quaternary

Review

# The Fish Tanks of the Mediterranean Sea

**Paris Oikonomou [1], Anna Karkani [1,*], Niki Evelpidou [1], Isidoros Kampolis [2] and Giorgio Spada [3]**

[1] Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, 15774 Athens, Greece
[2] Department of Geological Sciences, School of Mining & Metallurgical Engineering, National Technical University of Athens, 15773 Athens, Greece
[3] Dipartimento di Fisica e Astronomia (DIFA), Settore Geofisica, Alma Mater Studiorum Università di Bologna, 40126 Bologna, BO, Italy
* Correspondence: ekarkani@geol.uoa.gr

**Abstract:** Roman fish tanks are found in various coastal regions of the Mediterranean, although the vast majority is found on the Tyrrhenian coast of Italy. In this work, a database was developed with information on 62 fish tanks along the Mediterranean coasts to document and compare their features and characteristics. The analysis of the developed database from the Mediterranean fish tanks has shown that, among the 62 fish tanks, ~56% were cut into the rock, indicating that this type of construction was the most popular at that time and probably had advantages over the others. Fish tanks as sea level indicators can provide accurate data on the sea level 2000 years ago. Well-preserved installations with prominent architectural features have a crucial role in determining the paleo sea level. The architectural elements that are mostly used in fish tanks for paleo sea level reconstructions are the crepido, cataractae and channels. Besides the scientific importance of the fish tanks as sea level markers, they also have great cultural and historical significance. Fish tanks can be promoted as heritage monuments and scholarly models to strengthen awareness about climate change, sea level rise and its consequences.

**Keywords:** fish tanks; Roman period; sea level; geoarchaeology



**Citation:** Oikonomou, P.; Karkani, A.; Evelpidou, N.; Kampolis, I.; Spada, G. The Fish Tanks of the Mediterranean Sea. *Quaternary* **2023**, *6*, 24. https://doi.org/10.3390/quat6020024

Academic Editor: Svante Björck

Received: 2 February 2023
Revised: 14 March 2023
Accepted: 20 March 2023
Published: 3 April 2023



## 1. Introduction

Roman fish tanks are found in various coastal territories of the Mediterranean, but the vast majority is located in Italy [1]. Fish tanks are mainly located in the Tyrrhenian coast (54 in total, according to Giacopini et al. [2]), and only one is documented in the Adriatic [3]. More than twenty fishponds have been recorded in the rest of the Mediterranean, including Egypt [4,5], Greece [6–9], Croatia [10–12], Spain [13,14], France [15], and Israel [16–19].

Fish tanks were constructed between the 1st century BC and the 1st century AD for the farming of fish and their subsequent distribution to the market. This activity also provides information about the socioeconomic status of the areas of distribution and consumption and the people residing within those areas. Higginbotham [1] notes that the geomorphological traits, the proximity to water sources and some aesthetic parameters helped evaluate where fish tanks should be constructed. Any existing elements such as cavities and coves acted as natural barriers allowing the fish to be restrained within a specific territory. Another aspect influencing their location was sufficient access to salt and fresh water to ensure adequate water circulation and salt concentration. Fish tanks were either fully or partially constructed [1].

The presence of fish tanks along the present-day coasts allows us to understand the coastal evolution of the host area and the relative sea level changes. The characteristics of their design and construction allow us to determine the sea level during Roman times [20].

In 1972, Schmiedt [21] presented his major work on the examination of archaeological indicators of sea level change in the north-western Mediterranean. Since then, fish tanks have been extensively used to document relative sea level variations since Roman times [11,15,19,20,22]. Methods and principles for the investigation of fish tanks and their relation to the sea level have been developed by various researchers [15,18,20,22–24]. A crucial parameter for their use as an accurate sea level indicator is the proper interpretation of the position of the fish tank structural elements in relation to the sea level during their use [11,20,24,25].

*Methodology*

The applied methodology for this paper involved a comprehensive literature review on fish tanks in the Mediterranean. In addition to the use of online libraries such as ScienceDirect and Google Scholar, the review also included relevant books, such as "Piscinae Artificial Fishponds in Roman Italy" written by James Higginbotham in 1997 [1]. The search was conducted by using keywords such as "Roman fish tanks", "Roman fish tanks in the Mediterranean", "Roman fish tanks and sea level change", "fish ponds" and "fish tanks and sea level indicators". The applied criteria were articles that focused on the history and archaeology of fish tanks in the Mediterranean, and articles that used scientific data to analyze the role of fish tanks in the region. The time period for the search spanned from the earliest known evidence of fish tanks in the Mediterranean to the present day.

## 2. Overview of Fish Tanks Characteristics

Fish farming used to be an occupation of the rich [1] and symbolized wealth and luxury [2]. Originally, the first fish tanks were built inland near lakes or streams and provided a secure place for freshwater fish. Later, around the 1st century BC, a trend towards the consumption of sea water fish led to the development of seaside fishponds [1]. This consumption preference revealed social status differences, according to which the poor were content with freshwater fish while saltwater fish were destined to become the cuisine of high society.

### *2.1. Architecture of Roman Fish Tanks, Technical Aspects and Sea Hydraulics*

Fish tanks were either cut on shore platforms or were partly or wholly built (Figure 1). Their structure is closely related to the morphological characteristics of the coast. The Latin author Columella, in the 1st century A.D., distinguishes three types of fish tanks, the depths of which vary [26]: (a) those cut on a rocky platform, with their depth at about 9 feet (2.745 m) below sea level, which often consisted of a few built walls and included flow channels beginning at the outer limit of the platform, with a depth of 2 feet (0.61 m) near the tank; (b) those completely built on the shore, with their depth at 7 feet (2.135 m); and (c) those only 2 feet deep (0.61 m), similar to the previous one, designed for flat fish. The construction of artificial enclosures on rocky surfaces or on surficial rock exposures extending towards the sea was a common design characteristic of coastal fish tanks. Coastal geomorphology and lithology were often exploited. The selection of a rocky topography was influenced by the presence of natural cavities and bays that provided enclosures for the confinement of fish.

The construction of fish tanks was greatly determined by the need for access to both sea water and fresh water in sufficient quantity to ensure the circulation of water and suitable salinity. Frequently, brackish conditions had to be met inside the enclosures to ensure the proper environmental conditions for the fish. Several Latin authors, such as Columella and Varro [26,27], mention the usefulness of mixing fresh water with sea water to attract fish into the tank or to decrease the salinity in summertime.

Salt water from the sea was mixed with fresh water in sufficient quantities to reach the required salinity. The site selection for seaside fishponds was determined by the distance to inland water sources. Fresh water could be transferred to the ponds via pipes driven by the force of gravity. The supply of freshwater into the pond was directly related to the difference in altitude between the pond and the water source and controlled the rate of water flow inside the pond (Figure 2). However, the sea currents in the ponds were not controlled in the same way as the freshwater. Sea water hydraulics used the natural forces of the waves and coastal currents to allow the continuous circulation of sea water into the basins of the ponds [1].

**Figure 1.** La Mattonara fish tank, located on the Tyrrhenian coast of Italy, is an example cut on a shore platform.

**Figure 2.** Channel that enabled the transportation of fresh water into the Montazah fish tank of Alexandria, Egypt.

Coastal lagoons, rocky bays or natural coves provided ideal enclosures for the isolation of the pond and the conservation of the desired water mixture and temperature. Sea water hydraulics were also an important factor for the supply and distribution of the water inside the ponds. The fish tanks located on the coast took advantage of the natural sea forces for water circulation within the enclosures. The fish tanks that were supplied with sea water were always near the sea [1]. Sea water was moved by the tidal and wave force, and for this reason, it did not circulate far from its source. According to Columella [26], fish tanks of sea water should have been designed in such a way that incoming waves would move the water without allowing stagnant water to remain within the enclosure. A fish tank is similar to the open sea, where the turbulent water is circulated continuously by the winds and cannot be warmed as the waves disturb the cold water from the bottom to the top. Fresh water can be channeled to locations distant from its source, through aqueducts and water pipes. Gravity flow can maintain a hydraulic freshwater system of many kilometers long. The elevation difference between the fresh water source and the fish tank is in direct proportion to the pressure and flow rate of input water, thus providing a strong flow sufficient for circulation needs [1]. This technology enabled fish tanks to be constructed in a wide range of locations [1]. Beyond the architectural elements, standard scales relative to the sea level were used for the construction of the parts of the pond. For example, when constructing a fish tank, the sea level must have been seven Roman feet (2.06 m) above the bottom part of the pond [1].

Two main types of seaside fish tanks are recorded by Columella: those which were excavated in rock and those constructed in concrete. Fishponds entirely carved in the rock are scarce, as their construction was predominantly dependent upon the geomorphology of the coastal area. The second type of fishpond was built with the hydraulic concrete opus caementicium, a material excellent for underwater construction; concrete was beneficial in architectural design and allowed better space management for the owner's fish tank. Most fish tanks were either entirely built or consisted of concrete-made parts mainly due to the operational, constructional and aesthetic benefits of doing so. Protective moles or thick perimetric walls were constructed by placing wet mortar and aggregates between temporary wooden forms or shuttering. This construction method guaranteed the protection of an area where a fish tank could be built, defending the tank from waves. Arching walls had an ornamented, decorative appearance, and this type of architecture gave the impression of elevated luxury (Figure 3).

One of the main characteristics of the fish tanks was an outer protection breakwater (dock) constructed all around the basins that exceeded the basin depths [26]. Channels connected the tank with the open sea to ensure water renewal. Channel direction ranged according to the individual morphological and dynamic coastal characteristics of the area, trying to take advantage of wave power in order to let fresh sea water pass into the fishpond. Smaller channels (cuniculi) transferred water further into the fish tank and facilitated regular circulation [13].

The basins were delimited by walls over which foot-walks (crepidini) remained emerged. In some cases (e.g., Piscina di Lucullo, Formia, Astura, Punta della Vipera), lower levels of foot-walks have been found that were used for maintenance, oyster culture, etc. Several basins were connected through submerged arched openings (Piscina di Lucullo, La Banca, Punta della Vipera), or through metal fixed gates (cataractae) with holes, permitting the passage of water but not of fish (Ventotene), and depressions were cut at the top of the walls (Piscina di Lucullo, Fosso Guardiole, La Mattonara). Sluice gates along the channels or between the basins were operated along sliding grooves cut into stones. A representative example is the Piscina di Lucullo [2,28]. Such features can offer important information on past sea levels [20].

Columella states that fish tanks, either excavated from the rocky shore or constructed with hydraulic concrete, should be designed with channels that would allow the sea water to penetrate inside the enclosures [26]. Columella suggests that channels were positioned on every side of the fish tank, low on the wall of the enclosure so that the water forced through these openings would originate from the cooler depths of the sea.

**Figure 3.** Arching wall at the Montazah fish tank of Alexandria, Egypt, along with the channels that distributed water within the tank, ensuring its adequate circulation within the construction.

All openings into the fish tank were to be covered with gates to prevent the fish from escaping. Columella refers to the use of bronze gate pierced by small holes (cataracta), which would prevent the fish from escaping while not interfering in circulation [26].

Fish tanks, in many cases, were architectural attempts at formalizing and controlling natural fishing grounds. The earliest attempts at organized fish-raising probably began at spots where fish were known to congregate. Sheltered zones where freshwater reached the sea would have been ideal sites to catch fish or to confine them until they were to be consumed. For instance, the harbor and fishery at Cosa (Spain) were constructed to be able to exploit a naturally brackish lagoon [29]. Fish suitable for the waters of the lagoon had to pass through the narrows of a rock-cut channel that followed a natural fissure in the promontory. There they could be trapped and held until being harvested or directed into tanks positioned in the lagoon.

The architecture of the Roman fish tanks ensured two basic needs: (a) that fish would not escape, and (b) the regulation of the water circulation in the enclosure. Among inland ponds, circular and semicircular plans were common and are reminiscent of the forms used in many seaside fish tanks. The phi-shaped fish tank at Grottarossa near Rome, with its central island, compares favorably with coastal enclosures [1].

While Columella recommended a depth of seven feet (2.14 m) for the fish tank basin, the remains of fish tanks indicate a range of less than one meter to over three meters [26]. Many fish tanks were divided into smaller tanks, allowing the owner to segregate his fish by species or age. Species of fish such as conger and murena could not coexist peacefully, and Columella appealed to isolate eels in separate ponds from other species of fish. Vertical slots would have secured movable grates (cancelli) [1]. These barriers could slide up and down to allow fish to pass through the connecting channel or opening.

The walls that enclosed fish tanks were principally designed to prevent the fish from escaping. Certain species of fish such as the grey mullet (Mugil) required higher walls due to their ability to jump. Many fast-swimming types of fish would jump when agitated or when confined in crowded conditions. Some walls unearthed during the excavation of the lagoonal fishery at Cosa exhibit substantial differences in height, which, according to the investigators, may indicate that the enclosures were built for different species of fish [30]. The precise heights of fish tank walls relative to the ancient sea level are difficult to determine and they vary depending on the tidal range.

Other design features that may have prevented fish from escaping are the platforms or steps within the interior of the pond. These platforms principally functioned as walkways for those who maintained the fish tank. Either cut in rock or constructed from concrete, these walkways are found on the walls of many fish tanks [31]. They were designed to always be above the water level or to be slightly awash so that movement, by those using and servicing the ponds, would be unhindered. In addition, these structures would prevent fish from reaching sufficient depth near the wall to be able to accelerate and escape from the enclosure. The internal divisions of these fish tanks could take on shapes that were pleasant to the eye, as well as being functional. Each could be viewed from attached platforms or from their associated villas. Moreover, the curvilinear design could withstand the force of waves using less construction materials than a straight wall.

The archaeological evidence shows that most fish tanks were constructed on land or along the shorefront, near Roman villas. The location of these residences was often chosen to exploit a panoramic view or to take advantage of the natural coves and inlets along the shore. The fish tank, with its perimeter moles enclosing large areas of seascape, reflects the desire to control nature and to include plants, animals and fish within the confines of the villa property. On a smaller scale, some fish tanks were equipped with small platforms that projected toward the middle of the enclosures. From these platforms visitors could enjoy the view from a slightly better point of vantage [1]. While providing similar protection to the fish, these features also served to mimic the larger and more prestigious seaside fish tank. Many coastal fish tanks were built in conjunction with dining facilities [32]. The connection between ponds and dining areas is not solely aesthetic but also has a gastronomic component. Fish or eels fresh from the fish tank would make an impressive addition to a private meal among friends and honored guests.

It should be noted that not all fish tanks were constructed with the same specifications. The architectural style changed with each location, and the construction elements had to be adjusted to the local morphological conditions of the area. In addition, the fishponds found far from the Tyrrhenian coast present significant differences in the design and operational use of each element of the pond [33]. Therefore, the structural characteristics of a specific fishpond must be carefully studied when used as sea level indicators.

### *2.2. Architectural Elements Used as Sea Level Indicators*

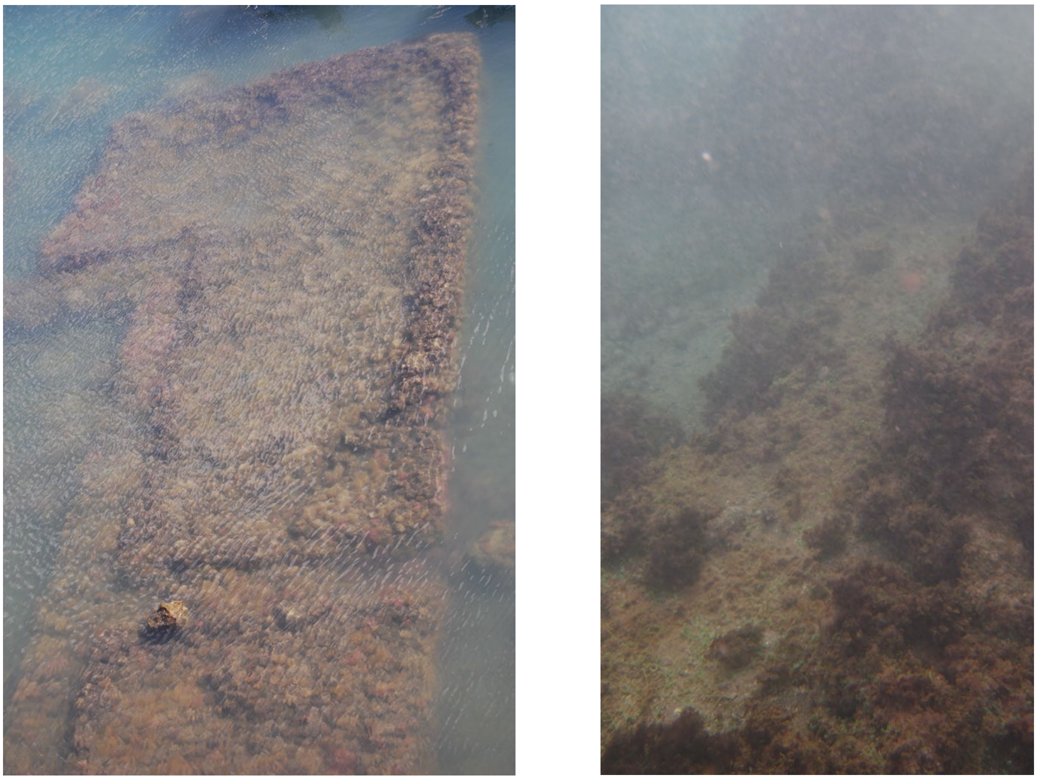
#### 2.2.1. Protective Docks

Similar to harbor design, docks were laid out to protect an area within which a fish tank could be constructed (Figure 4). The function of the perimeter docks was to protect the ponds from the action of the sea and to create calm conditions for breeding fish [34]. Docks may provide information on the relative sea level at the time of construction. According to Columella, one of the main characteristics of fish tanks is an outer protective breakwater constructed all around the basins, and higher than the m.s.l. at that time [21,26]: 'Mox praeiaciuntur in gyrum moles, ita ut complectantur sinu suo et tamen excedant stagni modum' [In addition docks are constructed all around in order to surround the basins and exceed their level]).

#### 2.2.2. Foot-Walks (Crepidine)

Foot-walks were narrow paths either cut in the rock or constructed with concrete along the inner tanks of many fish tanks (Figure 5a,b) [1]. These features were used by those using and servicing the ponds, and therefore, their original position would have been above sea level [1,13,20]. Evelpidou et al. [20] propose that the former mean sea level (m.s.l.) in a fish tank should be 35 cm below the top of the best-preserved upper crepidine (upper foot-walk). However, such an estimation has the drawback of lowering the ancient m.s.l. when the upper crepido is eroded [20]. In some cases, lower levels of foot-walks (lower crepidine) are found, which were used for maintenance, etc. (Figure 5b). Often, this morphological characteristic is very close to the bottom of the tank, and thus, it is impossible that it remained above water, because in this case, the depth of the water in the basin would have been insufficient for the fish to survive. It is obvious that this feature cannot be used as a sea level indicator but indicates only a limit.

**Figure 4.** Punta della Vipera fish tank, where the breaking of waves is visible in the outer breakwater.



(**a**) (**b**)

**Figure 5.** (**a**) Foot-walks at Formia fish tank, Italy. (**b**) The lower crepidines at the fish tank La Grottacce, Italy.

2.2.3. Sluice Gates (Cataractae)

Cataractae were fixed gates with holes that permitted the passage of water but not fish (Figure 6) [20]. Morhange et al. [15] report that in situ mid-tidal closing gates (cataractae), which are precise indicators of relative sea level change, are exceptionally rare, due to their original location in the wave-breaking zone. The cataractae could be solid, to stop incoming water, or a net or sluice with small holes to allow water to enter, while preventing larger fish from escaping. Cataractae existed in the upper part of the fish tank, at the levels of the tidal range [20]. Sluice gates along the channels or between the basins operated along sliding grooves cut into stones; their marks may be particularly useful, if interpreted well, to estimate the past sea level.

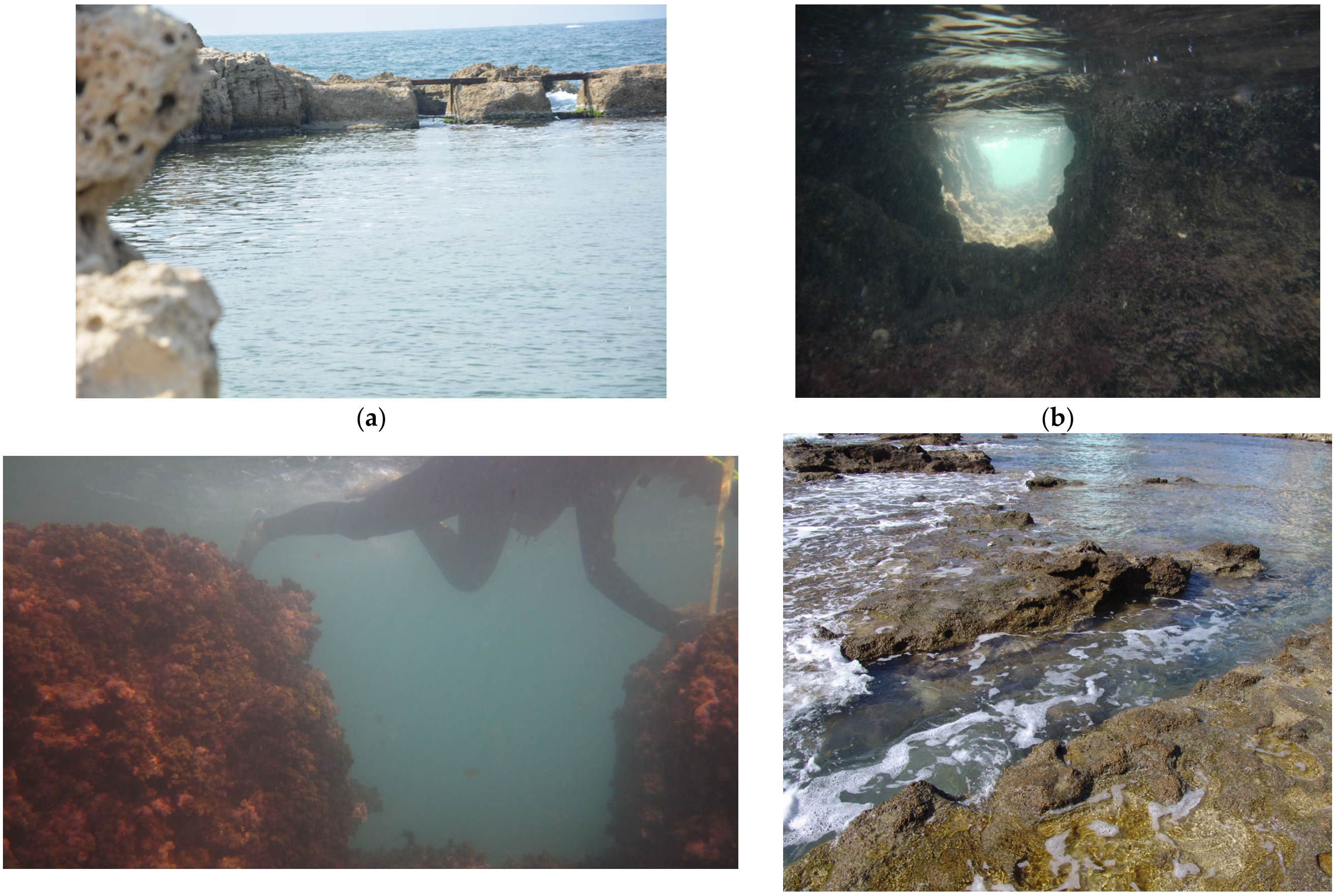
**Figure 6.** Sluice gate (cataracta) from the Grottacce fish tank, Italy, presently at the Santa Marinella Museum.

2.2.4. Channels

Channels connected the tank with the open sea to ensure water renewal (Figure 7). Channel direction depends on the individual morphological and hydrodynamic coastal characteristics of the area, as their purpose is to take advantage of wave power in order to renew the water in a fishpond. Columella has suggested that channels were positioned on every side of the fish tank, low on the wall of the enclosure, so that the water forced through these openings would originate from the cooler depths of the sea. Some of the channels are separated vertically by a bar. Smaller channels would distribute the water and further ensure adequate circulation between the smaller basins inside the fish tank. Some channels were used for bringing fresh water from the inland to the fish tank. These channels were used by some kinds of fish during their seasonal migrations, and they were perfect spots to catch fish. The outer part of the fish tank, towards the open sea, would have been blocked by gates in order to stop the fish migration towards the open sea.

Channels open to the sea supplied water at least during the high tide cycle [35]. According to Schmiedt [21], the top of the channels would have remained above water during the highest tides. In fact, he assumes that the top of the channels would have been 40 cm above former m.s.l. to allow the fish tank keepers to reach the entrance of the outer channels.

Estimates of the lower limits of the past sea level are based on the assumption that at least 10 cm of high tide water must have passed over the bottom of the supplying channel at the basin entrance in order to maintain viable conditions inside the tank [15,20,36–38].



(**a**) (**b**)

(**c**) (**d**)

**Figure 7.** (**a**) Channels at the Montazah fish tank, Alexandria, Egypt, that enabled water renewal in the fish tank. (**b**) Inner channel that connected two tanks at the fish tank of Montazah, Alexandria, Egypt. (**c**) Channel at the Odescalchi fish tank, Italy. (**d**) Channel at the Torre Valdaliga fish tank, Italy.

## 3. Distribution of Fish Tanks in the Mediterranean

A database with information about 62 fish tanks from the Mediterranean Sea was developed to document and compare their features and characteristics (Figure 8) (Table S1). Available bibliographic sources were used for the collection of information regarding published fish tanks, which were afterwards incorporated in the database.

### *3.1. Fish Tanks of Spain*

The fish tanks along the coasts of Spain are located at (a) Cape Trafalgar, Cadiz; (b) La Albufereta, Alicante; (c) Illeta dels Banyets in El Campello, Alicante; (d) Banos de la Reina in Calp, Alicante; and (e) Banos de la Reina in Xabia, Alicante [13]. They are found along the western Mediterranean coast, except from the one at Cape Trafalgar, which is located on the Atlantic coast of Spain, near Gibraltar [13]. These fish tanks are all completely carved into calcitic rock or sandstone to a depth of 2.7 m or less, depending on the type of the cultivated fish [23], and they are in good conservation condition, merely submerged or on land. Considering the level of preservation and the observed structural elements, the fish tanks of Spain that can be used as sea level indicators are those found along the Mediterranean coast [13].

### *3.2. Fish Tanks of France*

In France, the fish tanks are found along the southern coast and they are located in (a) Port-la-Nautique, Narbonne, Aude; (b) La Gaillarde, Roquebrune-sur-Argens, Var;

(c) Frejus, Var; (d) Ile Sainte-Marguerite, Cannes, Alpes-Maritimes; and (e) Antibes, Alpes-Maritimes [13]. They are cut into the coastal rock or reinforced with hydraulic concrete, partially submerged or found on land. Cataractae or channels are found with a good state of preservation.

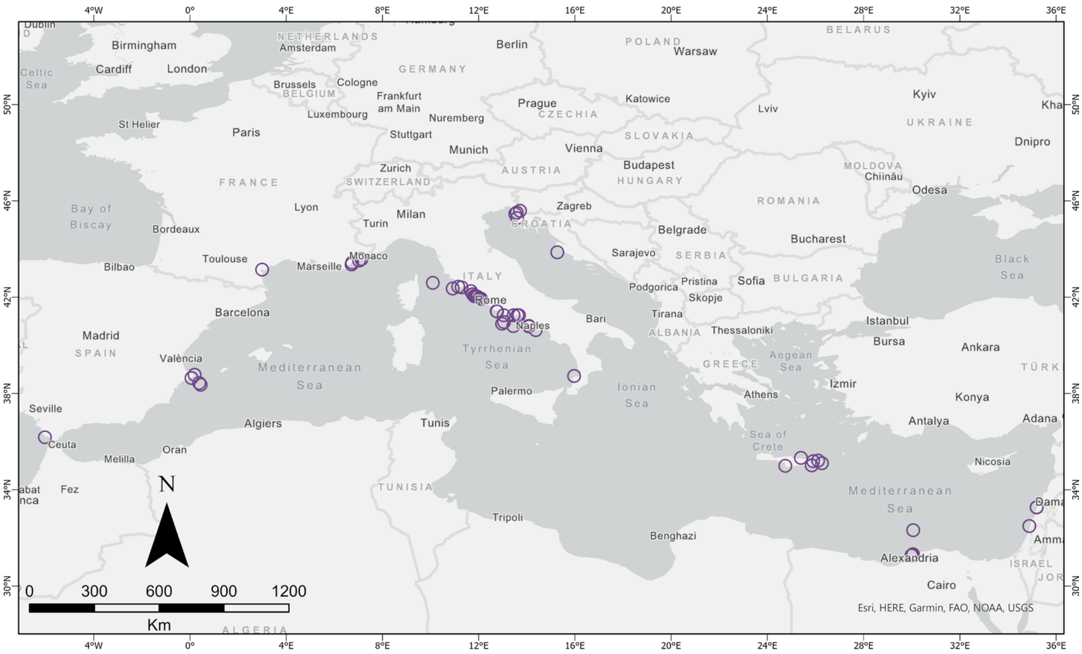



**Figure 8.** Fish tank distribution across the Mediterranean Sea.

The fish tank at Frejus, Var, located in southeastern Provence, was studied by Morhange et al. [15]. In the middle of the 1st century AD, the fish tank was entirely filled with silt and its operation stopped. Previous measurements and data were also obtained by Laborel et al. [39] and Devillers et al. [40]. In order to calculate the relative sea level during the Roman period, Morhange et al. [15] studied the zonation of fossil marine organisms attached to the fish tank walls. Combining evidence from architectural structures and biological sea level indicators, the relative sea level was estimated at 40 ± 10 cm below the present one [15]. Based on their measurements, Morhange et al. [15] further suggest that the use of fish tank channels is imprecise and tends to overestimate RSL rise. Sea level estimates by Morhange et al. [15] agree with Evelpidou et al. [20], who proposed a Roman sea level ranging from −32 ± 5 to −58 ± 5 cm (in respect to the present sea level) for the Tyrrhenian coast of Italy.

### *3.3. Fish Tanks along the Tyrrhenian Coast of Italy*

During the Roman period, pisciculture and the techniques of fish cultivation were thriving in Italy. Large enclosures bordering the sea or small fishponds were built near coastal villas, adding luxury to the landscape architecture.

The number of fish tanks recorded along the Tyrrhenian coast of Italy is fifty-four (54) according to Giacopini et al. [2], and only one is recorded on the Adriatic coast [33]. A study by Evelpidou et al. [20] provided sea level measurements from eight fish tanks along the Tyrrhenian coast (Figure 9). All these fish tanks were found to be submerged and carried archaeological evidence of past sea levels. Structural elements such as sluice gates, cataractae, crepidines and overflow carvings were used as sea level indicators by Evelpidou et al. [20], who concluded that the sea level did not exceed −58 ± 5 cm during Roman times in respect to the present sea level.

On the other hand, the study of Lambeck et al. [23] on the fish tanks of the Tyrrhenian coast concluded on a sea level of −1.3 m during the Roman period in respect to the present sea level. Using structural elements such as sluice gates, channels and foot walks in a complete state of preservation, Lambeck et al. [23] considered the top of the sluice gate to match with the height of the lower crepido and estimated that this lower crepido was 20 cm above the highest tide level. A suggestion was also that the water flow inside the tank was controlled by the tide.

**Figure 9.** The Formia fish tank, Italy, in which the rhombic shape was particularly used.

Another study from Auriemma and Solinas [11] in the fish tanks of the Tyrrhenian coast provided paleo sea level measurements based on indicative markers of crepidines, canals, cataractae and carvings. Aucelli et al. [41] provided data on sea level change at the Sorento Peninsula from archaeological markers including fishponds. At the Sorento fishpond, they estimated a sea level rise of 1.1 $\pm$ 0.3 m from the Roman period. This sea level rise fits well with the theoretical model of Lambeck et al. [23].

Evelpidou et al. [20] used a different interpretation of the fish tank characteristics for the paleo sea level measurements. The proposition was that the lower crepido was found at the infratidal zone and the mean sea level was found between the lower and the higher crepido levels. They also suggested that the upper part of the sliding grooves (cataractae) ended at the upper foot-walk (crepido) and not the lower one. In the same study, it is also proposed that the height of cataractae, according to the interpretation of Lambeck et al. [23], is not enough for the proper functioning of the fish tank. An agreed interpretation of the hydraulic position of the fish tanks has not yet been established, and therefore, the need for an interdisciplinary approach for the reconstruction of the sea level is useful [25].

In the Gulf of Naples, in the Sorrento area, Aucelli et al. [22] estimated a sea level rise of 1.1 $\pm$ 0.30 m in the past 2000 years, based on the location of the upper crepido in the fish tank.

### *3.4. Adriatic Sea Fish Tanks*

Five fish tanks have been recorded along the Adriatic coast: in Slovenia (S. Bartolomeo and Fisine) and Croatia (Katoro, Kupanja and Svrsata in Kornati Island). They were constructed with the technique of placing single stones (single rocks jetty), with pebbles and cobbles without the presence of mortar [11]. They consisted of multiple interior basins that were used for the division of different fish populations or fish of different ages [10].

Their construction dates to the 1st century A.D. In the Adriatic fish tanks, the water did not enter the fishpond via channels such as those on the Tyrrhenian coast but circulated from the sea into the tank through the permeable jetty. The jetty had structural elements such as blocks scattered or aligned for maintenance purposes.

Even though the fish tanks along the Adriatic coast lack architectural elements related to the sea level [11], there are two specific examples of accurate sea level markers at S. Bartholome and Fisine. Florido et al. [10] proposed a paleo sea level of ~$-1.60 \pm 0.20$ m in respect to present sea level, regarding the Adriatic Sea. The authors further compared their findings with glacio-hydro-isostatic modelling and calculated tectonic subsidence rates ranging between 0.63 and 0.89 mm/year since Roman times.

### *3.5. Fish Tanks of Greece*

Fish tanks have been reported in Greece as relics from the Roman Empire period. They are found in Crete on several coasts such as Ferma (Ierapetra area), Chersonissos, Matala, Siteia, Mochlos and the Gulf of Zakros [7–9,42]. Roman fishponds and fish traps in Crete were built close to the boisterous urban centers of that period [7]. Crete's central geographic position in the eastern Mediterranean has an economic advantage, as shipments from all the major commercial centers passed from Crete to deliver merchandise. There is a direct connection between sea level and coastal morphology and harbors, cities and other installations along the island's coasts. Any change in sea level or coastal morphology was associated with the socio-economic development of the coastal settlements [7]. Studies of fish tanks resulted in an estimation of the sea level at eastern Crete of 1.24 m $\pm$ 0.09 m below the present one during the Roman period [7]. Sea level estimates were based on depth measurements of the architectural and functional features of the fish tanks (e.g., fish tanks floor, depth of channels) in combination with other coastal landforms, such as beachrocks.

### *3.6. Fish Tanks of Israel*

Archaeological studies along the coast of Israel have revealed ancient coastal installations such as harbors and quarries. Several rock-carved pools with ambiguous function heights exist, but offer no reliable means of dating [43,44]. Some of these are located at Shiqmona-Haifa, Habonim, Dor, Yonim Island, Caesarea and Tel Baruch. In Caesarea lies a rectangular pool cut inside the rock with channels that supply the enclosure with sea water, and it has been interpreted as a fishpond [45]. In general, most of the coastal structures are close to the present-day sea level. The absence of underwater structures suggests that either coastal erosion has destroyed them, or indicates, in a more compelling case, that the morphology of the Israeli coast has been tectonically stable since Roman times [45]. Dean et al. [19] defined the functional height for a fishpond at Akziv in Israel [17] which suggests an almost stable sea level since its function. Sea level index points for this estimation were based on the elevation/depth of the base of intake gate, which was assumed to be below mean tidal level to ensure water flux, or the top of walkways.

### *3.7. Fish Tanks of Egypt*

Fish tanks and marine installations along the coast of Egypt have been reported from geoarchaeological studies (e.g., [4,5]). Fish tanks at Abou Kir peninsula, Alexandria, were first mapped by Bartocci [46] and were noted by Breccia [47]. Several fish tank installations have been noted in the coastal zone of Alexandria [5]. Three fish tanks from the Roman period have been studied in detail for paleo sea level reconstructions [5]. These are the fish tanks of Abou Kir (Figure 10), Miami island (Figure 11) and Montazah (Figure 12). They are cut into the rock and show a good state of preservation, except for the one in Abou Kir promontory, which is filled with sediments. At least four more fish tanks are evident in satellite images of the littoral area about 3 km from the east end of the Maamourah Bay towards Abou Kir promontory [5]. However, these structures are enclosed in military installations and even superficial observation of them is presently impossible.

**Figure 10.** The fish tanks of Abou Kir, in Alexandria, Egypt.

**Figure 11.** The Miami Island fish tank in Alexandria, Egypt, is a complex and sophisticated construction, carved in the southeastern region of the homonymous island.

**Figure 12.** The western part of the Montazah fish tank in Alexandria, Egypt.

In the Montazah fish tanks, located in the bay of Maamourah, the internal walls are constructed in a more delicate manner so visitors could walk around the perimeter of the installation and admire the view. This approach in construction style was probably inspired by the Tyrrhenian fish tanks such as the one in Torre Astura (Italy) [5].

Structural elements such as crepidines, cataractae and channels were identified and used as sea level indicators in combination with predictions from two Glacial Isostatic Adjustment (GIA) models [5]: ICE-6G (VM5a) [48] and ANU [49]. Sea level variations driven by glacioisostatic adjustment were modelled using an improved version of the Sea Level Equation solver SELEN [50]. For the past 3000 years, ICE-6G (VM5a) showed a stable RSL, while the ANU model revealed a very slight sea level high stand of ~15 cm at ~2000 years BP, followed by a slow sea level fall. Overall, the model calculations indicated that the GIA effects on RSL variations were limited during the time frame considered and have contributed little to sea level rise of 70 cm observed over the last 2000 years [5]. According to Evelpidou et al. [5], the sea level in Alexandria 2000 years ago was at 70 cm $\pm$ 5 cm below the present one.

### *3.8. Fish Tanks of Lebanon*

Two Roman fish tanks were discovered in 2017 by Goiran et al. [51] in the coastal region of western Tyre, Lebanon. The first fish tank is located in the north and the second in the southern part of Tyre. Both are crafted into coastal sandstone inside pre-existing quarries. They have a mixed structural style with both rock-cut and constructed features. The northern fish tank has a sub-rectangular shape and maintains architectural elements such as a U-shaped channel that connects the tank with the open sea and surrounding foot-walks (crepidine) [51]. The southern fish tank has a rectangular shape and holds an elongated U-shaped channel that connects the tank with the sea. Observations from the position of the channels and the ledges of the fish tanks relative to the current tidal range and the present day biological mean sea level led to the conclusion that the sea has risen by 0.6 m since the time of their construction [51]. In particular, Goiran et al. [51] assume that when the fish tanks were functional, high tide should not have overflown the fish tank ledges. They further state that the tidal range is 60 cm and suggest that the biological sea level must have been located at −0.60 m compared to the present level when the fish tanks were functioning.

## 4. Fish Tanks as Sea Level Indicators

The previous paragraphs demonstrate the most important characteristics of fish tanks recorded in the Mediterranean region. It is noteworthy that most fish tanks adhere to a standard constructional layout whose fundamental architectural elements are the crepido, cataractae and channels. It is further observed that as one moves away from the fish tanks of Italy, the construction techniques of the tanks vary to accommodate the local parameters determined by the geomorphology of the area and potentially relate to architectural styles devised by the local populations. Although most fish tanks are located on the Tyrrhenian coast of Italy, those found in the rest of the Mediterranean also provide information about their local history, pointing to increased commercial activity and developed urban centers.

Fish tanks as sea level indicators can provide accurate data on the sea level 2000 years ago. Well-preserved installations with prominent architectural features have a crucial role in determining the paleo sea level. The architectural elements that are most used in fish tanks for paleo sea level reconstructions are the crepido, cataractae and channels. However, a good understanding of the functioning of each fish tank must be developed in order to determine the exact position of the indicative structural elements present in relation to the sea level.

The study of fish tanks as sea level indicators must be considered within a wider framework which allows for a better understanding of the sea level during the late Holocene period. Data from sea level research studies conclude upon a paleo sea level of between −0.5 and −1.5 m during the Roman period compared to the present one [7,10,15,20,22,23] (Table 1). However, the tectonic history of the area should be taken into account as vertical tectonic movements may have contributed to the present-day altitude of the fish tanks since the time of their construction; such examples are the fish tanks of Crete (Greece), the Sorrento peninsula (Italy) and the Adriatic Sea. In France, sea level estimation comes from a tectonically stable area [15], suggesting an RSL rise of 0.4 ± 0.10 m since Roman times. Conversely, in Crete, the sea level has risen by 1.24 ± 0.09 over the same period, suggesting an average tectonic subsidence of ~0.65 mm/year [7]. Similarly, Florido et al. [10] report tectonic subsidence values between 0.63 and 0.89 mm/year since Roman times.

**Table 1.** Summary table of sea level estimates based on fish tanks.

| Fish Tank Region | Sea Level (m) | Reference |
|---|---|---|
| Frejus (France) | −0.4 ± 0.10 | [15] |
| Tyrrhenian coast of Italy | −0.58 ± 0.05 to −0.32 ± 0.05 | [20] |
| | −1.35 ± 0.07 | [23] |
| Sorrento (Italy) | −1.1 ± 0.30 | [22] |
| S. Bartolomeo (Slovenia) | −1.4 ± 0.2 | [10,52] |
| Fisine (Slovenia) | −1.5 ± 0.2 | [10] |
| Catoro (Croatia) | −1.75 ± 0.2 m | [10] |
| Kupanja (Croatia) | −1.4 ± 0.2 m | [10] |
| Svrsata (Croatia) | −1.5 ± 0.2 | [10] |
| Matala (Crete) | −1.24 ± 0.09 | [7] |
| Chersonissos (Crete) | −1.24 ± 0.09 | [7] |
| Mochlos (Crete) | −1.24 ± 0.09 | [7] |
| Gulf of Zakros (Crete) | −1.24 ± 0.09 | [7] |
| Ferma (Crete) | −1.24 ± 0.09 | [7] |
| Alexandria (Egypt) | −0.70 ± 0.05 | [5] |
| North and south Tyre (Lebanon) | −0.60 | [51] |

## 5. Overview of Construction and Architectural Characteristics

The analysis of the developed database from the Mediterranean fish tanks shows that, among the 62 fish tanks, 35 (~56%) were cut into the rock, indicating that this type of construction was the most popular at that time and probably had advantages over the others (Figure 13). Only 11 fish tanks were constructed with a combination of hydraulic concrete and rock cutting techniques. Three of them are found on the French coast; one on Pianosa Island, Italy, between Corse and Rome; one more in Italy in the Sperlonga area, along the Tyrrhenian coast; two in Slovenia; two in Egypt; and two in Lebanon. The small number of this type of construction may reflect its lack of operational efficiency or the high economic cost of its installation. Its spatial distribution allows neither any general supposition about the geographic locations in which they are placed nor any reason for construction. The remaining 16 fish tanks were constructed with hydraulic concrete, and they are found on the Tyrrhenian coast of Italy, with another one along the French coast. This type of construction had benefits both in terms of construction and operation; when the geomorphology of the site did not meet the requirements for the correct functioning of the fish tank, the design could be modified to take advantage of the sea dynamics and satisfy the need for both salt and freshwater inflow. Additionally, with this method, the architect of the fish tank could use his own designs and geometrical features, such as arches and curved walls. For instance, the fish tank of La Saracca, Nettuno, Roma, Italy, has a semi-circular shape and is separated by walls into concentric arches [13] that bear both technical and aesthetic value (i.e., avoiding sediment accumulation at the junctions of the installation). In addition, villa owners may have opted for concrete installations to add beauty with elaborate designs to the interior decoration of their villas near the coasts. On the other hand, concrete-made fish tanks are less resistant to erosion than those cut into the rock. Therefore, most of them are not in a good preservation state and most of them do not bear any notable architectural elements to study.

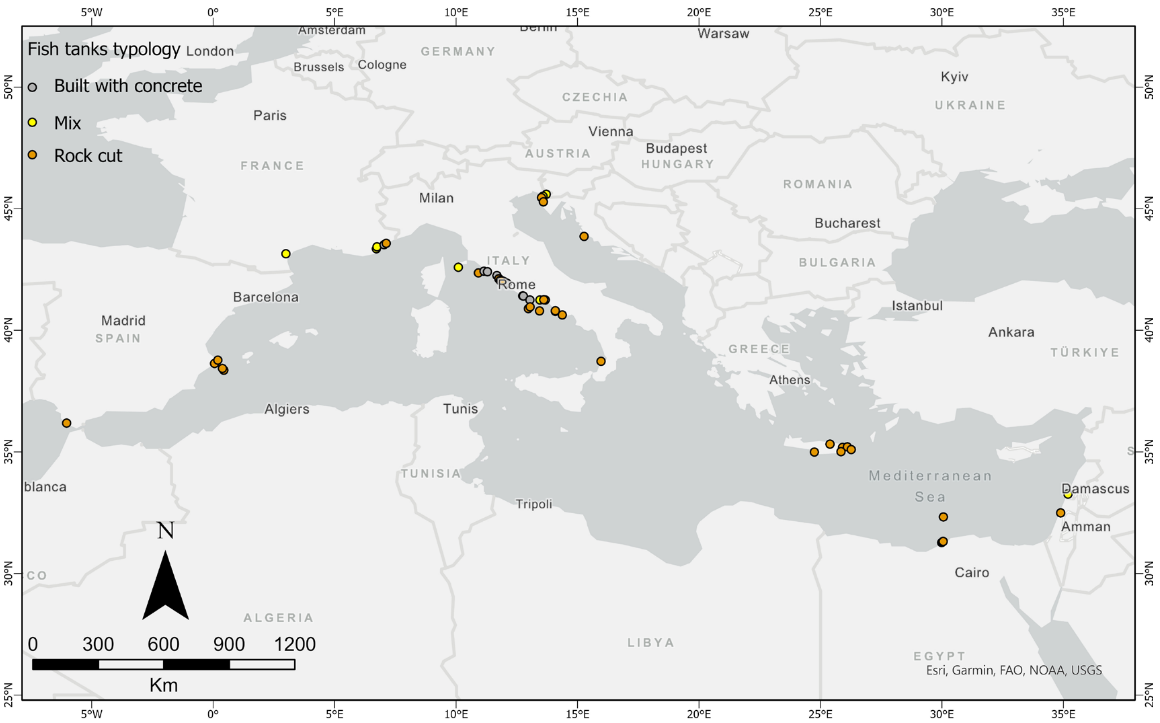



**Figure 13.** Distribution of fish tanks along the Mediterranean based on their construction type.

The fish tanks along the Adriatic coast were all cut into the rock, and they did not follow the traditional building technique as those on the Tyrrhenian coast. Additionally, the large size of the fish tanks in the Adriatic Sea and Egypt lent them a commercial use for fish production and selling. These tanks were solely constructed for economic purposes, and they have a different social value than in the Villae Maritima context found along the Tyrrhenian coast [10].

Besides the scientific importance of the fish tanks as sea level markers, they also have cultural and historical significance. Fish tanks can be promoted as cultural heritage monuments to strengthen awareness about climate change, sea level rise and its consequences. Fish tanks have been an integral part of the Mediterranean region for over two thousand years, and they reflect the sophisticated engineering skills of ancient Romans and their approach to fish farming. These fish tanks serve as a link between the past and present, and preserving them is vital to help future generations understand and appreciate the historical and cultural value of these sites.

Promoting fish tanks as heritage monuments can raise awareness about climate change and sea level rise and their consequences. By educating the public about these issues, we can encourage people to take action in reducing the impact of climate change on our environment. Furthermore, fish tanks can serve as a model for sustainable fish farming, especially in areas with limited access to marine resources. Preserving and promoting fish tanks can also boost tourism in the region, providing economic benefits to local communities. Overall, preserving fish tanks as cultural heritage sites not only benefits scientific research but also helps to promote sustainable development and cultural tourism.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/quat6020024/s1, Table S1: Database of Mediterranean fish tanks.

**Author Contributions:** Conceptualization, N.E.; methodology, N.E., P.O. and A.K.; formal analysis, P.O. and A.K.; investigation, N.E., P.O. and A.K.; writing—original draft preparation, P.O., N.E., I.K., G.S. and A.K.; writing—review and editing, N.E., A.K., I.K. and G.S.; supervision, N.E.; All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data are contained within the article.

**Acknowledgments:** This work is dedicated to Paolo Pirazzoli.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Higginbotham, J. *Piscinae: Artificial Fishponds in Roman Italy*; University of North Carolina Press: Chapel Hill, NC, USA, 1997.
2. Giacopini, L.; Marchesini, B.; Rustico, L. *L'Itticultura Nell'antichita*; Enel: Rome, Italy, 1994.
3. Lambeck, K.; Antonioli, F.; Purcell, A.; Silenzi, S. Sea-level change along the Italian coast for the past 10,000 yr. *Quat. Sci. Rev.* **2004**, *23*, 1567–1598. [CrossRef]
4. Torab, M. Geomophological & geoarchaeological indicators of the Holocene sea-level changes on Ras El Hekma area, NW coast of Egypt. *J. Afr. Earth Sci.* **2016**, *114*, 85–95. [CrossRef]
5. Evelpidou, N.; Repapis, C.; Zerefos, C.; Tzalas, H.; Synolakis, C. *Geophysical Phenomena and the Alexandrian Littoral*; Archaeopress: Oxford, UK, 2019; ISBN 9781789692358.
6. Mourtzas, N.D. Archaeological indicators for sea level change and coastal neotectonic deformation: The submerged Roman fish tanks of the gulf of Matala, Crete, Greece. *J. Archaeol. Sci.* **2012**, *39*, 884–895. [CrossRef]
7. Mourtzas, N.D. Fish tanks of eastern Crete (Greece) as indicators of the Roman sea level. *J. Archaeol. Sci.* **2012**, *39*, 2392–2408. [CrossRef]
8. Davaras, C. A rock-cut fish tank near Hierapetra. *Archaeol. Delt.* **1975**, *30A*, 149–154.
9. Davaras, C. Rock-cut fish tanks in Eastern Crete. *Annu. Br. Sch. Athens* **1974**, *69*, 87–93. [CrossRef]
10. Florido, E.; Auriemma, R.; Faivre, S.; Radić Rossi, I.; Antonioli, F.; Furlani, S.; Spada, G. Istrian and Dalmatian fishtanks as sea-level markers. *Quat. Int.* **2011**, *232*, 105–113. [CrossRef]
11. Auriemma, R.; Solinas, E. Archaeological remains as sea level change markers: A review. *Quat. Int.* **2009**, *206*, 134–146. [CrossRef]
12. Carre, M.-B.; Katunarić, T. Le Vivier de Katoro (Istrie, Croatie). *Chron. Act. Archéologiques L'école Française Rome* **2012**. [CrossRef]
13. Caballero-Rubio, F.J.; Viñals, M.J.; Tormo-Esteve, S. The Roman fish tanks of the Western Mediterranean basin as potential scenarios for research on sea-level changes. *J. Cult. Herit. Manag. Sustain. Dev.* **2022**, *12*, 92–106. [CrossRef]
14. Bernal-Casasola, D. Piscicultura y ostricultura en Baetica. Nuevos tiempos, nuevas costumbres. In *Pescar con Arte. Fenicios y Romanos en el Origen de los Aparejos Andaluces*; Bernal-Casasola, D., Ed.; Universidad de Cádiz: Cádiz, Spain, 2011; pp. 137–160.

15. Morhange, C.; Marriner, N.; Excoffon, P.; Bonnet, S.; Flaux, C.; Zibrowius, H.; Goiran, J.-P.; Amouri, M. El Relative Sea-Level Changes During Roman Times in the Northwest Mediterranean: The 1st Century A.D. Fish Tank of Forum Julii, Fréjus, France. *Geoarchaeology* **2013**, *28*, 363–372. [CrossRef]
16. Galili, E.; Salamon, A.; Gambash, G.; Zviely, D. Archaeological and natural indicators of sea-level and coastal changes: The case study of the caesarea roman harbor. *Geosciences* **2021**, *11*, 306. [CrossRef]
17. Anzidei, M.; Antonioli, F.; Benini, A.; Lambeck, K.; Sivan, D.; Serpelloni, E.; Stocchi, P. Sea level change and vertical land movements since the last two millennia along the coasts of southwestern Turkey and Israel. *Quat. Int.* **2011**, *232*, 13–20. [CrossRef]
18. Yasur-Landau, A.; Shtienberg, G.; Gambash, G.; Spada, G.; Melini, D.; Arkin-Shalev, E.; Tamberino, A.; Reese, J.; Levy, T.E.; Sivan, D. New relative sea-level (RSL) indications from the Eastern Mediterranean: Middle Bronze Age to the Roman period (~3800–1800 y BP) archaeological constructions at Dor, the Carmel coast, Israel. *PLoS ONE* **2021**, *16*, e0251870. [CrossRef]
19. Dean, S.; Horton, B.P.; Evelpidou, N.; Cahill, N.; Spada, G.; Sivan, D. Can we detect centennial sea-level variations over the last three thousand years in Israeli archaeological records? *Quat. Sci. Rev.* **2019**, *210*, 125–135. [CrossRef]
20. Evelpidou, N.; Pirazzoli, P.; Vassilopoulos, A.; Spada, G.; Ruggieri, G.; Tomasin, A. Late Holocene Sea Level Reconstructions Based on Observations of Roman Fish Tanks, Tyrrhenian Coast of Italy. *Geoarchaeology* **2012**, *27*, 259–277. [CrossRef]
21. Schmiedt, G. *Il Livello Antico del Mar Tirreno*; E. Olschki: Florence, Italy, 1972.
22. Aucelli, P.P.C.; Mattei, G.; Caporizzo, C.; Cinque, A.; Troisi, S.; Peluso, F.; Stefanile, M.; Pappone, G. Ancient Coastal Changes Due to Ground Movements and Human Interventions in the Roman Portus Julius (Pozzuoli Gulf, Italy): Results from Photogrammetric and Direct Surveys. *Water* **2020**, *12*, 658. [CrossRef]
23. Lambeck, K.; Anzidei, M.; Antonioli, F.; Benini, A.; Esposito, A. Sea level in Roman time in the Central Mediterranean and implications for recent change. *Earth Planet. Sci. Lett.* **2004**, *224*, 563–575. [CrossRef]
24. Vacchi, M.; Marriner, N.; Morhange, C.; Spada, G.; Fontana, A.; Rovere, A. Multiproxy assessment of Holocene relative sea-level changes in the western Mediterranean: Sea-level variability and improvements in the definition of the isostatic signal. *Earth-Sci. Rev.* **2016**, *155*, 172–197. [CrossRef]
25. Benjamin, J.; Rovere, A.; Fontana, A.; Furlani, S.; Vacchi, M.; Inglis, R.H.; Galili, E.; Antonioli, F.; Sivan, D.; Miko, S.; et al. Late Quaternary sea-level changes and early human societies in the central and eastern Mediterranean Basin: An interdisciplinary review. *Quat. Int.* **2017**, *449*, 29–57. [CrossRef]
26. Columella. De Re Rustica, XVII. In *Il Livello Antico del Mar Tirreno. Testimonianze da Resti Archeologici*; Schmiedt, G., Ed.; E. Olschki: Florence, Italy, 1972.
27. Varro. De Re Rustica, III. In *Il Livello Antico del Mar Tirreno. Testimonianze da Resti Archeologici*; Schmiedt, G., Ed.; E. Olschki: Florence, Italy, 1972.
28. Chiappella, V.G. Esplorazione della cosiddetta "Piscina di Lucullo" sul lago di Paola. Atti Della Accademia Nazionale Dei Lincei (CCCLXII). *Not. Scavi Antich.* **1965**, *8*, 146–160.
29. McCann, A.M. *The Roman Port and Fishery of Cosa: A Center of Ancient Trade*; Princeton University Press: Princeton, NJ, USA, 1987.
30. Gazda, E.K.; McCann, A.M. Chapter VII. Reconstruction and Function: Port, Fishery, and Villa. In *The Roman Port and Fishery of Cosa*; Princeton University Press: Princeton, NJ, USA, 2017; pp. 137–159.
31. Del Rosso, R. *Pesche e Peschiere Antiche e Moderne nell'Etruria Marittima*; Osvaldo Paggi: Firenze, Italy, 1905.
32. Ricotti, E.S.P. The importance of water in Roman Garden Triclinia. In *Ancient Roman Villa Gardens*; MacDougall, E.B., Ed.; Dumbarton Oaks: Washington, DC, USA, 1987; pp. 135–183.
33. Lambeck, K.; Anzidei, M.; Antonioli, F.; Benini, A.; Verrubbi, V. Tyrrhenian sea level at 2000 BP: Evidence from Roman age fish tanks and their geological calibration. *Rend. Lincei. Sci. Fis. Nat.* **2018**, *29*, 69–80. [CrossRef]
34. Martial. Epigrammaton libri X. Available online: https://www.tertullian.org/fathers/martial_epigrams_book10.htm (accessed on 1 January 2022).
35. Pirazzoli, P.A. Sea-level changes and crustal movements in the Hellenic arc (Greece), the contribution of archaeological and historical data. In *Archaeology of Coastal Changes, Proceedings of the First International Symposium "Cities on the Sea—Past and Present", Haifa, Israel, 22–29 September 1986*; Raban, A., Ed.; BAR International Series: Haifa, Israel, 1988; pp. 157–184.
36. Caputo, M.; Pieri, L. Eustatic sea variation in the last 2000 years in the Mediterranean. *J. Geophys. Res.* **1976**, *81*, 5787–5790. [CrossRef]
37. Flemming, N.C.; Webb, C.O. Tectonic and eustatic coastal changes during the last 10,000 years derived from archaeological data. *Z. Geomorphol. Suppl.* **1986**, *62*, 1–29.
38. Leoni, G.; Dai Pra, G. *Variazioni del Livello del Mare nel Tardo Olocene (Ultimi 2500 Anni) lungo la Costa del Lazio in Base ad Indicatori Geoarcheologici*; ENEA: Rome, Italy, 1997.
39. Laborel, J.; Morhange, C.; Lafont, R.; Le Campion, J.; Laborel-Deguen, F.; Sartoretto, S. Biological evidence of sea-level rise during the last 4500 years on the rocky coasts of continental southwestern France and Corsica. *Mar. Geol.* **1994**, *120*, 203–223. [CrossRef]
40. Devillers, B.; Excoffon, P.; Morhange, C.; Bonnet, S.; Bertoncello, F. Relative sea-level changes and coastal evolution at Forum Julii (Fréjus, Provence). *Comptes Rendus Geosci.* **2007**, *339*, 329–336. [CrossRef]
41. Aucelli, P.; Cinque, A.; Mattei, G.; Pappone, G. Historical sea level changes and effects on the coasts of Sorrento Peninsula (Gulf of Naples): New constrains from recent geoarchaeological investigations. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2016**, *463*, 112–125. [CrossRef]
42. Leatham, J.; Hood, S. Sub-marine exploration in Crete, 1955. *Annu. Br. Sch. Athens* **1959**, *53*, 263–280. [CrossRef]

43. Stanley, D.J. Evaluating use of rock-hewn features for sea level measurement, Israeli Coast. *J. Coast. Res.* **1999**, *15*, 326–331.
44. Dean, S. *3,000 Years of East Mediterranean Sea Levels: Archaeological Indicators from Greece Combined with Israeli Coast Data*; University of Haifa Faculty: Haifa, Israel, 2015.
45. Galili, E.; Sharvit, J. Ancient coastal installations and the tectonic stability of the Israeli coast in historical times. *Geol. Soc. London Spec. Publ.* **1999**, *146*, 147–163. [CrossRef]
46. Bartocci, M. Penisola di Abukir. Piano generale con indicazioni (in rosso) delle rovine di Canopo e di Menuti. In *Monuments de l'Égypte Gréco-Romaine, Vol I*; Breccia, E., Ed.; Officine de l'Istituto Italiano d'Arte Grafiche: Bergamo, Italy, 1926.
47. Breccia, E. *Alexandrea Ad Aegyptum*; Instituto Italiano d'Arti Grafiche: Bergamo, Italy, 1926.
48. Peltier, W.R.; Argus, D.F.; Drummond, R. Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model. *J. Geophys. Res. Solid Earth* **2015**, *120*, 450–487. [CrossRef]
49. Lambeck, K.; Purcell, A.; Johnston, P.; Nakada, M.; Yokoyama, Y. Water-load definition in the glacio-hydro-isostatic sea-level equation. *Quat. Sci. Rev.* **2003**, *22*, 309–318. [CrossRef]
50. Spada, G.; Stocchi, P. SELEN: A Fortran 90 program for solving the "sea-level equation. " *Comput. Geosci.* **2007**, *33*, 538–562. [CrossRef]
51. Goiran, J.-P.; Chapkanski, S.; Régagnon, E.; Pavlopoulos, K.; Fouache, E. Preliminary Results of Rock-cut Fish Tanks Evidence Along the Tyre Coast of Lebanon. Implication for Ancient Sea-level Reconstruction. *BAAL* **2019**, *19*, 259–266.
52. Antonioli, F.; Anzidei, M.; Lambeck, K.; Auriemma, R.; Gaddi, D.; Furlani, S.; Orrù, P.; Solinas, E.; Gaspari, A.; Karinja, S.; et al. Sea-level change during the Holocene in Sardinia and in the northeastern Adriatic (central Mediterranean Sea) from archaeological and geomorphological data. *Quat. Sci. Rev.* **2007**, *26*, 2463–2486. [CrossRef]

The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/2044-1266.htm

# The Roman fish tanks of the Western Mediterranean basin as potential scenarios for research on sea-level changes



Francisco Javier Caballero-Rubio
*Universitat Politècnica de València, Valencia, Spain*
María José Viñals
*Centro de Investigación en Arquitectura, Patrimonio y Gestión para el Desarrollo Sostenible, Universitat Politècnica de València, Valencia, Spain, and*
Santiago Tormo-Esteve
*Architectural Constructions, Universitat Politècnica de València, Valencia, Spain*

Received 27 May 2021
Revised 9 August 2021
Accepted 13 September 2021

## Abstract

**Purpose** – This paper analyses Roman fish tanks, which have functional elements that could be used to research on palaeo-sea-levels. Thus, the conditions of 37 installations in the Western Mediterranean basin are reviewed to identify those that have the best environmental and constructive conditions to be analyzed.

**Design/methodology/approach** – The methodology was largely based on the review of existing scientific bibliography dealing with sea-level variations from studies on historical constructions, existing historical documentation on Roman fish tanks on the Mediterranean coast, as well as the fieldwork carried out in fish tanks on the Mediterranean coasts.

**Findings** – The Roman coastal fish tanks located in the shoreline of the Western Mediterranean Sea have turned out to be an excellent indicator of sea-level changes. Nevertheless, current coastal retreat, erosion and storm surges are posing significant threats to their preservation, and they could be considered as a heritage at risk of disappearance. Moreover, variations in the tectonic behaviour of the different coastal sectors make it challenging to select these facilities as an indicator of the sea level.

**Originality/value** – The analysis of Late Holocene sea-level changes and palaeoenvironments from archaeological and biological evidences, although not without difficulties, is very convenient because it provides very precise data that cannot be obtained with other absolute dating methods. This approach is increasingly gaining popularity with researchers and is very innovative in its method of combining the results of several scientific disciplines.

**Keywords** Roman fish tank, Sea-level change, Western Mediterranean basin, Underwater cultural heritage, Climate change

**Paper type** Research paper

## Introduction

The Roman fish tanks *(piscinae)* were built in the Mediterranean nearshore platforms. These fish tanks were always practically linked to the existence of *villae* or other industrial buildings near their placement. They gave meaning to their existence and advanced their exploitation (storage of live fish for household consumption or sale at the market). The Roman pisciculture reached its greatest level of sophistication between around the 1st century BC and the 1st century AD (Higginbotham, 1997). Fishing, fish farming and fish processing represented a significant part of the economy around many Roman coastal settlements. What is more, these fish tanks also embodied an important tangible heritage legacy of Roman constructive

Thank the support of Professor Stefano Tortorella for his guidance and advice during the research stay developed at the Sapienza University of Rome.



2044-1266
DOI 10.1108/JCHMSD-05-2021-0096

engineering that has allowed us to better understand the eating habits and lifestyles of that time.

These fish farming facilities consisted of outdoor installations with single or multiple pools that connected to the open sea through channels. They were usually carved into rocks (calcareous beach rocks, volcanic rocks, etc.) or located in natural coastal caves. However, fish tanks could also be constructed from masonry on shores with deep or shallow foundations using *opus caementicium* (Roman concrete) or variations of this constructive material, such as *opus reticulatum*. They exhibited variable shapes and designs with hydraulic features that are related to local geomorphology, coastal currents and the type of fish selected for breeding.

Roman fish tanks can be found on all Mediterranean coasts. However, this work has focused on those existing in the Western Mediterranean basin because the climatic responses in the Eastern and Western Mediterranean basins have been significantly different (Comas *et al.*, 1996; Jiménez-Espejo *et al.*, 2007). In this regard, we have analyzed the remains of these *piscinae* into the shoreline rock of the central Tyrrhenian coast of Italy, coasts of France and central Mediterranean coasts of Spain.

In addition to their heritage and historical-social value, Roman fish tanks provide relevant palaeoenvironmental information as they are excellent indicators or markers of the mean sea-level position during Roman times. This is because their hydraulic functioning was strictly related to the sea level prevailing during the time when they were operational. In this regard, it is important to become acquainted with the construction elements of these facilities and their conservation conditions to carry out this type of study.

The studies on sea-level changes, in general, have traditionally been approached by geology, geomorphology, geodesy and geophysics; but, in recent decades, the archaeological perspective has been included to analyze the Late Holocene period in the Mediterranean by studying built structures (Blackman, 1973; Morhange *et al.*, 2001; Anzidei *et al.*, 2014; Melis *et al.*, 2012) at the coastal intertidal zone, like harbour structures, fish tanks, quarries and so on. It is noteworthy that the tidal amplitude in the Mediterranean is only a few centimetres, and this fact benefits this type of analysis. Auriemma and Solinas (2009) carried out a general study of these coastal constructions, concluding that one of the best sites for this type of study are fish tanks. Over the past 50 years, a series of studies were carried out that link the study of sea levels with fish tanks. These studies include the works of Schmiedt *et al.* (1972), Caputo and Pieri (1976), Lambeck *et al.* (2004, 2018), Profumo (2007), Goodman-Tchernov *et al.* (2009), Florido *et al.* (2011), Evelpidou *et al.* (2012), Morhange *et al.* (2013), Vacchi *et al.* (2016), Aucelli *et al.* (2016), Benjamin *et al.* (2017) and Caballero *et al.* (2020) in sites located both in the Eastern and Western Mediterranean coasts. Over time, the archaeological analysis has incorporated new methods (global positioning system (GPS), photogrammetry, biological evidence like fossilized marine benthos, etc.) that contributed to achieving accurate results (Goiran *et al.*, 2009; Anzidei *et al.*, 2014; Morhange and Marriner, 2015; Caporizzo *et al.*, 2020).

The study of sea levels in Roman fish tanks is based on the fact that they present a sophisticated construction system where their operation revolves around the sea level. Their design heavily relies on sluice gates that allow water exchange between the tanks and the open sea. Therefore, it is implied that the functional height (the elevation of this specific architectural element) corresponded to the mean sea-level position and with the tide variations at the time of their construction. From archaeological studies, it is known that Roman fish farms were built in a period between the 1st century BC and the 1st century AD (Morhange *et al.*, 2013). This narrow chronological window allows obtaining fairly accurate results on the position of the 2,000 BP palaeo-sea-level.

It is noteworthy that sea-level changes can be driven by variations in either the masses or the volume of the oceans (eustatism) and by glacial-hydro isostatic adjustment of the crust after the deglaciations or by changes of the land with respect to the sea surface (tectonics). Eustatic changes are related to climate causes and result in globally uniform mean sea-level variations, while tectonics (vertical land movements) are geological internal Earth processes that affect at regional level (moving a coastal area upwards or sinking it). Thus, the final interpretation of the results must take into account these local tectonic factors (Anzidei *et al.*, 2014; Rovere *et al.*, 2016).

The data acquired from fish tanks on palaeoenvironmental sea-level changes estimates a sea level during the Roman times ranging from $-135 \pm 0.7$ cm (Lambeck *et al.*, 2004) to $-40 \pm 10$ cm (Morhange *et al.*, 2013) or $-32$ to $-58 \pm 5$ cm (Evelpidou *et al.*, 2012) in the Western Mediterranean. These detected discrepancies can be attributed, among others, to varied interpretations of the hydraulic position of fish tank constructive elements relative to the estimated sea level or different tectonic behaviour in each region. Furthermore, a few Spanish–Roman fish tank scientific publications on marine levels (Olcina, 2015) presented a general approach to these installations in the Alicante province but did not focalize on sea-level changes. Rosselló (1999) analyzed the surroundings of the Illeta dels Banyets in El Campello (Alicante) and proposed that the sea levels increased and decreased at least once, with a range of $-50$ to $-80$ cm since the construction of the fish tanks.

Geological observations indicate that over the last 2,000 years, the changes in sea levels were small, with an average rate of only 0.0 mm–0.2 mm/yr. Oscillations in sea levels from 2,000 to 100 BP did not exceed $\pm 0.25$ m, based on the data provided by Roman–Byzantine–Crusader wells (Sivan *et al.*, 2004). Lambeck *et al.* (2004) concluded that the onset of the modern sea-level rise occurred between 1850 and 1950 AD, possibly accelerated by the man-induced phenomena on the climate.

The main goal of this paper is to analyze 37 Western Mediterranean Roman fish tanks to identify those that have the best environmental conditions and functional constructive elements to study palaeo-sea-levels.

## Methodology

In order to research this topic, specific bibliography was reviewed in various libraries in Rome, including several in the University of Sapienza, the German Archaeological Institute and the Spanish School of History and Archaeology in Rome, as well as existing publications edited by different public organizations in Spain. Additionally, an online bibliographic search was carried out combining the terms "fish tank" with "sea-level changes" to target publications that specifically focused on the subject of interest.

The descriptions of the archaeological sites and palaeoenvironmental analysis were made from bibliographic documentation as well as through series of on-site surveys from 2016 through 2019. Each author undertook the tasks closest to his/her competences. Below is a list of the 26 fish tanks where the observational fieldwork was carried out, and which are, ultimately, most of the best-known tanks in the Western Mediterranean.

(1) Spain: Cape Trafalgar, La Albufereta of Alicante, Illeta dels Banyets in El Campello, Baños de la Reina in Calp and Baños de la Reina in Xàbia;

(2) France: Port-La-Nautique (Narbonne); and

(3) Italy: Santa Liberata, Peschiera of Cosa, Pian di Spille, Torre Valdaliga, La Mattonara, Punta della Vipera, Fosso Guardiole, Villa delle Grottacce, Santa Severa, Torre Flavia, La Saracca, La Banca, Torre Astura, Lago di Paola, Sperlonga, Formia, Isola Ventotene, Miseno, Baia and Bagni Salvatore.

A photographic record of the current state of these elements was taken and compared to the data and images extracted from the scientific documentation and bibliography.

In addition to identifying the preservation conditions, this analysis focused on detecting constructional features and hydraulic functions (Plate 1). Thus, in accordance with Leoni and Dai Pra (1997), Lambeck *et al.* (2004, 2018) and Evelpidou *et al.* (2011), the present research work took the following constructional features as sea-level markers:

(1) *Crepido.* It is a perimeter foot-walk surrounding the tank and the pools. It is used to protect the inner basin from sea waves and for maintenance purposes; thus, the upper part had to be emerged above the highest tidal level.

(2) *Channel system.* This includes channels for water exchange within the pools equipped with single or multiple sluice gates that control the flow through them, as well as channels for water exchange with the open sea. To guarantee water supply, these channels had to be always submerged in the lower part, even during the low tide.

(3) *Cataracta.* It is a sluice gate that controlled the water exchange between tanks and the open sea.

These are the key elements of the fish tank that were directly related to the sea level for its proper hydraulic functioning.

However, there are discrepancies among the authors regarding the value as indicators of some of these elements due to certain structural and functional limitations that must be taken into account. For instance, Morhange *et al.* (2013) suggest that the *crepido* lies above mean sea level, and not all the channels correspond to the sea level; some of those can also be below the waterline. Therefore, these authors consider the *cataracta* is the best sea-level indicator or marker, even though they are rare due to their location in the wave-breaking zone, which makes them extremely exposed and vulnerable to erosive marine phenomena.

Therefore, the information on these fish tanks, that is key in the assessment of their potential for future studies on reconstructing the sea-level changes for the last 2,000 years, are as follows:

(1) Geographical location;

(2) Site elevation relative to the present sea level (submerged, at or above the present sea level);

(3) Geological placement and geomorphological features;

(4) Rock-carved structures (fish tanks must be excavated on bedrock; when built on unconsolidated material cannot be considered according to Auriemma and Solinas, 2009);

(5) Constructive elements (*cataracta,* channels*, crepido*);

(6) Preservation conditions (good condition, partially destroyed or damaged, scarce remains, etc.);

**Plate 1.**
Constructional features of the Roman Fish Tanks: Crepido (Baños de la Reina, Xàbia, Spain), Channel System (La Mattonara, Civitavecchia, Italy), and Cataracta (La Albufereta, Alicante, Spain)

(7) Definition of the site function;

(8) Historical data; and

(9) Presence of a tide gauge available within 50–100 km (necessary for future research).

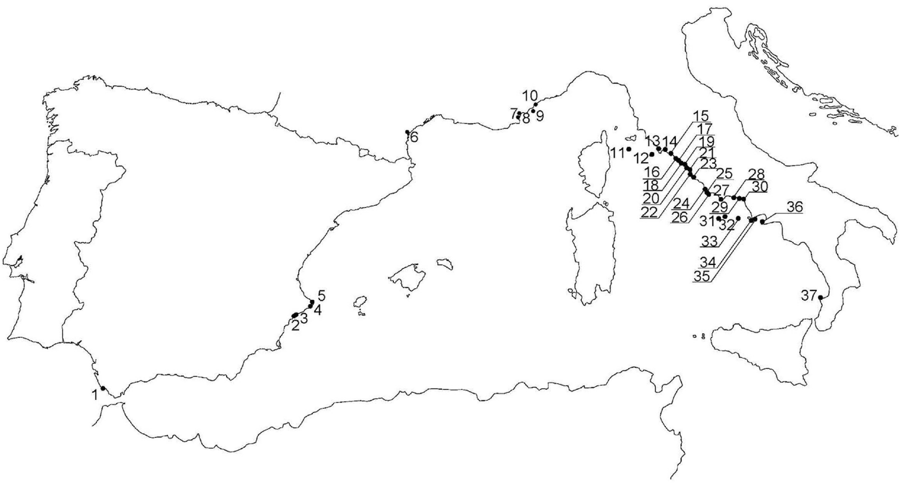
## Results

The results of the analysis performed on the selected fish tanks are presented below. A map with their location on the Western Mediterranean coast is given in Figure 1.

(1) *Cape Trafalgar,* Cádiz, Spain (36°10’55.32"N, 6°1’48.84"W). It is a large rock-carved installation (25 m × 8.5 m) in the eastern part of the Pleistocene beachbarrier, where a lighthouse stands. It seems that its use as a fish tank is the most appropriate given its characteristics (Bernal, 2011). Unfortunately, apart from the corner piece of a tank and a possible water withdrawal channel, the different parts of the site are impossible to identify to this day. Being located in the waters of the Atlantic Ocean, the effect of the tides makes it difficult to take it as a standard for calculating the variation in sea levels. The structure is visible at low tide, while at high tide, it is completely submerged. There is no active tide gauge nearby.

(2) *La Albufereta,* Alicante, Spain (38°21’43.16"N, 0°26’27.98"W). It is located in the northern part of the city. It consists of a tank (9 m × 5 m) carved in the calcarenite coastal rocks. The *crepido*, the two water supply channels (perpendicular to the waves direction), as well as the two water withdrawal channels (one in an oblique direction and other in parallel position to the waves), are easily identifiable. *Cataractae* position markings are still visible from some of the channels.

(3) *Illeta dels Banyets* in El Campello, Alicante, Spain (38°25’53.70"N, 0°22’49.84"W). It has two different fish tank areas, carved in calcarenite coastal rocks. One is located in the southwestern area of the site and the other is in the east. The first one consists of two rectangular tanks that have been heavily eroded in recent years and are currently



**1**.Trafalgar|**2**.Albufereta|**3**.I. dels Banyets|**4**.Calp|**5**.Xàbia|**6**.Port-La-Nautique|**7**.La Gaillarde|**8**.Fréjus|**9**.I. Sainte-Marguerite
**10**.Antibes|**11**.I. Pianosa|**12**.I. Giglio|**13**.Sta. Liberata|**14**.Cosa|**15**.Pian di Spille|**16**.T. Valdaliga|**17**.Mattonara|**18**.P. della Vipera
**19**.F. Guardiole|**20**.V. Grottacce|**21**.Sta. Severa|**22**.T. Flavia|**23**.Palo Laziale|**24**.Saracca|**25**.Banca|**26**.T. Astura|**27**.L. di Paola
**28**.Sperlonga|**29**.Formia|**30**.Scauri|**31**.Ponza|**32**.Zannone|**33**.Ventotene|**34**.Miseno|**35**.Baia|**36**.B. Salvatore|**37**.Sant’Irene

**Figure 1.** Location map of the selected Western Mediterranean fish tanks analysed in this work

submerged most of the time. The eastern part of the site presents a series of rectangular areas that are much better preserved. Although most of the archaeological material is lost, and the state of the fish tanks is quite fragile (Pérez *et al.*, 2013), the morphological features of the place can still be identified along with the existing channels; both between the different enclosures (inner channels), and some of which connected to the sea.

(4) *Baños de la Reina* in Calp*,* Alicante, Spain (38°38'27.41"N, 0°03'39.79"E). This is another example of fish tanks on the Spanish coast that is carved into the calcarenite rock. Its dimensions are 19.75 m × 8.50 m. Its main side faces the south with two Y-shaped channels for water access oriented towards the wave breaking; some mark of the possible placements of *cataractae* are on these channels. The *crepido* is also possible to identify.

(5) *Baños de la Reina* in Xàbia*,* Alicante, Spain (38°46'33.69"N, 0°11'26.18"E). This is a rectangular structure (27.30 m × 6.85 m) carved into the calcarenite of the Pleistocene beachrock. The channels for water renewal in this installation are about 20 m long; one oriented perpendicular to the waves and the other forming a 45° with the shore. The *crepido* carved in the rock, the access channels with the possible marks of the *cataractae* and the internal subdivision of the pools are clearly identifiable.

All fish tanks in the province of Alicante have the nearby presence of two tide gauges in the Port of the city. Moreover, the city of Alicante was chosen as the geodetic datum for the measurements of altitude above the sea level throughout Spain.

(6) *Port-la-Nautique,* Narbonne, Aude, France (43°08'38.04"N, 2°59'56.34"E). This is a circular tank of 67-m diameter, carved out of marl limestone rocks and located in a lagoonal space, which is currently infilled. According to Carayon *et al.* (2016), this fish tank is divided into four sectors, with vaulted channels, which have access to the sea to supply this fish facility. From the height of these channels, the variation in sea level could be calculated. There is a tide gauge at the entrance to the lagoon in Port-la-Nouvelle, just 15 km from the fish tank.

(7) *La Gaillarde,* Roquebrune-sur-Argens, Var, France (43°21'28.15"N, 6°43'08.12"E). This fish tank is carved into coastal rocks and divided by three walls. Unfortunately, no other remains were identified, which were used to observe the variation of the sea levels. This *piscina* is in bad conservation conditions; the whole complex is currently submerged underwater.

(8) *Fréjus,* Var, France (43°26'1.08"N, 6°44'26.45"E). Due to the growth of the city towards the seaside, this fish tank is currently located almost 1 km from the coastline. Its dimensions were 8.77 m × 8.33 m, and the tanks were about 5 m deep. They were carved into the rock and reinforced with *opus caementicium*. It is adequately preserved and is currently musealized. Relevant studies about sea-level changes from this site were carried out by Morhange *et al.* (2013).

(9) *Île Sainte-Marguerite,* Cannes, Alpes-Maritimes, France (43°31'12.52"N, 7°01'59.40"E). It is a possible fish tank that is very degraded (Formigé, 1947). The site cannot be taken as a reference point because it is preserved and has scarce traces of its existence.

(10) *Antibes,* Alpes-Maritimes, France (43°34'34.72"N, 7°07'35.29"E). This is a small tank located close to the urban centre of the town. Carved into the coastal rock, the channel that supplied water to the *piscina* is visible; however, any additional reference

elements cannot be observed. It is completely submerged most of the time, except during low tide. It is in an acceptable state of conservation.



The last four French fish tanks listed above are located less than 60 km from the Nice tide gauge.

(11) *Pianosa Island,* Tuscany, Italy (42°35'34.68"N, 10°05'37.51"E). It is also known as *Bagni di Agrippa* because it was part of the *villa* to which Augustus exiled his nephew Marco Agrippa Postumus. It is made up of two circular tanks, one of which is completely carved into the rock, while the other one is completed with a wall of *opus caementicium* that covers the most exposed face to the NW waves. It is quite degraded and submerged in the water; the *crepido* is between −20 and −76 cm below sea level (Schmiedt, 1972), leaving visible only the contours of the tanks. The closest reference tide gauge is located in Marina di Campo, on the Island of Elba, about 20 km away.

(12) *Giglio Island,* Grosseto, Tuscany, Italy (42°21'32.80"N, 10°55'21.32"E). This fish tank is also called *Bagno del Saraceno.* It is carved into the rock and is located in a small bay. It is completely submerged and not very well preserved; nevertheless, the *crepido*, the channel system and also the outer edge of the installation are identifiable.

(13) *Santa Liberata,* Porto Santo Stefano, Grosseto, Italy (42°26'08.48"N, 11°09'09.13"E). This fish tank is located at the foothills of Monte Argentario. It is a rectangular tank, built with *opus caementicium*, with interior dimensions of about 25 m × 50 m and divided into three parts (Del Rosso, 1905). The perimeter walls are quite thick, and the *crepido* is just levelled at the current sea level during low tide; the rest of the structure is completely submerged.

(14) *Peschiera of Cosa,* Ansedonia, Grosseto, Italy (42°24'33.14"N, 11°17'37.07"E). This fish tank is a series of pools built within a connecting channel between a small inland lagoon and the open sea. Later, the lagoon seems to have also been used as a fish tank. Currently, this lagoon is occupied by a functional fish farm. Presently, it is impossible to appreciate any archaeological remains of this Roman fish tank; existing information relies on previous studies (McCann, 1987).

(15) *Pian di Spille,* Tarquinia, Viterbo, Italy (42°14'57.42"N, 11°40'41.86"E). This fish tank is located in a beach area that was divided by a promontory formed by the remains of an ancient Roman *villa* with which the fish farm was associated. It was built with *opus caementicium*; at present, it has completely deteriorated. Being several metres from the shoreline, the fish tank is partially submerged, with only the highest parts of the perimeter structure standing out above sea level. In this regard, it is impossible to identify the reference markers in the present remains.

(16) *Torre Valdaliga,* Civitavecchia, Roma, Italy (42°7'26.34"N, 11°45'30.19"E). This fish tank is located in the north of the city. It was completely cut into the calcarenite rocks and presents a rectangular tank of 39 m × 19 m with walls lined with *opus reticulatum.* It is adequately preserved, and it is possible to identify its connection to the sea through three channels (oriented at different angles), apart from a small tank shielded from waves by a stone wall.

(17) *La Mattonara,* Civitavecchia, Roma, Italy (42°06'58.96"N, 11°46'06.06"E). This fish tank is also located in the north of the city. It is a rectangular tank of approximately 16.50 × 25.50 m dimensions and a perimeter ring of small rectangular pools. There is another small circular tank known as *Buca di Nerone,* located few metres from this

main complex. It is carved into a vein of stone that enters the sea, where the water supply channels are visible. The coastline is completely modified from that of Roman times due to the expansion of the Port of Civitavecchia; then the fish tank has become isolated from the Mediterranean Sea. However, the Port contributes to avoid the effects of marine erosion on the site.

(18) *Punta della Vipera,* Santa Marinella, Roma, Italy (42°02'55.26"N, 11°49'10.94"E). This fish tank is located in the south of the city. It is a large tank of about 48 m × 30 m, protected from waves by three large walls of width 2–3 m built with *opus caementicium.* It is possible to identify the *crepido* almost completely, as well as the three vaulted channels through which the water was supplied and expelled from the pools. The latter is completely submerged, and the *cataractae* were placed where these channels met the fish tank wall (Schmiedt, 1972).

(19) *Fosso Guardiole,* Santa Marinella, Roma, Italy (42°02'19.53"N, 11°49'48.02"E). There are two tanks that are currently completely submerged. Their conservation conditions are poor, but the *crepido* is still possible to identify (Evelpidou *et al.*, 2012).

(20) *Villa delle Grottacce,* Santa Marinella, Roma, Italy (42°02'19.73"N, 11°54'05.83"E). This is a semi-circle shaped fish tank, carved into coastal calcarenitic rock; however, most of it was built with *opus caementicium* (Giacopini *et al.*, 1994). This *piscina* is completely submerged and in poor conservation conditions, but it is still possible to locate the *crepido* (Evelpidou *et al.*, 2012).

(21) *Santa Severa* or *Pyrgi,* Santa Severa, Roma, Italy (42°00'56.40"N, 11°57'21.89"E). This is a rectangular fish tank with a 3-m wide perimeter wall carved out of calcarenitic rocks. It is practically submerged and much eroded; therefore, it is quite challenging to distinguish the sea-level markers, apart from the *crepido.*

(22) *Torre Flavia,* Cerveteri, Roma, Italy (41°58'03.55"N, 12°02'22.13"E). This fish tank is completely submerged. According to Giacopini *et al.* (1994) and Schmiedt (1972), it had a tank made of two concentric circles of *opus caementicium* with a diameter of 22 m, surrounded by a circular corridor of 3.65 m. However, during an on-site visit, a circular structure of about 44 m in diameter was identified. It is located several metres offshore, at a depth of about −30 to −40 cm, with no ability to identify any of the reference markers.

(23) *Peschiera di Palo Laziale,* Ladispoli, Roma, Italy (41°55'58.65"N, 12°06'2.57"E). Only the part of the perimeter wall of this very degraded fish tank has been preserved. No reference markers of sea-level changes can be identified.

The tide gauge located in the port of Civitavecchia serves as a reference point for all the fish tanks that are located north of the river Tevere, as they are less than 50 km away from it.

(24) *La Saracca,* Nettuno, Roma, Italy (41°25'14.83"N, 12°44'42.34"E). This is a semi-circle fish tank that is divided by walls into concentric arches. The inner corridors are further divided into small pools. It is constructed with *opus caementicium.* The tank is adequately preserved, which makes it possible to identify the internal division, the channel system, the *crepido* and the position of the *cataractae.*

(25) *La Banca,* Nettuno, Roma, Italy (41°25'01.97"N, 12°44'57.43"E). This is a simple rectangular tank with thick perimeter walls. It has two pools divided by an intersecting wall. It is built with *opus caementicium.* This fish tank is not as well

preserved as the previous one, which makes it impossible to clearly identify all the parts, apart from the *crepido*.

(26) *Torre Astura,* Nettuno, Roma, Italy (41°24'30.06"N, 12°45'53.83"E). This is one of the most sophisticated fish tanks. With an area of about 20,000 m$^2$, it is a rectangular *piscina* measuring around 150 m × 120 m and subdivided into various tanks. It is built with *opus caementicium.* This fish tank was adjacent to a strategically important port area and an island with a Roman *villa* on which it depended (Schmiedt, 1972). The supplying channels, the internal distribution, the position of some *cataractae* and the *crepido* are possible to identify. The closest tide gauge is in Anzio, less than 12 km from the Astura area.

(27) *Lago di Paola* or *Piscina di Lucullo,* Monte Circeo, Sabaudia, Latina, Italy (41°15'00.75"N, 13°02'30.93"E). This fish tank consists of a circular 32.5-m diameter tank built with *opus caementicium.* It is divided into four sectors through branching walls. According to the available information (Giacopini *et al.*, 1994), it is in a good conservation state. It is possible to identify the *crepido*, the entire channel system and the position of the *cataracta*, with a 150 cm × 25 cm space for manoeuvring the sluice gate. For this site, the Anzio and Gaeta tide gauges are the closest ones, about 40 km away.

(28) *Sperlonga,* Latina, Italy (41°15'00.92"N, 13°26'59.19"E). Known as *Grotta di Tiberio*, it is a fish tank linked to the *villa* or the *praetorium*, whose ownership was attributed to Emperor Tiberius (Andreae, 1995). It is a rectangular open-air tank built with *opus caementicium*, which is connected to another circular tank built inside a natural cave. It varies from the rest of the known fish tanks, as the elements connecting it with the open sea were not found. It is noteworthy that the absence of these elements can be attributed to the fact that openings were simply built into the masonry wall (Giacopini *et al.*, 1994). Its state of conservation is deemed good.

(29) *Formia,* Latina, Italy (41°15'19.64"N, 13°36'31.49"E). This is a rectangular tank divided into three parts. Its lateral parts have a diamond-shaped division. It is built with *opus caementicium* and currently submerged several centimetres below sea level inside the port area. Originally, it must have been closely related to the *villa* whose remains have been found nearby. In this fish tank, the *crepido*, the *cataractae* and the entire channel system can be fully identified, despite being completely submerged. The state of conservation is acceptable.

(30) *Scauri,* Formia, Latina, Italy (41°14'52.46"N, 13°40'29.71"E). This fish tank was located in a small bay and reused as a port later on. Only the remains of the lateral walls made with *opus caementicium* and fragments of the internal division of the pools can be identified from the whole installation. The tank is poorly preserved and makes it impossible to identify any of the reference elements, which could help get a clearer picture of the variation of sea levels.

For the last three sites, the reference tide gauge is that of Gaeta, located at a maximum distance of about 10 km.

(31) *Grotte di Pilato,* Ponza, Isole Pontine, Italy (40°53'42.37"N, 12°58'16.34"E). On the island of Ponza, this is the most striking and extensive fish tank of those excavated in a covered gallery carved into the volcanic rock. They are named after Pontius Pilate. This fish tank has four large rectangular underground tanks and an open-air tank. According to Jacono (1926), this fish tank was linked to a closed Roman imperial *villa.* The rise in sea level has most affected the outdoor pool, where there has been greater

erosion; therefore, it is quite poorly preserved. In the interior pools, given their characteristics and protection, erosion is much less pronounced, and the state of conservation is good. In this regard, grades in the main cave chamber, the *crepido*, the position of the *cataractae* and the entire system of channels that connected the tanks with the sea are identifiable.

(32) *Peschiera di Zannone,* Zannone, Isole Pontine, Italy (40°57'56.19"N, 13°02'56.17"E). On the island of Zannone, there is another small rock-cut fish tank excavated in a limestone rock gallery and connected to the sea through a vaulted slightly inward-sloped channel. There is no trace of a previous *cataracta* (Giacopini *et al.*, 1994) or *crepido.*

(33) *Ventotene,* Ventotene, Isole Pontine, Italy (40°47'48.32"N, 13°26'5.27"E). This is a rock-cut fish tank excavated in a volcanic rock gallery. It consists of two parallel domed enclosures carved into the rock of the coastal cliff and contains two covered fish tanks. The vault was detached due to the erosion caused by winds and sea waves. Additionally, the site had another open-sky tank that connected the two vaulted tanks and the sea. It is still possible to identify the system of channels, the completely submerged *crepido* and several areas where the *cataractae* were built.

All existing fish tanks in the archipelago of the Pontine Islands have the existing reference tide gauge on the island of Ponza. The closest one on the continent would be that of Gaeta, located about 45–60 km away from these installations.

(34) *Peschiere di Lucullo,* Miseno, Naples, Italy (40°47'3.16"N, 14°05'01.05"E). These fish tanks consist of a series of pools carved out in the sea cliff. They are currently semi-submerged because of the bradyseism phenomenon (Benini *et al.*, 2008) [1] in the volcanic calderas of Campi Flegrei in the Naples Bay (Del Gaudio *et al.*, 2014). Owing to this, this site cannot be considered a reference point to measure the variation in sea levels.

(35) *Baia,* Bacoli, Naples, Italy (40°48'32.68"N, 14°04'57.89"E). This site is a complex of several fish tanks which are historically mentioned in classical sources (Plinius, 77 AD). The one next to the Baia Castle is completely submerged underwater. This area is also subjected to bradyseism, which has made most of the area subsides. This substantial variation in the terrain means that it cannot be taken as a reference to estimate sea levels.

For the Miseno and the Baia sites, the closest tide gauge is in Naples, about 16 km away.

(36) *Bagni Salvatore,* Sorrento, Naples, Italy (40°37'40.19"N, 14°22'10.89"E). This fish tank is found in a gallery in the rock cliff, with several vaulted tanks interconnected by channels. It is linked to a *villa* where Marco Agrippa Postumus may have also resided. The *crepido* and the position of the *cataractae* are clearly observable. It is somewhat elevated compared to the current sea level. The condition of the interior enclosures is good; the exterior, however, is much degraded. Currently, it is used for recreational bathing activities. The tide gauges closest to Sorrento would be those in Naples, about 25 km away, and in Salerno, about 35 km.

(37) *Sant'Irene,* Scoglio della Galera, Briatico, Italy (38°43'31.22"N, 15°59'57.87"E). This fish tank is the southernmost one in Italy, about 150 m from the continental coast (Giacopini *et al.*, 1994). It is carved in the rock, with four aligned rectangular tanks. It is possible to identify the channels of water supply and extraction and the internal ones, the *crepido* and the position of the *cataracta.* Its state of conservation is quite good. The tide gauges closest to this site are Stromboleschi and Messina, some 65–70 km away.

## Discussion and conclusions

Given the presented results, Table 1 presents a classification of analyzed Roman fish tanks according to their typology (rock-carved, built, hybrid model), conservation conditions (good,



| Nº | Name | Typology[1] | Conservation conditions[2] | Sea-level markers[3] | Assessment as a palaeoenvironmental indicator |
|---|---|---|---|---|---|
| 1 | Trafalgar | a | b | - | ab |
| 2 | *Albufereta* | *a* | *a* | *a* | *aaa* |
| 3 | *Illeta Banyets* | *a* | *b* | *a* | *aba* |
| 4 | *Calp* | *a* | *a* | *a-b* | *aaa-b* |
| 5 | *Xàbia* | *a* | *a* | *a-b* | *aaa-b* |
| 6 | *Port-La-Nautique* | *c* | *a* | *a* | *caa* |
| 7 | La Gaillarde | c | b | c | cbc |
| 8 | *Fréjus* | *c* | *a* | *a* | *caa* |
| 9 | Sainte-Marguerite | b | c | c | bcc |
| 10 | Antibes | a | b | a | abb |
| 11 | Isola Pianosa | c | b | b | cbb |
| 12 | Isola Giglio | a | b | b | abb |
| 13 | Santa Liberata | b | b | b | bbb |
| 14 | Cosa | b | c | c | bcc |
| 15 | Pian di Spille | b | c | c | bcc |
| 16 | *Torre Valdaliga* | *a* | *b* | *a-b* | *aba-b* |
| 17 | *Mattonara* | *a* | *a* | *a-b* | *aaa-b* |
| 18 | *Punta della Vipera* | *b* | *a* | *a-b* | *baa-b* |
| 19 | Fosso Guardiole | b | c | b | bcb |
| 20 | Villa Grottacce | b | c | b | bcb |
| 21 | Santa Severa | a | b | b | abb |
| 22 | Torre Flavia | b | c | c | bcc |
| 23 | Palo Laziale | b | c | c | bcc |
| 24 | *La Saracca* | *b* | *a* | *a-b* | *baa-b* |
| 25 | *La Banca* | *b* | *b* | *b* | *bbb* |
| 26 | *Torre Astura* | *b* | *a* | *a-b* | *baa-b* |
| 27 | *Lago di Paola* | *b* | *a* | *a-b* | *baa-b* |
| 28 | Sperlonga | c | a | b | cab |
| 29 | Formia | b | b | a-b | bba-b |
| 30 | Scauri | b | c | c | bcc |
| 31 | *Ponza* | *a* | *a* | *a-b* | *aaa-b* |
| 32 | *Zannone* | *a* | *a* | *a* | *aaa* |
| 33 | *Ventotene* | *a* | *b* | *a-b* | *aba-b* |
| 34 | Miseno | a | b | c | abc |
| 35 | Baia | b | c | – | bc |
| 36 | *Bagni Salvatore* | *a* | *a* | *a-b* | *aaa-b* |
| 37 | *Sant'Irene* | *a* | *a* | *a* | *aaa* |

**Note(s):** 1 – Typology: *a* = Rock carved | *b* = Built | *c* = Mix
2 – Conservation conditions: *a* = Good | *b* = Fair | *c* = Bad
3 – Sea-level markers: *a* = *Cataractae*/Channels | *b* = *Crepido* | *c* = No markers

**Table 1.** Summary of the main features of the Roman fish tanks according to their typology, conservation conditions and the existence of sea-level markers

fair, bad) and the presence of sea-level markers (*cataracta*, channels, *crepido*, no markers). The table also highlights those installations that gained the best overall assessment for the palaeoenvironmental studies.

In this regard, the fish tanks that meet the required conditions to carry out studies on sea-level variation are the four on the Spanish Mediterranean coast: Albufereta, Illeta Banyets, Calp and Xàbia. In France, the two qualified tanks are Port-La-Nautique and Fréjus. In Italy, the ones that stand out are those located around the coast of Rome (Torre Valdaliga, Mattonara, Punta della Vipera, Saracca, Banca, Torre Astura), those existing along the coastline between Rome and Sorrento (Lago di Paola, Bagni Salvatore) and the Pontine Islands (Ponza, Zannone, Ventotene), as well as that of Calabria (Sant'Irene). The variation in sea level in the last 2,000 years can be analyzed, given the conservation conditions on these sites. In particular, they are constructive elements that act as markers of sea levels. However, an in-depth investigation would be necessary to know the tectonic behaviour of these coastal areas over the Late Holocene period, particularly, the ones on the coasts of Alicante (Spain) since the existing fish tanks are well preserved, probably due to the tectonic uplift that counteracts the effects of the sea-level rise. On the other hand, it is also important to analyze the bradyseism phenomena in areas of volcanic activity, such as the Bay of Naples, since the vertical movements of this area of the Tyrrhenian coasts could be related.

Furthermore, the Roman fish tanks carved in rocks have generally been better preserved than those built with *opus caementicium*.

In consequence, the results of this research contribute to the development of a more extensive knowledge on the topic, as well as can undoubtedly be exploited by researchers for a variety of purposes and in a variety of applications.

As a final reflection, it should be noted that, as it has been shown throughout this work, the value of these archaeological sites is exceptionally relevant, as they are significant not only from the perspective of history, socioeconomics or Roman engineering, but they have also been recognized as crucial palaeoenvironmental indicators in the last few decades. It should be pointed out, however, that not all the sites presented in this work are thoroughly scientifically documented; in fact, some of them have been scarcely studied. It is noteworthy that the submergence and the erosion phenomena suffered by most of the sites qualify those as "heritage at risk of disappearance", which is quite worrying. Therefore, this paper aims at being a call for attention to the urgency of taking the necessary protective measures to guarantee the integrity, as well as the need, to scientifically document and register these underwater heritage sites that are currently underestimated and not well known by the majority of people.

Beyond the scientific research, these sites hold an immense educational potential, along with the potential to raise awareness about heritage conservation and the management of the archaeological sites and to increase the understanding and consciousness about the effects of the climate changes, as those effects can ideally be observed through fish tanks/because fish tanks are ideal for observing these effects.

## Note

1. Bradyseism phenomenon is the gradual uplift or descent of part of the Earth's surface that is caused by the filling or emptying of an underground magma chamber and/or hydrothermal activity.

## References

Andreae, B. (1995), *Praetorium Speluncae. L'antro di Tiberio a Sperlonga ed Ovidio*, Rubbettino, Soveria Mannelli, Italy.

Anzidei, M., Lambeck, K., Antonioli, F., Furlani, S., Mastronuzzi, G., Serpelloni, E. and Vannucci, G. (2014), "Coastal structure, sea-level changes and vertical motion of the land in the

Mediterranean", in Martini, I.P. and Wanless, H.R. (Eds), *Sedimentary Coastal Zones from High to Low Latitudes: Similarities and Differences*, Geological Society, London, Special Publications, Vol. 388, pp. 453-479, doi: 10.1144/SP388.20.

Aucelli, P., Cinque, A., Mattei, G. and Pappone, G. (2016), "Historical sea level changes and effects on the coasts of Sorrento Peninsula (Gulf of Naples): new constrains from recent geoarchaeological investigations", *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 463, pp. 112-125, doi: 10.1016/j.palaeo.2016.09.022.

Auriemma, R. and Solinas, E. (2009), "Archaeological remains as sea level change markers: a review", *Quaternary International*, Vol. 206, pp. 134-146, doi: 10.1016/j.quaint.2008.11.012.

Benini, A., Ferrari, G. and Lamagna, R. (2008), "Le peschiere di Lucullo (Miseno-Napoli)", in *Atti VI Convegno Nazionale di Speleologia in Cavità Artificiali*, Opera Ipogea, Naples, Italy, Vol. 1, pp. 159-168.

Benjamin, J., Rovere, A., Fontana, A., Furlani, S., Vacchi, M., Inglis, R.H., Galili, E., Antonioli, F., Sivan, D., Miko, S., Mourtzas, N., Felja, I., Meredith-Williams, M., Goodman-Tchernov, B., Kolaiti, E., Anzidei, M. and Gehrels, R. (2017), "Late Quaternary sea-level changes and early human societies in the central and eastern Mediterranean Basin: an interdisciplinary review", *Quaternary International*, Vol. 449, pp. 29-57, doi: 10.1016/j.quaint.2017.06.025.

Bernal, D. (2011), "Piscicultura y ostricultura en Baetica. Nuevos tiempos, nuevas costumbres", in Bernal, D. (Ed.), *Pescar con arte. Fenicios y romanos en el origen de los aparejos andaluces*, Universidad de Cádiz, Spain, pp. 137-159.

Blackman, D.J. (1973), "Evidence of sea-level change in ancient harbours and coastal installations", in Blackman, D.J. (Ed.), *Marine Archaeology*, Butterworth, London, pp. 115-138.

Caballero, F.J., Viñals, M.J. and Tormo, S. (2020), "The effects of rising sea levels on the conservation of roman fish tanks in the Western Mediterranean basin", *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vols XLIV-M-1-2020, pp. 659-666, doi: 10.5194/isprs-archives-XLIV-M-1-2020-659-2020.

Caporizzo, C., Aucelli, P., Mattei, G., Cinque, A., Troisi, S., Peluso, F., Stefanile, M. and Pappone, G. (2020), *Photogrammetric Reconstruction of the Roman Fish Tank of Portus Julius (Pozzuoli Gulf, Italy): A Contribution to the Underwater Geoarchaeological Study of the Area*, Vol. 2020, Geomorphometry, Perugia, Italy, doi: 10.30437/GEOMORPHOMETRY2020_16.

Caputo, M. and Pieri, L. (1976), "Eustatic sea variation in the last 2000 years in the Mediterranean", *Journal of Geophysical Research*, Vol. 81 No. 33, pp. 5787-5790, doi: 10.1029/JC081i033p05787.

Carayon, N., Flaux, C., Sanchez, C., Piquès, G., Rovira, N., Tillier, M., Sanz -Laliberté, S., Cavero, J., Mathé, V., Wicha, S. and Cervellin, P. (2016), "Le vivier augustéen du Lac-de-Capelles à Port-la-Nautique", in Sanchez, C. and Jézégou, M.P. (Eds), *Les ports dans l'espace Méditerranéen antique. Narbonne et les systèmes portuaires fluvio-lagunaires, Supplément à la Revue Archéologique de Narbonnaise*, Vol. 44, pp. 87-97.

Comas, M.C., Zahn, R., Klaus, A., Aubourg, C., Belanger, P.E., Bernasconi, S.M., Cornell, W., de Kaenel, E.P., de Larouzière, F.D., Doglioni, C., Doose, H., Fukusawa, H., Hobart, M., Iaccarino, S.M., Ippach, P., Marsaglia, K., Meyers, P., Murat, A., O'Sullivan, G.M., Platt, J.P., Prasad, M., Siesser, W.G., Skilbeck, C.G., Soto, J.I., Tandon, K., Torii, M., Tribble, J.S., Wilkens, R.H. and Riegel, R.N. (1996), Proceedings ODP Init. Reports, *Ocean Drilling Program*, College Station, TX, Vol. 161, doi: 10.2973/odp.proc.ir.161.1996.

Del Gaudio, C., Aquino, I., Di Vito, M.A. and Ricco, C. (2014), "Giuseppe Mercalli e lo studio del bradisismo flegreo", *Miscellanea INGV*, Vol. 24, pp. 71-77.

Del Rosso, R. (1905), *Pesche e peschiere antiche e moderne nell'Etruria marittima*, Osvaldo Paggi, Firenze, Italy.

Evelpidou, N., Pirazzoli, P.A., Saliège, J.F. and Vassilopoulos, A. (2011), "Submerged notches and doline sediments evidence for Holocene subsidence", *Continental Shelf Research*, Vol. 31, pp. 1273-1281, doi: 10.1016/j.csr.2011.05.002.

Evelpidou, N., Pirazzoli, P.A., Vassilopoulos, A., Spada, G., Ruggieri, G. and Tomasin, A. (2012), "Late Holocene sea level reconstructions based on observations of Roman fish tanks, Tyrrhenian Coast of Italy", *Geoarchaeology*, Vol. 27, pp. 259-277, doi: 10.1002/gea.21387.

Florido, E., Auriemma, R., Faivre, S., Radić Rossi, I., Antonioli, F., Furlani, S. and Spada, G. (2011), "Istrian and Dalmatian fishtanks as sea level markers", *Quaternary International*, Vol. 232, pp. 105-113, doi: 10.1016/j.quaint.2010.09.004.

Formigé, J. (1947), "La station antique de Lero à l'île Sainte-Marguerite (Alpes-Maritimes)", *Gallia*, Vol. 5 No. 1, pp. 146-155, doi: 10.3406/galia.1947.2021.

Giacopini, L., Marchesini, B. and Rustico, L. (1994), *L'Itticoltura nell'Antichità*, ENEL, Roma.

Goiran, J.P., Tronchere, H., Collalelli, U., Salomon, F. and Djerbi, H. (2009), "Découverte d'un niveau marin biologique sur les quais de Portus: le port antique de Rome", *Méditerranée*, Vol. 112, pp. 59-67, doi: 10.4000/mediterranee.3177.

Goodman, B.N., Reinhardt, E.G., Dey, H.W., Boyce, J.I., Schwarcz, H.P., Sahoğlu, V., Erkanal, H. and Artzy, M. (2009), "Multi-proxy geoarchaeological study redefines understanding of the paleocoastlines and ancient harbours of Liman Tepe (Iskele, Turkey)", *Terra Nova*, Vol. 21, pp. 97-104, doi: 10.1111/j.1365-3121.2008.00861.x.

Higginbotham, J. (1997), *Piscinae, Artificial Fishponds in Roman Italy*, Chapel Hill, London.

Jacono, L. (1926), "Solarium di una villa nell'isola di Ponza", in *Notizie Degli Scavi dell'Antichità*, Vol. 2, pp. 219-232.

Jimenez-Espejo, F.J., Martinez-Ruiz, F., Sakamoto, T., Iijima, K., Gallego-Torres, D. and Harada, N. (2007), "Paleoenvironmental changes in the western Mediterranean since the last glacial maximum: high resolution multiproxy record from the Algero–Balearic basin", *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 246, pp. 292-306, doi: 10.1016/j.palaeo.2006.10.005.

Lambeck, K., Anzidei, M., Antonioli, F., Benini, A. and Esposito, A. (2004), "Sea level in Roman time in the Central Mediterranean and implications for recent change", *Earth and Planetary Science Letters*, Vol. 224 No. 3, pp. 563-575, doi: 10.1016/j.epsl.2004.05.031.

Lambeck, K., Anzidei, M., Antonioli, F., Benini, A. and Verrubbi, V. (2018), "Tyrrhenian sea level at 2000 BP: evidence from Roman age fish tanks and their geological calibration", *Rendiconti Lincei. Scienze Fisiche e Naturali*, Vol. 29, pp. 69-80, doi: 10.1007/s12210-018-0715-6.

Leoni, G. and Dai Pra, G. (1997), *Variazioni del Livello del Mare nel Tardo Olocene, Ultimi 2500 Anni, Lungo la Costa del Lazio in Base ad Indicatori Geo-Archeologici: Interazioni fra Neotettonica, Eustatismo e Clima*, ENEA, Unità Comunicazione e Informazione, Rome.

McCann, A.M. (1987), *The Roman Port and Fishery of Cosa*, Princeton University Press, N.J.

Melis, R., Furlani, S., Antonioli, F., Biolchi, S., Degrassi, V. and Mezgek, K. (2012), "Sea Level and paleoenvironment during Roman times inferred from coastal archaeological sites in Trieste (Northern Italy)", *Alpine and Mediterranean Quaternary*, Vol. 25 No. 1, pp. 41-55.

Morhange, C. and Marriner, N. (2015), "Archaeological and biological relative sea-level indicators", Shennan, I., Long, A. and Horton, B.P. (Eds), *Handbook of Sea Level Research*, Wiley, pp. 146-156.doi: 10.1002/9781118452547.ch9.

Morhange, C., Laborel, J. and Hesnard, A. (2001), "Changes of relative sea level during the past 5000 years in the ancient harbor of Marseilles, Southern France", *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 166 No. 3, pp. 319-329, doi: 10.1016/S0031-0182(00)00215-7.

Morhange, Ch., Marriner, N., Excoffon, P., Bonnet, S., Flaux, C., Zibrowius, H., Goiran, J.P. and El Amouri, M. (2013), "Relative sea-level changes during Roman times in the Northwest Mediterranean: the 1st century A.D. Fish Tank of Forum Julii, Fréjus, France", *Geoarchaeology*, Vol. 28, pp. 363-372, doi: 10.1002/gea.21444.

Olcina, M. (2015), "Los viveros romanos de la costa alicantina", in Olcina, M. and Pérez, R. (Eds), *La Illeta dels Banyets y los viveros romanos de la costa mediterránea española. Cuestión de* *conservación*, MARQ, Museo Arqueológico de Alicante, Diputación Provincial de Alicante, Spain, pp. 42-63.

Pérez, R., Olcina, M. and Alonso, J. (2013), *Proyecto de ejecución para la consolidación y estabilización de los viveros romanos del yacimiento arqueológico de la Illeta dels Banyets*, Diputación Provincial de Alicante, Alicante, Spain.

Plinius (77 AD), *Naturalis Historia*, Vol. IX. (consulted edition: Hernández, F. 1996. Historia Natural Plinio el Viejo. Ed. Universidad Nacional de México, México D.C.).

Profumo, M.C. (2007), "Archeologia della costa: la situazione marchigiana", in Auriemma, R. and Karinja, S. (Eds), *Terre di mare. L'archeologia dei paesaggi costieri e le variazioni climatiche*, Trieste-Pirano, pp. 360-368.

Rosselló, V.M. (1999), "La Illeta dels Banyets del Campello: nivels marins i arqueologia al migjorn valencià", in Fumanal, M.P. (Ed.), *Geoarqueología i Quaternari Litoral. Memorial Maria Pilar Fumanal*, Universitat de València. Departamento de Geografía, Valencia, pp. 229-243.

Rovere, A., Stocchi, P. and Vacchi, M. (2016), "Eustatic and relative sea level changes", *Current Climate Change Reports*, Vol. 2 No. 4, pp. 221-231, doi: 10.1007/s40641-016-0045-7.

Schmiedt, G. (1972), *Il livello antico del mar Tirreno. Testimonianze dei resti archeologici*, Olschki, Firenze.

Sivan, D., Lambeck, K., Toueg, R., Raban, A., Porath, Y. and Shirman, B. (2004), "Ancient coastal wells of Caesarea Maritima, Israel, an indicator for relative sea level changes during the last 2000 years", *Earth and Planetary Science Letters*, Vol. 222 No. 1, pp. 315-330, doi: 10.1016/j.epsl.2004.02.007.

Vacchi, M., Marriner, N., Morhange, C., Spada, G., Fontana, A. and Rovere, A. (2016), "Multiproxyassessment of Holocene relative sea-level changes in the western Mediterranean: sea-level variability and improvements in the definition of the isostatic signal", *Earth-Science Reviews*, Vol. 155, pp. 172-197, doi: 10.1016/j.earscirev.2016.02.002.

**Corresponding author**
Francisco Javier Caballero-Rubio can be contacted at: fjcaballero.arq@gmail.com