THE ROMAN FISH TANKS OF THE WESTERN MEDITERRANEAN BASIN AS POTENTIAL SCENARIOS OF SEA-LEVEL CHANGES RESEARCH

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 analysed.

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. The analysis of Late Holocene sea-level changes and palaeoenvironments from archaeological and biological evidence, 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.

Key words: Roman Fish Tank, Sea-Level Change, Western Mediterranean Basin, Underwater cultural heritage, climate change

Article classification: 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 B.C. and the 1st century A.D. (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 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 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 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 analysed 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.

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 analyse the Late Holocene period in the Mediterranean by studying built structures (Blackman, 1973; Morhange *et al.*, 2001; Anzidei *et al.*, 2011; Melis *et al.*, 2012) at the coastal intertidal zone, like harbour structures, fish tanks, quarries, etc. 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 fifty 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 (GPS, photogrammetry, biological evidence like fossilized marine benthos, etc.) that contributed to achieving accurate results (Goiran *et al.*, 2010; Anzidei *et al.*, 2013; 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 2000 BP palaeo-sea-level.

It is noteworthy that sea-level changes can be driven either by variations in 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 ± 0,7 cm (Lambeck *et al.*, 2004) to −40 ± 10 cm (Morhange *et al.*, 2013), or −32 to −58 ± 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) analysed 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 2000 years, the changes in sea levels were small, with an average rate of only 0.0 mm to 0.2 mm/yr. Oscillations in sea levels from 2000 to 100 BP did not exceed ± 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 A.D., possibly accelerated by the man-induced phenomena on the climate.

The main goal of this paper is to analyse 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.

- 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
- France: Port La Nautique (Narbonne)
- Italy: Santa Liberata, 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:

- *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.
- *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.
- *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.

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

Nº	Name	Typology1	Conservation conditions2	Sea-level markers3	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

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

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 2000 years, is as follows:

- Geographical location
- Site elevation relative to the present sea level (submerged, at or above the present sea level)
- Geological placement and geomorphological features
- Rock-carved structures (fish tanks must be excavated on bedrock; when built on unconsolidated material cannot be considered according to Auriemma and Solinas, 2009)
- Constructive elements (*cataracta,* channels*, crepido*)
- Preservation conditions (good condition, partially destroyed or damaged, scarce remains, etc.)
- Definition of the site function
- Historical data
- 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 Plate 2.

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

Plate 2. Location Map of Western Mediterranean Roman Fish Tanks

1. *Cape Trafalgar,* Cádiz, Spain (36°10'55.32"N, 6°1'48.84"W). It is a large rock-carved installation (25 m x 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 x 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 of 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 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 was 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 de 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 x 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 c*repido* is also possible to identify.

5. *Baños de la Reina de Xàbia,* Alicante, Spain (38°46'33.69"N, 0°11'26.18"E). This is a rectangular structure (27.30 m x 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-degree angle 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 x 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 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/-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 in the foothills of Monte Argentario. It is a rectangular tank, built with *opus caementicium*, with interior dimensions of about 25 m x 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 remain 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 meters 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 excavated in the calcarenite rocks and pesents a rectangular tank of 39 m x 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 x 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 meters 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 x 30 m, protected from waves by three large 2-3 m-wide walls 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 Grottacce,* Santa Marinella, Roma, Italy (42°02'19.73"N, 11°54'05.83"E). This is a semi-cercle shape 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 meters offshore, at a depth of about -30/-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 x 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 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 x 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 remains of the lateral walls made with *opus caemeticium* 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* (Giacoppini *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,* as well as 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, N.H., IX). 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 I presents a classification of analysed Roman fish tanks according to their typology (rock-carved, built, hybrid model), conservation conditions (good, 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, 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 2000 years can be analysed, 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 analyse 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 camenticium*.

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 change, as those effects can ideally be observed through fish tanks/because fish tanks are ideal for observing these effects.

Notes

[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.

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