Geomorphology

Challenging reconstruction of the plurisecular morphodynamics of hybrid urban deltas: a trajectory leading to the end of a delta in the Western Mediterranean area?

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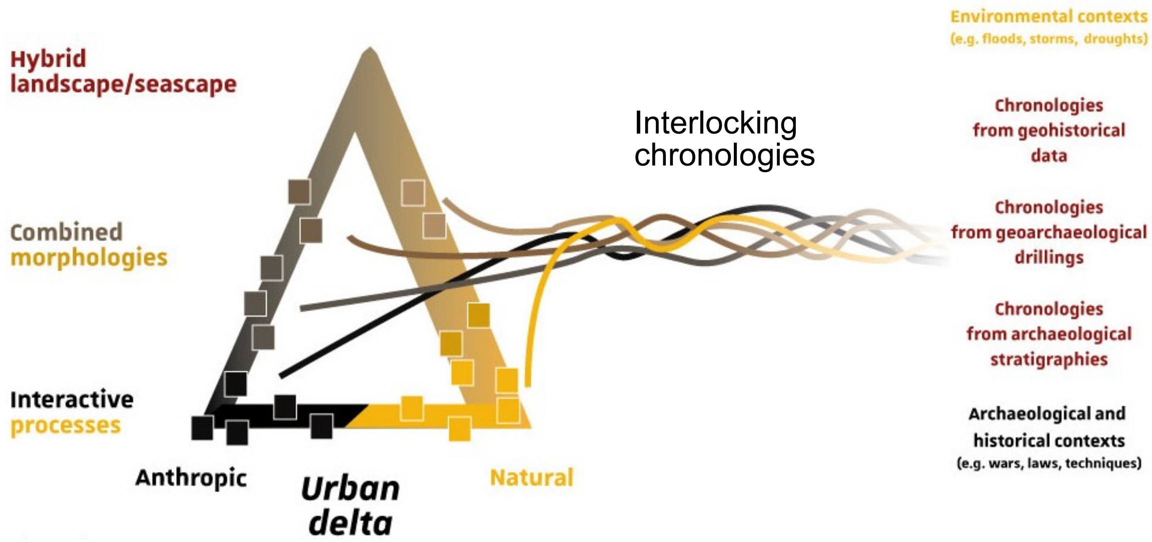
Highlights

- Development of tools to reconstruct the evolution of hybrid urban deltas in the last centuries;
- Identification of the transitions between a human-dominated delta and an anthropic estuary;
- ~~Reversely, this study suggests the steps to follow to restore the natural Francolí delta~~.



The above image is a crop from Figure 12, with 'interlocking chronologies' text from that figure added.

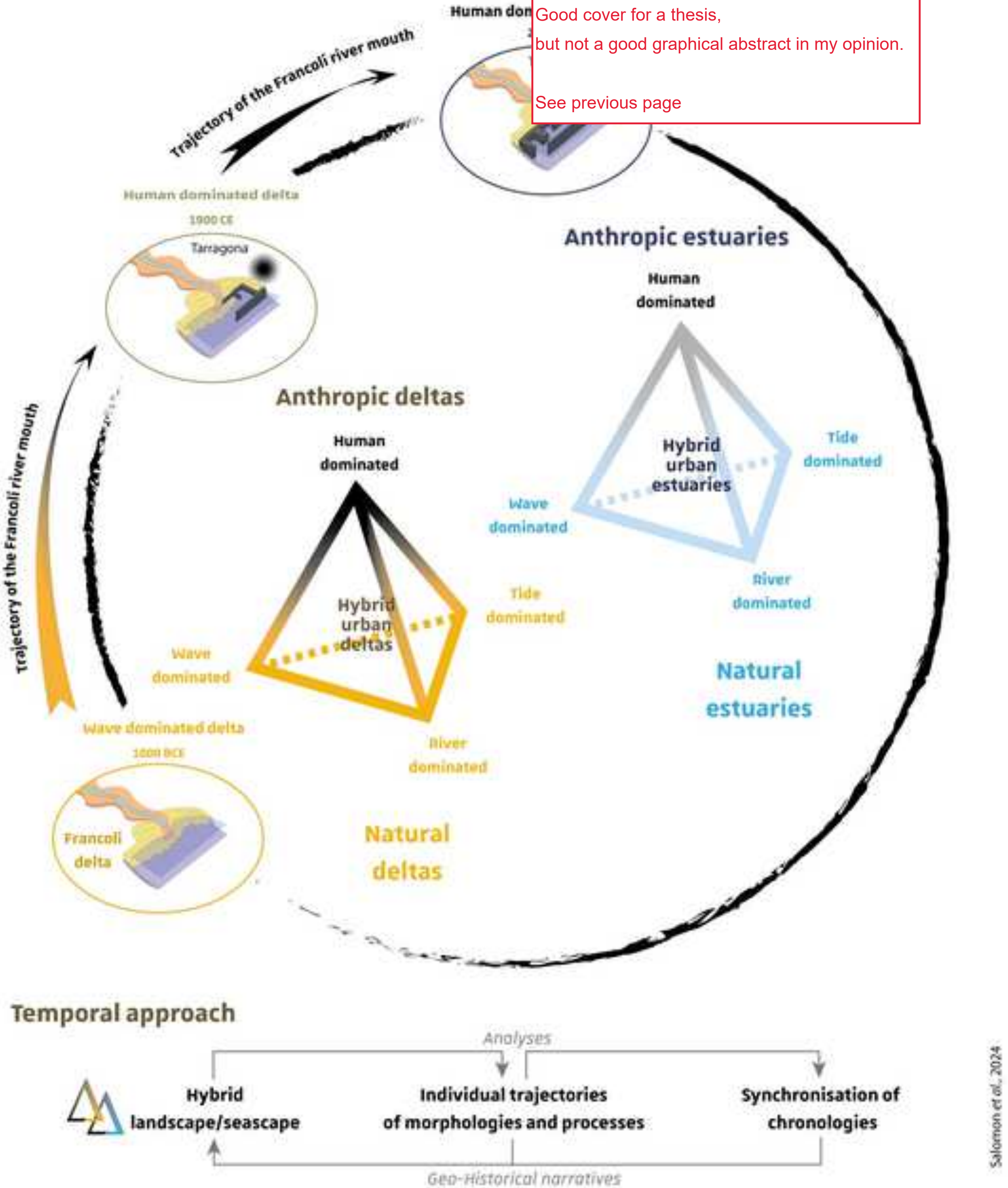
I think it is a better graphical abstract for this paper than what the authors propose

Graphical Abstract

This graphic abstract is an extra figure not in main text.

Good cover for a thesis,
but not a good graphical abstract in my opinion.

See previous page



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Challenging reconstruction of the plurisecular morphodynamics of hybrid urban deltas: a trajectory leading to the end of a delta in the Western Mediterranean area?

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1. 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). 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). The world population has grown 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, 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, coasts have been affected by intensification of land use, 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. The reconstruction of the temporal trajectories of port cities and their environment could help to better assist the transition towards more sustained developments in such context.

This study aims to bring a different perspective and a more standardised methodological framework to the subject of reconstructing long term evolution of harbour infrastructure in relation to fluvio-coastal environments. 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 map records) in order to reconstruct long term trajectories. It also defends a more systematic approach that would contribute to increased interdisciplinarity between natural and social sciences, specifically regarding ports and river deltas. A first paper was recently published regarding plurimillennial evolution of hybrid urban deltas (Salomon et al., 2024), this paper focuses on the last centuries.

During the last centuries, each port city has been adjusting 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, led inevitably to trends in the way ports were shaped over time. 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. 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.

Tarragona also offers an interesting case study for human-nature interactions between the port city and the Francolí river delta (Figure 1). The first paper published about Tarragona demonstrates that its physical location has never been ideal regarding its harbour potential (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, but we do not know how long the Roman port remained efficient. Sedimentary cores drilled in the ancient harbour showed that it has always been prone to sedimentation from the floods of the Francolí and to erosion from storms. The location was not any better two centuries ago in terms of harbour potential. However, modern engineers reiterated the plan and location of the Roman harbour and had to deal with the same problems. 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 repercussion for the environment.

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 (Andrade et al., 2021; Amore et al., 2002), but more often developments in the last two 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 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. Examining in detail bathymetric evolution and harbour infrastructure of the port of Tarragona since 1790, this paper seeks to demonstrates 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).

Figure 1.

2. Geographical and historical context

Global, regional and local contexts are essential to the new data produced in this paper (harbour infrastructure and bathymetry). Main characteristics of the Francolí delta, its watershed and the marine conditions are presented in paper 1. 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.

2.1. Geographical context

For the last two centuries, better flood series and records have been available than for previous periods (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 1 600m^3/s at Tarragona. During this event, 415mm of precipitation were recorded in 24 hours upstream at the station of Alforja (Agencia 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, 30km 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.

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 time in which pollutants are located in the harbour, with studies demonstrating 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 (Ahedo, 2010), and although wind plays a secondary role for water circulation (Mestres et al., 2007), it is important for air pollution.

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

In the 18th century, Tarragona was ~~essentially~~ an ecclesiastical 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 century did not provide adequate shelter for merchant ships. The town represented a secondary economic centre, characterised by low population growth compared to other Catalan cities (Aresté Bargès, 1982). Locally, Reus was the most populated city for concentrating 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 an important port city ~~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 to provide space for this development and in 1868-1870 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, becaming 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 Ricomá'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 of 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.

~~Over the last three centuries, the port of Tarragona was affected by major changes. Initially a small port town, it is now an important port city. This paper will contribute to a better understanding of its evolution in the modern period.~~

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 (Figure 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 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) (Figure 2 - Dataset).

The bathymetric dataset covers more than 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.

3.2. Georeferencing

The quality of the georeferencing is essential to this research since it ensures consistent matching between maps over time (Figures 2, 3 and 4). We proposed here to gather all data for the georeferencing stages 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 mainly controlled by urban renewals and important harbour transformations. In this 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 ~~older documents. These documents include~~ aerial photographs dated to 1946 and old maps dated to 1883, 1882, 1824, 1803 and 1790 (Figure 4). ~~These documents were chosen before or during major change in the city or the harbour~~. 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 (Figure 3). 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 Figure 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

Figure 3 presents the results of the georeferencing including the reference points. The map is zoomed in the city and the inner part of the current harbour where most of the reference points are located. More precisely, the georeferenced maps include all the harbour area and sometimes include the Upper City or the bay of Tarragona. The reference control points are mainly located around the harbour and in the Lower City, the focus of our study. The size of the circles corresponds to the number of documents georeferenced using one or the other reference control 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 because the density of points is higher in this area which makes the georeferencing more constrained. The average residual of the georeferencing of all documents is 14.13 metres and the median is 10.19m. The median (med.) and average (avg.) residuals are the highest for the reference points from around the bay of Tarragona (med. = 29.38m; avg = 34.88m). The different areas of the Lower City (med. = 10.37m; avg = 17.15m), the Upper City (med. = 12.48m; avg = 13.50m), and the harbour (med. = 12.31m; avg = 14.31m) have roughly similar median and average residuals between 10 and 17m. The reference points located on 19th century maps have higher residuals (avg. 1790 = 16.1m; avg. 1803 = 25.70m; avg. 1824 = 26.50m; avg. 1882-1883 = 35.62m) comparing to the points located on the 1946 aerial map (avg. 1946 = 22.16m) but especially on the 2020 satellite imagery (avg. 2020 = 14.04m). This is due to the quality of the maps and to the residual added when reference points are located on documents with sources 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 40m, and they are used to georeference less than 11 documents. By contrast, the reference points used to georeference more than 15 documents have residuals below 20 metres. The residuals drop to less than 10m 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. 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 correspond 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 24m (maps dated to 1891 and 1911) and 86m (map dated to 1876). The average mean distance in all these maps is 48m. 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.

Regarding 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 results of the digitisation of the harbour are shown in Figure 5.

3.4. Digitisation

Our dataset presents 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. Figure 2 (Digitisation) presents all information related to the digitisation of our maps. The old harbour, later called the 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 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 = 0,278635 metre. 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 1m 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.

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 1m, and from 1978 it is 5m. 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 1m isolines that complete our dataset to the present day. Comparing 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 bathymeric measurements with a thin-plate spline (TPS) technique at a 10m 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 splitted 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.

3.6. Annual reports for 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 harbour since the end of the 18th century were collected in the archives of the port of Tarragona. The digitisation of most part of the archives of the port from the 18th to the beginning of the 19th century was of great help. These scans, including maps, projects, and reports, are available online at https://www.porttarragona.cat/en/digital-archive.

4. Results

4.1. 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 more the harbour grew, the more stabilised became the land-sea interfaces. However, the river mouth area demonstrates the difficulty of stabilising riverbanks at the mouth of the Francolí river seasonally and interannually.

Throughout its history, the harbour of Tarragona had to face hazards from two sides: (1) waves from the north-east and (2) sedimentation from the Francolí river from the south-west. Dealing with these two constrains, 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).

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 1790s / beginning of the 1800s, extending the existing 15th century mole. The new mole reached ca. 1000m long, while it was initially 200m. An extra 650m 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 Figure 6, 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 doubles 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. 630m between 1871 and 1885 and a submarine part of ca. 650m 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 was a structure parallel to the coast (*Dique de Oeste)*. This longshore structure reached 1500m 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 harbour to the south was built (*Dique transversal*). For the first time, the harbour of Tarragona had an enclosed harbour 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*). These two structures enclosed the Inner Harbour (*Dique transversal*, *Muelle paralelo al de Costa* – Figure 1). 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. 550m. 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 was only 175 ha, compared to 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), 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. 70m to the west (1942-1947). Maps and aerial photographs show accumulation of sands 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 (*Pantalá Repsol / de Petroli cru* and *Pantalá 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 *Pantalá Repsol* during the last 50 years to reach nearly 5km 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.

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 (-3.5m at 250m from the coastline, 1:70 or 1.4% slope) (Figure 6, 7, 8 and 9). In addition, the remains of the Roman harbour of Tarragona reduced the modern harbour extent. 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 area. The Roman mole is covered by sediments by 1813 (see paper 1). Sediment texture near the coastline is characterised by finer deposits (1813) (Figure 6). 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). By 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. From 1790 to 1876, the harbour basin is mainly affected by sedimentation (Figure 8). This sedimentation is generally located behind the *Dique de Levante*, but also along the coast. The period 1827-1852 is characterised by stronger erosion (Figure 8). This situation is possibly due to fewer fluvial inputs 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 (Figure 8).

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 less than 4m 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 (Figure 6). From 1876 onwards, the harbour was dredged down to 6-7m depth especially to the entrance of the harbour along the inner part of the *Dique de Levante* (Figures 6 and 7). The repartition of the bathymetries in the harbour area change after 1876 (Figure 7). For the period before 1876, depth histograms are bimodal, with a mode near the sea level (0m or the coastline) and a second mode between 3 and 4m. For the period after 1876, the first mode near 0m is no longer visible and the second or sometimes third modes are moving from -4m to deeper values (Figure 8). The disappearance of the mode towards 0m 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 (Figures 6 and 8). In 1883, the new aim was to reach -8m at the entrance and in the western part of the Inner Harbour and towards the Lower City (Figure 7). 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. In the ancient documents, the coarse material was considered such as the substratum. It slowed down the dredging of the new harbour. Additionally, during the 1880s, 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 de Costa* down to -9m instead of -8m (Memoria, 1886-1887; p12) (Figures 6, 7 and 8).

At the end of the 19th century, the harbour presented an area with a bathymetry of -9 metres along the *Dique de Levante* and an area at -7 / -8m along the *Muelle de Costa*. By 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 -9m (dredging project maps of 1911, 1917 and Figure 8). Sedimentation coming from the river was accumulating 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 (Darsena del Varadero)*.

In parallel, the *Dique transversal* was transformed into a quay called *Muelle transversal*. This marine channel entrance was dredged to -10m as was the southern part of the Inner Harbour. By 1970, the area between -10 and -11m was expanded and covered half of the Inner Harbour. The other section was kept to between -9 and -10m in depth, while along the *Muelle de Costa* the depth was between 7 and 8m. Near the *Muelle de Pescadores*, the depths were between -4 and -1m. 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 -18m at its southern end. Today, the *Pantalán Repsol* has several berths at -8.20m, -11.25m and -14.75m 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 -24m deep at the entrance of the harbour and -14m deep towards the Inner darsena. It leads to a darsena with quays at -12m depth for car carriers (*Muelle de Galicia*) and -15.50m depth for large container ships (*Muelle d'Andalusia*). The river mouth of the Francolí in the harbour provides several quays for chemical ships down to -15.10m (*Muelle de la Quimica and Darsena del Molino*). In front of that, and on the main breakwater, a coal terminal is located with a quay at -18.50m depth (*Muelle de Catalunia*). Closer to the Inner darsena, the channel is at -14m deep with Agribulk quays at -13.25m on both sides (*Muelle Aragon and Muelle de Castilla*). Inside the Inner Harbour, the *Muelle de Costa* is today at -6.30m depth and the waters of the Inner darsena mostly between -9 and -11m deep 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 / -23m deep 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).

5. Discussion

5.1. 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 12km of which 5km is now occupied by the harbour of Tarragona, covering the 2.5km long coastline of the Francolí delta. 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 (Figures 9 and 10):

Period 1: until 1800 – ***Sedimentation/erosion cycles with low harbour infrastructure and management*** (Salomon et al., 2024). Before the 19th century, harbour structures only affected the margin of the delta. A short mole was built in the 15th century 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 century. 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 eroded 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. This resulted in a staged sedimentation 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 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 century CE).

Period 2: 1800 to 1880 – ***Progressive expansion of the harbour infrastructure in the delta front***. 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 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). 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 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 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). 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 perfect for the 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 3: 1880 to 1970 – ***Towards a disconnected harbour and deltaic dynamics***. During Period 3, the harbour infrastructure was constructed in a continuation of those from 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 -8m to -10m 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. By 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 century / early 20th century (*Dique de Oeste* and *Dique submarino*) and the original river mouth was moved to the west in the 1940s. Large and periodic dredging characterised this period. In the 1880s, the port authorities wanted to accommodate ships from the *Compañía Transatlántica* and adjusted the water depth (*Memoria, Junta de Obras del Puerto de Tarragona* from 1983 to 1989). 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 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 Francoli. Urbanisation started to grow quickly from the late 1950s onwards.

Period 4: 1970 to today – ***Quick expansion of the harbour and full integration of the Francolí delta in the harbour***. During the last decade, harbour infrastructure extended across the whole bay of Tarragona. In the 1970s, long jetties were built in the middle of the bay towards the south-west of the harbour. This infrastructure was 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 1970s and the 1990s 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-1990s, 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 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), 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.

5.2. 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 entangled phenomena. The chronological analysis proposed is a decomposition of parameters involved into single chronologies.

In the following parts, we develop four geo-historical narratives associated to the evolution of the harbour of Tarragona and the Francolí delta since the 18th century. Figure 11 offers a synthetic view of the evolution of 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.

5.2.1. Evolution of the cartography and transformation of the port city

Modern ports and harbours all have rich datasets of maps with bathymetric and textural information about their basins (Figure 2 - Dataset). Most importantly, updates about the bathymetry and the bottom texture of the harbour are regularly conducted and mapped through. 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 (Figures 2, 3 and 4). In addition, these graphs are not only giving information about the quality of the georeferencing but also tell us about the evolution of the city and the harbour. Dynamic urban areas erase progressively reference control points and few can be tracked through time. Main period of urban or harbour changes are also period of important reference points creation and destruction. The four periods identified above can be observed in the georeferencing assessment (Figure 4). 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 (Figure 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 has experienced throughout its history. High density of bathymetric points was produced and mapped in 1790, in the period 1880-1891, and the period 1958-1971. 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 (between 5 and 10 meters) and show 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.

5.2.2. 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; 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.

The 18th century and the beginning of the 19th century 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 1790s and early years of the 19th century 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 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). Regarding transportation, this first economic globalisation is marked by the expansion of railways transport and steam shipping. In the second part of the 19th century, 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 1870s and especially in the 1880s 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 1945 or 1960 and still continues today (Baldwin and Martin, 1999). Regarding harbours, this second wave is characterised by a growth of the maritime trade (e.g., more ships), and by containerisation spreading since the 1970s. The number, the sizes, and the draughts of the ships grew quickly since then (Figure 11). Container ships and oil tankers with draughts up to 15-20m 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 (24.6m – 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 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).

5.2.3. 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 1880s (Salomon et al., 2024). 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 1880s 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 (PIANC, 2014).

5.2.4. 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 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).

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 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 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 600m groyne was built in the 1980s 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.

5.3. 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.

5.3.1. 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 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.

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 century, 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 10 and 11 in Salomon et al. 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).

5.3.2. 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 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.~~ 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 archaeomorphologies 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 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 such as a delta dominated by the 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 typology, the Francolí-Tarragona urban delta would be a small system dominated by harbour infrastructure shaping an anthropic bay-head delta first and then a human-made estuary.

6. 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. 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). 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 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);
- Man-made morphologies are always combined with natural morphologies through time creating hybrid landscapes;
- Quantifying land- and seascape transformations is essential to have a broader and detailed view of changes through time;
- Chronological visualisations are as much important as geoarchaeological and geohistorical mapping to reconstruct transformations of hybrid land-/seascapes;
- Producing and sharing chronologies produced for each case study will help to synchronise dynamics of river deltas, harbours, port cities or else 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 replaced 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 harbour infrastructure to the international standards and to the different waves of globalisation. In parallel, these dates correspond also 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 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.

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Figure captions

Figure 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.

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 digitising, and the interpolation of the bathymetric data. All data are plotted referring to 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 century (1813 and 1880).

Figure 7. – Quantitative analysis of the bathymetry from 1790 to 1971. The ~~bathimetries~~ are represented on 18 maps and 18 graphs.

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

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

Figure 1

Click here to access/download;Figure (Color);Fig. 1 - Bay_Harbour-01.jpg

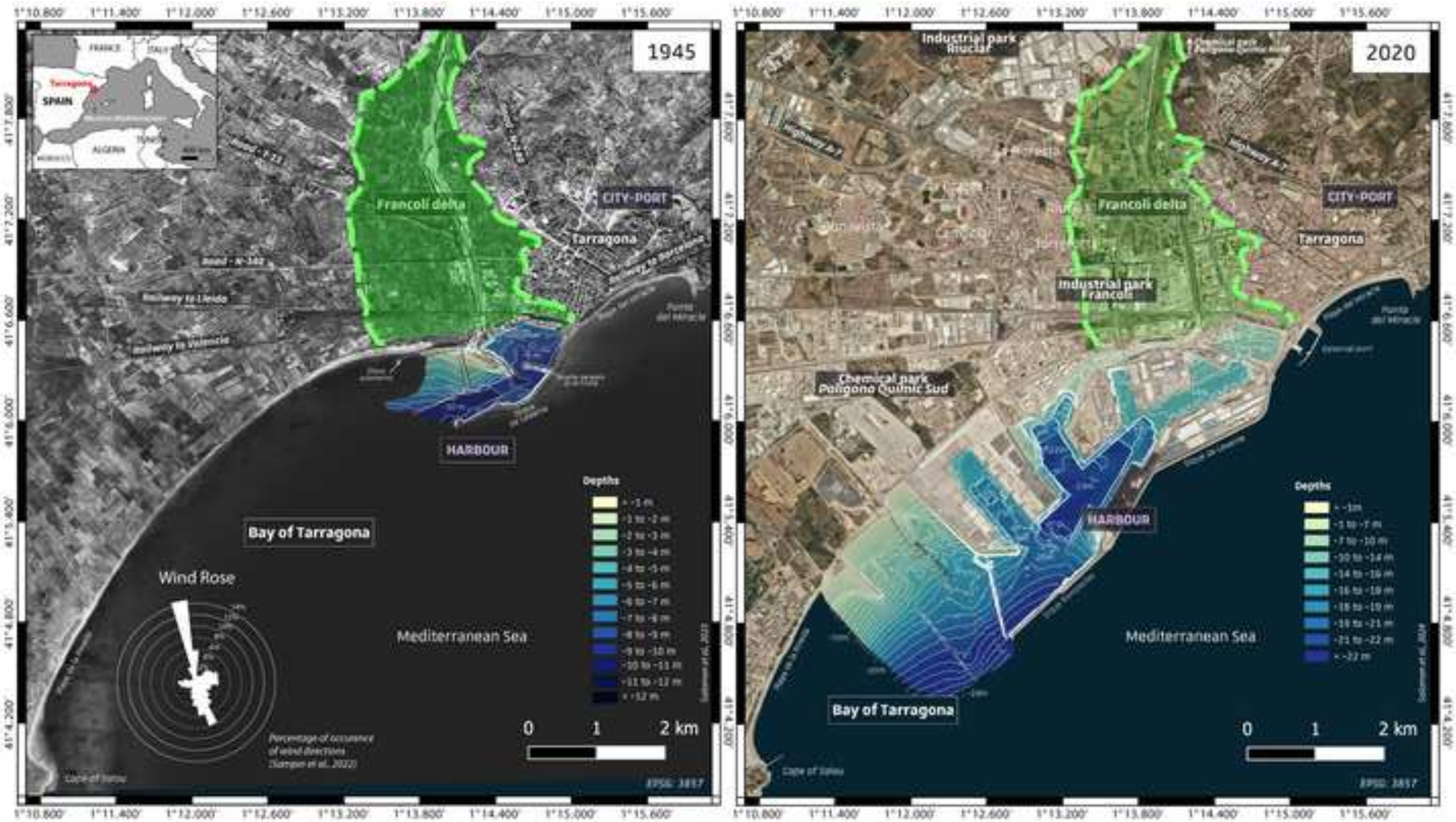


Figure 2

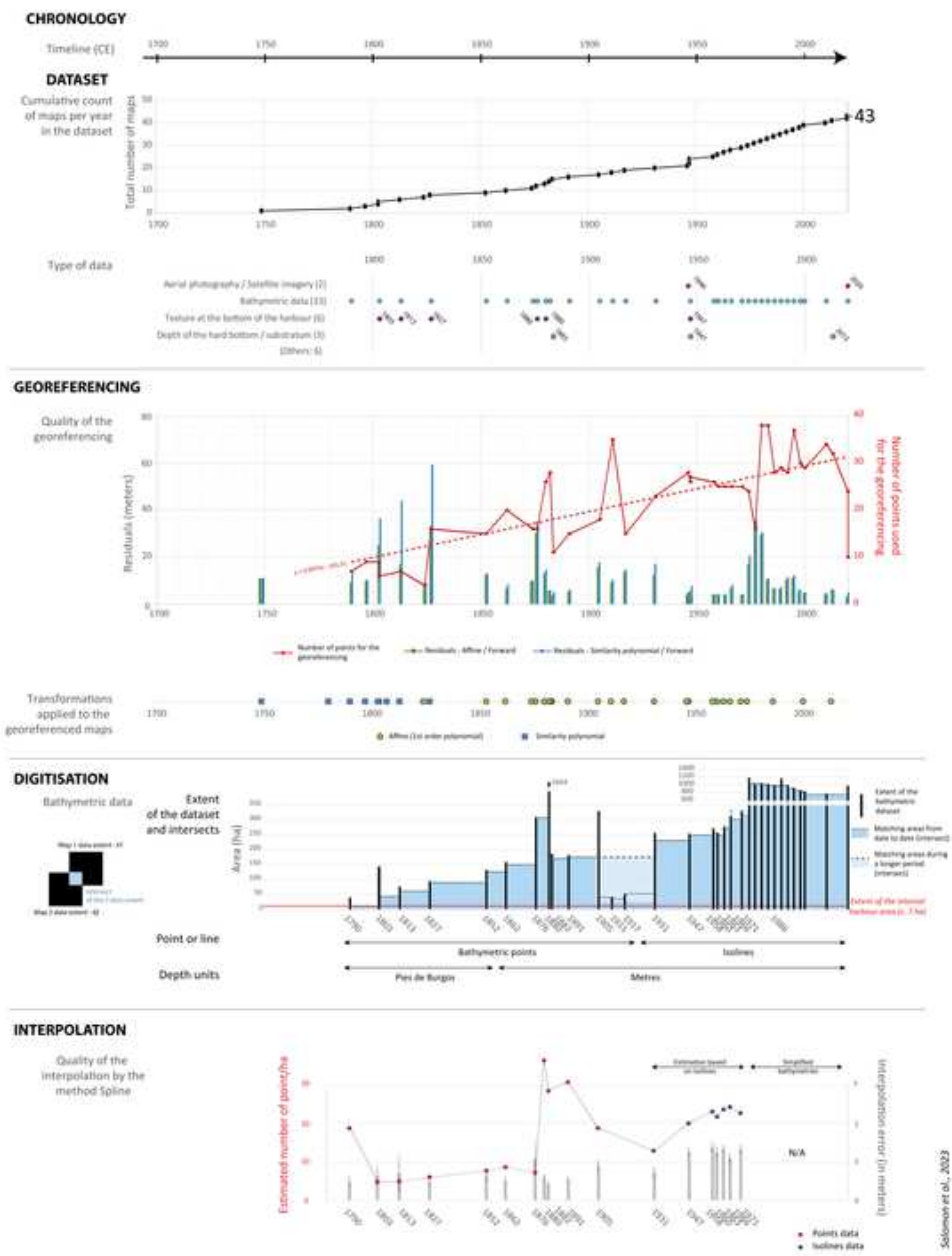
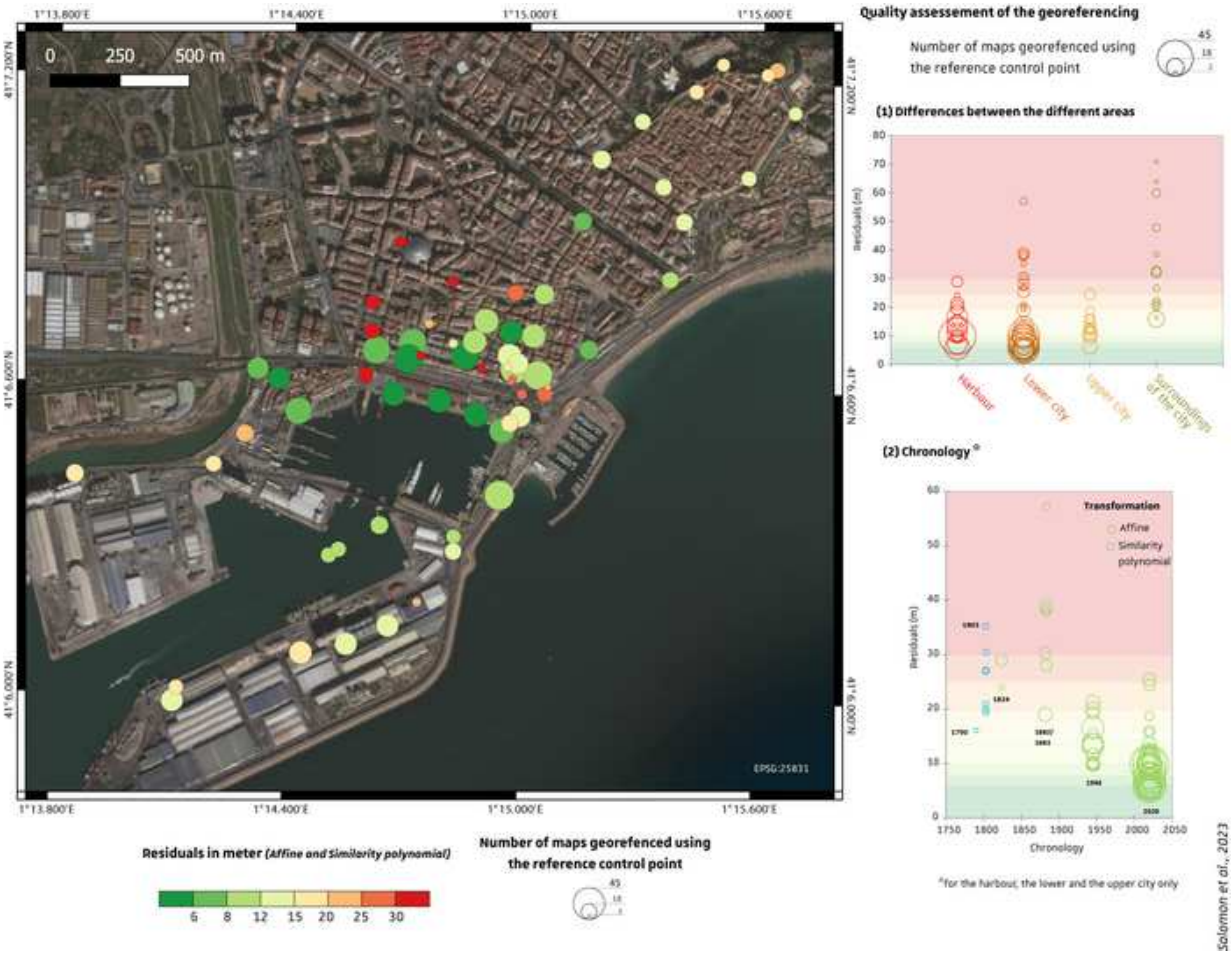

CHRONOLOGY
Timeline (CE)
DATASET
Cumulative count of maps per year in the dataset
Total number of maps
43
Type of data
GEOREFERENCING
Quality of the georeferencing
Residuals (meters)
Number of points used for the georeferencing
Transformations applied to the georeferenced maps
DIGITISATION
Bathymetric data
Extent of the dataset and intersects
Area (ha)
Point or line
Bathymetric points
Isolines
Depth units
Pies de Burgos
Metres
INTERPOLATION
Quality of the interpolation by the method Spline
Estimated number of point/ha
Interpolation error (in meters)
N/A
Points data
Isolines data
Salomon et al., 2023

Figure 3



0 250 500 m
EPSG:25831
Quality assessement of the georeferencing
Number of maps georefenced using the reference control point
(1) Differences between the different areas
Residuals (m)
Harbour
Lower city
Upper city
Surroundings of the city
(2) Chronology *
Transformation
Affine
Similarity polynomial
Chronology
*for the harbour, the lower and the upper city only
Residuals in meter (Affine and Similarity polynomial)
6 8 12 15 20 25 30
Number of maps georefenced using the reference control point
Solomon et al., 2023

Figure 4

Click here to access/download;Figure (Color);Fig. 4. - Tarragona - Georef-02-02.jpg

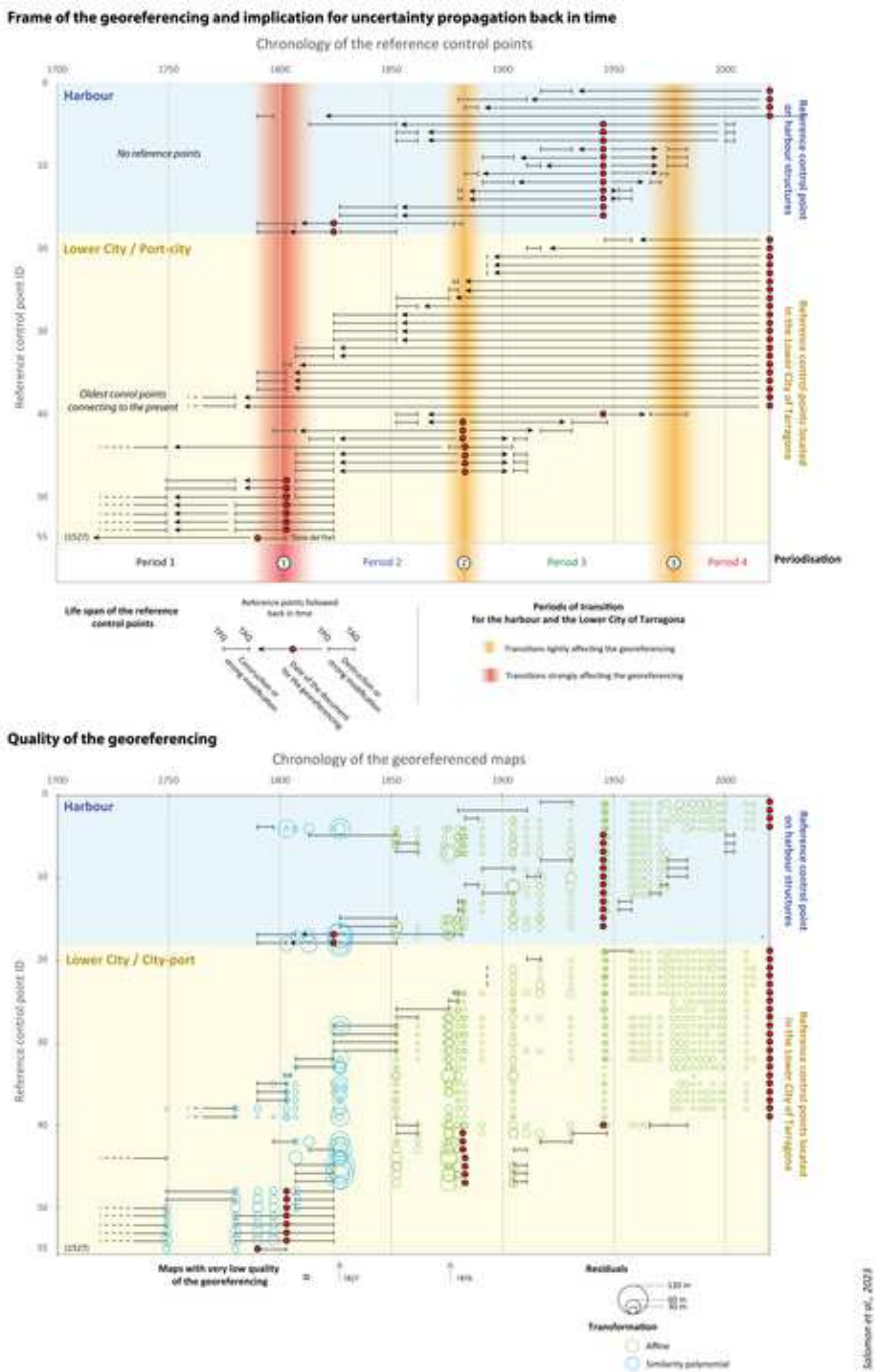


Figure 5

Click here to access/download;Figure (Color);Fig. 5. - Coaslines_19-21th C2..jpg

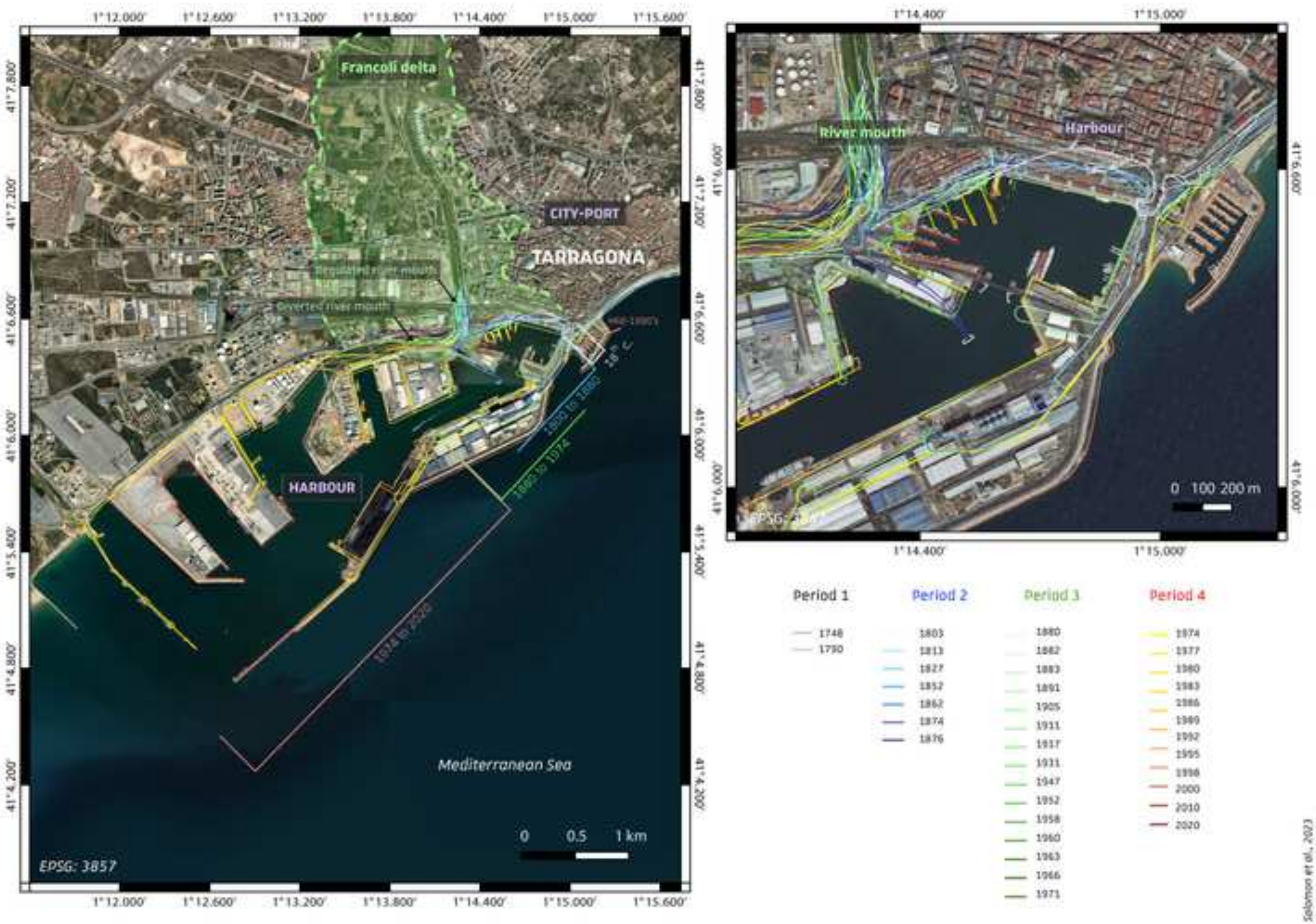


Figure 6

Click here to access/download;Figure (Color);Fig. 6. - Analyse qualitative.jpg

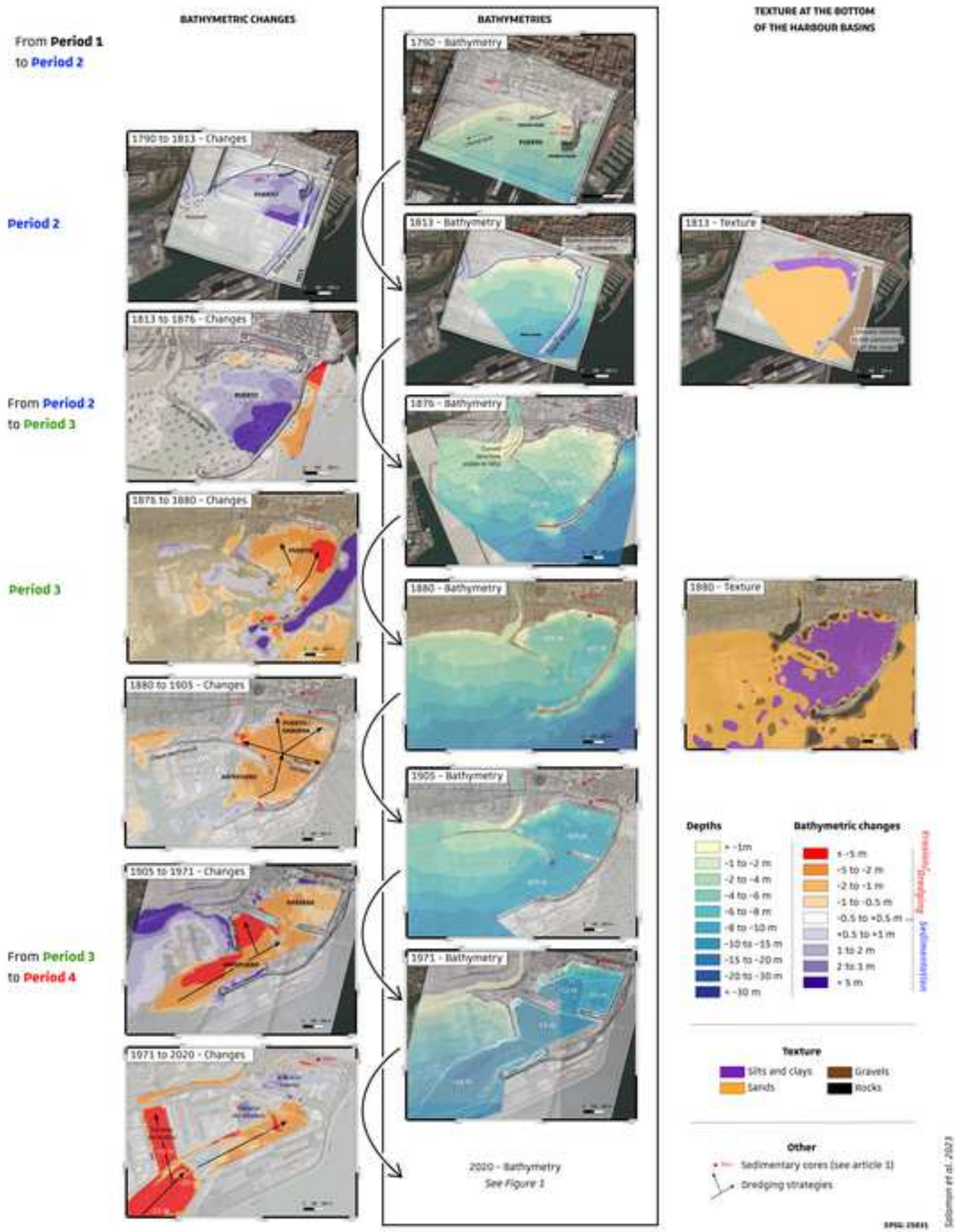


Figure 7

Click here to access/download;Figure (Color);Fig. 7 - 2023_plot_export_map_monodates_bigZone_2-01.jpg

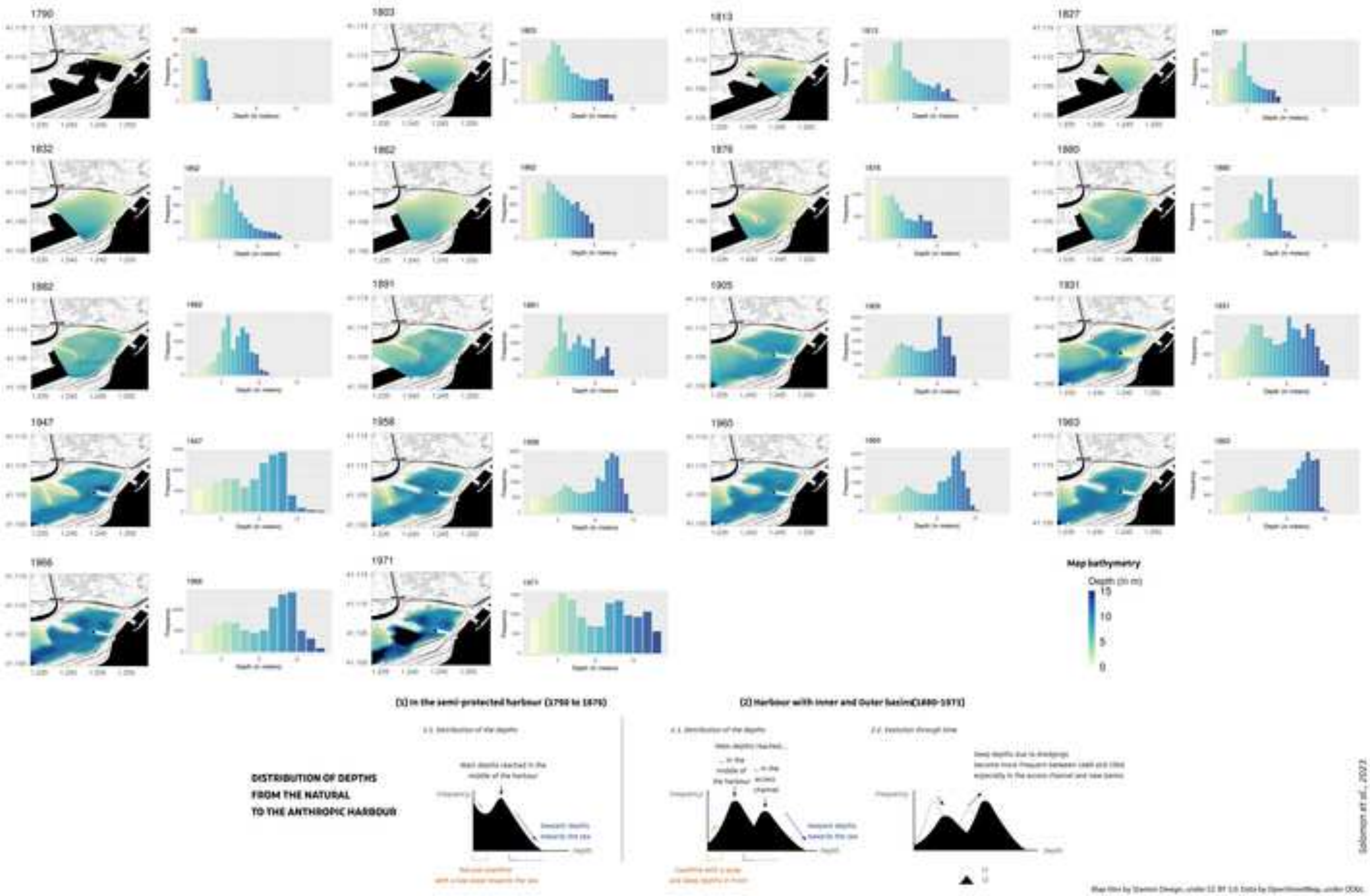


Figure 8

Click here to access/download;Figure (Color);Fig. 8 - BIGZONE - 2023_plot_export_map_change__BigZone.jpg

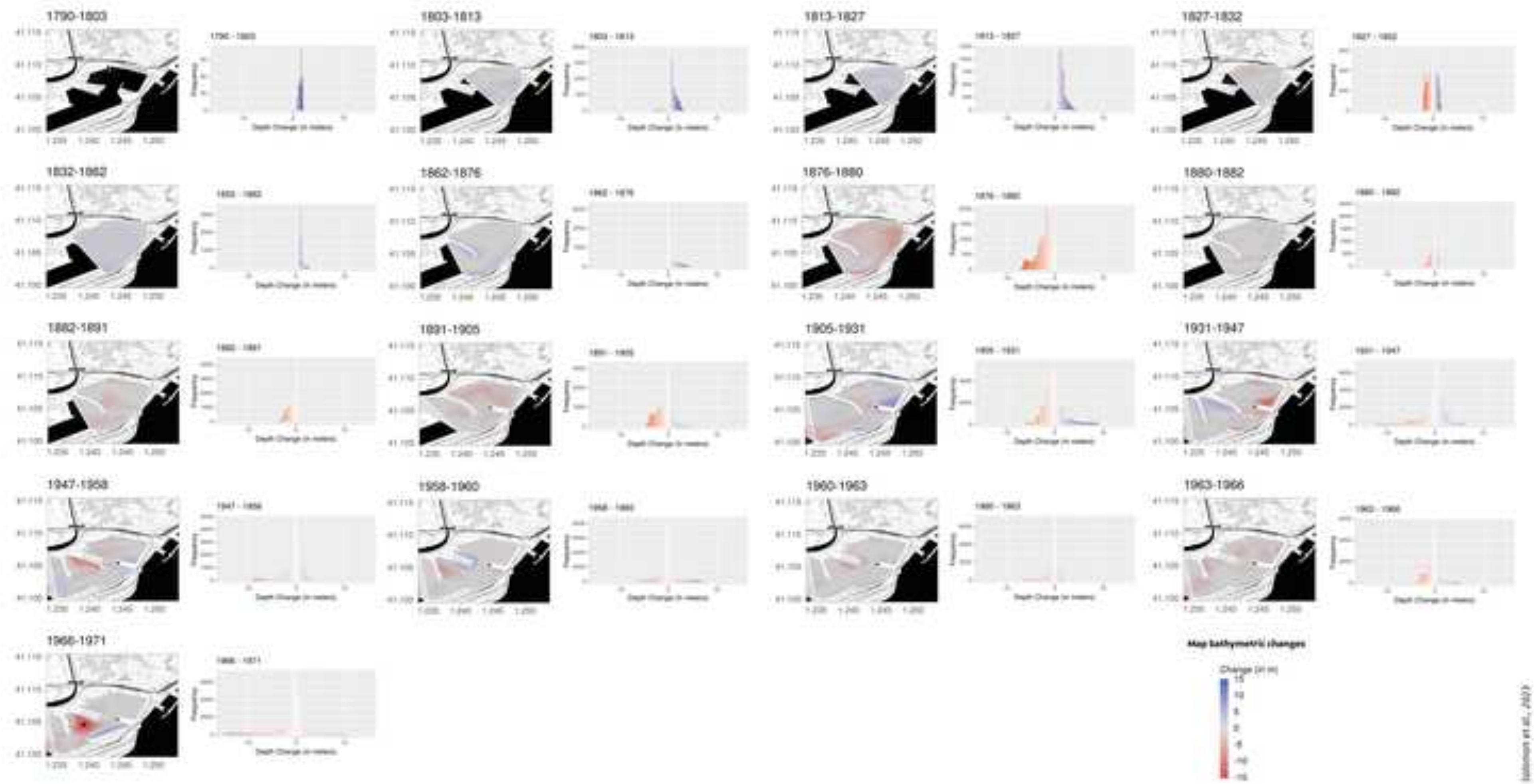


Figure 9

Click here to access/download;Figure (Color);Fig. 9. - Tarragona - Georef-03 (2).jpg

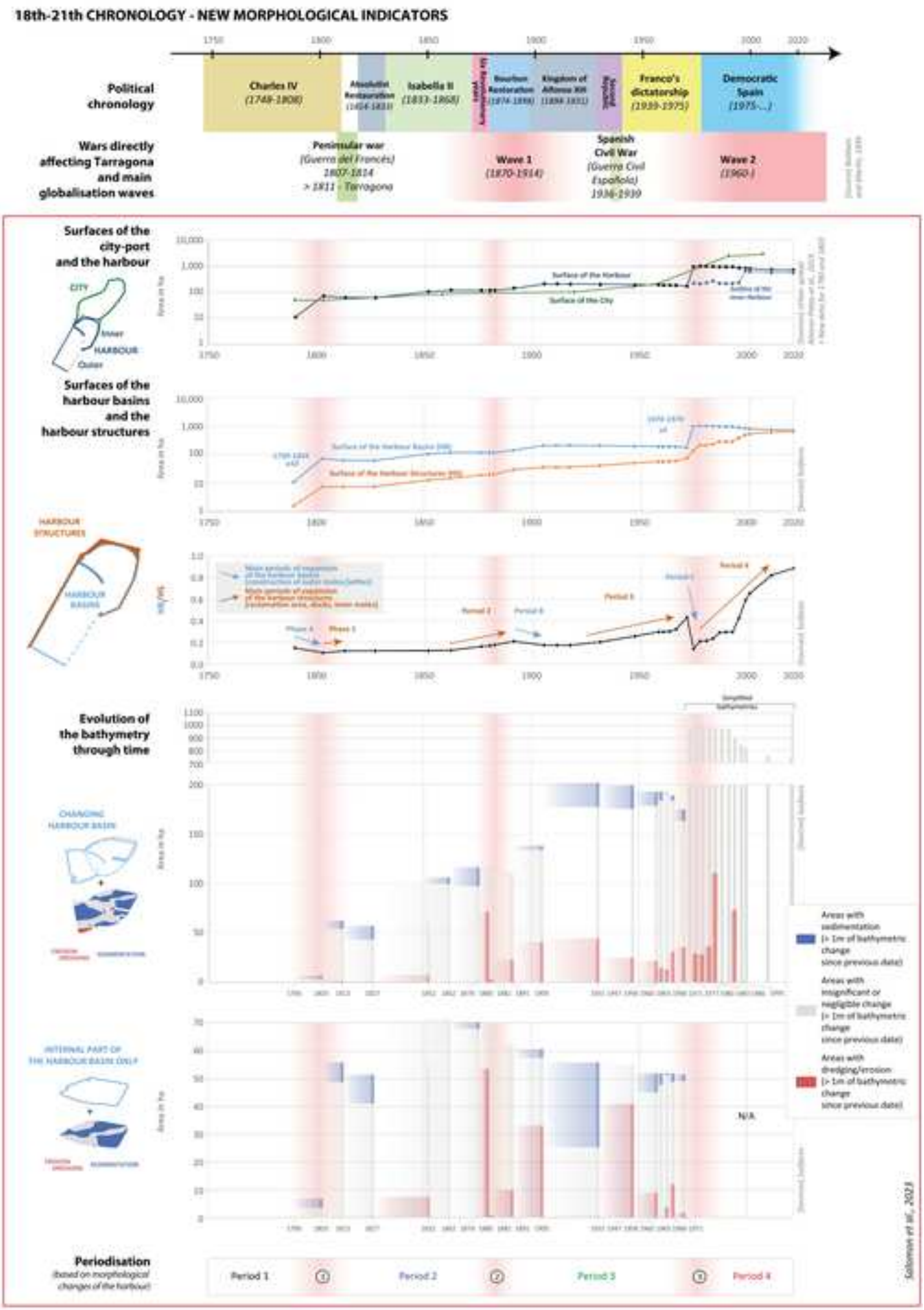


Figure 10

Click here to access/download;Figure (Color);Fig. 10. - Tarragona - Georef-03.jpg

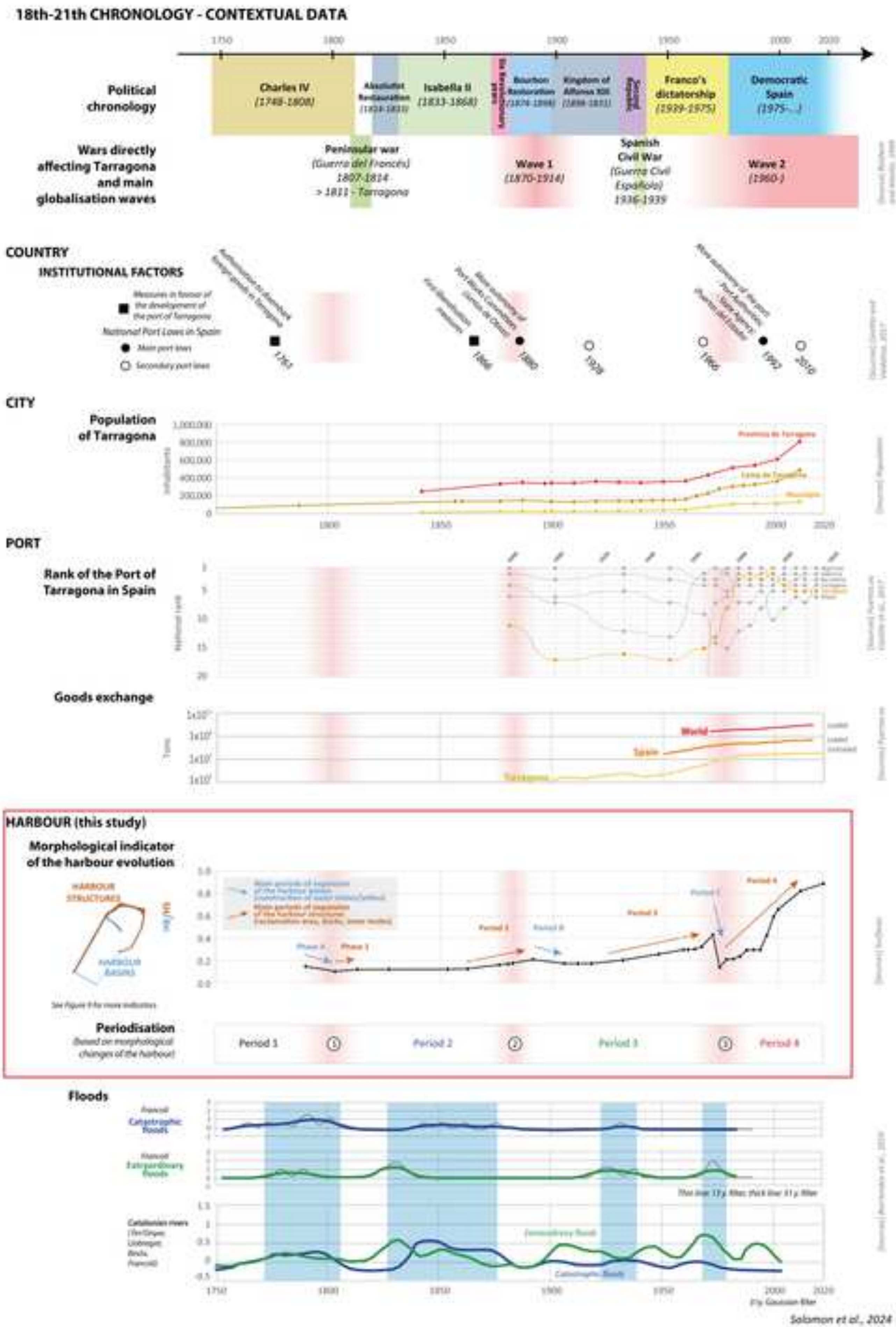
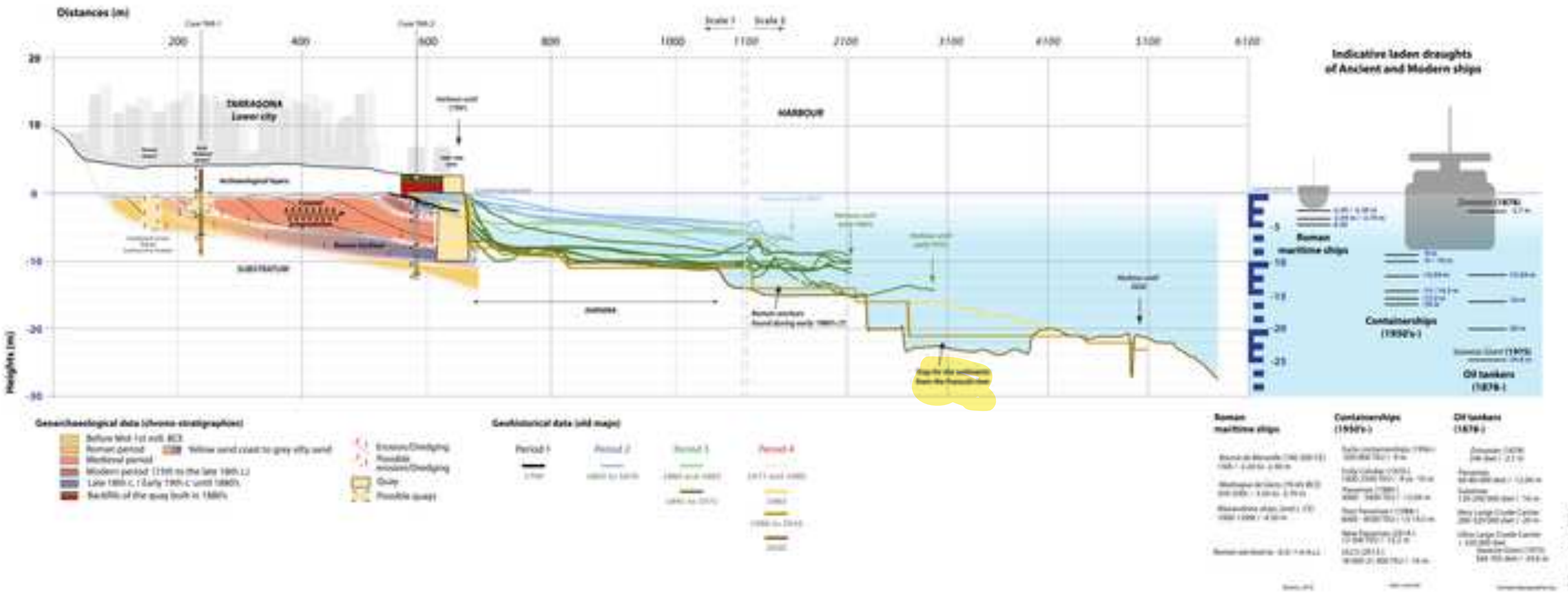


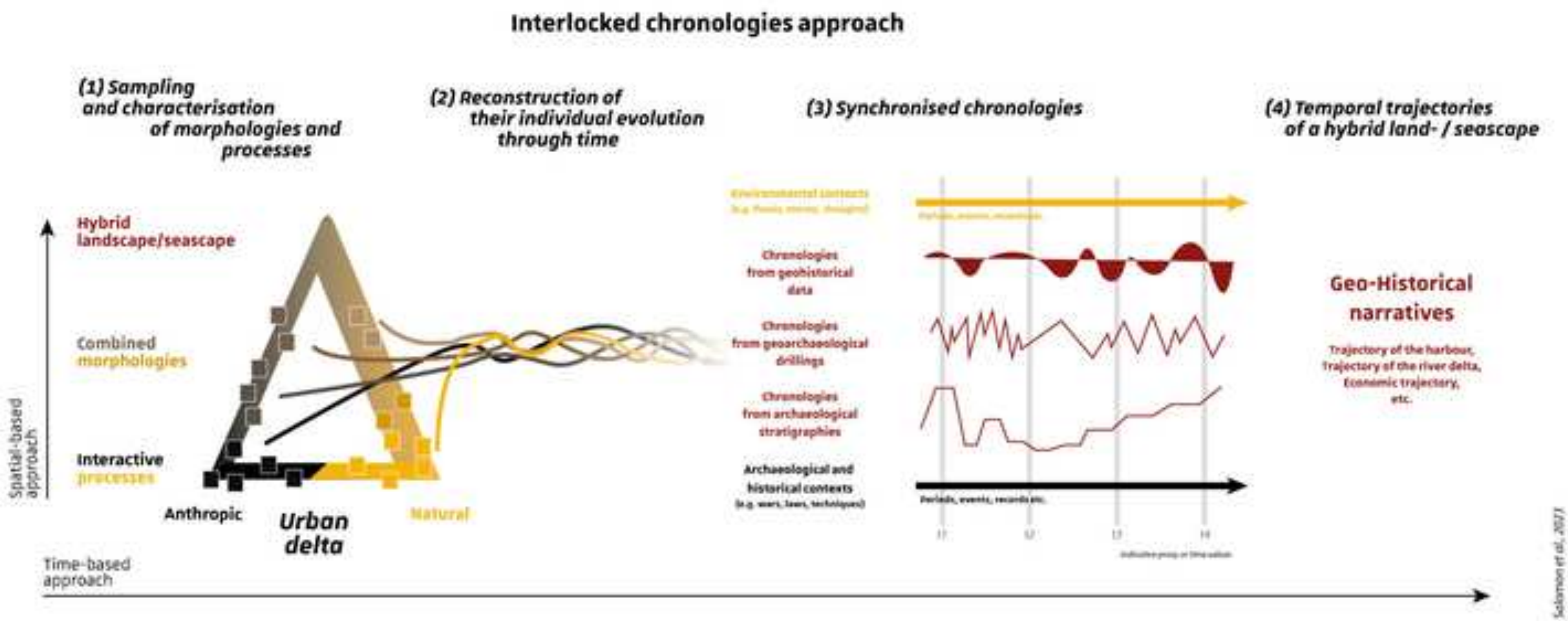
Figure 11



Distances (m)
Heights (m)
TARRAGONA
Lower city
HARBOUR
Indicative laden draughts
of Ancient and Modern ships
Roman maritime ships
Containerships (1950's-)
Oil tankers (1976-)
Geoarchaeological data (chrono-stratigraphies)
Geohistorical data (old maps)

Figure 12

Click here to access/download;Figure (Color);Fig.12-Model delta hybrid_traject.jpg



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Supplementary material for online publication only
S1P2 - Ancien maps.xlsx