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REPORT

Geological and hydrogeological reconstruction of the main aquifers of the Maltese islands

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Abstract

Geological and hydrogeological conceptualizations of the five main aquifers of Malta were performed by means of characterization of the groundwater bodies' geometries to assess their hydraulic properties. The starting point was 23 new geological cross-sections, intended to intercept all the main structural features of the Maltese archipelago at once. This conceptual analysis constitutes a fundamental phase in the development of groundwater models, and in turn influences the assessment of transmissivity and the numerical models' structure, calibration and related uncertainties. Besides the construction of the geological sections, a crucial step in building a coherent geological conceptual model involved data homogenization and use of different tuning scales, with respect to both geometric and hydraulic aquifer features. Cross-section quality was spatially assessed by the fit on both a high-resolution digital terrain model and the surface geological data, and the information was subsequently merged with previously determined inconsistencies within borehole stratigraphic data collected from various sources. The geological boundaries data (contact lines and point data) and the dense fault system of the Maltese islands (horst and graben structure) were interpolated by means of the "spline with barriers" algorithm. The resulting surfaces of the main geological formation beds constitute the new detailed geological conceptual model of the whole Maltese archipelago, needed for a more reliable assessment of hydrogeological parameters. The achieved hydrogeological conceptual models of the main Maltese groundwater bodies constitute the basis for groundwater numerical modelling to better understand and quantify the groundwater resources available within the hydrological reservoirs.

Keywords Conceptual models · General hydrogeology · Aquifer geometry reconstruction · Malta · Groundwater bodies

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Introduction

Due to the geographic and climatic conditions of the Maltese islands, freshwater is a very scarce resource. Like most of the Mediterranean countries, Malta is facing water stress due to both water scarcity and resource deterioration, moreover it has no surface water that can be efficiently exploited (Mangion et al. 2005). Groundwater abstraction has been estimated to reach around 40 million m^3, i.e. 61% of the total national water demand (Sapiano 2020). The need for characterizing these hydrogeological reservoirs of the Maltese islands, in order to use these resources more efficiently, is therefore urgent. A complete review and update of the existing geological and hydrogeological conceptual models of the islands constitutes the preliminary phase for the management of Malta's groundwater resources (Anderson et al. 2015). Geological conceptualization allows for drafting of the geometry and

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properties of the aquifer of interest, starting the iterative process of hypothesis testing by means of numerical models (Gupta et al. 2012). The complexity of natural systems is obviously not representable by any numerical simulator, which instead needs to undergo prediction-related simplification. This simplification would have to “keep” the features salient in groundwater management, and “skip” the uncountable details that have no specific influence (Enemark et al. 2019). Selection of what is important is not trivial and requires several loops among field activity, conceptualization and numerical investigations (Doherty and Welter 2010).

In this regard, during 2018, the Energy and Water Agency of the Government of Malta (EWA) launched a new project to review and update the existing groundwater conceptual models of the five most important aquifers in the islands by means of numerical models. Conceptual and numerical modelling were set down as parallel, rather than as sequential, activities. This is particularly important in case of complex, data-scarce aquifers, where the conceptual model is typically composed by a puzzle made of assumptions, hypothesis and incomplete data, whose consistency can only be tested with a companion numerical model. Furthermore, a detailed geological conceptualization allows the proper evaluation of the transmissivity, a fundamental hydrogeological parameter structurally controlled by the geological formations’ geometry, which constitutes a crucial input to the numerical model when other data are scarce. In fact, combining geological maps, borehole data logs, types and geometry of groundwater bodies, and 3D configuration of the system is a tested workflow to achieve the conceptualization of the main studied aquifer systems (Fenelon et al. 2010).

The main conceptualizations oriented to hydrogeology and/or to groundwater modeling in Malta aquifers were performed by BRGM (1991) and Sapiano (2015), without neglecting the fundamental conceptual hydrogeological contribution of Morris (1952). However, they consider only a part of the main aquifers of the Maltese islands, so their interpretations could be partial or at least not homogeneous for the whole archipelago. This report proposes a global geological conceptual model of the whole archipelago at once, keeping the uniform legend proposed by OED (1993). This approach (which should be anything but new) has been named the Numerically Enhanced Conceptual Model (NECoM, Lotti et al. 2021) and has been applied to the main Maltese aquifers. At this stage, the developed NECoMs delivered to EWA had the main purpose to point out the main data gaps (with specific reference to the management aims) and improve the groundwater monitoring network currently under development. At a later time, they are supposed to provide the Agency with an ability to make predictions whose uncertainties are quantified and reduced through data assimilation as soon as new data are available. The risks associated with contemplated courses of management action can therefore be properly assessed before they are implemented.

This report describes the geological characterization of the five main Maltese aquifers and their main hydrogeological unknowns. These were tested through numerical models with the result that some of them could be answered, some others constrained to a short list of options, and some others have been added to the list of the new field investigations list (Lotti et al. 2021).

In particular, this work reports the results in terms of: (1) review and processing of existing geological (just to give some examples, Costain 1958a, Pedley et al. 1976, OED 1993), hydrogeological (for instance BRGM 1991, Sapiano 2015), and water management information and data in the Maltese islands (MRA 2003); (2) development of the preliminary hydrogeological conceptual models for the five different groundwater bodies. The complete workflow that included the NECoMs development could not be included in the present report and is described for the only Mean Sea Level Aquifer (MSLA) of Malta in a dedicated paper (Lotti et al. 2021).

Materials and methods

Geological and hydrogeological setting

The Maltese archipelago lies in the central Mediterranean Sea directly south of Italy and north of Libya, and it comprises Malta (the southern island), Gozo (the northern island), and (in between) the small island of Comino. The islands are located on the Hyblean-Maltese platform, part of the Pelagian Block of the African Plate (Fig. 1a), in the foreland of the Apennine-Maghrebianfold-and-thrust belt. In more detail, it is located on the northern flank of the Pantelleria Rift (Fig. 1b) and is characterized by widespread NE–SW striking normal faults developing a series of horst and graben structures. In the southern part of Malta, NW–SE striking faults are also present (Pedley et al. 1976, 1978; Pedley 1990; Illies 1981; Reuther and Eisbacher 1985; Grasso et al. 1986; Pedley and Grasso 1992; Gardiner et al. 1995; Villani et al. 2018). Following Dart et al. (1993), the two fault systems developed contemporaneously as response to a regional N–S directed extension.

The Maltese islands can be subdivided into three regions, primarily consisting of two elevated blocks separated by the two major NE–SW faults, namely the Għajnsielem-Qala Fault in the north and the Victoria Fault (VLF) in the south. Between these two faults a structural graben stretching between southern Gozo, Comino and northern Malta separates the two blocks.

Stratigraphy

The stratigraphic succession outcropping in the Maltese archipelago is represented by Oligocene to Quaternary rocks—

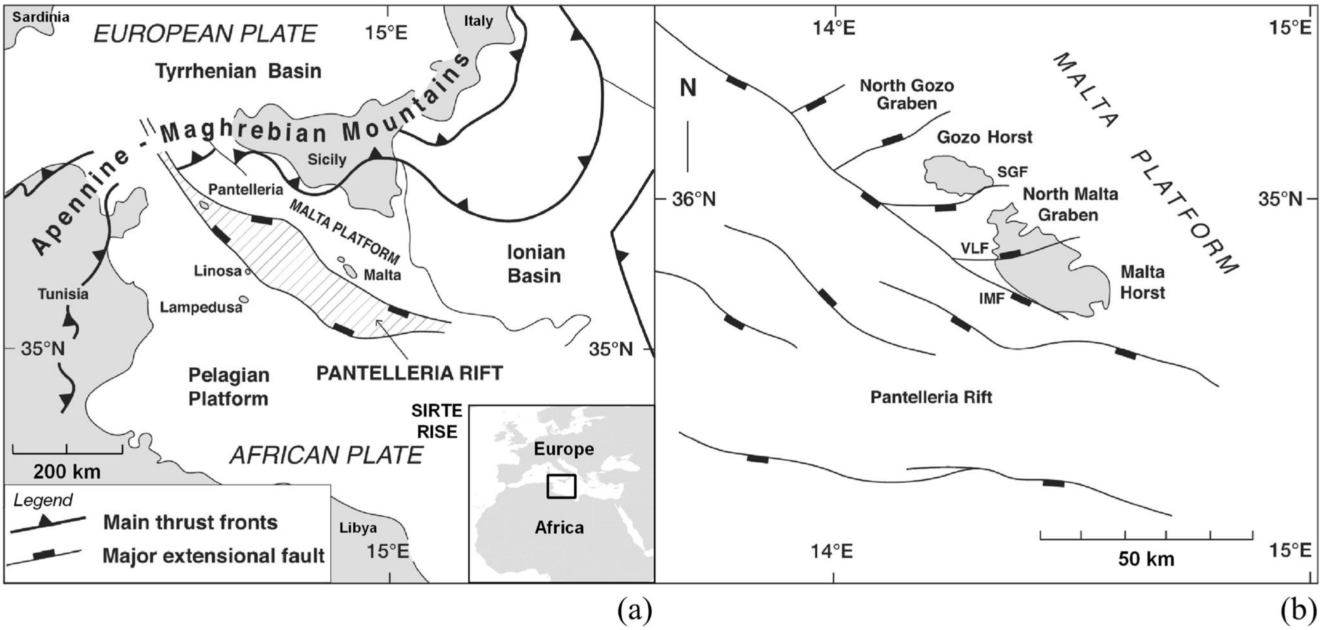


Fig. 1 **a** Structural map of the central Mediterranean. **b** Main tectonic features of the Pantelleria Rift and Malta platform. After Dart et al. (1993), modified: IMF Il Maghlaq Fault, SGF South Gozo Fault, VLF Victoria Lines Fault

Fig. 2; the complete version of the stratigraphy record is shown in the electronic supplementary material (ESM)—and the following lithostratigraphic units can be recognized:

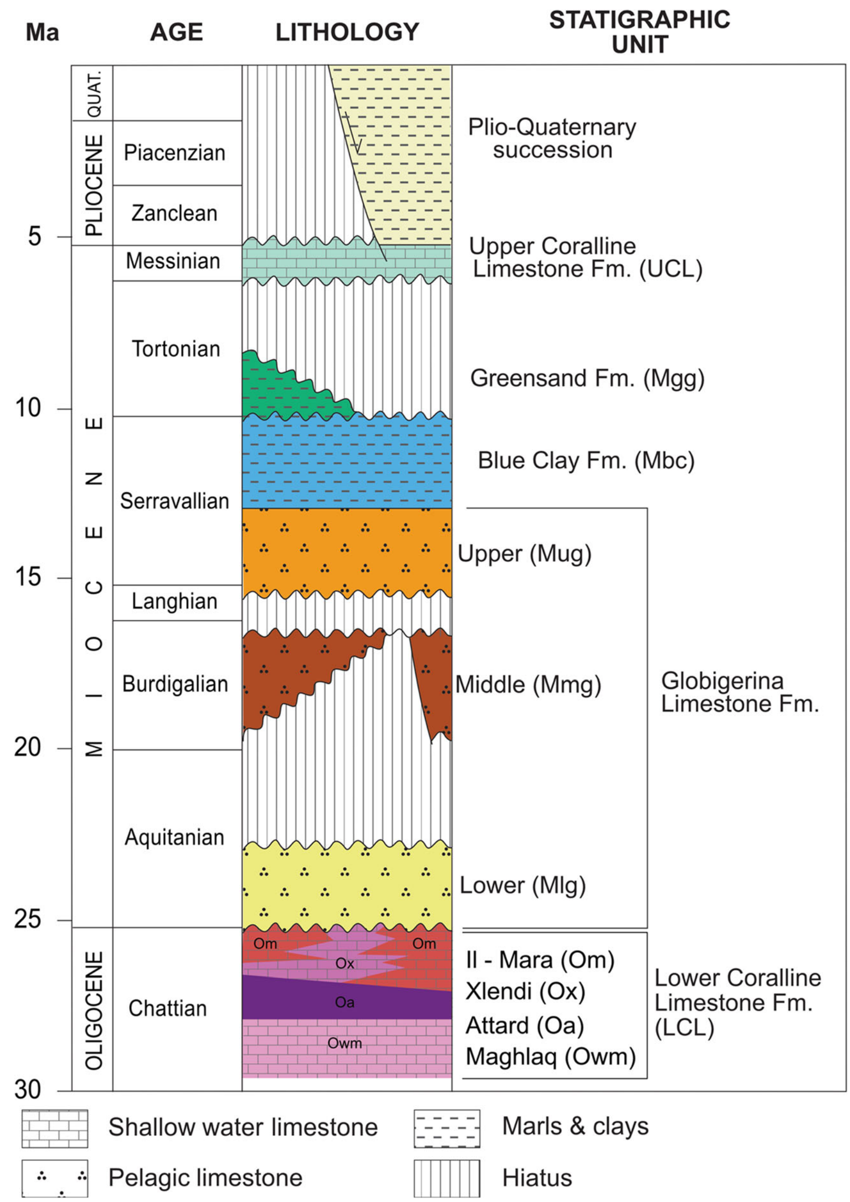
- Lower Coralline Limestone
- Globigerina Limestone
- Blue Clay Formation
- Greensand Formation
- Upper Coralline Limestone
- Quaternary deposits

Essentially, the islands of the Maltese archipelago are built-up of clays and marls—the Blue Clay Fm. and the Globigerina Limestone Fm., which are two semi-permeable formations placed between two permeable limestone formations, the Upper and the Lower Coralline Limestone formations. The rocks are only very gently folded, and only one outcrop shows folds with overturned limbs. Normal faulting is instead widespread, in all the archipelago and at all scales of observation. From a geomorphological point of view, the Upper and Lower Coralline Limestone formations usually form bare karstic plateaus. The widespread Globigerina Limestone defines a gentle topography and the soils are intensively cultivated and terraced. The fertile Blue Clay, aided by water seeps from the overlying units, supports the lushest vegetation on the islands.

Lower coralline limestone (LCL) The LCL formation is a thick succession of algal foraminiferal limestone divided into four distinct members (Pedley et al. 1978), all having a direct bearing on the infiltration processes through the unsaturated zone and on groundwater flow within the aquifer. The LCL is extremely heterogeneous with frequent lateral variability from patch reef deposits to lagoonal and fore-reef facies such as the lateral transitions from the coarse-grained biocalcarenites of the Xlendi Member to the finer compact yellow limestones of the Maghlaq member. The following four members can be recognized: (1) Maghlaq Mb. (Owm), which are massive bedded, pale yellowish-grey carbonate mudstones, poorly exposed and are only recognized in the Il-Hnejja quarries (thickness: unknown. Age: Oligocene, Chattian); (2) Attard Mb. (Oa), constituted by grey limestones typical throughout Malta (thickness: 10–15 m; age: Oligocene, Chattian); (3) Xlendi Mb. (Ox), which is composed of planar to cross-stratified, coarse-grained limestones with abundant foraminifera fragments. The member is best developed in NW Gozo in the cliffs W of Reqqa point, near Żebbuġ (thickness: 0–22 m; age: Oligocene, Chattian); (4)Il-Mara (Om), composed of tabular beds of pale-cream to pale-grey carbonate mudstones, wackestones and packstones in 1–2-m-thick units. The member is only locally present in N Gozo and in E Gozo around Qala Point (thickness: 0–6 m; age: Oligocene, Chattian).

Globigerina limestone (GL) The GL formation overlies the LCL formation and is predominantly composed of pelagic carbonate limestones, with abundant planktonic foraminifera. It outcrops over large areas of central and southern Malta and Gozo, capping the underlying aquifer system that constitutes the main groundwater bodies that are one of the objects of the present study (Fig. 3). The GL varies in thickness from almost 23 m near Fort Chambray (south of Gozo) to 207 m around Marsaxlokk

Fig. 2 Stratigraphic log of the Maltese area, after Dart et al. (1993), modified



(south east of Malta). Based on two laterally persistent phosphorite conglomerate hardgrounds, the GL formation is subdivided into three members: Lower, Middle and Upper Globigerina Limestone. The conglomerate hardgrounds are considered as important pathways for surface infiltration and also have a direct influence on mineralization and qualitative aspects of groundwater. The following three members can be recognized: (1) Lower Globigerina Limestone Mb. (Mlg), composed of pale cream to yellow planktonic foraminiferal packstones becoming wackestones a short distance above the base. (thickness: 5–40 m; age: Miocene, Aquitanian to Oligocene, Chattian); (2) Middle Globigerina Limestone Mb. (Mmg), a planktonic foraminifera-rich sequence of massive, white, soft carbonate mudstones locally passing into pale-grey marly mudstones. The sequence is absent from E Gozo but thickness significantly increases towards the west and north (thickness: 0–15 m; age: Miocene, Aquitanian to Burdigalian); (3) Upper Globigerina Limestone Mb. (Mug), a tripartite, fine-grained planktonic foraminiferal limestones sequence (except in W Gozo) consisting of a lower cream-colored wackestone, a central pale grey marl and an upper pale cream-colored limestone. It is conformable in eastern outcrops but locally lies above a hard ground and erosion surface W of Għarb (thickness: 2–15 m; age: Miocene, Langhian).

Blue clay formation (Mbc) The Mbc consists of blue/grey pelagic marls interbedded with thick paler layers with higher carbonate content (less than 30%). Kaolinite is the main clay mineral present within the formation, followed by chlorite, palygorskite, illite and smectite. The maximum thickness of the Mbc is about 75 m,

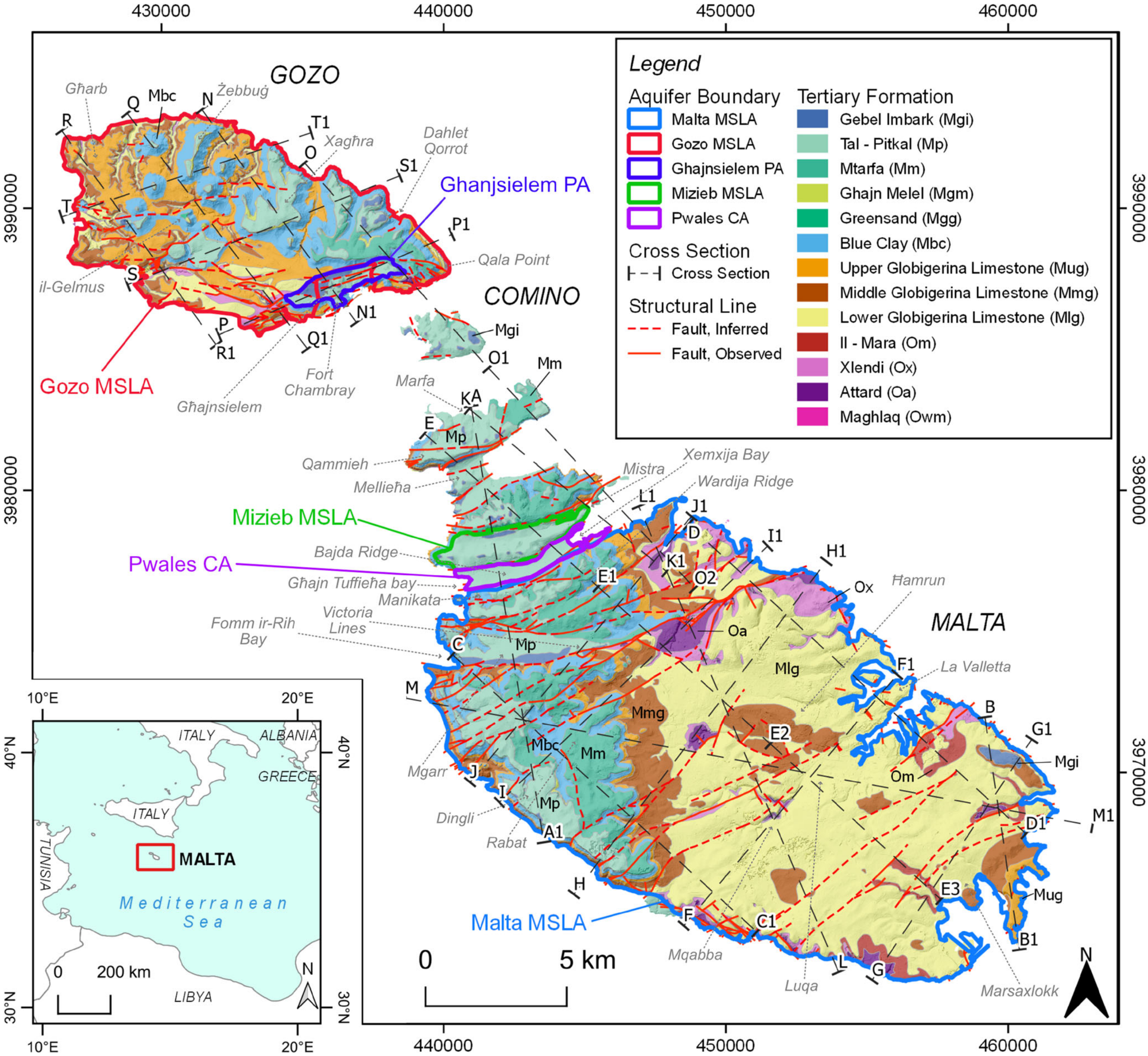


Fig. 3 Malta archipelago's main five aquifers and cross-section profiles realized according to the reference geological map (modified from OED 1993). All the geological sections can be consulted in the electronic supplementary material (ESM)

recorded at Xagħra (northern Gozo) and on the western coast of Malta, north of Fomm Ir-Rih Bay.

Greensand formation (Mgg) The Mgg consists of poorly cemented bioclastic and glauconitic limestones deposited in a warm marine environment. Thin layers (generally less than 1 m thickness) separate the Upper Coralline Limestone from Mbc across all the Maltese archipelago. However, due to its angular unconformity, significant hiatus and bioturbation (particularly in the eastern part of Malta), the Mgg formation outcrops only in the area of Il-Gelmus (Gozo), where it attains its thickest development of 11 m.

Upper coralline limestone (UCL) The UCL Formation is a shallow-water carbonate platform sequence, exhibiting complex facies deposited in very shallow marine environments from shallow subtidal to intertidal and supratidal. It reaches a maximum thickness of 104 m at Comino Island and Mellieħa (northern Malta). Four members of the UCL formation have been defined, all characterized by several lithological variations, laterally and vertically: (1) Ghajn Melel Mb. (Mgm), composed of massive bedded dark to pale brown foraminiferal packstones with glauconite, above a basal erosional surface in western Gozo (thickness: 0–16 m; age: Miocene, Late Tortonian); (2) Mtarfa Mb. (Mm), mainly made of massive to thickly bedded carbonate mudstones and wackestones, yellowish at the base, unconformable above the Greensand Fm. in western outcrops. Carbonates become white and chalky in the upper portion of eastern outcrops. (thickness: 2–16 m; age: Miocene, Late Tortonian); (3)Tal-Pitkali (Mp), composed of pale grey and brownish-grey coarse grained wackestone and packstones containing significant coralline algal, mollusks and echinoid bioclasts. Reefs are best developed in eastern Gozo, especially N of Dahlet Qorrot. Similar structures, with patch-reefs in the west occupy most of the island of Comino; (4) Gebel Imbark (Mgi), that are hard pale-grey carbonates deposits now restricted to erosional outliers and syncline cores (thickness: 4–20 m; age: Miocene, Early Messinian).

Quaternary deposits (Q) Quaternary deposits, mostly Pleistocene in age, are limited to slope scree, raised beach deposits, cliff breccias, and sedimentary covers (of valleys and caves). They are of limited hydrogeological importance except where valley fills occur at sea level such as at the coastal end of the Pwales and Qammieh aquifer systems (northern Malta); the first of these constitutes a coastal groundwater body that is object of the present study (Fig. 3).

Hydrogeology

The geological succession described in the preceding directly influences groundwater circulation in the Maltese islands. The thick layer of Blue Clay locally allows the overlapping of two carbonate aquifers mainly hosted in UCL and LCL formations. Therefore, in accordance with the local structural asset of the Maltese archipelago, the following typologies of groundwater bodies can be distinguished (Lotti et al. 2021):

1. Sea-level groundwater bodies developed mostly in the LCL formation as freshwater lenses floating over seawater and locally referred as MSLAs. These groundwater bodies are ubiquitous and occur extensively in Malta, Gozo and Comino. MSLAs are also present where the UCL forms synclinal structures (basins and troughs) over the Mbc at sea level, and storage occurs within a thick saturated zone which reaches its maximum depth at the base of the syncline.
2. Unconfined (phreatic) perched groundwater bodies (perched aquifer, PA) hosted in the UCL formation perched over the Mbc formation. The perched aquifers overlie, in western Malta and in Gozo, the MSLAs. Perched aquifers are absent in central and eastern Malta where the UCL and the clay aquitard have been completely eroded.
3. Coastal groundwater bodies (coastal aquifer, CA) occurring in depressed valley areas within the UCL formation where the Mbc lies below sea level and freshwater is laterally bounded at its contact with seawater (e.g. Pwales, Mellieħa and Marfa).

The present study deals with the main aquifer (Fig. 3) actually and/or potentially harmed by salinization such as Malta MSLA, Gozo MSLA, Mizieb MSLA (type a) and Pwales (type c). The perched aquifer of Għajnsielem was also included (type b), while other perched aquifers such as the Rabat plateau and the Mgarr aquifer in Malta are not considered. Hydraulic properties, groundwater heads and freshwater/saltwater interface depth were mostly available for Malta MSLA, as described in Lotti et al. (2021).

Geological reconstruction

The existing geological conceptual model (OED 1993) was improved and detailed in this work by realizing several geological cross-sections drawn according to the main geological features (Fig. 3**;** all the geological sections can be consulted in the ESM), then integrated by hydrogeological data to better define the initial hydrogeological conceptual models of the Malta archipelago's main aquifers.

About 20 new geological cross-sections at scale 1:25,000 were drawn for this study, modifying the three sections provided by OED (1993), as the basis of the hydrogeological conceptual model to be utilized for the NECoM (Lotti et al. 2021). In particular, this study improved them (and increased their number) by utilizing other data such as deep borehole log data provided by EWA, literature maps and articles, as well as previous technical reports (for example Pedley et al. 1976; BRGM 1991; Dart et al. 1993; Pedley 2011; Sapiano 2015; Prampolini et al. 2018a, b), in order to intercept all the main structural features, covering some recent uncovered areas, and crossing all the main islands through Comino (cross-section O-O1-O2 in Fig. 3**.** All original sections are provided as ESM). The cross-section profiles were extracted by intersecting the digital terrain model (DTM; spatial resolution 1 m, from ERDF project LIDAR data of 2012 provided by MEPA 2013). Note that the DTM was corrected by filling the anomalous No Data pixels within the inner areas of Malta and Gozo islands. This correction was performed by interpolating the voids through the "Elevation void fill" algorithm (ESRI 2019). Moreover, the filled DTM was spatially corrected to fit the existing geographical data (i.e. base maps such as Google Satellite).

All cross-sections were spatially projected in an explorative three-dimensional(3D) model (Fig. 4), in order to assess the resulting quality and their fit on both the morphological profile (on a vertically exaggerated DTM) and the geological map data. Once the assessment on the 3D explorative model was performed the hand-made cross-sections were skewed to fit the original 1:1 profile extracted from the DTM. The skewed geological cross-sections were then overlapped with the

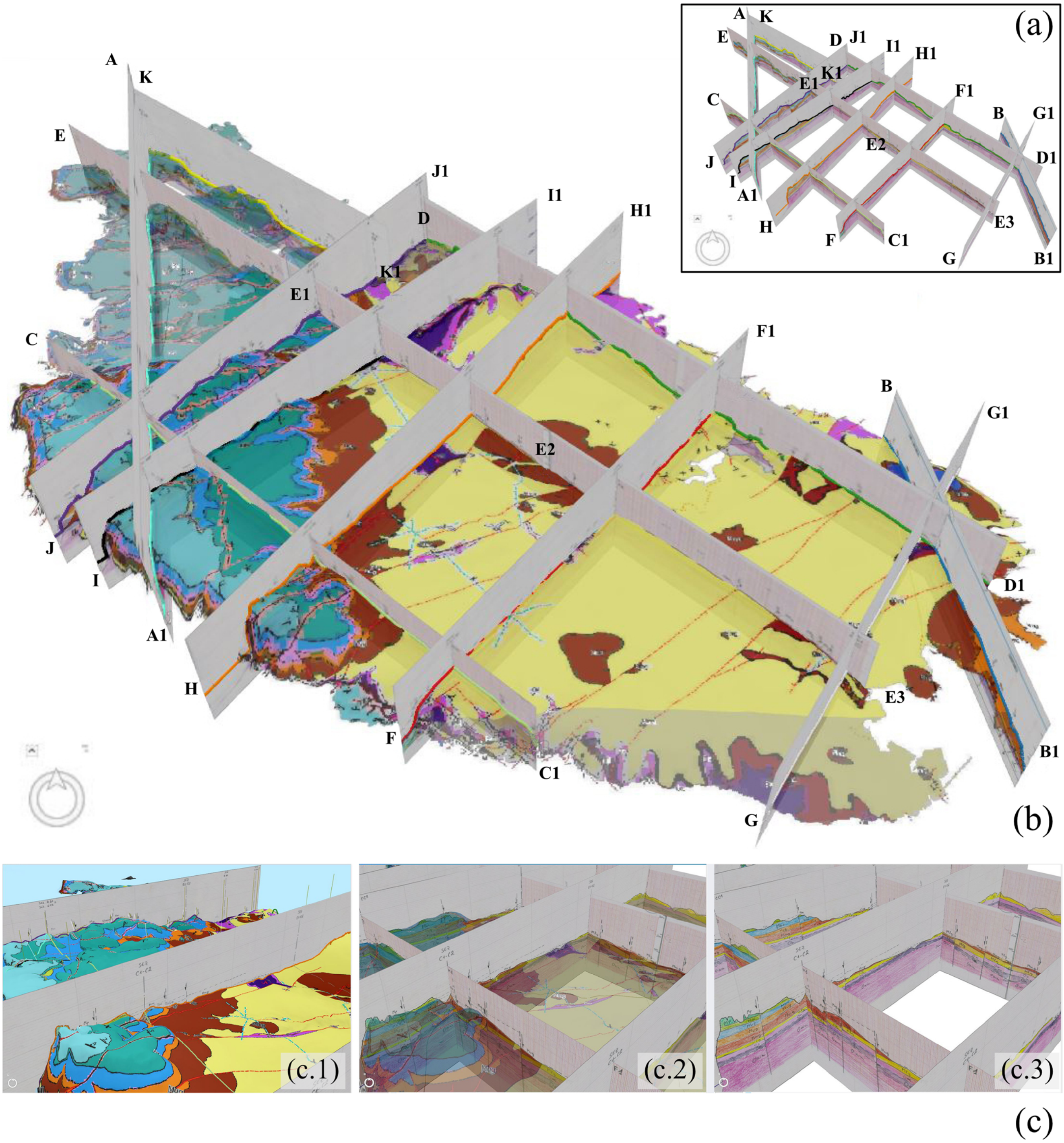


Fig. 4 **a**Three-dimensional(3D) projection of some selected geological cross-sections (vertical scale factor 5); **b** 3D projection of some selected geological cross-sections (vertical scale factor 5) and the geological map is draped on the DTM (the light blue dashed lines represent the water galleries' pathways); **c** Quality assessment of the 3D geological cross-sections junctions (vertical scale factor 5) by means of cross-sections cutting the geological map (raster on DTM); c.2 as for c.1, but in transparency; c.3 shows the intersections of geological cross-sections

spatially referenced profile and digitized using computer-aided design software (CAD) to reconstruct the geological boundaries of each formation and members on a 3D georeferenced space. Each digitized cross-section geological boundary was merged at the cross-sections' junctions to create a single polyline representing a single 3D geological boundary.

The 3D georeferenced polylines obtained were interpolated together with borehole stratigraphy information (Fig. 5) and geological outcrops, to build a geological conceptual model representing the main geological formations beds (UCL, Mbc, GL) of the Maltese archipelago main islands. The stratigraphic data were collected from EWA and other literature sources—e.g. Sapiano (2020); Sapiano et al. (2015); BRGM (1991); Costain (1958a), 1958b); Royal Engineers (1952)—then screened in order to detect the reliable data and discard the data presenting inconsistencies within the borehole data itself or with the geological map.

The boundaries of each geological formation were extracted from the spatially adjusted geological map as lines corresponding to the polygon boundaries. Aiming to get only boundaries representing a depositional geological contact, the line features overlapping faults or seashores were excluded. The resulting vertices were densified until reaching a maximum distance from two connected vertices of the same line equal to 10 m. While this may seem excessive for its intended use or even computationally inefficient, in reality it was mainly necessary to reproduce the minimal displacements that characterize several normal faults in the archipelago. Once the vertices were densified, an absolute elevation value obtained by the bathymetry DTM integrated raster was assigned to each vertex. Finally, all the vertices were extracted as point features, containing as main attributes and geometric properties all the 3D spatial information (North, East and absolute elevation). Once all the available information was collected and homogenized as 3D points, several interpolators—such as inverse distance weighting (IDW), ordinary kriging, thin plate splines, kernel interpolation—were assessed in order to choose the most effective. The "spline with barriers" (ESRI 2019) was the interpolation algorithm with the best case-specific performance, due to the resulting surfaces with faults (the boundaries of the main sinkholes were also included as barriers), close to the real data, and local trends were respected, even if a trial-and-error procedure was required by adding "dummy points" for keeping the interpolation under control. The interpolator performances, which are generally too basic for inferring local variation of geological surface, were enhanced by the trial-and-error procedure, in order to reproduce estimated phenomena at the local level. The geological surfaces were then clipped on the base of the geological map, in order to obtain several different parts that finally merged into a model. Such a model ultimately consists of a

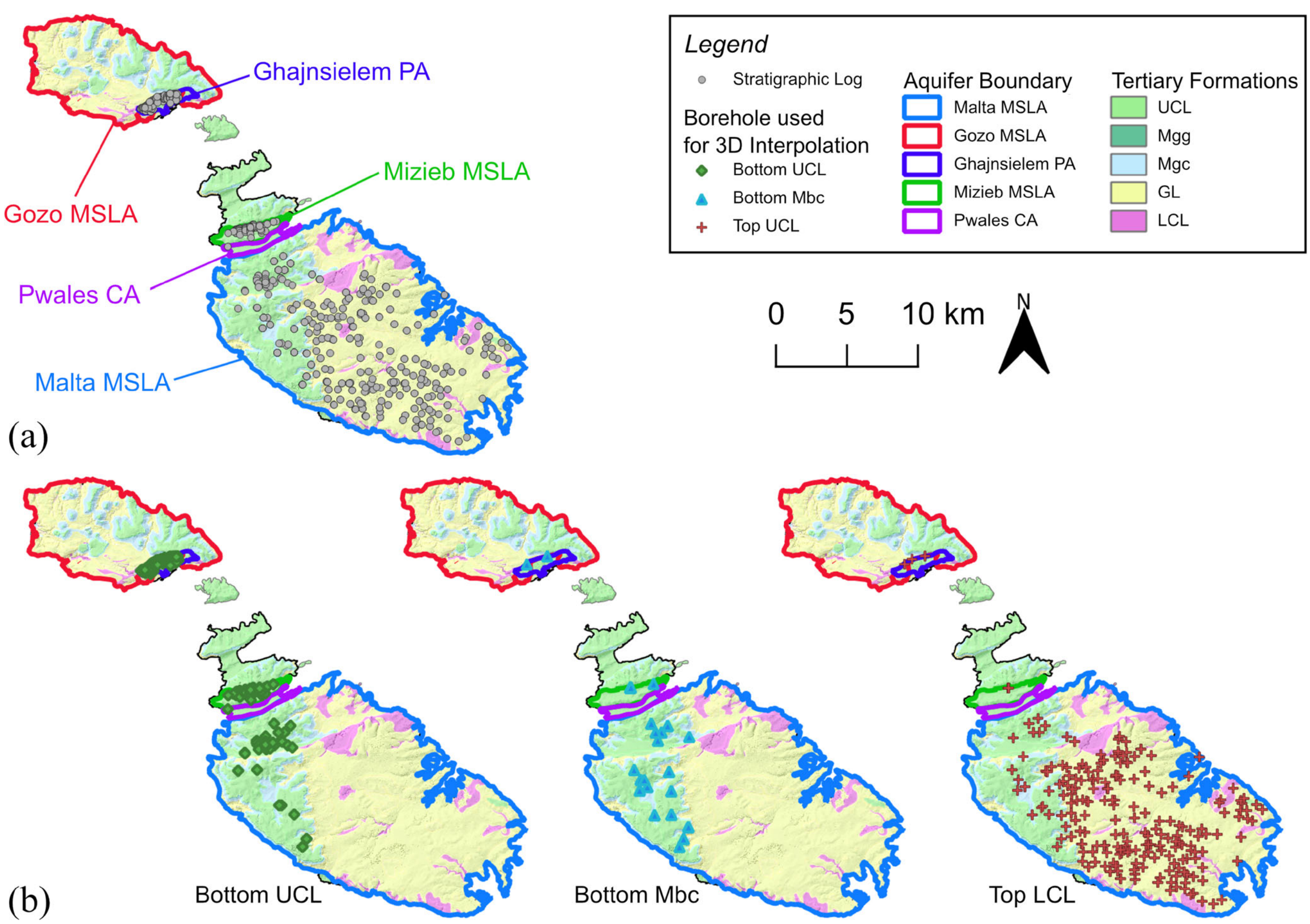


Fig. 5 Borehole stratigraphic **a** data collected and **b** data utilized to interpolate the main formation surfaces (bottom of the UCL, bottom of the Mbc and top of the LCL)

geological conceptual model corroborated by the presence of three interpolated formation tops, very useful also for a proper assessment of transmissivity values to be assigned to the studied aquifers (Fig. 6).

Hydrogeological initial parameters

The climate of the Maltese islands is typically semiarid Mediterranean, characterized by hot, dry summers and mild, wet winters. During the summer season, particularly from June to August, Malta is characterized by dominant high atmospheric pressure resulting in high temperature and very rare rainfall (SEWCU 2015). The rainfall time series data analysis reveals a mean annual cumulative rainfall of about 553 mm on Malta Island and 450 mm on Gozo Island, generally concentrated between October and February, but with high seasonal and interannual variability (Sapiano 2008; Sapiano 2015; Stuart et al. 2010).

Rainfall events are characterized by storms of high intensity but relatively short duration. Most runoff occurs after heavy torrential rain. This is the only time when surface-water runoff flows along some of the major valleys (SEWCU 2015). Rainfall, while being the principal groundwater source, is not the only source recharge for the Maltese archipelago aquifers since another source of recharge (artificial) is due to leakages from the potable supply and sewerage network.

One of the most important sources of water over the Maltese archipelago is represented by the deep water galleries, a kind of storage reservoir system mainly dug into Upper Coralline or Greensand strata since the Medieval period (Buhagiar 2008) in the central and southern part of Malta Island, maintained and managed until today for underlying water source exploitation (the main ones are shown in the ESM). Their importance is not only due to the considerable volume abstracted each year (around 1 Mm^3, 10% of the total Malta Island public abstracted groundwater according to EWA), but also because the entire potentiometric surface of Malta and Gozo MSLA is dominated by the water head elevation inside the galleries, which cover a total length of 46 km. Regardless of their importance, the actual contribution of each gallery section and the local outflows from fractures occurring along the length of the gallery system are unknown, as well as their correct geometry and elevations—in m above mean sea level (amsl). Note that only periodical data on heads, chemical-physical parameters and discharge at each pumping stations are available.

In terms of the hydraulic properties of the aquifers, Maltese limestones (UCL, GL and LCL) have relatively high primary porosity. Primary porosity of the GL was found to be between 32 and 40% (Cassar et al. 2008) and primary porosity of the UCL is reported to be 41–45%. The primary porosity of the LCL is lower and more variable, ranging from 7 to 20% (Table 1). There is little data on matrix permeability, although Bakalowicz and Mangion (2003) suggest that it is generally low, and state that permeability (presumably primary) for the UCL is around 1×10^{-6} cm/s (or 9×10^{-4} m/day). BRGM (1991) reports that permeability is higher in unfractured samples from the Upper

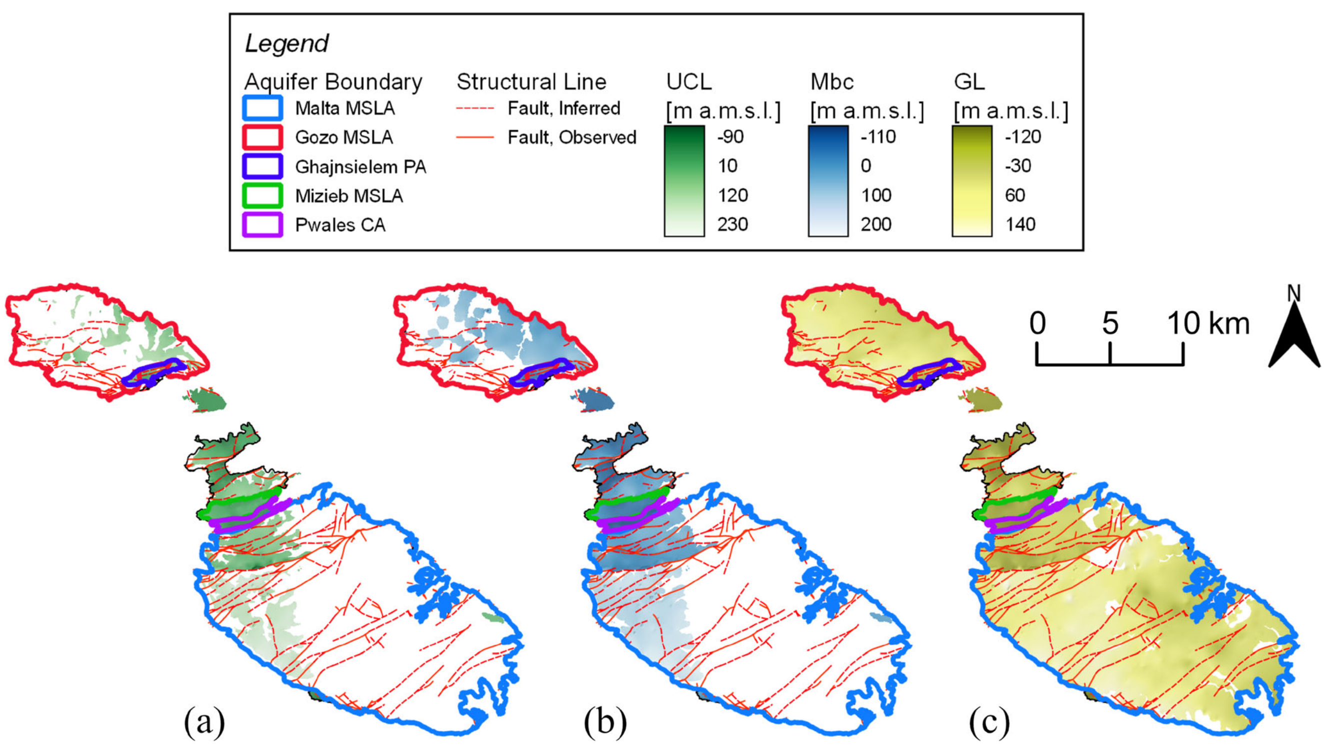


Fig. 6 Reconstructed formational bed of **a** UCL, **b** Mbc, and **c** GL

Table 1 Main hydrogeological parameters (from Stuart et al. 2010; Cassar et al. 2008; Bakalowicz and Mangion 2003; BRGM 1991)

Parameter	UCL	GL	LCL
Primary porosity [%]	41–45	32–40	7–20
Effective porosity [%]	–	–	10–15
Matrix permeability [m/day]	9×10^{-4}	9×10^{-3} (vertical)	< UCL
Aquifer hydraulic conductivity [m/day]	–	–	35
Transmissivity [m^2/day]	–	–	1–8,640 (geometric mean 259)
Diffusivity [m^2/s]	–	–	1.4–322 (geometric mean 26)

Coralline than the Lower Coralline without adding any further information. They also report that vertical permeability in the Globigerina Limestone is 1×10^{-7} m/s. Flow in the matrix in all three limestones is therefore likely to be slow. For the LCL, results of 45 pumping tests are reported in BRGM (1991), covering transmissivity values from 10^{-1} to 10^{-5} m^2/s, with a geometric mean of 3×10^{-3} m^2/s. Even though the hydraulic conductivity parameter is often carefully characterized, the aquifer bottom that defines the exploitable thickness and allows one to calculate the transmissivity is often not adequately defined. So, this is one of the leading factors for the detailed interpolation of the three main formation tops, as limits of the main hydrogeological units, aimed to adapt the transmissivity values found in literature. In Stuart et al. (2010), LCL transmissivity from pumping tests is between 1×10^{-4} and 1×10^{-3} m^2/s and hydraulic conductivity is reported as 4×10^{-4} m/s. Diffusivity (i.e., transmissivity storage coefficient ratio) was estimated by BRGM (1991) in the same report through 41 tide tests performed in 28 boreholes, ranging from 1.4 to 322 m^2/s, with a geometric mean of 26 m^2/s, confirming the high variability of the hydraulic parameters (Table 1). No hydrogeological parameters are available for Mbc.

Results and discussion

The Maltese islands' geological and hydrogeological conceptual models based on the geological surfaces interpolated in the present study are described in this section. The updated geological conceptual models for the main aquifers are presented by showing, for the sake of briefness, only the cross-sectionsH–H1(Figs. 7a and 9), a portion of A–A1(Figs. 7b, 10 and 11), N–N1(Figs. 8a and 12), P–P1(Fig. 8b and 13). The geological conceptual model built constituted the basis of the hydrogeological conceptual models, discussed in the following separately for each aquifer system Figs. 9.

Geological conceptual model of Maltese archipelago

The Malta Island main aquifer is mainly hosted within the LCL formation (Figs. 3 and 7a). The LCL is continuously present across the whole island of Malta, although it is divided into horst and graben blocks, particularly north of the Pwales Fault. Some major synclines, the Mqabba Syncline, south of Luqa, and the Ħamrun Syncline, south of La Valletta, and the syncline around Marsaxlokk harbor in the south-eastern portion of the island, characterize the central and southern portion of Malta.

The Mizieb area, located in the northern region of Malta, is mainly formed by the UCL formation (Fig. 3). The Mizieb syncline occurs on the downthrown side of the Mizieb-Mistra Fault that cuts across Mellieħa Ridge from west to east, dissecting the northern part of Malta into several ridges and valleys. The rim of the syncline is determined by the height of the clay on its side of the fault. The lowest point occurs at 14.9 m amsl on the southern flank at Bajda Ridge overhanging Pwales Valley, and 15.2 m amsl on the eastern saddle leading to Mistra.

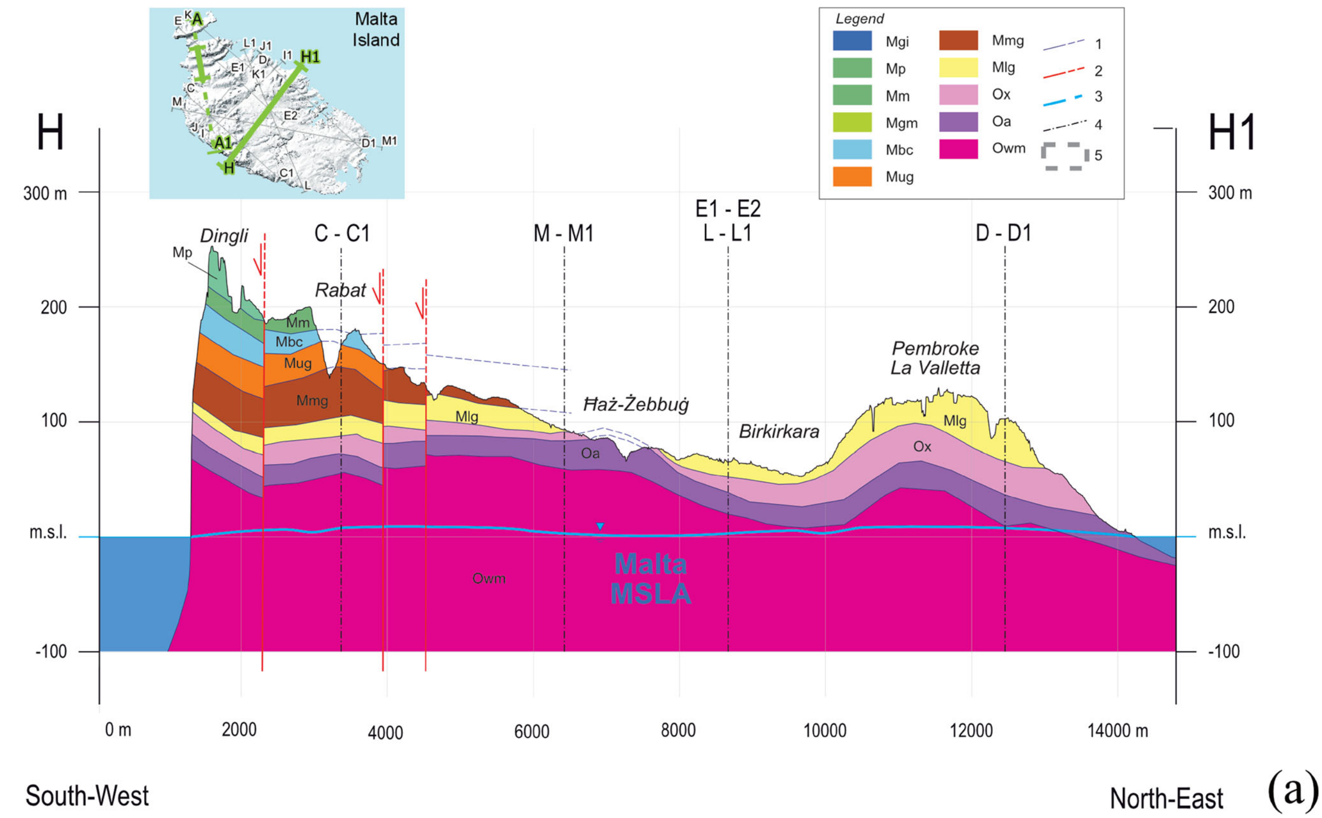
The Pwales coastal plain in northern Malta lies on a downthrown syncline of UCL, within the two faults bounding Wardija Ridge and Bajda Ridge (Figs. 3 and 7b), which sits over BC formation at an elevation of 21 m amsl in the western side near Għajn Tuffieħa and it dips below sea-level to a depth of around –30 m below sea level at the eastern side along Xemxija Bay.

The main aquifer of Gozo Island is mostly hosted in the LCL (Fig. 3), except for two areas: (1) a relatively small area in the south-eastern part of Gozo, around the harbor of Mgarr, where the Mbc occurs at sea-level, due to faulting; (2) a wider area in the north of the Gozo island, around Xagħra, where due to deformative structures, the GL can be found at sea level (Fig. 8a).

The Ghajnsielem area is characterized by the carbonates of the UCL formation, enclosed between the Għajnsielem-Qala Fault and the Mbc (South-Eastern Gozo; Figs. 3 and 8b). In the central area of Għajnsielem, a syncline, bounded by two faults (the Għajnsielem-Qala Fault and a subsidiary fault), forms a graben.

Hydrogeological conceptual model

The geological conceptual models of the Maltese islands, achieved by combining borehole data logs, types of



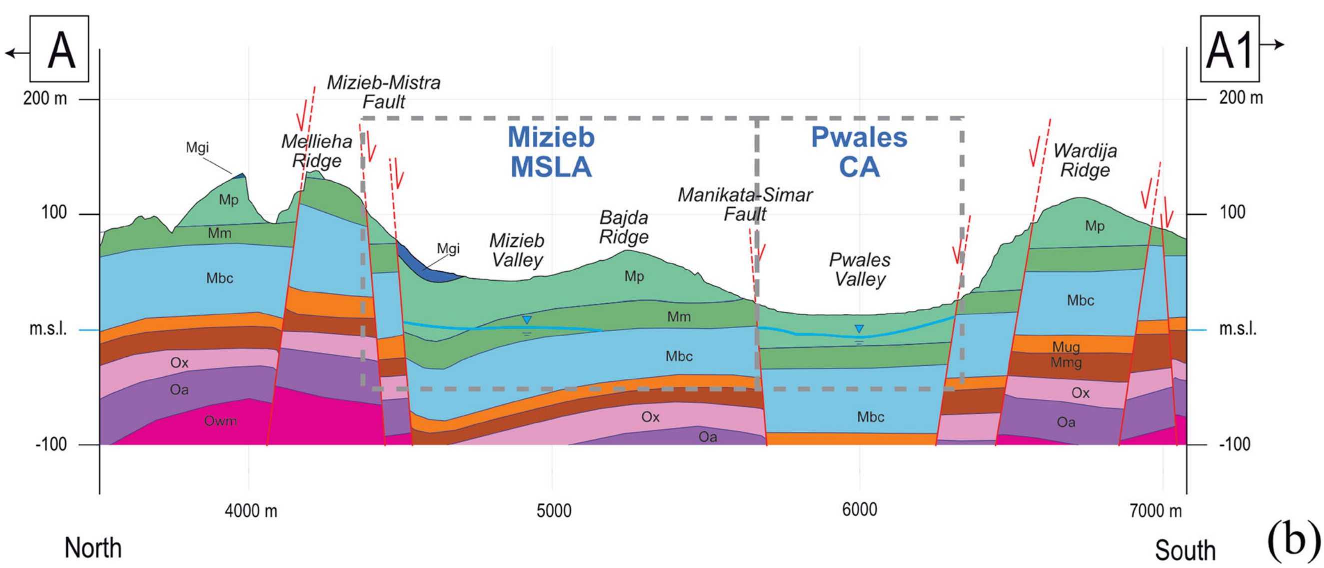


Fig. 7 **a** Malta MSLA geological conceptual scheme across section H–H1(Fig. 3); **b** Mizieb MSLA and Pwales CA geological conceptual schemes across section A–A1 (Fig. 3, starting at 3,500 m from the initial point "A"). Legend: colored polygons - geological formations; 1 - geological contacts (observed or inferred); 2 - faults (observed or inferred); 3 - estimated mean hydraulic head; 4 - other vertical geological sections intersecting the H-H1 section; 5 – aquifer locations in A–A1 section; vertical scale factor 5

groundwater bodies, and geometry of the aquifer coming from spatialization of the three surfaces separating the main hydrogeological units, were the basis of the hydrogeological conceptual models of the five main studied aquifer systems; these are discussed separately here. Furthermore, the recognized hydrogeological units are coherent with the geological cross-sections and the geological formations (see section "Stratigraphy" and the ESM). In particular, as exposed by Lotti et al. (2021) in detail, these units were identified and obtained by merging

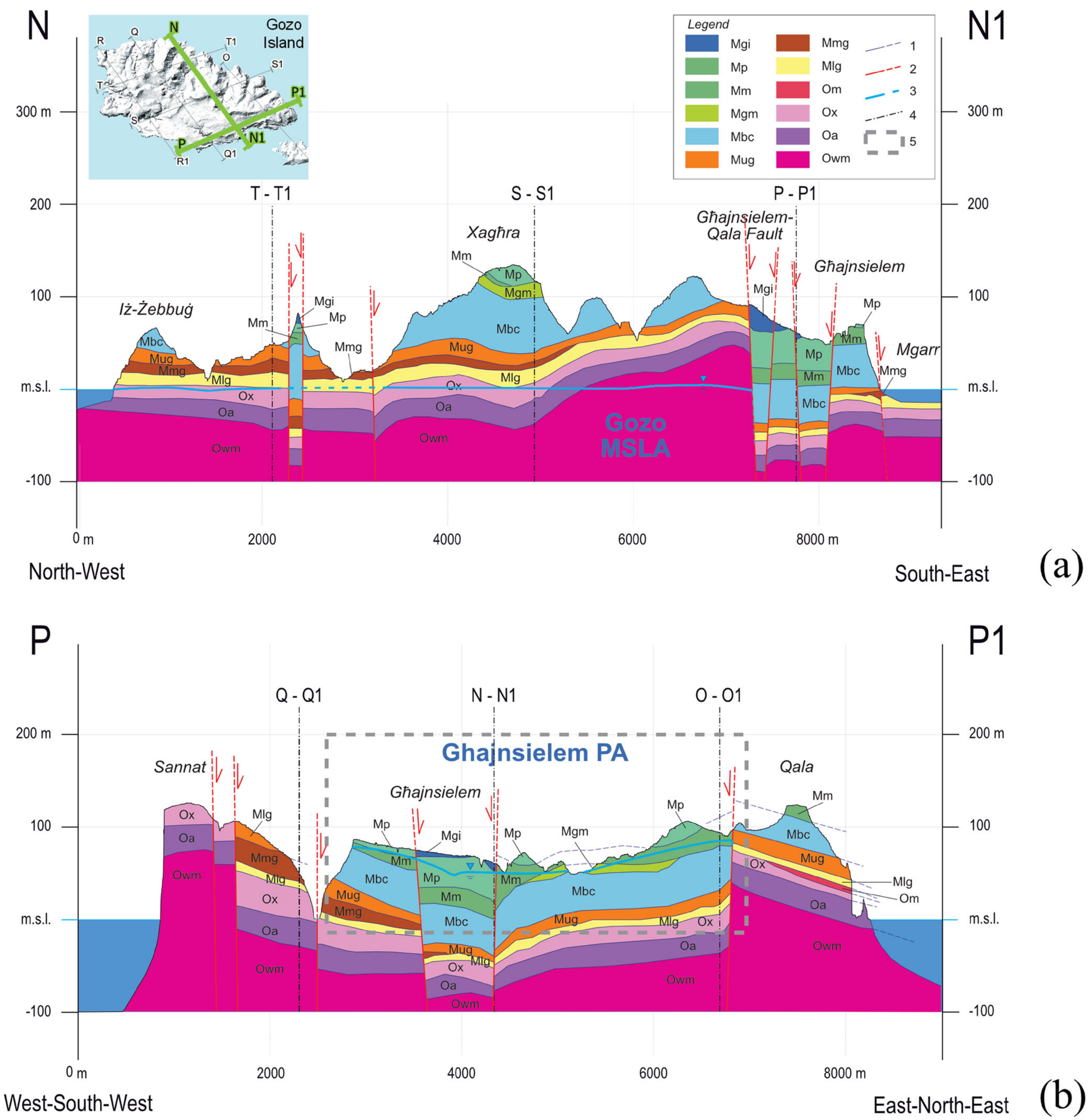


Fig. 8 **a** Gozo MSLA geological conceptual scheme across section N–N1(Fig. 3); **b** Ghajnsielem PA geological conceptual scheme across section P–P1(Fig. 3). Legend: colored polygons - geological formations; 1 - geological contacts (observed or inferred); 2 - faults (observed or inferred); 3 - estimated mean hydraulic head (water table or locally confined); 4 - other vertical geological sections; 5 - area of interest of Ghajnsielem PA; vertical scale factor 5

members and formations hydraulically similar, and by handling several kinds of data, such as transmissivity (reliably assessed), head (spot measurements taken in 1944, 1969 and 1990, plus the continuous monitoring data starting in some wells from 1998 till 2015, provided by EWA), pumping and tide tests (BRGM 1991), abstraction time series (provided by EWA), water losses (provided by Water Service Corporation of Malta), and geochemical analyses (provided by EWA). This conceptual model then provides a basis for construction of the numerical model of the Malta MSLA (Lotti et al. 2021) as well as the other main aquifers of the Maltese islands.

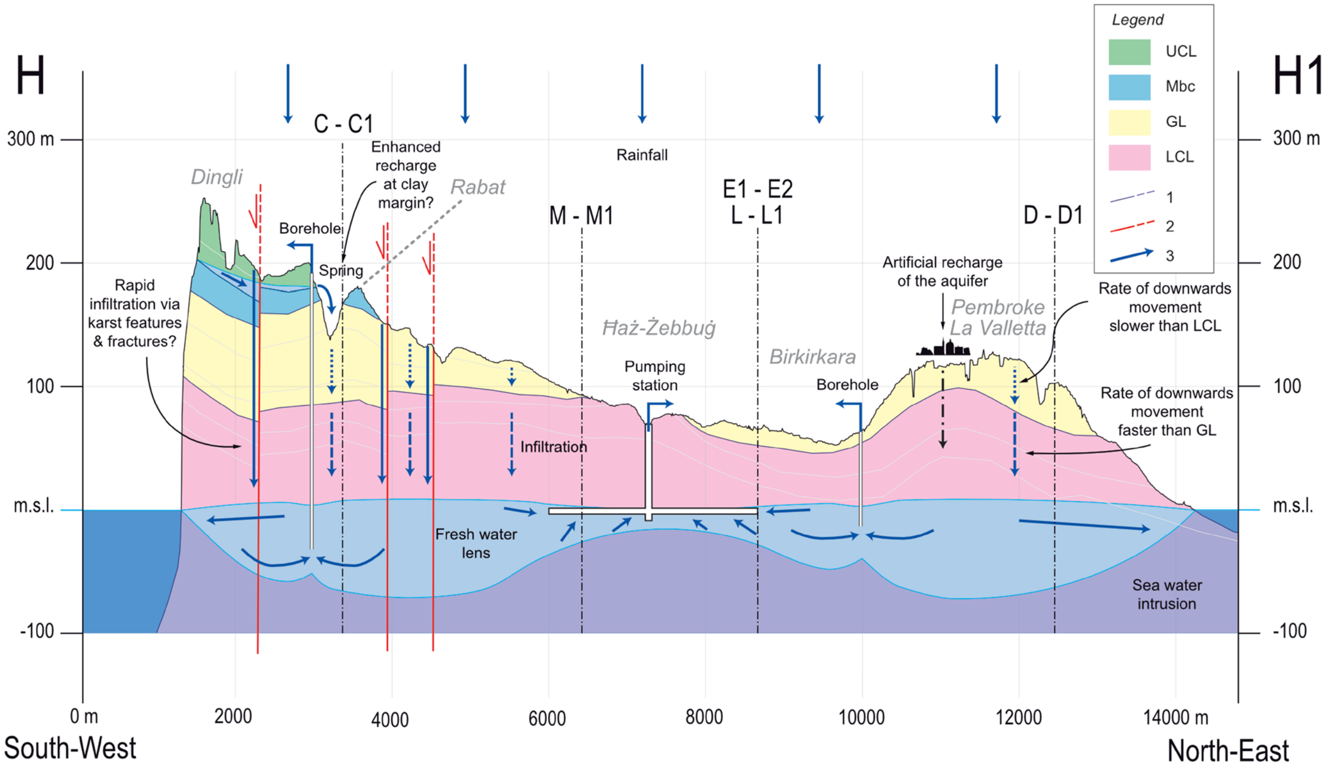


Fig. 9 Malta MSLA hydrogeological conceptual scheme across section H–H1(Fig. 3 and Fig. 7a). Legend: Colored polygons - hydrogeological units; 1 - hydrogeological units contacts; 2 - faults (observed or inferred); 3 - flow direction. Artificial recharge, mostly due to pipelines leakage, of the aquifer is outlined under the "La Valletta" city skyline; vertical scale factor 5

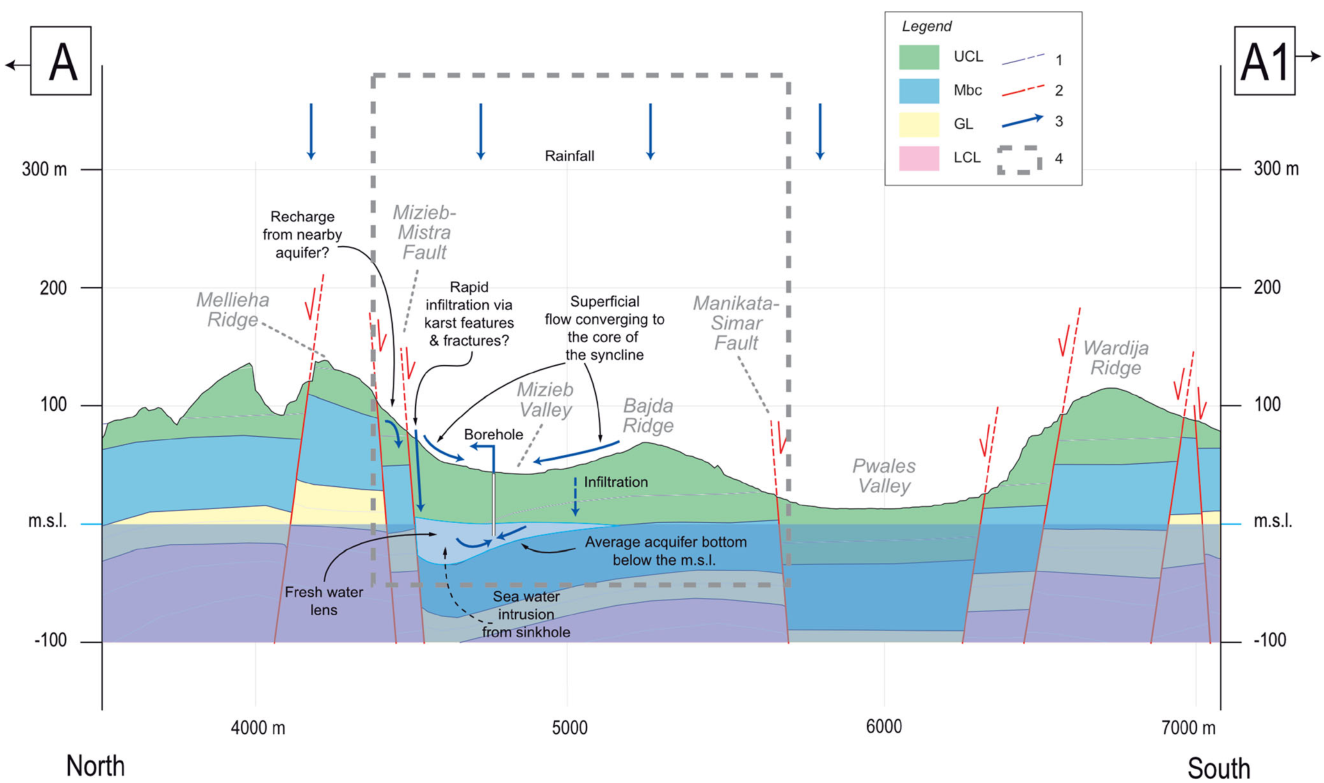


Fig. 10 Mizieb MSLA hydrogeological conceptual scheme across section A–A1 (Fig. 3, starting at 3,500 m from the initial point "A"). Legend: Colored polygons - hydrogeological units; 1 –hydrogeological-unit contacts; 2 - faults (observed or inferred); 3 - flow direction; 4 - Area of interest of Mizieb MSLA; vertical scale factor 5

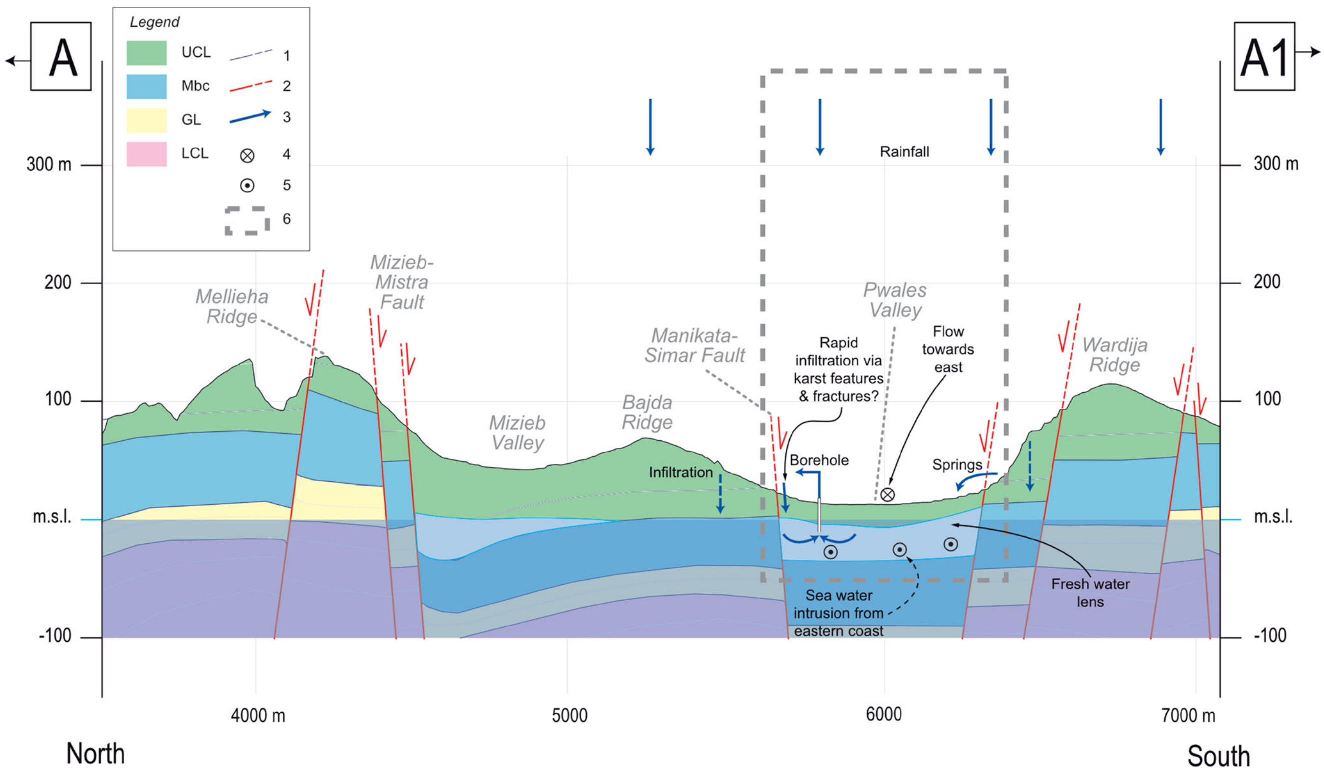


Fig. 11 Pwales CA hydrogeological conceptual scheme across section A–A1 (Fig. 3, starting at 3,500 m from the initial point "A"). Legend: Colored polygons - hydrogeological units; 1 –hydrogeological-unit contacts; 2 - faults (observed or inferred); 3 - flow direction; 4 - superficial and groundwater flow path towards the eastern sea coast; 5 sea-water intrusion from the eastern coast; 6 - area of interest of Pwales CA; vertical scale factor 5

Malta mean sea-level aquifer

The Malta MSLA is the wider aquifer of the archipelago, with an extension of about 217 km^2; it is mainly hosted within the LCL formation continuously present across the whole island, although it is divided into horst and graben blocks, and it is mostly bounded by the Mediterranean Sea (Figs. 3 and 7a). This groundwater body extends over the whole southern and central parts of Malta Island, under the Rabat-Dingli Plateau, the Mgarr Plateau, and the Wardija Ridge up to the Pwales Valley at its northern boundary. Two main synclines, the Mqabba Syncline and the Ħamrun Syncline, can be considered as a partial boundary between the central and southern portion of the Malta MSLA, since the GL present at the core of both synclines is characterized by lower hydraulic conductivity than the LCL (Morris 1952). The syncline around Marsaxlokk harbor could be assumed as another partial boundary in the Malta MSLA.

The Malta MSLA can be assumed as a lens-shaped body of freshwater floating on the denser seawater, with a thickness of freshwater below sea level theoretically equal to around 36 times the piezometric head, according to the density ratio of the well-knownGhyben–Herzberg formula (see for instance Verruijt 1968). For most of its extent, the Malta MSLA aquifer is mainly unconfined (Fig. 9), with local exceptions where the GL formation dips below the sea level (like in the eastern area of the Malta Island).

The natural recharge happens predominantly through fractures in the overlying GL outcrops, but an additional indirect recharge is assumed as leakage from the perched aquifer through possible faults in the Mbc layer. In fact, according to Stuart et al. (2010), the Mbc layer might be considered as an aquitard between UCL and LCL, but, nevertheless, groundwater levels monitored below the perched aquifer present a nonzero correlation with precipitation, in particular, closer to the Victoria Fault, thanks to the contribution of freshwater seeping through it in the north-western boundary of Malta MSLA (Morris 1952; BRGM 1991).

The potentiometric surface, influenced by recharge, water galleries' geometry, abstraction and aquifer properties, reaches a maximum elevation of only 3 m amsl, meaning that: (1) the aquifer can be assumed unconfined, since the elevation of the GL rarely dips below 3 m amsl; (2) the aquifer transmissivity is generally high; (3) the bottom elevation of the abstraction galleries could play a fundamental role in controlling the whole potentiometric surface, being mostly placed in the aquifer recharge areas rather than in the discharge areas (i.e., at lower elevations, closer to the coastline).

The water salinity (BRGM 1991) and the distribution of chloride and other major ion concentrations (Stuart et al.

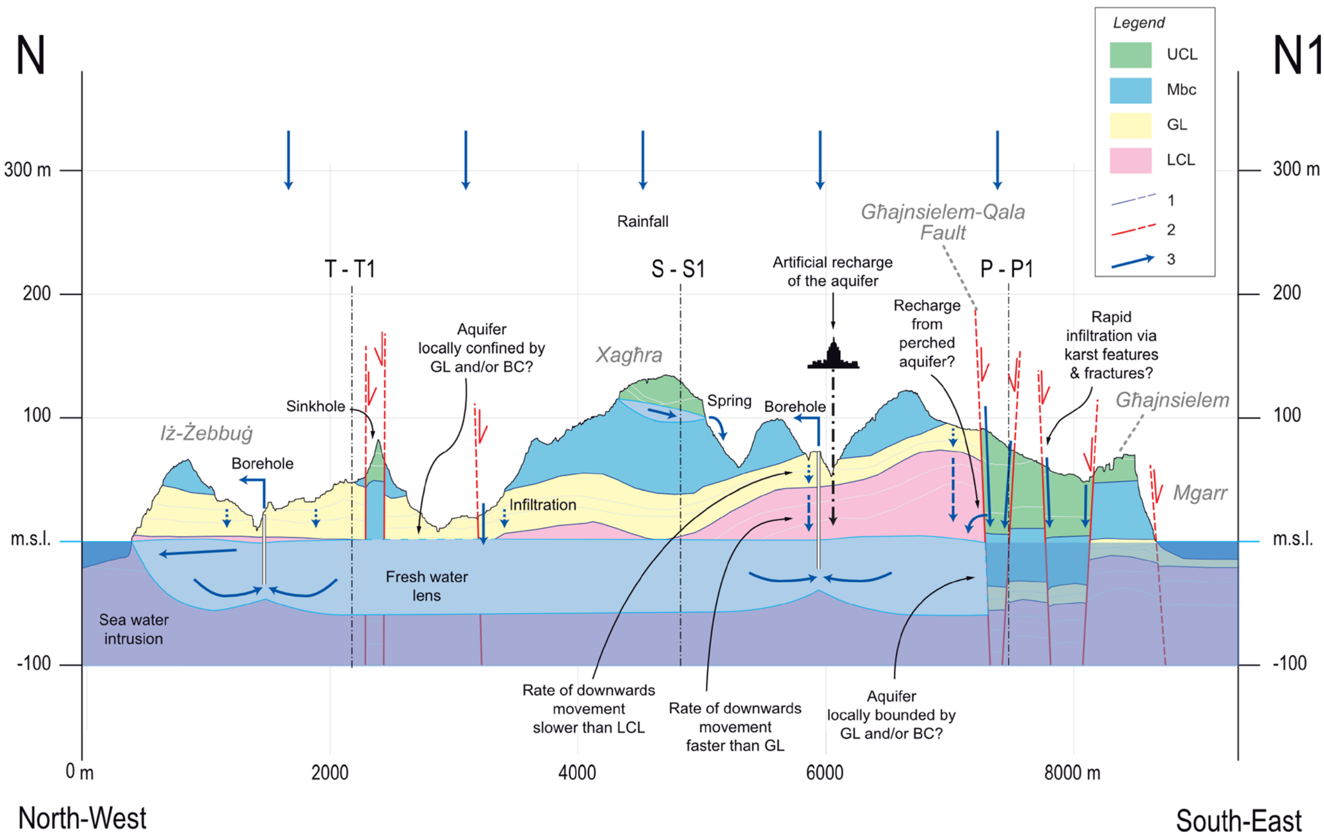


Fig. 12 Gozo MSLA hydrogeological conceptual scheme across section N–N1(Fig. 3). Legend: Colored polygons - hydrogeological units; 1 – hydrogeological-unit contacts; 2 - faults (observed or inferred); 3 - flow direction. Artificial recharge, mostly due to pipelines leakage, of the aquifer is outlined under the "Għajnsielem" village skyline; vertical scale factor 5

2008) show the pattern of saline intrusion, with high values for some parts of the south of Malta MSLA. Abstraction (potable supply, irrigation, secondary domestic and industrial purposes) leads to vertical saline upconing and lateral seawater intrusion and therefore to a general increase in salinity in time. On the other hand, the isochlores show also that local intensification of faulting and fissuring in the LCL, like in the neighborhood of Victoria Lines Fault, may facilitate the dissipation of freshwater to the sea (Morris 1952).

Mizieb mean sea-level aquifer

The Mizieb MSLA is composed of the UCL formation (northern Malta; Fig. 3). It is bounded by the Mizieb-Mistra Fault (north) and the Manikata-Simar Fault (south). The Mizieb syncline is the largest 'closed' basin structure known within the Maltese islands; the occurrence of the Mbc underlying the UCL in a synclinal structure represents an ideal groundwater storage feature (7b).

Within the Mizieb MSLA the UCL reaches a maximum thickness of about 100 m with considerable variations in hydrogeological properties due both to primary and secondary permeability. Reefal facies prevail along the western flank of the syncline passing to lagoonal facies in the east, while intense fracturing along the fault plane plays an important role in the groundwater flow of the Mizieb MSLA. Mizieb aquifer groundwater flow and quality are also heavily conditioned by the presence of karstic sinkholes (Costain 1958a), especially closer to the Mizieb syncline. The most prominent sinkholes are concealed by surface deposits and soil cover and show a diameter of 90 m. They extend through the UCL, penetrating and breaching the Mbc down to −40 m below sea level and, therefore, bring the saturated zone in direct contact with seawater. As a consequence, the Mizieb MSLA is highly susceptible to seawater intrusion (Fig. 10).

The geological and morphological settings of the area also create preferential superficial flow paths converging toward the main sinkhole structures where the Mbc is deeper. Groundwater flows similarly to the superficial flow, according to the few groundwater heads measured by Costain (1958a).

The increased displacement of the western part of the Mizieb-Mistra Fault, which rapidly increases from 8 to 60 m amsl at the western cliffs in conjunction with the eastward thinning of the Mbc, probably places some part of the previous beds of the syncline in contact with the GL. So, it provides a line of discharge to the sea on the western coast, where GL can be seen to pass below sea level for a considerable distance in the southern flank of the Mellieħa uplift (Morris 1952).

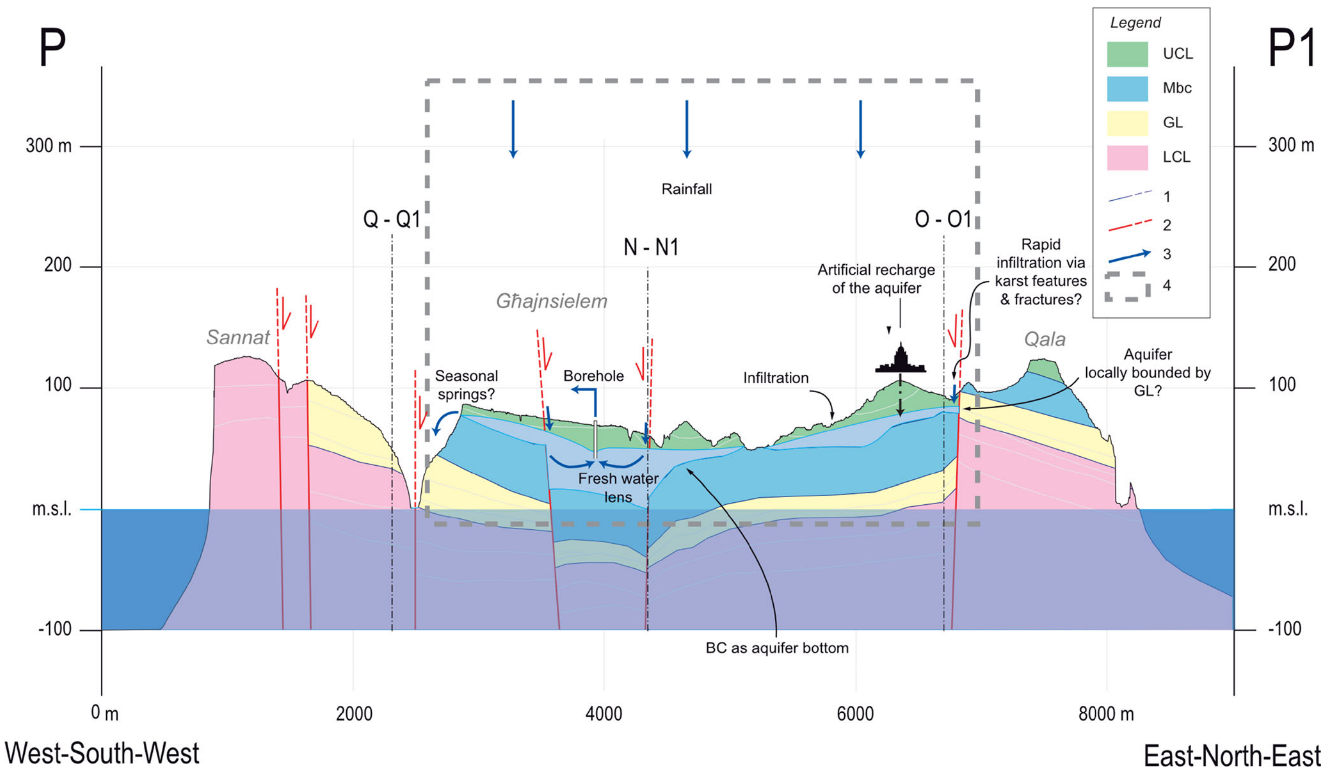


Fig. 13 Ghajnsielem PA hydrogeological conceptual scheme across section P–P1(Fig. 3). Legend: Colored polygons - hydrogeological units; 1 hydrogeological-unit contacts; 2 faults (observed or inferred); 3 flow direction; 4 area of interest of Ghajnsielem PA. Artificial recharge, mostly due to pipelines leakage, of the aquifer is outlined under the "Għajnsielem" village skyline; vertical scale factor 5

Pwales coastal aquifer

The Pwales area is one of the most fertile valleys of Malta and the intensive agriculture activity is maintained by abundant irrigation water. Close to Xemxija Bay, the aquifer forms a small coastal aquifer heavily exploited for irrigation purposes. The valley receives freshwater discharged over the Mbc from several springs at the northern and southern boundaries of the aquifer such as the springs of Wardija. The Pwales CA occurs within a UCL graben (Figs. 3 and 7b) over BC formation that dips below the sea-level toward the east along Xemxija bay, resulting in a limited volume perched above sea level. While at the western end of the valley, where the base of the UCL rises above sea level, the underground drainage of a small portion of the Pwales valley (0.15 km^2) probably discharges into Għajn Tuffieħa Bay but not eastward down the pitch of the main syncline (Morris 1952).

Salinity intrusion processes differ from the MSLA; whereas the MSLA is predominantly affected by vertical intrusion where upconing of seawater intrudes the freshwater lens at the basal interface, at Pwales the intrusion occurs in the form of a quasi-horizontal tongue of seawater spreading from East to West (Fig. 11). The wells located at the western edge of the valley are least susceptible to seawater intrusion as the Mbc is elevated above sea-level(SEWCU 2015), except at the cliff below Torri ta' Għajn Tuffieħa (overlooking the bay of the same name, on the south-eastern border of the aquifer), where a minor synclinal fold brings the horizon down to approximately the mean sea level for several meters (Morris 1952).

Gozo mean sea-level aquifer

The Gozo MSLA is the main aquifer of Gozo Island, mainly hosted in the LCL; it extends at sea level across the whole island (Fig. 3), except around the harbor of Mgarr (south-eastern Gozo), where the Mbc occurs at sea-level, and around Xagħra (Northern Gozo), where the GL at sea level partially confines the aquifer (Fig. 8a). The surface catchment area is mostly covered either by outcrops of the UCL and the underlying Mbc formation or by GL formation, resulting in only small outcrops of the LCL.

The water table of Gozo MSLA is mainly controlled by abstraction and the piezometric surface stands at only a few meters above sea level. Abstraction also leads to regional and local saline upconing and a consequent increase in salinity in groundwater. The relatively low porosity means that the rate of downwards movement in the aquifer matrix will be greater than in the perched aquifers, but the unsaturated travel time will be long in the thicker parts of the aquifer. The limited number of detections of coliforms (Stuart et al. 2010) indicates that rapid transport from the surface to the aquifer is limited except where the LCL outcrops at the surface (Fig. 12).

The residence time of the water in the saturated zone is in the range of 25–60 years(Stuart et al. 2008). Combined with the low estimates of transmissivity from pumping tests, this suggests, as for Malta MSLA, that movement in enlarged solution features may be limited (SEWCU 2015). The distribution of chloride and other major ion concentrations shows the pattern of saline intrusion, with high values for the Gozo MSLA (Stuart et al. 2008).

Ghajnsielem perched aquifer

The Ghajnsielem PA lies in the south-east of Gozo Island (Fig. 3). It is enclosed between the Għajnsielem-Qala Fault (north) and the Mbc (south-east and west)(Fig. 8b). The aquifer area is tilted southwards and ranges in elevation from a maximum of 125 m amsl at Qala, falling south-east and south-west to approximately 75 m amsl along the cliffs. The Ghajnsielem PA is hosted by the highly fractured and cavernous UCL formation. In the central area of Għajnsielem, the syncline forms a downthrown trough, or graben, where the aquifer reaches its widest thickness.

The Ghajnsielem PA lies within the highly fractured and cavernous UCL formation, which reaches a maximum thickness of 87 m and shows considerable variations in permeability and porosity due to its complex geological structure (Fig. 13). The floor of the deepest synclinal depression (graben) corresponds to the top of the Mbc placed at sea level. At the western flank of the graben, Mbc rises to around 60 m amsl, whereas to the east it reaches around 40 m amsl, leaving only limited groundwater discharge paths. The graben has been estimated to have a groundwater storage capacity of 1.9 Mm^3(Costain 1958). Aside from the graben, the deepest clay level of the basin is around 30 m amsl, whilst its rim stands at an elevation of around 80 m amsl. This configuration allows for an estimated storage of approximately 540,000 m^3 assuming a 15% saturation of the UCL (SEWCU 2015). Unlike the graben, the basin is not susceptible to seawater intrusion as its base is 30 m higher than sea level. The piezometric height decreases from south-east to north-west(Costain 1958b). Groundwater is supposed to have a short residence time (Stuart et al. 2008).

Conclusions

A comprehensive review of the geological and hydrogeological characteristics of the Maltese islands has allowed for development of an improved conceptual understanding of five main Maltese aquifer systems namely: the Malta MSLA, Mizieb MSLA, Pwales CA, Gozo MSLA and Ghajnsielem PA.

The geological information gathered from literature review and the borehole log data provided by EWA enabled about 20 new geological cross-sections, drawn as the first stage of conceptualization, aimed to interpolate three main formation tops as limits of main hydrogeological units to be conceptualized. The interpolation method chosen was the "spline with barriers" where the main known (or inferred) geological faults were utilized as barriers, which helped to reproduce the sharp local variations of stratigraphy near the main fault systems.

The resulting geological model was merged with hydrogeological information of the studied aquifer systems, providing the starting point in the NECoM process as, for instance, described in Lotti et al. (2021) for the case of Malta MSLA. In the case of Mizieb MSLA, Pwales CA and Ghajnsielem PA, this work provided the model structure defined by the impervious surfaces that constitute the bottom of the aquifers. As it is known, the aquifer transmissivity is given by the aquifer thickness times the hydraulic conductivity; while great attention and processing effort is usually given to this last parameter, the aquifer bottom (defining the thickness) is often not properly characterized. In the analyzed aquifers, the structural control (bottom geometry and faults) is dominant, and it plays a fundamental hydrogeological control that constitutes the most solid source of information in the numerical model, given the insufficiency of other sources of data.

Along with the deep review of the scientific literature and of the data collected by the Maltese government since the last century, the present study could identify several data gaps in particular for the Mizieb MSLA, Pwales CA, Gozo MSLA and Ghajnsielem PA. Differently from the Malta MSLA, the related numerical models could not go through a proper data assimilation process as the basis of the NECoM approach. The modelling phase could only prepare the "boxes" on the basis of the present geological scheme, to be filled with information as soon as they are collected in the field.

The main geological data gaps, presenting repercussions with respect to understanding the hydrogeological behavior of the system, include the following: (1) water fluxes in both unsaturated and saturated zones; () hydraulic parameters and hydrogeological control determined by faults; (3) the role of fractures also in connection with detailed local geo-structural studies; (4) estimates of the aquifer recharge via leaching from perched aquifers and the associated mechanisms (e.g. through sinkholes, faulting in BC); (5) direct infiltration allowed by GL zones with a higher degree of fracturing; (6) stratigraphic boreholes data for Mizieb MSLA, Pwales CA, Gozo MSLA and Ghajnsielem PA. In addition, the geometry and the degree of fracturing in the main water abstraction galleries needs to be detailed, in particular with reference to the water inflow in each gallery system, along with the relative contribution to water flow from the rock matrix and open fractures. The filling of these data gaps should be the starting point of further studies on the aquifer systems of the Maltese islands.

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Declarations

Conflict of interest Authors disclose any commercial or other associations that might pose a conflict of interest in connection with the submitted material.

References

Anderson MP, Woessner WW, Hunt RJ (2015) Modeling purpose and conceptual model. In: Anderson MP, Woessner WW, Hunt RJ (eds) Applied groundwater modeling. Elsevier, Amsterdam, pp 27–67. https://doi.org/10.1016/B978-0-08-091638-5.00002-X

Bakalowicz M, Mangion J (2003) The limestone aquifers of Malta: their recharge conditions from isotope and chemical surveys.In: Hydrology of the Mediterranean and semiarid regions. Proceedings of an international symposium, Montpelier, 2003, Publication no. 278, IAHS, Wallingford, UK

Buhagiar K (2008) Water management in medieval and early modern Malta. In: Bonanno A, Militello P (eds) Malta in the Hybleans, the Hybleans in Malta. Officina di Studi Medievali, Palmero, Italy, pp 259–267

Bureau de Recherche Géologique et Minière (BRGM) (1991) Study of the fresh-water resources of Malta. BRGM, Orléans, France

Cassar J, Marocchi A, Santarelli ML, Muscat M (2008) Controlling crystallization damage by the use of salt inhibitors on Malta's limestone. Mater Constr 58(289–290):281–293 https://core.ac.uk/download/pdf/46604106.pdf

Costain LTD (1958a) Report on geological investigation of the Miziep Basin. Government of Malta - Water Supply, Valletta, Malta

Costain LTD (1958b) Report on geological investigation of the Ghajnsielem/Qala area and fault. Government of Malta - Water Suppl, Valletta, Malta

Dart CJ, Bosence DWJ, Mcclay KR (1993) Stratigraphy and structure of the Maltese graben system. J Geol Soc 150(6):1153–1166

Doherty J, Welter D (2010) A short exploration of structural noise. Water Resour Res. 46:1–14. https://doi.org/10.1029/2009WR008377

Enemark T, Peeters LJM, Mallants D, Batelaan O (2019) Hydrogeological conceptual model building and testing: a review. J Hydrol 569(2019):310–329. https://doi.org/10.1016/j.jhydrol.2018.12.007

ESRI - Environmental Systems Research Institute (2019) ArcMap (release 10.5): spline with barriers. Online manual. https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/spline-with-barriers.htm. Accessed December 2019

Fenelon J, Sweetkind DS, Laczniak RJ (2010) Groundwater flow systems at the Nevada Test Site, Nevada: a synthesis of potentiometric contours, hydrostratigraphy, and geologic structures. US Geol Surv Prof Pap 1711, 110 pp. http://pubs.usgs.gov/pp/1771/. Accessed September 2021

Gardiner W, Grasso M, Sedgeley D (1995)Plio-pleistocene fault movement as evidence for mega-block kinematics within the Hyblean—Malta plateau, Central Mediterranean. J Geodynam 19(1):35–51

Grasso M, Reuther CD, Baumann H, Becker A (1986) Shallow crustal stress and neotectonic framework of the Malta platform and the southeastern Pantelleria Rift (Central Mediterranean). Geol Romana 25:191–212 http://www.dst.uniroma1.it/Volumi/VOL%2025/GR_25_191_211_Grasso%20et%20al.pdf. Accessed September 2021

Gupta HV, Clark MP, Vrugt JA, Abramowitz G, Ye M (2012) Towards a comprehensive assessment of model structural adequacy. Water Resour Res 48:1–16. https://doi.org/10.1029/2011WR011044

Illies JH (1981) Graben formation: the Maltese islands—a case history. Dev Geotecton 17:151–168

Lotti F, Borsi I, Guastaldi E, Barbagli A, Basile P, Favaro L, Mallia A, Xuereb R, Schembri M, Alexander MJ, Sapiano M (2021) Numerically enhanced conceptual modelling (NECoM) applied to the Malta mean sea level aquifer. Hydrogeol J 29:1517–1537. https://doi.org/10.1007/s10040-021-02330-2

Malta Environmental and Planning Authority - MEPA (2013) ERDF 156 data Developing National Environmental Monitoring Infrastructure and Capacity. Floriana, Malta

Malta Resources Authority – MRA (2003) Annual Report 2002–2003. https://mra.org.mt/wpcontent/uploads/2012/08/Annual-Report-2002-2003.pdf. Accessed May 2020

Mangion J, Micallef P, Attard G (2005) Treated sewage effluent: an alternative water supply for the Maltese islands. In: Hamdy A (ed)Non-conventional water use: WASAMED project. https://om.ciheam.org/article.php?IDPDF=800772. Accessed September 2021

Morris TO (1952) The water supply resources of Malta. Government Printing Press, Valletta, Malta

OED Oil Exploration Directorate, Office of the Prime Minister (1993) Geological map of the Maltese Islands: sheet 1- Malta; sheet 2 - Gozo and Comino. Government of Malta, Valletta, Malta

Pedley HM (2011) The Calabrian stage, Pleistocene highstand in Malta: a new marker for unravelling the late Neogene and Quaternary history of the islands. J Geol Soc London 168(2011):913–925. https://doi.org/10.1144/0016-76492010-080

Pedley HM (1990) 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. Mar Pet Geol 7(2):171–180

Pedley HM, Grasso M (1992) Miocene syntectonic sedimentation along the western margins of the Hyblean-Malta platform: a guide to plate margin processes in the Central Mediterranean. J Geodyn 15(1–2):19–37

Pedley HM, House MR, Waugh B (1976) The geology of Malta and Gozo. Proc Geol Assoc 87(3):325–341

Pedley HM, House MR, Waugh B (1978) The geology of the Pelagian block: the Maltese islands. In: Nairn AEM, Kanes WH, Stehli FG (eds) The ocean basins and margins, vol 4B. Plenum, New York, pp 417–433

Prampolini M, Blondel P, Foglini F, Madricardo F (2018a) Habitat mapping of the Maltese continental shelf using acoustic textures and bathymetric analyses. Estuar Coast Shelf Sci 207:483–498. https://doi.org/10.1016/j.ecss.2017.06.002

Prampolini M, Gauci C, Micallef AS, Selmi L, Vandelli V, Soldati M (2018b) Geomorphology of the north-eastern coast of Gozo (Malta, Mediterranean Sea). J Maps 14(2):402–410. https://doi.org/10.1080/17445647.2018.1480977

Reuther CD, Eisbacher G (1985) Pantelleria rift: crustal extension in a convergent intraplate setting. Geol Rundsch 74(3):585–597

Royal Engineers (1952) Boreholes drill performed from 1943–1952 for groundwater resource exploration in Malta. Energy and Water Authority Archive, Valletta, Malta

Sapiano M (2008) Measures for facing water scarcity and drought in Malta. Eur Water 23(24):79–86 https://www.ewra.net/ew/pdf/EW_2008_23-24_07.pdf. Accessed March 2019

Sapiano M (2015) MARSOL project - deliverable D10.1: characterisation of the sea-level aquifer system in the Malta south region. http://www.marsol.eu/. Accessed March 2019

Sapiano M (2020) Integrated water resources management in the Maltese Islands. Acque Sotterranee - Ital J Groundw 9(3). https://doi.org/10.7343/as-2020-477

SEWCU Sustainable Energy and Water Conservation Unit (2015) The 2nd water catchment management plan for the Malta Water catchment district 2015–2021. Environment and Resources Authority, Spencer Hill Marsa, Malta. https://era.org.mt/wp-content/uploads/2019/05/2nd_Water_Catchment_Management_Plan-Malta_Water_in_Maltese_Islands.pdf. Accessed: 3 November 2020

Stuart ME, Heaton THE, Maurice L, Chilton PJ, William PJ (2008) A preliminary study on the identification of the sources of nitrate contamination in groundwater in Malta: results and interpretation. British Geological Survey Commissioned Report, CR/08/094. BGS, Keyworth, UK, 4 pp

Stuart ME, Maurice L, Heaton THE, Sapiano M, Micallef Sultana M, Gooddy DC, Chilton PJ (2010) Groundwater residence time and movement in the Maltese islands: a geochemical approach. Appl Geochem 25(5):609–620. https://doi.org/10.1016/j.apgeochem.2009.12.010

Verruijt A (1968) A note on the Ghyben-Herzberg formula. Int Assoc Sci Hydrol Bull 13(4):43–46. https://doi.org/10.1080/02626666809493624

Villani F, D'Amico S, Panzera F, Vassallo M, Bozionelos G, Farrugia D, Galea P (2018) Shallow high-resolution geophysical investigation along the western segment of the Victoria Lines Fault (Island of Malta). Tectonophysics 724:220–233