

National and Kapodistrian University of Athens  
Faculty of Geology and Geoenvironment



ΕΛΛΗΝΙΚΗ ΔΗΜΟΚΡΑΤΙΑ  
Εθνικόν και Καποδιστριακόν  
Πανεπιστήμιον Αθηνών

Roman fish tanks of the Mediterranean Sea  
and their relation to sea level change

**Diploma Thesis**  
**Author: Paris-Konstantinos Oikonomou**  
**Supervisor: Dr. Evelpidou Niki**  
**Athens 2023**

## **Table of Contents**

***Abstract ... 4***

***Introduction ... 5***

***Methodology ... 7***

***Technical specifications of fish tanks and seawater hydraulics ... 7***

Construction materials ... 9

***Architectural characteristics ... 10***

Internal design ... 11

The Function of Roman Fish Tanks ... 12

***Sea-level change ... 12***

The research of sea level in the Mediterranean ... 13

***Fish tanks in Greece ... 15***

***Fish tanks along the Tyrrhenian of Spain and the Western Mediterranean basin ... 16***

***Fish tanks of France ... 17***

***Fish tanks along the Tyrrhenian coast of Italy ... 18***

***Adriatic Sea Fish Tanks ... 21***

***Fish tanks of Israel ... 22***

***Fish tanks of Egypt ... 23***

***Fish tanks of Lebanon ... 28***

***Data base analysis and observations ... 31***

Overview of construction and architectural characteristics ... 30

***Fish tanks as sea level indicators ... 34***

***Fish tanks as historical and architectural monuments ... 35***

***Conclusion and discussion ... 35***

Table presenting the measured sea level in each fish tank in the  
Mediterranean: ... 36

***Classification of Roman fish tanks based on their structural features,  
condition and building technique ... 38***

***References ... 41***

## Abstract

Roman fish tanks are found in various coastal regions of the Mediterranean, although the vast majority is found in the Tyrrhenian coasts 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 high 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

## Introduction

Roman fish tanks are observed in coastal territories of the Mediterranean, and most of them are detected in Italy (Higginbotham 1997). These are found mainly in the Tyrrhenian coastlines (54), and only one is documented in the Adriatic coastline (Lambeck et al. 2004). More than twenty fishponds have been recorded in the rest of the Mediterranean in such countries as Ras El Hekma in Egypt (Torab, 2016; Evelpidou et al., 2021), Greece (Mourtzas et al., 2012; Davaras, 1974,1975,2012; Flemming and Pirazzoli 1987; Nakassis 1987), Cyprus (Galili et al., 2015; Lambeck et al., 2004b), Croatia (Florido et al., 2011; Auriemma & Solinas, 2009), Spain (Caballero et al., 2021; Olcina, 2015; Bernal, 2011), France (Morhange et al., 2013), and Israel (Gallili & Sharvit, 1998).

The development of fish tanks took place between the 1st century BC and 1st century AD to create adequate environmental conditions to uphold the cultivation of fish, their preservation, and subsequent distribution to the market. In this sense, this activity also delivers information about the socioeconomic status of the areas of distribution and consumption and the people residing within those areas. Higginbotham (1997) notes that the geomorphological traits, proximity from water sources, and some aesthetic parameters helped evaluate where fish tanks should be formed. Any existing elements such as cavities and coves acted as natural barriers allowing the fishes to be restrained within a specific territory. Another aspect influencing their location was sufficient access to salt and sweet water to ensure adequate water circulation and salt concentration. Fish tanks were either fully or partially constructed (Higginbotham, 1997 as cited by Caballero-Rubio et al., 2021).

Their contribution in terms of the physical geography of the geologic past of a territory should not be neglected. Characteristics about their design and construction provided a method to determine the sea level— which was widely used during Roman times (Lambeck et al., 2004) — mainly because their position in diodes enabled the seawater to enter the fish tanks. However, a limitation stemming from this is the corrosive quality of seawater (Higginbotham, 1997). Essential in using fishponds as effective sea-level indicators is their function between the 1st century BC and 1st century AD, as this specific period allows for precise estimations to be drawn on the sea's level 2000 years from today (Morhange et al., 2013).

In 1972 Schmiedt presented his major work for the examination of archaeological indicators of sea-level change in the North-western Mediterranean. Since then fish tanks have been extensively used to measure Relative Sea Level variations since Roman times (Auriemma & Solinas, 2009). Methods and principles for the investigation of fish tanks and their relation to the sea level have been developed by researchers such as Evelpidou et al., 2012 & Lambeck et al., 2004. An essential parameter for comparing the structural characteristics of fish tanks with the mean sea level of an older period concerns that the tanks were in open contact with the sea at their time of operation. (Kurt Lambeck et al., June 2018). Also crucial parameter is the proper interpretation of the position of the fish tank's structural elements and the determination of standard design scales of these elements according to the sea level (Evelpidou et al., 2012).

As noted by Plato, the cultivation of fish occurred prior to the Roman era in the shores of the Nile whereas similar methods of fish cultivation were common in the Hellenic territory (Higginbotham 1997). The Egyptians constructed large enclosures connected to religious groups of buildings and royal palaces (Besta 1921, as cited by Evelpidou et al., 2019).

In the Italian peninsula, the cultivation of fish is a long-standing tradition. According to Varro and Columella, it originated in sweet water lakes and streams. Originally the fish grown in fish tanks were mainly freshwater fish destined for the poor. With time the practice expanded and was applied to coastal areas where salt water fish were grown. The architectural design of fish tanks was also improved. Their creation served aesthetic purposes and was used for the decoration of private gardens in Roman villas. At the beginning of the 1<sup>st</sup> century AD, the cultivation of fish became the predominant occupation of the rich and the ownership of fishponds an indicator of social and economic ability (Higginbotham 1997).

Paleoenvironmental research based on sea indicators of fishponds has shown that during the Roman period the level of the sea in the Western Mediterranean was approximately 50 cm below the current level with numbers ranging from 30 cm to 135 cm (Lambeck et al., 2004) (Morhange et al., 2013) (Evelpidou et al., 2012).

## Methodology

This paper is based on Caballero's et al. (2021) work titled The Roman fish tanks of the Western Mediterranean basin as potential scenarios for research on sea-level changes, which examines fish tanks in France, Spain and Italy. Other bibliographical sources were used for the description of fish tanks that are not included in the work mentioned above. Also, field work has been conducted in Egypt where fish tanks were studied in situ.

## Technical specifications of fish tanks and seawater hydraulics

Archaeological evidence shows that most fish tanks were built on land or along the coastline near Roman villas.

Records reveal two types of fish tanks. Those that were completely excavated in rock, are the rarest and their construction heavily depends on the geomorphology of the chosen coastline for the location of the fish tank.

Fish tanks attached to rocky cavities were naturally protected and provided shelter to fish populations, which helped with the selection of similar coastal spots for the construction of fishponds (Higginbotham 1997). Their construction techniques were determined by the geomorphological traits of the coast and distinguished into three categories:

1. Those entirely carved into the coastal rock (Higginbotham, 1997)
2. Those entirely made of cement (Higginbotham, 1997)
3. Those that are a combination of the two techniques mentioned above (Caballero et al., 2021)

Those in the first category typically extend 2.7 meters below the sea surface (Higginbotham 1997), e.g., Torre Valdaliga and Mattonara (Evelpidou et al., 2012). Part of the second category is those with a deep foundation stretching 2.1 meters below the sea surface, e.g., Piscina di Lucullo (Chiapella, 1965), Punta della Vipera, Forima, Fosso Guardiole as well as those with a shallow foundation stretching 0.6 meters below the sea surface, which is designed for flatfishes (Evelpidou et al., 2012). A representative example is a small arched tank in Fosso Guardiole (Evelpidou et al., 2012).

Archaeological findings from the study of fish tanks stay in agreement with the demand for the provision of salt water mentioned by Columella (a Roman author whose written work concerned agriculture during the Roman period in the 1<sup>st</sup> century AD). Mainly, any tank with adequate water circulation can function as a fish farm and the detailed design characteristics described by historians such as Columella and Vitruvius are ideal cases of construction – which are not generally observed in any isolated fish tank (Higginbotham, 1997).

The largest fish tanks consisted of multiple cavities whose purpose was to separate groups of fish based on size (Morhange et al., 2013), type or age (Higginbotham, 1997). This was achieved by constructing vertical cuts on the walls' openings within were placed movable grids (cancelli).

Their up-and-down movement allowed fish to move to neighboring tanks (Higginbotham, 1997). The edges of the circumferential walls were always above the sea, even when the weather conditions were unfavorable (Morhange et al., 2013). The walls that surrounded the fish tanks were designed in such a way as to prevent the fish from escaping. Importantly, some fish could jump out of the water; Therefore, higher walls were required. Further, the fish that move faster tend to jump out when there is overcrowding or confined space. Some of the walls discovered in the Cosa fishpond differ significantly in height, which suggests that they were constructed specifically for the protection of different types of fish (Higginbotham, 1997). The precise correlation between the height of the walls of fish tanks and the old sea level is complex, as their construction also considered the amplitude of the oceanic tide.

However, there are architectural features that can help estimate the level of the sea when the fish tanks had still been active. As noted by Morhange et al. (2013), the external walls were higher than the internal walls in order to defend fishponds against storms and keep the fish inside. In addition, the channels directly connected to the sea needed to transfer water into the fishpond during the high tide (Pirazzoli, 1988), as mentioned by Morhange et al., 2013.

Researchers such as (Caputo & Pieri, 1976; Flemming & Webb, 1986; Leon & Dai Pra, 1997; Evelpidou et al., 2012) pay particular attention to the fact that at least 10 cm of the height of the water the high tide must go through the channels in the entrance of the fish tanks to ensure the smooth circulation of the water in their interior as stated by Morhange et al., 2013.

Other design features that prevented fish from escaping were platforms or steps that lined the interior of the fish tanks. These served mainly as pathways for the caretakers of the fish tanks and were designed slightly above or near the water's surface so that they were lightly splashed and did not hinder the maintenance or use of the fish tank. In addition, their design prevented fish near the walls from reaching an adequate depth to develop the necessary speed towards the surface and jump out of the fish tank. (Higginbotham, 1997).

## Construction materials

The composition materials of hydraulic cement are pozzolana, lime, and aggregates. Its use gave architects and owners more options for selecting a location to construct a fish tank in order to leverage the space's design better. Vitruvius describes some methods of creating structures with cement. Each method acts as a construction guide depending on the characteristics of the shore and the prevailing weather conditions, even in the absence of materials that compose cement (Higginbotham, 1997).

The plasticity of cement allows for the construction of curvy walls for the fish tanks rather than restricting it solely to linear ones. The arched walls are more efficient as breakwaters because the curvy formations contribute to the more effective circulation of water within the fish tank while also reducing the concentration of sediments on the edges. Moreover, the aesthetic result is of higher quality and entails the use of fewer construction materials than those required for linear walls (Higginbotham, 1997). more developed constructions included channels that connected to the open sea in order to renew the water within the tank. The tanks were demarcated by walls over which protruded passages that were used for the preservation of the

tank but also for the cultivation of oysters such as the Piscina di Lucull, Formia Astura, Punta della Vipera (Evelpidou et al., 2012). This construction method ensured that the tank would be protected from the corrosive properties of the water.

## Architectural characteristics

Most of the positions of the fish tanks along the Tyrrhenian coast are associated with villas or private residences, the location of which was chosen to take advantage of the panoramic view and also to benefit from the naturally formed coves. The architectural design reflects man's attempt at controlling nature during that era. Many coastal fish tanks included facilities for dining by the seaside. The relationship between the fish tanks and the dining facilities serves not only aesthetic purposes but also has gastronomic value, as seafood was collected directly from the fish tanks, adding an impressive character to the table among the guests and hosts. (Higginbotham, 1997)

Columela, a historian of the 1st century AD, mentions the importance that architects placed on shaping a natural environment within the interior of the fish tanks (Higginbotham, 1997). The construction of specially formed soils and surfaces on the walls of the fish tanks was crucial for creating a suitable environment for all kinds of fish.

After completing the construction and securing water supply, recesses (*specus*) were added to the inside of the walls of the fish tanks. The architect's intention in constructing them was to provide shady areas for the fish. The recesses were built in such a way that some fish were simply protected from the heat, while others were wrapped up and confined inside them (Higginbotham, 1997). A more artistic solution to the problem of creating shade is the construction of walls with straight or semi-circular recesses, such as in Pompeii and Palatine Rome (Higginbotham, 1997). The numerous angles and curves ensure that there will be shade in some part of the fish tank during the day. Additionally, an alternative solution was the construction of arch bridges inside the fish tanks and the placement of ceramic jars or cooking utensils in which the fish found coolness and shelter from predators (Higginbotham, 1997).

## Internal design

The design of all Roman *piscinae* includes a channel system that enables seawater to enter the installation. The channels' orientation is determined by morphological and coastal characteristics and seeks to take advantage of the sea wave energy so the freshwater can penetrate the pond. Because a continuous water input is necessary, fish ponds must consistently be underwater, even during the high tide (Higginbotham, 1997). Smaller channels (*cuniculi*) transfer water further into the fish pond and facilitate regular circulation. (Caballero et al., 2021). Each opening into the fishpond had to be covered with fixed gates (*cancelli* or *cataractae*) to prevent any fish from escaping and allow the seawater to flow effectively. These gates were positioned along the channels or between the basins of the ponds and operated along sliding notches cut into the rock. A representative example is the Piscina di Lucullo (Chiapella, 1956, Formia, Astura, Giacomini, Marchesini, & Rustico, 1994). A thorough investigation of their marks can offer an idea of past sea levels (Evelpidou, Pirazzoli, et al., 2011).

Above the sea, a perimetric walkway (*crepido* or *crepidini*) borders the fish pond. The emerged part of the walls distinguishes the fish pond from the open sea, protecting it from the waves. It was used for access to the pond and its conservation, and its construction above the highest level of the tide was necessitated. These architectural elements point directly to the main sea level for the regular function of the fish tank (Caballero et al., 2021). Nevertheless, opinions diverge regarding the validity of each structural element as a sea-level indicator. For instance, the *crepido* cannot invariably be used as a credible indicator due to its position at the outermost part of the tank and exposure to sea erosion. Moreover, Mohrange et al. (2013) claim that the *crepido* is found above the main sea level, and only some channels correspond to the sea level.

## The Function of Roman Fish Tanks

Roman fish tanks were used primarily for fish farming, as they provided a controlled environment for the breeding and raising of fish. The tanks were often stocked with a variety of fish species, including mullet, sea bream, and sea bass. The fish were harvested when they reached maturity, typically after several months of growth. Different species of fish were kept in tanks modified specifically for their needs and characteristics. An example is the grey mullet (*Mugil*) which had the ability to leap over the water and for this reason it was confined in fish ponds with higher walls. Higginbotham mentions that several walls of the fish tank in Cosa have different heights and probably they were designed for different species of fish. Despite having this information there is no direct relation between the heights of the fish tank walls and the ancient sea level. The fish tanks of Praedia Iuliae Felicis, the Villa di Diomede, and the Casa di Meleagro located at Pompeii are all built with high protective walls that stand 60 cm above the water outlets and act as barriers for the jumping fish. Other types of fish mentioned were the bass (*lupus*), the conger and murena. The last two mentioned cannot get along with each other and had to be isolated in different ponds.

## Sea-level change

The sea level is defined as the average height of the sea surface and its variation is a result of the movement of land and changes in the volume of ocean water. The term "relative sea level" refers to the level of the sea surface in relation to land (Καρύμπαλης Ευθύμιος Παράκτια Γεωμορφολογία, Αθήνα, Εκδόσεις Ιων, 2010).

Sea level should be considered as relative (Relative Sea Level) because its position can be changed either by the movement of land or by the increase or decrease of the sea surface due to the melting of polar ice caps or other causes. (Liberatore et al., 2022)

The variation in the volume of glaciers can lead to changes in ocean volume, the shape of the sea surface and the surface of the land (Kurt Lambeck et al., 2004). As many coasts in the Mediterranean are tectonically active, the change in relative sea level in many areas is common

(Mourtzas et al., 2012). Sea level in the Mediterranean is dependent on both geophysical and geological factors such as the continental isostatic balance of glacial cover at high geographic elevations (Kurt Lambeck et al., 2018).

Various opinions have been formulated regarding the causes of sea level change. One of these suggests that the deposition of sediments on the ocean floor is responsible for this change, however, this interpretation does not satisfactorily explain large-scale variations. Contemporary research suggests that the primary cause of the phenomenon is the increase in the volume of seawater due to the planet's climatic changes. (Karimpalis Efthimios Coastal Geomorphology).

Sea level variations on a global scale that are due to fluctuations in ocean water are called eustatic (Evelpidou book). On a local scale, sea level changes are affected by factors other than eustasy, such as tectonic activity and isostasy. Usually, it is difficult to clarify whether the change resulted from eustatic or local causes, however, the final result appears to be a combination of both processes. (Karimpalis Efthimios Coastal Geomorphology).

## The research of sea level in the Mediterranean

The sea level in the Mediterranean has been studied by researchers for two centuries. Interest in the vertical movements of land and sea has been recorded since the Roman era, while the first modern research on sea level is attributed to Lyell (1833) and Negris (1903a, 1903b; 1904). Gignoux (1913), Issel (1914), and Blanc (1920) were the first to define the Tyrrhenian as a chronostratigraphic unit along the Tyrrhenian coast of Italy, especially in Sardinia, Tuscany, and Lazio (Benjamin et al., 2017).

In the early 20th century, the prevailing scientific view supported the stability of sea level during historical times in the Mediterranean region. In scientific discussions related to underwater scientific findings on the coasts of the Mediterranean, such as Delos, Lefkada, and Aegina, the Greek geologist F. Negris disagreed with his French colleague Cayeux. Negris had observed that sinking was not due to land movement but to the rise of the sea, in contrast to Cayeux, who believed that changes were due to the compression of sediments. Ignoring

documented archaeological evidence, such as the raised harbor of Phalasarna in western Crete, Negris did not accept local variations as a cause of changes in sea level. In the mid-20th century, the use of modern technological methods for dating materials in archaeological excavations led to a more specific chronological limit for sea level changes. During the 1970s and 1980s, scientists such as Flemming (1969), Pirazzoli (1976b), Blackman (1982a, b), and Raban (1985) reintroduced geoarchaeological research on sea level in order to better understand archaeological sites. Schmiedt also used Roman fish tanks in the Adriatic in 1972 in research on recording sea level changes over the last 2,000 years (Morhange and Marriner, 2015).

In the late 19th century, the investigation of sea level in the Mediterranean progressed significantly and became a distinct scientific subject of research for scientists of various specialties such as geologists, archaeologists, biologists, geophysicists, and geochemists. Scientists recognized the connection between sea level and human migrations along the coasts. Changes in coastal conditions affected landscapes, aquatic areas, ecological zones, and people as coastlines changed due to erosion, sediment deposition, and related changes in sea level. At the same time, archaeologists of the 20th century recorded coastal cities that showed maritime activity in the Mediterranean. The study focused more on the most recent periods, from the time of the use of metals and written language, while less importance was given to earlier periods. The eastern Mediterranean is an important area for integrated research on landscape evolution and archaeology. The results of research in this area have contributed significantly to the understanding of the spread and migrations of human populations, as well as to terrestrial and maritime trade routes (Benjamin et al., 2017).

The Mediterranean Sea is unique from a historical and archaeological perspective, as it served as a privileged space of communication for the peoples living on its coasts. The civilizations of these peoples have left evidence such as the constructions of their cities and infrastructure (Antonioli et al., 2007). Some objects or installations that are currently underwater can provide significant information for the reconstruction of ancient coastlines (Antonioli et al., 2007 as cited by Auriemma et al., 2008).

The unique climatic and historical conditions of the Eastern Mediterranean make it one of the ideal locations for analyzing relative sea level. The limited connection of the basin to the Atlantic Ocean gives the Mediterranean region a key advantage, which is the low tidal range with an average of 40 cm. Along all the coastal areas of the Mediterranean, the indications of sea level are visible in sea notches, beaches, biogenic constructions, and artificial structures. In order to find the boundaries of ancient shorelines, two elements of the sea level indicators need to be known: their creation date and the difference in elevation from their creation until today (M. Liberatore et al., 2022).

The types of marine indicators include archaeological ones, which are related to ancient constructions such as fish tanks or port structures, the construction age and functional height of which can be calculated if they are not already mentioned in ancient texts. Their chronology can be determined either based on their construction characteristics, which belong to a specific historical period, or based on radiocarbon dating of the construction sample (M. Liberatore et al., 2022). The construction date of fish tanks is well-defined from the archaeological record within a narrow time frame (1st century BC - 1st century AD) and is an invaluable aid in investigating RSL in combination with the fossilized microorganisms found on the walls of the fish tanks (Christofe Morhange et al., 2013).

The closest approximation of the age of the creation of marine indicators is achieved when data from both chronological methods are available and mutually supported. Materials suitable for dating these constructions can be any organisms that live in a biological environment near the surface of the sea, such as cephalopods (M. Liberatore et al., 2022).

## Fish tanks in Greece

Roman age fish tanks have been reported in Greece as relics from the Roman Empire period. They are located in Crete on several coasts such as Ferma (Ierapetra area), Chersonissos, Matala, Siteia, Mochlos, and Gulf of Zakros as recorded and studied by Mourtzas (2012) and researchers that are mentioned in the previous paragraphs of this research paper. Roman fishponds and fish traps in Crete were built close to the boisterous urban centers of that period. Crete's central geographic position in the eastern Mediterranean establishes a critical economic

advantage: shipments from all the major commercial centers passed from Crete to deliver merchandise. There is undoubtedly 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 (Mourtzas, 2012).

The island's robust neotectonic activity is affected by its position, which is near the subduction zone of the lithospheric plates along the southern part of the Hellenic Arc. Strong earthquakes produce vertical movements of the land and divide the island into blocks. Holocene age tectonic uplifts and submersions have led to alterations in the coastal geomorphology of the island. Therefore, they are vital in calculating paleo sea level from the current positions of fish tanks (Mourtzas, 2012).

Studies of these fish tanks by Mourtzas (2012) resulted in an estimation of the sea level of the eastern Mediterranean at  $1,24 \text{ m} \pm 0,09 \text{ m}$  below the present one during the Roman Era.

## Fish tanks along the Tyrrhenian of Spain and the Western Mediterranean basin

The fish tanks found in Spain are those of

- 1) Cape Trafalgar, Cadiz
- 2) La Albufereta, Alicante
- 3) Illeta dels Banyets in El Campello, Alicante
- 4) Banos de la Reina in Calp, Alicante
- 5) Banos de la Reina in Xabia, Alicante as stated by (Caballero-Rubio et al. 2021)

They are found along the western Mediterranean coast except from the one at cape Trafalgar which is found at the Atlantic coast of Spain near Gibraltar as shown in Figure 1. Map from Caballero-Rubio et al. 2021. These fish tanks are all completely carved into calcitic rock or sandstone to a depth of 2,7 m or less depending to the type of the cultivated fish (Lambeck et al. 2004) and they are in good conservation condition, merely submerged or on land. Fish inside the tanks are distributed by size in different basins that communicate via narrow channels (itineras) (Higginbotham 1997) and they are separated with sluice gates

cataractae (F.J Caballero et al. July, 2020). Considering the level of preservation and the observed structural elements, the fish tanks that can be used for a paleo sea level estimation are these found on the Mediterranean coast (F.J Caballero et al. July, 2021).



**Location map of selected fish tanks in the Western Mediterranean basin analysed in the work of Caballero et al., 2021**

## Fish tanks of France

These are found at the southern coast of France and are recorded from west to east as follows with numbers corresponding to points at Figure 1

- 6) Port-la-Nautique, Narbonne, Aude
- 7) La Gaillarde, Roquebrune-sur-Argens, Var
- 8) Frejus, Var
- 9) Ile Sainte-Marguerite, Cannes, Alpes-Maritimes
- 10) Antibes, Alpes-Maritimes with numbers corresponding to points at Figure 1.

They are cut into the coastal rock or reinforced with opus caementicium (hydraulic concrete), partially submerged, or found on land. They adduce cataractae or channels with a good state of preservation.

The fish tank number 8 at Frejus, Var located in Southeastern Provence has been studied by Morhange et al. 2013 especially for sea level changes. At the mid of the 1<sup>st</sup> century A.D the fish tank was filled entirely with silt and its operation stopped. Previous measurements and data have been also obtained in the same area by Devillers et al. (2007) and Laborel et al. (1994). To calculate the relative sea level during the Roman period, Morhange et al. (2013) employed the palaeozonation of marine fossil organisms attached to the fish tank walls. The theory of biological zonation propose that marine benthic animals and plants can live only in very adapted environments and ecological conditions. Changes in relative sea level led to alteration of the organisms with more resistant species or forms of life taking their place. Combining evidence from architectural structures and biological sea-level indicators such as palaeozonation of marine benthos, the Relative Sea Level was estimated at  $40 \pm 10$  cm below the present one (Morhange et al., 2013). 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 These numbers accord with Evelpidou et al. (2012) who proposed a Roman sea level ranging from  $-32 \pm 5$  to  $-58 \pm 5$  cm on the Tyrrhenian coast of Italy.

## 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 with the sea or small fish ponds were built near coastal villas adding luxury to the landscape architecture. Fish raising used to be an occupation of the rich (Higginbotham, 1997) and symbolized wealth and luxury (Giacopini, Marchesini, & Rustico, 1994). Originally the first fish ponds were built inland near lakes or streams and provided a secured place for freshwater fish. Only later around the 1st century B.C when a trend towards the consumption of sea water fish led to the development of seaside fishponds (Higginbotham, 1997). This consumption preference made social status differences while the poor were content with freshwater fish and saltwater fish were be destined for the cuisine of the high society.

## Construction and operation

Frequently brackish conditions had to be met inside the enclosures to ensure the proper environmental conditions for the fish. Salt water from the sea was mixed with fresh water in sufficient quantities to reach the required salinity. The site selection for seaside fish ponds 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. However, the control of the sea currents into the ponds had not the same manipulation as with 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 (Higginbotham, 1997).

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. Seawater hydraulics were also an important factor for the supply and the distribution of the water inside the ponds. Beyond the architectural elements described previously in this paper (architectural characteristics) standard scales relative to the sea level were proposed for the construction of the parts of the pond. For example, when constructing a fish tank, the sea level must be seven Roman feet (2.06 m) above the bottom part of the pond (Higginbotham, 1997).

However not all fish ponds were constructed with the same specifications. The architectural style changed on each location and the construction elements had to be adjusted to the local morphological conditions of the fish pond area. In addition, the fish ponds found far from Tyrrhenian coast present significant differences in the design and in the operational use of each element of the pond (Lambeck et al., 2018). Therefore, the structural characteristics of a specific fishpond have to be carefully studied when choosing a sea level marker.

The number of fish tanks recorded along the Tyrrhenian coast of Italy is fifty-four (54) (Giacopini, Marchesini&Rustico, 1994) and only one is recorded on the Adriatic coast (Lambeck et al., 2018).

A study from Evelpidou et al. (2012) provides sea level measurements from data acquired from 8 fish tanks of the Tyrrhenian coast. All these fish tanks are found submerged and carry archaeological as well as geomorphological evidence of past sea levels. They conclude that

the sea level at the eastern Mediterranean did not exceed  $58 \pm 5$  cm. Structural elements such as sluice gates, cataractae, crepidines and over flow carvings were used for an accurate mean sea level estimation.

The fish tanks that have been studied are these of:

- 1) Sarinola located in the town of Formia
- 2) Punta della Vipera near the town of Civitavecchia
- 3) Torre Valdaliga
- 4) Mattonara
- 5,6) Two fish tanks near the mouth of Fosso Guardiole
- 7) Odescalchi
- 8) Grottace

Sarinola and Odescalchi are the only fish tanks in Italy where both grooves are preserved

On the other hand, the study of Lambeck et al. 2004 at Roman Fish tanks of the Tyrrhenian coast concluded to a Relative Sea Level of -1,3 m in the Roman period. Using structural elements such sluice gates, channels and foot walks in complete state of preservation Lambeck et al. (2004) 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.

Evelpidou et al. (2012) used a different reference system of the hydraulics of the fish tanks 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. Also they suggested that the upper part of the cataractae coincide with the upper crepido and not the lower one. In the same study it is also claimed that the height of cataractae from the hydraulics system model of Lambeck et al., 2004 is not enough for the proper function of the fish tank. Not a standard interpretation of the hydraulic position of the fish tanks has been established yet and therefore the need for an interdisciplinary approach for the reconstruction of the sea level is essential (Benjamin et al., 2017).

Another study from Auriemma and Solinas (2009) in the fish tanks of the Tyrrhenian provided paleo sea level measurements based on indicative markers of crepidines, captation canals, cataractae and carvings. Aucelli et al. (2016) provided data on sea level change at the Sorrento Peninsula from archaeological markers including fishponds. At the Sorrento fishpond they measured the height of the upper crepido at 0.8m below sea level and they estimated a sea level rise of  $1.1 \pm 0.3$  m from the Roman period. This sea level rise fit well with the theoretical model of Lambeck et al. (2004).

In the Gulf of Naples, in Sorrento area, Aucelli et al., 2020 have estimated a sea level rise of  $1.1 \pm 0.30$  m in the last 2000 years, based on the location of the upper crepido in the fish tank.

## Adriatic Sea Fish Tanks

Fish tanks recorded along the Adriatic coast are those of Slovenia (Bartolomeo/Jernejeva and Fizine), Croatia (Catoro, Kupanja, Svrsata in Kornati Island), and one in Italy. They are created with the technique of throwing single stones (single rocks jetty) into the sea (Auriemma and Solinas, 2009). They consist of multiple interior basins that were used for the division of different fish population or fish with different age (Florido et al., 2011). Their construction dates to the 1<sup>st</sup> century A.D. Despite the fact that the fish tanks along the Adriatic coast lack in architectural elements related to the level of the sea (Auriemma and Solinas, 2009) there are two specific examples of legitimate sea level markers at S. Bartholome/Jernejeva Draga and Fizine/Fisine.



**Aerial photograph demonstrating the submerged fish tanks at Fazine (photo from Benjamin Jonathan) Image from Stokin et al., 2008**

Florido et al. (2011) concluded to an average paleo sea level of around  $1.60 \pm 0.20$  m at the Adriatic Sea.

## Fish tanks of Israel

Archaeological studies along the coast of Israel have revealed ancient coastal installations such as harbours and quarries. They are found close to the modern sea level and the most provide a well state of conservation. Coastal rock-cut installations are sensitive indicators of the tectonic movements and can contribute to the study of relative sea level changes. Various rock-cut installations such as pools have been reported. Some of these are those at Shiqmona-Haifa, Habonim, Dor, Yonim Island, Caesarea, Tel Baruch. In Caesarea lies a rectangular pool cut inside the rock with channels that supply the enclosure and it is considered as a fish pond (Gallili & Sharvit, 1998). The upper parts of the installation match with the sea level at the time of investigation and in general the most of the coastal structures are close to the present-day sea level. The absence of underwater structures shows that either erosion phenomena at the foreshore region ruined them or a more compelling case indicates that the morphology of the Israeli coast had been tectonically stable since Roman times (Gallili & Sharvit, 1998).

## Fish tanks of Egypt

It is noteworthy that fish farming activities have been recorded from Latin and Greek authors along the Nile river before the Roman period. The Egyptians used to build enclosures filled with water to accompany religious and royal monuments as Plato mentions.

Fish tanks and marine installations along the coast of Egypt have been reported from and geoarchaeological studies such as these of Torab (2016) and Evelpidou et al., (2021). In Alexandria Egypt, three fish tanks from the Roman period have been identified and studied for paleo sea-level reconstructions (Evelpidou et al., 2021). These are the fish tanks of Abou Kir, the fish tank on Miami island and the Montazah fish tanks group. All of them are cut into the rock and provide a good state of preservation, except of that in the Abou Kir promontory which is filled with sediments.. In the Montazah fish tanks located in the bay of Maamourah the internal walls are observed to be constructed in a more delicate manner so visitors could

walk around the perimeter of the installation and admire the view. This approach of construction style is inspired by the Tyrrhenian fish tanks such as this in Torre Astura (Italy) (Evelpidou et al., 2021).

Structural elements such as crepidines, cataractae and channels were identified and used to measure their elevation from the current sea level. In accordance with the measurements results of the study of Evelpidou et al. (2021) the sea level in the area of Alexandrian coast 2000 years B.P was at  $70 \text{ cm} \pm 5 \text{ cm}$  below the present one.



**Internal of Montaza fish tank**



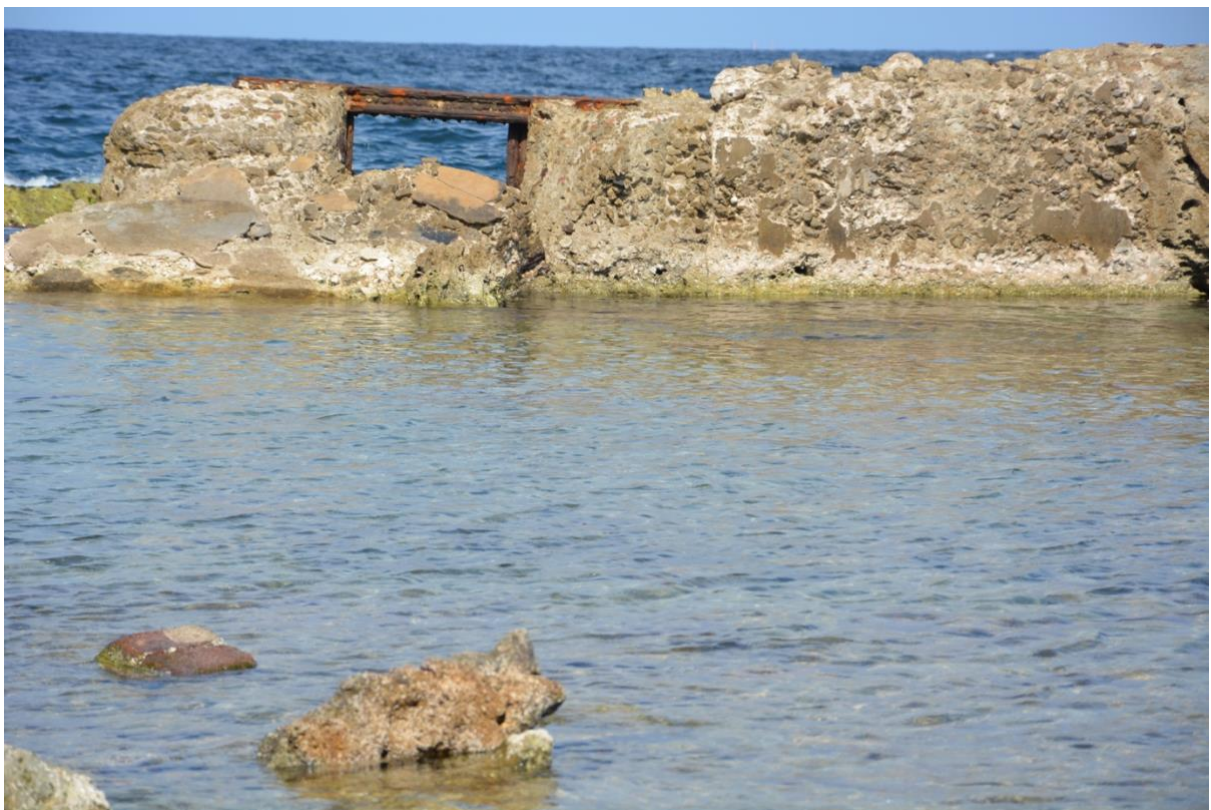
**Montaza fish tank (internal walls and channel connecting with the sea)**



**Abou Quir fish tank (borders of the fish tank)**



**Maiami fish tank (channel)**



**Montaza fish tank (inside space)**



**Montaza fish tank (view of the interior space)**



**Miami fish tank (cuniculi channel)**

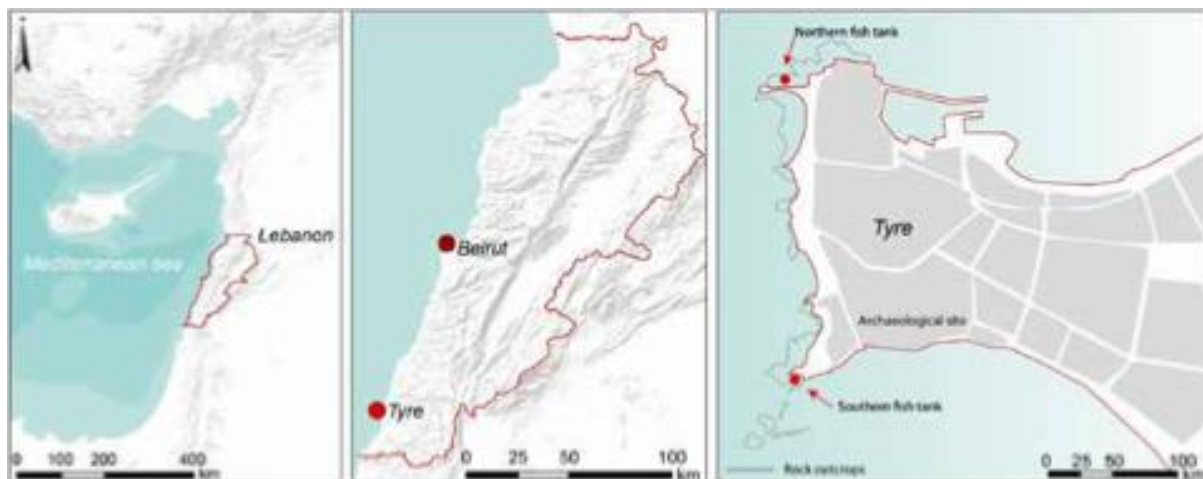


**Maiami fish tank (architectural feature)**

## Fish tanks of Lebanon

Two roman fish tanks have been discovered in 2017 by Jean-Philippe Goiran and his team (Goiran et al., 2019) in the coastal region of western Tyre, Lebanon. The first fish tank is located at the north and the second one at the southern part of Tyre. Both are crafted into coastal sandstone inside preexisting 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 feet walks (crepido). 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 up to 0.6 meters from the time of the construction of the fish tanks. In particular, Goiran et al., 2019 assume that when the fish tanks were functional, high tide should not have overflowed 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 when the fish tanks were functioning.



**Geographic Location of the two fish tanks in Tyre (Goiran et al., 2019)**



Index of spacing between two successively architectural features (Goiran et al., 2019)

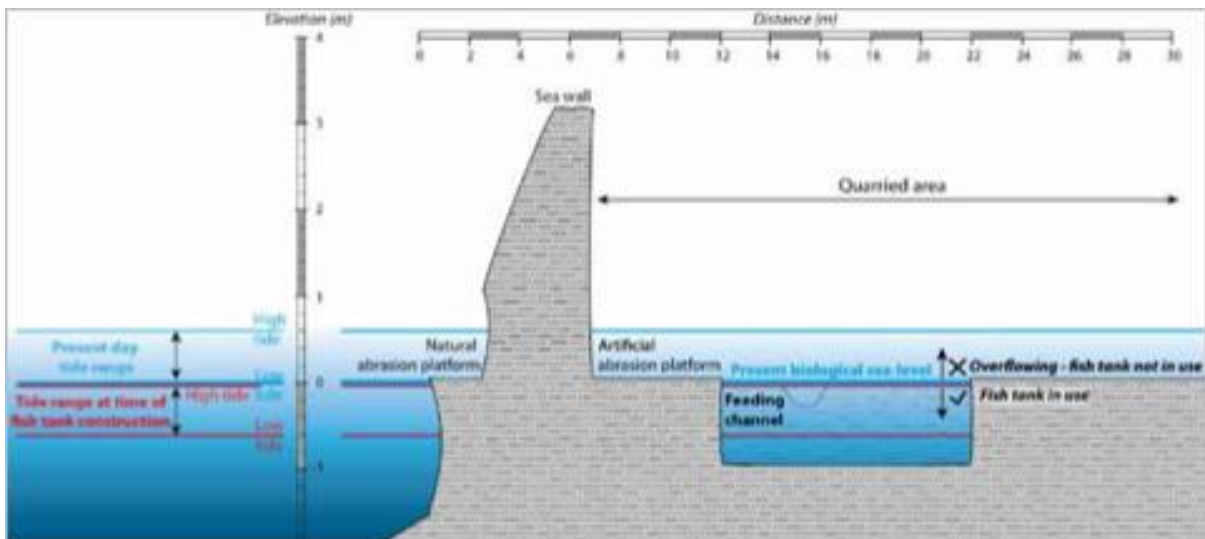


Image illustrating the architectural features of the fish tanks and their relative position with the sea level (Goiran et al., 2019)

## Data base analysis and observations

A database with information about 54 fish tanks from all over the Mediterranean sea was created to observe similarities or differences between them. Among them, 32 fish tanks (~60 %) are cut into the rock, indicating that this type of construction was the most popular at that time and probably had advantages over the others. Only 6 fish tanks are constructed with a combination of *opus caementicium* and rock cutting techniques. The three of them are found on the French coast, one in Pianosa Island of Italy between Corse and Rome, one more in Italy at Sperlonga area along the Tyrrhenian coast, and one in Egypt at the Bay of Maamourah. The small number of this type of construction may reflect their lack of operational efficiency or the high economic cost of installation. Spatially, these fish tanks with mixed characteristics are located near France except for one found in Egypt, but no general supposition can be developed about their geographic location or reason for construction. The remaining 16 fish tanks are constructed with *opus caementicium* or Hydraulic concrete and they are found on the Tyrrhenian coast of Italy and one along the French coast. This type of construction had benefits both in terms of construction and operation e.g. when the geomorphology of the selected area did not meet the requirements for the right function of the fish tank, the design could be modified to take advantage of the sea dynamics and satisfy the need for both salt and fresh water inflow. Also, with this method, the architect of the fish tank could give his own fish tank design geometrical features such as arches and curved walls (La Saracca, Nettuno, Roma, Italy that has a semi-circular shape and is separated by walls into concentric arches (Caballero et al., 2021) that has both technical and aesthetic value (e.g. avoiding the assembly of sediment at the junctions of the installation). In addition, villa owners may opt-in favor of 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 show lower erosion resistivity than those cut into the rock. Therefore, most of them are not in favorable preservation conditions and most of them do bear not any observable architectural elements to study.

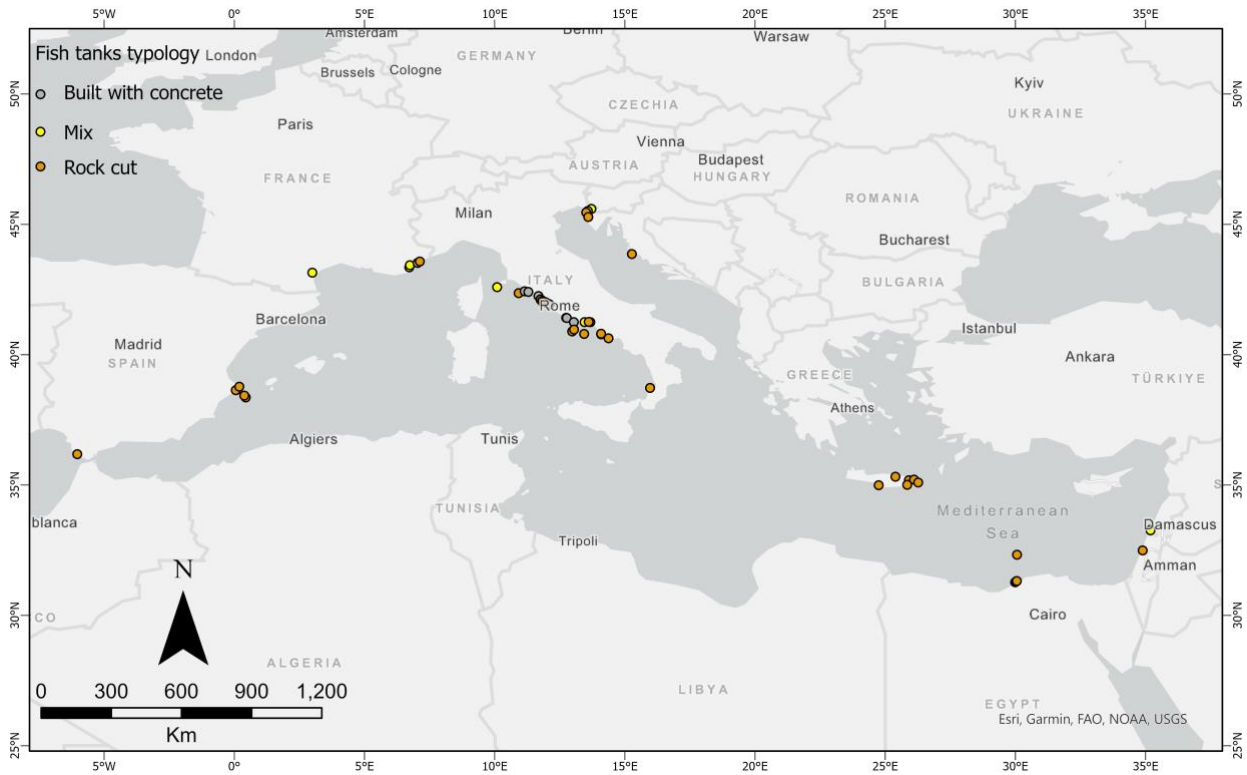
Fish tanks along the Adriatic coast are all cut into the rock and they do not follow the traditional building technique as these on the Tyrrhenian coast. Also, the large size of the Adriatic fish tanks gives them a definite commercial use for fish production and selling. These tanks are solely constructed for economic purposes and they have a different social value from the villae Maritima context found along the Tyrrhenian coast (Florido et al., 2010).

The architectural elements that are mostly used in fish tanks for paleo sea level reconstructions are the crepido, cataractae and the channels. The elevation of these elements relative to the current sea level combined with the original place of the elements relative to the former sea level can show the sea level change from the time of the fish tank construction until today. A major annotation is that the sea level during the Roman period is not the same in all the coastal regions of the Mediterranean Sea. Hence, it is reasonable to identify different sea level measurements between regions separated by an important distance. (E.g. The sea level in Alexandria is different from the sea level in the French coast.)

## Overview of construction and architectural characteristics

The analysis of the developed database from the Mediterranean fish tanks has shown that among the 62 fish tanks, 35 (~56 %) are cut into the rock, indicating that this type of construction was the most popular at that time and probably had advantages over the others. Only 11 fish tanks are constructed with a combination of hydraulic concrete and rock cutting techniques. Three of them are found on the French coast, one in Pianosa Island of Italy between Corse and Rome, one more in Italy at 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 their lack of operational efficiency or the high economic cost of installation. Their spatial distribution does not allow any general supposition about their geographic location or reason for construction. The remaining 16 fish tanks are constructed with hydraulic concrete, and they are found on the Tyrrhenian coast of Italy and 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 function 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. Also, with this method, the architect of the fish tank could give his own design 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 that has both technical and aesthetic value (e.g. 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 good preservation state and most of them do not bear any notable architectural elements to study.



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

Fish tanks along the Adriatic coast were all cut into the rock, and they do not follow the traditional building technique as these on the Tyrrhenian coast. Also, the large size of the fish tanks in the Adriatic Sea as well as Egypt gives them a commercial use for fish production and selling. These tanks were solely constructed for economic purposes, and they have a different social value from the villae Maritima context found along the Tyrrhenian coast.

## Fish tanks as sea level indicators

The previous paragraphs demonstrate the most important characteristics of fish tanks recorded in the Mediterranean region. What is noteworthy is 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 an architectural style 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 mostly used in fish tanks for paleo sea level reconstructions are the crepido, cataractae and channels. However, a good understanding of the functioning for each fish tank must be developed in order to determine the exact position of the indicative structural elements 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 with a paleo sea level between -0.5 and -1.5 m during the Roman period in respect to the present one. 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), Sorrento peninsula (Italy) or the Adriatic Sea. In France, sea level estimate come from a tectonically stable area, suggesting a RSL rise of  $0.4 \pm 0.10$  m since Roman times. Conversely, in Crete sea level has risen by  $1.24 \pm 0.09$  for the same period, suggesting an average tectonic subsidence of  $\sim 0.65$  mm/year. Similarly, Florido et al., 2011 report tectonic subsidence values between 0.63 and 0.89 mm/year, since Roman times.

## Fish tanks as historical and architectural monuments

Despite the challenges posed by sea level fluctuations, Roman fish tanks were an important aspect of Roman society and culture. They served as a source of food, entertainment, and economic activity, and played a significant role in the development of aquaculture practices. Today, the remains of Roman fish tanks can still be seen throughout the Mediterranean region, serving as a testament to the ingenuity and resourcefulness of the ancient Romans.

Besides the scientific importance of the fish tanks as sea level markers, they have cultural and historical significance, too. Fish tanks can be promoted as 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 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 strengthen awareness about climate change, sea-level rise, and their consequences. By educating the public about these issues, we can encourage people to take action to reduce 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.

## Conclusion and discussion

The previous paragraphs demonstrate the most important characteristics of fish tanks recorded in the Mediterranean region. What is noteworthy is that most fish tanks adhere to a more or less standard constructional layout whose fundamental architectural elements are the crepido, cataratae, and canals. 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 given area and potentially relate to an architectural style 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 give information about their location per se, pointing to increased commercial activity and well-developed urban centers.

Studying fish tanks as sea-level indicators can provide legitimate data about the sea level 2000 years B.P. Well preserved installations with prominent architectural features have a crucial role in measuring the paleo sea level. However, a robust functioning system for each investigated fish tank must be developed to determine the exact position of the indicative structural elements in relation to the sea level. Additionally, the tectonic history of the fish tank's area should also be investigated in connection to the vertical movements that impacted the altitude of the fish tank from the time of its construction.

Fish tanks that are best preserved are those curved directly into the rock, as they can resist natural erosion phenomena better than those built with concrete. The study of fish tanks as sea-level indicators must be considered within an interdisciplinary framework, which will allow for a better understanding of the sea level rise during the late Holocene period. Data from all the research studies that aim to calculate the sea level during the Roman times conclude to a paleo sea level between -0,5 and -1,5 m. Over the last 2000 years, there has been a general increase in the sea volume and melting of the ice sheets. Also, the human impact on climate change should not be ignored, and it could be used as a warning sign for the future of coastal regions. Besides the scientific importance of the fish tanks as paleoenvironmental markers, they have high cultural and historical consequences. It is an opportunity to demonstrate fish tanks as heritage monuments and scholarly models to strengthen awareness about climate change and its consequences.

### Measurements of sea level in each fish tank

Fish tank region	Mean Sea level (m)	References
Tyrrhenian coast of Italy	-0.58 ± 0.05 to -0.32 ± 0.05	(Evelpidou et al., 2013)
Lebanon (North and South Tyre)	-0.6	(Goiran et al., 2019)
Matala (Crete)	-1.25	(Mourtzas et al., 2012)
Chersonissos (Crete)	-1.45 to -1.20	(Mourtzas et al., 2012)
Mochlos (Crete)	-1.4 to -1.1	(Mourtzas et al., 2012)
Gulf of Zakros (Crete)	-1.3 to -1	(Mourtzas et al., 2012)
Ferma - Ierapetra area (Crete)	-1.25	(Mourtzas et al., 2012)
S.Bartolomeo (Slovenia)	-1.4 ± 0.2	(Florido et al., 2010)
Fisine (Slovenia)	-1.5 ± 0.2	(Florido et al., 2010)
Catoro (Croatia)	-1.75 ± 0.2 m	(Florido et al., 2010)
Kupanja (Croatia)	-1.4 ± 0.2 m	(Florido et al., 2010)
Svrsata (Croatia)	-1.5 ± 0.2	(Florido et al., 2010)
France (Frejus)	-0.4±0.10	Morhange et al., 2013
Santa Liberata	-1.04 ± 0.25	Lambeck et al., 2018
Torre Valdaliga	-0.87 ± 0.20	Lambeck et al., 2018
Punta della Vipera	-1.286 ± 0.20	Lambeck et al., 2018
Fosso Guardiole A	-1.17 ± 0.20	Lambeck et al., 2018
Fosso Guardiole B	-1.17 ± 0.20	Lambeck et al., 2018
Le Grottacce	-1.385 ± 0.20	Lambeck et al., 2018
Odescalchi	-1.387 ± 0.20	Lambeck et al., 2018
S.Marinella	-1.065 ± 0.20	Lambeck et al., 2018
Astura La Saracca	-0.935 ± 0.20	Lambeck et al., 2018
Astura La Banca	-1.09 ± 20	Lambeck et al., 2018
Astura	-0.974 ± 20	Lambeck et al., 2018
Ponza indoor	-1.58 ± 20	Lambeck et al., 2018
Ponza outdoor	-1.372 ± 0.20	Lambeck et al., 2018
Ventotene	-1.545 ± 20	Lambeck et al., 2018
Serapo	-1.48 ± 20	Lambeck et al., 2018
Sarinola	-1.08 ± 20	Lambeck et al., 2018

## Classification of Roman fish tanks based on their structural features, condition and building technique

No	Site Name	Y_coord	X_field	Region	Country	Architectural elements/features	Conservation conditions	Structural typology
1	Port-La-Nautique	43,1439	2,998983	Narbonne, Aude, France	France	Cataractae, Channels	Good	Mix
2	La Gaillarde	43,357819	6,718922	Roquebrune-sur-Argens, Var, France	France	Not architectural elements have been found	Fair	Mix
3	Frejus	43,433633	6,740681	Var, France	France	Cataractae, Channels	Good	Mix
4	Ile Sainte Margeurite	43,520144	7,033167	Cannes, Alpes-Maritimes, France	France	Not architectural elements have been found	Bad	Built with concrete
5	Antibes	43,576311	7,126469	Alpes-Maritimes, France	France	Crepido, Channel	Fair	Rock cut
6	<b>Spain</b>							
7	Trafalgar	36,182033	6,030233	Cadiz, Spain	Spain	Not architectural elements have been found	Fair	Rock cut
8	Albufereta	38,361989	0,441106	Alicante, Spain	Spain	Cataractae, Channels	Good	Rock cut
9	Illeta Banyets	38,431583	0,380511	El Campello, Alicante, Spain	Spain	Cataractae, Channels	Fair	Rock cut
10	Banos de la Reina	38,640947	0,061053	Calp, Alicante, Spain	Spain	Cataractae, Channels, Crepido	Good	Rock cut
11	Banos de la Reina	38,776025	0,190606	Xabia, Alicante, Spain	Spain	Cataractae, Channels, Crepido	Good	Rock cut
12	<b>Tyrrhenian coast of Italy</b>							
13	Isola Pianosa or Bagni di Agrippa	42,592967	10,093753	Pianosa Island, Tuscany	Italy	Crepido	Fair	Mix
14	Isola Giglio	42,359111	10,922589	Grosseto, Tuscany	Italy	Crepido	Fair	Rock cut
15	Santa Liberata	42,435689	11,152536	Porto Santo Stefano, Grosseto	Italy	Crepido	Fair	Built with concrete
16	Peschiera of Cosa	42,409206	11,293631	Ansedonia, Grosseto	Italy	Not architectural elements have been found	Bad	Built with concrete
17	Pian di Spille	42,249283	11,678294	Tarquini, Viterbo	Italy	Not architectural elements have been found	Bad	Built with concrete
18	Torre Valdaliga	42,123611	11,758333	Civitavecchia, Roma	Italy	Cataractae, Channels, Crepido	Fair	Rock cut
19	La Mattonara	42,116389	11,758333	Civitavecchia, Roma	Italy	Cataractae, Channels, Crepido	Good	Rock cut
20	Punta della Vipera	42,048889	11,819722	Santa Marinella, Roma	Italy	Cataractae, Channels, Crepido	Good	Built with concrete
21	Fosso Guardiole	42,038611	11,83	Santa Marinella, Roma	Italy	Crepido	Bad	Built with concrete
22	Villa Grottacce	42,038333	11,898611	Santa Marinella, Roma	Italy	Crepido	Bad	Built with concrete

23	Santa Severa or Pyrgi	42,015667	11,956081	Santa Severa, Roma	Italy	Crepido	Fair	Rock cut
24	Torre Flavia	41,967653	12,039481	Cerveteri, Roma	Italy	Not architectural elements have been found	Bad	Built with concrete
25	Peschiera di Palo Lazial	41,932958	12,100714	Ladispoli, Roma	Italy	Not architectural elements have been found	Bad	Built with concrete
26	La Saracca	41,420786	12,745094	Nettuno, Roma	Italy	Cataractae, Channels, Crepido	Good	Built with concrete
27	La Banca	41,417214	12,749286	Nettuno, Roma	Italy	Crepido	Fair	Built with concrete
28	Torre Astura	41,40835	12,764953	Nettuno, Roma	Italy	Cataractae, Channels, Crepido	Good	Built with concrete
29	Lago di Paola (Piscina di Luculo)	41,250208	13,041925	Monte Circeo, Sabaudia, Latina	Italy	Cataractae, Channels, Crepido	Good	Built with concrete
30	Sperlonga	41,250256	13,449775	Latina	Italy	Crepido	Good	Mix
31	Formia	18,255456	13,608747	Latina	Italy	Cataractae, Channels, Crepido	Fair	Built with concrete
32	Scauri	41,247906	13,674919	Latina	Italy	Not architectural elements have been found	Bad	Built with concrete
33	Grotte di Pilato	40,895103	12,971206	Ponza, Isole Pontine	Italy	Cataractae, Channels, Crepido	Good	Rock cut
34	Peschiera di Zannone	40,965608	13,048936	Zannone, Isole Pontine	Italy	Cataractae, Channels	Good	Rock cut
35	Ventotene	40,796756	13,434797	Ventotene, Isole Pontine	Italy	Cataractae, Channels, Crepido	Fair	Rock cut
36	Peschiere di Lucullo	40,784211	14,083625	Miseno, Naples	Italy	Not architectural elements have been found	Fair	Rock cut
37	Baia	40,809078	14,082747	Bacoli, Naples	Italy	Not architectural elements have been found	Bad	Built with concrete
38	Bagni Salvatore	40,627831	14,369692	Sorrento, Naples,	Italy	Cataractae, Channels, Crepido	Good	Rock cut
39	Sant'Irene	38,725339	15,966631	Scoglio della Galera, Briatico	Italy	Cataractae, Channels	Good	Rock cut
40	Odeschalchi	42,031944	11,863889		Italy			
41	Sarinola	41,255556	13,608889		Italy			
42	<b>Adriatic coast</b>					In the adriatic fish ponds the water does not enter the fishpond via cannals like those in the Tyrrhenian coast but circulates from the sea into the tank through the permeable jetty. The jetty curies structural elements like blocks scattered or alligned for maintenance purposes		
43	S.Bartolomeo (Slovenia)	45,593	13,7151		Slovenia	~		Rock cut
44	Fisinae (Slovenia)	45,51464	13,580701		Slovenia	~		Rock cut
45	Katoro	45,460447	13,51653	Umago	Croatia	~		Rock cut
46	Svresata Vela island	43,8624	15,2704	Kornati Islands	Croatia	~		Rock cut
47	Kupanja	45,2829	13,5923	Parenjo	Croatia	~		Rock cut

48	Greece							
49	Matala	34,9934140	24,7459456	Gulf of Matala SW Crete	Greece			Rock cut
50	Chersonissos	35,32329580	25,39395310	N Crete	Greece			Rock cut
51	Mochlos	35,18434960	25,90528650	NE Crete	Greece			Rock cut
52	Sitia	35,21036400	26,10865250	NE Crete	Greece			Rock cut
53	Gulf of Zakros	35,10094620	26,26664790	SE Crete	Greece	entrance, channel	Poor	Rock cut
54	Fish tank of Ferma (Ierapetra) or Vothroni Kakia skala	35,01137990	25,84198470	SE Crete (Ierapetra)	Greece			Rock cut
56	Israel							
57	Caesaria	32,497222	34,8875		Israel			Rock cut
59	Egypt							
60	Abou Kir	32,324181	30,061406	Abou Kir promontory	Egypt	Two <i>crepidines</i> , channel		Rock cut
61	Miami island	31,272222	29,99	(Gezirah) Gabal Al Khour island or Miam island	Egypt	channels, submerged arches, <i>crepidines</i> and sliding grooves		Rock cut
62	Montazah fish tanks	31,294514	30,020453	Bay of Maamourah	Egypt			
63	Northern Tyre	33,275569	35,191503	Tyre	Lebanon	Channel, ledges, <i>crepidine</i>	-	Mix
64	Southern Tyre	33,26704990	35,19199090	Tyre	Lebanon	Channel	-	Mix

## References

- 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, doi:10.3390/w12030658.
- Auriemma, R., & 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.
- 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.
- 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., Vinals, 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.
- 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.
- Evelpidou, N., Pirazzoli, P.A., Saliege, 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.
- Florido, E., Auriemma, R., Faivre, S., Radic Rossi, I., Antonioli, F., Furlani, S. and Spada, G. (2011), "Istrian and Dalmatian fish tanks as sea level markers", *Quaternary International*, Vol. 232, pp. 105-113, doi: 10.1016/j.quaint.2010.09.004.
- Gallili, E., & Sharvit, J., (1998, January). "Ancient coastal installations and the tectonic stability of the Israeli coast in historical times", *Geological Society London Special*

Publication No 146. pp 147-161.

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

Goiran, Jean-Philippe & Chapkanski, Stoil & Régagnon, Emmanuelle & Brocard, Gilles & de Graauw, Arthur. (2022). Fish tanks and past relative sea-level variations in Tyre, Lebanon.

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

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.

M. Liberatore, E. Gliozzi, P. Cipollari, N. Öğretmen, G. Spada, D. Cosentino, Vertical velocity fields along the Eastern Mediterranean coast as revealed by late Holocene sea-level markers, *Earth-Science Reviews*, Volume 234, 2022, 104199, ISSN 0012-8252, <https://doi.org/10.1016/j.earscirev.2022.104199>.

Magdy Torab, Geomorphological & Geoarchaeological Indicators of the Holocene Sea-Level Changes on Ras El Hekma Area, NW Coast of Egypt, *Journal of African Earth Sciences*, Volume 114, 2016, Pages 85-95, ISSN 1464-343X, <https://doi.org/10.1016/j.jafrearsci.2015.11.001>.

Melis, R., Furlani, S., Antonioli, F., Biolchi, S., Degrassi, V., & 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.

Olcina, M. (2015), "Los viveros romanos de la costa alicantina", in Olcina, M. and Perez, R. (Eds), *La Illeta dels Banyets y los viveros romanos de la costa mediterranea espanola. Cuestion de conservacion*, MARQ, Museo Arqueologico de Alicante, Diputacion Provincial de Alicante, Spain, pp. 42-63.

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

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.

Καρύμπαλης Ευθύμιος Παράκτια Γεωμορφολογία, Αθήνα, Εκδόσεις Ιων, 2010).