generalised or are related to the particular natural site-specific conditions prevailing in the Malta MSLA.

The second question is answered in chapter 6. As referred before, it must be considered that profiles measured in Deep Monitor Boreholes (DMBs) (chapter 6.2) are more adequate basis to characterize aquifer salinization mechanisms triggered by groundwater exploitation than standard shallow monitoring boreholes. However, the results obtained in this work using piezometric heads to calculate the freshwater/sea-water interface depth show that gauging boreholes equipped with CTD divers are still useful to predict interface depths where DMBs are absent. Without the MSLA conceptual model developed on the basis of the transmissivity spatial distribution map, it would have been very difficult to interpret Temperature Depth (TD) spatial distribution maps to monitor the vulnerability to saltwater ingression threatening the qualitative status of the Malta MSLA. On the other hand, time-management issues related to the employment of skilled technical staff measuring a large number of TD profiles in the shortest time period possible need to be pointed out. Therefore, the installation of automated monitoring systems of TD profiles should be sought together with high frequency monitoring of the 50% mixing between freshwater and saltwater.

Despite the positive results obtained in this work, it must be remarked that the prevailing natural conditions usually present in carbonate aquifers in which fissured/conduit flow occurs is most likely not representative in

DMBs that create a hydraulic connection between different preferential flow levels in the surrounding of the aquifer. Therefore, the results obtained to characterize saltwater intrusion mechanisms in the Malta MSLA lead to a certain degree of uncertainty in the conceptualization of the “real saltwater intrusion mechanisms”. In fact, the hydrogeological role of preferential fissured/conduit flow highlighted through high resolution images of the edge of DMBs still has not been perfectly identified given that they may yield conspicuous flows of different salinity. This is in contradiction with the findings of Specific Conductance profiles which exhibit a freshwater column of constant salinity. However, taking into account the high heterogeneity and anisotropy entailed in the aquifer system, this is the only way to monitor aquifer salinization mechanisms in a cost-management and time-consuming efficient way. It must be emphasized that this is the major drawback associated to the preliminary risk assessment technique employed in this work.

Prior to the elaboration of the aspects deserving special attention in future developments, as derived from the present work, a synopsis of the obtained results is presented in the next section regarding: (i) the actual knowledge about the hydrogeology of the Malta MSLA and (ii) the actual implementation of a seawater intrusion barrier. The development on these levels shows that the reliability of the outcomes of this thesis can be improved by monitoring the advancement of the saltwater intrusion into the groundwater body and by complementary hydrogeologic studies, mainly related to the collection of detailed datasets characterising the state of aquifer recharge. On the other hand, it must be considered that the improvement of the knowledge regarding the hydrogeology of the Maltese aquifer system depends also on the characterisation of the Blue Clay layer overlying the main recharge area of the MSLA. The hydrogeologic characterisation of these lithologies will contribute to the definition of more accurate boundary conditions in the MSLA.

7.2 Perspective for further research

The present state of the art of the Malta MSLA shows that some modifications must be introduced in the MSLA flow model in order to reduce the uncertainty of the forecasted hydraulic behaviour of a saltwater intrusion barrier in the carbonate freshwater lens system. The results obtained with the implemented numerical flow model contribute to the definition of a more objective planning for future fieldwork conducted in order to improve the knowledge of the hydrogeology of the Malta MSLA.

A basic problem to solve regarding the aspects related to the saltwater intrusion in the carbonate freshwater lens system consists in obtaining longer time-series of salinity profiles with better measurement frequency. The time scale of the salinization mechanisms involved both in individual recharge events (wet season) and in intense groundwater withdrawal (dry periods) is in the order of few hours. Therefore, the monthly and weekly datasets available for this work cannot seize the time variability of hydraulic head linked to freshwater/seawater interface fluctuations during stress periods. The efficiency of the present version of the regional flow model for simulation of recharge events and intense withdrawal conditions cannot be validated without prior acquisition of daily datasets. On the other hand, data collection from the three DMBs object of this study is essential to establish general relationships between groundwater level variability and freshwater/seawater interface fluctuations. The

Temperature-Depth maps of the Malta MSLA are important to monitor future advancement of saltwater intruding in the aquifer system. The development of these maps on six-monthly basis will allow to optimize the existing monitoring network infrastructure and infer considerations leading to a safe and sustainable MSLA MAR network.

The interpretation of field data as well as the results from flow simulations show that the implementation of a seawater intrusion barrier in the Malta MSLA is feasible. However, the site-specific conditions challenge local water engineers to adopt unconventional MAR techniques. The proposed 15.5 km length infiltration gallery to be drilled through the unsaturated zone in the centre of the 216 km^2 carbonate aquifer would intercept crystalline rock in places altered by karstified dissolution features generating a combination of fast and slow recharge flows typical of karst aquifers. These types of recharge mechanisms shall be quantified through analysis of groundwater level hydrographs and precipitation patterns for quantifying net infiltration volumes to the top of the groundwater body. Although the source of MAR has been addressed with New Water, highly treated wastewater thoroughly filtered through RO membranes, attention shall be made on monitoring the removal of Emerging Contaminants in the source water of MAR. If Emerging Contaminants are detected, risk assessment stages related to exposure patterns and burden to human life shall be carried out.

Boundary conditions for the MSLA flow model can be defined in a more accurate way by characterizing net infiltration mechanisms from the surface including from ephemeral streams flowing through watercourses during the wet season in the MSLA water catchment basin. However, the modification of these recharge factors into the model must be preceded by the implementation of an objective monitoring network.

The main objectives referred in the last paragraphs for further investigations are related to the implementation of a more detailed version of the MSLA flow model presently available. On the other hand, it must be considered that some of the identified problems related to the possibilities of improving the aquifer conceptual model and consequently the flow model cannot be approached by the use alone of the methods applied during this work. The more important aspect on this level is related to the simulation of individual recharge events of different magnitude and duration. As in many other carbonate aquifers, recharge in the Malta MSLA occurs as diffuse infiltration and partially as concentrated infiltration. The definition of the proportion for each of these kinds of water inputs is only one of the aspects of a very complex problem. In fact, after the definition of a hypothetical scenario on this level, based on some experimental criteria or simply on use of a model on a trial-and-error basis, one more difficult problem remains: the definition of the contribution of each doline, sinkhole and geological fault relative to one another. The lack of methods in literature dealing with this problem is among the most important drawbacks with respect to the actual possibilities in characterizing carbonate aquifers on the levels required for forecasting MAR impacts through groundwater flow numerical models. The identification of this problem, in conjunction with bouncy of the freshwater column overlying water of higher salinity, is one of the aspects deserving more attention in future development of the present work.

8 References

Abarca, E.; Vázquez-Suñé, E.; Carrera, J.; Capino, B.; Gámez, D.; Batlle, F. (2006) – Optimal design of measures to correct seawater intrusion. Water Resour.Res. 42, doi:10.1029/2005WR004524.

Abdoulhalik, A.; Ahmed, A.; Hamill, G.A. (2017) – A new physical barrier system for seawater intrusion control. Journal of Hydrology, Elsevier, Volume 549, pp. 416-427, doi.org/10.1016/j.jhydrol.2017.04.005.

Anderson, M.P. (2005) – Heat as a ground water tracer. Groundwater, doi.org/10.1111/j.1745-6584.2005.00052.x.

Aquilina, L.; Emblanch, C.; Fidelibus, M.D.; Zuppi, G.M. (2005) – Geochemical diagenesis of rock and groundwaters in karstic coastal aquifers. Groundwater management of coastal karstic aquifers, Environmental tracing, pp. 158-171.

Balacco, G.; Alfio, M.R.; Parisi, A.; Panagaopoulos, A.; Fidelibus, M.D. (2022) – Application of short time series analysis for the hydrodynamic characterization of a coastal karst aquifer: the Salento aquifer (Southern Italy). Journal of Hydroinformatics, Vol 00, No 0, 1 doi:10.2166/hydro.2022.135.

Bakker, M.; Schaars, F.; Hughes, J.D.; Langevin, C.D.; Dausman, A.M. (2013) – Documentation of the seawater intrusion (SWI2) package for MODFLOW: U.S. Geological Survey Techniques and Methods, book 6, chap. A46, http://pubs.usgs.gov/tm/6a46/.

Bear, J.; Dagan, J. (1964) – Some exact solutions of interface problems by means of the hodograph method. J. Geophys. Res., 69, 1563-1572, doi.org/10.1029/JZ069i008p01563.

Bear, J.; Cheng, A. H.D.; Sorek, S.; Ouazar, D.; Herrera, I. (1999) – Seawater Intrusion in Coastal Aquifers – Concepts, Methods and Practices. Springer Science, ISBN 978-90-481-5172-1, pp. 13-69, doi:10.1007/978-94-017-2969-7.

Birdi, N. (1996) – Water Scarcity in Malta. GeoJournal. Kluwer Academic Publishers, Netherlands. 41.2: 181-191.

BGS (British Geological Survey) (2008) – A preliminary study on the identification of the sources of nitrate contamination in groundwater in Malta. Results and interpretation. Groundwater Resources Programme, Commissioned Report CR/08/094, Nottingham, pp. 23-64.

Blanco-Coronas, A.M.; Duque, C.; Calvache, M.L.; Lopez-Chicano, M. (2021) – Temperature distribution in coastal aquifers: Insights from groundwater modelling and field data. Journal of Hydrology, Elsevier, doi.org/10.1016/j.jhydrol.2021.126912.

Bredehoeft, J.D.; Papaopulos, I.S. (1965) – Rates of vertical groundwater movement estimated from the earth's thermal profile. Water Resources Research, vol. 1, No. 2, pp.325-328.

BRGM. (1991) – Study of the fresh water resources of Malta. Services sol et sous-sol, Departement EAU, 6, pp. 74-77.

Brown, T.N. (1998) – Risk-Based Corrective Action: A New Approach to Contaminated Sites. Professional Corporation, San Francisco, California, pp. 3-11.

Christodoulou, G.; Dokou, Z.; Tzoraki, O.; Gaganis, P.; Karatzas, G. (2013) – Attenuation capacity of a coastal aquifer under managed recharge by reclaimed wastewater. Proc. SPIE 8795, First International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2013), doi.org/10.1117/12.2029178.

Clark, W.E. (1967) – Computing the barometric efficiency of a well. Journal of the Hydraulics Division, 93, pp. 93-98.

Clesceri, L.S.; Greenberg, A.E.; Eaton, A.D. (1998) – Standard methods for the examination of water and wastewater (20th ed.). American Public Health Association, Washington D.C., p. 1220.

Cotecchia, V.; Limoni, P.P.; Polemio, M. (1999) – Identification of typical chemical and physical conditions in Apulian groundwater (southern Italy) through well multi-parameter logs. XXXIX IAH Congress, "Hydrogeology and land use management", Bratislava, pp. 353-358.

Custodio, E. (1997) – Studying, monitoring and controlling seawater intrusion in coastal aquifers. Guidelines for Study, Monitoring and Control, FAO Water Reports No. 11, pp. 7-23.

Dagan, G.; Bear, J. (1967) – Solving the problem of local interface upconing in a coastal aquifer by the method of small perturbation. Journal of Hydraulic Research, 6:1, 15-44, doi: 10.1080/00221686809500218.

Daniell, T.M.; Falkland, A.C. (1983) – Information and investigations required for assessing water resources for water supplu on islands. Proc. ESCAP Meeting on Water Resources Development in S. Pacific, United Nations Water Resources Series, No. 57, pp. 120-126.

Davis, D.R.; Rasmussen, T.C. (1993) – A comparison of linear regression with Clark's Method for estimating barometric efficiency of confined aquifers, Water Resour. Res., 29, 1849–1854, doi.org/10.1029/93WR00560.

De Josselin de Jong (1965) – A many-valued hodograph in an interface problem. Water Resour. Res., 1, 543-555, doi.org/10.1029/WR001i004p00543.

Dillon, P. (2005) – Future management of aquifer recharge. Hydrogeol J, 13, 313–316. doi.org/10.1007/s10040-004-0413-6.

Dillon, P.; Pavelic, P.; Page, D.; Beringen, H; Ward, J. (2009) – Managed aquifer recharge: An Introduction. Waterlines Report Series No. 13, February 2009, pp. 1-7.

Drogue, C. (1971) – Coefficient d’infiltration ou infiltration efficace, sur les roches calcaires. Actes colloque d’hydrologie en pays calcaire, Besançon, 121-131.

Falkland, A.; Custodio, E. (1991) – Hydrology and water resources of small islands: a practical guide. Unesco, International Hydrological Programme, IHP-III, Project 4.6, Paris, France, pp. 1-8, 29-37, 88-131.

Fernández Escalante, E.; Henao Casas, J.D.; Vidal Medeiros, A.M.; Sauto, J.S.S. (2020) – Regulations and guidelines on water quality requirements for Managed Aquifer Recharge. International comparison. Acque Sotterranee, Italian Journal of Groundwater, 9 (2), 7-22. doi.org/10.7343/as-2020-462.

Ferris, J.G. (1951) – Cyclic fluctuations of water level as a basis for determining aquifer transmissivity. Assoc. Int. Hydrol. Sci., pp. 148-155.

Fidelibus, M.D.; Tulipano, L. (1986) – Mixing phenomena owing to sea water intrusion for the interpretation of chemical and isotopic data of discharge waters in the Apulian coastal carbonate aquifer (southern Italy). Proc. 9th Salt Water Intrusion Meeting, Delft, pp. 591-600.

Fidelibus, M.D.; Balacco, G.; Gioia, A.; Iacobellis, V.; Spilotro, G. (2016) – Mass transport triggered by heavy rainfall: the role of endorheic basins and epikarst in a regional karst aquifer. Wiley, doi:10.1002/hyp.11037.

Flinchem, E. P.; Jay, D.A. (2008) – An introduction to Wavelet Transform Tidal Analysis Methods. Estuarine, Coastal and Shelf Science 2000, doi:10.1006/ecss.2000.0586.

Ghyben, B. W. (1888) – Nota in Verband met de Voorgenomen Putboring Nabij Amsterdam. Tijdschr. Kon. Inst. Ing, 9, pp. 8-22.

Glover, R.E. (1959) – The pattern of fresh-water flow in a coastal aquifer. J. Geophys. Res., 64, pp. 457-459.

Golshan, M.; Colombani, N.; Mastrocicco, M. (2018) – Assessing Aquifer Salinization with Multiple Techniques along the Southern Caspian Sea Shore (Iran). Water, MDPI, 10(4), 348, doi:10.3390/w10040348.

Guo, H; Jiao, J.J.; Li, H. (2010) – Groundwater response to tidal fluctuation in a two-zone aquifer. J Hydrol 381(3–4), 364–371, doi.org/10.1016/j.jhydrol.2009.12.009.

Hayashi, M. (2004) – Temperature-electrical conductivity relation of water for environmental monitoring and geophysical data inversion. Environmental Monitoring and Assessment, v.96, pp. 119-128.

Herbert, P.T. (1955) – The geology of the Maltese Islands. Malta College of Arts, Science & Technology, pp. 22-33.

Herndon, R.; Markus, M. (2009) – Large-Scale Aquifer Replenishment and Seawater Intrusion Control Using Recycled Water in Southern California. International Water Resources Association Workshop on Artificial Recharge for Groundwater Management in Palma de Mallorca, Spain.

Herzberg, A. (1901) – Die Wasserversorgung einiger Nordseebäder, J. Gasbeleucht. Wasserversorg, 44, pp. 815–819, 842–844.

Isaacs, L.T.; Hunt, B. (1985) – A simple approximation for a moving interface in a coastal aquifer. Journal of Hydrology, 83 29-43, Elseview Science Publishers B.V., Amsterdam, Netherlands.

Jacob, C.E. (1950) – Flow of Groundwater. Rouse H (ed) Engineering hydraulics. Wiley, Hoboken, pp. 321-386.

Kiraly, L.; Müller, I. (1979) –Heterogeneity of the permeability and the infiltration in the karst: effect on the karstic springs water chemistry variations. Bulletin du Centre d'Hydrogéologie, 3:237-285.

Klimchouk, A.B. (2000) – The formation of Epikarst and Its role in Vadose Speleogenesis. National Speleological Society, 91-99.

Lotti, F.; Borsi I., Guastaldi, E.; Barbagli, A.; Basile, P.; Favaro, L.; Mallia, A.; Xuereb, R.; Schembri, M.; Mamo, J.; Sapiano M. (2021) – Numerically enhanced conceptual modelling (NECoM) applied to the Malta Mean Sea Level Aquifer. Hydrogeol J 29, 1517–1537 (2021). doi.org/10.1007/s10040-021-02330-2.

Luyun, R.; Momii, K.; Nakagawa, K. (2011) – Effects of recharge wells and flow barriers on seawater intrusion. Ground Water. 49, 239-249.

Magri, O. (2006) – A geological and geomorphological review of the Maltese Islands with special reference to coastal zone. Territoris Universitat de les Illes Belears, Territoris 4.

Mangin, A. (1975) – Contribution à l'étude hydrodynamique des aquifères karstiques. Thèse Univ. Dijon. Annales de spéléologie, 29/3: 283-332, 29/4: 495-601, 30/1: 21-124.

Masciopinto, C.; Palmiotta, D. (2013) – Relevance of solutions to the Navier-Stokes equations for explaining groundwater flow in fractured karst aquifers. Water Resour. Res., 49, doi:10.1002/wrcr.20279.

McMillan, T. C.; Rau, G. C.; Timms, W. A.; Andersen, M. S. (2019) – Utilizing the Impact of Earth and Atmospheric Tides on Groundwater Systems: A Review Reveals the Future Potential. Rev. Geophys., 57, 281–315, https://doi.org/10.1029/2018RG000630.

Micallef, P.; Attard, G.; Mangion, J. (2004) – Water Resources Management in Malta: Cultural Heritage and Legal and Administrative Set-up. OPTIONS méditerranéennes, Series B, n° 48, ISBN 2-85352-300-4.- p. 199-207.

Moriarty, E.; Nokes, C. (2014) – Public health risk assessment of sewage disposal by onsite wastewater treatment and disposal systems in the Darfield and Kirwee Communities. Ministry of Health contract for scientific services, New Zeeland, pp. 7-14.

Natural Resource Management Ministerial Council; Environmental Protection and Heritage Council; National Health and Medical Research Council (2009) – Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Managed Aquifer Recharge. National Water Quality Management Strategy, Document No 24 July 2009, Canberra, Australia, pp. 10-151.

Newbery, J. (1968) – The perched water table in the upper limestone aquifer of Malta. Government of Malta, pp. 551-570.

OED (Oil Exploration Directorate), Office of the Prime Minister. (1993) – Geological Map of the Maltese Islands: Sheet 1- Malta.

Ortuño, J.; Molinero, J.; Custodio, E.; Juárez, I.; Garrido, T.; Fraile, J. (2010) – Seawater intrusion barrier in the deltaic Llobregat aquifer (Barcelona, Spain). SWIM21 – 21st Salt Water Intrusion Meeting, Azores, Portugal.

Oude Essink, G.H.P. (2001) – Improving fresh groundwater supply—problems and solutions. Ocean Coast.Manage. 44, 429-449.

Pedley, H.M. (1989) – Syndepositional tectonics affecting Cenozoic and Mesozoic deposition in the Malta and SE Sicily areas (Central Mediterranean) and their bearing on Mesozoic reservoir development in the N Malta offshore region. Butterworth & Co, (Publishers) Ltd, 171-178, doi:0264-8172/90/020171-10.

Perrin, J. (2003) – A conceptual model of flow and transport in a karst aquifer based on spatial and temporal variations of natural tracers. Centre of hydrogeology, Universite de neuchatel faculte des sciences institute de geologie, pp. 9-44.

Poeter, E.; Fan, Y.; Cherry, J.; Wood, W.; Mackay, D. (2020) – Groundwater in Our Water Cycle. Getting to Know Earth's Most Important Fresh Water Source. The groundwater project, Guelph, Ontario, Canada, pp. 73-76.

Polemio, M.; Zuffianò, L.E. (2020) – Review of Utilization Management of Groundwater at Risk of Salinization. ASCE (American Society of Civil Engineers), doi: 10.1061/(ASCE)WR.1943-5452.0001278.

Rahi, K.A. (2010) – Estimating the hydraulic parameters of the Arbuckle-Simpson aquifer by analysis of naturally-induced stresses. PhD Thesis, Oklahoma State University, Stillwater, OK, USA.

Rau, G.C.; Cuthbert, M.O.; Acworth, R.I.; Blum, P. (2020) – Technical note: Disentangling the groundwater response to Earth and atmospheric tides to improve subsurface characterisation. Hydrol. Earth Syst. Sci., 24, 6033–6046, doi.org/10.5194/hess-24-6033-2020.

Rowe, D.R.; Abdel-Magid, I.M. (1995) – Handbook of Wastewater Reclamation and Reuse. Lewis, Boca Raton, FL.

Rotzoll, K.; El-Kadi, A.I.; Gingerich, S.B. (2008) – Estimating hydraulic properties of coastal aquifers using wave setup. J Hydrol 353(1-2):201-21, doi: 10.1016/j.jhydrol.2008.02.005.

Rotzoll, K.; Stephen, B.G.; John, W.J.; Aly, I.E. (2013) – Estimating hydraulic properties from tidal attenuation in the Northern Guam Lens Aquifer, territory of Guam, USA. Hydrogeology journa, 1-5, doi:10.1007/s10040-012-0949-9.

Salgot, M.; Huertas, E.; Weber, S.; Dott, W.; Hollender, J. (2006) – Wastewater reuse and risk: definition of key objectives. Desalination, Elsevier. doi.org/10.1016/j.desal.2005.04.065.

Sánchez-Úbeda, J.P.; Calvache, M.L.; Duque, C.; López-Chicano, M. (2016) – Estimation of hydraulic diffusivity using tidal-extracted oscillations from groundwater head affected by tide, 24th Salt Water Intrusion Meeting and the 4th Asia-Pacific Coastal Aquifer Management Meeting, Cairns, Australia, 1–2.

Sapiano, M.; Capone, F.; Fernández Escalante, E.; Schüth, C. (2017) – Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought. Policy document for decision makers. MARSOL, pp. 4-7.

Sauter, M. (1992) – Quantification and forecasting of regional groundwater flow and transport in a karst aquifer (Gallusquelle, SW Germany). PhD dissert, University of Tübingen.

SEWCU (Sustainable Energy and Water Conservation Unit); ERA (Environmental and Resources Authority). (2015) – The 2nd Water Catchment Management Plan for the Malta Water Catchment District 2015 – 2021. Government of Malta, 2015, pp. 41 – 65 and 107 – 124.

Solinst (2022) – Bladder Pump Operation. High Quality Groundwater & Surface Water Monitoring Instrumentation, Canada, available at https://www.solinst.com/products/groundwater-samplers/407-bladder-pumps/datasheet/bladder-pump-operation.php, on November 4th, 2022.

Srzić, V.; Lovrinović, I.; Racetin, I.; Pletikosić, F. (2020) – Hydrogeological Characterization of Coastal Aquifer on the Basis of Observed Sea Level and Groundwater Level Fluctuations: Neretva Valley Aquifer, Croatia, Water, doi.org/10.3390/w12020348.

Sprenger, C.; Hartog, N.; Hernández, M.; Vilanova, M.; Grützmacher, G.; Scheibler, F.; Hannappel, S. (2017) – Inventory of managed aquifer recharge sites in Europe: Historical development, current situation and perspectives. Hydrogeol. J.

Tomasicchio, U.; (2015) – Manuale di ingegneria portuale e costiera.Ulrico Hoepli Editore S.p.A., Milano, Italy pp. 76-82.

Turnadge, C.; Crosbie, R.S.; Barron, O.; Rau, G.C. (2019) – Comparing Methods of Barometric Efficiency Characterization for Specific Storage Estimation. Groundwater, 57, 844-859, doi:10.1111/gwat.12923.

USGS (2010) – Effects of Groundwater Withdrawal on Borehole Flow and Salinity Measured in Deep Monitor Wells in Hawai'I – Implications for Groundwater Management. Scientific Investigations Report 2010-5058, pp. 11-34.

USGS (2019) – National Field Manual for the Collection of Water-Quality Data (NFM). Water Resources, https://www.usgs.gov/mission-areas/water-resources/science/national-field-manual-collection-water-quality-data-nfm#overview

Verruijt, A. (1969) – An interface problem with a source and a sink in the heavy fluid. Journal of Hydrology, Volume 8, Issue 2, ISSN 0022-1694, pp. 197-206, doi.org/10.1016/0022-1694(69)90121-8.

Williams, P.W. (1983) – The role of the subcutaneous zone in karst hydrology. Journal of Hydrology, pp. 45-67

World Health Organization (2016) – Quantitative Microbial Risk Assessment: Application for Water Safety Management. WHO Document Production Services, Geneva, Switzerland, pp. 12-31 and 39-69.

Zhou, Q.; Deng, X.; Wu, F.; Li, Z.; Song, W. (2018) – Impacts of Water Scarcity on Socioeconomic Development in Inland River Basins. In: Deng, X., Gibson, J. (eds) River Basin Management. Ecohydrology. Springer, Singapore. doi.org/10.1007/978-981-10-0841-2_15-1