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Management of fluvio-coastal dynamics in the Tiber delta during the Roman period: using an integrated waterways system to cope with environmental challenges at Ostia and Portus

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Abstract
The modern Tiber delta includes two river mouths flowing into the Tyrrhenian sea, the Fiumara to the South and the Fiumicino to the North. While the Fiumara is a natural channel, the Fiumicino is a canal that was excavated during the Roman period. Two major Roman archaeological sites are associated with these two watercourses: Ostia, founded between the 4th and the 3rd c. BCE, built at the mouth of the Fiumara; and Portus, founded in the 1st c. CE, built with a series of canals including the Fiumicino *(Fossa Traiana)*, three kilometres north of Ostia. In this paper we shall explore strategies used by the Romans on these two sites to manage river mouth environments, which were characterised by high fluvial sedimentation inputs and rapid fluvio-coastal mobility. We will observe possible urban adjustments to natural constraints at Ostia, and demonstrate how Portus was, building on the experience from Ostia, from its inception designed to reduce fluvial sedimentation in the harbour basins and to lower lateral mobility of the canals. Finally, we will propose the existence of an integrated management system for the watercourses at Portus and Ostia in the Imperial period.

Keywords Geoarchaeology · Watercourse management · Roman canals · Roman harbours · Ostia and Portus · Tiber delta

Introduction

Located at the mouth of the River Tiber (Fig. 1), Ostia and Portus were essential for the economic and transport connectivity of Rome, linking the city with the Mediterranean Sea. Ostia was initially a fortified colonial settlement built on the left bank of the mouth of the River Tiber, and became an important port-city over time (Calza et al. 1953; Zevi 2002; Heinzelmann 2021). By contrast, Portus was built *ex novo* with the aim of creating an Imperial harbour installation (Lugli and Filibeck 1935; Keay et al.

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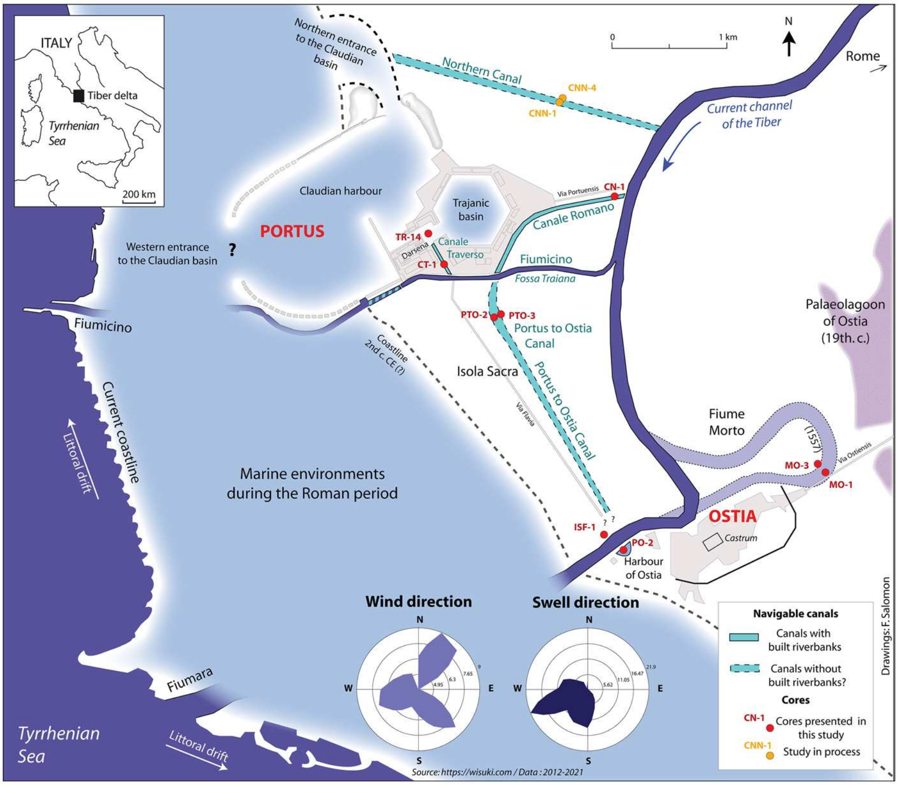

Fig. 1 Site location – Two archaeological sites at the mouth of the River Tiber during the Roman period

2005; Keay 2012). Both provided harbour facilities for ships to load and unload different kinds of goods. Both, however, faced considerable environmental risks and constraints. River mouths are geomorphologically unstable environments. Riverbanks and coastlines can be modified by single events (floods/storms) and on a seasonal basis. This is particularly true during high frequency changes and exceptional events (Noli et al. 1996; Bencivenga et al. 2000). Generally, coastal risks during the Roman period are expressed in terms of coastline mobility (Vella et al. 2000; Brückner 2019), storms (Sabatier et al. 2010, 2012) or tsunamis (Luque et al. 2002; Dey and Goodman-Tchernov 2010). Studies considering fluvial risks during the Roman period focus mainly on flood intensity and frequency, their extent (Le Gall 1953; Berger et al. 2003; Ollive et al. 2006; Arnaud-Fassetta 2008; Arnaud-Fassetta et al. 2009), and adjustments to water levels (Bravard et al. 1990; Allinne 2007, 2015; Leveau 2017)—with many studies focussing on the 1st c. BCE—2nd c. CE, when a hydro-sedimentary crisis can be observed (Cherkauer 1976; Bravard et al. 1992; Brown and Ellis 1995; Arnaud-Fassetta and Landuré 2003; Ollive et al. 2006; Berger and Bravard 2012). The construction of Portus has also been studied in relation to this specific palaeoclimatic context (Salomon 2013), which is also called the Roman Climate Optimum (Harper and McCormick 2018; Strutt 2019). By contrast, fewer studies have considered the consequence of fluvial lateral mobility on Roman cities (Bravard and Presteau 1995; Franc and Vérot-Bourrély 2015; Salomon et al. 2018).

Ostia and Portus offer an interesting case study for observing (infra)structural adjustments to fluvio-coastal dynamics. In this paper, we propose a hypothesis that the port-city of Ostia and the port complex at Portus formed an integrated water management system in the delta of the Tiber, developed over time to combat specific environmental challenges. The first source of evidence that we draw on are the physical remains of structures and archaeological features at Ostia and Portus, concentrating on their planning and orientation. We contextualize this evidence with data from geoarchaeological cores collected from the study area, discussing the sedimentological (sediment deposition–erosion) and geomorphological (lateral mobility[1] aspects of the Tiber channels, canals, and sedimentation/erosion of the river mouth bars) issues related to the Tiber in Ostia and the canals of Portus. Hydrological constraints (e.g. floods) will not be discussed in detail in this paper, but they remain of primary importance during the Roman period (Le Gall 1953; Salomon 2013).

Material and methods

Two sets of data are considered in this paper. First, the urban fabric of Ostia and Portus will be analysed and compared, seeking tangible evidence of incorporation of harbour infrastructure and river water management into the planning of the sites. A synthesis of the geoarchaeological cores drilled in the palaeochannels and harbour of Ostia is then presented and compared to the cores drilled in the canals of Portus, allowing us to assess this evidence and elaborate on the interactions between the Tiber, the canals, the harbours and the layout of Ostia and Portus.

Urban fabric

The urban morphology of Ostia reveals an existence of districts within the city (Fluvial, Coastal, River mouth), with possible adjustments to the urban fabric responding to the mobility of the riverbanks already having been observed (Salomon et al. 2018). In this paper, we apply the same type of GIS analysis on the orientation of archaeological features to Portus, while using the existing case study of Ostia as a *comparandum* aimed at comparing and contrasting the observed patterns (Figs. 2, 3).

The shapefile of Ostia has been drawn based on excavated archaeological structures (roads, walls, etc.). By contrast, Portus has not been extensively and continuously excavated. The dataset from Portus is based on the map from Keay et al. (2005). It represents a mix of visible excavated *archaeological structures* (Lanciani 1868; Lugli and Filibeck 1935; Testaguzza 1970; Paroli 2004; Keay et al. 2005) and *archaeological features* identified from geophysical surveying (Keay et al. 2005). Archaeological features are interpretations of magnetic anomalies and may or may not be actual archaeological structures from the Roman period. However, the quality of the magnetic signal from archaeological structures in and around Portus is of particularly good quality (Keay et al. 2005, 2020). The interpretations from 2005 were also largely confirmed by later excavations conducted

[1] Lateral mobility of a channel or a canal is a specialist term relating to a displacement of the riverbanks in a planimetric view.

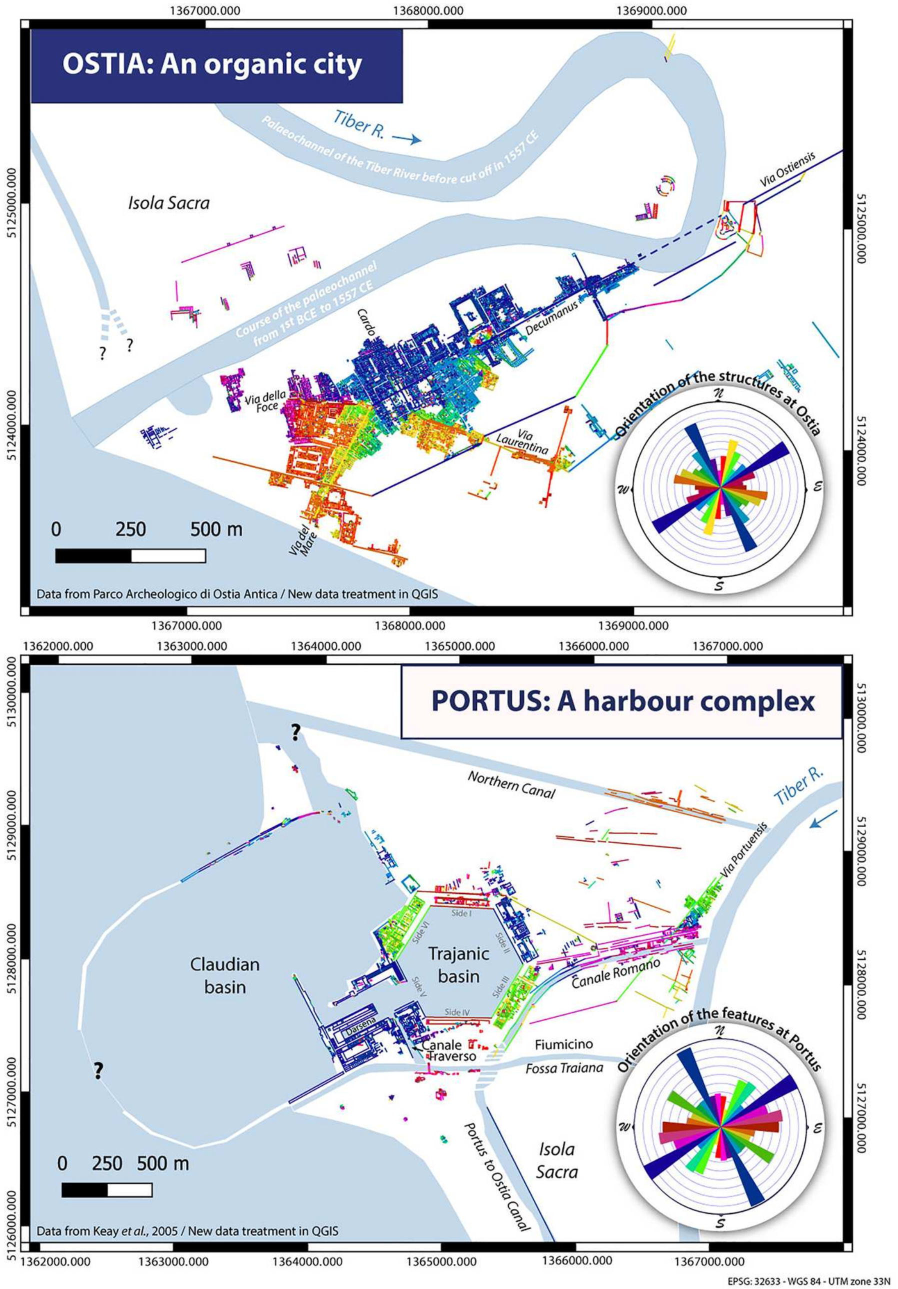

Fig. 2 Map of the orientation of the structure/features in Ostia and Portus

by the University of Southampton in the area of the *Palazzo Imperiale* between the Claudian and Trajanic basins (particularly the extent and the orientation of the main buildings) (Keay et al. 2011, in press).

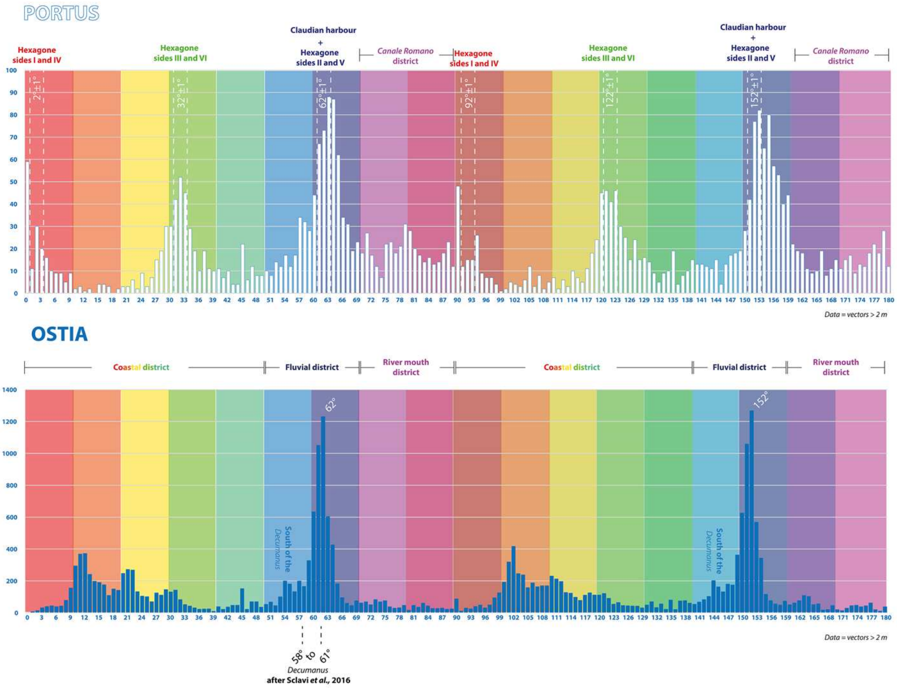

Fig. 3 Diagram of the orientation of the archaeological structures/features in Ostia and Portus

The GIS database includes the shapefiles for Ostia and Portus in the coordinate system WGS 84/UTM 33N (EPSG: 32,633). Transverse Mercator projection is conformal since it preserves angles. The preservation of the angles is essential for the analysis. Orientations of archaeological structures and features were calculated in the QGIS software within the range 0° to 179°. In order to compare Ostia and Portus, classes of orientations were defined every 10° and assigned different colour values. The maps containing orientation analysis of the two sites are presented in Fig. 2. Figure 3 presents the orientation of the structures and features to a degree. We can observe that the dataset of Ostia (96,915 lines distributed according to the Y-axis on the right) is more detailed than the one available for Portus (3594 lines distributed according to the Y-axis on the left). The dataset from Portus will in future be made more complete by research currently being conducted by the Parco Archeologico di Ostia Antica, the University of Southampton (Keay et al. 2011, in press), the École Française de Rome (Bukowiecki and Panzieri 2013; Bukowiecki et al. 2018), and the Universidad Huelva (Bermejo et al. 2018), but the overall orientation of the main features of the site will not change.

Geoarchaeological cores

For the last 20 years, much geoarchaeological fieldwork involving sedimentary drillings has been conducted at Ostia (Goiran et al. 2014; Hadler et al. 2015; Salomon et al. 2018) and Portus (Arnoldus-Huyzendveld 2005; Bellotti et al. 2009; Giraudi et al. 2009; Goiran et al. 2010). These cores were studied using a large range of palaeoenvironmental analyses (*e.g*. Pollens: Sadori et al. 2010, Pepe et al. 2016; Ostracods: Mazzini et al. 2011; Geochemistry: Delile et al. 2014; Foraminifers: Bella et al. 2011, Hadler et al. 2015).

In this paper, we use a selection of cores drilled in the fluvial environments around Ostia and in the canals around Portus (Fig. 1). For Ostia, we chose two cores drilled in the palaeomeander, immediately upstream of the *Porta Romana* (Cores MO-3 and MO-1 from Salomon et al. 2017), and two cores drilled downstream of the city near the river mouth and in the fluvial harbour of Ostia next to the *Palazzo Imperiale* (Core PO-2 from Goiran et al. 2014; Core ISF-1 from Salomon et al. 2018). For Portus, we chose, on the one side, cores drilled in the *Canale Romano* (Core CN-1 from Salomon et al. 2014)*,* the *Canale Traverso* (Core CT-1 from Salomon et al. 2012), and the harbour pool of Portus (TR-14 from Goiran et al. 2010 and Delile et al. 2014), and on the other side, cores drilled in the Portus to Ostia Canal (Cores CPO-2 and 3 from Salomon et al. 2020). These cores will provide evidence of the lateral stability or mobility of the palaeochannels/canals, but also the hydrodynamic conditions during their periods of activities and their periods of abandonment.

Only a few of the palaeoenvironmental analyses are reported in Figs. 4 (Ostia) and 5 (Portus). For the aims of this paper we focus on the stratigraphic logs, a short description of the facies, the texture (*coarse fraction* > 2 mm; 2 mm > *sand* > 63 µm; and *silts and clays* < 63 µm), and the radiocarbon dates recalibrated according to Reimer et al. (2020). These essential data provide chronostratigraphical evidence and a basic proxy of the hydrodynamic conditions during the deposition of the sediments.

Results of the Gis and palaeoenvironmental analyses

Orientations of archaeological structures and features at Ostia and Portus

Ostia is generally considered to have grown organically from a fortified early settlement (*Castrum*) built between the 4th and the 3rd c. BCE (Zevi 2002). Initially, the *Castrum* was built not far from the left riverbank of the Tiber (Constans 1926; Salomon et al. 2018). The last section of the via *Ostiensis* coming from Rome towards the sea corresponds to the *decumanus* of the *Castrum* that the city was built around. Interestingly, the *decumanus* displays slightly different orientations within Ostia (Sclavi et al. 2016). The alignment of the eastern and western gates of the *Castrum* probably best represent the initial orientation of the *decumanus* (Calza et al. 1953), while the sections of the *decumanus* leading to *Porta Romana* could have been modified through time in response to urban dynamics along the street. Sclavi et al. (2016) put the orientation azimuth of the *decumanus* within the *Castrum* at 58.14° (238.14°) and the section of the *decumanus* the closest to *Porta Romana* at 60.48° (240.48°), measured on the ground with a professional GPS (averaging 100 measures per point with ± 0.5° uncertainty). According to georeferenced maps we collected, the orientation of the *Castrum* from the eastern to the western gate measures 61° ± 1° (241° ± 1°). A large part of the urban fabric of Ostia that grew out of the *Castrum* conforms to the orientations of the *decumanus* and the *cardo*; e.g. the orientation of streets within the Fluvial district ranges between 61 and 63°. The coastal and river mouth areas do not follow the same pattern and might follow other features, such as the Via *Laurentina*, Via *della Foce*, Via *del Mare*, and possibly palaeocoastlines and palaeoriverbanks.

At Portus, the main excavated sections of Claudian moles are oriented at 62° ± 1° (242° ± 1°) (Fig. 2). Similar orientations are recorded in the area of the *Darsena*. Trajan's architects used this orientation for sides II and V of the new hexagonal basin. Following

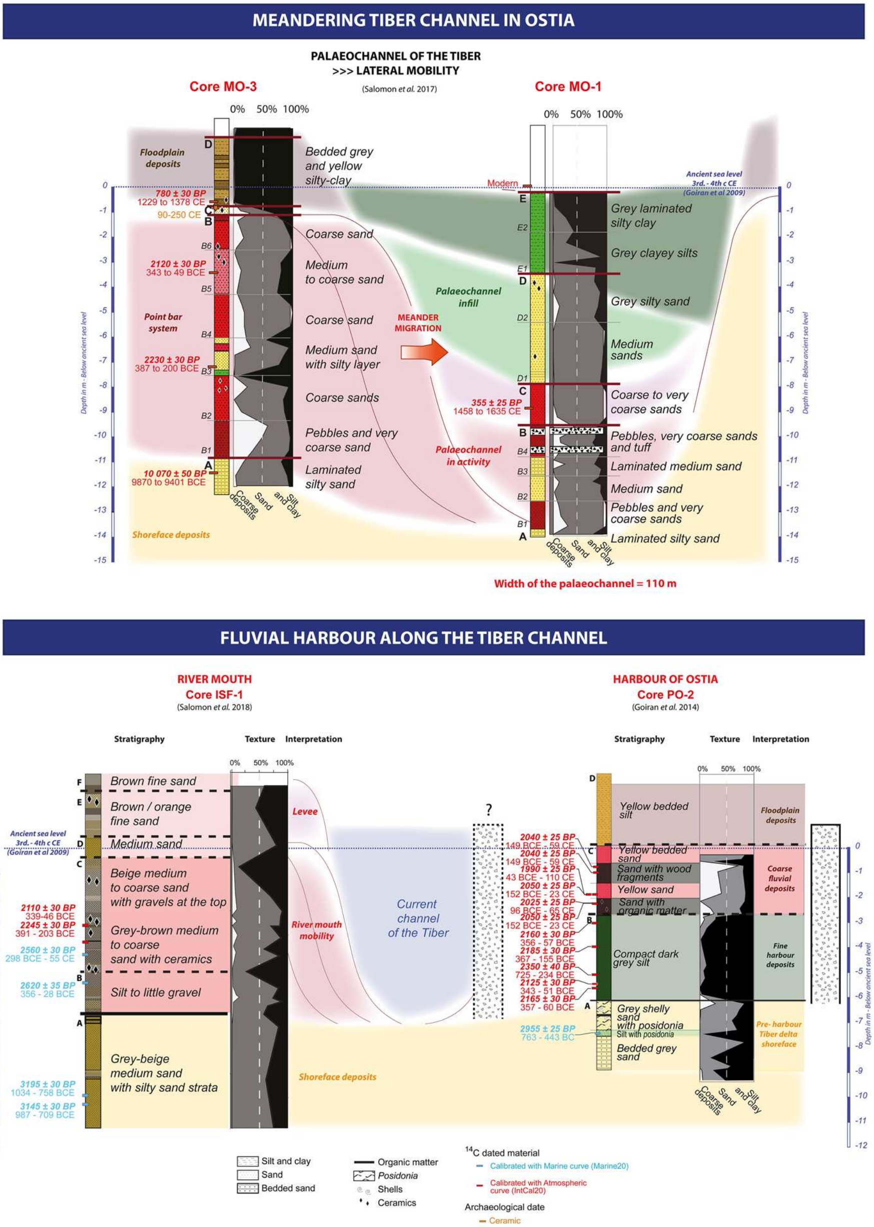

Fig. 4 Fluvial mobility and harbour construction along the River Tiber—Synthesis of chronostratigraphical data

geometric rules, sides III and VI are at 32° ± 1° (112° ± 1°) and sides I and IV are at 92° ± 1° (272° ± 1°). The eastern part of the *Canale Romano* (upstream) is aligned with the structures located east of Portus (the via *Portuensis* and the aqueduct). Upstream, the canal is oriented at 77° ± 1° and downstream it conforms to the side III of the hexagonal basin.

The northern canal is out of the main grid of planned features of Portus with 104° ± 1° on the left riverbank and 106° ± 1° on the right riverbank. The actual orientation of the *Fossa Traiana* – Fiumicino is difficult to characterise due to small curves in its outline. It was probably related to the orientation of the side IV of the hexagon. The *Canale Traverso* conforms to the Claudian orientations. The left riverbank of the Portus to Ostia canal is a straight line oriented at 152°/332° ± 1°, while interestingly, the right riverbank is irregular and its orientation cannot be measured.

Evidence of fluvial lateral mobility at Ostia and Portus

The two cross-sections of cores selected for Ostia demonstrate fluvial lateral mobility during the Roman period (Fig. 4). All cores are characterised at their base (Units A) by yellow layered sands corresponding to shoreface deposits from the 1st part of the 1st millennium BCE (Unit A in Core PO-2) or before (Salomon 2020).

Coarse sands and small pebbles are the bedload-derived facies of the deltaic Tiber (Salomon et al. 2017). They are observed in most of the stratigraphy of Core MO-3 and correspond to the point bar deposits of the palaeochannel of Ostia. Similar point bar successions are observed in Core TEV-4A (Hadler et al. 2020). Core MO-1 demonstrates a decrease of the grain-size from Units B and C (composed of coarse sands and pebbles) to Unit D (composed of sand) and Unit E (composed of silts and clays). This decrease in grain-size is a typical stratigraphic succession from a cut-off palaeochannel. Similar stratigraphies of cut-off palaeochannels are also observed in Cores TEV-1, TEV-3A, possibly TEV-2 in the neck of the *Fiume Morto* (Hadler et al. 2020), and possibly below the *cardo* of Ostia (Core CAT-3 in Salomon et al. 2018).

At the mouth of the Tiber, Units B, C, and D, from Core ISF-1, contain many layers of different grain-size and facies, from silts and clays to coarse sands. Quick-changing depositional conditions characterise river mouth environments affected by both fluvial and coastal processes. The sedimentation in Core ISF-1 could be related to a migration of the river mouth channel to the south or a contraction of the channel width. The two hypotheses relate to riverbank mobility. On the left side of the Tiber, a harbour was excavated between the 4th and the 2nd c. BCE (Goiran et al. 2014). The harbour muds are sealed by coarse fluvial deposits with sediments presenting a bedload-derived facies (Goiran et al. 2014; Delile and Salomon 2020). A large part of the fluvial harbour was filled up in the 1st c. CE (Goiran et al. 2014).

Interestingly, all evidence of riverbank mobility in the palaeomeander of Ostia (Salomon et al. 2017; Hadler et al. 2020), north of the *Castrum* (Salomon et al. 2018), or at the river mouth (Goiran et al. 2014; Salomon et al. 2018) is dated to the 1st c. CE at the latest. Most of the evidence of fluvial lateral mobility dates to the second part of the 1st millennium BCE, during the Republican period of Ostia. Morphogenetic activities of the river started again much later in the 10th—13th c. CE (Hadler et al. 2015; Delile and Salomon 2020) and after 1557 CE.

The sedimentary cores drilled in the canals around Portus reveal different types of stratigraphical successions (Fig. 5). Three canals will be presented: the *Canale Romano*, the *Canale Traverso*, and the Portus to Ostia Canal. The first cross-section shows the *Canale Traverso* leading to Fiumicino (*Fossa Traiana*), and then the *Canale Traverso* and the Portus pool between the harbours of Claudius and Trajan. Similar to the area of Ostia, all cores reach a Unit A composed of yellow layered sand corresponding to shoreface deposits.

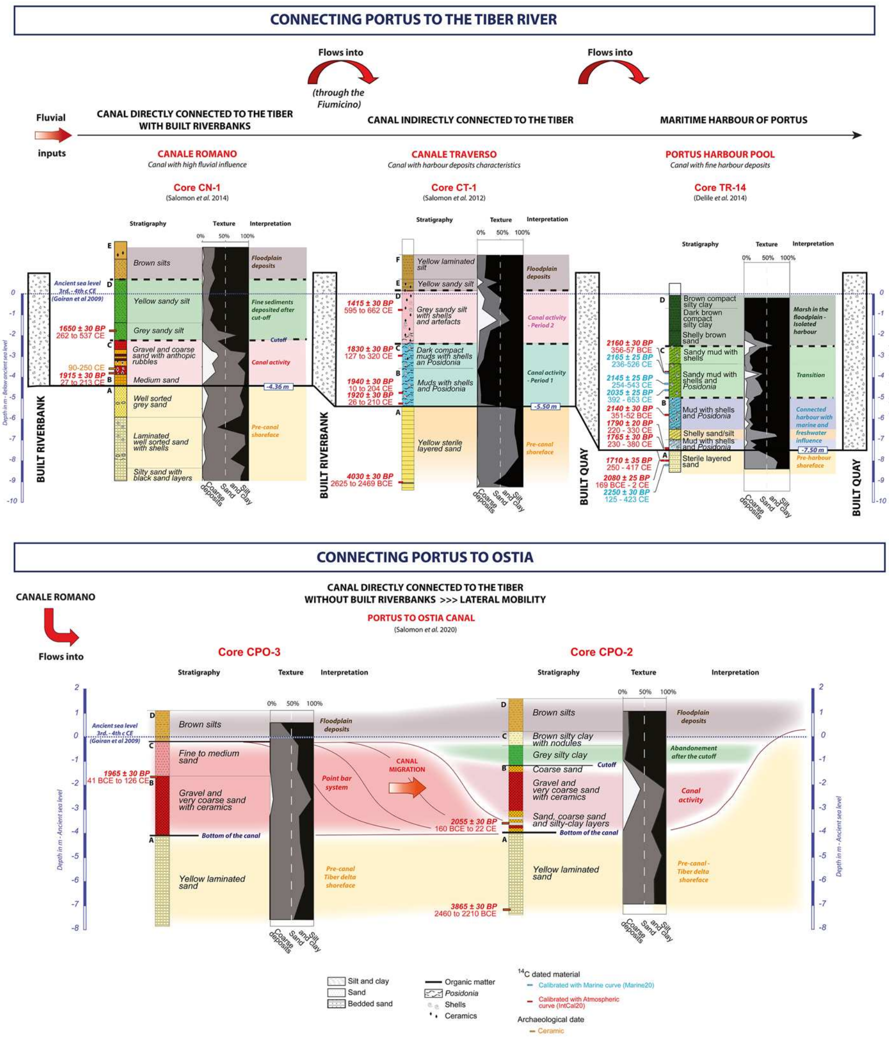

Fig. 5 From the canals to the harbours of Portus—Synthesis of chronostratigraphical data

These deposits date back to the first part of the 1st millennium BCE or earlier (Giraudi 2004; Bellotti et al. 2007; Salomon 2020).

Core CN-1 from the *Canale Romano* reveals the typical stratigraphy of a cut-off channel (Salomon et al. 2014). Units B and C are composed of medium-to-coarse sands, suggesting bedload-derived facies. A sharp limit marks the change from the coarse deposits in Unit C to the fine deposits in Unit D characteristic of sediment deposited after a cut-off. Finally, the canal is covered by fine floodplain deposits (Unit E). No core is available yet from the Fiumicino (*Fossa Traiana*) since the canal is still in activity.

Core CT-1 drilled in the *Canale Traverso* has more in common with a protected harbour stratigraphy (Core TR-14) than that of a fluvial canal (Core CN-1). No bedload-derived facies are observed at the bottom of the canal. Muds from Unit B were found directly lying on shoreface sands (Unit A). Coarse material is observed in Unit D relating to the second phase of use of the canal. The sedimentation in the canal was likely controlled by dredging (Salomon et al. 2012) and possibly also by a sluice-gate (Testaguzza 1970; Lisé-Pronovost et al. 2019).

No lateral mobility is observed in the magnetometer survey around Portus for the *Canale Romano* and the *Canale Traverso* (Keay et al. 2005). However, along the two canals high local magnetic fields are observed (Keay et al. 2005). These certainly indicate structures along the canals rather than lateral mobility. The two canals were probably articulated by built riverbanks or quays similar to the Fiumicino—*Fossa Traiana* (Testaguzza 1970). Palaeoenvironmental analyses of the cores from the Northern Canal are currently in process of being studied. Magnetometer survey revealed no lateral mobility of the canal, nor any features that could be associated with a built riverbank.

The lower part of Fig. 5 shows a cross section of the Portus to Ostia Canal. The two cores CPO-2 and 3 can be compared to the cores from the palaeomeander of Ostia (MO-1 and MO-3). Core CPO-3 shows bedload-derived facies up to the Roman sea level in units B and C, similar to point bar deposits. However, Core CPO-2 demonstrates first a Unit B composed of coarse sands and gravels and then fine deposits (Unit C). These two stratigraphic successions led us to consider a lateral mobility of the Portus to Ostia canal (Salomon et al. 2020). In the area of the cross section, magnetometry revealed lateral mobility, but no features relating to built riverbanks.

Discussion

Ostia, a port-city affected by rapid fluvial sediment deposition and lateral mobility of the river channel

The *Castrum* at Ostia was originally built in the 4th—3rd c. BCE to control access to the Tiber channel from the sea (Calza et al. 1953). By the end of the Republican period, Ostia's close association with the river (Heinzelmann and Martin 2002; Goiran et al. 2014) and the coastlines (Strabo V, 3, 5) was shaping the urban fabric through harbour interfaces and their mobility (Salomon et al. 2018), turning Ostia into a port-city (Zevi 2001, 2002). Along the shore, possible harbour structures were built between the end of the 1st c. BCE/1st c. CE and the beginning of the 3rd c. CE (Raddi and Pellegrino 2011). Little is, however, known about the coastal interface management for earlier periods.

With the urbanisation of the two sides of the river (Germoni et al. 2018; Keay et al. 2020), the harbour within Ostia took a linear form along the banks of the Tiber. Along the left bank of the Tiber, one or several small harbours indented the riverbanks. Geoarchaeological evidence confirmed the existence of one of these small harbours at the mouth of the Tiber (Goiran et al. 2014). Meanwhile, a thick layer of fine deposits observed north of the *Castrum* could suggest the existence of similar harbour deposits (Core CAT-3 Unit C in Salomon et al. 2018); the *molo repubblicano* in the palaeomeander of Ostia could also be interpreted as a harbour structure (Pannuzi et al. 2021).

The linear harbour of Ostia indented by small basins was clearly exposed to fluvial and coastal risks. The main problem reported by ancient authors is related to the Tiber access for maritime ships due to the formation of river mouth bars. This frequent problem was notably reported in 205–204 BCE (Livy, *Ab Urbe Condita*, 29.14.11; Ovid, *Fasti* 4.291–304), and at the end of the 1st c. BCE-beginning of the 1c. CE (Dionysius of Halicarnassus, *Antiquitates Romanae* 3. 44; Strabo 5.3.5). Though these bars appear to have formed regularly at the river mouth, such unsteady morphologies are not easy to identity using sedimentary cores.

The channel of the Tiber conveyed water and sediment through the city of Ostia. Consequently, small harbour basins along the river were exposed to quick sedimentation. Unfortunately, the estimation of the sedimentation rate in the harbour at the river mouth is particularly difficult to ascertain. The calibrations of the radiocarbon dates performed in the harbour muds (Core PO-2, Unit B in Fig. 4) offer dates ranging from the 4th to the 2nd c. BCE (Goiran et al. 2014). During this first phase, the harbour was maybe prone to quick fine sedimentation, but coarse material derived from the bedload did not reach the harbour. However, during the second phase, the harbour was sealed by 2.5 m of coarse material deposited during flood events (Core PO-2, Unit C—Goiran et al. 2014; Delile and Salomon 2020). Additionally, the regular modification of the profile of the river channel at the entrance to the harbour might have affected access (Goiran et al. 2017).

Regarding the river channel itself, fluvial mobility possibly eroded infrastructure, like the via *Ostiensis* to the north-east of Ostia (Bertacchi 1960; Arnoldus-Huyzendveld and Paroli 1995; Salomon et al. 2017), or moved the riverbanks away from the city, such as those north of the *Castrum* (Constans 1926; Salomon et al. 2018).

Portus, a harbour complex planned to reduce river mouth risks

Portus is the result of two main phases of planning. Founded during the reign of the emperor Claudius (mid 1st c. CE), it was reorganised at the beginning of the 2nd c. CE by the emperor Trajan (Lugli and Filibeck 1935; Keay et al. 2005). Due to this Trajanic intervention some of the details of the initial Claudian plan are not fully known. Other phases of construction have also been identified, notably during the reigns of Nero and Hadrian, but these interventions did not considerably affect the plan established by their predecessors (Keay et al. 2005).

While Ostia may be understood as a port city, we suggest that Portus ought to be considered as a harbour complex. In terms of planning, while there is a fort at the centre of Ostia, Portus is organised around its harbour basins. No residential occupation has been attested at the site (Keay et al. 2020, p. 159), and it is only at the beginning of the fourth century CE that Portus became an urban settlement with municipal status (*cf*. *CIL* XIV 4449, dated to CE 337–345 or 334–341 (Keay et al. 2005).

The configuration of Portus suggests that the harbour system was conceived to reduce the fluvial inputs in the harbour basins (Figs. 1, 6). The harbour basins and the Tiber channel were not directly connected by waterways (Salomon et al. 2012; Salomon 2013). The Northern canal and the Fiumicino (*Fossa Traiana*) are connected upstream to the Tiber with outlets in the sea north and south of Portus. The canal mouth bars would thus form away from Portus and the harbour basins. In between these two channels, the *Canale Romano* is also connected upstream to the Tiber, and instead of flowing straight, with the attendant risk of flowing into a harbour basin, the canal curves towards the south, follows one side of the hexagonal basin of Trajan, and empties into the Fiumicino (*Fossa Traiana*). The *Canale Romano* was thus a harbour canal (Salomon et al. 2014) only indirectly connected to the Trajanic harbour via the side III of the Hexagonal basin, possibly to facilitate transhipment.

Nevertheless, connections existed between the fluvial waterways and the harbour basins. The northern entrance to the Claudian basin (Goiran et al. 2011) and the *Canale Traverso* (Salomon et al. 2012; Lisé-Pronovost et al. 2019) are indirectly connected to the Tiber

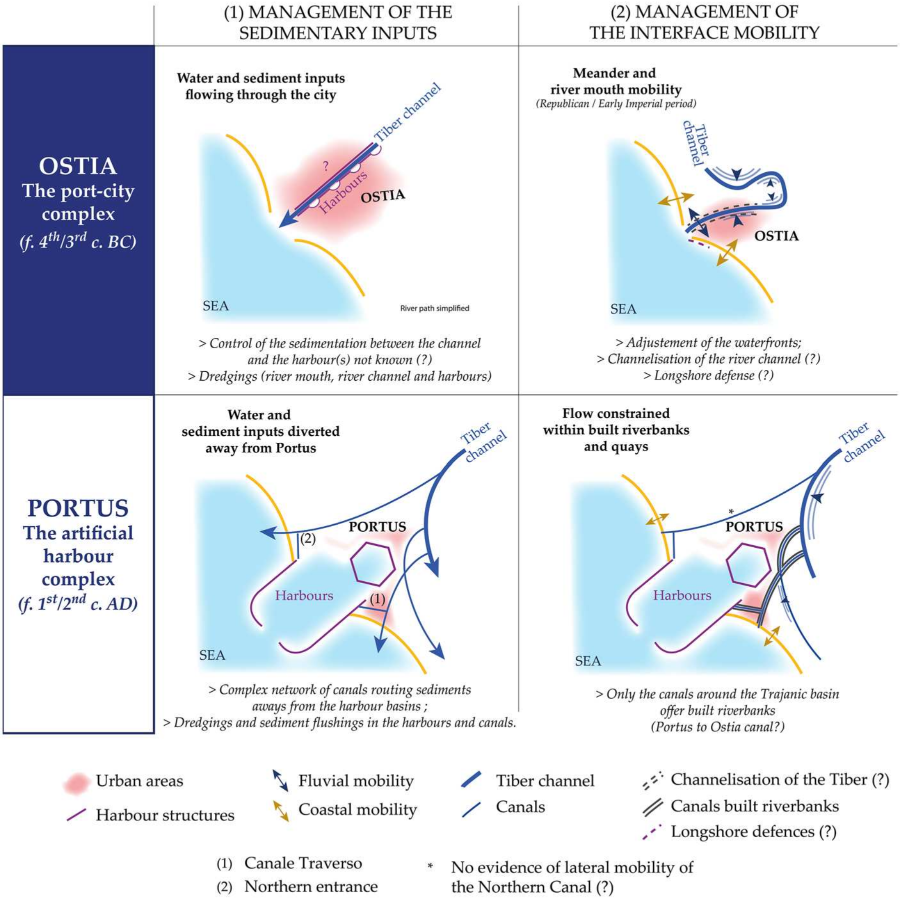

Fig. 6 River mouth management in the port-city of Ostia and the artificial harbour complex of Portus

through the Northern canal and the Fiumicino (*Fossa Traiana*) respectively (Fig. 1). This layout reveals a complex flow and sediment routing management planned by Roman engineers. Additionally, the Northern entrance to the Claudian basin and the *Canale Traverso* could have contributed to reduce sediment deposition in the harbour. Models demonstrate that stronger currents induced by winds in the north-eastern channel and the *Canale Traverso* could have reduced rapid sediment infilling in the harbour basin system (Millet et al. 2014). In this context, these stronger currents in the north-eastern channel could have possibly removed sediments deposited at the mouth of the Northern canal. In addition, sluice gates were possibly built in the narrow *Canale Traverso* to better control sediment inputs in the harbours during river floods by blocking both water and sediment discharge towards the harbour basins (Lisé-Pronovost et al. 2019).

Roman engineers working in Portus had to deal with fluvial inputs in the harbour basin, but also with riverbank mobility prevention. It should be noted that fluvial erosion affects natural channels as much as canals. Lateral canal mobility is observed on images produced by the magnetometer survey of the Portus to Ostia Canal (Keay and Paroli 2011; Keay et al. 2020) and has been confirmed by sedimentary drillings (Fig. 5, lower part) (Salomon et al. 2020). The *Canale Romano*, the Fiumicino (*Fossa Traiana*), and the *Canale Traverso,* however, show evidence of built riverbanks. Archaeological evidence revealed riverbanks along the Fiumicino, at least along the reach south of Portus, and the northern part of the *Canale Traverso* (Testaguzza 1970). Results from geophysical survey identified high magnetic features along the *Canale Romano* and the *Canale Traverso* suggesting built riverbanks and no lateral mobility in the canals. Surprisingly, magnetic surveys revealed no riverbanks and no lateral mobility for the Northern canal. Analyses in progress on cores drilled in the Northern canal will probably shed new light on this feature. A clear pattern emerges: the closer the canal to Portus, the better channelised it was. The channelisation of the canals next to Portus and their shorter width (< 50 m) compared to the Tiber channel (> 100 m) would have made them easier to maintain by dredging.

The study of the canal system of Portus thus reveals engineering solutions to sedimentological, geomorphological, and possibly hydrological constraints first faced at Ostia.

From ostia to the ostia-portus system

Portus was clearly not conceived independently from Ostia (Keay 2012), and the two sites present an integrated system of complementary units.

In this respect, it is interesting to observe the matching orientation of the original structures at the two sites: the *Castrum* at Ostia and the Claudian structures at Portus. Alignments of the mentioned structures (marked in blue on Fig. 2) follow the original axis of the *Castrum* at Ostia (*decumanus* = 62°/238° ± 6° and *cardo* = 152°/332° ± 6°—Le Gall 1975; Sclavi et al. 2016; Sparavigna 2017). Ostia's original orthogonal grid orientation of c. 238° is solar and corresponds to the Winter Solstice Sunset at the time of the town's foundation (Sclavi et al. 2016). Solar orientation was not uncommon among Roman colonies in Italy or in towns founded across the Roman Empire (Magli 2008, though note that the orientation value for Ostia used in Table 1 is off by 10°). Though Roman town foundation ritual incorporated a symbolic dimension, in practice the laying out of the new town grid was predominantly governed by local topography (González-García and Magli 2015; Orfilia Pons et al. 2017). At Ostia, local factors included the positions of the coastline and the riverbanks, limitations imposed by the salt lagoon of Stagno di Ostia, the prevailing winds, and any pre-existing land division and road infrastructure.

Winds have been given particular consideration in Vitruvius, the only surviving Roman architecture treatise that deals explicitly with city foundation. The *Castrum* of Ostia conforms fully to the advice given (Vitruvius, *De Architectura*, 1.6.8): the predominant NE and SE winds would indeed break upon the walls of the fortress, as recommended (*cf.* Figure 1). The *Castrum* thus positioned was also aligned with the riverbank (Fig. 2), the continued importance of which is reflected in the orientation of the Fluvial district, which although representing a later organic growth of the town still respects the first alignment. At Portus, harbour engineers repeated the same alignment, matching that of Ostia, time and time again—in the original layout of Claudius, the enlargement of Trajan, and the large warehouse block added in the Severan period. Bearing in mind that land division on the Isola Sacra is most probably late first century CE in date (Keay et al. 2020: 151), and there is no evidence yet for any land division on either the Isola Sacra or at Portus predating the construction of the Claudian Harbour, it is clear that the orientation of structures and features at Portus was not dictated by a pre-existing land grid, but that it was either copied from Ostia or decided upon based on the same environmental considerations.

Wind and water swell direction would have been even more important in designing a harbour environment than a town, and the orientation that offered protection from the prevailing winds must have been seen as advantageous. Preliminary modelling does in fact suggest that the alignment and height of the structures surrounding the Trajanic basin was effective in protecting it from wind, and the same is most likely the case for the *Darsena* (Keay et al. 2021a, pp. 390–391). Unfortunately, we cannot tell how successfully the harbour design combatted the destructive force of water swells, as we currently cannot reconstruct the position of the original Portus harbour entrance with absolute certainty.

While some canals display orientation independent of either Portus or Ostia (the upstream reach of the *Canale Romano*, the Northern Canal), most likely for hydrological reasons, other elements of the canal network align with the Trajanic layout of Portus (the downstream reach of the *Canale Romano* follows side III of the Trajanic hexagonal basin, *Canale Traverso* that of the district of the *Darsena*). The Portus to Ostia canal, on the other hand, seems to conform to the original orientation of Ostia and later of Portus (the left/eastern bank not affected by lateral erosion). This alignment of the navigable link between Ostia and Portus adds to the evidence of the existence of a general plan regulating the River Tiber mouths in the Imperial period.

Lateral mobility of the Tiber in Ostia seems to stop between the end of the 1st c. BCE and the beginning of the 3rd c. CE (Salomon et al. 2017, 2018). It restarts in the 10th–13th c. CE at least with fluvial coarse deposits observed in the river mouth harbour of Ostia (Hadler et al. 2015; Delile and Salomon 2020). Several hypotheses can be proposed to explain the end of the lateral mobility of the Tiber in Ostia during the Imperial period and for a millennium. Climatic variations could have reduced the intensity and the frequency of the Tiber floods during this period; palaeoclimatic data, however, do not confirm this hypothesis for the long period under consideration (*e.g.* the hydroclimatic crisis in the 8th c. CE—Le Gall 1953; Berger and Bravard 2012; McCormick et al. 2012—is yet to be observed in the sediments of Ostia). Alternatively, the creation of large canals at Portus would have locally diverted large amounts of water and the flow competence of the river could have been largely reduced at Ostia, notably limiting the lateral erosion. It should be noted that while all the dates related to the coarse fluvial deposits at Ostia indicate periods before the 1st c. CE (Goiran et al. 2014; Hadler et al. 2015, 2020; Salomon et al. 2017, 2018; Vött et al. 2020; Delile and Salomon 2020), the radiocarbon dates from the canals of Portus fit in a timespan ranging from the middle of the 1st to the 7th c. CE. It is also possible that some of the solutions applied to the canals of Portus would have also been adopted for the natural channel of the Tiber at Ostia, with built riverbanks facilitating its channelization. In this case, Portus was not the sole solution to the problems at Ostia, but Ostia itself also adapted against fluvial hazards.

Additional studies would be necessary to reconstruct precisely the mobility of the downstream reach of the Tiber and the management of the riverbanks of Ostia between the Republican and the Imperial period. The long history of Ostia would offer the possibility of detailing the temporal trajectory and the different phases of fluvial management during the Roman period.

Conclusion

The main hazards recorded by ancient texts for the port-city of Ostia were the large amount of sediment deposited at the river mouth affecting the harbour and the presence of river mouth bars constraining the access to large maritime ships. Geoarchaeological sedimentary drillings confirmed the important sedimentation at the river mouth (Goiran et al. 2014; Salomon et al. 2018, 2020) and revealed the importance of the lateral mobility of the Tiber in Ostia (Salomon et al. 2017, 2018). This study demonstrates how a city like Ostia tried to manage dynamic river mouth environments through time, and how the Imperial harbour facility at Portus was planned from its foundation with these problems in mind (Fig. 6).

Fluvial mobility. During the Republican period, Ostia was founded along the natural channel of the Tiber. The city expanded and eventually urbanised the two banks of the river mouth (Germoni et al. 2018; Keay et al. 2020). During the Republican period, the river moved laterally and Ostia adjusted to these changes by rebuilding riverine infrastructures (Salomon et al. 2017, 2018). A few kilometres to the north, in the middle of the 1st c. CE, the maritime harbour at Portus was conceived away from the Tiber and its direct erosion. Nevertheless, canals had to be excavated to connect Portus to the Tiber and allow direct transhipment via the river to Rome. Built riverbanks were used in the canals close to Portus in order to limit their lateral mobility (Fiumicino—*Fossa Traiana*, *Canale Romano, Canale Traverso* and possibly some parts of the Portus to Ostia canal). These riverbanks are currently known via geophysical survey alone (Keay et al. 2005, 2020).

Water and sediment routing. In Ostia, the Tiber flowed through the city with a high sediment discharge during floods. Consequently, the harbours excavated along the Tiber were more prone to be filled by sediments. In Portus, the canal system dispatched the main water and sediment discharges of the Tiber to the south and north of Portus. Additionally, the connection between the river flow and the harbour basins was indirect (e.g. a secondary connection via channels/canals, transhipping between the Trajanic harbour and the *Canale Romano*). While the river channel and the harbours are joint or closely interconnected in Ostia, the river system (including canals) and the harbour basins are separated at Portus (Fig. 6).

Finally, the corresponding orientation of archaeological structures observed at Ostia, the harbour of Claudius and Trajan, and the Portus to Ostia canal that aimed at reducing the adverse impact of wind and likely also waves, further supports the existence of a common planning logic. The management of sediment and water discharge was, furthermore, conceived in considering the possibility of navigation between the different harbour units of Ostia and Portus (the Tiber channel, canals, harbour basins of Ostia and Portus), indicating the existence of a single integrated water management and harbour system.

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