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Recent evolution of river mouths in the Marche region (central Adriatic, Italy)

Abstract: Aringoli D., Bendia F., Bisci C., Bufalini M., Farabollini P., Gentilucci M., Lampa F., Materazzi M. Pambianchi G., *Recent evolution of river mouths in the Marche region (central Adriatic Italy)*. (IT ISSN 0391-9838, 2026). The Marche Region (Central Italy) hosts a 170 km long gravelly-sandy coastline facing the Adriatic Sea, where mostly torrential rivers deliver sediment to a narrow continental shelf. Over the last century, this sediment supply has been profoundly altered by dams, in-stream gravel mining, channelization, and the construction of ports and coastal defence structures. Here we reconstruct the historical-to-recent evolution of ten major river mouths (Foglia, Metauro, Misa, Esino, Musone, Potenza, Chienti, Tenna, Aso and Tronto) using a homogeneous GIS workflow applied to multi-temporal cartography and remote sensing (late 19th-century topographic maps, mid-20th-century maps, 1977 aerial photographs, 1999-2000 and 2010 orthophotos, and 2024 satellite imagery). Shorelines and mouth planforms were digitized, georeferenced in a common coordinate system, and interpreted considering dataset-dependent positional uncertainty. Results show that most river mouths were protruding and locally prograding in the late 19th century, whereas a marked and widespread retreat occurred between the 1950s and the late 1970s, in several cases exceeding 100-400 m. Since the late 1970s, the planform evolution has been increasingly controlled by hard engineering: detached breakwaters and groynes have promoted local accretion updrift of structures and, in many sectors, have compartmentalized the coastline, producing apparent stabilization of the shoreline and the river mouths. Where major new structures were built (e.g., the Tenna loading pier), strong asymmetries developed, with rapid updrift progradation and persistent downdrift erosion. These findings indicate a transition from a naturally river-fed coastal system to an engineered, sediment-starved coast, with direct implications for integrated sediment management and for adaptation to future sea-level rise and storm impacts.

Key words: River mouths evolution, Anthropogenic impacts, Marche region, Adriatic side of Central Italy.

INTRODUCTION

River mouths and deltaic coasts are highly dynamic because they sit at the interface between catchment-scale sediment production/transfer and marine reworking by waves, currents, tides and sea-level change. In microtidal settings such as the Mediterranean, relatively small fluctuations in fluvial sediment supply, storminess and longshore transport can rapidly shift the balance between progradation, stability and erosion, reorganizing mouth planforms, inlet positions and adjacent beach-bar systems. River mouths therefore act as geomorphological “sensors” of environmental

change, integrating signals from upstream hydro-sedimentary regimes, nearshore hydrodynamic climate and relative sea-level trends across short and long timescales. Many Mediterranean and Italian coasts reflect a Holocene inherited framework: after rapid post-glacial sea-level rise, coastal plains, barrier-lagoon systems and river-mouth embayments developed, while mid-late Holocene deceleration and relative stabilization of sea level favored shoreline progradation where sediment supply exceeded accommodation creation (Lambeck *et al.*, 2004; Long, 2001; Lambeck *et al.*, 2011). In Italy, relative sea-level reconstructions and stratigraphic/geomorphological evidence show how this long-term forcing, interacting with local sediment budgets, produced divergent trajectories – from the expansion of large deltaic plains (e.g., the Po) to smaller cusped deltas and beach-ridge plains (Bondesan *et al.*, 1995; Bellotti *et al.*, 2004). In the Adriatic, the legacy of early-mid Holocene transgression and subsequent high-stand conditions sets boundary conditions within which later climatic and

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anthropogenic perturbations drove centennial- to decadal-scale adjustments. Superimposed on this template, late Holocene climatic variability and shorter hydroclimatic anomalies modulated hillslope instability, flood frequency and sediment delivery; in the central Adriatic, mass movements, accelerated erosion and historically documented river-mouth variability have been interpreted as evidence of climatic fluctuations linked to changes in surface and groundwater circulation (Materazzi *et al.*, 2010). Where eustatic forcing is comparatively limited at centennial scales, river mouths can retain a “memory” of catchment transformations, alternating between enhanced supply during hydrologically effective events and reduced supply during slope stabilization and sediment storage (Materazzi *et al.*, 2010). At the Mediterranean scale, many deltas and low-lying coasts show a late Holocene-historical shift from natural progradation to stagnation and, in several settings, net “destruction”, driven by climatic variability, relative sea-level trends and intensifying human pressures (Anthony *et al.*, 2014). Italian examples highlight this transition: the multi-centennial evolution of the Ofanto delta links construction/reorganization to changes in flood frequency and synoptic circulation, whereas recent decades are dominated by anthropogenic sediment subtraction (e.g., dams and in-channel extraction) that overwhelms climatic signals (De Santis *et al.*, 2018). On the Tyrrhenian margin, the Voltorno delta plain records major channel, floodplain and delta-environment changes and coastline retreat following centuries of reclamation and land-use change (Ruberti and Vigliotti, 2017), while stratigraphic analyses document incision-aggradation cycles and valley filling in an active tectono-volcanic setting during the late Quaternary and Holocene (Amorosi *et al.*, 2012). Along the central Adriatic, the Marche Region is a key natural laboratory where Holocene evolution was strongly influenced by human activities affecting sediment production/transfer and the organisation of alluvial plains and coastal sectors (Coltorti, 1997; Coltorti *et al.*, 1991). Over the last century, river regulation, land-use change, infrastructure development and sediment extraction increasingly controlled river-mouth erosional-depositional dynamics (Materazzi *et al.*, 2010; Aringoli *et al.*, 2015), while coastal engineering and port works disrupted longshore transport and locally amplified erosion/accretion. Yet region-wide, quantitative assessments of planform change based on homogeneous multi-temporal sources remain scarce for the central Adriatic; GIS-based integration of 19th-20th century IGM sheets, archival aerial photographs and recent orthophotos enables consistent metrics of shoreline and mouth-position change and helps evaluate local interventions and sediment-budget discontinuities (De Santis *et al.*, 2018; Ruberti and Vigliotti, 2017). Within this framework, this study provides a diachronic analysis of selected river mouths along the gravelly-sandy coast of the Marche Region (late 19th century to present),

quantifying shoreline and mouth-morphology changes and discussing the relative roles of natural forcing and human drivers to support process-based interpretation and coastal-zone management.

STUDY AREA

Regional setting

The Marche coastline extends for about 172 km along the central Adriatic Sea, between the Emilia-Romagna border (north) and the Tronto River mouth at the Abruzzo border (south). It includes three main morphodynamic sectors: (i) a largely straight, northeast-oriented gravelly-sandy coast from Gabicce Mare to the port of Ancona; (ii) the Conero promontory, forming the major rocky headland with cliffs and pocket beaches; and (iii) the southern coast, where low-lying gravelly-sandy beaches alternate with short cliff sectors near Pedaso (Bisci and Dramis, 1991; Dramis *et al.*, 2011; Bisci *et al.*, 2023).

The regional hydrographic network is dominated by several Apennine rivers flowing WSW-ENE into the Adriatic. This work focuses on ten mouths with the clearest multi-temporal shoreline expression and the most extensive historical documentation: Foglia, Metauro, Misa, Esino, Musone, Potenza, Chienti, Tenna, Aso and Tronto (fig. 1a). These catchments range from a few hundred to about 1500 km² and are characterized by marked seasonality and high inter-annual discharge variability, which favors episodic sediment delivery during major floods. From a geological perspective, the region exposes the marine sedimentary deposits of the Umbro-Marchigiana Succession, uplifted and folded during Neogene-Quaternary tectonics (Calamita and Deiana, 1986; Centamore and Deiana, 1986; Centamore *et al.*, 1991). In their upper reaches, rivers drain carbonate rocks, whereas in middle and lower sectors they cut into marly-arenaceous units and Plio-Quaternary deposits. This lithological assemblage supports mixed gravel and sand supply to the coastal zone, consistent with the widespread gravelly-sandy beaches of the Marche littoral (fig. 1b).

Concerning the oceanographic and climatic characteristics, the Adriatic Sea is a large, elongated gulf (~70 nautical miles wide and ~350 nautical miles long), oriented NNW-SSE and connected to the Mediterranean to the south. Its northern sector is shallow, extending offshore from the Po delta to near Pescara, where the alluvial plain reached maximum extent during the Last Glacial Maximum (Würm glaciation). South of this, the seafloor deepens into the Central Adriatic Depression and reaches its greatest depths in the Southern Adriatic Depression. The Marche coast lies along the central-northern Adriatic, where bathymetry deepens progressively from north to south, from ~40 m to >100 m in the northernmost part of the Central

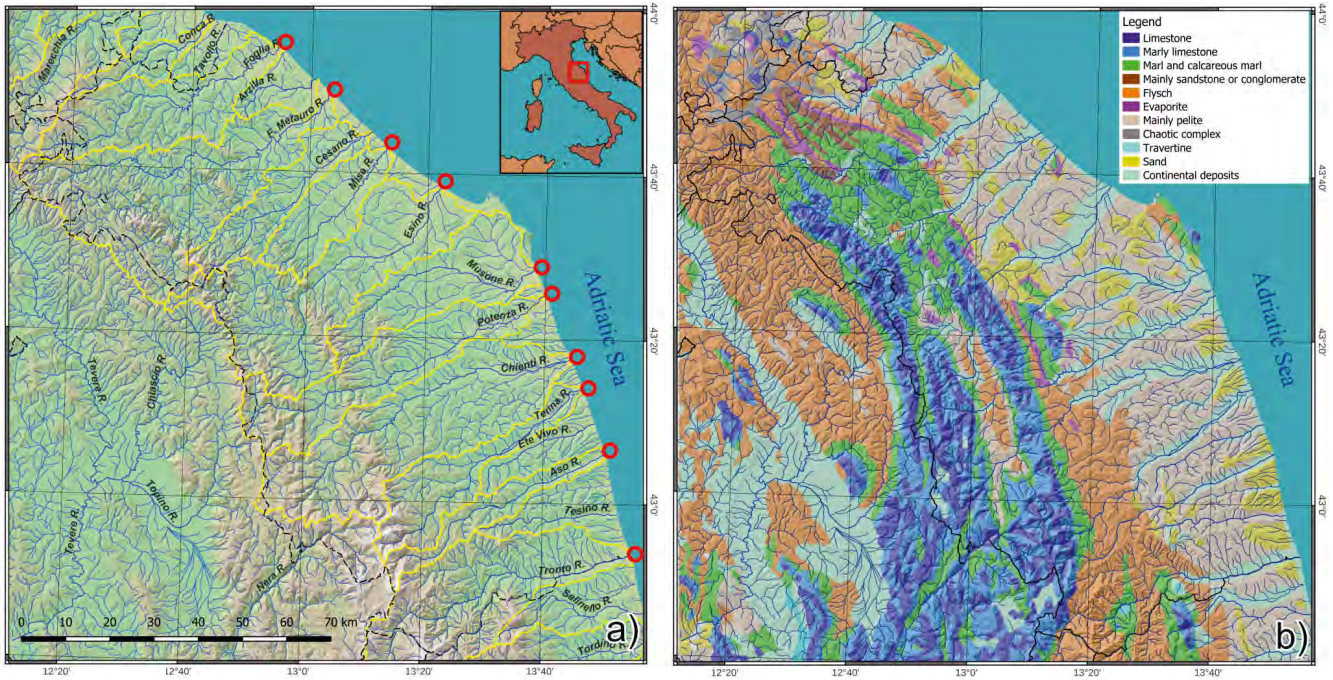


Figure 1 - a) Fluvial network and hydrographic basins in the Marche Region: red circles indicates the study cases described in the text. b) Lithologic sketch of the Marche region.

Adriatic Depression. Circulation is predominantly anticyclonic in winter-spring, while summer-autumn alternates between anticyclonic and cyclonic gyres; the East Adriatic Current (EAC) flows northward and the Western Adriatic Current (WAC) southward. Summer stratification reflects weaker hydrodynamics, whereas winter Bora-driven cooling promotes dense-water formation and southward export in spring (Bisci *et al.*, 2021b). Sea-level variability is controlled by tidal and meteorological forcing, with highest levels under low pressure and Levant/Sirocco winds, exceeding 1 m and increasing northward. Along the Marche coast, Sirocco (SSE) most frequently drives storm surges, while Bora (NE) and Grecale (ENE) generate the strongest winter storms (>4 m waves), yielding predominantly south-to-north longshore transport (Acciarri *et al.*, 2016; Bisci *et al.*, 2021b).

Historical evolution of central Adriatic river mouths and surrounding shorelines from the Last Glacial Maximum to the end of the Little Ice Age

During the Last Glacial Maximum (Würm maximum, ~20,000 years B.P.), Adriatic Sea level was ~120 m below present. Eastward-flowing rivers in the region were right-bank tributaries of the Po River, whose delta lay a few dozen kilometers SSE of the southern Marche boundary, offshore of present-day Pescara (Storms *et al.*, 2008). Intense debris production on slopes favoured widespread valley-bottom aggradation as flow velocities decreased and bedrock permeability increased, infilling pre-existing val-

leys with thick alluvial deposits and generating sub-horizontal top surfaces (Bisci and Dramis, 1991; Coltorti, 1991 and 1997; Coltorti and Farabollini, 2008; Acciarri *et al.*, 2016; Bisci *et al.*, 2021c, 2023).

With the onset of the Holocene, progressively warmer and more humid conditions towards the Holocene Climatic Optimum drove rapid sea-level rise during the Flandrian transgression (to ~6,000 years B.P.), at average rates of ~0.5-1.5 cm/yr (Bisci and Dramis, 1991; Gasparini and Tabacchi, 2011; Acciarri *et al.*, 2016; Bisci *et al.*, 2021c). Vegetation quickly colonised slopes and alluvial plains, and rivers incised into the cold-phase valley fills (Coltorti, 1991, 1997; Bisci *et al.*, 2021c). The lower valley reaches were drowned, producing deep rias that terminated in pocket beaches and were separated by active wave-cut cliffs (Speranza, 1934; Buli and Ortolani, 1947; Bisci and Dramis, 1991; Coltorti, 1991 and 1997; Coltorti and Farabollini, 2008; Gasparini and Tabacchi, 2011; Acciarri *et al.*, 2016; Bisci *et al.*, 2021c).

The first historical phase of progradation (Roman times) is mainly attributed not to climate, still favourable to vegetation cover, but to increasing anthropogenic pressure initiated in the Late Bronze Age and intensified during the Iron Age. Population growth and improved socioeconomic conditions promoted deforestation for timber and land clearing for cultivation, boosting debris supply; rias were progressively infilled and river outlets advanced to build lagoon-beach systems a few hundred metres landward of the cliffs, as supported by archaeological evidence (Speranza, 1934; Coltorti, 1997; Coltorti *et al.*, 1991; Galiè, 2001; Acciarri *et al.*, 2016).

Between the early 5th and mid-8th centuries, climatic deterioration (Hegerl *et al.*, 2007) combined with socioeconomic decline reduced populations, allowing vegetation recovery, decreasing sediment delivery and promoting shoreline retreat (Pranzini, 2001; Materazzi *et al.*, 2010; Bisci *et al.*, 2021c, 2023). The Medieval Climatic Optimum (~1100 AD; Hegerl *et al.*, 2007) reversed this trend: renewed demographic growth, deforestation and agriculture increased slope erosion, driving river-mouth advance (likely as small deltas), limited shoreline progradation, beach initiation and cliff deactivation (Coltorti, 1997; Williams, 2000; Abulafia, 2004; Bisci *et al.*, 2021c, 2023). This phase ended with the Little Ice Age (from the 14th century; Hegerl *et al.*, 2007), when population declined again, especially after the Black Death (1363), leading to farmland abandonment, vegetation expansion, reduced sediment loads, delta dismantling, shoreline retreat and local cliff reactivation (Grove, 2001; Ladurie, 2004; Materazzi *et al.*, 2010; Acciarri *et al.*, 2016; Bisci *et al.*, 2021c, 2023). Subsequent climatic improvement supported demographic growth (from ~400,000 at the end of the 14th century to ~710,000 by the early 19th century) and, together with political stability and new land-distribution systems, renewed deforestation and agricultural expansion. Increased debris production, amplified by downslope ploughing, triggered a further progradation phase, especially near river mouths (Pranzini, 1995; Ladurie, 2004; Arzeni *et al.*, 2012; Lee and Zhang, 2015; Bisci *et al.*, 2021c, 2023), rendering most cliffs inactive except the Conero promontory, the San Bartolo area and small sectors near Pedaso (Bisci *et al.*, 2021c, 2023).

MATERIALS AND METHODS

The research presented in this study is based on a multidisciplinary approach combining geomorphological, cartographic, and remote sensing analyses. The main objective was to reconstruct the recent evolution of the principal river mouths along the Marche coastline (fig. 1a), identifying morphological changes and understanding the processes that have shaped them through time.

To achieve this goal, a wide set of cartographic, photographic, and digital sources was used, covering a temporal span from the late 19th century to the present. These data allowed for the diachronic comparison of shoreline positions and morphologies at different stages of evolution, enabling the assessment of both long-term and short-term changes (tab. 1).

The workflow includes (i) data acquisition and georeferencing, (ii) shoreline and mouth digitization, (iii) estimation of positional uncertainty, and (iv) computation and interpretation of change metrics. All spatial processing was carried out in QGIS 3.40.3 (Bratislava).

Data sources

Six time slices were used to cover the late 19th century to present-day evolution (tab. 1). Historical topographic maps provide the earliest consistent depiction of the shoreline and river-mouth morphology. Mid-20th-century maps and 1977 aerial photographs document the onset and the peak of widespread coastal erosion. Orthophotos and recent satellite imagery capture the modern phase, strongly influenced by coastal engineering.

Georeferencing and positional uncertainty

All datasets were georeferenced in a common GIS environment using stable, well-identifiable ground control points (e.g., church towers, road junctions, long-standing buildings, bridge abutments) and a second-order polynomial or rubber-sheet transformation as appropriate for each source. For historical maps, the typical planimetric error includes (i) map scale-related cartographic generalization, (ii) scanning and digitizing error, and (iii) georeferencing residuals. For aerial photos and orthophotos, uncertainty is mainly controlled by image resolution, orthorectification quality and the interpretative choice of a shoreline proxy. To avoid over-interpreting small changes, we estimated a dataset-specific positional uncertainty (U) by combining (in quadrature) the georeferencing root mean square error (RMSE) and an additional term for feature interpretation and digitizing (commonly approximated as one map line width or one-to-two pixels). Shoreline displacements smaller than the combined uncertainty of the two compared time slices were treated as not significant.

Shoreline and river-mouth mapping

Shoreline position was digitized as the coastline depicted on historical maps and, for images, as the most consistent visible proxy (the wet/dry boundary or the instantaneous waterline on calm-day imagery). For each river mouth, we digitized: (i) the shoreline in a window extending at least 1-2 km on both sides of the outlet; (ii) the river-channel banks near the mouth; and (iii) emergent mouth bars or cusped protrusions where visible. Hard structures (jetties, groynes, detached breakwaters and shore-parallel revetments) were digitized as separate layers. They were not treated as 'shoreline' unless the backshore was physically connected to the structure and the beach surface was continuous with it (a situation that is explicitly discussed in the Results and Discussion). Historical maps were georeferenced in the Gauss-Boaga / Rome 1940 system (EPSG:3003) and all layers were stored and measured consistently in the same projection.

Finally, the above observations have been compared with the anthropic interventions occurred in the meanwhile in the catchment of each river, with special attention to mod-

Table 1 - Cartographic, photographic and digital sources used to reconstruct shoreline and river-mouth changes.

Dataset	Nominal scale / resolution	Date	Use in this study
IGM topographic map (III Military Survey)	1:50,000 (printed map)	1892-1894	Historical shoreline and mouth planform
IGM topographic map	1:25,000 (printed map)	1948-1955	Pre-engineering / early engineering phase
Aerial photographs (black and white)	photo scale ~1:33,000 (scan-dependent)	1977	Erosion peak and first defence works
Orthophotos	0.5-1 m pixel	1999-2000	Post-defence coastline configuration
Orthophotos	0.5 m pixel	2010	Recent evolution and nourishment/maintenance effects
Satellite imagery	sub-metric to few-metric (provider-dependent)	2024	Current shoreline and river-mouth configuration

Table 2 - Indicative positional uncertainty adopted for shoreline/mouth digitization and change interpretation.

Data type	Typical positional uncertainty (U)	Main contributors
1:50,000 historical maps	±20-30 m	cartographic generalization; georeferencing RMSE; line width
1:25,000 maps	±10-20 m	generalization; georeferencing RMSE; line width
1977 aerial photos	±5-15 m	orthorectification/georeferencing; shoreline proxy interpretation
Orthophotos (1999-2000, 2010)	±2-5 m	pixel size; shoreline proxy interpretation
Recent satellite imagery (2024)	±2-5 m	provider geolocation; shoreline proxy interpretation

ifications potentially affecting the river sediment load, and along the littoral (seawalls, revetments, breakwaters, and beach nourishment). For the former, data mostly derived from studies carried out in the region or in comparable areas (Buli and Ortolani, 1947; Buccolini and Gentili, 1986; Bisci *et al.*, 1992, 2021a, 2023; CNR-MURST, 1997; Aringoli *et al.*, 2015, 2025; Dramis *et al.*, 2011; Materazzi *et al.*, 2010; Gasparini and Tabacchi, 2011; Arzeni *et al.*, 2012; Giacompetti *et al.*, 2015; Bufalini *et al.*, 2022, 2023; Beleggia, 2023).

Change metrics

For each time interval, we assessed (i) shoreline displacement (retreat/progradation) at the mouth apex and on the updrift and downdrift flanks, measured as the shortest distance between shoreline polylines; and (ii) areal changes in protruding depositional bodies (mouth bars and cusped deltas) when mappable. Because uncertainty varies among datasets, results are reported as ranges and interpreted focusing on changes that substantially exceed the combined uncertainty thresholds.

RESULTS

The multi-temporal analysis highlights a common regional trajectory: (1) late 19th-century protruding mouths and locally prograding shorelines; (2) widespread mid-20th-century retreat culminating around the 1970s; and (3) a late-20th to early-21st century phase increasingly controlled by coastal engineering, with localized accretion near structures and persistent erosion in unprotected sectors. Below, the main changes are summarized for each river mouth.

Foglia River

As early as 1894, the mouth of the Foglia River (fig. 2) had already undergone significant artificial modifications with the construction of three groins – two positioned at the edges of the river’s outlet and another about 200 m further north – designed to channel river sediments offshore. This configuration remained unchanged through the 1950s, but its effects on the surrounding coastline became evident, with the retreat of around 50 m to the south and more than 100 m to the north, where the beach had nearly disappeared.

By 1977, there was a slight retreat of the section between the two groins, with the left-bank groin undergoing minor alterations and the addition of a small canal port on the left bank. In 1999, previous rigid coastal structures had been further modified to create a small harbour between the two outermost piers, while the beach immediately north of the fortified mouth had expanded by about 50 m. Recent satellite imagery (2024) confirms this trend; the harbour piers have been modified and extended, while the surrounding coast remains largely stable, except for minor localized retreat north of the harbour, despite the widespread presence of protective barriers covering almost the entire coastline.

Metauro River

In 1894, the mouth of the Metauro River (fig. 3) exhibited a typical convex shape, extending nearly 250 m beyond the average shoreline and spanning a couple of kilometres laterally, indicating a progradational trend. This morphology persisted in 1948, although slightly retreated by a few dozen meters, likely due to reservoir construction along the river’s course.



Figure 2 - Recent variation of the Foglia River mouth.

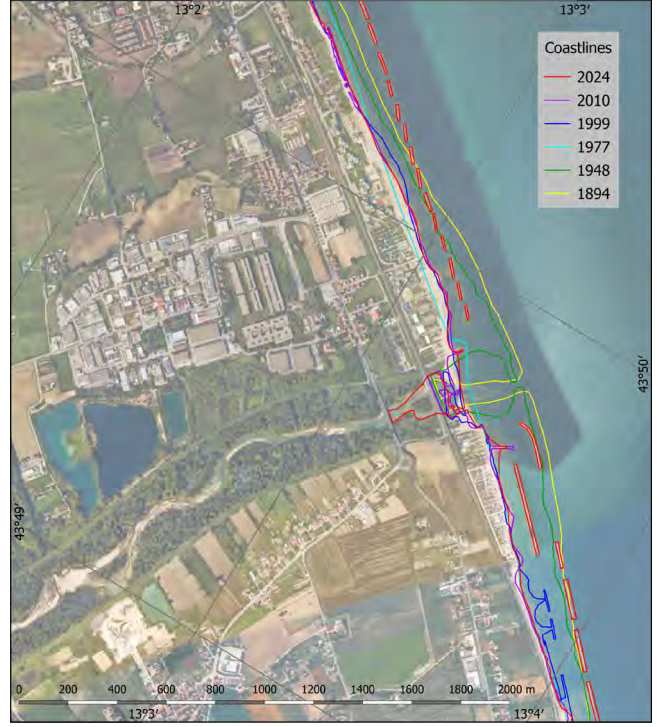


Figure 3 - Recent variation of the Metauro River mouth.



Figure 4 - Recent variation of the Misa River mouth.

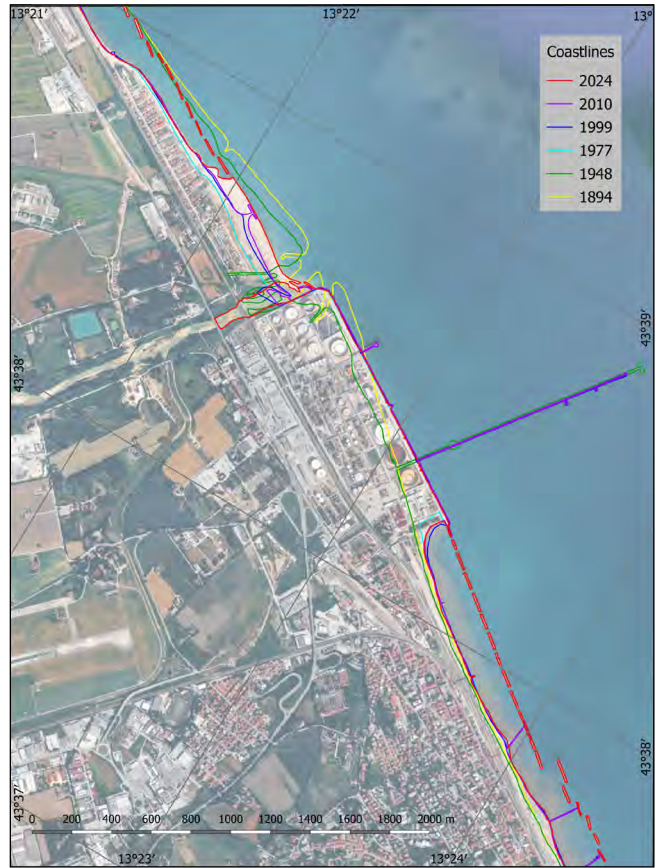


Figure 5 - Recent variation of the Esino River mouth.

By 1977, the situation had dramatically changed: the combined impact of multiple anthropogenic factors had dismantled the entire sedimentary body, and the river mouth appeared recessed compared to the average shoreline, demonstrating that fluvial sediment supply could no longer compensate for wave erosion.

Subsequently, the mouth and surrounding coastline stabilized, largely due to engineering interventions, including numerous offshore barriers approximately 100 m from the shore and two small groins near the river's outlet.

Misa River

The 1894 map indicates the presence of a small groin on the right bank of the Misa River's mouth (fig. 4), which created a slight protrusion in the coastline, more pronounced to the south, likely due to sediment accumulation from the groin's influence. In 1948, the situation remained nearly unchanged south of the mouth, while the northern coastline displayed a somewhat irregular retreat of a few dozen meters.

By 1977, the northern coast showed a modest advance near the river mouth. In 1999, harbour structures had been built, and the southern coast exhibited a slight progradational trend, while the northern section was retreating near the harbour yet advancing in its farther reaches. In the following years, the southern coast remained stable, except for its northernmost extreme where minor progradation occurred, while the northern coast experienced pronounced progradation – advancing over 50 m near the harbour – thanks to the construction of continuous offshore barriers located more than 100 m from the shore.

Esino River

In early maps, the Esino River mouth (fig. 5) displayed clear progradation trends, with a convex morphology extending over 200 m beyond the average shoreline and spanning approximately 3 km laterally. In 1948, the mouth's sediment deposits showed a moderate retreat, with a less accentuated curvature.

By 1977, significant anthropogenic modifications were evident on the right bank near the mouth, attributed to the construction of a large oil refinery. This development led to artificial shoreline advancement in the affected area, which was protected by attached structures and presented a perfectly linear profile. South of this embankment, the coastline remained largely undisturbed, while to the north of the river mouth, a notable retreat was observed.

In the following years, the retreat near the river mouth was mitigated by the installation of offshore barriers about 100 m from the shoreline. Similar structures, sometimes connected to the mainland via groins, have largely preserved the southern coastline's stability.

Musone River

At the end of the 19th century, the Musone River mouth (fig. 6) displayed a significant convex-shaped sedimentary body extending nearly 100 m offshore from the average shoreline and spanning laterally over a kilometer. By the mid-20th century, the northern portion of this deposit showed an average advance of about 20 m near the river mouth while remaining stable farther north, whereas the southern portion experienced an average retreat of a few dozen meters.

By 1977, the coastline appeared almost perfectly linear, as the entire sedimentary body extending offshore had been eroded, likely due to the previously discussed complex anthropogenic influences. In subsequent years, the shoreline remained relatively straight, although in 2010 a slight progradation was observed to the north, which was later dismantled in the most recent images. Meanwhile, a retreat occurred near the immediate vicinity of the river mouth, unprotected by rigid coastal defence structures.

Potenza River

In 1894, the Potenza River mouth (fig. 7) exhibited a modest convex-shaped sediment accumulation extending some dozen meters offshore, with a lateral spread of several hundred meters. By the mid-20th century, this deposit had significantly grown, especially in its northern section and immediately south of the river outlet, where shoreline advancements exceeded 50 m.

The 1977 map revealed the complete dismantling of this sedimentary body, leaving a relatively linear shoreline. This situation remained largely unchanged in 1999 despite the presence of an initial small groin, and subsequent years showed no major variations except for the construction of additional engineering defence structures. These included a continuous series of offshore barriers south of the river mouth, which locally induced a minor progradation just south of the river outlet.

Chienti River

At the end of the 19th century, the Chienti River (fig. 8) exhibited a substantial sediment accumulation, projecting approximately 300 m beyond the average shoreline and spanning over 2 km laterally.

In the post-war period, significant retreat was observed, locally reaching 250 m, likely due to the upstream sediment blockage caused by the dams of Polverina, Caccamo, Fiastra, and Grazie. However, in the northern sector, the construction of harbour structures in Civitanova Marche led to considerable sediment accumulation, inducing shoreline progradation of about 250 m near the southern pier.

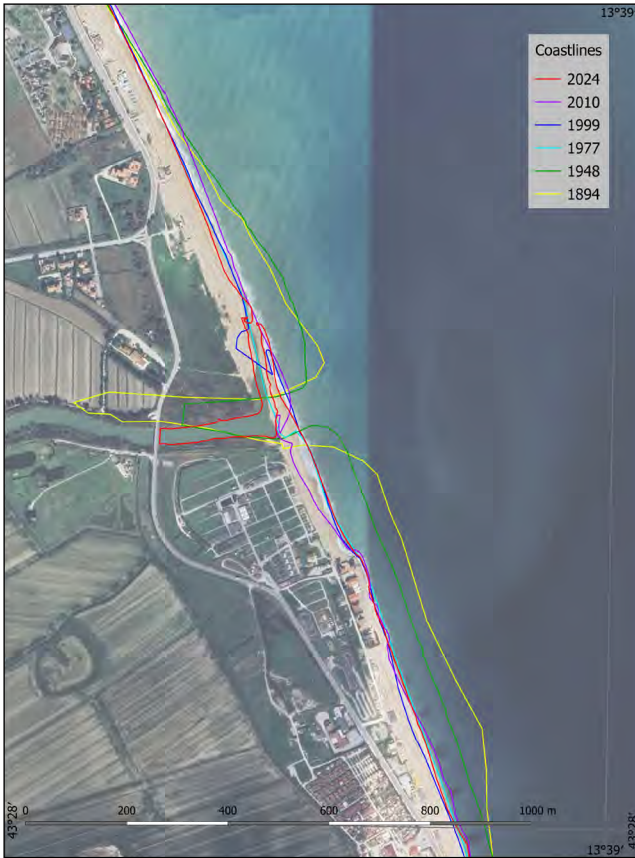


Figure 6 - Recent variation of the Musone River mouth.

Both trends remained evident by 1977. More recently, the shoreline has remained largely stable, except for a minor recent advancement just south of the port structures.

Tenna River

At the end of the 19th century, the Tenna River mouth (fig. 9) extended over 200 m offshore from the average local shoreline, with a lateral spread of about 2 km. However, by the early post-war period, this sedimentary accumulation has been almost completely eroded and the river outlet protruded about 100 m.

By 1977, the mouth was nearly aligned with the surrounding shore due to further retreat. This trend continued in the following years, leading to the complete removal of the sediment deposit by the end of the century.

The subsequent construction of a loading pier, oddly placed on the left bank (updrift relative to the dominant sediment transport), led to a significant sediment accumulation south of the structure, which now extends about 150 m offshore. This has restored the southern coastline to near its post-war positions, aided by continuous protective barriers. However, this intervention also induced severe erosion problems north of the river mouth, prompting the

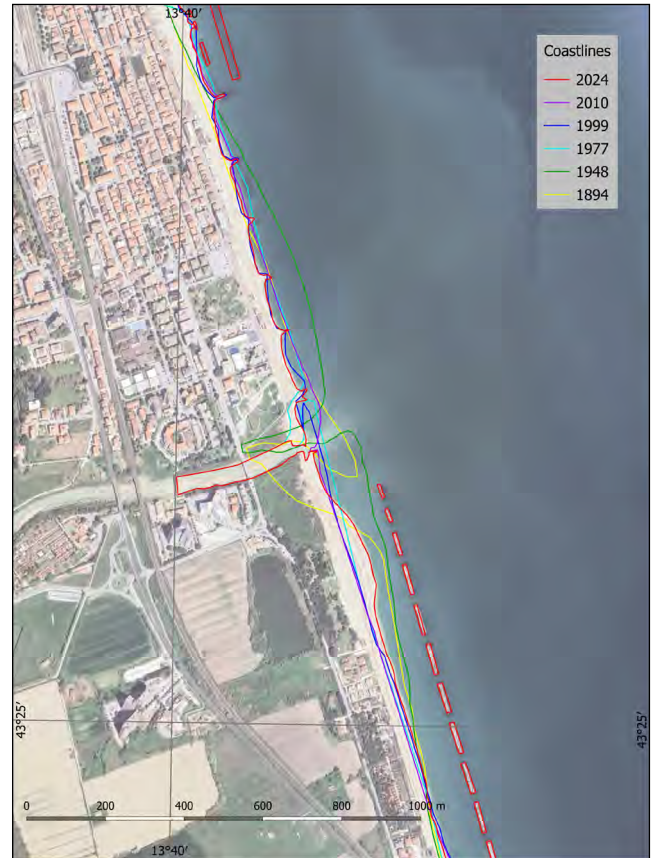


Figure 7 - Recent variation of the Potenza River mouth.

construction of an extensive series of barriers about 200 m offshore. These barriers have artificially reshaped what was previously the longest stretch of natural shoreline south of the Conero Mt. and, despite two artificial nourishment projects and the extension of the loading pier, erosion remains ongoing.

Aso River

The Aso River (fig. 10), the smallest of the studied streams, displayed a convex-shaped sedimentary body in early maps, extending about 70 m offshore and spanning over 1.5 km laterally.

However, by the post-war period, much of the northern mass had been lost, and the southern portion was completely eroded, likely due to reduced sediment inputs following the construction of the Gerosa Dam.

By 1977, a further significant retreat of the entire shoreline was observed, leading to the construction of numerous coastal protection structures (groins and barriers) by the late 20th century. However, these interventions proved to be largely ineffective in reversing shoreline retreat, as did the later installation of a large protection works on the right bank, which now exhibits characteristics of a small estuary.

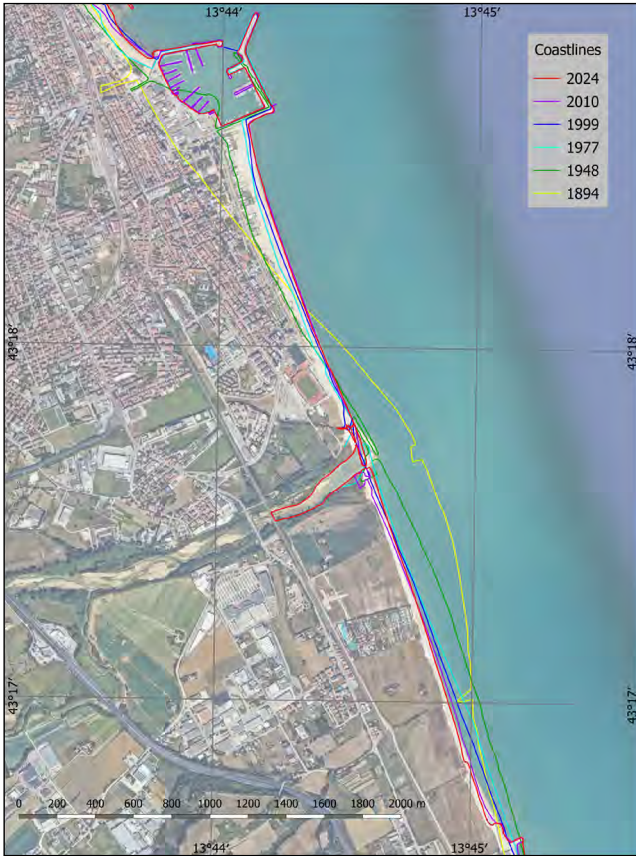


Figure 8 - Recent variation of the Chienti River mouth.

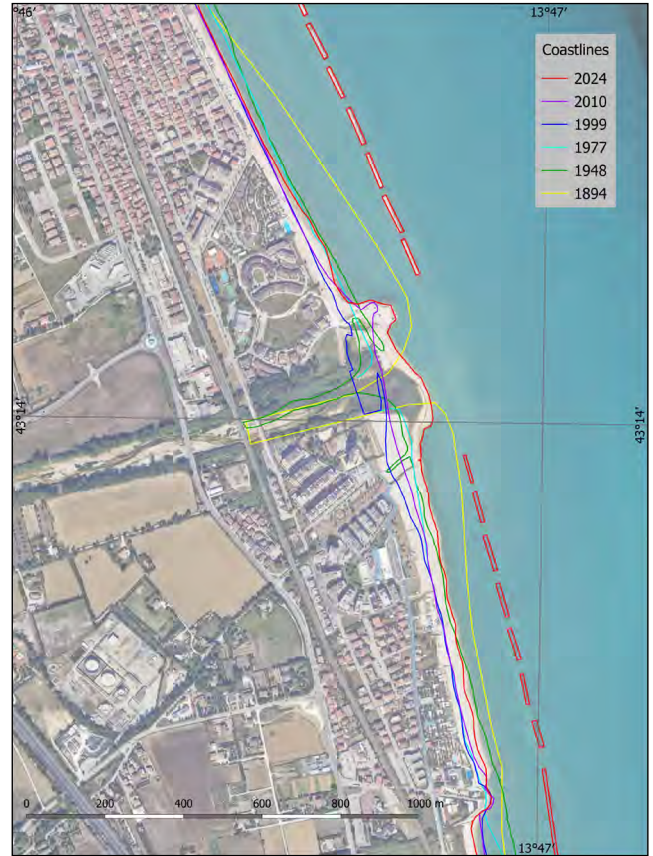


Figure 9 - Recent variation of the Tenna River mouth.

Tronto River

The Tronto River (fig. 11), which has the largest drainage basin among those studied, also marks the border between the Marche and Abruzzo regions. The 1894 map showed a substantial sediment accumulation, more developed in its southern section, extending about 400 m offshore and spanning over 4 km laterally.

However, upstream sediment reduction due to the construction of the Campotosto, Scandarello, and Talvacchia reservoirs led to rapid retreat of the river mouth. By the first half of the 20th century, the northern sector had retreated by about 100 m, while the southern portion was almost completely dismantled, with local retreat reaching nearly 400 m.

To counteract this trend, a pier was constructed on the right bank to reinforce the mouth. Unfortunately, this structure not only failed to restore the shoreline on the Abruzzo side, where subsequent defensive works (groins and barriers) proved ineffective, but worse still it accelerated erosional processes in the northern sector, affecting the Regional Nature Reserve of Sentina, where, by 1977, coastal retreat exceeded 400 m from the initial measurements. This process was exacerbated by intensive aggregate mining in the riverbed; while erosion has slowed in more recent years, the lack of sediment supplies compatible with wave energy remains, coupled with

the effects of a continuous series of offshore barriers from the Port of San Benedetto del Tronto to the northern boundary of the former river mouth accumulation, preventing contributions from storm surges coming from the first quadrant.

DISCUSSION

The reconstructed trajectories indicate a clear shift in the dominant controls on river-mouth morphology along the Marche coast. Large protruding mouths mapped in the late 19th century imply a coastal system that was still able to translate episodic fluvial sediment pulses into net progradation or at least maintenance of mouth bars. The pronounced retreat observed between the 1950s and the late 1970s is consistent with a region-wide reduction in sediment supply caused by dam construction, bedload extraction and channel regulation, combined with the post-war expansion of coastal infrastructure (such as the “Adriatic” railway and urbanization) (fig. 12).

Similar transitions from progradation to erosion have been documented for other Italian deltas and river-mouth systems, including the Ofanto delta in Apulia and the Volturno system in Campania (De Santis *et al.*, 2018; Amorusi *et al.*, 2012; Ruberti *et al.*, 2017).

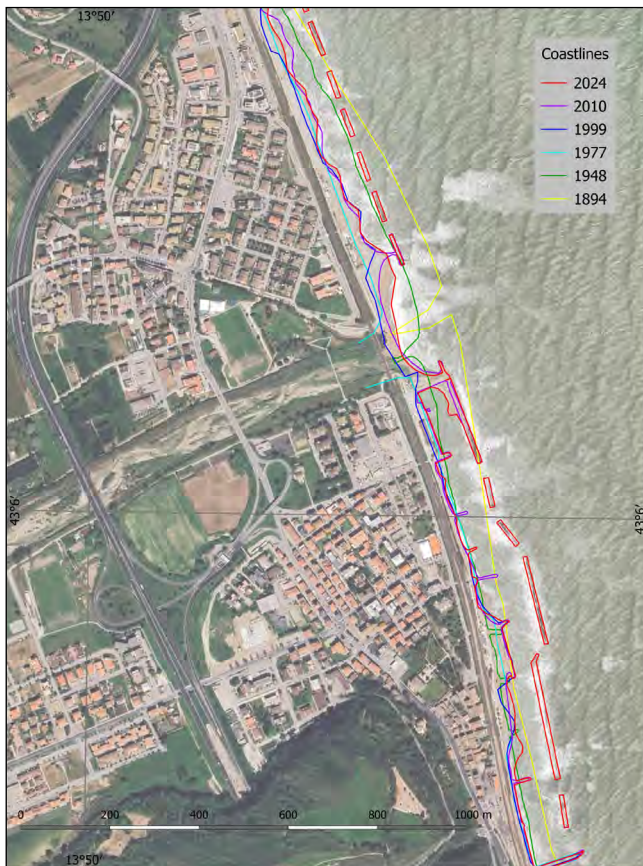


Figure 10 - Recent variation of the Aso River mouth.

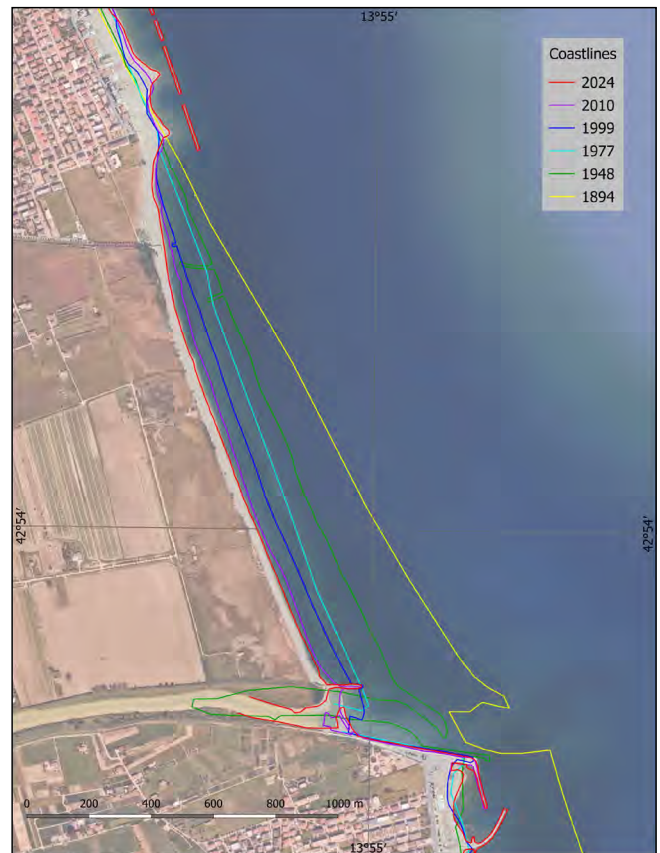


Figure 11 - Recent variation of the Tronto River mouth.

At the local scale, the results highlight that since the late 1970s shoreline evolution has been increasingly controlled by hard engineering. Detached breakwaters and groynes interrupt and redistribute longshore sediment transport, producing characteristic accretion in sheltered areas and persistent erosion in downdrift sectors. This mechanism is especially evident at the Tenna mouth, where the loading pier generates a strong planform asymmetry, with rapid updrift progradation and ongoing downdrift retreat. Similar, albeit smaller-scale, effects occur near harbor and river-training works (e.g., Pesaro, Senigallia, Civitanova Marche and San Benedetto del Tronto), where local accretion often reflects sediment impoundment rather than recovery of the regional sediment budget.

An important implication is that the apparent stabilization of many mouths after the 1970s does not necessarily indicate a return to a natural equilibrium. Instead, it reflects a transition toward an ‘armoured’ coast, where shoreline position is constrained by structures and where sediment is redistributed within short compartments (fig. 13). In such settings, engineering maintenance and nourishment can mask persistent sediment deficit, while increasing the vulnerability of adjacent unprotected tracts.

Uncertainty analysis is crucial when interpreting historical shoreline change. For early maps, the uncertainty

is on the order of tens of metres; therefore, only changes substantially exceeding this threshold should be used to support process inferences. The largest retreats documented here (hundreds of metres at several mouths) are robust, whereas small decadal oscillations in the recent datasets may reflect short-term hydrodynamic variability, seasonal shoreline position and management interventions.

From a management perspective, the results support basin-to-coast approaches that couple river sediment continuity with coastal planning. Measures such as sediment bypassing at dams, regulation of gravel extraction, strategic nourishment, and redesign of defence systems to reduce downdrift impacts should be evaluated within an integrated sediment budget framework. This is particularly relevant in the context of accelerating relative sea-level rise, which is expected to increase the exposure of engineered, sediment-starved coasts to storm impacts.

CONCLUSION

This study provides a consistent reconstruction of shoreline and river-mouth planform changes along the Marche coast over the last ~130 years, based on integrated

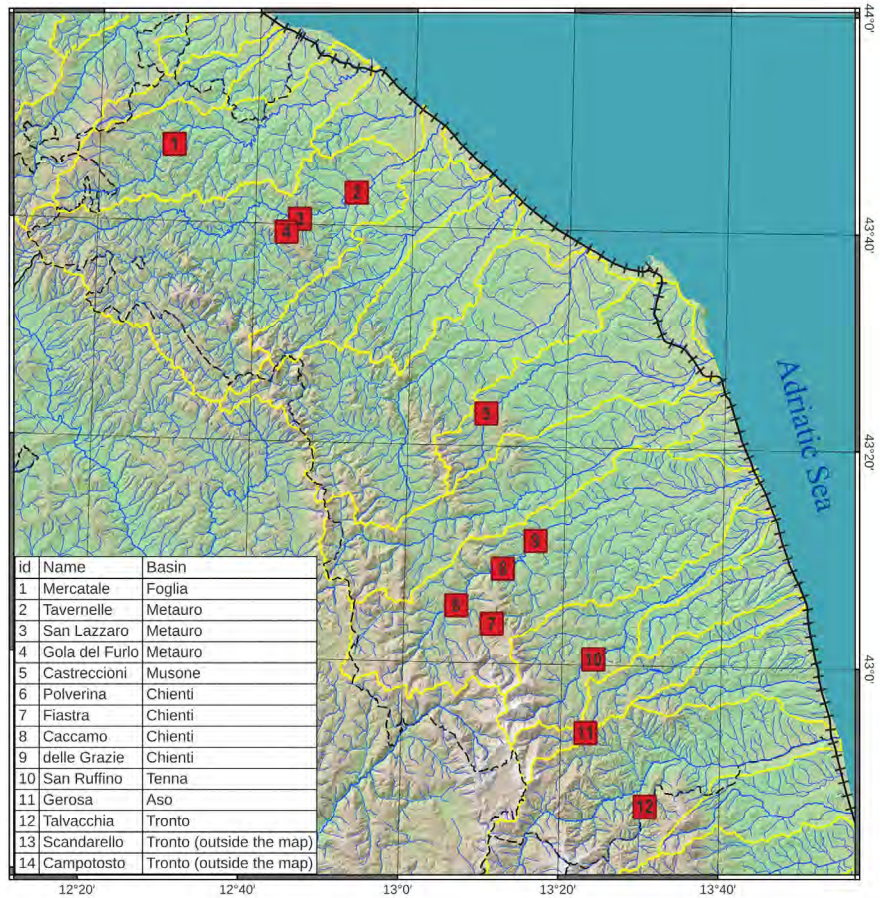


Figure 12 - “Adriatic” railway line and major river barriers in the Marche region.

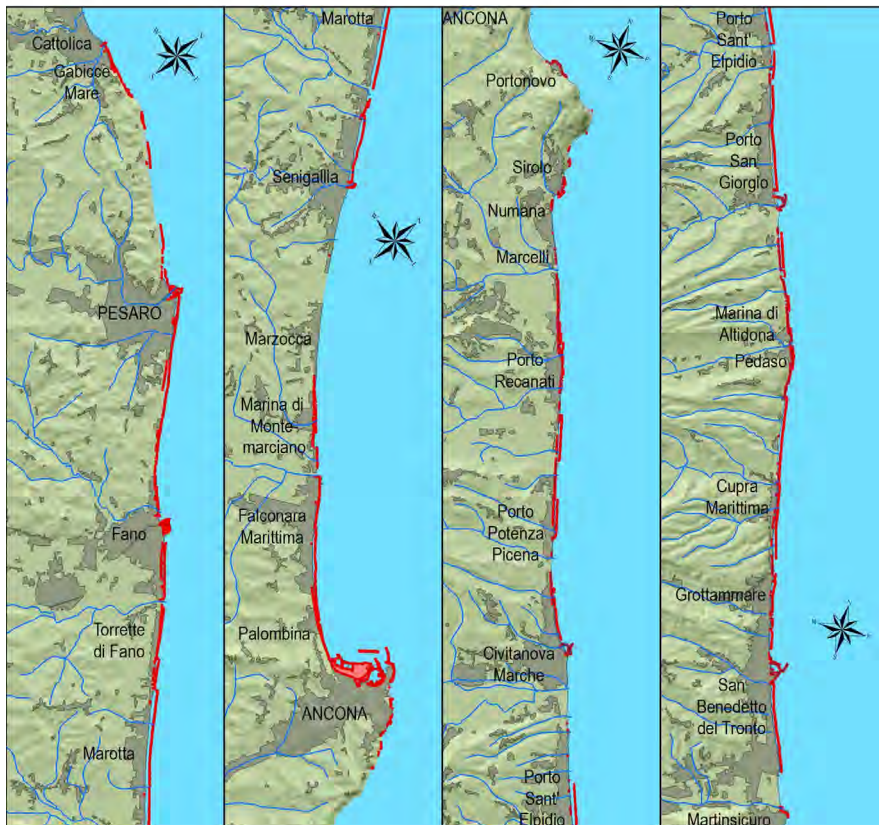


Figure 13 - Distribution of rigid coastal protection structures (in red) in 2020.

historical cartography, aerial photography and recent imagery. The main conclusions are:

- In the late 19th century, most mouths displayed protruding depositional forms, suggesting an active fluvial contribution to coastal sediment budgets.
- A widespread phase of retreat occurred between the 1950s and the late 1970s, locally exceeding 100-400 m, consistent with a strong reduction in sediment supply and increasing coastal pressures.
- Since the late 1970s, shoreline evolution has been increasingly constrained by hard engineering. Detached breakwaters, groynes and port structures promoted localized accretion but also created downdrift erosion and compartmentalized shoreline behaviour.
- Present-day stability of several mouths largely reflects structural control and maintenance actions rather than recovery of a natural sedimentary equilibrium. Overall, the Marche river mouths illustrate a broader transition from river-fed coastal progradation to an engineered, sediment-starved coast. Future research should complement planform reconstructions with quantitative sediment budgets and wave-current modelling to support adaptive coastal management.

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