D2.2 – Joint Gap Analysis

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About this document

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Table of Contents

List of Abbreviations

AI – Artificial Intelligence

ARMS – Autonomous Reef Monitoring Structures

Cal/Val – Calibration / Validation

CTD – Conductivity, Temperature, Depth

DIC – Dissolved Inorganic Carbon

DNA – Deoxyribonucleic Acid

EMODnet – European Marine Observation and Data Network

ENA – European Nucleotide Archive

EO – Earth Observation

EOSC – European Open Science Cloud

ERIC – European Research Infrastructure Consortium

ESA – European Space Agency

ESFRI – European Strategy Forum on Research Infrastructures

FAIR – Findable, Accessible, Interoperable and Reusable

GNSS – Global Navigation Satellite System

HF – High Frequency

HF radar – High-Frequency radar

INFRA-DEV – Infrastructure Development (Horizon Europe call)

INFRA-SERV – Infrastructure Services (Horizon Europe call)

INFRATECH – Infrastructure Technology (Horizon Europe call)

InSAR – Interferometric Synthetic Aperture Radar

LCD – LandSeaLot Co-Designer forum

LCOS – LandSeaLot Common Observation Strategy

LIL – LandSeaLot Integration Lab

LSC – LandSeaLot Science Committee forum

LSI – Land-Sea Interface

MSFD – Marine Strategy Framework Directive

MSP – Maritime Spatial Planning

OBIS – Ocean Biodiversity Information System

OGC – Open Geospatial Consortium

pCO_2 – Partial pressure of carbon dioxide

RI – Research Infrastructure

RIA – Research and Innovation Action

WFD – Water Framework Directive

Executive Summary

This deliverable presents the first gap analysis of the land-sea interface (LSI) research and observation capacities across Europe. This deliverable builds on the LandSeaLot Common Observation Strategy (LCOS, D2.1), inputs from two LandSeaLot Research Infrastructure (RI) workshops and detailed RIs questionnaires responses, stakeholder fora, and existing European and national initiatives. This document identifies key scientific, technical, organisational, geographical, and policy-related gaps that currently limit Europe's ability to observe, understand, and manage the LSI.

The parameter-level analysis based on RIs questionnaires confirms that Europe possesses strong thematic excellence within individual RIs. Capabilities are distributed across complementary domains:

- Hydrology, ecology, sediments and source-to-sea integration (DANUBIUS-RI);
- High-frequency coastal physics and biogeochemistry (JERICO);
- Carbon system observations (ICOS-ERIC);
- Biodiversity and genomic monitoring (EMBRC-ERIC);
- Geohazards and coastal risk monitoring (EPOS-ERIC).

Together, these infrastructures provide the building blocks for a comprehensive LSI observation system.

However, the dominant gaps are not primarily due to a lack of observation capacity. Rather, they stem from fragmentation and insufficient cross-domain integration. Key structural weaknesses include:

- Limited operational linkage across the river–estuary–coastal–marine continuum;
- Weak process coupling between sediments, biodiversity, nutrients, carbon and hazards;
- Absence of harmonised Essential LSI Variables and shared ontologies;
- Heterogeneous repositories and limited machine-actionable interoperability;
- EO products frequently used but not structurally integrated via sustained Cal/Val pipelines;
- Project-based coordination rather than sustained cross-RI governance mechanisms;
- Major disparities regarding coverage of observation between LSI areas around Europe.

The following priority technical gaps emerge clearly from the parameter-level analysis:

- Enhanced process-level biodiversity observation and systematic co-location with physical and biogeochemical drivers remain essential to understand ecosystem functioning under climate and anthropogenic pressures;

- Continuous, high-quality chemical observation (including contaminants) in dynamic estuarine and general coastal intertidal environments, where harsh gradients, turbidity and biofouling limit sustained high-frequency observations;
- Broader coastal carbon system coverage and improved integration of long-term autonomous platforms, particularly in low-salinity and highly variable LSI zones.

A critical extension of this analysis was carried out during the 2026 LandSeaLot Week, through LandSeaLot Common Observation Strategy (LCOS, D2.1) – Joint Gap Analysis (D2.2) Working Groups direct feedback and Stakeholders' consultations on the draft versions of the above-mentioned documents through an online questionnaire. Participating experts and stakeholders emphasised that current observation systems focus primarily on environmental state variables, while human activities and pressures (e.g. dredging, wastewater discharge, harbour operations) are insufficiently observed. This limits the ability to understand cause-effect relationships and to inform policy and management.

The most significant gaps identified are:

- Fragmentation across disciplines, infrastructures, and governance systems;
- Weak integration along the river–estuary–coastal continuum;
- Limited observation and quantification of human pressures;
- Lack of harmonised Essential Land–Sea Variables (ELSV) and shared ontologies;
- Existing data that are often not actionable, not interoperable, or not accessible;
- Insufficient investment in data stewardship, FAIR implementation, and digital infrastructure;
- Lack of sustained coordination mechanisms and unclear institutional responsibility;
- Underutilisation of Citizen Science and local observatories.

Scientific gaps include limited understanding of:

- Habitat-scale dynamics and coastline definitions;
- Cross-domain process coupling;
- Carbon fluxes and Blue Carbon[1] storage processes;
- Interactions between pollutants and ecosystem/human health.

Technical gaps include:

- Limited observation in dynamic estuarine and intertidal zones;
- Incomplete EO–*in-situ* integration and validation pipelines;

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[1] Blue Carbon is carbon captured and stored by marine and coastal ecosystems

- Temporal resolution mismatches and sensor limitations.

Again, a key finding is that data gaps are not primarily about data absence, but about usability, accessibility, and governance. Many datasets exist but remain fragmented, inaccessible, or insufficiently standardised.

The analysis highlights that the key European challenge is one of coordination, incentives, and institutional alignment, rather than technological capability.

An important structural limitation of this analysis must be acknowledged. While focused on ESFRI/ERIC and major European RIs, Europe also hosts a large number of local, regional and national coastal observatories outside these frameworks. A comprehensive inventory of their measured parameters, methodologies, data standards, accessibility and long-term time series is currently missing.

Overall, this Joint Gap Analysis demonstrates that Europe's challenge is one of consolidation rather than duplication. The most critical gaps concern integration, harmonisation and sustained coordination - not the absence of observatories. Addressing these gaps aligns directly with ESFRI Landscape consolidation priorities.

LandSeaLot is positioned as a catalyst for structured European LSI integration, enabling coordination across existing infrastructures, co-definition of shared priorities, and strategic alignment with the European INFRA-DEV, INFRA-SERV and INFRATECH funding instruments. The findings provide a robust foundation for the next iteration of the LandSeaLot Common Observation Strategy and for coordinated European action towards integrated, sustainable Land–Sea Observation capacity.

1. Background

1.1. The Land–Sea Interface Challenge

The land-sea interface (LSI) encompasses coastal zones, and shelf seas, as well as river catchments, transitional waters, estuaries and deltas. It is a dynamic continuum where physical, biogeochemical, ecological, and socio-economic processes interact across scales. The LSI is a hotspot of anthropogenic pressures, climate change impacts and socio-economic activities, making it a priority area for observation, research, and a key component of European policy frameworks (WFD, MSFD, Floods Directive, MSP, emerging Water Resilience Strategy, European Ocean Pact, Zero Pollution Action Plan) and the blue economy.

Despite its importance, observation and research in the LSI remain fragmented across disciplines, administrative boundaries and infrastructures. Terrestrial, freshwater, and marine scientific communities often operate separately, using different concepts, variables, standards and data systems. This fragmentation results in observation gaps that limit scientific understanding, policy support, societal resilience and business sustainability.

A critical limitation is that human activities and pressures are insufficiently recorded and the results not well integrated in the measured data series, despite being major drivers of LSI dynamics.

1.2. Purpose and Scope of the Gap Analysis

This deliverable:

- Identifies and characterises gaps in current LSI observation across Europe;
- Integrates RI parameter-level information into a structured gap assessment;
- Assesses complementarities and overlaps among Research Infrastructure (RIs);
- Provides evidence to guide joint actions, supersites, and future European RI consolidation efforts.

The scope of the analysis covers:

- *In-situ* observations, EO, modelling and Citizen Science observations;
- Pan-European, national, regional, and local observational RIs;
- The full land-sea continuum: from catchments to coasts and nearshore waters.

2. Methodological Approach

2.1. Sources of Information

The analysis builds on:

- ESFRI Landscape Analysis 2024[2];
- LandSeaLot D2.1 – Towards a common observing strategy of the Land-Sea interface, and joint services (LCOS-v1);
- LandSeaLot RIs Workshops (January and July 2025);
- LandSeaLot RIs Workshops minutes and synthesis documents;
- LandSeaLot RIs Questionnaires responses (i.e., RI self-assessments of observed variables, methods, coverage, and data repositories) from:
    - DANUBIUS-RI
    - JERICO
    - ICOS-ERIC
    - EMBRC-ERIC
    - EPOS-ERIC
- Inputs from LandSeaLot WP3 - Integrated observation and model frameworks, WP4 - Increasing the observation capacity, WP5 - LandSeaLot Integration Labs (LIL) and WP6 - Data Management and services;
- Discussions and direct feedback during the 2026 LandSeaLot Week on the LandSeaLot Common Observation Strategy (LCOS, D2.1) and Joint Gap Analysis (D2.2) from LCD-LSC Workshop Working Groups;
- Stakeholders' consultations on the draft versions of the LCOS and Joint Gap Analysis documents through online questionnaire.

Limitations:

- There is the probability that other gap analyses were performed in other projects and not identified and integrated;
- Inland observation systems remain underrepresented;
- Repeated consultations risk stakeholder fatigue.

2.2. Analytical Dimensions

Gaps were analysed across six complementary dimensions:

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[2] https://landscape2024.esfri.eu/

(1) Scientific gaps – missing variables, processes, or system understanding;
(2) Technical and observational gaps – limitations in sensors, platforms, methodologies, and interoperability;
(3) Spatial and temporal coverage gaps – uneven geographical coverage and observation frequency, and insufficient long-term observations;
(4) Data and digital interoperability gaps – FAIRness, standardisation, integration, and AI-readiness;
(5) Data stewardship and usability gaps;
(6) Governance and coordination gaps – fragmentation across RIs, policies, and stakeholder communities.

2.3. Analysis of the information

To complement the qualitative outcomes from the RI workshops, LandSeaLot collected a structured questionnaire on parameters and capabilities from environment-related Research Infrastructures (DANUBIUS, JERICO, ICOS, EMBRC, EPOS). The responses provide a first comparable snapshot of what is currently observed and/or modelled, where, and with which access pathways, specifically relevant to the land-sea interface (LSI).

The Excel questionnaire responses came from:

- DANUBIUS-RI,
- JERICO,
- ICOS-ERIC,
- EMBRC-ERIC,
- EPOS-ERIC.

And were uploaded (in)to ChatGPT (= AI, see Box) and ChatGPT was instructed/asked to extract:

- Cross-RI observed parameters coverage snapshot (sub-chapter 3.3.1.1);
- RIs specific highlights and constraints (sub-chapter 3.3.1.2).

This ensured the gap analysis was grounded in empirical RI-reported capability.

The ChatGPT output was copy-pasted in the related chapters and further refined and improved by the authors. Then the LandSeaLot Science Committee forum (LSC) was asked to review the draft D2.2 – Joint Gap Analysis. This review included:

- A look back at the original questionnaires
- A sanity check of the ChatGPT output, including possible enrichment, assessment of essential missing pieces, other priorities, etc.

We further integrated into the current Joint Gap Analysis the direct feedback received from LandSeaLot Co-Designer forum (LCD) and LSC experts during the 2026 LandSeaLot Week, as well as stakeholders' feedback on the draft versions through online questionnaire consultations.

Box: Use of AI in LandSeaLot (LSL)

Grant Agreement: "*The project will make use of novel artificial intelligence approaches. The LSL consortium will ensure that the highest ethical standards are used during the development, deployment, and/or use of AI-based solutions. Those will be clearly described in the project deliverables. The ethics advisor with appropriate expertise in the ethics of new and emerging technologies will be involved in the development stage. The Assessment List for Trustworthy Artificial Intelligence (ALTAI) will be followed to develop procedures to detect, assess the level and address potential risks. If at any time in the project, a Regulation laying down harmonized rules on artificial intelligence by the EU legislator is adopted, the regulations will be followed.*"

Ethics report: "*Finally, as Artificial Intelligence (AI) is evolving quickly and its role in all kinds of domains is growing, partly even without notice, there is a need in LSL to be clear about the direct or indirect use of AI. This deliverable, therefore, needs to produce an overview of the role of AI in the methods, techniques and deliverables of the LSL project.*

- Transparency which includes that AI (supported) decisions need to be explained in a way that is adapted to the stakeholder as well as that humans are aware that they are in contact with an AI system
- Accountability for both the AI system as well as its outcome and therefore auditability of its algorithms, data and design processes

The question if these key requirements are of relevance, starts with the identification of the methods, techniques and deliverables of the LSL project in which AI is applied."

Conclusion: the use of AI for the purpose as we used it to construct this document is allowed, but its use should be described in this document, which is done.

3. European RI-related Landscape for the LSI

3.1. ESFRI Landscape Perspective

From an ESFRI Landscape Analysis perspective, LSI research and observation is not served by a single dedicated infrastructure but emerges from the interaction of multiple thematic RIs, each providing complementary expertise, spanning environmental, marine, biodiversity, solid Earth, and atmospheric domains.

Key characteristics include:

- Strong thematic excellence within individual RIs;
- Partial overlap in variables and methods across RIs;

- Limited structural integration across domains;
- Increasing reliance on EO and digital infrastructures.

The key issue is that even though strong complementarity exists, operational integration is weak.

3.2. Key Research Infrastructures in the LSI

A number of pan-European Research Infrastructures was identified as being relevant for the understanding of processes and dynamics of the LSI. These RIs are listed below and they were the main actors for the first rounds of consultations regarding the present state of knowledge, gaps and needs. These are:

- DANUBIUS-RI – river–sea systems observation and modelling, catchment-to-coast integration;
- JERICO – coastal and shelf sea observations;
- ICOS-ERIC – carbon cycle observations, including coastal, river and atmospheric carbon fluxes;
- EMBRC-ERIC – marine biological and ecological observations;
- EPOS ERIC – observation of geohazards, solid Earth processes relevant to coastal risk;
- LifeWatch ERIC – biodiversity and ecosystem observations;
- eLTER RI – long-term ecosystem observations in terrestrial and freshwater systems.

EO programmes (Copernicus, ESA missions) and data infrastructures (such as EMODnet, EOSC) are considered integral components of the landscape.

3.3. RI-related Questionnaire Responses Analysis

3.3.1. Cross-RI coverage of Parameter-domains

Cross-RI coverage snapshot:

Domain / parameter family	**DANUBIUS-RI**	**JERICO**	**ICOS-ERIC**	**EMBRC-ERIC**	**EPOS-ERIC**
Water quality	*in-situ* (continuous + periodic), EO, models	*in-situ* (continuous), EO (*used/not managed*)	—	*in-situ* (periodic)	—

Water quantity / hydrodynamics	*in-situ* (continuous), EO, models	*in-situ* (continuous), EO (*used/not managed*)	—	—	—
Nutrient loads	*in-situ* (continuous + periodic), EO, models	*in-situ* (seasonal/periodic)	—	*in-situ* (periodic)	—
Sediment quantity & quality	*in-situ* (continuous + periodic), EO, models	*in-situ* (periodic/seasonal)	—	*in-situ* (periodic)	—
Suspended sediment / turbidity	EO, models	*in-situ* (continuous)	—	—	—
Bedload	*in-situ* (periodic), models	—	—	—	—
Carbon cycle (coastal)	*in-situ* (periodic) + EO (where applicable)	*in-situ* (pCO_2, pH - continuous)	pCO_2 (in-situ; core focus)	—	—
Biology (plankton/benthos)	EO (selected products) + *in-situ* (benthos periodic)	*in-situ* (benthos continuous/periodic; plankton continuous/periodic)	—	DNA-based biodiversity (periodic)	—
Geohazards / sea level / coastal risk	In situ, EO, models	*in-situ* (continuous – waves, coastal current)	—	—	*in-situ* (seismology /sea level where relevant) + hazard services

					(tsunami, submarine landslides, GNSS/InSAR displacement, etc.)

RI-specific highlights and constraints:

DANUBIUS-RI: Broadest, end-to-end "source-to-sea" observation scope across water quality/quantity, sediments, nutrients, pollutants with *in-situ* and EO sources plus modelling as a core component. Strong potential as an integrator across the river-delta/estuary-coast continuum. Needs a stronger integration of the *in-situ* – EO – Analysis – Modelling workflow in all its Supersites (some are fully operational, whilst others are still under development). Also needs a wider extension around European River-Sea Systems (and not only) and a proper integration / transition with environmental RIs in areas of joint interest / where 2 or more RIs are being actively involved.

JERICO: Strong coastal *in-situ* capability (Physics: CTD, currents, waves, Biogeochemistry: O_2/turbidity/fluorescence/nutrients/pH/CDOM/etc.), Biology: plankton/benthos). EO and modelling are explicitly used but often not managed as core RI pipelines (suggesting integration/CalVal/data-flow gaps rather than EO data itself). Technological innovation towards the consolidation of an *in-situ* observation capacity for biological and contaminants compounds.

ICOS-ERIC: Coastal carbon observation focuses primarily on pCO_2; needs explicitly mentioning of integrating long-term autonomous deployments into the network. This supports a broader carbon-gap finding: limited routine multi-parameter carbon system coverage in dynamic LSI zones.

EMBRC-ERIC: Primarily marine biological/ecological observations in coastal waters with periodic measurements; strong in biodiversity (DNA-based) and metadata deposition practices (OBIS/ENA referenced). Needs including of automation/standardisation, increased frequency, and integration of imaging + molecular approaches, plus sustainable funding links to national programmes.

EPOS-ERIC: Adds a complementary LSI-relevant layer on coastal hazards (seismology, tsunamis, submarine landslides, GNSS/InSAR displacement, sea level monitoring services), with access through multiple platform endpoints. This expands the gap analysis beyond biogeochemistry/ecology into risk, resilience, and hazard information services.

3.3.2. Cross-RI Strengths

DANUBIUS-RI

- Full river-sea continuum coverage (catchment, river, estuary, delta, coastal);
- Hydrology, sediment transport, geomorphology, water quality, nutrients, pollutants;
- Integration of EO (satellite water quality, flood extent, coastal erosion), *in-situ* and modelling (1D-2D-3D coupling);
- Explicit focus on Cal/Val and OGC-compliant data standards.

JERICO

- High-frequency observations of coastal processes, integrating disciplines (physics, biogeochemistry, biology) and observation technologies (HF radar, buoys, ferrybox, drifter, gliders, profilers);
- Dense operational coastal observatories along all European coasts;
- Numerical modelling integration at coastal scale and strong connection to Copernicus Marine Service).

ICOS-ERIC

- Carbon system variables (pCO_2, DIC, alkalinity, salinity, temperature);
- High-quality, standardised long-term carbon observations;
- Limited but strategic coastal and estuarine carbon flux coverage.

EMBRC-ERIC

- Marine biological and genomic observations (metagenomics, metabarcoding, ARMS);
- Focus on biodiversity and ecosystem functioning;
- Coastal marine emphasis rather than riverine domain.

EPOS-ERIC

- Geohazards and solid Earth processes (earthquakes, tsunamis, landslides, ground displacement);
- GNSS, seismic networks, tsunami monitoring;
- Coastal risk and hazard components indirectly linked to LSI.

3.3.3. Cross-RI Complementarity

- Hydrology, Coastal Oceanology & Sediments (DANUBIUS-RI) + Coastal Physics (JERICO) = potential seamless physical continuum.

- Carbon cycle (ICOS) + Water quality & Nutrients (JERICO/DANUBIUS-RI) = integrated carbon-nutrient budgets.
- Biology (EMBRC/JERICO/DANUBUS-RI) + Physico-chemical drivers (JERICO/DANUBIUS-RI/ICOS) = ecosystem response capacity.
- Geohazards (EPOS) + Hydrodynamics & Morphology (DANUBIUS/JERICO) = integrated coastal risk assessment.

However, even if complementarities do exist, this advantage is not operational - RIs function as separate entities, without a detailed operational plan to develop a joint functional system.

3.3.4. Key observations emerging from the questionnaire analysis

(1) Complementarity is strong; integration is weak. The five RIs cover complementary "slices" of the LSI system (river/coast hydro-sediment-biogeochemistry; coastal physics/biology/sedimentology; coastal carbon; geohazards/sea-level). However, cross-RI joint workflows (shared variables, harmonised protocols, joint products) are still limited.

(2) *In-situ* dominates; EO is often not operationally integrated. EO is widely used but not consistently connected through sustained RI-level Cal/Val pipelines and interoperable data flows.

(3) Modelling capability is uneven. DANUBIUS deals with modelling as one of the main scientific pillars, while others do so selectively. This supports the need for explicit coupling pathways between river/hydrological and coastal/open-sea modelling communities.

(4) Carbon observations remain narrow and fragile in LSI zones. ICOS reports pCO_2 as core and identifies an integration need for autonomous systems-highlighting gaps in multi-parameter carbon system observations (and in the harsh, low-salinity, high-gradient LSI environment).

(5) Repository/access heterogeneity persists. EPOS provides multiple endpoints; JERICO is distributed through EMODnet and Copernicus Marine service (CMEMS-INSTAC for near realtime quality-checked data); ICOS uses its data centre/Carbon Portal; EMBRC references OBIS/ENA. This reinforces the need for cross-domain discovery, harmonised metadata, and machine-actionable catalogues across the LSI.

4. RI-related Identified Scientific Gaps

4.1. Continuous (geographic and temporal) Sediment and Nutrient Observation

Both DANUBIUS-RI and JERICO observe sediments and nutrients, but:

- Sediment quantity, quality and transport are often site-specific and need to be better harmonised;
- Integration with EO sediment products is not fully operational (for suspended sediments, a major effort is needed for bedload sediments);
- Continuous nutrient measurements are not systematically deployed along all coasts and estuaries and access to relevant time series of information is limited.

Gap: Operational, harmonised sediment and nutrient flux observation system at European LSI scale.

4.2. Biology-Physics-Biogeochemistry Integration

EMBRC-ERIC delivers high-level biological and genomic data as its core activity, while JERICO develops an operational observation capacity for plankton and eDNA, with DANUBIUS focussing on plankton, benthos and eDNA, but:

- Biological observations are not consistently co-located with high-frequency physical and chemical measurements (ongoing cooperation EMBRC with JERICO);
- Cross-RI workflows linking biodiversity shifts to hydrological or carbon drivers are limited (ongoing cooperation EMBRC with JERICO);
- No harmonised Essential LSI Biological Variables framework as trans-RI operational tool.

Gap: Functional ecosystem-level integration across domains.

4.3. River-Estuary-Coastal Carbon Fluxes and Coastal Storage Processes

Carbon dynamics at the land–sea interface (LSI) are governed by a combination of lateral carbon fluxes, transporting carbon from terrestrial and freshwater systems to the coastal ocean and vertical and long-term storage processes, particularly within coastal and transitional ecosystems (Blue Carbon). Together, these processes determine whether the LSI acts as a carbon source, transformer, or sink, and are therefore critical for climate regulation and greenhouse gas budgets, biogeochemical cycling, ecosystem functioning and services, policy frameworks (e.g. EU climate targets, Nature Restoration Law).

While important observation capacities exist – particularly through RIs such as ICOS-ERIC, DANUBIUS-RI and JERICO – significant gaps remain in achieving an integrated understanding and observation of carbon dynamics across the full land–sea continuum.

ICOS-ERIC provides high-quality carbon variables, while DANUBIUS-RI and JERICO provide operational carbon system observations, but:

- Limited coverage in low-salinity and highly dynamic estuarine zones;
- Few continuous carbon measurements in intertidal environments;
- Limited coupling of carbon data with sediment and nutrient transport observations.

Blue Carbon ecosystems – including salt marshes, seagrass meadows, mangroves (where applicable), tidal flats, and coastal wetlands – play a critical role in the long-term sequestration and storage of carbon at the land–sea interface (LSI). In contrast to lateral carbon fluxes (e.g. riverine transport), these systems act as carbon sinks, where carbon is stored over decadal to millennial timescales through burial processes.

Despite their importance for climate mitigation, ecosystem functioning, and policy frameworks (e.g. EU climate targets, Nature Restoration Law), Blue Carbon processes remain insufficiently observed and integrated into current LSI observation systems.

Gaps:

- Integrated lateral carbon flux quantification along the coasts and across the full continuum remains structurally weak;
- Limited long-term and high-quality datasets;
- Lack of coherent observation framework;
- Insufficient integration with sediment and geomorphological processes;
- Weak integration with EO and modelling.

4.4. Human Activities, Pollutant Interactions and Combined Pressures

Human activities and the pollutants they generate are a dominant driver of environmental change at the land–sea interface (LSI), shaping physical, biogeochemical, and ecological processes across the continuum. These pressures originate from multiple sectors and scales, including:

- Urban and industrial systems (wastewater discharge, stormwater runoff);
- Agriculture (nutrients, pesticides, land-use change);
- Coastal and maritime activities (ports, shipping, dredging, aquaculture, wind farms);
- Infrastructure development (coastal protection, land reclamation);
- Resource extraction (oil & gas, sand mining, groundwater abstraction).

While significant progress has been made in monitoring individual pollutant groups, current observation systems largely assess pollutants in isolation, rather than considering their combined behaviour and cumulative impacts on ecosystems and health.

Despite their central role, human activities and pressures are not systematically observed or integrated into LSI observation systems, which remain primarily focused on environmental state variables. A major gap is the lack of a dedicated and harmonised framework for observing human activities.

4.5. Habitat and Coastline Definition

Accurate representation of (transitional) habitats and the coastline is fundamental for understanding processes at the LSI, supporting environmental assessment, and enabling effective policy implementation. However, significant conceptual, observational, and methodological gaps exist in how coastlines and habitats are defined, mapped, and observed across Europe.

These gaps limit the ability to integrate observations across domains, compare datasets, and assess environmental status consistently.

A fundamental issue is the absence of a consistent and operational definition of the coastline. Different disciplines define the coastline based on:

- geomorphology (shoreline position),
- hydrodynamics (mean sea level, tidal limits),
- administrative or legal boundaries,
- ecological transitions (habitat zones).

Definitions vary depending on:

- spatial scale,
- temporal resolution,
- application (scientific, regulatory, operational).

This leads to:

- Inconsistencies in:
  - data collection,
  - mapping,
  - reporting.
- Misalignment between:
  - terrestrial,
  - freshwater,
  - marine observation systems.

Coastlines are inherently dynamic. They change due to tides, storms, sediment transport, sea-level rise, subsidence. The position of the coastline can vary over hours (tidal cycles), seasonally, or very long-term climate trends. However, many observation systems treat the coastline as static, fixed in space. This limits the ability to capture variability, assess risks, understand long-term change.

The LSI, besides the “classic” coastal zones, includes a wide range of transitional and highly dynamic habitats, such as estuaries and deltas, lagoons and coastal wetlands, tidal flats and intertidal zones, river plumes and mixing zones. These habitats are often underrepresented in observation systems and difficult to observe due to strong gradients, turbidity and accessibility constraints. As a result, key ecological and biogeochemical processes are poorly captured and observation coverage is uneven.

Habitat mapping and classification are fragmented across:

- European frameworks (e.g. Natura 2000, EUNIS);
- National classification systems;
- RI-specific or project-specific schemes.

This leads to lack of interoperability between datasets and difficulties in integrating physical, biological, chemical observations, as well as challenges in scaling from local to European assessments.

Current observation systems often separate habitat mapping from physical processes, biogeochemical cycles or human pressures. This limits the understanding of habitat dynamics and ecosystem functioning and the ability to link habitat changes to drivers (e.g. sediment supply, pollution, climate).

4.6. Geohazards-Ecosystem Interface

EPOS-ERIC provides strong hazard monitoring and observation (seismicity, tsunamis, ground displacement), but:

- Limited operational integration with coastal hydrodynamics water quality and ecosystem observations, performed by JERICO;
- Except for cooperation in several DANUBIUS-RI Supersites (e.g. Danube Delta) for joint cooperation on observing subsidence and related sea-level variations (eustatic and neo-tectonic + subsidence induced), there is no integration along the European LSI of hazard monitoring and observation and overall evolution of LSIs.
- Hazard-ecosystem response chains are weakly monitored;
- Data standards differ significantly from those of some of the other environmental RIs.

Gap: Integrated hazard-ecosystem and coastal risk LSI observatory framework (including understanding of overall vertical motion of the sea levels at different time and space scales).

4.7. Social Science Integration

The land–sea interface (LSI) is not only a biophysical system but also a socio-ecological system, shaped by human behaviour, governance structures, economic activities, cultural values, and policy frameworks. Effective observation, understanding, and management of the LSI therefore require the integration of social sciences alongside natural sciences.

However, social science perspectives are currently underrepresented in LSI observation systems, leading to important gaps in understanding and managing human–environment interactions.

Current LSI observation systems focus primarily on:

- Physical variables (e.g. hydrodynamics, sediment transport);
- Biogeochemical variables (e.g. nutrients, carbon);
- Ecological indicators (e.g. biodiversity).

However, they rarely include:

- Socio-economic drivers (e.g. agricultural practices influence nutrient loading, urban development affects runoff and pollution);
- Governance structures and decision-making processes (e.g., coastal management decisions impact habitats and sediment dynamics);
- Behavioural patterns and stakeholder interactions.

This limits:

- Understanding of why changes occur (drivers), not just what changes occur (states);
- Ability to design effective and socially acceptable management measures.

4.8. Cross-Domain Process Understanding

Questionnaire responses confirm that the observation of key process chains (water - sediments - nutrients - pollutants - carbon - biology - hazards) is distributed across different RIs, with limited integrated workflows spanning the European coasts as well as the full continuum. This reinforces the gap in cross-domain process understanding and end-to-end assessments along morphodynamic and salinity gradients.

4.9. Essential Variables for the LSI

The responses from the questionnaires illustrate that even for core parameter families (water quality/quantity, sediments, nutrients, pollutants), observation coverage and frequency differ substantially among RIs. Across-RI agreement on a minimal set of Essential LSI Variables and associated protocols is recommended.

Building on this need for convergence, the LandSeaLot findings indicate that a pragmatic Essential LSI Variable set should combine biogeochemical “state” variables with prerequisite physical context (e.g., water level, discharge, meteorology) and be accompanied by harmonised metadata, calibration and sampling protocols to enable cross-RI comparability and EO/model integration. LandSeaLot’s WP3 *Integrated observation and model frameworks priority list* (including: temperature, dissolved oxygen, turbidity/SPM, chlorophyll, DOC/CDOM, NO_3 and *in-situ* reflectance) emerged from expert surveys and workshops as the minimum common core capable of addressing multiple societal challenges across LILs.

5. RI-related Technical and Observational Gaps

5.1. Measurement Challenges

Hard-to-measure continuous chemistry:

JERICO identifies 'complex parameter for continuous observation' as a challenge, highlighting persistent technical gaps in robust, high-frequency chemical analysers in dynamic coastal and transitional zones. DANUBIUS-RI has *in-situ* sensors for high frequency chemical analyses in several supersites (operational and/or under construction) but the robustness and cost effectiveness of high-precision sensors is a major challenge. Biofouling of measurement buoys and connected sensors is another issue that requires cost-effective and trustworthy solutions.

EO-*in situ* alignment:

JERICO explicitly reports EO as 'used (not managed)', suggesting that a major gap is not EO availability *per se* but sustained Validation pipelines, match-up strategies, and interoperable data flows linking EO and *in-situ* coastal observations. DANUBIUS-RI proper integration of *in-situ* and EO data is still under development, seen the site-specificities of each supersite.

Across RIs:

- Low-salinity, high-turbidity, high-gradient zones are technically difficult when observation (*in-situ* and EO) is concerned;
- Biofouling and sensor degradation limit long-term deployments;

- Carbon and optical sensors have reduced reliability in turbid waters.

Gap (to be considered also as Need): Development of sensors and of smart observatories (use of AI/onboard intelligence) and harmonised deployment standards for dynamic LSI zones.

Need for sensor-satellite synergy.

5.2. Observation of Pressures

Current observation frameworks emphasise compliance with environmental indicators and do not systematically include activity-based observations, operational data from human systems. This limits the cause-effect analyses, attribution of environmental change, effectiveness of management actions.

Key limitations include:

- Monitoring of activities (e.g. dredging, discharges, land use) is sector-specific, administrative and is not designed for environmental integration;
- Lack of real-time or near-real-time data;
- Absence of harmonised monitoring protocols.

This results in:

- Disconnection between environmental and operational datasets;
- Limited ability to integrate pressures into scientific analyses.

5.3. Geographical and Coverage Gaps

Uneven coverage across Europe:

- Strong coastal coverage and strategic supersites in shelf seas (JERICO);
- Strategic supersites in river mouths, delta fronts and lagoons (DANUBIUS-RI);
- Limited coordinated pan-European coverage of deltas and smaller estuaries;
- Underrepresentation of groundwater-coastal interactions;
- Limited integration of local observatories;
- Underrepresentation of outermost regions and widening countries.

Gap: Coupling/coordinate across coastal and river-mouth supersites with gradient coverage.

Citizen Science can help fill gaps, but cannot replace long-term observation systems.

A major step that needs to be taken for the proper evaluation of the state-of-the-art concerns the analysis of existence and distribution of coastal observatories, parameters measured / observed, methodologies, storage and access to data, compatibility with other similar facilities. All categories of information regarding collected data (including existence and availability of long time series for data and meta-data) must be extended by taking into account this category of coastal research infrastructure assets.

5.4. Citizen Science

Citizen Science (CS) is increasingly recognised as a valuable component of observation systems at the land–sea interface (LSI), contributing to data collection, stakeholder engagement, and environmental awareness. It enables the participation of non-professional actors - such as local communities, NGOs, and civil society - in observations and knowledge generation.

However, despite its potential, CS is not yet systematically integrated into LSI observation frameworks, and its role remains unevenly defined and underutilised.

CS faces challenges related to:

- Perceived data quality and reliability;
- Lack of standardisation in methods and protocols;
- Limited recognition within scientific and policy communities.

As a result, CS data are often underused in scientific analysis, policy reporting and operational applications.

CS should not be seen as a replacement for long-term, systematic, professional monitoring programmes. Instead, it should be positioned as a complementary component within a hybrid observation system combining *in-situ* monitoring, EO, modelling and citizen-based data.

Key considerations include:

- Matching methods to monitoring objectives;
- Ensuring appropriate use of CS data;
- Maintaining scientific rigor and consistency.

5.5. Temporal Continuity

Many LSI observations depend on short-term projects, leading to:

- Discontinuities in time series (e.g., carbon and sediment fluxes require multi-decadal continuity), including changes in methodological approaches during decades in areas with long time series;
- Temporal resolution mismatch in information collected by different RIs.

- Reduced value for policy reporting and digital twin applications.

Gap: Sustained baseline funding model for LSI observation continuity. Consider a fit-for-purpose observation capacity of the LSI as a critical asset for Europe and the implementation of European policies (e.g., WFD, MSFD, Ocean Act, Green Deal, etc.).

5.6. Strategic Deployment of Observation Systems

Observation systems at the land–sea interface have traditionally evolved through a combination of historical investments, institutional priorities, and site-specific research interests. While this has resulted in valuable long-term datasets and well-instrumented locations (e.g. supersites), it has also led to uneven spatial coverage and suboptimal allocation of observation resources.

A key gap identified is the lack of strategic, system-level approaches to the deployment of observation infrastructures, based on scientific priorities, uncertainty assessment, and societal needs.

Numerical models and uncertainty analyses can Identify gaps in observation systems and highlight areas where model uncertainty is highest and additional observations would provide maximum benefit. However, observation deployment is rarely informed by systematic modelling-based prioritisation. There is a limited use of sensitivity analyses and data assimilation frameworks. This results in missed opportunities to optimise observation networks.

6. RI-related Data and Digital Interoperability Gaps

6.1. Data Accesibility

Data accessibility is a central pillar of effective observation systems at the land–sea interface (LSI). While large volumes of data are collected across Research Infrastructures (RIs), national monitoring systems, and local observatories, access to these data remains fragmented, inconsistent, and often limited.

A key finding of this gap analysis is that data accessibility – not data availability – is one of the primary bottlenecks in European LSI observation systems.

A substantial amount of LSI-relevant data already exists:

- In RI repositories;
- Within national and regional monitoring programmes;
- In project-based datasets;
- Held by private sector operators and agencies.

However, many datasets are not publicly available, difficult to access or not discoverable through common platforms. This creates a situation where data gaps are perceived, even when data physically exist.

Data accessibility is often constrained by:

- Institutional policies;
- Legal and licensing restrictions;
- Commercial confidentiality concerns;
- National regulations.

In particular, operational data (e.g. from industry or infrastructure) are often restricted, while publicly funded data are not always made openly available.

This highlights a critical governance issue: accessibility is often limited not by technical constraints, but by institutional and policy barriers.

A major barrier to data accessibility is the lack of clear and harmonised licensing. Many datasets lack explicit licences or have unclear reuse conditions. Users may be uncertain about whether data can be used or how they can be reused. A dataset without a clear licence is effectively not reusable, and therefore not accessible in practice.

Data accessibility is also affected by:

- Delays in data release (e.g. embargo periods);
- Lack of real-time or near-real-time access;
- Slow data processing and publication workflows.

This limits:

- Operational use of data;
- Integration into forecasting systems and digital twins;
- Timely response to environmental events.

6.2. Data Repository Heterogeneity

Data remain distributed across multiple RI-specific repositories with:

- Inconsistent metadata and vocabularies;
- Variable levels of openness and machine readability;
- Limited cross-domain discoverability.

Questionnaire responses show heterogeneous repository and access models: distributed European data nodes (JERICO), multiple service endpoints (EPOS), RI-specific data centres (ICOS), and thematic repositories (EMBRC with OBIS/ENA). This confirms the need for cross-domain discovery layers, harmonised metadata, and machine-actionable catalogues to support LSI-scale integration.

Gap: No unified LSI data discovery layer enabling seamless cross-domain search and machine-actionable integration.

6.3. Data Stewardship, Licensing and Reuse

Effective observation at the land–sea interface (LSI) depends not only on data generation but on the ability to manage, curate, share, and reuse data over time. This requires robust data stewardship practices and full implementation of the FAIR (Findable, Accessible, Interoperable, Reusable) principles.

The primary bottleneck in LSI data systems is not data availability, but data stewardship, usability, and governance.

While large volumes of data are collected across RIs, national monitoring systems and local observatories, their value is often constrained by insufficient investment in data management, lack of incentives, and weak governance frameworks.

Data stewardship encompasses:

- Data curation and quality control;
- Metadata creation and standardisation;
- Long-term storage and preservation;
- Accessibility and reuse;
- Governance and accountability.

However, data stewardship is often underfunded, decentralised and treated as a secondary activity. Responsibility for data management is unclear or fragmented, and the long-term sustainability of datasets is not guaranteed. This leads to loss of valuable data, reduced usability and accessibility, inefficiencies and duplication of effort.

Unclear or inconsistent licensing is a major barrier to effective data reuse, integration, and policy application.

A significant proportion of LSI-relevant datasets do not include explicit licensing information, provide incomplete or ambiguous terms of use or are shared informally without clear reuse conditions. In such cases, users cannot determine whether data can be reused, under what conditions, for which purposes. As a result, a dataset without a clear licence is effectively non-reusable, even if technically accessible.

Due to unclear or complex licensing, users may avoid using datasets altogether. Legal uncertainty leads to risk-averse behaviour and reduced data utilisation.

This reduces the scientific impact, the innovation potential and the policy relevance.

6.4. Metadata and Standards

Although RIs emphasise FAIR principles:

- Parameter naming conventions differ;
- Protocols for sediment, nutrient, and carbon flux harmonisation differ;
- Hazard data models differ strongly from water-quality models.

Gap: Harmonised Essential LSI Variables and ontology aligned with EOSC and EMODnet.

6.5. Freshwater Data Gap

The land–sea interface (LSI) fundamentally depends on the continuity between freshwater, transitional, and marine systems. Rivers, catchments, and inland waters provide critical inputs of water, sediments, nutrients, carbon, pollutants, and biota to coastal environments.

Despite this, a major structural gap exists in the availability, accessibility, standardisation, and integration of freshwater data within LSI observation systems. Compared to marine and coastal domains, freshwater data systems are less harmonised, less accessible, and less integrated at European scale.

Marine data in Europe benefit from relatively mature and coordinated infrastructures, such as EMODnet, Copernicus Marine Service, RI-based data systems.

In contrast, freshwater data are highly fragmented across national agencies, regional authorities, basin-level organisations.

There is no equivalent system providing standardised access, harmonised datasets, cross-border integration for freshwater observations.

6.6. AI-Readiness and Digital Twin Integration

Parameter questionnaires reveal modelling capacities (especially DANUBIUS-RI and JERICO), but:

- No common and shared approaches cross-RI on data assimilation;
- Limited shared uncertainty quantification frameworks and tools;
- Insufficient harmonisation in approaches for data assimilation and AI applications;
- Incomplete integration of different relevant modules, such as hazard, hydrology, carbon and ecosystem modules;

- Organisation and volume of data (datasets) that enabled the appropriate training, validation and update of AI models
- Limited operational data pipelines feeding Digital Twins of the LSI.

Gap: AI-ready cross-domain data structure and pipelines for Digital Twins of the LSI.

7. RI-related Governance and Coordination Gaps

7.1. Inter-RI Coordination

Despite strong goodwill, cross-RI coordination remains largely project-based. Gaps include:

- Absence of sustained mechanisms for joint planning and prioritisation;
- Limited shared roadmaps for technology, standards, and services;
- Harmonisation efforts depend on project funding.

The questionnaires revealed that integration challenges are often organisational rather than purely technical (e.g., EO 'used but not managed'; distributed national-node governance). This reinforces the need for sustained inter-RI coordination mechanisms (beyond projects) to maintain harmonisation and integrated services.

There is a clear need to strengthen the position of the Land Sea Interface areas, as parts of the coastal/shelf areas, a scientific must for the background of the future Ocean Act. Efforts must be permanently made for the recognition of the critical role of LSI in the management of the marine basins but also for the sustainability of the hydrographic basins and continents as a whole. This is why it is a strategic need to consider the LSI areas as “bridges” and not boundaries between domains, with a dedicated observation plan at the continental scale.

7.2. Institutional Fragmentation

Institutional fragmentation is one of the most critical structural barriers to effective observation, integration, and management of the LSI. While Europe benefits from a rich landscape of RIs, national monitoring systems, and regional initiatives, these operate largely in parallel rather than as a coordinated system.

Siloed structures, fragmented responsibilities and lack of coordination limit the effectiveness of existing observation capacities.

LSI observation spans multiple scientific domains, often organised in separate communities supported by different RIs and funding streams. They use different concepts, variables, standards, data systems. This results in limited cross-domain integration, gaps in understanding processes across the continuum, duplication of efforts and inefficiencies.

Although RIs provide complementary capabilities, they are not fully integrated operationally:

- Limited joint planning and prioritisation;
- Few shared workflows and products;
- Lack of sustained coordination mechanisms beyond projects.

This reinforces:

- Siloed operation;
- Missed opportunities for synergy.

7.3. Stakeholder Engagement

Stakeholders – including public authorities, monitoring agencies, industry actors, NGOs, and local communities – are not only users of data, but also producers, contributors and co-designers of observation systems. However, despite its recognised importance, stakeholder engagement remains fragmented, uneven and often insufficiently integrated into the design and operation of LSI observation systems.

Stakeholders play multiple roles:

- Data providers (e.g. environmental agencies, monitoring networks, operational services, industry datasets);
- Data users (e.g. policymakers, planners, researchers, private sector);
- Knowledge holders (e.g. local communities, practitioners, citizen scientists);
- Co-design partners (in defining observation needs and priorities).

Despite this, observation systems are still largely science-driven, top-down and insufficiently co-designed with stakeholders. Stakeholders are often involved late in project cycles, in consultation rather than decision-making roles. Observation priorities are not always aligned with user needs, operational requirements, policy demands. This leads to mismatch between data produced and data needed, reduced relevance and uptake of observation systems.

Stakeholders often face barriers in:

- Accessing relevant data;
- Contributing their own data;
- Using data in operational contexts.

Challenges include:

- Complex or fragmented data platforms;
- Lack of user-friendly tools and services;

- Limited support for data integration and interpretation.

This limits:

- Practical use of observation systems;
- Impact on decision-making.

7.4. Policy Alignment Gaps

While individual RIs support WFD, MSFD and hazard directives:

- No integrated LSI indicator suite spanning hydrology-carbon-ecosystem-hazard domains;
- Reporting cycles are not fully aligned from a temporal point of view (e.g. different reporting periods for the MSFD and the WFD – or evaluation of national policies) ;
- Policy maker requirements are not yet consolidated across RIs.

Gap: Co-designed LSI policy indicator framework.

7.5. Fragmentation Management

Fragmentation is an inherent characteristic of the LSI observation landscape. It arises from:

- The diversity of scientific domains (terrestrial, freshwater, marine);
- The multiplicity of institutional actors (RIs, national agencies, regional systems);
- The coexistence of different policy frameworks;
- The distributed nature of observation systems and data infrastructures.

While fragmentation is often perceived as a limitation, it also reflects diversity of expertise, specialisation of observation systems, adaptation to local and regional contexts.

A key conclusion of this analysis is that fragmentation cannot be eliminated, but must be effectively managed to enable integration, interoperability, and coordinated action.

Traditional approaches aim to reduce fragmentation through centralisation and standardisation. However, full centralisation is neither feasible nor desirable in the LSI context. Fragmentation is a structural feature of multi-scale systems, distributed governance, diverse observation needs. The challenge is therefore to shift from eliminating fragmentation to managing and leveraging it.

Fragmentation occurs across multiple dimensions:

- Scientific fragmentation (separate disciplines and methodologies);
- Institutional fragmentation (multiple organisations with overlapping roles);
- Data fragmentation (distributed repositories and formats);

- Geographical fragmentation (uneven spatial coverage);
- Policy fragmentation (different frameworks and reporting requirements);
- Stakeholder fragmentation (diverse and disconnected communities).

These dimensions are interrelated and reinforce each other.

If fragmentation is not effectively managed, it leads to:

- Duplication of efforts and inefficiencies;
- Gaps in spatial and thematic coverage;
- Inconsistent data and methodologies;
- Limited interoperability and integration;
- Reduced usability of observation systems;
- Increased burden on stakeholders and users.

This ultimately reduces:

- Scientific impact;
- Policy relevance;
- Cost-effectiveness of investments.

When properly managed, fragmentation can provide:

- Diversity of data sources and perspectives;
- Resilience and redundancy in observation systems;
- Flexibility to address local and regional needs;
- Innovation through multiple approaches and technologies.

Therefore, the objective is to enable coherence without uniformity.

Effective fragmentation management requires:

- Coordination frameworks rather than centralisation;
- Linking systems across scales:
  - Local observatories;
  - Regional and national observation systems;
  - European RIs;
  - Global initiatives.

Key challenges include:

- Ensuring compatibility across scales;
- Integrating diverse data sources;
- Maintaining relevance for local users while enabling global assessments.

8. Synthesis of RI-related Gap Categories

Our gap analysis identifies nine overarching gap categories:

(1) **Integration and Fragmentation Gaps**
(2) **Geographical and Continuum Coverage Gaps** - incomplete operational linkage along the coasts of Europe, as well as in the catchment-to-sea approach;
(3) **Human Pressure Observation Gaps**
(4) **Process Coupling Gaps** - weak integration of carbon, nutrients, sediments, biodiversity and hazards;
(5) **Standardisation Gaps** - variables, methods, metadata, and protocols;
(6) **Digital and Interoperability Gaps** - AI-readiness, accessibility and interoperability;
(7) **Data Stewardship and FAIRness Gaps**
(8) **Governance and Coordination Gaps**
(9) **Sustainability and Funding Gaps** - funding continuity and governance integration.

9. Implications for Joint Actions of RIs

The identified gaps provide a clear rationale for joint (i.e. among RIs):

- Development of multi-RI LSI supersites covering full gradients;
- Co-definition of Essential LSI Variables;
- Harmonised sediment-carbon-nutrient flux observation strategy;
- Joint Validation reference stations;
- Strengthened links between *in-situ*, EO, and modelling communities;
- Creation of a federated LSI data discovery and integration layer;
- Strategic engagement with ESFRI and EU policy processes.
- Influencing and strategically use INFRA-DEV, INFRA-SERV and INFRATECH calls;

These implications will be further elaborated in subsequent LandSeaLot deliverables and in the next iteration of the LCOS.

10. Gaps and Needs expressed by stakeholders in the LandSeaLot Integration Labs

10.1. Role of stakeholder consultations in the Joint Gap Analysis

In addition to the Research Infrastructure (RI) questionnaires and European-level analyses, we conducted structured stakeholder consultations across all LandSeaLot Integration Labs (LILs). These workshops engaged local and regional authorities, environmental agencies, research institutes, NGOs, and operational monitoring organisations to identify observation needs, data practices, and perceived gaps along the LSI.

The LIL consultations provided a complementary bottom-up perspective to the RI-centred analysis presented in previous chapters. While RI inputs describe existing European observation capacities, the LIL stakeholder discussions reveal how these capacities are perceived, used, and required at local and regional operational scales.

Across all LILs, stakeholders highlighted the high relevance of LSI observations for environmental management, policy implementation (WFD, MSFD), coastal risk reduction, and ecosystem protection and restoration. However, they consistently pointed out fragmentation, limited accessibility, and insufficient integration of existing data and observation systems.

10.2. Stakeholder landscape and engagement patterns

The stakeholder composition across LILs shows a consistent multi-actor landscape including:

- Regional and national environmental authorities and water agencies;
- Monitoring and hydrographic institutions;
- Universities and research centres;
- NGOs and citizen organisations;
- Operational coastal and maritime services.

Stakeholders are often themselves data producers (monitoring networks, modelling outputs, EO use) and therefore represent both users and providers of LSI observations. For example, agencies in several LILs operate buoys, coastal stations, modelling systems, or environmental monitoring programmes.

Across LILs, stakeholders showed strong interest in continued engagement – under appropriate governance conditions – through:

- Data sharing and integration;
- Co-design of observation strategies;
- Participation in low-cost sensor deployment;
- Citizen Science activities;
- Consultation on the LandSeaLot observation strategy.

10.3. Observation and data gaps identified by the stakeholders

Despite regional diversity, stakeholder consultations revealed highly consistent gap categories across LILs, largely aligned with the scientific and technical gaps identified from RI analyses.

10.3.1. Fragmentation and limited interoperability of regional data

Stakeholders across LILs reported that relevant LSI data exist but remain distributed across institutions, projects, and platforms with heterogeneous access conditions and standards. Several LIL discussions highlighted the need to inventory and compile existing monitoring and research data at regional scale.

Operational datasets (e.g., buoy networks, coastal webcams, FerryBox systems, modelling outputs) are often not interoperable or not accessible in real time, limiting their integration into broader LSI analyses and services.

This directly confirms the digital and interoperability gaps identified at RI level, including heterogeneous repositories and lack of unified discovery layers.

10.3.2. Insufficient integration across the land–sea continuum

Many stakeholders emphasised the importance of understanding catchment-to-coast processes for management tasks such as nutrient reduction, sediment dynamics, or ecosystem status assessment. For example, water management stakeholders stressed that upstream measures often show unclear effects in coastal waters, highlighting weak continuum understanding.

Similar concerns were raised in multiple LILs regarding river fluxes, coastal carbon transport, sediment dynamics, and eutrophication processes. These needs mirror the RI-level scientific gaps on integrated river–estuary–coastal flux quantification and cross-domain process understanding.

10.3.3. Operational monitoring limitations in transitional and coastal zones

Stakeholders consistently identified insufficient monitoring coverage and resolution in transitional waters, estuaries, and nearshore zones. Examples include:

- Lack of continuous nutrient and sediment observations;
- Insufficient turbidity and water-quality observations;
- Limited estuarine and intertidal measurements;
- Gaps in carbon and ecosystem observations.

Regional agencies and monitoring organisations stressed the need to strengthen observation networks and integrate satellite, *in-situ*, and modelling data.

10.3.4. Need for harmonised methodologies and quality control

Several LIL discussions – particularly in the Wadden Sea–Rhine–Elbe, Po Delta and North Adriatic and North Aegean LIL – highlighted challenges related to sensor calibration, quality control, and harmonised protocols. Stakeholders expressed interest in shared monitoring guidelines and best practices (e.g., turbidity monitoring manuals and common validation procedures).

This confirms the standardisation gaps identified at RI level, including divergent protocols and variable definitions across observation domains.

10.3.5. Limited long-term sustainability of regional observations

Stakeholders noted that many monitoring or observation activities depend on projects or regional funding cycles, affecting continuity and long-term data series availability. They also emphasised the need to ensure afterlife and integration of data from past projects.

This corresponds to the temporal continuity and sustainability gaps identified in the RI responses.

10.4. Stakeholder perspectives on participation and co-design

Overall, stakeholder engagement across LILs ranges from willingness to share data and participate in consultations to active co-development of monitoring strategies and citizen-science initiatives, confirming strong regional readiness for co-designed LSI observation systems.

LIL-specific perspectives further illustrate regional engagement patterns:

Tagus and Sado Estuaries System LIL (Portugal)

Stakeholders showed interest in expanding observation capacity (e.g. additional buoys/sensors) and integrating satellite and *in-situ* data into modelling and operational applications, indicating readiness to co-design observation enhancements.

Wadden Sea–Rhine–Elbe LIL (Germany)

Key institutional stakeholders (e.g. BSH, LKN.SH) expressed strong interest in collaboration, data integration (e.g. FerryBox, Copernicus), and joint definition of parameters and workflows, confirming commitment to co-develop observation strategies.

Wadden Sea–Rhine–Elbe LIL (Netherlands)

Stakeholders focused on alignment of environmental targets and coordinated observation initiatives across projects and countries, demonstrating interest in joint knowledge development and collaborative observation planning.

Baltic LIL (Finland)

Regional authorities and sustainability organisations welcomed the LIL plan and actively engaged in discussions on observation needs and connections, indicating willingness to contribute expertise and data to the co-design process.

Baltic LIL (Sweden)

Participants expressed interest in continued participation, structured stakeholder–science interaction, and compilation of existing monitoring data, highlighting readiness for sustained collaboration and co-design.

Danube Delta and coastal area LIL (Romania)

All stakeholders confirmed willingness to engage in observation gap filling through data sharing, low-cost sensor deployment, citizen science, and consultations on the observation strategy.

North Aegean LIL (Greece)

Stakeholders emphasised collaboration on maintaining monitoring networks, consolidating data across authorities, and supporting participatory observation (including low-cost sensors and citizen involvement), reflecting strong co-design potential.

Po Delta and North Adriatic LIL (Italy)

Stakeholders indicated openness to share data, test sensors, and connect to international initiatives, with particular interest in integrating existing observation practices and datasets into LandSeaLot activities.

Seine Estuary and Bay LIL (France)

The workshop highlighted an established multi-actor observation community already collaborating through regional programmes, demonstrating readiness to integrate LandSeaLot into ongoing stakeholder-science coordination structures.

10.5. Synthesis: Stakeholder-related gap categories

The cross-LIL analysis confirms five overarching stakeholder-related gap categories, consistent with the RI-related gap analysis:

1. **River-to-Sea Continuum Observational gaps**
   Limited integration of catchment–estuary–coastal processes in observation and management.
2. **Geographical (along coastline) Observational gaps**
   Insufficient coverage and resolution in transitional and coastal environments.
3. **Standardisation gaps**
   Need for harmonised methods, protocols, and quality control across institutions.
4. **Digital and interoperability gaps**
   Fragmented datasets, limited accessibility, and lack of regional data integration.
5. **Governance and sustainability gaps**
   Project-based observations, weak coordination, and lack of long-term funding continuity.

These stakeholder-related gap categories strongly reinforce the RI-based findings that Europe’s primary LSI challenge lies in integration and coordination rather than absence of observation capacity.

10.6. Implications for the LandSeaLot LSI observation strategy

The LIL stakeholder consultations indicate that:

- Regional observation and monitoring systems represent a major but under-integrated component of European LSI observation capacity;
- Stakeholders are willing to contribute data and participate in co-design if coordination mechanisms exist;
- Integration of regional observation assets is essential to close identified European LSI gaps.

These findings support the RI-related gap analysis conclusion that a comprehensive inventory and integration of local and regional coastal observatories is a critical next step for the LandSeaLot Common Observation Strategy.

Accordingly, stakeholder engagement through LILs should be considered a core pillar of future European LSI observation consolidation, complementing RI-level integration and contributing to the development of multi-scale LSI supersites and harmonised observation frameworks.

11. Conclusions

The analysis of the RIs Questionnaire responses provided concrete, parameter-level evidence that LSI observation capability is distributed across multiple European RIs, each covering complementary parts of the hydrology–sediment–carbon–ecosystem–hazard continuum. This confirms that Europe does not suffer primarily from a lack of scientific excellence or isolated observation capacity.

Rather, the questionnaire responses clarified that the most critical gaps concern integration and operationalisation (e.g., shared protocols, unified discovery, EO Validation pipelines,), not just missing observatories or sensors. These include:

- Insufficient cross-RI integration of workflows and data pipelines;
- Limited operational EO–*in situ* calibration/validation chains at the LSI scale;
- Absence of harmonised Essential LSI Variables and shared ontologies;
- Fragmented discovery layers and machine-actionable interoperability across repositories.

The following priority gaps are particularly well pointed out by the RIs questionnaire evidence:

(1) **Continuous, high-quality chemical observations (including contaminants) in nearshore and transitional waters.** JERICO responses highlight constraints in sustained, harmonised, high-frequency chemical monitoring in dynamic estuarine and intertidal environments.
(2) **Broader coastal carbon system coverage and autonomous integration**. ICOS responses confirm the need to expand multi-parameter carbon observations and better integrate long-term autonomous deployments within highly variable LSI zones.
(3) **Enhanced observation of the biodiversity and ecosystem functioning (process level) across the LSI.**

The gap analysis in this deliverable confirms that Europe possesses strong but fragmented capabilities to observe and understand the land-sea interface. Fragmentation arises from:

- The diversity of scientific domains (terrestrial, freshwater, marine);
- The multiplicity of institutional actors (RIs, national agencies, regional systems);
- The coexistence of different policy frameworks;
- The distributed nature of observation systems and data infrastructures.

While fragmentation is often perceived as a limitation, it also reflects diversity of expertise, specialisation of observation systems, adaptation to local and regional contexts.

A key conclusion of this analysis is that fragmentation cannot be eliminated, but must be effectively managed to enable integration, interoperability, and coordinated action.

Traditional approaches aim to reduce fragmentation through centralisation and standardisation. However, full centralisation is neither feasible nor desirable in the LSI context. Fragmentation is a structural feature of multi-scale systems, distributed governance, diverse observation needs. The challenge is therefore to shift from eliminating fragmentation to managing and leveraging it.

Fragmentation occurs across multiple dimensions:

- Scientific fragmentation (separate disciplines and methodologies);
- Institutional fragmentation (multiple organisations with overlapping roles);
- Data fragmentation (distributed repositories and formats);
- Geographical fragmentation (uneven spatial coverage);
- Policy fragmentation (different frameworks and reporting requirements);
- Stakeholder fragmentation (diverse and disconnected communities).

These dimensions are interrelated and reinforce each other.

If fragmentation is not effectively managed, it leads to:

- Duplication of efforts and inefficiencies;
- Gaps in spatial and thematic coverage;
- Inconsistent data and methodologies;
- Limited interoperability and integration;
- Reduced usability of observation systems;
- Increased burden on stakeholders and users.

This ultimately reduces:

- Scientific impact;
- Policy relevance;
- Cost-effectiveness of investments.

When properly managed, fragmentation can provide:

- Diversity of data sources and perspectives;
- Resilience and redundancy in observation systems;
- Flexibility to address local and regional needs;
- Innovation through multiple approaches and technologies.

Therefore, the objective is to enable coherence without uniformity.

Effective fragmentation management requires:

- Coordination frameworks rather than centralisation;

- Linking systems across scales:
    - Local observatories;
    - Regional and national observation systems;
    - European RIs;
    - Global initiatives.

Key challenges include:

- Ensuring compatibility across scales;
- Integrating diverse data sources;
- Maintaining relevance for local users while enabling global assessments.

The most critical gaps are not absence of observation capacity *per se*, but lack of cross-domain integration, harmonisation, and sustained coordination. Addressing these gaps requires consolidation rather than duplication and alignment with ESFRI Landscape priorities and positioning LandSeaLot as a catalyst for structured European LSI integration.

The outcome of the engagement with the stakeholders in the LandSeaLot Integration Labs (LILs)supports the overall conclusions regarding the RI-related gap analysis. Stakeholder consultations across all LILs provide robust empirical evidence that regional observation systems exist but remain fragmented, insufficiently integrated, and often unsustained. The gaps identified by stakeholders closely match those derived from the RI-related gap analyses, confirming the systemic nature of European LSI observation fragmentation.

The LIL process demonstrates both the necessity and feasibility of integrating regional stakeholders and observatories into the European LSI observation landscape. Strengthening these linkages will be essential for achieving an operational, integrated, and sustainable Land–Sea Observation capacity in Europe.

A major gap identified in this deliverable regards the need for detailed information concerning the existence and services offered by the plethora of coastal observatories of local, regional and national interest, scattered throughout Europe. All aspects concerning measured parameters, methodologies for data collection, analysis, storage and accessibility to long-term data series must be dealt with before coming to strong conclusions on how to fill the relevant gaps in knowledge for a Land Sea Observation Strategy.

Implications and Actions derived from the current gap analysis:

Several of these proposed actions are to be implemented by the relevant European Research Infrastructures with interest in Observing the Land Sea Interface, as well as with the major institutional partners with similar interests.

(1) Permanent

- Harmonise metadata and standards

(2) Short-term
  - Develop Essential Land–Sea Variables (ELSV) framework;
  - Strengthen EO–*in-situ* validation;
  - Improve data accessibility.

(3) Medium-term
  - Integrate regional observatories;
  - Establish federated data systems.

(4) Long-term
  - Strengthen governance structures;
  - Align EU policies;
  - Develop sustainable funding models.

12. Annexes

- RIs questionnaires responses or https://gis.geoecomar.ro/stocare/index.php/s/zsF44SJ4Kiycsyt
- LSL Week 2026: LCOS - Gap Analysis workshop groups feedback or https://gis.geoecomar.ro/stocare/index.php/s/rKtX7DmAzQJEjQe