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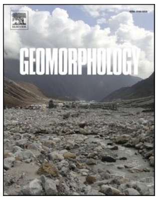

Reconstructing the plurisecular trajectory of an exemplary hybrid urban delta (Tarragona-Francolí system, Spain): Towards the end of a delta?

Ferréol Salomon [a,*], Patricia Terrado Ortuño [b], Pierre-Alexis Herrault [a], Kenji Fujiki [a], Olivier Finance [a], Ada Lasheras González [c], Josep-Maria Macias-Solé [c], Arthur de Graauw [d], Kristian Strutt [e], Simon Keay [e]

[a] *Laboratoire Image Ville Environment (UMR 7362), National Centre for Scientific Research (CNRS), University of Strasbourg and ENGEES, 3 Rue de l'Argonne, 67000 Strasbourg, France*
[b] *Universitat Rovira i Virgili, Av. Catalunya, 35, 43002 Tarragona, Spain*
[c] *ICAC - Institut Català d'Arqueologia Clàssica, Pl. Rovellat, 43003 Tarragona, Spain*
[d] *Archéorient (UMR 5133), Centre National de la Recherche Scientifique (CNRS) and Université Lyon2, MOM, 7 Rue Raulin, 69007 Lyon, France*
[e] *Department of Archaeology, School of Humanities, University of Southampton, Avenue Campus, Southampton SO17 1BF, UK*

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ABSTRACT

Today, anthropic morphologies in river deltas are widespread. The natural morpho-dynamics interact with engineered structures or urbanisation and shape hybrid features not grasped in traditional natural classifications of deltas. However, it is challenging to reconstruct the trajectory of the shifting balance between the natural and the anthropogenic factors over time. This study demonstrates how to systematically integrate human impacts to reconstruct the evolution of deltas at a plurisecular timescale. The approach advocated here is to consider separately the local and global drivers affecting deltaic evolution in using multiscale interdisciplinary chronologies. The high-resolution reconstruction of the evolution of the Francolí Delta in interaction with the city of Tarragona for the last two centuries reveals that the river mouth morpho-dynamics are successively deflected, interacting with an outer harbour and finally fully integrated in modern harbour basins with more significant dredgings at the river mouth. In this last case, the river mouth of the Francolí is no more a delta but a *human dominated estuary*. Over the past three centuries, the changes affecting the delta of the Francolí are linked to economic globalisation and associated with an increase in ship size.

1. Introduction

Over the past two centuries, coastal plains and especially river deltas have been particularly affected by human impacts (Syvitski and Saito, 2007; Anthony, 2014; Besset et al., 2019; Nicholls et al., 2020; Syvitski et al., 2022). During the same period, the world population has grown from ca. 1 billion inhabitants in 1800 to ca. 8 billion today (Federico and Tena-Junguito, 2019; Bolt and van Zanden, 2020) and port cities encountered major changes across the world (Bird, 1963; Ducruet et al., 2018; Hein and Van Mil, 2019). The maritime economy (Talley, 2012), ship building (Lyon and Winfield, 2003; Notteboom, 2004), and port and harbour engineering (Jarvis, 2016) were deeply transformed in relation to increased productions and economic exchanges together with technological leaps developed in many different fields. Consequently, river mouth systems have been affected by land use intensification, engineering interventions, natural resource extraction, urbanisation, industrialisation and pollution (Renaud et al., 2013; Wright et al., 2019; Nicholls et al., 2020). Conflicts between economic pressure and environmental issues are particularly pronounced when considering engineered port cities involved in the competitive global economy and environmentally fragile river deltas. Issues are raised regarding feedback between engineering alteration (harbour expansion), maintenance (dredging) and morphodynamic system behaviours as well as the drive to monitor the waters in and around the harbour by economic activity itself. The reconstruction of the temporal trajectories of port cities and their environment could help to better assist the transition towards more

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* Corresponding author.

E-mail addresses: ferreol.salomon@live-cnrs.unistra.fr (F. Salomon), patricia.terrado@urv.cat (P. Terrado Ortuño), pierre-alexis.herrault@live-cnrs.unistra.fr (P.-A. Herrault), kenji.fujiki@live-cnrs.unistra.fr (K. Fujiki), olivier.finance@live-cnrs.unistra.fr (O. Finance), alasheras@icac.cat (A. Lasheras González), jmmacias@icac.cat (J.-M. Macias-Solé), arthur.degraauw@outlook.fr (A. de Graauw), K.D.Strutt@soton.ac.uk (K. Strutt).

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sustained developments in such contexts.

Particularly, each port city has adjusted its own harbour infrastructure to offer safer and wider anchorages, longer quays and better logistics to welcome larger fleets, bigger ships and new types of cargoes (Cox et al., 2021). They have also tried to increase their rank within the port systems in which they were involved (Castillo and Valdaliso, 2017; Ducruet et al., 2018). The timing of the adjustments was specific to each port and region depending on their socio-economic, institutional and political contexts (Palmer, 2020). However, the development of trade, the interconnectivity between ports and the technological transfer from one place to another, inevitably led to trends in the way ports were shaped over time.

Generally, morphological models considering port development focus on the emerged features only. Different types of models were developed to embrace morphological changes of the ports and harbours (Bird, 1963; Hoyle, 2000; Ducruet, 2007). We can cite the Anyport Model (Bird, 1963), the port-city interface model (Hoyle, 1989), and all historical-morphological maps produced in geography, economy or history with more or less abstract representations (Norcliffe et al., 1996; Van den Berghe, 2016; Hein and Van Mil, 2019). Some studies reconstruct port evolution across several millennia up until the present day (Amore et al., 2002; Andrade et al., 2021), but more often developments in the last two centuries (Bird, 1963; Hein and Van Mil, 2019). Aside from the disciplines working traditionally on modern and current ports such as economy, human geography and history, geosciences also developed studies considering ports through the lens of harbours and their bathymetry (Pearl River delta in Wu et al., 2018; Rhine delta Cox et al., 2021, 2022). They observe river mouth areas and coasts impacted by engineering structures or by dredging.

This study aims to bring a more standardised methodological framework and systematic approach to the subject of reconstructing multi-century trajectories of harbour infrastructure development in relation to fluvio-coastal systems. The method incorporates various kinds of data sources and collate river, coast and harbour geographical and bathymetric changes over time (e.g., 18th – 21st centuries' historical, geographical and economic information; multi-faced contextual data such as economic, political, and hydro-climatological data). This paper focus on the youngest centuries of the evolution of the Tarragona port city and Francolí Delta mainly using ancient maps, while a recent paper reconstructed millennial changes mainly using sedimentary cores data (Salomon et al., 2024).

Tarragona, an important Mediterranean port (Mareï and Ducruet, 2014), is one of the top 5 ports of Spain, while two centuries ago, the town barely had a harbour. From *Punta del Miracle* to the Cape of Salou, there are approximately 12 km of which 5 km is now occupied by the harbour of Tarragona, covering the 2.5 km long coastline of the Francolí Delta. Though Tarragona is still a secondary harbour in the current global economy (Ducruet et al., 2018), it constitutes a good example for studying the development of a multipurpose industrial port during the last two centuries, adjusting to global maritime economic changes and natural context. Throughout its history, the harbour of Tarragona had to face hazards from two sides: (1) waves from the south-east and north-east and (2) floods and sedimentation from the Francolí River. Dealing with these two constraints, the harbour first had to develop larger protected basins (in the last two centuries) and then to develop larger space to unload and store goods (especially during the last decades). The Francolí Delta is rather small but challenging as flash floods are particularly strong and destructive (Alfieri et al., 2011; Ruiz-Bellet et al., 2015; Llasat et al., 2016). In addition, current sea level rise will increase the vulnerability of the harbour to storms in the next decades (Sierra et al., 2016). The iterative construction of the harbour of Tarragona that will be studied in this paper also creates new environmental challenges. Sediments from the Francolí River spreading along the coast of Tarragona remain an issue to the development of the port, and the port management has strong repercussions for the environment (Galofré et al., 2018). Tarragona also offers an interesting case study for human-nature interactions between the port city and the Francolí river delta (Fig. 1).

Examining in detail bathymetric evolution and harbour infrastructure of the port of Tarragona since 1790, this paper seeks to demonstrate that old maps are relevant to both geosciences and social sciences. More specifically, this study will be conducted on the harbour of Tarragona (marine structures and bathymetry) and on the delta front (coastline, bathymetry). By insisting on multiple chronologies and temporal trajectories, this paper shows how to better reconstruct the recent evolution of a hybrid urban delta.

2. Geographical and historical context

2.1. Harbour hydraulics

Tarragona is now one of the most important petrochemical clusters in southern Europe (Ahedo, 2010). Important engineering works characterise the coast of Tarragona including the harbour. Dredging is conducted in the harbour where the mouth of the Francolí River is located. The currents inside the harbour have a lighter upper layer of fresh water that goes out to sea, while the lower layer brings coarse bedload sediment into the harbour (Martínez Velasco, 2012). This water circulation is also important with respect to water quality and the time in which pollutants are located in the harbour, with studies demonstrating that pollution tends to stay in the harbour (Mestres et al., 2007; Mestres et al., 2010). This is important since pollutants may affect the city to the north and other port activities conducted around the basins.

2.2. Francolí river discharge

For the last two centuries, good flood series information is available (Alberola et al., 2016; Barriendos et al., 2019). During the period 1842–2000, Pino et al. (2016) recorded 24 catastrophic floods in the NNE Iberian Peninsula. Important events in this time span included the floods of 22–23/09/1874, 18/10/1930, 27/11/1936, 11/10/1970, and 10/10/1994 (Roca et al., 2009). These flash floods were triggered by coastal convective events occurring during the summer or autumn (Gil-Guirado et al., 2022; Pino et al., 2016). The last catastrophic flash floods of the Francolí River were recorded in 1994 and 2019 (Valera-Prieto et al., 2020). On the 10th of October 1994, the flood reached 1600m^3/s at Tarragona. During this event, 415 mm of precipitation were recorded in 24 h upstream at the station of Alforja (Agència Catalana de l'Aigua, 2005). The strongest flash flood dates to the 19th century when the reconstructed water discharge of the Francolí River was estimated at 3289m^3/s at Montblanc, 30 km upstream of Tarragona for the Santa Tecla event in 1874 (Ruiz-Bellet et al., 2015). The flood prevention system now set up by the municipality of Tarragona includes embankments and drainage canals for over-flooding waters.

2.3. History of Tarragona and its harbour

The natural opportunities initially offered by the coast were not ideal to welcome ships (Salomon et al., 2024). Even so, the Romans chose the city to become the capital of a large and rich province, *Hispania Tarraconensis*. They tried to improve the harbour potential with built infrastructure (e.g. a jetty/mole), but we do not know how long it remained safe for ships. Later, the mole built in the 15th century did not provide adequate shelter for merchant ships and the remains of the Roman jetty in the middle of the modern harbour was an obstacle in the harbour until the end of the 19th century. Sedimentary cores drilled in the ancient harbour basin showed that it has always been prone to either quick sedimentation in the harbour during the floods of the Francolí and quick erosion in the harbour during storms. The location was not any better two centuries ago in terms of harbour potential (see references in Salomon et al., 2024). However, modern engineers reiterated the plan and location of the Roman harbour and had to deal with the same problems.

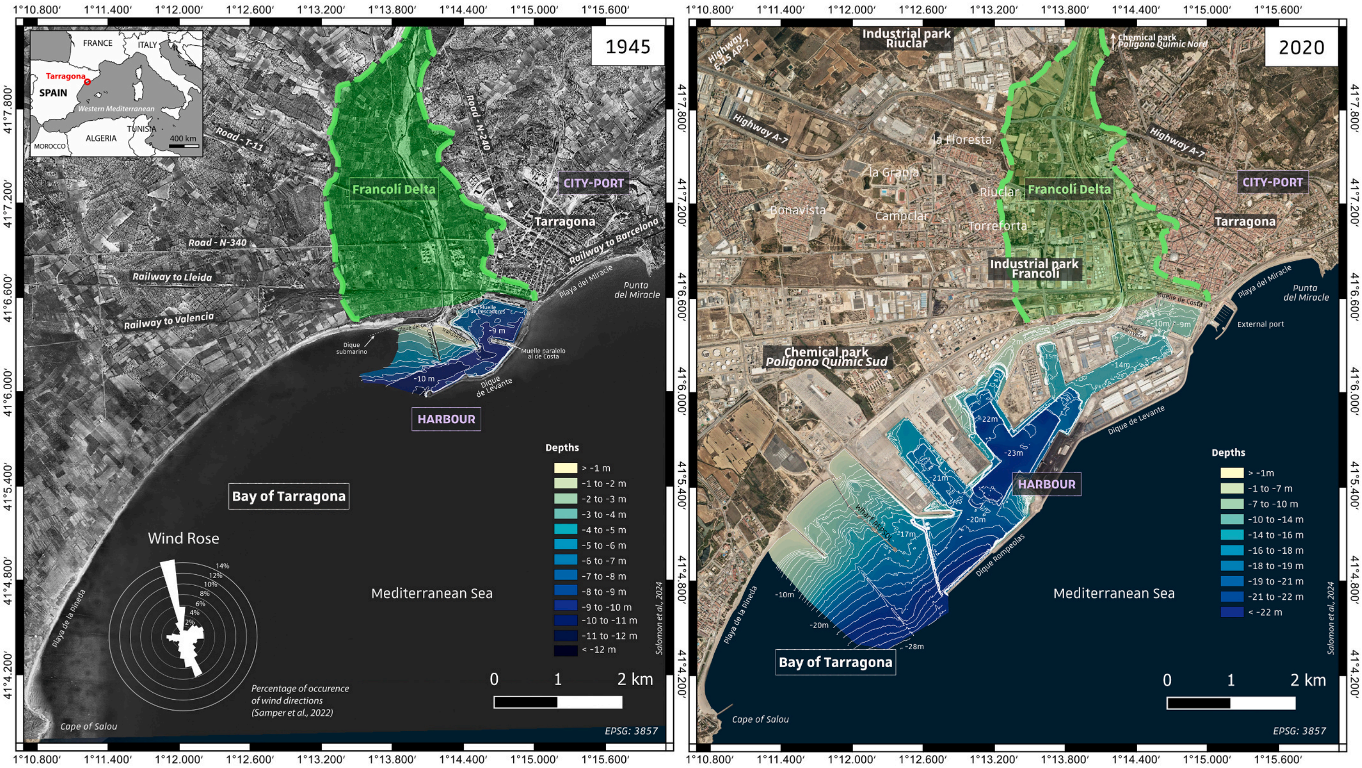


Fig. 1. Location maps of Tarragona, its harbour and the Francolí Delta in 1945 and 2020. Bathymetric data are available for these two dates for the harbour and the delta front.

In the 18th century, Tarragona was essentially an ecclesiastical capital and a military fortress (Magriñá, 1901; Jordà Fernàndez, 1988). The city had 4554 inhabitants in 1725–1735 and 8741 in 1787 (Serrano Sánchez, 2018). The town represented a secondary economic centre, characterised by low population growth compared to other Catalan cities (Aresté Bargès, 1982). Nearby Reus was the city that saw population growth and concentration of economic activities (14,440 inhabitants in 1786–1791 - Montserrat, 2012). Located inland, it used the harbour of Salou to the south, which gave a better shelter for ships at that time. The Port of Tarragona was limited in its development by the fact that between 1717 and 1761, the port did not have authorisation to disembark foreign or non-Catalan goods (Serrano Sánchez, 2018). In the last years of the 18th century and the first years of the 19th century, a new harbour project was initiated in Tarragona along with a renewal of the Lower City conducted first by Juan Ruiz de Apodaca from 1790 to 1799–1800 and then by John Smith (Aresté Bargès, 1982; Escoda Múrria, 2000; Serrano Sánchez, 2018; de Ortueta Hilberath, 2022). The development of the port city and its harbour stopped during the Peninsular War (March 1809–September 1814). After the war, Tarragona counted only 1500 inhabitants and many destroyed buildings (Serrano Sánchez, 2018). However, the merchants quickly came back to Tarragona, which was equipped with a long jetty started before the Peninsular War (*Dique de Levante*). The new architect Vicente Teixeiro continued to build the mole after the war until 1836, the date of his death. Afterwards, between the 1840s – 1870s, works in the port were directed by managers for shorter periods of time (Serrano Sánchez, 2018).

During the 19th century, Tarragona switched from being a military city to a port city of importance on the Mediterranean coast of Spain. Commercial activities concentrated around the harbour and led to an expansion of the urban area of the Lower City (*Nueva Población del Puerto*). The city wall was gradually removed in this area to provide space for port development and in 1868–1870 the function of Tarragona was no longer a fortress (de Ortueta Hilberath, 2006). While for centuries, Tarragona was divided into an Upper City (*Ciudad Alta*) and a Lower City (*Marina*), urbanisation finally filled the gap between the Lower and the Upper City by the middle of the 19th century. The population of Tarragona reached 18,023 inhabitants in 1857 (Bagés, 1981; Serrano Sánchez, 2018). Tarragona developed its trade within more connected networks and also became a regional city with reinforced regional power, becoming capital of the province in 1833, overtaking the Reus-Salou system. The harbour itself adjusted to the new needs and to the growth of economic activities. New moles, quays and warehouses were built during the 19th century. The harbour exported more wine throughout the 19th century. In addition, the first railway to connect Tarragona with Reus was completed in 1857. After the grape phylloxera epidemic affected vineyards in France, vineyards developed from ca. 1870 in the hinterland of Tarragona. The port activities of Tarragona were even more specialised for the wine trade from that time. In the 1870s and 1880s, the harbour adjusted to new standards in harbour infrastructure and important changes were made. However, international instabilities and the wine crisis linked to phylloxera eventually affected Tarragona in the 1880s and 1890s. Consequently, the population lost ca. 5000 inhabitants by the end of the 19th century. From then until the 1960s, the extension of the city towards the west and the Francolí Delta developed more slowly (e.g., Ramón Salas Ricomà's project of 1884).

During the first part of the 20th century, the city of Tarragona was characterised by a continuous growth from 23,423 inhabitants in 1900 to 43,519 in 1960, corresponding to an increase of ca. 3000 inhabitants every ten years and a slow increase in the trade of the port. Some adjustments changed the urban and harbour areas (Serrano Sánchez, 2018). The Civil War particularly affected the city and its harbour with several bombing raids on the city taking place. A new economic impulse started in the late 1950s and 1960s with the construction of industrial parks to the west in the deltaic plain of the Francolí (*Polígono Entrevías* in 1958 and *Polígono Francolí* in 1965). The first General Urban Ordinance Plan (*Plan General de Ordenación urbana*) was approved in 1960 followed by new plans in 1973, 1977, 1984, 1995 and 2008. The population rose quickly between 1960 and 1981, notably with immigration related to the construction of petrochemical installations and the development of mass tourism on the coast. The city sprawled quickly, and highways were built to connect part of the territory.

Today, the commercial port of Tarragona is the most important in Spain for agricultural products and wheat and one of the first regarding the petrochemical industry, coal and cars. Regionally, the fishing harbour is the first in Catalonia, providing fish for essentially local consumption. Tarragona also has a marina with around 400 moorings.

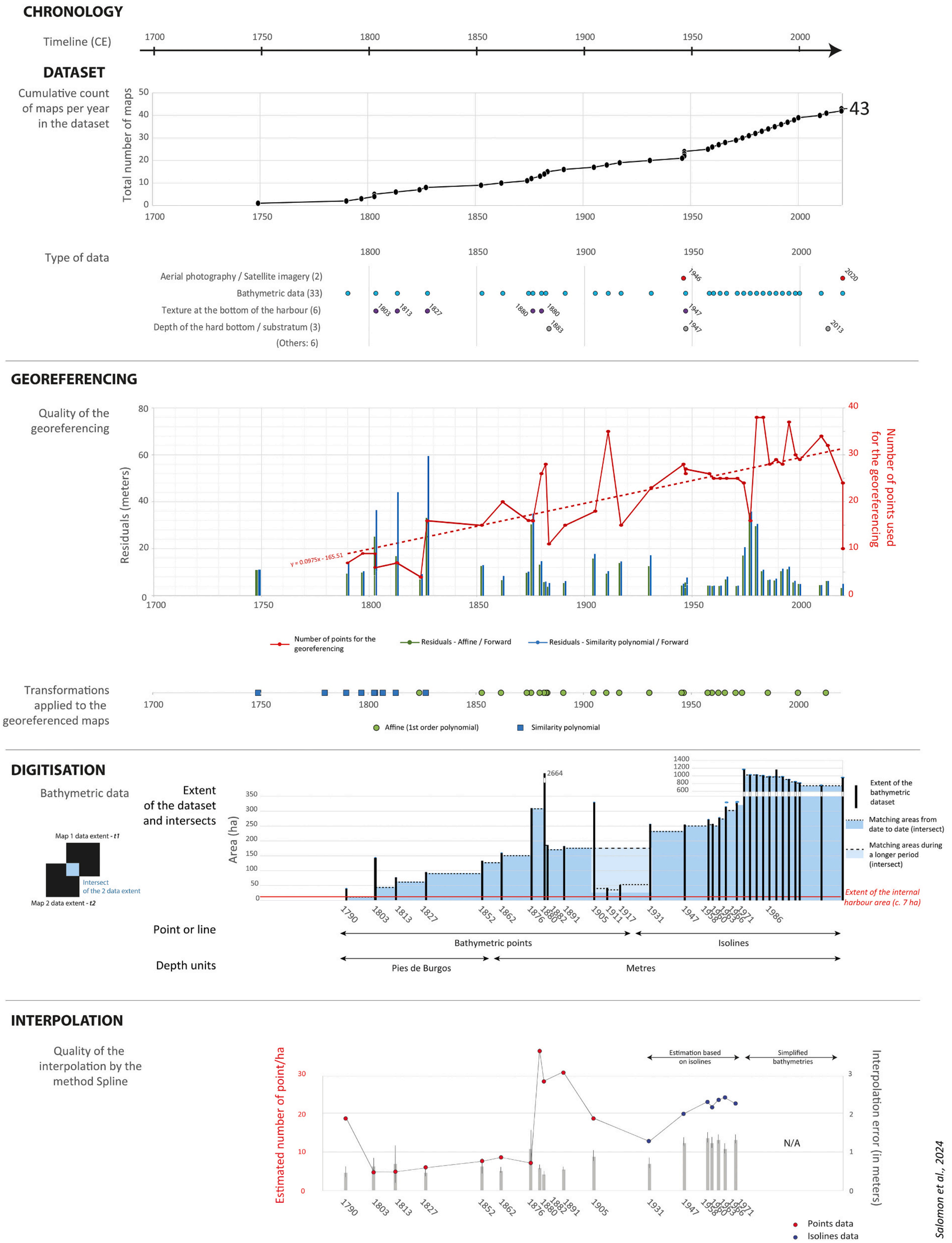


Fig. 2. Dataset of old maps and their characteristics, including a quality assessment of the georeferencing of the maps, the digitising, and the interpolation of the bathymetric data. All data are plotted referring to the date of the map.

3. Methodology

3.1. Dataset

This paper is based on the analysis of 42 maps ranging from 1749 to 2020, black and white aerial photographs at various resolutions dated to 1946 and satellite imagery from 2020 (Fig. 2). All gathered maps focus on the harbour basin of Tarragona often including the city of Tarragona and sometimes the entire bay. Most of them come from the online digital archives of the Port of Tarragona (https://www.porttarragona.cat/en/digital-archive) and military archives (Supplementary material and Terrado, 2021). Our interest in the old maps was to observe the evolution of the layout of the harbour of Tarragona, but most importantly its bathymetry. 33 maps from 1790 to 2020 present bathymetric data from the harbour, 6 maps have indications of the texture of the sediment at the bottom of the harbour (1803, 1813, 1827, 1880 and 1880 modified in 1901, 1947), and 3 maps about the “hard bottom” of the harbour (1947, 1883) or substratum (geological map dated from 2013) (Fig. 2 - Dataset).

The bathymetric dataset covers >2 centuries of harbour evolution. The best temporal resolution is available between 1958 and 2000 with a bathymetric map every 3 years. The period between 1790 and 1858 is represented by a map every 5 to 15 years except during the second quarter of the 19th century (1927–1952) with a gap of 25 years.

To improve our understanding of the morphological data extracted from old maps, we used complementary historical texts. Additional data related to dredging of the harbour since the end of the 18th century were collected in the archives of the port of Tarragona. These scans, including maps, projects, and reports, are available online at https://www.porttarragona.cat/en/digital-archive.

3.2. Georeferencing

The quality of the georeferencing is essential to this research since it ensures consistent matching between maps over time (Figs. 2, 3 and supplementary material). We made further use of all data gathered in georeferencing stages to conduct a quality assessment but also to evaluate the urban and harbour changes across time. We considered that the creation and the disappearance of *reference or matching points* in built areas is mainly controlled by urban renewals and important harbour transformations. That way, the life span of the matching points is considered as a proxy for the urban and harbour changes.

In total, 81 *reference control points* were selected for the georeferencing of the 42 maps and the aerial photography of 1946 (1335 points). More than half of the reference points are located on 2020 imagery from ESRI (46 points). However, only two reference control points can be tracked from 2020 to the 18th century due to changes to the urban area and countryside or to harbour developments. Consequently, reference points were not only located on satellite imagery from 2020 but also on aerial photographs dated to 1946 and old maps dated to 1883, 1882, 1824, 1803 and 1790 (Fig. 3). They were georeferenced using more recent reference documents. For instance, aerial photographs from 1946 were georeferenced using the 2020 satellite imagery, the old map of 1883 was georeferenced using the 1946 aerial photographs and the 2020 satellite imagery. Average residuals were calculated for each reference document and added to the residuals of the more recent reference documents used.

Reference points are generally located on harbour structures, buildings, and crossroads (Supplementary material). They were placed around the harbour (18 points - blue) and the Lower City of Tarragona (37 points). For maps covering a larger extent, some other points are also located in the Upper City of Tarragona (12 points) and around the bay of Tarragona (14 points). In total, 1335 points were georeferenced for the 42 maps. Georeferenced points are mainly located around the harbour and the Lower City (1014), while few are placed on the Upper City and coastal areas outside Tarragona (228).

Different transformations have been applied to the georeferenced maps. We observed that the similarity polynomial transformation proposed in ArcGIS provided better results for older maps with larger scales, while the affine transformation (1st order polynomial) is better for more recent maps. The change for the map transformation was identified in the 1820s. The residual expressed in metres in Fig. 2 (Georeferencing) seems to contradict this observation and show much higher uncertainties using the similarity polynomial also in ancient maps. However, in correspondence with the sparse topographical markers from ancient topography (for instance the 15th century mole) and archaeological discoveries (a late 18th century ship found against the ancient mole), the transformation of the maps with similarity polynomial is clearly better (Supplementary material). This is probably because for older periods fewer reference control points were available for georeferencing the maps. In addition, the spatial distribution of the control points in the old maps of the harbour only provide reference points in the Lower City but not on the mole. Finally, an affine transformation leads to stronger geometric changes. The right angles and distances were well drawn by ancient cartographers, which is in accordance with the similarity polynomial transformation algorithms.

3.3. Quality assessment of the georeferencing

Fig. 3 presents an overview of the results of the georeferencing considering each map or aerial photograph. Only the harbour and the Lower City areas are represented here. Reference points are reported on the y-axis and time is on the x-axis. To spot individual maps and aerial photographs, the time-axis (x-axis) should be observed (date of the documents). The red dots are the reference points by date. Their life span is also represented. The size of the circles corresponds to the residuals in metres of each map regarding each reference point used. The first graph shows the time-structure of the georeferencing. Since reference points were mainly located on harbour structures or Lower City buildings, the end or beginning of each reference point corresponds to harbour or urban renewals. We identified four periods separated by 3 periods of urban/harbour transitions (ar. 1800; ar. 1880s.; ar. 1960/70s).

Logically, the second graph demonstrates that the georeferencing is better for recent maps and is lower for older periods. Nevertheless, we can identify maps with much lower quality in 1827 and 1876. It also shows that aerial photographs and old maps used as relay for old reference points show relatively good quality.

For old maps with bathymetric point data (1790–1917), the mean distance between two points is ranged between 24 m (maps dated to 1891 and 1911) and 86 m (map dated to 1876). The average mean distance in all these maps is 48 m. Considering that these 19th century / early 20th century maps have less reliable georeferencing, this indicates that the georeferencing is relevant to studying the evolution of the bathymetric data.

3.4. Digitisation

A georeferenced dataset of 36 documents dated between 1748 and 2020 was used to reconstruct the planimetric evolution of the harbour. We first digitised the harbour limits in 2020 and we gradually changed its initial shape through retrogressive analysis. This explains why structures from different dates are perfectly matching.

The georeferenced dataset contains also a large set of maps with bathymetric data from 1790 to 2020. Nevertheless, the extent of the bathymetric data in the harbour or in the open sea is variable through time from map to map along with the density of point or bathymetric lines. Fig. 2 (Digitisation) presents all information related to the digitisation of our maps. The old harbour, later called the Internal Harbour or Dársena Interior, is the area that can be tracked in time through almost all of the bathymetric maps. Blue and dotted lines represent the extent of the bathymetric data with an overlay from map to map. For the period 1905–1931 (light blue), we decided to not consider the bathymetric

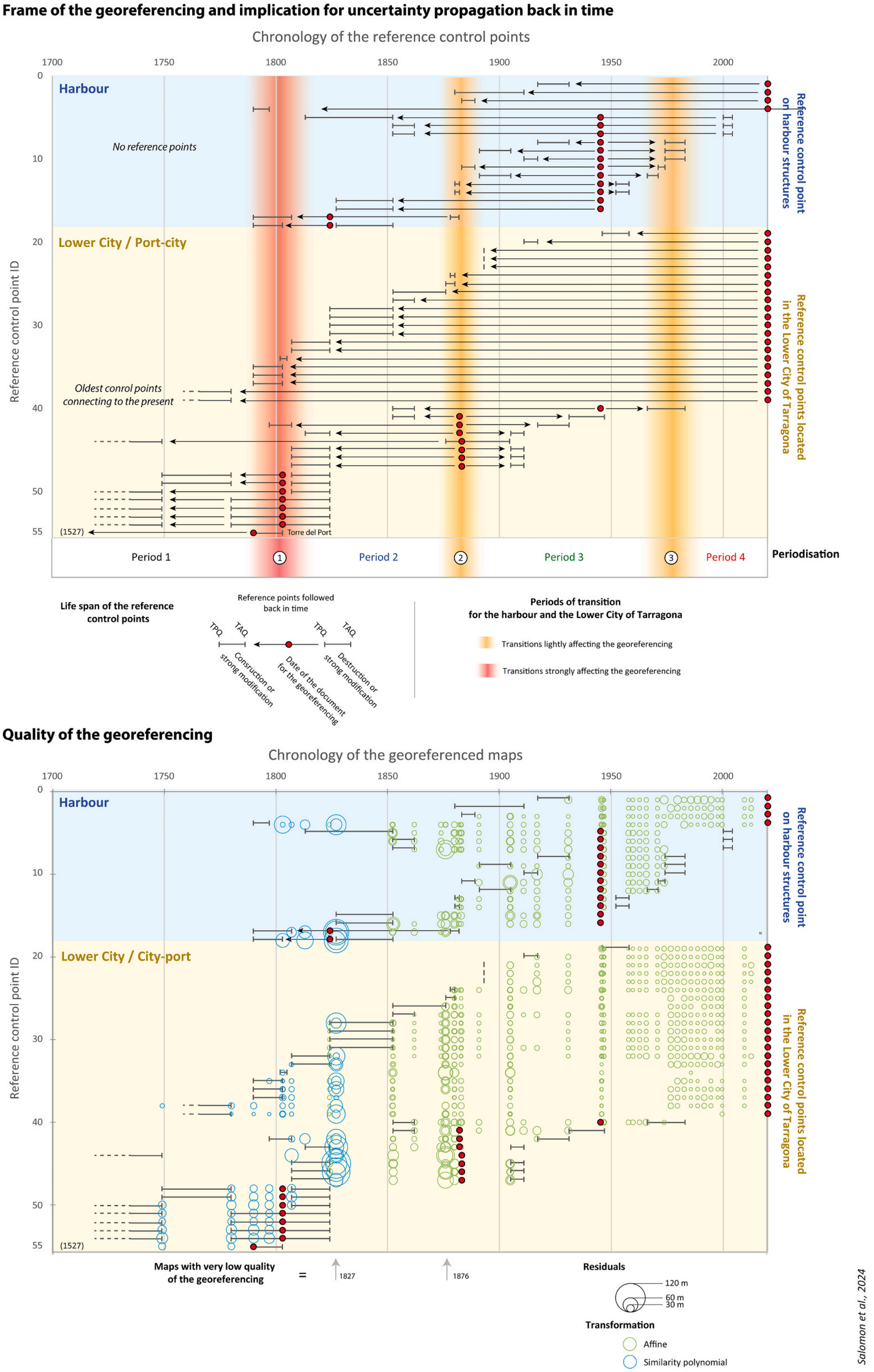


Fig. 3. Quality assessment of the georeferencing. The two graphs focus on the reference points located in the harbour and in the Lower City. Each *reference point* (y-axis) in red is presented in relation to the date of the *reference document* (x-axis). The life span of the reference point is presented by a date of beginning and date of end estimated by a TPQ (*Terminus Post Quem*) and a TAQ (*Terminus Ante Quem*). In the graph above, main periods of changes in the harbour and the Lower City are expressed. It demonstrates the correlation between urban or harbour changes and the end or beginning of the reference points. In the graph below, the circles express the uncertainty of the georeferencing (residual) in metres. The maps with very low quality of georeferencing are easily identified (1827 and 1876). Additionally, the trend shows the increase of the uncertainty back in time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

maps of 1911 and 1917 as these only show bathymetries at the entrance to the harbour where dredging was conducted.

Between 1790 and 1917, the bathymetric data were recorded directly on the old map with numbers. Each number was digitised into a bathymetric point in a shapefile. Initially (1790–1852), all depths were expressed in *Pies de Burgos*. In the attribute table, all depths were expressed in metres considering the following relation: 1 Pie de Burgos = 0,278,635 m. Later, all bathymetric indications are in metres.

From 1931, the bathymetric data was already processed and manually interpolated into isolines. We did not have access to the initial depth measurements. The bathymetry is provided with 1 m isolines. Bathymetric maps are provided in almost every year in the reports of the port. However, updated bathymetric data are only provided in the reports of the ports of 1931, 1947, 1958, 1960, 1963, 1966, 1971.

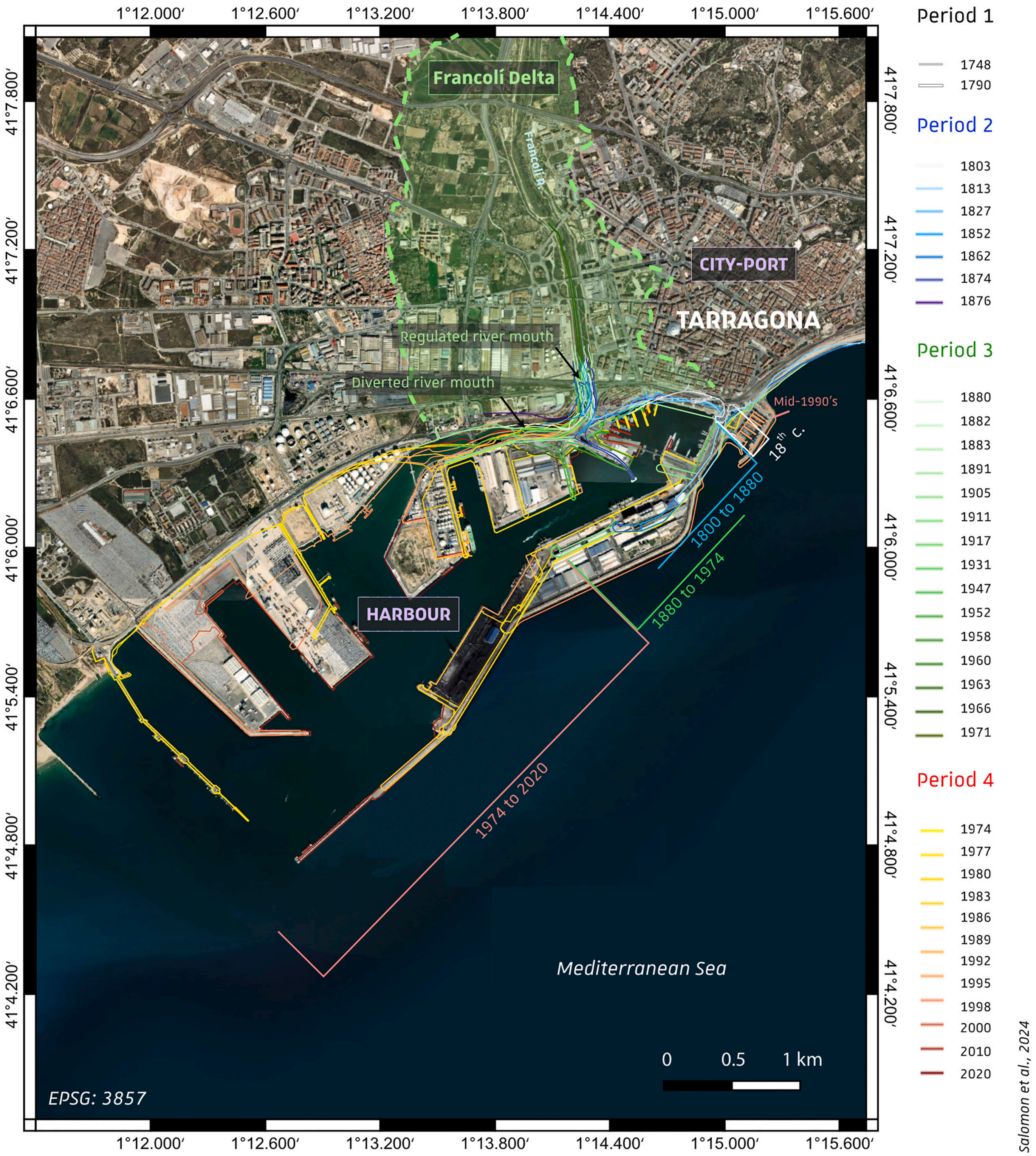


Fig. 4. Maps showing the mobility of the coastlines, the riverbanks of the Francolí and the harbour interfaces from 1748 to 2020. The periodisation of the planimetric evolution of the river mouth and the harbour is proposed. This periodisation corresponds to the one identified in Fig. 3.

From 1974 to 2000, the annual reports of the harbour of Tarragona (*Memoria anual del Puerto de Tarragona*) provide simplified maps of the bathymetry and records the averaged and theoretical depth for each part of the harbour. From 1974 to 1977 the precision is 1 m, and from 1978 it is 5 m. Since 2001, the annual report of the harbour of Tarragona did not provide maps of the bathymetry except for 2010. More detailed maps are available for recent periods but separate to the annual reports.

The Museum of the Port of Tarragona provided us an updated and detailed bathymetric map of 2020 with 1 m isolines that complete our dataset to the present day. Compared to the set of maps dated from the 1970s in the annual reports of the harbour, this map displays the latest interpolated depths of the harbour and will serve as a reference for further analysis hereafter.

3.5. Interpolation

Continuous bathymetric surfaces were calculated by interpolating original local bathymetric measurements with a thin-plate spline (TPS) technique at a 10 m spatial resolution. TPS divides the studied areas into different sub-areas with vertices matching the existing points. A polynomial model was then calibrated in each sub-area. TPS was well suited to this dataset. TPS provides high performances with irregularly spaced data such as bathymetry in old maps (Dooley et al., 1976). In particular, it predicts new values by considering the local bathymetric context and the polynomial degree adjusts to the different size of neighbourhoods. We calculated cubic splines (third order polynomial) for each map since it was a good balance between the density of original points and the interpolation quality at the scale of the harbour through time. The function *tps()* from the package R fields was used.

The interpolation assessment was made according to a *Leave-one-out* cross-validation principle. For each map, the data set of *n* original points was split into a training set and testing set represented by only one observation (e.g., the *leave-one-out*). Then, for each split, a TPS interpolation model was calibrated and used to predict the new value of the observation left out. The mean square error was calculated to measure the prediction quality. After repeating the process *n* times, we calculated the average of the mean squared error.

4. Results

4.1. Planimetric evolution of the harbour and the river mouth of the Francolí

Between 1790 and 1852, the harbour basin grew 10 times bigger, from ca. 11 ha to ca. 107 ha due to the removal of a part of the ancient Roman mole in 1843 (Salomon et al., 2024) and to the construction of the new mole called *Dique de Levante* (Figs. 4 and 5). The mole was initiated in the last years of the 1790s / beginning of the 1800s, extending the existing 15th century mole, from 200 m originally to eventually ca. 1000 m in length. An extra 650 m is added in the next decades. By contrast, the river mouth of the Francolí was not constrained by any infrastructure at first. Some maps show the river mouth channel deflected towards the south-west (1807, 1813), with more sand accumulation to the left bank (1803, 1832), or running straight (1790, 1824). The deflected morphology of the river mouth was stabilised by the mid-19th century. In 1852, the map shows a curved structure on the left bank of the river mouth (indicated on Fig. 5, see the 1876 map). The right bank remains untouched by engineering infrastructure.

The harbour basin grew slowly from the 1830s to the 1880s (118 ha in 1882) but doubled its size by 1900, especially the Outer Harbour (ca. 210 ha in 1905). The growth at the end of the 19th century is mostly due to the extension of the curved structure on the left bank of the Francolí river mouth that became the *Dique de Oeste* also called *Dique del Francolí* (extended by ca. 630 m between 1871 and 1885 and a submarine part of ca. 650 m by 1915). Since the beginning of the 19th century, a long curved mole to the west in front of the river mouth was planned but never built. Instead, successive extensions of the lower reaches of the Francolí river channel were constructed. The right riverbank is the northern coastline of the Francolí river outlet towards the south-west, and the left riverbank is the *Dique de Oeste* mentioned above. This longshore structure reached 1500 m in length by 1915.

Another major change characterised the evolution of the harbour in the second part of the 19th century. The harbour was split into two basins: the Inner Harbour (*Puerto*) and Outer Harbour (*Antepuerto*). This change was gradual. Between 1874 and 1883, a transversal jetty closing the Inner Harbour to the south was built (*Dique transversal*) (Fig. 1). For the first time, the harbour of Tarragona had an enclosed basin with two moles and a narrow entrance. Between 1890 and 1897, an internal mole was added across the entrance to increase the protection of the Inner Harbour (*Muelle paralelo al de Costa*). During this second part of the 19th century, the *Dique de Levante* remained stable. The Outer Harbour (*Antepuerto*) was expanded due to the *Dique de Oeste* (1871–1885) and *Dique Submarino* (1904–1915). The *Dique de Levante* was extended later between 1904 and 1915 by an extra ca. 550 m. A new internal quay was built between 1885 and 1888 called *Muelle de Costa.*

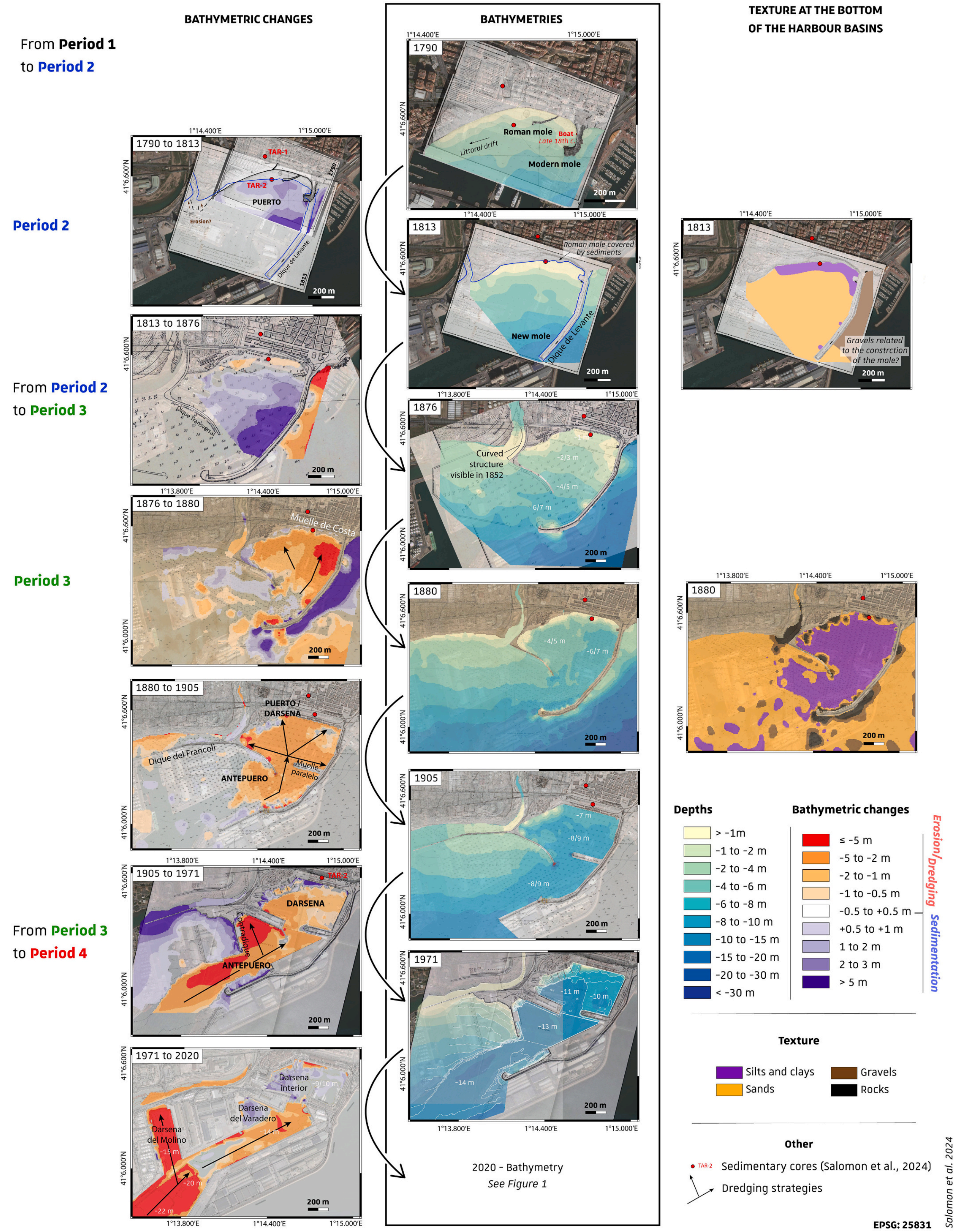
For most of the 20th century, the harbour of Tarragona kept its configuration from the last part of the 19th century. However, internal changes were conducted, especially on the quays. In 1971, due to infrastructure built inside the harbour, the size of the basin decreased to 175 ha, while it was 213 ha in 1917. The *Muelle de Levante* was extended (1927–1931), the last beaches in the Inner Harbour were replaced by quays (*Muelle de Pescadores* – 1940-1942), and the *Dique transversal* was transformed into a platform (*Muelle transversal* – 1947-1962). The only new mole was an internal structure built in the Outer Harbour (*Contradique* – 1940-1946). Additionally, the lower reaches of the Francolí River were translated ca. 70 m to the west (1942–1947). Maps and aerial photographs show accumulation of sand at the mouth of the Francolí behind the *Dique del Oeste*. Sediments were routed away from the Inner Harbour area, but this sedimentation issue remained for the Outer Harbour and for flash flood management at the river mouth. Dredging was less frequent, with no dredging at all between 1929 and 1944 (Serrano Sánchez, 2018).

Major changes affected the harbour in the 1970s. Two jetties were built in the Bay of Tarragona south of the Outer Harbour of Tarragona (*Pantalán Repsol / de Petroli cru* and *Pantalán Asesa / Betum Asfàltic*). In 1974, the inclusion of both jetties into the harbour waters made the harbour reach ca. 1000 ha in size. This was an increase of 5 times the size in a few years. The maximum size of the harbour waters reached 1025 ha in 1977. During the last 50 years, new quays and platforms were built inside this large Outer Harbour basin. The historical Inner Harbour area became a basin amongst others (*Dársena interior*). The harbour now has at least 5 different basins. The harbour waters were 979 ha in 1989, 814 ha in 2000 and are 737 ha today. This reduction of the harbour waters is due to the construction of new port terminals (cars, containers, coal). The *Dique de Levante* was extended gradually towards the *Pantalán Repsol* during the last 50 years to reach nearly 5 km today.

This overview of the last 230 years demonstrates that the harbour of Tarragona quickly became a well-protected harbour in the 19th century using engineering solutions. However, the fluvial sediment inputs from the Francolí River are still challenging harbour maintenance (Figs. 4 and 5).

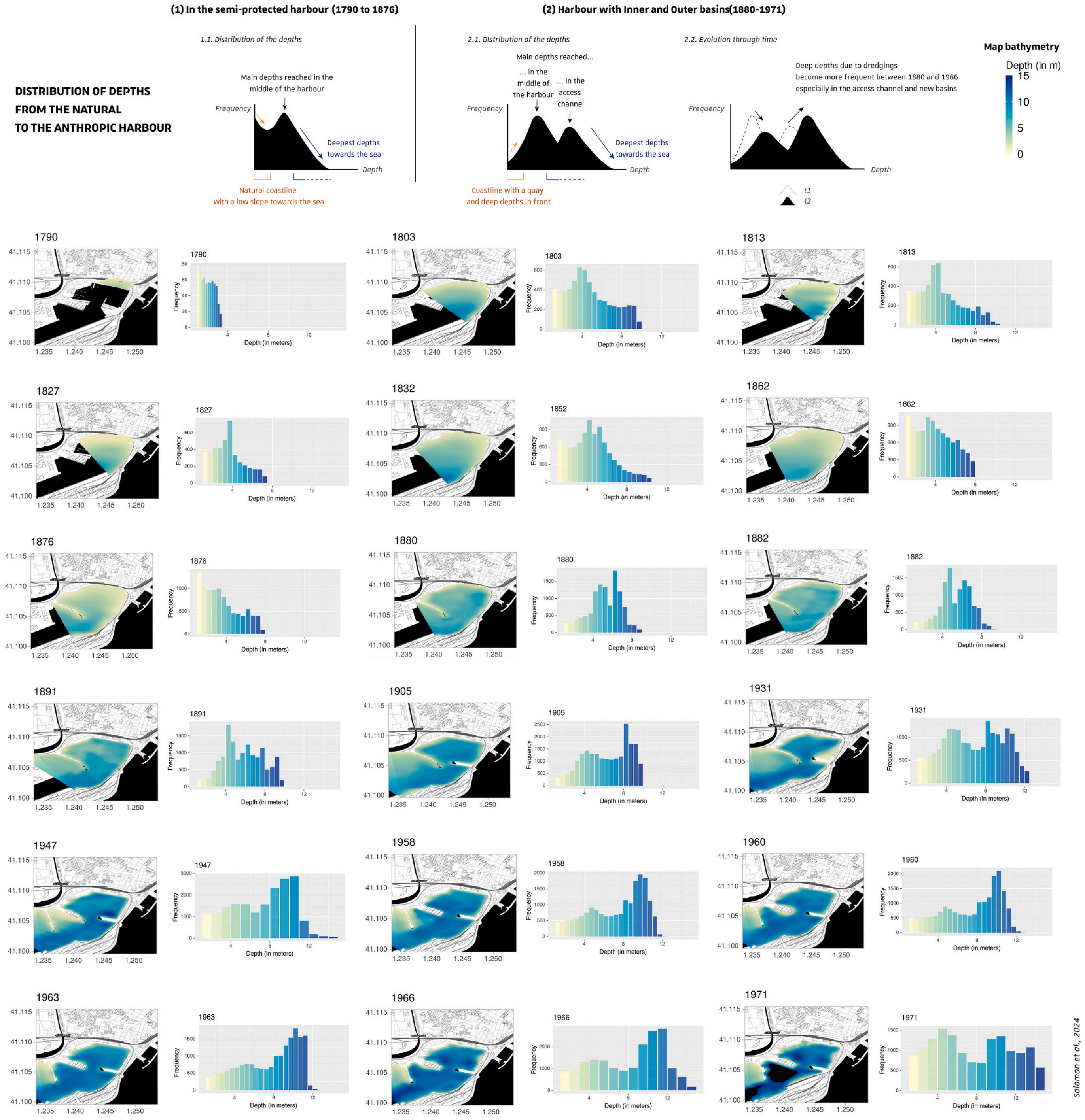
4.2. Bathymetric evolution of the harbour and the river mouth of the Francolí

At the end of the 18th century, the harbour protected by the 15th century mole was a sandy beach area with a shallow slope (−3.5 m at 250 m from the coastline, 1:70 or 1.4 % slope) (Figs. 4, 5, 6, and 7). In addition, the remains of the Roman harbour of Tarragona reduced the modern harbour extent (e.g. jetty/mole). The construction of the long mole at the end of the 1790s / beginning of the 1800s (*Dique de Levante*) possibly explains the increased sedimentation inside the new sheltered



(caption on next page)

Fig. 5. Qualitative analysis of the evolution of the bathymetry from 1790 to 2020. Individual maps have been selected to provide an overview of the different periods of evolution of the river mouth and harbour areas as well as the main transitional periods (from Period 1 to 2 around 1800, 2 to 3 around 1880). Only one bathymetric map is available for the Period 1 (1790). Consequently, no changes can be observed within this period. For the last period we could not focus on the transitional period since the maps between 1971 and 2020 are only showing theoretical depths. Nevertheless, we show the major changes that appear between 1971 and 2020, the last date of our dataset. Finally, we propose two old maps that also record textural data with a good resolution in the 19th century (1813 and 1880).



Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under ODbL

Fig. 6. Quantitative analysis of the bathymetry from 1790 to 1971. The bathymetries are represented on 18 maps and 18 graphs.

area. The Roman mole is covered by sediments by 1813 (Salomon et al., 2024). Sediment texture near the coastline is characterised by finer deposits (1813) (Fig. 5). In 1790, bathymetric isolines converge towards the river mouth but no underwater lobe is observed at the river mouth. The coast is eroded, and the Roman structure is visible too (Salomon et al., 2024). In contrast, the map of 1813 shows an underwater river mouth lobe in the bathymetry, and we observe sediment accumulation outside of the harbour along the *Dique de Levante* showing the littoral

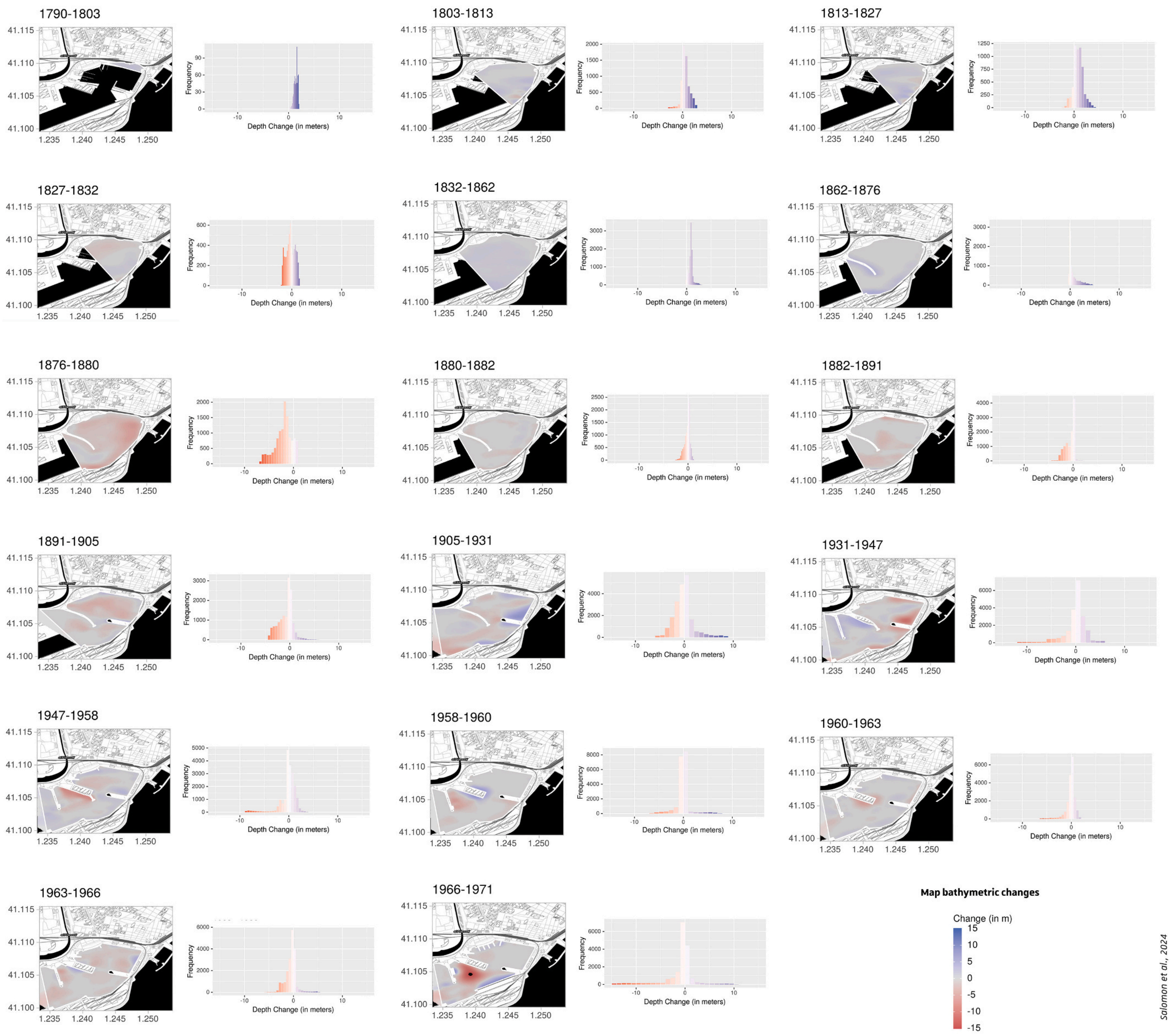


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Fig. 7. Quantitative analysis of the evolution of the bathymetry from 1790 to 1971. The changes are represented on 17 maps and 17 graphs.

drift following a north to south direction. From 1790 to 1876, the harbour basin is mainly affected by sedimentation (Fig. 7). This sedimentation is generally located behind the *Dique de Levante*, but also along the coast. The period 1827–1852 is characterised by stronger erosion (Fig. 7). This situation is possibly due to fewer fluvial inputs and/or more active storms. It should be noted that main areas of erosion or sedimentation between 1790 and 1852 show forms following the morphology of the cove behind the *Dique de Levante*. Deposition along the *Dique Transversal* during the period 1862–1876 can either be due to material accumulated during its construction or to natural sedimentation (Fig. 7).

The 1880s mark a major turn in the history of the harbour. Moles were enclosing the Inner Harbour, which made it easier to manage the sediments and to dredge. The sediments of the harbour were removed using a dredge from 1876 (*draga*) and two steam-powered vessels (*vapores gánguiles*) called *Ebro* and *Francolí* since 1878 (*Memoria del Puerto de Tarragona*, 1871–1883). In 1876, most of the harbour was shallow with <4 m of water depth. No specific strategies related to dredging can be read on the water depth, while the underwater lobe of the Francolí river mouth is visible (Fig. 5). From 1876 onwards, the harbour was dredged down to 6–7 m depth especially at the entrance of the harbour along the inner part of the *Dique de Levante* (Figs. 5 and 6). The repartition of the bathymetries in the harbour area changes after 1876 (Fig. 6). For the period before 1876, depth histograms are bimodal with a mode near the sea level (0 m or the coastline) and a second mode between 3 and 4 m. For the period after 1876, the first mode near 0 m is no longer visible and the second or sometimes third modes are moving from −4 m to deeper values (Fig. 6). The disappearance of the mode towards 0 m is related to the construction of the *Muelle de Costa* that replaced a natural foreshore with a shallow slope with a vertical drop in front of this new dock. The periods after 1876 until the present are mainly characterised by sediment removal and should be interpreted in relation to strategies of dredging activities (Figs. 5 and 7). In 1883, the new aim was to reach −8 m at the entrance and in the western part of the Inner Harbour and towards the Lower City (Fig. 6). However, difficulties appeared while dredging near the coast of the Lower City to prepare the construction of the *Muelle de Costa*. Two kinds of material compose the bottom of the harbour in this location: (1) muddy sediments; (2) very coarse material and blocks of stone. The muddy sediments produced very strong smells according to the engineers of the time (*Memoria*, 1885–1886, p. 12). Due to an epidemic of cholera in the city, the dredging of this muddy deposits along the *Muelle de Costa* was stopped in 1885 to improve the public health. In the ancient documents, the coarse material was considered as the substratum. It slowed down the dredging of the new harbour. Additionally, during the 1880s, this limit defined by transatlantic trade was redefined. In 1886–1887, the Port of Tarragona wanted to welcome steam-powered vessels (“*grandes vapores transatlánticos”)* from the *Compañía Transatlántica*, which meant they had to again excavate from offshore to the entrance towards the *Muelle de Costa* down to −9 m instead of −8 m (Memoria, 1886–1887; p12) (Figs. 5, 6, and 7).

At the end of the 19th century, the harbour presented an area with a bathymetry of −9 m along the *Dique de Levante* and an area at −7 / -8 m along the *Muelle de Costa*. In contrast, a foreshore with a shallow slope still characterised the coast along the district of San Pedro near the ancient outlet of the Francolí.

During the first part of the 20th century, the main projects of dredging affected the entrance area of the harbour maintaining the depth at −9 m (dredging project maps of 1911, 1917 and Fig. 7). Sedimentation coming from the river accumulated in the underwater river mouth lobe against the *Dique transversal* and the *Dique del Oeste*. The river mouth lobe progressed towards the entrance of the Inner Harbour where periodic dredging was conducted. Unfortunately, not enough maps allow us to reconstruct the evolution more precisely for this period.

In 1947, the Outer Harbour looked more like a marine channel leading to the Inner Harbour and a new basin was created between the *Contradique* and the *Dique transversal (Dársena del Varadero)*. In parallel, the *Dique transversal* was transformed into a quay called *Muelle transversal*. This marine channel entrance was dredged to −10 m as was the southern part of the Inner Harbour. By 1970, the area between −10 and −11 m was expanded and covered half of the Inner Harbour. The other section was kept to between −9 and −10 m in depth, while along the *Muelle de Costa* the depth was between 7 and 8 m. Near the *Muelle de Pescadores*, the depths were between −4 and −1 m. This bathymetric distribution is roughly the same today in the now called Inner Darsena.

During the last 50 years, most of the bathymetric changes affected parts of the harbour that were expanding. Built in the 1970s, in line with the prevailing wind direction, the *Pantalán Repsol* reached the isoline of −18 m at its southern end. Today, the *Pantalán Repsol* has several berths at −8.20 m, −11.25 m and −14.75 m depth for gas carriers, and an offshore deep-water buoy for oil tankers. The Outer Harbour channel was initiated at the end of the 19th century and its creation progressed quickly in the last 50 years with several extensions of the main breakwater undertaken until 2006, and the latest addition of a cruise terminal in 2021. The harbour channel is between −24 m deep at the entrance of the harbour and −14 m deep towards the Inner Darsena. Along this channel lay quays at −12 m depth for car carriers (*Muelle de Galicia*) and −15.50 m depth for large container ships (*Muelle de Andalucía*). The river mouth of the Francolí in the harbour provides several quays for chemical ships down to −15.10 m (*Muelle de la Química and Dársena del Molino*). In front of that, and on the main breakwater, a coal terminal is located with a quay at −18.50 m depth (*Muelle de Catalunya*). Closer to the Inner Darsena, the channel is at −14 m deep with Agribulk quays at −13.25 m on both sides (*Muelle Aragon and Muelle de Castilla*). Inside the Inner Harbour, the *Muelle de Costa* is today at −6.30 m depth and the waters of the Inner Darsena mostly between −9 and −11 m deep like in 1971.

Sedimentation from the Francolí River has to still be managed by limiting the underwater lobe of the river mouth. Therefore, the main channel of the harbour is over-deepened and dredged down to −22 / -23 m deep in front of the river mouth to create a large sediment sink of more than a million of cubic metres, which should be able to absorb several years of sediment input from the river (Fig. 1).

4.3. Periodisation of the hybrid urban delta trajectory

Since the 18th century, we identified four main periods of evolution leading to this configuration considering the interactions between the river delta dynamics and transformations of the harbour infrastructure (Figs. 8 and 9).

4.3.1. Period 1: 1484 to 1800 – Sedimentation/erosion cycles with low harbour infrastructure and management

At the end of the 18th century, the harbour infrastructure was still limited to a single mole, with the Francolí river mouth adjacent but separated from the harbour embayment. Additionally, remains of the Roman mole were still in the middle of the harbour. In this configuration, floods of the Francolí periodically brought sediment to the coast and the sandy material was redistributed along the shore by the longshore drift (Salomon et al., 2024). The harbour structures contributed to trap sand along the coast, before storms eroded the shore and removed sediment from the harbour. These semi-cyclic fluvio-coastal dynamics together with longshore drift are involved in long-term deltaic trends with low anthropogenic impacts (Salomon et al., 2024).

4.3.2. Period 2: 1800 to 1880 – Progressive expansion of the harbour infrastructure in the delta front

This period saw great socio-economic growth of Tarragona. The urban junction between the Lower and Upper City took place in the middle of this period, while urbanisation around the harbour remained on the eastern fringe of the delta. Period 2 is characterised by important construction in the harbour, but with limited dredging activities. Additionally, strong floods and storms still had an important impact on the deltaic and harbour areas. The underwater river mouth lobe was still active during this period and expanded towards the harbour to the east. It was partly deflected by the structure built at the river mouth and the *Dique transversal* modified its morphology towards the end of Period 2.

From the end of the 18th century onwards, the main concern of the engineers was to offer a safe anchorage for ships. Their first aim was to stop the influence of the waves and storms coming from the south-east and the north-east. Consequently, they first built a long mole (breakwater) called the *Muelle de Levante*. However, in 1821, a storm coming from the SSW showed that the harbour was still exposed to waves – 35 out of 48 ships sank in the harbour (Capitania del puerto de Tarragona, 1822) (Figs. 8 and 9). The risk coming from the south was reduced with the construction of the *Dique transversal* at the end of this period (1874 to 1883). In the mid-19th century, the harbour authorities also started dealing with the sedimentary inputs coming from the Francolí. Engineers built a wall to stabilise the left side of the mouth of the Francolí, leading it to the west. The role of this structure was to keep sediment away from the harbour. Then, it was connected to the *Dique transversal*, which also helped keep the sediment away. In 1874, the powerful flash flood of Santa Tecla damaged the structures built at the river mouth (Ruiz-Bellet et al., 2015) and momentarily stopped the work engaged on the *Dique transversal* (Montserrat, 2012).

4.3.3. Period 3: 1880 to 1970 – Towards disconnected harbour and deltaic dynamics

During Period 3, major changes to the harbour infrastructure affected the relationship between the delta and the harbour. Between 1880 and 1900, the harbour was clearly divided into an Inner and an Outer basin. By 1900, the Inner Harbour was very well protected from western and southern winds and possible storms (*Dique Transversal* and then the *Muelle paralelo*). Period 3 was really the first period where regular dredging became a strategy in operating the harbour. For instance, a long marine channel was dredged from the Outer Harbour towards the Inner Harbour and periodic dredging was conducted to

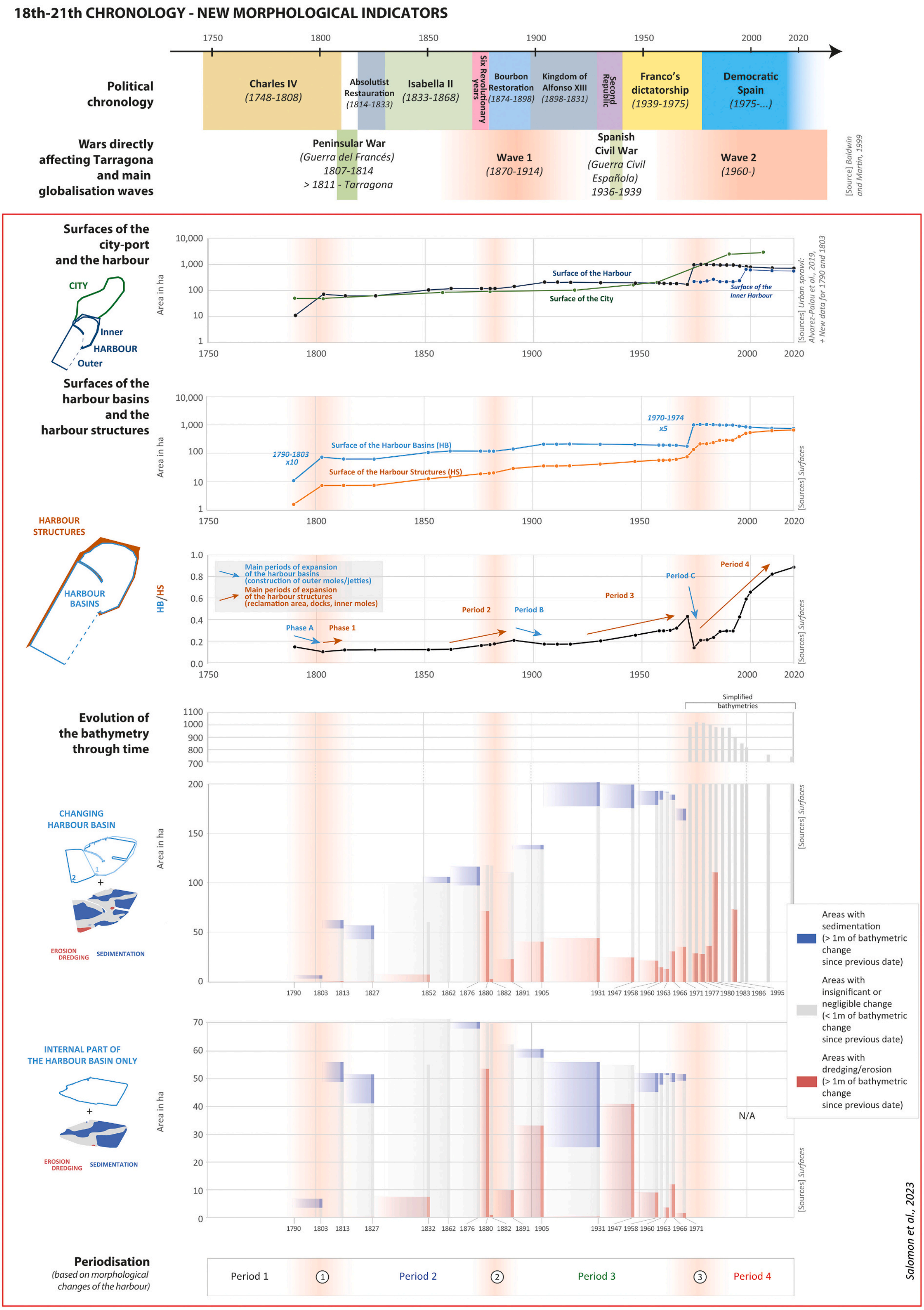

Fig. 8. Chronologies of the evolution of the mouth of the Francolí River and the harbour of Tarragona during the last two centuries. More precisely, it shows the evolution of the bathymetry of the initial harbour / Inner Darsena, the bathymetry of the full harbour, the harbour structures, the link between the extent of the harbour and the extent of the city and the population. Contextual historical data are also added to the chronologies.

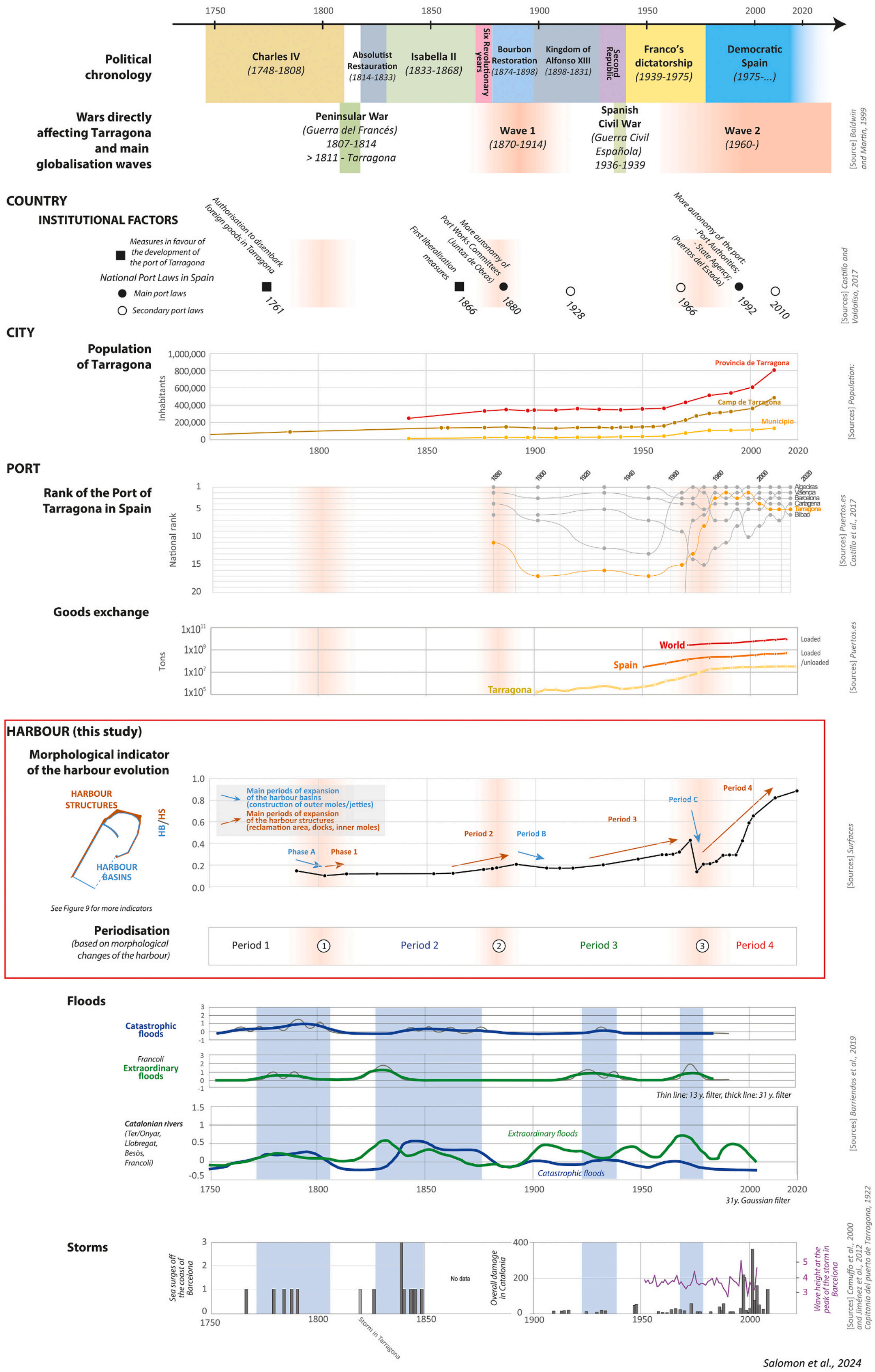

Fig. 9. Contextual economic, historical, floods and storms data to accompany the chronology of the evolution of the harbour of Tarragona during the last two centuries. In regards to institutional factors (Castillo and Valdaliso, 2017), the rank of the port in Spain and good exchanges in Tarragona in comparison to national and international values (*Puertos.es*).

prevent the underwater lobe of the Francolí to extend towards the Inner Harbour. The Inner Harbour was fully managed by the end of this period: moles, quays, and sedimentation controlled by dredging of the access channel. In contrast, the Outer Harbour was still exposed to southern winds and sedimentary inputs from the Francolí river mouth. Continued engineering in the form of mole, dam and breakwater construction hence continued in the Outer Harbour, modifying it further.

The first part of Period 3 (1880–1914) was characterised by significant changes in the harbour configuration. Afterwards, the history of Spain and Catalonia was unstable, affected by the First World War and the Spanish Civil War. Important harbour transformations happened again during the 1940s, while Francoist Spain was partly aside from the Second World War conflict. Urbanisation extended to the river mouth but remained confined to the left bank of the Francolí. Urbanisation started to grow quickly from the late 1950s onwards.

4.3.4. *Period 4: 1970 to today – Quick expansion of the harbour and full integration of the Francolí river mouth in urban Tarragona*

During the last decades, harbour infrastructure extended across the whole bay of Tarragona, which forced the Francolí river mouth to integrate in it. The development of the infrastructure from the 1970s was related to the establishment of oil refineries and propelled the Port of Tarragona towards a higher national and international rank. This newly created harbour area was then protected behind the extended *Dique de Levante* and *Dique Rompeolas* for the last 50 years. The 1970s and the 1990s were periods of important construction within the Inner and Outer harbour. In the mid-1990s, construction of goods terminals in the Outer harbour forced the river mouth of the Francolí River to integrate within the harbour. This was an important turn in the history of the interaction between the Francolí River and the harbour. Before that, sediments were routed away to the south-west, now the present harbour was designed to trap river sediments inside the harbour. The bottom of the harbour is kept over-deepened near the river mouth and sediment deposited there is knowingly committed to be dredged regularly.

Major changes in the harbour are observed since the 1970s but socio-economic changes already affected Tarragona and its region since the late 1950s, including new industrial parks and faster population growth. According to Alvarez-Palau et al. (2019), the urbanised area of Tarragona was 12 times bigger in 1990 than it was in 1957 just before the beginning of the urban sprawl. The development of the urbanisation slowed down during the last 40 years.

5. Discussion

5.1. *Intertwined chronologies of a hybrid urban delta*

The periodisation that is the outcome of the analysis concisely describes the geographical evolutionary trajectory of the studied hybrid urban delta. Rightly, it can be argued that it oversimplifies its history and that it considers only one aspect of the processes at stake. In fact, this periodisation does not show the transitions and aggregate different intertwined chronologies that would have relevance on their own. Research objects such as harbours, ports, cities, or deltas are complex entities with entangled phenomena. The chronological analysis proposed is a decomposition of the parameters involved into single chronologies. In the following parts, we develop four geo-historical narratives associated with the evolution of the harbour of Tarragona and the Francolí Delta since the 18th century. Fig. 10 offers a synthetic view of the evolution of the Francolí-Tarragona hybrid urban delta from north-east to south-west. This cross-section is perpendicular to the ancient coastal dynamics and in the alignment of the harbour evolution during the last two centuries.

5.1.1. *Evolution of the cartography and harbour bathymetric quality*

Modern ports and harbours all have rich datasets of maps with bathymetric and textural information about their basins (Fig. 2 - Dataset). Most importantly, updates about the bathymetry and the bottom texture of the harbour are regularly conducted and thoroughly mapped. Nevertheless, good georeferencing of generational sets of maps is essential following precise protocols. Consequently, we developed new ways to conduct quality assessments in providing synoptic graphs (Figs. 2 and 3), which also provide a proxy metric for the evolution of the city and the harbour. Dynamic urban areas progressively erase reference control points and few can be tracked through time. Overlapping reference targets should be used (i.e. our 2020 - > 1946 - > 1883/82 - > 1824 - > 1803 - > 1790 steps). We observe that main periods of urban or harbour changes are also periods of important reference points creation and destruction. The four periods identified above can be observed in the georeferencing assessment (Fig. 3). In this way, reference points are a proxy of the urban and harbour changes.

The analysis of bathymetric maps highlights a non-linear evolution of the recorded points or lines until 1971 (Fig. 2 – Interpolation). This does not indicate an improvement in the accuracy of the maps in line with the evolution of bathymetric techniques. However, it appears to be more correlated with major events and large-scale projects that the port

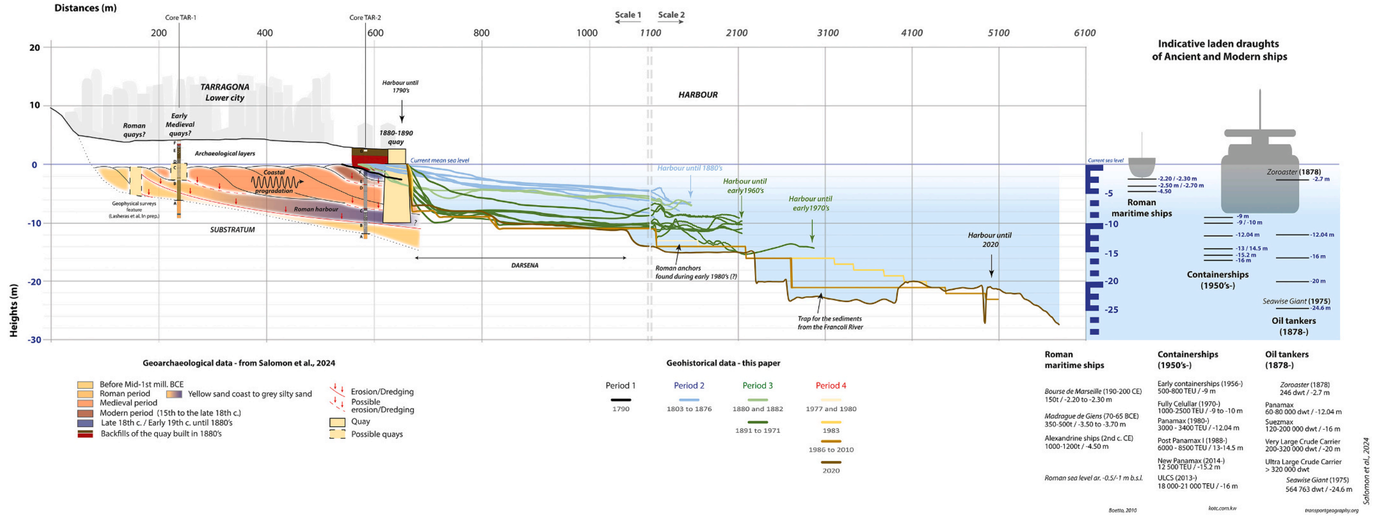

Fig. 10. Synthetic cross-section of the evolution Francolí Delta front and the harbour of Tarragona using geoarchaeological and geohistorical data. It combines results from Salomon et al., 2024 and this paper.

has experienced throughout its history. High density of bathymetric points were produced and mapped in 1790, in the period 1880–1891, and the period 1958–1971 (Fig. 2 - Dataset). It is likely that a greater number of surveys were commissioned by the authorities of the port to gain better knowledge and adjust projects accordingly. Surprisingly, the quality of the interpolation remains relatively constant (in average 1 m ± 0.5 m) and shows no statistical relationships with the number of bathymetric points. One plausible explanation is that the bathymetry of the harbour basins, initially natural and later heavily impacted by human activity, exhibited smoothed morphologies. Coupled with the still rudimentary bathymetric techniques (lead line sounding), this may have resulted in a relative homogeneity in depth measurements across different dates, as well as in interpolation performances. After 1971, it can be expected that new techniques such as sonar (introduced in the 1960s) and bathymetric LiDAR (developed since the 1980s) provide more precise measurements and higher interpolation quality.

5.1.2. *From the local to the international port*

Since the end of the 18th century, the port city of Tarragona underwent major transformations from a small and open cove (Period 1) to an international harbour (Period 4). Many elements explain the morphological evolution of the harbour reconstructed in this paper throughout the last two centuries. They include political, economic, social, technological, and institutional factors playing at different spatial scales. All of these aspects can be found in the different studies conducted mainly by historians and geographers locally (Magriñá, 1901; Jordà Fernàndez, 1988; Escoda Múrria, 2000; Serrano Sánchez, 2018) or at larger scales (Castillo and Valdaliso, 2017; Ducruet et al., 2018). Individually, successive harbour configurations were also steps impelling further developments. All significant developments occurred between the end of one period and the beginning of another. The waves of globalisation and the changes they have brought since the 19th century were already visible in the two preceding decades.

The 18th century and the beginning of the 19th century is characterised by a local competition between Tarragona and the Reus-Salou port system (Period 1 to Period 2). The initiation of the construction of the *Dique de Levante* in the 1790s and early years of the 19th century was essential to help Tarragona in its new role of regional port (Period 2). This achievement originates from the authorisation to disembark foreign goods in 1761 during a flourishing economic period. The role of the nobles and ecclesiastics from Tarragona was also important in supporting the project of a new mole for the port. At that time, the Archdiocese of Tarragona gave the city the status of the religious capital of Catalonia (Serrano Sánchez, 2018).

The 19th century is characterised by the rise of the first globalisation wave initiated in the 1820s but fully developed in the period 1870–1914 (Baldwin and Martin, 1999) (Period 2 to Period 3). Regarding transportation, this first economic globalisation was marked by the expansion of railway transport and steam shipping (Period 2). In the second part of the 19th century, the average size of steamship vessels increased and larger and deeper harbours were necessary to accommodate them (Fig. 4, Period 3). In parallel, new standards for loading and unloading ships arose. Tarragona followed this trend from the 1870s and especially in the 1880s with large dredging activities and new dock-building. These works were facilitated by the new Spanish Port Law of 1880 giving more autonomy to the Port Works Committees (*Juntas de Obras*) (Castillo and Valdaliso, 2017).

The second globalisation wave started in 1945 or 1960 and still continues today (Baldwin and Martin, 1999) (Period 3 to Period 4). Regarding harbours, this second wave was characterised by a growth of maritime trade (e.g., more ships) and containerisation spreading since the 1970s (Period 4). The number, the sizes, and the draughts of the ships have grown quickly since then (Fig. 10). Container ships and oil tankers with draughts up to 15–20 m were built from the 1970s onwards (Very Large Crude Carrier – *VLCC* and Ultra Large Containerships of 24,000 TEU – *ULCS*). The biggest ship ever built was the *Seawise Giant*, an oil tanker with the deepest loaded draught built in 1975 (24.6 m – Fig. 10 – *transportgeography.org*). Like during the first globalisation wave, harbours had to adapt their morphology to host more and larger ships. Tarragona highly benefited from this period and is considered an emergent port in the path dependency analysis of the port system of Spain conducted by Castillo and Valdaliso (2017). The size of the Port of Tarragona grew quickly in the 1970s and adjusted logistics strategies to the new needs. Tarragona was a secondary port behind Barcelona for a long time but reached equal importance in the 1970s. Geographically, Tarragona benefited from the new container corridors towards the Mediterranean part of Spain, while Atlantic ports that were stronger in the 19th century, declined (Castillo and Valdaliso, 2017).

5.1.3. *Rise of the modern port, heritage loss and dredging gain*

In parallel to the development of the modern harbour during the last 200 years, the remains of the Roman and medieval harbours disappeared from the land- and seascape of Tarragona. The Roman mole that was the most prominent structure of the ancient harbour was partly removed from 1843 to the 1880s (Salomon et al., 2024). Fig. 10 synthesises and visualises the development of the harbour of Tarragona towards the south-west, associated with deeper dredging conducted successively through time in the bay. Each new phase of dredging erased a part of the history of Tarragona recorded in the sediment. One of the most suggestive events dates from the early 1980s when dredging activities brought to surface Roman anchors without any information on their sedimentary contexts, which could have contributed to better date these anchors or to understand the condition of their abandonment.

The Upper City is on the World Heritage List for its well-preserved Roman structures, while the harbour area that contributed to the development of the Roman City is now erased or invisible under the port of the 19th–20th century. To generate more data about the ancient harbours, it would be necessary to encourage authorities and companies to systematically involve geoarchaeologists with their geotechnical teams (see European Convention on the Protection of the Archaeological Heritage, Valetta, 16.I.1992). Sedimentary cores would then not only be used for geotechnical diagnostics of the subsoil, but also shared with geoscientists to answer paleoenvironmental and historical questions about the city and its harbour. It would also be necessary to perform drillings offshore before dredging undisturbed sediments to keep a record of the sediment archives and answer similar questions at a larger scale. A guidance document was issued on this very subject in 2014 by PIANC, the World Association for Waterborne Transport Infrastructure (PIANC, 2014).

5.1.4. *Increased environmental segmentation of the delta*

The development of the port city of Tarragona is expressed morphologically by a gradual extension of the harbour. The new intermodal infrastructure contributed to improve the connectivity of the port to regional and international maritime routes (harbour) but also to better connect the port city to its hinterland (roads, railways, highways) (de Ortueta Hilberath, 2006).

Consequently, the development of the connectivity of the port led to the segmentation of the environments of the Francolí Delta. The river is a conveyor of water and sediment connecting the watershed to the sea in a source-to-sink continuum. The construction of the railways during the first globalisation wave and the highways during the second globalisation wave contributed to segment the upstream and downstream continuity of the deltaic plain. To protect the Lower City and the urbanised areas spreading towards the deltaic plain from catastrophic flash floods, large embankments were built along the Francolí River. This conducted water and sediment directly towards the sea in the harbour area. In the delta front of the Francolí, the strategy of the engineers was to route the sediments always further away from the harbour basins towards the south-west since the late 1820s – early 1830s onwards to avoid sediment deposition inside the harbour basins. However, this strategy changed in the 1990s when construction of jetties and platforms perpendicular to the coastline in the south-west of the river mouth trapped the outlet of the Francolí within the harbour.

In this new context, waves and storms that were originally (Periods 1 and 2) main contributors to redistribute sediment along the coast or to the offshore were not active anymore (Periods 3 and 4). In place of these, periodic dredging was necessary to prevent formation of a delta within the harbour. Harbours generally create a break in the land-ocean continuum, becoming the main sink of the fluvial sediments and redistribution along the coastline, which must now be taken over by humans. Consequently, beach nourishment must be conducted at the Playa del Miracle to the north and the Playa de la Pineda to the south (Canovas et al., 2011). In addition, a 600 m groyne was built in the 1980s to stop sediment movement from La Pineda beach into the harbour (*Espigo dels Prats*).

5.2. Hybrid urban deltas and their transformation over time

The study of the seascape leads directly to the study of the coastline and its dynamics controlled by both natural dynamics and anthropogenic factors (e.g., mole, jetty, quay construction). In the deltaic plain, not developed in this study, there would be a similar approach considering first the channel or paleochannel morphologies through time, the riverbanks, the adjacent lands or wetlands and the urban areas. Coastal geo- and archaeomorphologies contribute to the influence of sedimentological processes in the deltaic front and harbour. Similarly, waterfront management of the city is interactive with the urban fabric, the harbour fabric and the sedimentological dynamics. All these interrelations contribute to shape a hybrid urban delta (Salomon et al., 2024).

5.2.1. From a hybrid urban delta to a hybrid urban estuary

The port city of Tarragona now strongly impacts the Francolí Delta both in the deltaic plain and on the delta front. Additionally, urban processes can be tracked back to the Roman period with high resolution based on the rich archaeological dataset in Tarragona from the Upper City to the river mouth of the Francolí (Macias et al., 2007). Knowledge about the agricultural impacts in the deltaic plain of the Francolí still has to be reconstructed in the long-term. We tested this interdisciplinary study mainly on the coastal fringe of the Francolí Delta, the delta front in relation to the Lower City of Tarragona and its harbour. This paper contributes to demonstrate the importance of the bathymetry to reconstruct long-term evolution of a harbour and a deltaic area (Wu et al., 2018; Cox et al., 2021).

In the last two millennia, natural thresholds and/or anthropogenic impacts along the coast contributed to generate deltaic progradation (Salomon et al., 2024). In the last decades, the hybrid urban delta of the Francolí completely reshaped the coastal morphology south of Tarragona. The bay of Tarragona is progressively overbuilt with harbour infrastructure, while the delta front of the Francolí is totally included into the harbour since the mid-1990s. The currents inside the harbour are characteristic of an estuarine environment with two layers with different densities (Martínez Velasco, 2012; Samper et al., 2022). Initially, the morphology of the delta of the Francolí would have been categorised as a delta dominated by waves (Wright and Coleman, 1973). However, its morphology is now totally dominated by human infrastructure. A new diagram would have to be designed to integrate the diversity of the human impacts on river deltas and to observe patterns. In such a typology, the Francolí-Tarragona urban delta would be a small system first dominated by harbour infrastructure shaping a hybrid urban delta (Periods 1, 2 and 3) and then a hybrid urban estuary (Period 4) (Fig. 11).

5.2.2. Temporal trajectories of a hybrid urban delta

Traditionally, the evolution of river deltas or port cities is visualised through a series of maps at different periods. At slightly more zoomed-out scales, for the land- and seascapes hosting these harbours, palaeogeographical or geohistorical (Arbouille and Stanley, 1991; Bellotti et al., 1995; Coleman et al., 1998; Vella et al., 2005) reconstructions show morphological changes of river deltas from map to map enhancing coastal progradation or erosion. Similarly, sets of maps of a port through time (Hein and Van Mil, 2019) or diachronic models (Bird, 1963) show changes of port cities morphologies at different periods or dates.

Without dedicated and systematic attention (Salomon et al., 2024 and this paper), comparative analyses through time and space are

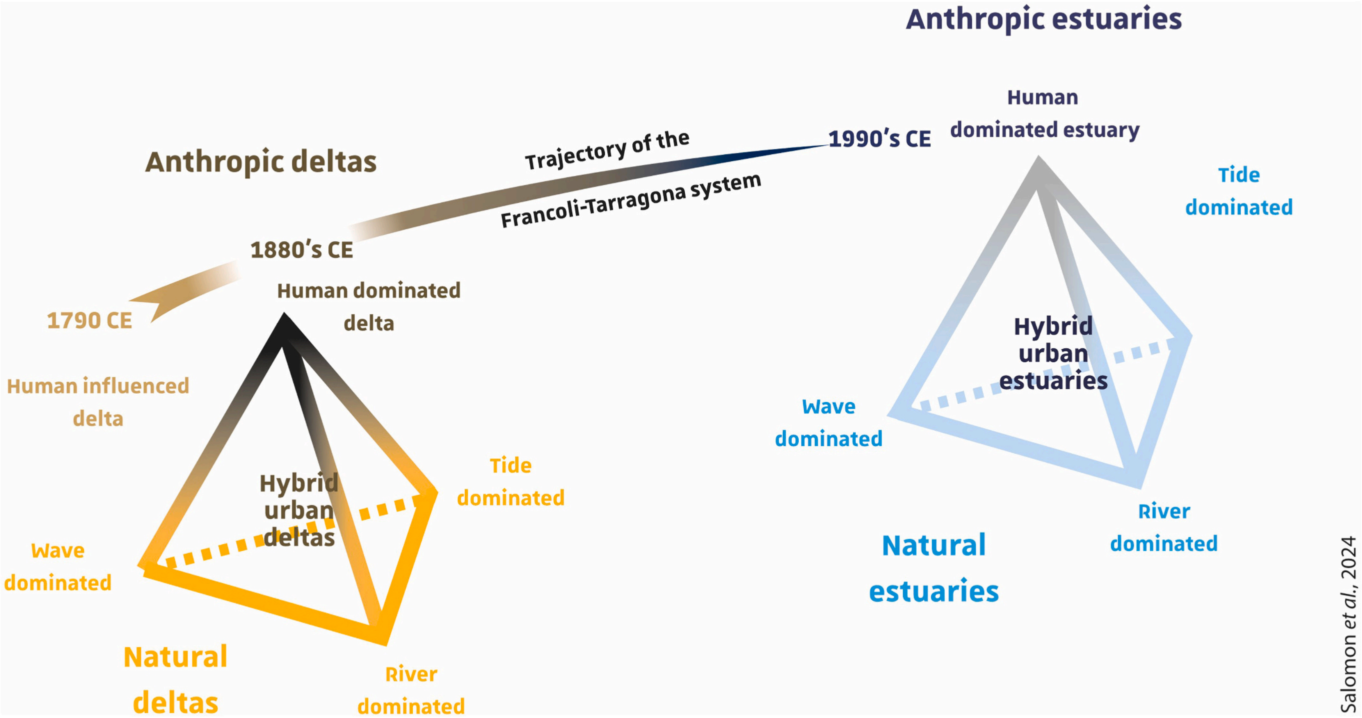

Fig. 11. From a hybrid urban delta to a hybrid urban estuary.

generally difficult to carry quantitatively in only using maps. Additionally, the diversity of the processes at stake, "local particularities" (Hein and Van Mil, 2019) and contextual data (e.g., economic, political, institutional, climatic) need to be supplemented with cartographic representations. Instead of considering only spatial representations, we also advocate seeking timelines and time series to reconstruct the evolution of hybrid urban deltas (Fig. 12). Synchronisation of different temporal inputs is essential to understand all aspects of hybrid environments (Lespez and Dufour, 2021; Sajaloli et al., 2023). The spatial-based approach remains essential to characterise single morphologies or processes drivers to later track them in time. Regarding the Tarragona case, each morphological change and processes involved are visualised in a common chronological framework (Figs. 8 and 9). Additionally, relevant sequence of events or time series can be added to better explain the new chronological data produced. It can be either data related to the environmental and climatic contexts or data produced by historical archaeological, demographic, and geographic studies about the anthropic contexts. All chronologies are potentially of interest but their selection can be challenging. Different spatial scales can be considered depending on their relevance to the object studied: palaeoclimatic, historical and archaeological data for stratigraphy, technical developments and socio-economic data for a harbour structure (Fig. 12).

Practically, all data produced in this paper are represented with maps and time series. All steps of the GIS analyses are expressed in the chronological framework: maps collected since the 18th century, the evolution of the precision of the maps through their georeferencing, the overlap of the maps, and the quality of the interpolation (Fig. 2). The construction of the spatio-temporal dataset is as important as the results in terms of coastline mobility or erosion/sedimentation evolution. It is shown that they are all proxies of the hybrid urban delta evolution. This paper (and also Salomon et al., 2024: their Figs. 10 and 11) provides a new chronological synthesis with new datasets and collected chronologies in the literature.

Ultimately, synchronised chronologies produced or gathered provide better ways to reconstruct temporal trajectories of complex objects such as hybrid urban deltas. They allow the researcher to interconnect parameters from a single case study in order to observe different tempos, rhythms, and delays in the influences. Timelines and time series also offer the possibility to be reused to compare similar objects across the world (e.g., cities, ports, deltas, coastlines) and related parameters (e.g., sizes, volumes, rate of evolution) (Fig. 12).

6. Conclusion

This work conducted on a case study contributes to a better understanding of the natural and anthropogenic processes involved in the evolution of a land- and seascape composed by deltaic, urban and harbour areas. The work bridges human geography and physical geography, but also different interdisciplinary academic communities (archaeology-geomorphology and history-geography-geomorphology-engineering) and promotes an interlocked chronologies approach to reconstruct long-term evolution of urban deltas. It also participates to the fields of the deltaic geomorphology (Stanley and Warne, 1993; Giosan, 2007; Hori et al., 2004; Tamura, 2012; Anthony, 2014) and urban geomorphology (Coates, 1976; Cooke, 1976; Thornbush and Allen, 2018; Brandolini et al., 2020). Our results and discussion highlight elements in conducting studies of hybrid urban deltas over centuries:

- Clarifying the different geo- and archaeomorphological units at stake, their different spatial expressions and their possible drivers;
- Clarifying both human and natural processes and their interactions in considering the system in which they are embedded (e.g., river delta, river, coast, city, port, waterfront);
- Considering not only human impacts on *landscape* of river deltas but also *waterscapes/seascapes* (topography versus bathymetry, quarries versus dredging);
- Human-made morphologies are always combined with natural morphologies through time creating hybrid landscapes;
- Quantifying land- and seascape transformations (e.g., harbour geometry and bathymetry map time series) is essential to have a broader and detailed view of changes through time;

Chronological visualisations are as important as geoarchaeological and geohistorical mapping to reconstruct transformations of hybrid land−/seascapes. Ultimately, producing and sharing chronologies produced for each case study will help to synchronise dynamics of river deltas, harbours, port cities or hybrid urban deltas. Ultimately, it would contribute to a better understanding and timing of the regional and global trajectories through time.

The data produced about the Francolí-Tarragona system were emplaced in the evolution of the port city and the global economy. It demonstrates that the case study followed roughly the main trends of the Spanish and world maritime economy. For Tarragona, the decades 1800–1810, 1870–1890, 1960–2000 have been essential to adjust the

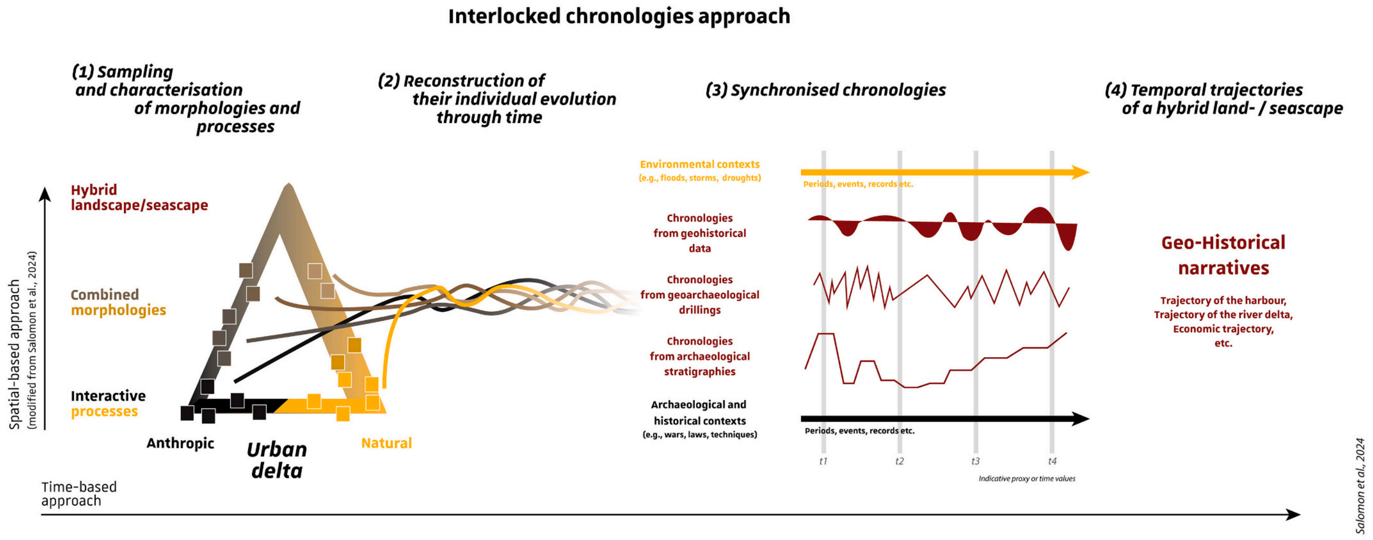

Fig. 12. Conceptual methodology followed to study hybrid urban deltas through time.

harbour infrastructure to the international standards and to the different waves of globalisation. In parallel, these dates also correspond to periods of strong impacts on the Francolí Delta environments and the heritage of the ancient city. These observations were obtained by transforming all spatio-temporal data into time series. GIS approaches have been essential to produce interdisciplinarity knowledge in the last decades and still are. The development of interdisciplinary timelines and any representation of processes including time remains a challenge to better understand the complexity of our world and how it formed. Such approaches are essential to characterise transitions in the past and to reflect on future transitions towards more sustainable types of management.

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CRediT authorship contribution statement

Ferréol Salomon: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Patricia Terrado Ortuño:** Writing – review & editing, Writing – original draft, Resources, Data curation, Conceptualization. **Pierre-Alexis Herrault:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Kenji Fujiki:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Olivier Finance:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Ada Lasheras González:** Writing – review & editing, Conceptualization. **Josep-Maria Macias-Solé:** Writing – review & editing, Conceptualization. **Arthur de Graauw:** Writing – review & editing, Writing – original draft, Investigation. **Kristian Strutt:** Writing – review & editing, Conceptualization. **Simon Keay:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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