# Hybrid urban delta (2): Long term interactions between the Francolí delta and the port city of Tarragona (1790 to 2020 CE)

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## Highlights (3 to 5 bullets; 85 characters per bullets points including space)

* Bathymetric evolution of the harbour and the delta front for le last 200 years;
* Temporal trajectory of the Francolí-Tarragona hybrid urban delta for the last 200 years;
* Transformation of a cove dominated by natural processes into an international harbour;

## Keywords (3-7 keywords, using British spelling)

River delta, port city, harbour, old maps, GIS analysis, geohistory, geography

## Abstract

In this second paper, we reconstruct the gradual changes affecting the Francolí delta-front and the harbour of Tarragona during the last two centuries and we determine the causes of these evolutions. This work is based on GIS analyses of old maps mostly produced by the Spanish authorities or by port authorities through time. It promotes collaborations between approaches developed in geohistory, history, geomatics and human geography to better reflect the complexity of our world. The main outcomes are represented by timelines reflecting the temporal trajectories of the Francolí-Tarragona hybrid urban delta. Since 1790, major changes characterise the interactions between the Francolí delta and the port city of Tarragona. Inland, the urban sprawl increased during this period and the harbour of Tarragona expanded offshore towards the occupation of the whole Bay of Tarragona including the whole front of the Francolí delta. Consequently, the natural delta of the Francolí gradually turned into a delta constrained by human activities. The port city developed land- and seaward connectivity, promoting its integration into a global economy while the source-to-sink path of the sediment from the Francolí river to the sea is now segmented by the harbour basins. Consequently, sand nourishment is conducted on the surrounding disconnected beaches. This study demonstrates that sediment transfer processes are of paramount importance for the sustainability of port operations.

## Figure captions

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

**Figure 2**. – Presentation of the dataset of old maps used in this paper and their characteristics. It is also a quality assessment of the georeferencing of the maps, the digitalising, and the interpolation of the bathymetric data. All data are plotted referring at the date of the map.

**Figure 3**. – Quality assessment of the georeferencing – Part 1. Each point of the map is a *reference point* used to georeference the maps and aerial photographs of this study (42 documents). The map focuses on the harbour, the Lower and the Upper City, the main areas of interest in this study (67 reference points out of 81 in total). Their sizes correspond to the number of maps georeferenced using the reference point and the colours express the average uncertainty of the georeferencing for each point. On the right are two graphs showing the average uncertainty of the georeferencing depending (1) on the area considered and (2) on the date of the reference document whether it is a map, an aerial photography, or a satellite image (7 reference documents).

**Figure 4**. – Quality assessment of the georeferencing – Part 2. 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.

**Figure 5**. – 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 river mouth and the harbour is proposed. This periodisation corresponds to the one identified in Figure 4.

**Figure 6**. – 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 depth. 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 record as well textural data with a good resolution in the 19th c. (1813 and 1880).

**Figure 7**. – Quantitative analysis of the evolution of the bathymetry from 1790 to 1971. The changes are represented on 17 maps.

**Figure 8**. – Quantitative analysis of the evolution of the bathymetry from 1790 to 1971. The changes are represented on 17 graphs.

**Figure 9**. – 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 evolutions 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.

**Figure 10**. – Chronologies of the evolution of the harbour of Tarragona during the last two centuries. In regard 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*). Contextual historical data are also added to the chronologies.

**Figure 11**. – Synthetic cross-section of the evolution Francolí delta front and the harbour of Tarragona using geoarchaeological and geohistorical data. It combines results from the two papers published in this issue of *Science of the Total Environment*.

**Figure 12**. – Conceptual approach followed to study hybrid urban deltas through time.

## Introduction

During the last two centuries, port cities encountered major changes across the world (Bird, 1963; Ducruet et al., 2018; Hein and Van Mil, 2019) and coastal areas and especially river deltas have been particularly affected by human impacts (Syvitski and Saito, 2007; Besset et al., 2019; Nicholls et al., 2020; Nienhuis et al., 2020). World population grew from ca. 1 billion inhabitants in 1800 to ca. 8 billion today (Federico and Tena-Junguito, 2019; Maddison Project Database et al., 2020). During the same period, maritime economy (Talley, 2012), ship building (Lyon and Winfield, 2003; Notteboom, 2004), port and harbour engineering (Jarvis, 2016) were deeply transformed in relation to increasing productions and economic exchanges together with technological leaps developed in many different fields. Consequently, coasts have been affected by intensification of land use, engineering interventions, natural resources 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. The reconstruction of the temporal trajectories of port cities and their environment could help to better think the transition towards more sustained developments in such context.

During the last centuries, each port city has been adjusting its own harbour infrastructures to offer safer and wider anchorages, longer quays and better logistics to welcome larger fleets, bigger ships and new types cargoes (Cox et al., 2021). They 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 the 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, led inevitably to trends in the way ports were shaped over time. Different types of models were developed on this line (Bird, 1963; Hoyle, 2000; Ducruet, 2007). Today, Tarragona is one of the top 5 ports of Spain while two centuries ago, Tarragona barely had a harbour. While Tarragona is still a secondary harbour in the current global economy (Ducruet et al., 2018), it constitutes a good example to study the development of a multipurpose industrial port during the last two centuries adjusting to global maritime economy changes.

Tarragona also offers an interesting case to study human-nature interactions between the port city and the Francolí river delta. The first paper published about Tarragona in this issue demonstrates that its physical location has never been ideal regarding its harbour potential. Even so, the Romans did choose the city to become the capital of a large and rich province, *Hispania Tarraconensis* centred on the Ebro river, probably because of the Francolí river providing fresh water not too far from the Ebro delta. They tried to improve the harbour potential with built infrastructures, butwe do not know how long the Roman achievement remained efficient. Sedimentary cores drilled in the ancient harbour showed that it has always been prone to sedimentation issued from the floods of the Francolí and to erosion from storms. The location was not any better two centuries ago regarding the harbour potential. However, Modern engineers reiterated the Roman attempt and had to deal with the same problems. The Francolí delta is rather small but challenging as flash floods are particularly strong and destructive. In addition, current sea level rise will increase the vulnerability of the harbour to storms in the next decennia (Sierra et al., 2016). The iterative construction of the harbour of Tarragona that will be studied in this paper did also create new environmental challenges. Sediments from the Francolí river spreading along the coast of Tarragona remain an issue to the development of the port and their management have now strong repercussion on the environment.

This study aims to bring a different perspective and a more standardised methodology to reconstruct long term evolution of fluvio-coastal infrastructures in relation to their environment. This is an attempt to identify research objects that can be studied with different kind of data (e.g., archaeological data versus historical and geographical data; sedimentological data versus old maps records) in order to reconstruct long term trajectories. It also defends a more systematic approach that would contribute to increase interdisciplinarity between natural and social sciences specifically regarding ports and river deltas.

Generally, morphological models considering port development focus on the emerged features only. 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 until today (Andrade et al., 2021; Amore et al., 2002), but more often regarding the last centuries (Bird, 1963; Hein and Van Mil, 2019). Aside from the disciplines working classically on modern and current ports such as economy, human geography and history, geosciences also developed studies considering port 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. Examining in detail bathymetric evolution and harbour infrastructures of the port of Tarragona since 1790, this paper seeks to demonstrates that such data is 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).

Figure 1.

## Historical and geomorphological context

Chronological data discussed in this section are reported in Figure 9. Global, , and local contexts are essential to the new data produced in this paper (harbour infrastructures and bathymetry). Compared to paper 1, we paid less attention to the flood and storm series affecting the Francolí delta since they were not essential to understand the main morphological evolution of the hybrid urban delta of the Francolí during the last two centuries. However, more detailed information about the hydrodynamics of the present harbour will be provided.

## Geographical context: the watershed, the delta, the harbour, and the bay

For the last two centuries, better flood series and records are available than for previous periods (Alberola et al., 2016; Barriendos et al., 2019). During the period 1842-2000, Pino et al. (2016) record 24 catastrophic floods in NNE Iberian Peninsula. Important events in this time span include 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 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 1600 m3/s at Tarragona. During this event, 415 mm of precipitation was recorded in 24 hours upstream at the station of Alforja (Agencia Catalana de l’Aigua, 2005). The strongest flash flood dates to the 19th c. when the reconstructed water discharge of the Francolí River was estimated at 3289 m3/s at Montblanc, 30 km upstream of Tarragona, for the Santa Tecla event in 1874 (Ruiz-Bellet et al., 2015). The flood prevention system set up by the municipality of Tarragona include embankments and drainage canals for over-flooding waters.

Today, important engineering works characterise the coast of Tarragona including the harbour and dredging is conducted in the harbour where the mouth of the Francolí river is located. The currents inside the harbour have an 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 residence time of pollutants in the harbour and studies demonstrate that pollution tends to stay in the harbour (Mestres et al., 2010). This is important since pollutants may affect the city to the north and other port activities conducted around the basins. It should be noted that Tarragona is one of the most important petrochemical clusters in southern Europe andalthough wfor water circulation , it is important for air pollution

## Historical and geographical context during the last three centuries: the port city and the harbour

In the 18th c., Tarragona was essentially an ecclesiastic capital and a military fortress (Magriñá, 1901; Jordà Fernàndez, 1988). The city had 4 554 inhabitants in 1725-1735 and 8 741 in 1787 (Serrano Sánchez, 2018). Its coast was not particularly blessed with a natural harbour and the mole built in the 15th c. was not providing an ideal shelter for the merchant ships. It was a secondary economic centre characterised by a low population growth comparing to other Catalan cities (Areste Barges, 1982). Locally, Reus was the most populated city concentrating economic activities (14 440 inhabitants in 1786-1791 - Montserrat, 2012). Located inland, it was using the harbour of Salou to the south with 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 c. and the first years of the 19th c., 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 (Areste Barges, 1982; Serrano Sánchez, 2018). The development of the port city and its harbour was stopped during the Peninsular War (March 1809-September 1814). After the war, Tarragona counted only 1500 inhabitants and many destroyed buildings. However, the merchants came back quickly in Tarragona now equipped with a long jetty finished before the Peninsular War (*Dique de Levante*). The new architect Vicente Teixeiro continued to build the mole after the war and until 1836, date of his death. Afterwards, between the 1840’s – 1870’s, works in the port were directed by managers for shorter periods of time (Serrano Sánchez, 2018).

During the 19th c., Tarragona switched from a military city to an important port city of the Mediterranean coast of Spain. Commercial activities concentrated around the harbour and led to an expansion of the urbanisation from the Lower City (*Nueva Población del Puerto*). The city wall was gradually removed to provide space for this development and in 1868-1870 Tarragona is no more a fortress. While for centuries, Tarragona was divided into an Upper City (*Ciudad Alta*) and a Lower City (*Marina*), urbanisation finally filled the gap from the Lower to the Upper City by the middle of the 19th c. 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. Tarragona became capital of the Province in 1833 and overcame the system Reus – Salou locally prevailing in the 18th c. The harbour itself adjusted to the new needs and to the growth of economic activities. New moles, quays, warehouses were built during the 19th c. The harbour was exporting more and more wine throughout the 19th c. In addition, a first railway connected Tarragona with Reus in 1857. After the grape phylloxera epidemic affecting vineyards in France, vineyards developed ca. 1870 in the hinterland of Tarragona. The port activities of Tarragona were even more specialised on wine trade from that time. In the 1870’s - 1880’s, the harbour adjusted to new standards in harbour infrastructures and important changes were made. However, international instabilities and the wine crisis linked to the phylloxera finally strongly affected Tarragona in the 1880’s-1890’s. Consequently, the population lost ca. 5000 inhabitants at the end of the 19th c. From then to the 1960’s, the extension of the city towards the west and the Francolí delta developed more slowly (e.g., Ramón Salas Ricomá’s project of 1884).

During the first part of the 20th c., the city 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 especially because of several bombings (deaths, destructions). New economic impulse started in the late 1950’s – 1960’s with the construction of industrial parks towards 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. 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 structure the territory.

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

## Methodology

Figure 2 shows essential information about the dataset used in this paper, the control of the georeferencing, the digitalisation of the harbour extent and the bathymetric data, and the interpolation between bathymetric points or isolines.

### Dataset

This paper is based on the analysis of 42 maps ranging from 1749 to 2020, aerial photographs at different resolutions dated to 1946 and satellite imagery from 2020. 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>) (Supplementary data and Terrado, 2021). Our interest in the old maps was to observe the layout evolution of the harbour of Tarragona, but most importantly the characteristics of the bottom of the harbour. 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 (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 of 2013).

The bathymetric dataset covers more than 2 centuries of harbour evolution. The best resolution is between 1958 and 2000 with a bathymetric map every 3 years. The period between 1790 and 1858 is roughly presenting a map every 5 to 15 years except during the second quarter of the 19th c. (1927-1952) with a gap of 25 years.

### Georeferencing

The quality of the georeferencing is essential to this paper. We proposed here to gather all data of the georeferencing to conduct a quality assessment but also to evaluate the urban and harbour changes across time. We tested the hypothesis that the creation and the disappearance of *reference or matching points* in built areas is controlled by urban renewals and important harbour transformations. In this way, the life span of the matching points is considered a proxy of the urban and harbour changes.

In total, 81 *reference points* have been selected to georeference the 42 maps and the aerial photography of 1946. More than half of the reference points were located on a 2020 imagery from ESRI (46 points). Easily identifiable and relatively stable reference points have been selected (see Supplementary material - Matching points). They are mainly located on harbour structures, buildings, and cross-roads. Most of the reference points were placed around the harbour structures (18 points - blue) and the Lower City of Tarragona (37 points). For larger extent maps, 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 less are placed on the Upper City and coastal areas outside Tarragona (228).

Only two points can be tracked from 2020 to the 18th c. due to urban and countryside changes, or to harbour developments. Relay documents have been selected to create reference points in the past. Reference documents include aerial photographs from a mosaic dated to 1946 (18 points – Affine average residual = 5.4 m / Similarity polynomial average residual = 6.1 m), olds map from 1883 (5 points - Affine residual = 8.2 m / Similarity residual = 7.6 m), 1882 (2 points - Affine residual = 5.9 m / Similarity residual = 6.3 m), 1824 (2 points - Affine residual = 5.8 m / Similarity residual = 7.4 m), 1803 (7 points - Affine residual = 14.8 m / Similarity residual = 17.5 m) and 1790 (1 points - Affine residual = 8 m / Similarity residual = 11.8 m). Average residuals for the georeferencing of each map are used to calculate the diffusion of uncertainty from point to point and map to map back in time. We simply added average residual of the aerial photographs or maps taken in reference to the residual of the new georeferenced points (Supplementary material – Georeferenced data). These reference documents were selected considering the quality of their georeferencing based on the 2020 reference points. On old maps, periods of urban and harbour transitions revealed to be the best for having both current and old reference points.

Different transformations have been applied to the georeferenced maps. We observed that the similarity polynomial transformation proposed in ArcGIS provide better results for older maps, while the affine transformation (1st order polynomial) is better for recent maps. The change was identified in the 1820’s. The residual expressed in metres in Figure 2 (Georeferencing) seems to contradict this observation and show much higher uncertainties using similarity polynomial also in ancient maps. However, in correspondence with few topographical markers from ancient topography (15th c. mole) and archaeological discoveries (late 18th c. ship found against the ancient 15th mole), the transformation of the maps with similarity polynomial is clearly better (Supplmentary material). This is probably because, for older periods, we have less reference points to georeference the maps, e.g., the georeferencing of old harbour maps provides only reference points in the Lower City and not on the mole. Finally, the right angles and distances were well drawn by ancient cartographers according to the similarity polynomial transformation logics.

### Digitalisation

Our dataset presents a good resolution 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. Figure 2 (“Digitalising”) presents all information related to the digitalisation of our maps. The old harbour, later called Internal Harbour or Darsena Interior is the area that can be tracked in time trough almost all 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 maps of 1911 and 1917 that only show bathymetries at the entrance of the harbour where dredging was conducted.

Between 1790 and 1917, the bathymetric data are reported directly on the old map with numbers. Each number was digitalised into a bathymetric point in a shapefile. Initially (1790-1852), all depths are expressed in *Pies de Burgos*. In the attribute table, all depths were expressed in metres considering the following relation: 1 Pie de Burgos = 0,278635 metre. Later, all bathymetric indications are in metres.

From 1931, the bathymetry is already processed and manually interpolated into lines. We did not have access to the initial depth measurements. The bathymetry is provided with 1 m isolines. Bathymetric maps are provided 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.

From 1974 to 2000, the annual reports of the harbour of Tarragona (*Memória annual del Puerto de Tarragona*) provide simplified maps of the bathymetry and insists on the averaged and theoretical depth for each part of the harbour. From 1974 to 1977 the precision is 1 m, and later 5 m. Since 2001, the annual report of the harbour of Tarragona does not provide maps of the bathymetry except in 2010. More detailed maps are available for recent periods but are no more part of 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. Comparing to the set of maps dated from the 1970’s 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.

### Interpolation

Pierre-Alexis

* Interpolation: Methodes et objectifs
* Erreur d’interpolation >> Fig 2

### Annual reports of the port of Tarragona

To improve our understanding of the morphological data extracted from old maps, we used complementary historical texts. Additional data related to dredging of the port since the end of the 18th c. were collected in the archives of the port of Tarragona. The digitalisation of most part of the archives of the port from the 18th to the beginning of the 19th c. was of great help. These scans, including maps, projects, and reports, are available online at <https://www.porttarragona.cat/en/digital-archive>. From 1870 onward, more statistical data are available on the price of dredging and on the volume of extracted sediments.

## Results

### Quality assessment of the georeferencing

Figure 3 presents the results of the georeferencing considering the reference points. The size of the circles corresponds to the number documents georeferenced using the one or the other reference point. The residuals expressed in metres are either related to the affine or similarity polynomial according to the choice made initially (see above). Georeferenced points best matching the reference points (lower residual) are located around the harbour and in the Lower City. This is mainly because the density of points is higher in this area which makes the georeferencing better constrained. The average residual of the georeferencing of all documents is 14.13 metres and the median is 10.19 m. The median (med.) and average (avg.) residuals are the highest for the reference points from around the bay of Tarragona (med. = 29.38 m; avg = 34.88 m). The different areas of the Lower City (med. = 10.37 m; avg = 17.15 m), the Upper City (med. = 12.48 m; avg = 13.50 m), and the harbour (med. = 12.31 m; avg = 14.31 m) have roughly similar median and average residuals between 10 and 17 m. The reference points located on 19th c. maps have higher residuals (avg. 1790 = 16.1 m; avg. 1803 = 25.70 m; avg. 1824 = 26.50 m; avg. 1882-1883 = 35.62 m) comparing to the points located on the 1946 aerial map (avg. 1946 = 22.16 m) but especially on the 2020 satellite imagery (avg. 2020 = 14.04 m). This is due to the quality of the maps and to the residual added when reference points are located on documents other than the 2020 satellite image taken as a reference. Importantly, we observe that the reference points most used have lower residuals. Only 5 reference points have a residual over 40 m, and they are used to georeference less than 11 documents. In contrast, the reference points used to georeference more than 15 documents have residuals below 20 metres. The residuals drop to less than 10 m for referenced points used to georeference more than 25 maps.

Figure 4 presents an overview of the results of the georeferencing considering each map or aerial photograph. 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 are 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 correspond to harbour or urban renewals. We identified four periods separated by 3 periods of urban/harbour transitions (c. 1800; c. 1880’s.; c. 1960/70’s).

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

Regarding the planimetric evolution of the harbour. We first digitalised the harbour limits in 2020 and we changed gradually its initial shape by getting back in time. This explains why structures from different dates are perfectly matching while the georeferencing is worst back in time. This iterative method was considering the georeferencing results. We georeferenced the main structures on maps with better georeferencing. The results of the digitalisation of the harbour are reported in Figure 5.

### Planimetric evolution of the harbour and the river mouth of the Francolí

Figures 5 and 6 show the planimetric evolution of the harbour between 1748 and 2020. It demonstrates that the bigger the harbour grew, the more stabilised are the land-sea interfaces. However, the river mouth area demonstrates the difficulty to stabilise riverbanks at the mouth of the Francolí river seasonally and interannually.

All along its history, the harbour of Tarragona had to face to main hazards from two sides: (1) waves from the north-east and (2) the sedimentation from the Francolí river from the south-west. Dealing with these two constrains, the harbour first had to develop larger protected basins (last two centuries) and then to develop larger space to unload and store goods (especially during the last decennia).

Between 1790 and 1852, the harbour basin grows 10 times bigger, from ca. 11 ha to ca. 107 ha due to the removal of the ancient Roman mole in 1843, and to the construction of the *Dique de Levante*. This mole was built in the last years of the 1790’s / beginning of the 1800’s, extending the existing 15th c. mole. The new mole reached ca. 1000 m long, while it was initially 200 m. An extra 650 m is added in the next decennia. In contrast, the river mouth of the Francolí is not constrained by any infrastructures 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 straight (1790, 1824). The deflected morphology of the river mouth is stabilised by the mid-19th c. CE. In 1852, the map shows a curved structure on the left bank of the river mouth. The right bank remains untouched by engineering infrastructures.

The harbour basin grows slowly from the 1830’s to the 1880’s (118 ha in 1882) but doubles its size by 1900 especially the Outer harbour (ca. 210 ha in 1905). The growth at the end of the 19th c. 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 c., a long-curved mole to the west in front of the river mouth is planned but never achieved. Instead, successive extensions of the lower reach of the Francolí river channel are constructed:. The right riverbank is the northern coastline of the Francolí river outlet towards the south-west, and the left riverbank was a built structure parallel to the coast (*Dique de Oeste)*. This longshore structure reaches 1500 m in 1915.

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

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

Major changes affect the harbour in the 1970’s. Two jetties are built in the bay of Tarragona south of the Outer harbour of Tarragona (*Pantalá Repsol / de Petroli cru* and *Pantalá Asesa / Betum Asfáltic*). In 1974, the inclusion of both jetties into the harbour waters made the harbour reach ca. 1000 ha. This was an increase of 5 times the size in a few years. The maximum size of the harbour waters reaches 1025 ha in 1977. During the last 50 years, this new harbour waters between the historic harbour and the *Pantalá Repsol* was built with new quays and platforms. The historical Inner harbour area became a basinamongst others (*Dársena interior*). The harbour now counted 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 became quickly in the 19th c. a well-protected harbour using engineering solutions. However, the fluvial sediment inputs from the Francolí river are still challenging the harbour maintenance.

### Bathymetric evolution of the harbour and the river mouth of the Francolí

Bathymetric data are an essential parameter contributing to reconstruct the evolution of a hybrid urban delta through time. Figures 1, 6, 7 and 8 allow us to reconstruct the spatial evolution of the bathymetry in the harbour. Figures 9 and 10 replace the evolution of the bathymetry in chronological relation to other factors. Finally, Figure 11 shows the evolution of the bathymetry using a cross-section.

At the end of the 18th c., the harbour protected by the 15th c. mole is a sandy beach area with a flat slope (-3.5 m at 250 m from the coastline, 1:70 or 1.4% slope) (Figure 6). In addition, the remains of the Roman harbour of Tarragona reduce the modern harbour extent. The construction of the long mole at the end of the 1790’s / beginning of the 1800’s (*Dique de Levante*) possibly increased the sedimentation inside the new sheltered area. We observe sedimentation inside the harbour, as sediments accumulate behind the new mole. The Roman mole is covered by sediments by 1813 (see paper 1). Sediment texture near the coastline is characterised by finer deposits (1813). 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 (see paper 1). 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 drift following a north to south direction.

The 1880’s mark a major turn in the history of the harbour (see paper 1). 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 since 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 is shallow with less than 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. From 1876 onwards, the harbour is dredged down to 6-7 m depth at the entrance of the harbour along the inner part of the *Dique de Levante* (Figure 6). 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. 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 were producing 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. The coarse material was considered as the substratum. It slowed down the dredging of the new harbour. Additionally, during the 1880’s, this limit defined by transatlantic trade is redefined. In 1886-1887, the Port of Tarragona wants to welcome steam-powered vessels (“*grandes vapores transatlánticos”)* from the *Compañía Transatlántica*, which means they had to excavate again from offshore to the entrance towards the *Muelle di Costa* down to -9 m instead of -8 m (Memoria, 1886-1887; p12).

At the end of the 19th c., the harbour features an area at -9 metres along the *Dique de Levante*, an area at -7 / -8 m along the *Muelle de Costa*. A gentle slope leads to the coastline of the district of San Pedro near the ancient outlet of the Francolí.

During the first part of the 20th c., main project of dredging affected the entrance area to maintain the depth at -9 m (maps of 1911, 1917). Sedimentation coming from the river was accumulating in the underwater river mouth lobe, against the *Dique transversal* and the *Dique de 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 looks more like a marine channel leading to the Inner harbour and a new basin is created between the *Contradique* and the *Dique transversal (Darsena del Varadero)*. In parallel, the *Dique transversal* is transformed into a quay called *Muelle transversal*. This marine channel entrance is dredged to -10 m as well as the southern part of the Inner harbour. By 1970, the area between -10 and -11 m was expanded and concerned half of the Inner harbour. The other part was kept between -9 and -10 m, while along the *Muelle de Costa* the depth is 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 in expansion. Built in the 1970’s, in line with the prevailing wind direction, the *Pantalán Repsol* is reaching the isoline of the -18 m at its end. Today, the *Pantalán Repsol* has several berths at 8.20 m, 11.25 m and 14.75 m for gas carriers, and an offshore deep-water buoy for oil tankers. The Outer harbour channel was initiated at the end of the 19th c. and progressed quickly in the last 50 years with several extensions of the main breakwater until 2006, and the latest addition of a cruise terminal in 2021. The harbour channel is between -24 m at the entrance of the harbour and -14 m towards the Inner darsena. It leads to a darsena with quays at -12 m for car carriers (*Muelle de Galicia*) and -15.50 m for large container ships (*Muelle d’Andalusia*). The river mouth of the Francolí in the harbour provides several quays for chemical ships down to -15.10 m (*Muelle de la Quimica and Darsena del Molino*).In front of that, and on the main breakwater, a coal terminal is found with a quay at -18.50 m (*Muelle de Catalunia*). Closer to the Inner darsena, the channel is at -14 m 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 and the waters of the Inner darsena mostly between 9 and 11 m like in 1971.

Sedimentation from the Francolí river has still to 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 in front of the river mouth to create a large sediment sink of more than a million of cubic meters which should be able to absorb several years of sediment input from the river (Figure 1).

## Discussion

## Main periods of evolution of the Francolí delta, the harbour and the city of Tarragona since the 18th century

From *Punta del Miracle* to the Cape of Salou, there are approximately 12 km among which 5 km is now occupied by the harbour of Tarragona, covering the 2.5 km long coastline of the Francolí delta. Since the 18th c., we identified four main periods of evolution leading to this configuration considering the interactions between the river delta dynamics and the harbour infrastructures transformations:

***Period 1***: until 1800 – ***Sedimentation/erosion cycles with low harbour infrastructures and management*** *(see paper 1)*. Before the 19th c., harbour structures only affected the margin of the delta. A short mole was built in the 15th c. in continuity of the cape of Tarragona and after some reparations, it was still the only construction to protect a small harbour to the west at the end of the 18th c. In this past configuration, floods of the Francolí periodically brought sediment to the coast and the sandy material was redistributed along the shore by the longshore drift. The harbour structures contributed to momentarily trap sand along the coast, before storms would erode the shore and remove sediment from the harbour. These cyclic fluvio-coastal dynamics are involved in long-term deltaic trends. Natural thresholds and/or anthropic impacts along the coast contributed to trap sediment for longer periods of time and generated deltaic progradation. It resulted into a sedimentation "in stages" recorded in the chrono-stratigraphies of the Tarragona margin of the delta.

The Upper City and the Lower City followed different historical paths. The Upper City was more resilient towards socio-economic changes across history. It was the refuge during more unstable periods. Even today, urbanism and architecture is strongly marked by a continuity since the Roman period. The Lower City developing towards the south and the deltaic area is more connected to the socio-economic and political factors. It can be affected by strong and fast developments (e.g., the Roman period and the last two centuries), or being neglected (e.g., 8th-11th c. CE).

***Period 2***: 1800 to 1880 – ***Progressive*** ***expansion of the harbour infrastructures in the delta front***. From the end of the 18th c. 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 north-east. Consequently, they built first a long mole (breakwater) called *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 drowned in the harbour (Capitania del puerto de Tarragona, 1822). This 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 c., the harbour authorities also started dealing with the sedimentary inputs coming from Francolí. Engineers built a wall to stabilise the left side of the mouth of the Francolí and leading it to the west. The role of this structure was to keep sediment away from the harbour. Then, it connected to the *Dique transversal* contributing also partly to this task. 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). Period 2 is characterised by these important constructions, but with limited dredging activities. 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 for some years before Period 3.

This period was opportune for the socio-economic growth of Tarragona. The urban junction between 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 3***: 1880 to 1970 – ***Towards disconnected harbour and deltaic dynamics***. During Period 3, harbour infrastructures were constructed in continuity of those conducted in Period 2, but major changes 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*). A long marine channel was dredged from the Outer harbour towards the Inner harbour and periodic dredging was conducted to prevent the underwater lobe of the Francolí to extend towards the Inner harbour. The depth of the Inner harbour was kept around -8 m to -10 m during this period. Finally, during Period 3, the coastline in the Inner harbour was progressively built with quays (*Muelle de Costa* and then *Muelle de Pescadores*). 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. Two sets of constructions contributed to reduce these constrains. First, the *Dique de Levante* continued to be extended during this period. Second, the wall on the left side of the Francoli river mouth was extended along the coast during the late 19 c. / early 20th c. (*Dique de Oeste* and *Dique submarino*) and the original river mouth was moved to the west in the 1940’s. Large and periodic dredging characterised this period. In the 1880's, the port authorities wanted to accommodate ships from the *Compañía Transatlántica* and adjusted the water depth (REF). Subsequently, gradual deepening of the marine channel was conducted, extending it further out to sea and down to -14m.

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 instable, affected by the First World War and the Spanish Civil War. Important harbour transformations happened again during the 1940’s 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 Francoli. Urbanisation started to grow quickly from the late 1950’s onwards.

***Period 4***: 1970 to today – ***Quick expansion of the harbour and full integration of the Francolí delta in the harbour***. During the last decennia, harbour infrastructures extended across the whole bay of Tarragona. In the 1970’s, long jetties were built in the middle of the bay towards the south-west of the harbour. These infrastructures were related to the establishment of oil refineries and propelled the port of Tarragona towards a higher national and international rank. Consequently, between 1970 and 1974, the relative surface of the harbour basins increased quickly. This newly created harbour area was then protected behind the extended *Dique de Levante* and *Dique Rompeolas* for the last 50 years. The 1970’s and the 1990’s were periods of important constructions within the harbour. The size of the basins reduced from 1025 ha in 1977 to 737 ha today due to newly built port terminals. In the mid-1990’s, the construction of the Car Terminal (*Terminal de Vehiculos*), now the Container Terminal (*Terminal de Contenedores*), had for consequence to integrate the river mouth of the Francolí river within the harbour. This new configuration was an important turn in the history of the interactions between the Francolí delta and the harbour. While before that, sediments were routed away to the south-west, now the present harbour is designed to trap river sediments inside the harbour. The bottom of the harbour is over-deepened near the river mouth and sediment deposited there is dredged when needed.

Major changes in the harbour are observed since 1970’s, but socio-economic changes already affected Tarragona and its region since the late 1950’s including new industrial parks and faster population growth. According to Alvarez-Palau et al. (2019), 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 40-30 years.

## Intertwined chronologies of the Francolí-Tarragona hybrid urban delta since the 18th century

The periodisation just proposed above clarifies the main phase of evolution 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 their relevance on their own. Research objects such as harbours, ports, cities, or deltas are complex entities with tangled phenomena. The chronological analysis proposed is a decomposition of parameters involved into single chronologies. In the following parts, we develop four historical narratives associated to the evolution of the harbour of Tarragona and the Francolí delta since the 18th c. Figure 11 offers a synthetic view of the evolution of Francolí-Tarragona hybrid urban delta. This cross-section is perpendicular to the ancient coastal dynamics and in the alignment of the harbour evolution during the last two centuries.

### Evolution of the cartography – precision - harbour maps (???)

Modern ports and harbours have all rich datasets of maps with bathymetric and textural information about their bottom. Most importantly, updates about the bathymetry and the bottom texture are regularly conducted and mapped to better reconstruct evolutions through time. Nevertheless, a good georeferencing of these maps is essential following precise protocols. We developed in this paper new ways to conduct quality assessments in providing synoptic graphs. In addition, these graphs are not only giving information about the quality of the georeferencing but also tell us the precision of the maps, the evolution of the city and the harbour. Dynamic urban areas have not many matching points remaining though time. Main period of urban or harbour changes are also period of important reference points creation and destruction. In this way, reference points are a proxy of the urban and harbour changes.

### From the local to the international port

Since the end of the 18th century, the port-city of Tarragona operated major transformations from a small and open cove to an international harbour. Many elements explain the morphological evolutions 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 these aspects can be found in the different studies conducted mainly by historians and geographers locally (Magriñá, 1901; Jordà Fernàndez, 1988; 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.

The 18th c. and the beginning of the 19th c. is characterised by a local competition between Tarragona and the Reus-Salou port system. The initiation of the construction of the *Dique de Levante* in the 1790’s and early years of the 19th c. was essential to comfort Tarragona in its new role of regional port. 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 Archidiocese of Tarragona was giving to the city the status of Religious capital of Catalonia (Serrano Sánchez, 2018).

The 19th c. is characterised by the rise of the first globalisation wave initiated in the 1820’s but fully developed in the period 1870-1914 (Baldwin and Martin, 1999). Regarding transportation, this first economic globalisation is marked by the expansion of railways transport and steam shipping. In the second part of the 19th c., the average size of the vessels of steamships increased and larger and deeper harbours were necessary to accommodate them (Figure 5, Period 3). In parallel, new standards for loading and unloading ships arose. Tarragona followed this trend from the 1870’s and especially in the 1880’s with large dredging activities and new dock-building. These works were facilitated by the new Spanish Port Law dated of 1880 giving more autonomy to the Port Works Committees (*Juntas de Obras*) (Castillo and Valdaliso, 2017).

The second globalisation wave starts in 1960 and still continue today (Baldwin and Martin, 1999). However, some authors suggest it started right after the Second World War in 1945 (REF). Regarding harbours, this second wave is characterised by a growth of the maritime trade (e.g., more ships), and by containerisation spreading since the 1970’s. The number, the sizes, and the draughts of the ships grew quickly since then (REF – Figure 11). Container ships and oil tankers with draughts up to 15-20 m were built from the 1970's onwards such as the *Seawise giant*, still the oil tanker with the deepest loaded draught built in 1975 (24.6 m – Figure 11 – *transportgeography.org*). Like during the first globalisation wave, harbours had to adapt their morphology to host more ships 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 1970’s 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 1970’s. Geographically, Tarragona benefited from the new container corridors towards the Mediterranean part of Spain, while Atlantic ports that were stronger in the 19th c., declined (Castillo and Valdaliso, 2017).

### The rise of the modern port and the disappearance of the Roman harbour

In parallel to the development of the Modern harbour during the last 200 years, the remains of the Roman harbour 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 1880’s. A part of the mole was preserved on shore behind the *Muelle de Costa* built between 1885 and 1888. In front of the *Muelle de Costa*, the harbour basin was dredged and sedimentary archives dating back to the Roman period were removed. Figure 11 synthesises the development of the harbour of Tarragona towards the south-west, associated to 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 1880’s 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 case of Tarragona is particularly instructive regarding heritage preservation. 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 modern port. To generate more data, it would be necessary to encourage authorities and companies to systematically involve geoarchaeologists with their geotechnical teams. 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 in 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.

### Increased connectivity of the port city of Tarragona and segmentation of the environments of the Francolí delta

The development of the port-city of Tarragona is expressed morphologically by a gradual extension of the harbour. The port had first to develop and then to adapt to remain competitive. Through time, the harbour needed larger protected basins, deeper basins and accesses, longer docks adapted to changing ships and changing logistics related to the loading and unloading of ships, larger areas to handle goods, and improved interoperability system between different modes of transportation (ships/trains/trucks). The new intermodal infrastructures 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).

Consequently, the development of the connectivity of the port led to the segmentation 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 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 1820’s – early 1830’s onwards to avoid sediment deposition inside the harbour basins. However, this strategy changed in the 1990’s, 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 mainly contributing to redistribute sediment along the coast or to the offshore (Period 1), were not active anymore. In place of that, periodic dredging was necessary to prevent formation of a delta within the harbour. The harbour thus creates a break in the land-ocean continuum becoming the main sink of the fluvial sediments coming from the Francolí River and redistribution along the coastline must now be taken over by humans. Consequently, beach nourishments must be conducted at the Playa del Miracle to the north and Playa de la Pineda to the south (Canovas et al., 2011). In addition, a 600 m groyne was built in the 1980’s to stop sediment movement from La Pineda beach into the harbour (*Espigo dels Prats*).

The present harbour layout led to intensified dredging in the basins and at the river mouth, and artificial nourishment of the local beaches compensates the reduction of sediment input originally supplied by the river. As a result, sediment movements in the Francolí delta are now totally managed by humans.

## Hybrid urban deltas through time

In this last section, we conceptualise the study of a hybrid urban delta in a long-term perspective based on the example of the Francolí-Tarragona system. We also propose to reconsider morphological typologies of deltas in including direct anthropic impacts.

### Temporal trajectories of a hybrid urban delta

The first paper exposes a *spatial-based approach* of a hybrid urban delta considering interactive human-nature processes shaping combined morphologies, leading to a hybrid land- and seascape. In this second paper, we propose to clarify the *time-based approach* used to study hybrid urban deltas in a long-term perspective (Figure 12). This approach was implemented in the two papers to produce a 3000-year temporal trajectory of the Francolí-Tarragona system.

Traditionally, evolutions of river deltas or port-cities are visualised through series of maps at different periods. Palaeogeographical (REF) or geohistorical (REF) 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 (REF) or diachronic models (Bird, 1963) show changes of port-cities morphologies at different periods or dates.

Comparative analyses through time and space are generally difficult to carry quantitatively in using only 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) are often missing on the cartographic representations. Instead of considering only spatial representations, we suggest also seeking timelines and time series to reconstruct the evolution of hybrid urban deltas. Synchronisation of different time datasets is essential to understand all aspects of hybrid environments. The spatial-based approach remains essential to characterise single morphologies or processes drivers for later tracking them in time. Regarding the case study, each morphological change, and processes involved are visualised in a common chronological framework (Figures 9 and 10). 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, geographic studies about the anthropic contexts. All chronologies are potentially of interest, but their selection can be challenging. Different spatial scale can be considered depending on their relevance for the object studied: paleoclimatic, historical and archaeological data for a stratigraphy; technical advance timeline, socio-economic data for a harbour structure.

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 c., the evolution of the precision of the maps through their georeferencing, the overlap of the maps, and the quality of the interpolation (Figure 2). The construction of the spatio-temporal dataset is as important as the results in term of coastline mobility or erosion/sedimentation evolutions. It is shown that they are all proxies of the hybrid urban delta evolution. Figures 11 and 12 in the first paper and Figure 9 and 10 in this second paper provide different 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, 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).

### Hybrid urban delta or hybrid urban estuary? Towards a new morphological typology of deltas integrating human impacts

The port city of Tarragona now impacts strongly 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 Solé et al., 2007). Knowledge about the agricultural impacts in the deltaic plain of the Francolí specifically 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.

While the coastline is very important to reconstruct coastal evolutions in the long-term, its location also depends on submerged coastal morphologies generally not clearly visible. Different landscapes of the Francolí-Tarragona hybrid urban delta during the last centuries are presented in Figure 13. This paper contribute 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). It can be observed by both chrono-stratigraphies and old bathymetric maps.

The study of the seascape leads directly to the study of the coastline and its dynamics controlled by both natural dynamics and anthropic factors (e.g., mole, jetty, quay construction). Coastal geo- and archaeo-morphologies contribute themselves to influence the 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. In the deltaic plain, not developed in this study, it 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.

In the last decennia, the hybrid urban delta of the Francolí completely reshaped the coastal morphology south of Tarragona. The bay of Tarragona is progressively overbuilt with harbour infrastructures while the delta front of the Francolí is totally included into the harbour since the mid-1990’s. The currents inside the harbour are characteristic of an estuarine environment with two layers with different densities (Martínez Velasco, 2012). Initially, the morphology of the delta of the Francoli would have been categorised such as a delta dominated by the waves (Wright and Coleman, 1973; Nienhuis et al., 2020). However, its morphology is now totally dominated by human infrastructures. 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 typology, the Francolí-Tarragona urban delta would be a small system dominated by harbour infrastructures shaping an anthropic bay-head delta or even a human-made estuary.

## Conclusion

This work conducted on a case study contributes to a better understanding of the natural and anthropic processes involved in the evolution of a land- and seascape composed by deltaic, urban and harbour areas. The two papers attempt to build a bridge between human geography and physical geography, but also between different interdisciplinary academic communities (archaeology-geomorphology and history-geography-geomorphology-engineering) and to promote geoarchaeological and geohistorical approach to reconstruct long-term evolution of urban deltas. In this conclusion, we insist on the following elements to conduct the study of hybrid urban deltas in the long-term:

* Clarifying the different geo- and archaeo-morphological units at stake, their different spatial expressions and their possible drivers;
* Clarifying both human and natural processes at stake 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);
* Man-made morphologies are always combined with natural morphologies through time creating hybrid landscapes;
* Quantifying land- and seascape changes through time is essential to have a broader view of changes through time.

The data produced about the Francolí-Tarragona system were replaced in the evolution of the port city and the global economy. It demonstrates that the case study followed the main trends of the Spanish and world maritime economy. For Tarragona, the decennia 1800-1810, 1870-1890, 1960-2000 have been essential to adjust the harbour infrastructures to the international standards. In parallel, these dates correspond also 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 decennia and still are. The authors are here also convinced that the development of interdisciplinary timelines and any representation of processes including time is the new challenge to reach more understanding of the complexity of our world and how it formed. These knowledges are essential to characterise transitions in the past and to reflect on future transitions towards more sustainable types of management.

## Acknowledgements

We would like to thank the Port of Tarragona, the ERC-Project “PortusLimen” (FP7/2007-2013/ERC grant agreement n° 339123) and the Pilot Project “Deltime”.

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